Clarinet Toneholes:

A Study of Undercutting and its Effects

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Abstract.

Clarinets made from the eighteenth century to the present have been examined to determine the degree of undercutting which has been applied to the toneholes. Early clarinets with small toneholes, designed to permit fork fingerings, were routinely undercut to improve the volume and tone quality. However it has been found that as keywork mechanisms allowed toneholes to be enlarged and placed according to acoustic requirements, the practice of undercutting continued.

Good quality Boehm system instruments manufactured today are invariably undercut, but some twentieth-century makers produced professional models in which there was no undercutting.

Experiments have been made in which the acoustic input impedance of specially prepared clarinets with interchangeable toneholes has been measured. The acoustic input impedance spectra showed only small changes in mode alignment as a result of undercutting at low drive levels. Under normal playing conditions, using an artificial mouth to maintain a constant embouchure, it has been demonstrated that undercutting a single hole can shift the frequency ratio between corresponding notes in the lower and upper register closer to 3:1 (i.e. a musical twelfth). Also, asymmetric upstream undercutting is shown to be an effective method of achieving this change.

The artificial mouth has also been used to explore the inadequacies of fork fingerings in the chalumeau region of the 'Classical' clarinet. Also the effects of undercutting, rather than uniformly enlarging the holes, on tuning and timbre has been examined.

An experiment was performed,in which eighteen clarinettists were asked to appraise specially prepared clarinets. Three identical cheap clarinets were obtained, none of which was undercut. One was left as a control, one was undercut and the third had all of the sharp edges at the intersections of the toneholes with the bore carefully rounded and smoothed. Whilst the undercut instrument was rated to be of significantly higher quality than the control, a majority of players preferred the smoothed instrument, mainly because of its even playing quality. Subsequently the undercut clarinet was adjusted and re-tested and a selected group of the original testers found it to be marginally better than the smoothed instrument, which they had previously rated as good.

CONTENTS.

Appendices:

Bibliography.[1]

[1] The Bibliography section at the end includes books and papers cited in the text and others which are relevant to the work. Papers are shown as: [Author, Date]. Books are shown with Bold face for the author: [**Author**, Date].

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Introduction

Undercutting is the process of enlarging woodwind instrument toneholes in the region where they meet the bore whilst leaving the external hole size unchanged. Manufacturers of clarinets may undercut the toneholes either as part of the design specification or as a means of final adjustment. When used for adjustment, a skilled craftsman (or occasionally the purchaser) would play the instrument and then undercutting would be used to correct minor deficiencies, usually of tuning.

In general, good quality clarinets manufactured today are undercut during manufacture as part of the design, but cheaper 'student' models may not be. The cost of undercutting is a factor here. However, in the twentieth century, some of the major manufacturers produced top-of-the-range instruments for professional use which were not undercut.

The use of undercutting as a design feature is complicated. The effect of undercutting depends not only on the shape and extent of the enlargement but also on the bore size, the tonehole sizes and the wall thickness. Historically, all of these parameters have tended to increase during the evolution of the clarinet, and the overall effect has been to make the effects of undercutting more subtle. This will be discussed in the section on the development of the instrument.

Various claims, some contradictory, are made about the differences in tone quality produced by clarinets with and without undercutting. In reality, because of other factors involving the instrument and the player, it is not possible to judge reliably from the sound produced whether the instrument is undercut [**Gibson** 1994]. Furthermore, most players are unable to relate any differences in the 'feel' of the instrument to the geometry of the toneholes with any degree of confidence.

Where undercutting is used as an adjustment procedure, individual toneholes are progressively enlarged, usually to raise the pitch of a note or notes associated with the hole, or to improve the quality of an individual note. Players use the expression 'stuffy' to describe a note which is inferior in volume or timbre in comparison with adjacent notes. Undercutting has a similar (but not identical) effect to increasing the hole diameter, but has the advantage that no changes need to be made to the key work or pad seatings, since the exterior part of the tonehole remains unchanged.

A particular problem with clarinets is the difficulty of designing an instrument in which the musical interval of a twelfth between the lower and upper registers is accurate over the full range of notes. This is a characteristic of a quarter-wave, open-closed cylinder which is forced to 'overblow' by opening a single speaker hole at a fixed position, as will be described in Part 1, which is a brief outline of clarinet acoustics.. The problem has been largely overcome by slightly perturbing the bore from a true cylinder at the ends. However it has been found empirically that, in some parts of the instrument, judicious asymmetrical undercutting of an individual tonehole can be used to adjust the pitch in one register whilst leaving the pitch of the equivalent note in the other register relatively unchanged. The physical explanation for this effect is not well understood but the technique is well established in practice (as for other woodwind instruments).

A survey of clarinets has been undertaken to establish the history of the use of undercutting, against the background of the acoustical development of the instrument. This survey, and the conclusions drawn from it, form Part 2 of this thesis.

Whilst carrying out the survey, a number of questions about the role of undercutting arose. Acoustic measurements and playing experiments have been made in an attempt to find physical explanations for some of its observed and perceived effects. This experimental work forms Part 3.

The work is summarised in Part 4 and conclusions are presented.

This study has two main objectives:

1. To survey the extent to which undercutting has been applied to the toneholes of the clarinet throughout its history and to relate the findings to the development of the instrument.

2. To determine the effects of undercutting by physical (acoustic) measurements, and subjectively, by playing the instruments. This part of the work includes experiments: i) to measure the effect on modal ratio of undercutting a single tonehole under playing conditions; ii) to determine whether acoustic input impedance spectra measured at low drive levels can be used to detect improved mode alignment resulting from

undercutting; iii) to compare undercutting with cylindrical hole enlargement in the context of fork fingering in an early 'classical' type of clarinet; and iv) to record players' observations when playing specially prepared clarinets with different tonehole shapes and finishes.

To achieve these aims, specialised equipment was made or modified for the project, including an internal three-point bore gauge, a travelling telescope for tonehole position measurements, an internal inspection device ('borescope') for examining undercutting, the artificial mouth referred to above to play a clarinet with constant embouchure, an acoustic input impedance measuring head and its associated circuitry, and a number of experimental clarinets.

Conventions:
The clarinet is a transposing instrument. Throughout this thesis the musical notes referred to in the text relate to clarinet fingerings (e.g. D_4 on a Bb clarinet sounds C_4 Concert Pitch using the U.S.A. Standard Association octave notation). Appendix A shows other octave notation and the range of frequencies for Bb and A clarinets, based on an equally tempered scale with A_4 Concert pitch = 440 Hz. Subscript octave numerals have been used throughout.
Roman numerals have been used to specify fingerholes as shown in Section 1.2.2.

Part 1. Clarinet Acoustics: A Brief Outline

1.1. Overview of Clarinet Acoustics

The acoustical behavior of the clarinet has been extensively studied, particularly in the last decades of the twentieth century. There are many papers in the scientific journals which cover all aspects of the physical processes involved in the operation of the clarinet. Much of this material has now appeared in textbook form, the most important being those by Backus, Benade, Campbell and Greated, Fletcher and Rossing, Fletcher, and Nederveen. Books specifically about the clarinet which refer to its acoustic behavior include those by Brymer, Ferron, Gibson, Rendall, and Baines (who covers all woodwind). Details can be found in the References section.

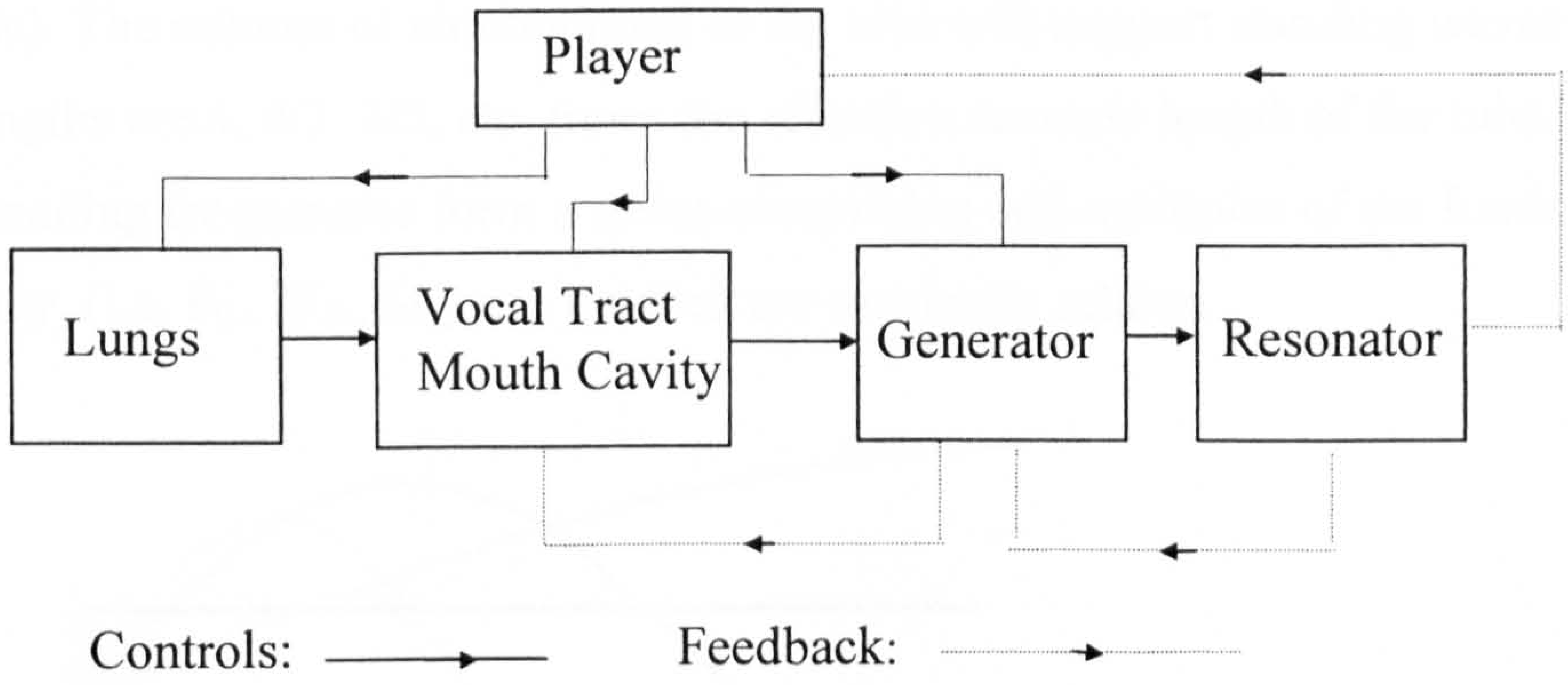
In this section an outline of clarinet acoustics is presented. The intention is not to give a complete account, but to provide sufficient information that the acoustic measurements on undercut toneholes which appear later can be understood.

1.1.1 Acoustic Description of a Clarinet.

The clarinet can be treated as a combination of a resonator and a generator (or excitation system), coupled together via a feedback mechanism. The resonator behaves mostly linearly, whereas the excitation system behaves mostly non-linearly. Physically, the resonator is the column of air contained in the effective length of the bore of the instrument. That is, to a first approximation, the air between the top of the mouthpiece and a point some way below the first open hole or the end of the bell, if all toneholes are closed. The generator, or excitation system, is the combination of the reed, the top of the mouthpiece and the player's embouchure, together with the air pressure in the player's mouth. When attempting to describe the physical behaviour of the instrument it is usual to treat the linear and non-linear parts separately.

A linear system is one in which the response to a stimulus is proportional to the magnitude of the stimulus. When the system is also time invariant, Fourier transforms between the time and frequency domains and vice versa can be applied. More complicated techniques are required to deal with the non-linear phenomena in which the response is not proportional to the stimulus.

The interactions between the player, the resonator and the generator can be depicted schematically [Fletcher 1990] as below:



Control and feedback mechanisms for a clarinet.

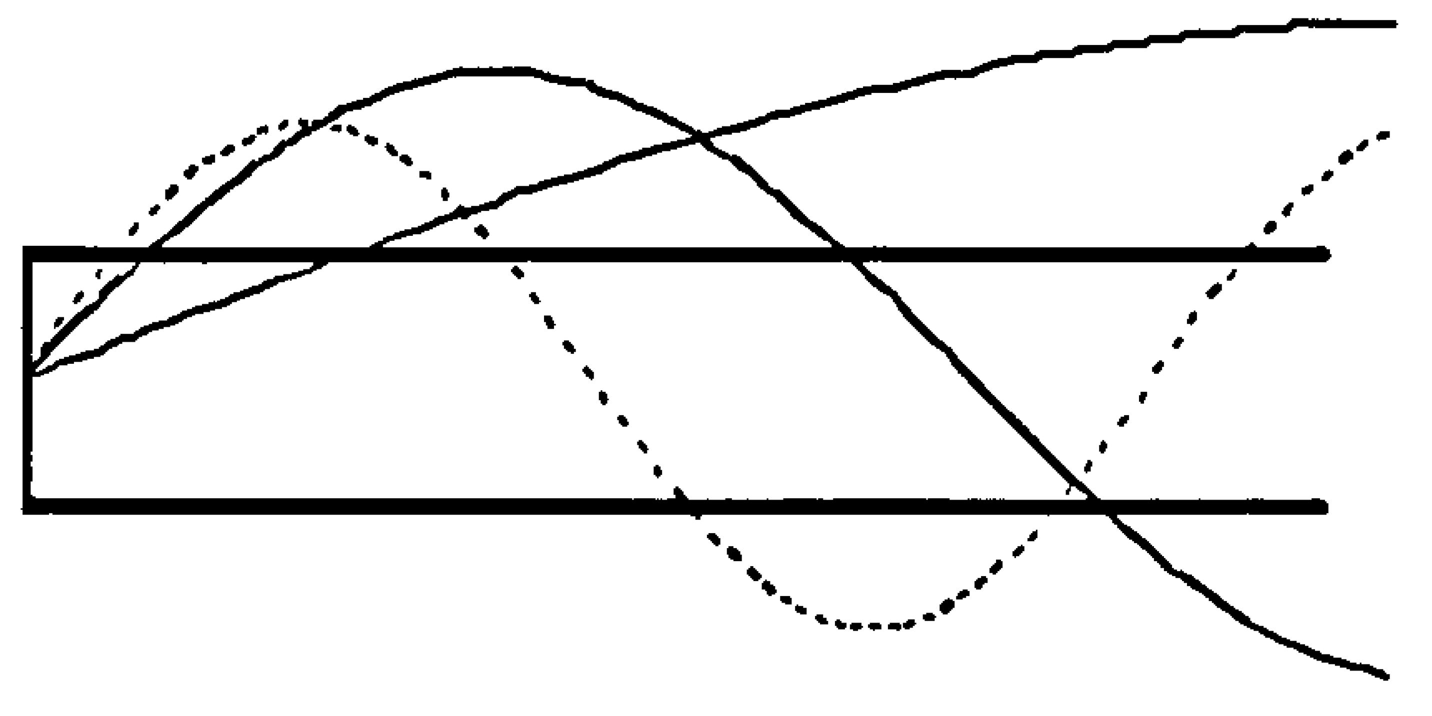
Fletcher and Rossing [**Fletcher** 1997] have estimated that when playing loudly, the input energy supplied by the player might be in the region of 0.3 to 0.5W for an acoustic output of about 1 mW. Most of the energy loss occurs by dissipation in the generator, which behaves as a pressure controlled flow valve. Of the energy residing in the resonating column of air, most is dissipated by viscous and thermal losses at the tube walls. The radiated loss, which is the sound the instrument makes, represents only about 1% of the internal acoustic energy in the resonator.

In the following sections the linear parts will be considered first, followed by the non-linear parts and the feedback mechanism.

1.1.2 Linear System. The Resonator.

1.1.2.1 Standing Waves.

Acoustically the clarinet behaves to a first approximation as a cylindrical tube closed at the reed end (displacement node) and open at the other (displacement antinode). The column of air contained in the tube will support standing waves whose wavelengths are 4, 4/3, 4/5, etc. times the effective acoustic length of the tube. The corresponding frequencies form a series comprising odd multiples of the fundamental frequency, (i.e. f_0, $3f_0$, $5f_0$,etc.), which are musically related.



Displacement Amplitudes (Velocities) for the First Three Longitudinal Modes Supported by an Open-Closed Cylinder.

This simple model is useful in that it explains why a clarinet produces notes an octave lower than other woodwind instruments of the same length, which behave as tubes open at both ends. In these, the effective length represents half the fundamental wavelength rather than a quarter. It also explains the characteristic timbre of the notes in the chalumeau range since they comprise essentially only odd harmonics.

1.1.2.2 Musically Useful Air Column Shapes.

For a woodwind instrument to be able to play musical scales requires that the length of the resonating air column can be altered. This is achieved by opening, in sequence, a series of holes in the body of the instrument, the toneholes, to change the effective acoustic length of the column. If the same set of holes is to be used to produce musically related notes in more than one register, (that is, for more than one mode), then not only must the modal ratio have musical significance, but the geometrical parameter of the tube which determines this ratio must be independent of length. These requirements can be summarised as:

1) The normal mode frequency ratios must be independent of the length of the tube, and

ii) The frequencies of the higher order resonances must be (ideally) integer multiples of the frequency of the fundamental mode.

The first condition is satisfied by Bessel Horns [Benade1974] for which the cross sectional area, (S), and hence the radius, (r), of the tube varies with distance along the tube, (x), such that:

$$S = c\,(x+x_0)^{-2e}$$

or $$r = d\,(x+x_0)^{-e}$$

where c and d are constants, x_0 is the position of the mouth of the horn, and 2e is referred to as the "flare parameter".

For practical purposes, only Bessel horns with flare parameters of 0 (the cylinder), and 2 (the cone), meet this second condition. The next value satisfying the condition is 2e = 7, but this produces a shape which increases in size much too rapidly to be of practical use.

1.1.2.3 Playing a Chromatic Sequence of Notes in the Lowest (Chalumeau) Register.

As stated above, for a clarinet, the first overtone of a given air column has a frequency three times that of the fundamental. In musical terms this is an interval of twelfth, or nineteen semitones. To play this range chromatically without recourse to fork fingerings (i.e. closing holes below the first open hole to flatten the pitch), each note requires its own tonehole, some of which may be duplicated. On a standard modern Boehm system clarinet, six of these holes are closed by the fingers and one by a thumb, and the rest can be closed with pads via a keywork mechanism.

The lowest note of the instrument, E_3, (see Appendix A for note terminology) sounds when all the toneholes are closed and the bell determines the effective length. As the toneholes are opened in sequence, the effective length decreases until, ignoring the B_4

trill key, the note Bb_4 is reached. The next note in the chromatic sequence is B_4, which is the first overtone of E_3, the bottom note of the instrument.

1.1.2.4 Going 'Over the Break': the Upper (Clarinet) Register and Above.

To continue up the scale, all of the holes are then re-closed with the exception of the hole nearest the top of the instrument (the speaker, or register hole). Opening the speaker hole has the effect of shifting the frequency of the fundamental mode so that it can no longer co-operate with the higher order modes and is damped out. The leak caused by opening the speaker hole is in the vicinity of the amplitude antinodes of the higher register modes, so they are not suppressed; they become the 'fundamental' or sounding frequencies for the higher register. Because of the acoustic properties of a cylinder (described earlier), all of the fingerings used in the bottom register can be re-used with the speaker key open, to obtain the chromatic sequence to reach C_6.

For maximum efficiency, for a perfect cylinder, the speaker hole should ideally be situated one third of the length of the resonant column from the top end of the instrument, but this would require separate speaker holes for each note in the higher register. As a compromise, the speaker hole is usually positioned so that it gives a good A_3/E_5 twelfth. For notes above and below this, the modal ratio deviates from a twelfth, but this can be corrected by adjusting the bore and embouchure. To make matters worse from an acoustics point of view, the speaker hole normally doubles up as a tonehole for the note Bb4 and consequently is made larger than the optimum size for its speaker role. Ideally, separate holes with the appropriate keywork should be provided, and the speaker hole made smaller and placed slightly further up the instrument than is the normal practice. In the larger clarinets, such as the bass clarinet, it is necessary to use two speaker keys but, even so, the lower hole normally still doubles as a tonehole.

The role of the speaker hole is further discussed in Section 2.6.1 (Introduction to Speaker Tube Bore Profiles).

To reach the fifth harmonic, the first fingerhole is opened as well as the speaker, to frustrate the mode corresponding to the third harmonic, and some modifications to the fingerings are necessary for good tuning. Thereafter, the fingerings become less well defined and reliance is placed to a greater extent on embouchure control to achieve the extreme notes at the top of the range.

1.1.2.5 Acoustic Input Impedance

When describing acoustic impedance, some care must be exercised in the definition of terms. In musical acoustics it is normally the specific acoustic impedance which is referred to. Acoustic impedance is the complex ratio of the sound pressure on a surface of a wave front to the volume velocity through a unit area on that surface. It is useful to be able to measure the acoustic input impedance of the resonator part of a wind instrument: the real part is the acoustic resistance and the imaginary part is the acoustic reactance. In the case of an idealised infinitely long cylindrical pipe with perfect smooth lossless rigid walls, the characteristic acoustic impedance (Z_0) that is, the acoustic impedance measured at any position along the pipe is:

$$Z_0 = \frac{\rho . c}{S}$$

where ρ is the density of air,

c is the velocity of sound in air

and S is the cross sectional area of the cylinder.

For infinite ideal tubes with typical clarinet bores, the characteristic acoustic impedance is in the range 2.25 to 2.35 x 10^6 acoustic ohms, and would be independent of frequency. In this idealised case this, expression is the same as that for a plane acoustic wave propagating in free space.

The diameter of a clarinet bore will propagate only longitudinal sound waves over the frequency range of the instrument. All other propagation modes are cut off. If the idealised case is again taken, as above, and the tube is assumed to terminate at a finite length, (L), into a load impedance (Z_L), then the input impedance, (Z_{IN}), measured at the origin is given by:

$$Z_{IN} = Z_0 \left[\frac{Z_L + jZ_0 \tan kl}{Z_0 + jZ_L \tan kl} \right]$$

where k is the wave propagation number

(in the ideal lossless case=$2\pi/\lambda$)

The wave propagation number is defined as the phase change per unit length. This expression is periodic in frequency. If it is assumed that the tube is rigidly terminated at one end and there is zero load impedance at the other, then to a first approximation the equation has solutions at:

$$\omega / 2\pi = (2n-1)\, c / 4\, L$$

where n is a positive integer. This is the same result as that found earlier from consideration of the standing wave patterns.

In real pipes, as well as radiation losses at openings, there are thermal and viscous losses which occur at the pipe wall. The wave propagation number, k, then becomes complex, indicated now as k':

$$k' = \alpha + j\, \omega / v_p$$

where α is the attenuation coefficient and

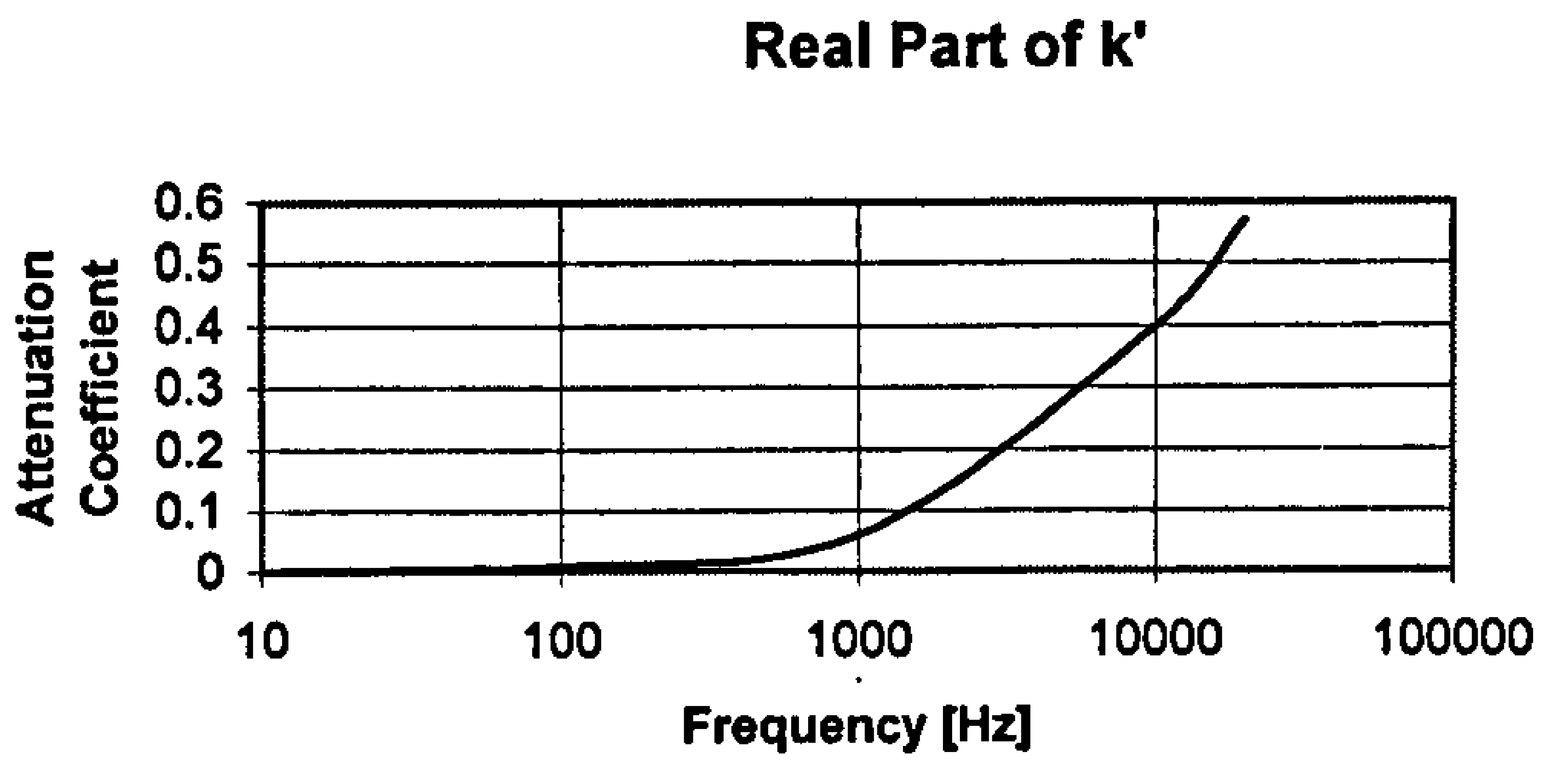
v_p is the phase velocity

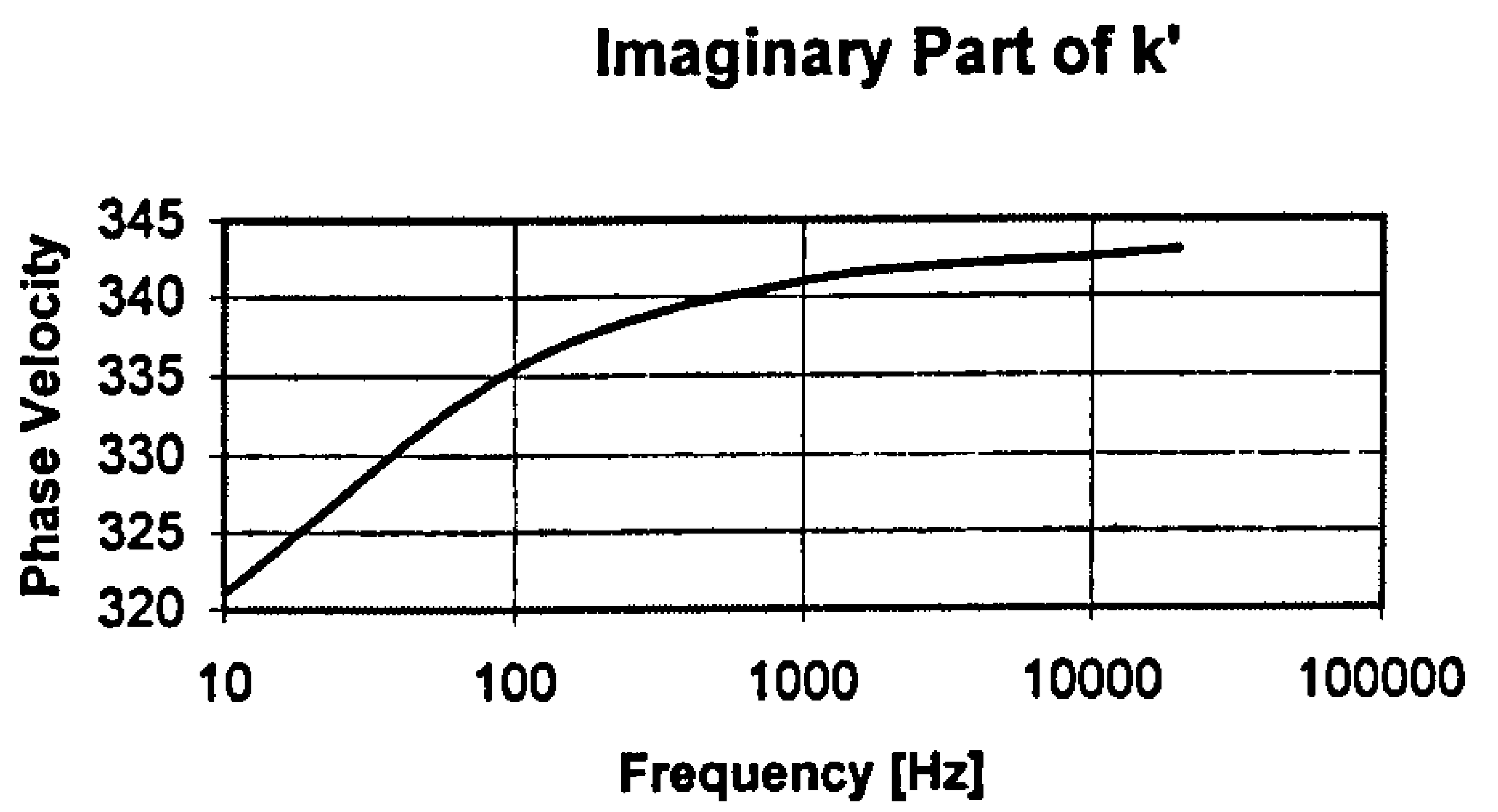
Various expressions have been derived for α and v_p **[Rayleigh 1894] [Benade 1968]** in terms of the ratios of the bore radius to the thicknesses of the viscous boundary layer, r_v, and to the thickness of the thermal boundary layer, r_t

where:
$$r_v = a\sqrt{\frac{\rho\,\omega}{\eta}}$$

and
$$r_t = a\sqrt{\frac{\rho\,\omega\,Cp}{\kappa}}$$

Hence both the attenuation coefficient and the phase velocity are frequency dependent. The phase velocity is low at low frequencies and increases with frequency to the speed of sound in free space, and the attenuation coefficient is zero at low frequency and increases with frequency as shown below:





Hence a clarinet behaves as a waveguide for sound waves, the phase velocity being lower than it would be in free space, the effect being greatest for low frequencies. The attenuation is low at low frequencies and increases with frequency. This phenomenon is a cause of inharmonicity in the partials supported by the resonator.

When the thermal and viscous losses are included, the wave propagation number becomes complex and the expression for the input impedance of a finite-length open-closed pipe takes the form:

$$Z_{IN} = Z_0 \left[\frac{\tanh \alpha L + j \tan(\omega L/\upsilon)}{1 + j \tanh \alpha L \tan(\omega L/\upsilon)} \right]$$

This expression still shows a periodicity as before but the amplitudes of the impedance peaks decrease with frequency and the peaks are closer together than in the lossless case.

In this simple model, which is applicable to the lower (chalumeau) register of the clarinet, the lowest frequency peak has the highest impedance. When driven by a reed generator, this determines to a good approximation the frequency of the fundamental. The slight difference between the peak frequency and the sounding frequency arises from the interaction between the vibrating reed and the air column as will be discussed below.

By measuring the input impedance of a clarinet vented to produce a required note, the frequencies of the impedance peaks provide a good indication of the way the instrument will behave when blown. Examination of measured spectra shows how close the frequency ratios are to simple integers (i.e. harmonics).

Cutoff occurs at the frequency above which travelling longitudinal sound waves are no longer reflected back to build up the standing wave patterns. Above the cutoff, the wave energy travels on past the open toneholes or the bell of the instrument and is radiated as an (un-amplified) sound from the end of the instrument. This phenomenon also occurs in electrical waveguides, from which the acoustic analogy was first derived.

When a travelling wave at a particular frequency (below the cutoff frequency) encounters a change in the acoustic impedance, such as that brought about by an open tonehole or the bell end of the instrument, part of the wave energy reflects back with a reversal of phase. On reaching the top of the instrument, which behaves essentially as a closed pipe, a further reflection occurs, this time in phase, and the process is repeated. These special frequencies, for which the timing is right for reinforcement to occur, are the resonant frequencies for the pipe. The combination of the small part of the energy at the standing wave frequencies which is not reflected at the open end, and the un-amplified higher harmonics above the cut-off frequency, produces essentially the sound which is heard.

There will usually be one or more open toneholes below the first open hole which sets the effective acoustic length. Benade has shown that the spacing of the first two open holes, their size and the bore, determine the cutoff frequency. The open tonehole lattice behaves as a high-pass filter, setting the frequency at which cutoff occurs. Essentially the cutoff frequency determines the harmonic content or timbre of the notes emitted. How the energy is distributed between the available modes depends on the non-linear behavior of the reed and mouthpiece as is described below.

A special case occurs for the lowest notes of the instrument, where the cutoff frequency is controlled by the flared expansion of the bore into the bell, which is designed to simulate the impedance change of an open tonehole lattice. The cutoff frequency would be expected at first sight to be that frequency whose wavelength matches the diameter of the end of the bell. In fact, the flare from the bore leading to the bell causes a slow decrease in the acoustic impedance, and this has the effect of considerably reducing the bell-mouth cutoff frequency (by a factor of ~3), so that the bell notes can be made to cut off at similar frequencies to the other notes which terminate in a tonehole lattice, typically 1.5 kHz for a clarinet.

1.1.3 Non-Linear System: the Pressure-Controlled Valve

The excitation system for a clarinet can be described as a non-linear pressure-operated reed valve, which converts the nearly steady pressure of the air inside the player's mouth into a periodic train of pulses inside the instrument. It comprises the reed and mouthpiece in conjunction with the player's embouchure and blowing pressure.

A clarinet reed is effectively a composite material comprising fibres (which provide the stiffness and hence the restoring force), and a matrix of pithy material (which causes damping). The flat surface is held against the table of the mouthpiece with some form of ligature. Its profiled surface is machined or hand finished to close tolerances to reduce the thickness at the sides and at the tip, whilst leaving a thicker region along the axis. An experienced player may make fine adjustments to the reed geometry (by scraping) to optimise its performance when played with a given embouchure and mouthpiece. Equally important are its elastic properties. Thes are affected by its moisture content and temperature while being played as well as by its state of maturity and previous storage conditions.

The reed acts essentially as a vibrating cantilever with a high natural (un-blown) resonant frequency. However, this is not the frequency at which the reed vibrates when attached to a mouthpiece and blown to produce a musical note from the instrument. Under these conditions the reed is forced to vibrate at the frequency at which the pressure inside the mouthpiece is fluctuating. For the clarinet the lowest frequency impedance peak has the highest amplitude and the reed couples to this resonance (i.e. the frequency of the (quarter) standing wave).

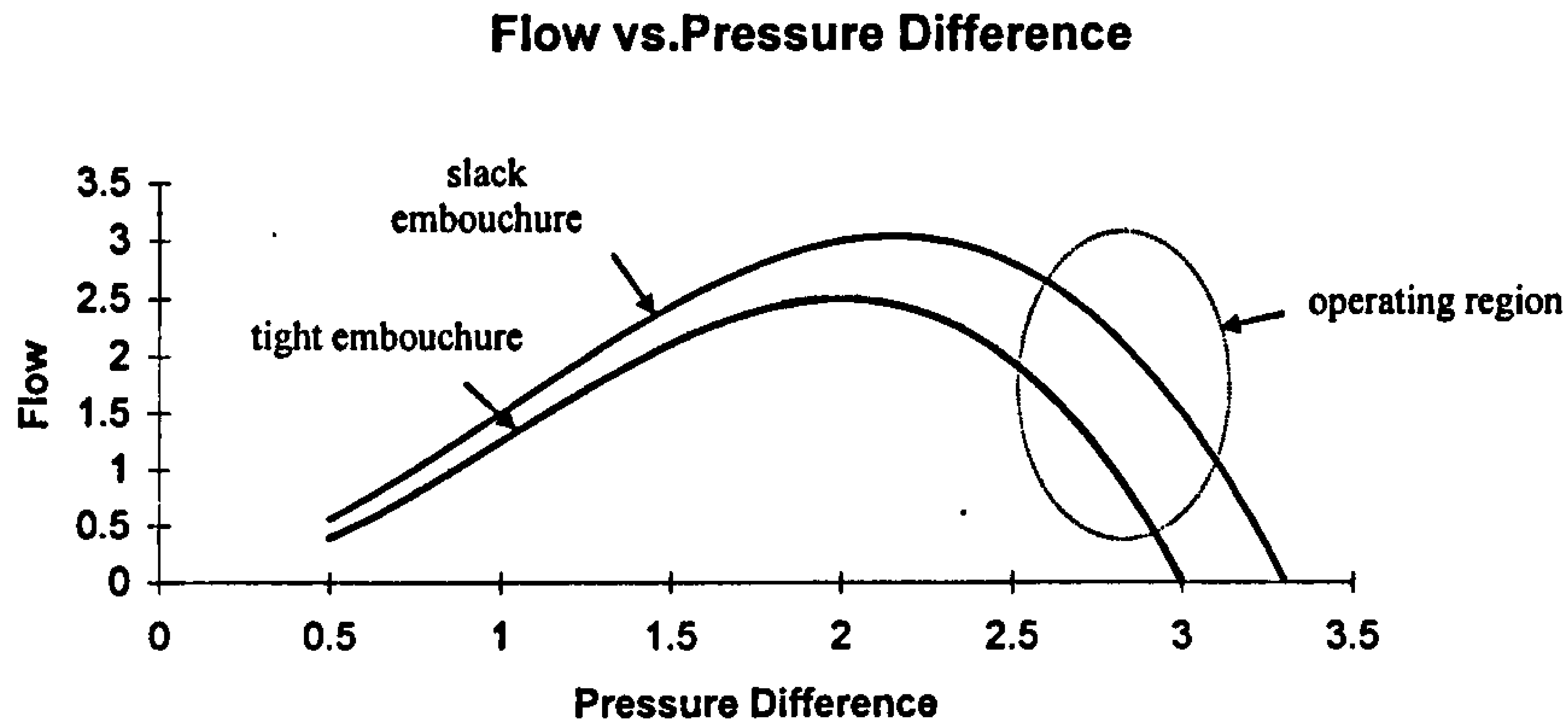
The Q factor of the reed is in the region of 10 when vibrating freely, but this is reduced to about 3 - 5 by the damping caused by the player's lip.

1.1.3.1 The Nature of the Nonlinearity.

The pressure-controlled flow valve (the reed and mouthpiece under the influence of the player's embouchure), represents the nonlinear component. This nonlinearity is essential to create and maintain the higher-order modes of vibration in air column which, in combination with the fundamental mode, give the instrument its characteristic sound.

The fundamental mode in a clarinet has a pressure antinode at the mouthpiece. The oscillating pressure tries to force the reed to vibrate at the same frequency as the air column vibration. The reed has a low mass, stiffness and Q, and is heavily damped by the presence of the lower lip in contact with it. It couples to the fundamental mode (forced vibration) and the resultant frequency is 'pulled' to a slightly lower frequency than that of the air column alone.

In the absence of nonlinearity, a similar process would be required to sustain other air column modes. This would require the reed to vibrate simultaneously at different frequencies rather than at the fundamental frequency. The reed valve behaves nonlinearly since the flow of air through it is not directly proportional to the total pressure applied to it. For a clarinet, the applied pressure when the instrument is sounding is the difference between the mouth pressure, which may be assumed constant, and the instantaneous pressure inside the mouthpiece, which is fluctuating with time. For the sound to be sustained, the pressure difference must always be positive to make up the energy lost both internally, (e.g. viscous/thermal losses to the walls), and externally, (i.e. the sound radiated from the instrument). Furthermore the pressure difference must exceed a critical value such that the reed is operating under conditions in which positive feedback can occur, so that the system is self-sustaining. This requirement is met when an increase in pressure difference causes a *decrease* in the air flow past the reed. For a clarinet, the flow/pressure relationship is roughly parabolic, with the position and peak height of the flow under the control of the player's embouchure. The player is required to adjust the embouchure so that under playing conditions the reed valve is operating on a steep part of the flow/pressure characteristic, where the flow is most sensitive to the pressure oscillations inside the instrument. Experienced players intuitively find combinations of embouchure tensions and blowing pressures in order to operate under optimum conditions



It is the nonlinearity of the flow/pressure characteristic which provides the conditions in which heterodyne effects can occur when a set of air column modes are present which are nearly harmonically related. As a valve, the reed and mouthpiece permit a small signal, (i.e. pressure difference), to control an air flow, and the steepness of the characteristic at the operating point defines the sensitivity of the valve's operation. If the characteristic was a straight line, then the valve would behave linearly, (i.e. the flow would be inversely proportional to the pressure difference). Any deviation from a straight line results in a non-linear relationship. For example, if a sinusoidally varying pressure difference is applied to the valve, the form of the flow will be a distorted sine wave. The distortion can be Fourier-transformed to reveal the harmonic content. This is one approach to visualising how a non-linear element in a vibrating system can generate and sustain harmonics. The non-linearity may be thought of as causing distortion which generates harmonics which couple with the nearly harmonically related higher-order pipe modes, and feeds energy into them to sustain them. Benade describes this phenomenon as 'regimes of oscillation'.

Whereas the energy available from the non-linear system described here will be exactly harmonically related, the modes provided by the linear system are close to, but not necessarily exactly harmonically related. Under these circumstances the phenomenon of 'mode-locking' will occur. Provided the frequencies are sufficiently close, 'pulling' will take place, so that the resultant wave form contains harmonically related components. The better the mode alignment, the more readily will the modes be excited, and the instrument will feel more responsive to the player

1.1.4 Tonehole Models and Studies

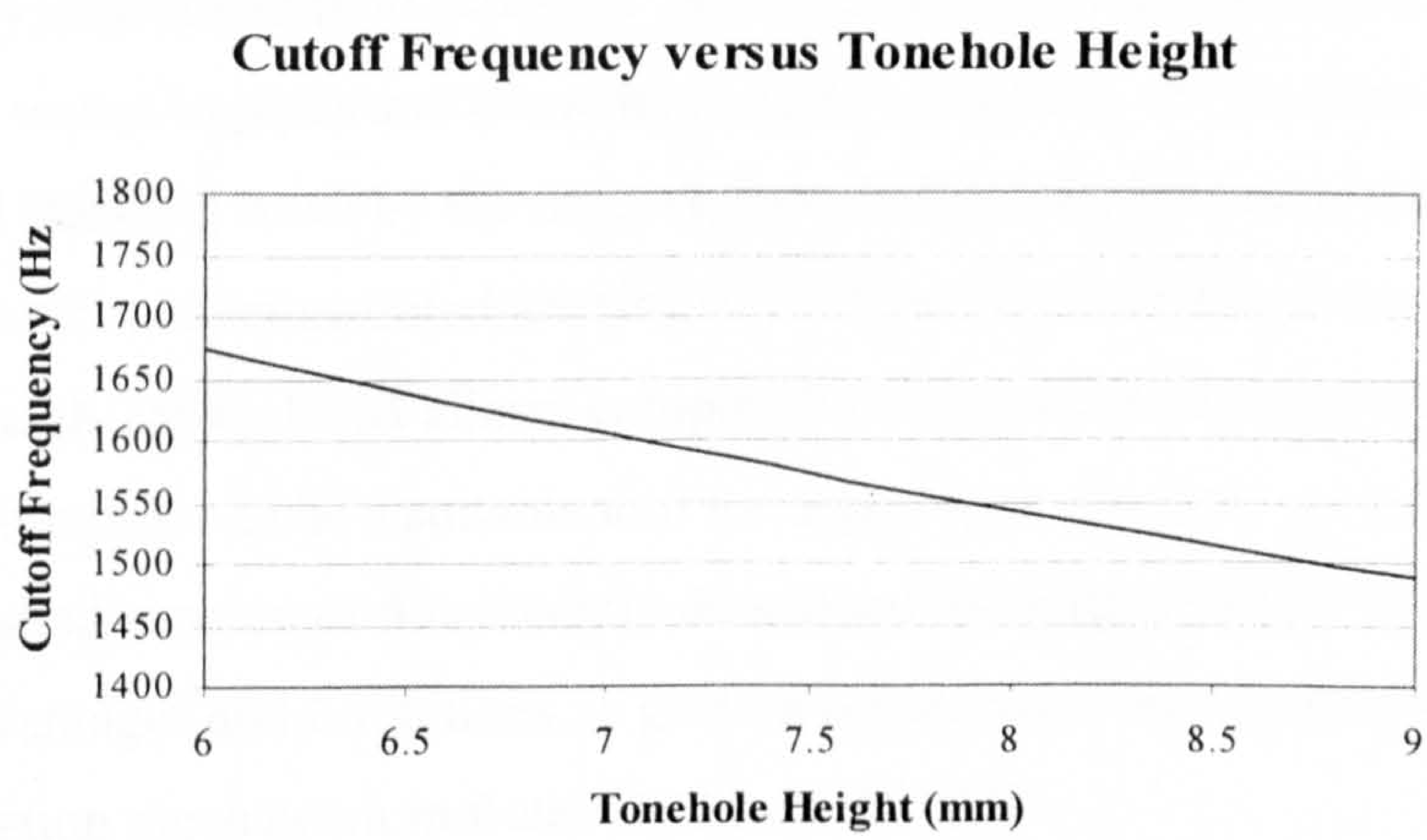
The physical processes taking place in the region of a tonehole are complicated and difficult to model. Benade [Benade 1960] approached the problem by assuming that any real array of toneholes can be approximated by a tonehole lattice comprising equally spaced holes of equal size. The characteristic impedance and wave equations for a cylinder of infinite length with this type of tonehole lattice can then be calculated for plain wave propagation. The impedance of open and closed toneholes can be approximated by those of equivalent open-open and open-closed cylindrical sections respectively. Using this model Benade [Benade 1960] and Keefe [Keefe 1990] have shown that closed toneholes increase the effective cross-section of the bore, and an open tonehole lattice behaves as a high-pass filter which causes the cutoff frequency. Benade [**Benade 1976**] has provided a formula for the open tonehole lattice cutoff frequency referred. By considering only the first two holes forming the lattice in a cylinder of diameter 2a, with toneholes of diameter 2b spaced at distance 2s, the cutoff frequency, f_c , is determined to a good approximation by:

$$f_c = 0.11\ c\ (b/a)\ (1/st_e)^{1/2}$$

where t_e is the acoustic length of the toneholes and c the velocity of sound.
For clarinet toneholes, the acoustic length is related to the physical height of the toneholes, t, by the approximation [Benade and Murday1967]:

$$t_e \approx (t + 1.5\ b)$$

Using typical values found in clarinets, for example 15mm bore, 7.0mm hole diameters at 20mm spacing and assuming a sound velocity of 346m/s, the following graph can be plotted:



This demonstrates the sensitivity of cutoff frequency to chimney height and if, to a first approximation, undercutting is considered to be simply a reduction in wall thickness, it causes an increase in cutoff frequency.

Keefe [Keefe 1982a, 1982b] carried out an experimental study of a single tonehole and provided an alternative theoretical analysis using modal decomposition. This is complicated and makes use of methods originally developed for microwave circuits but is in concordance with Benade's treatment. Keefe's model takes account of the actual geometry of a cylindrical tonehole where it meets the bore. A good presentation of both Benade's and Keefe's analyses can be found in the thesis by Scavone [Scavone 1997]. Subsequently Keefe's theory has been reworked [Dubos V et al. 1999] and problems of applying this type of analysis to cylindrical geometries have been revealed. However new formulae have been proposed which give an accurate representation of the results of numerical modeling using a Boundary Element Method. Recently the predictions of the best available theoretical models have been compared with accurate experimental measurements for a single open tonehole [Dalmont et al. 2002]. One of the aims of the study was to make measurements at high power levels to determine what modifications to the model are required to include non-linear effects. It was found that under certain conditions the measured real part of the shunt impedance in the equivalent circuits as modeled by Keefe was influenced by the edge sharpness at high drive levels.

The complexity of the mathematical techniques involved and the various approximations which need to be applied mean that, as yet, the subtleties of undercutting have not yet yielded to analytical approaches. Current theoretical work in the field of musical acoustics includes the application of the lattice Boltzmann model (LBM) to simulate fluid flows. In 1998, LBM was used to simulate the propagation of sound waves in pipes and to model acoustic streaming arising from the attenuation of a forced standing wave by the interaction with the walls [Buick J.M et al. 1998]. The flow patterns demonstrated are similar to those predicted theoretically by Rayleigh [Rayleigh 1894]. LBM allows complex boundary conditions to be modelled and may therefore prove to be a suitable tool for applying to the study of tonehole undercutting. A detailed account of this recently developed technique, which includes a discussion of its advantages and limitations, is given a recent paper on the simulation of the sound generation mechanism in flutes [Kühnelt H 2003].

Particle Image Velocimetry (PIV), an experimental technique used to study fluid flows, has recently been applied to woodwind instruments. Smoke particles are introduced into the oscillating air column and illuminated with a sheet of coherent light using a pulsed laser. A sequence of images is recorded and, by selecting the appropriate time interval between images, instantaneous acoustic velocity fields can be constructed. From this data the presence of acoustic streaming and vortex shedding can be revealed.

In one study [Skulina, D.J et al. 2003], a cylindrical tube with a plain end was driven at resonance at high power levels and the flow patterns at the end of the tube recorded. As the drive level was increased it was found that with a sharp edged tube, the flow pattern showed a marked change at the same acoustic amplitude at which a discontinuity in the terminating impedance had been observed [Atig M et al. 2003]. Below this threshold, turbulence was localised at the end of the tube and the vortices were drawn back into the tube during the inflow part of the acoustic cycle. Above the threshold the vortices become detached from the end and were shed periodically. When the inner edge of the tube end was rounded with a radius of 0.3mm, the drive voltage at which the threshold occurred increased by approximately 50%. When the radius at the edge was increased to 1.0mm, this threshold was not reached under the conditions of the experiment.

Although turbulence occurs above and below the threshold, this experiment indicates that the acoustic energy loss associated with high power vortex shedding regime will make woodwind instruments more difficult to play at high dynamic levels. A small rounding off of sharp edges will raise the acoustic amplitudes at which the flow pattern change occurs.

PIV has also been used to the study of flow patterns in woodwind toneholes [Skulina D.J et al. 2002]. Experiments were performed with Perspex tubes mounted on a loudspeaker and driven from the lower end at sufficiently high sound pressure levels that acoustic streaming from a side hole occurs. (In clarinets acoustic streaming can easily be detected in the chalumeau region at volume levels well within the normal playing range).

First a single hole was placed at the midpoint of the tube and the air column was excited at the first resonant mode and at frequencies above and below. Contour maps of the flow showed acoustic streaming occurring with the jet direction strongly influenced by driving frequency.

Measurements were then made on a tube with two holes spaced symmetrically about the mid point. There are two frequencies either side of resonance at which the pressures at the holes are equal and it is shown that, at the lower of these frequencies, streaming occurs symmetrically from both toneholes. Below this frequency the pressure in the lower hole exceeds that at the upper and streaming occurs from only the lower hole. There is a small range of frequencies between the points at which the pressures are equal where the situation is reversed and streaming is seen to occur mainly at the upper hole.

The effects of edge rounding have also been demonstrated using an artificially blown clarinet-type tube with different end geometries [Gilbert J et al. 2003]. The acoustic pressure in the mouthpiece versus the mouth pressure for increasing (crescendo) mouth pressure was plotted for tubes with zero, 0.1, 0.3, 1.0 and 4mm radii of curvatures at the inner edge of the termination, as well as for a tube with a sharp bevelled (20°) edge. The mouth pressure at which the reed suddenly closes (extinction threshold) is clearly shown to be affected by the sharpness of the edge. The maximum acoustic pressures which can be achieved within the tube increase as the radius increases, implying that non-linear loss process are occurring at the end.

On reducing the mouth pressure (decrescendo) only slight differences in the pressure plots for different terminations are observed. This is because the threshold at which the reed opens and resumes oscillation occurs at a lower mouth pressure and non-linear losses are less prominent.

The authors have also performed a simulation which assumes linear losses within the tube and non-linear losses at the end which shows good agreement with the experimental observations.

The phenomena described above show that at acoustic power levels attained within the normal playing range of clarinets, non-linear loss processes occur and their onset is influenced by the sharpness of edges. When the effective acoustic length is determined by an open tonehole the sharpness of the tonehole edges would be expected to influence the loss mechanisms associated with the tonehole. The absorption of energy limits the dynamic range of an instrument and it is probable that the onset of these non-linear losses may well be detectable by the player when comparing instruments with different tonehole geometries.

It appears that PIV will be a viable technique for future research on the effects of undercutting and edge-rounding of toneholes.

1.2 The Evolution of the Clarinet.

There are a number of excellent reference sources for the history of the clarinet which include details of the multiplicity of keywork systems which have been invented for the instrument **[Baines 1957] [Kroll 1968] [Brymer 1976]** [**[Lawson 1995][Lawson 2000]**. In order to put the study of tonehole undercutting into context, only a brief outline of the subject follows.

The main keywork systems are:

(i) Those leading to the and including the 'Classical' 5-keyed clarinet and its descendants.

(ii) Müller's improved clarinet and its successors including the 'Albert' or 'Simple' 13-key System.

(iii) The 'Boehm' System clarinet

1.2.1 The Earliest Clarinets

The uncertainties about the origin of the clarinet have been the subject of much discussion and research and the relationship between the chalumeau and the early clarinet is not clear-cut. The instrument stamped J.C.Denner in the Bavarian National Museum in Munich, (No.136 [K20]), which was often cited in the literature as the earliest known clarinet, is now classified as a tenor chalumeau **[Lawson 1995]**. The two keys on this instrument, and others surviving from this period, open holes of different diameters placed *diametrically* opposite each other.

According to Shackleton [New Grove clarinet article], the essential requirement for a clarinet is that it has a speaker key venting a small hole placed so that it plays easily in the register now known as the 'clarinet' register, a musical interval of one twelfth above the fundamental (chalumeau) register. The chalumeau on the other hand is primarily designed to play well in the fundamental register.

A clarinet cannot easily be forced to play in its upper register when the speaker key is closed. This is a consequence of the relative heights of the input impedance peaks seen from the top of the instrument. The fundamental peak dominates and must be effectively suppressed through the shift of its frequency caused by opening the speaker. It can then no longer collaborate with the other modes and the next strongest peak, close to the third harmonic, takes charge.

According to Baines [**Baines** 1957], opening the thumb key on the J C Denner chalumeau 'gives the upper register perfectly well'. Whether this observation is based on playing tests made on the original instrument or on a copy is not stated. Stubbins [**Stubbins** 1974] surmises that a 'slight opening' of either key may have provided the speaker action which pointed the way to the clarinet. Brymer [**Brymer** 1976] notes that, from his personal experimentation, the chalumeau hole placement does not allow proper overblowing to be achieved. Whatever the speculation, it is most probable that the intention of placing the two keyed holes diametrically opposite each other was to extend the range of the chalumeau upwards to B_4 (in clarinet parlance) and any speaker effect would have been serendipitous.

The earliest clarinets with two keys which survive are three instruments by Jacob Denner dating from probably the first and second decades of the eighteenth century. The 'D' instrument in the Germanisches Nationalmuseum in Nuremberg [No. 149] illustrates the developments which had been applied to improve the 'clarinet' qualities of the instrument. The hole operated by the thumb key is now further up the instrument and reduced in size to improve the speaker action and the front key on its own gives A_4. When opened with the speaker key, Bb_4 is produced, but there is now no effective way of playing B_4. The bore is relatively wide (14 mm according to Stubbins) and flares at the lower end into a bell whose size is somewhat smaller than that of a modern clarinet. From photographs, the toneholes appear to be at least 6 mm in diameter and the hole in the lowest joint, integral with the bell, is drilled obliquely to bring it within reach of the little finger, a practice retained through to the 'Classical' clarinet.

Jacob Denner is also credited with inserting a metal sleeve in the speaker hole projecting well into the bore. This may have been intended as a means of preventing water from collecting in the hole but also, from an acoustic point of view, makes the impedance of the hole more resistive rather than reactive, as required for an effective speaker role.

1.2.2 Keywork Development

The loss of B_4 on opening both keys referred to above can safely be assumed to be the stimulus for adding a third key. The body of the instrument was soon lengthened downwards and a third key added to make the missing B_4, the lowest note of the clarinet register. This extension of the instrument also added E_3 at the bottom of the range. The bore flare and bell termination already incorporated in the two-keyed instruments then became even more desirable to improve the quality of the lowest notes in both registers, as well as having a (small) beneficial effect on adjusting the frequency ratios closer to a musical twelfth. If the timbre of the bell notes is to match those of the other notes, then the flare in the bottom of the instrument must be designed to have a similar high-pass cutoff filtering action as a row of open toneholes (i.e. the cutoff frequency must be similar). Flaring the bore into a bell achieves this to some extent and it is notable that this was discovered so early in the life of the clarinet using an entirely empirical approach.

Originally the third key was designed to be operated by the right thumb but this was apparently not popular, as there are surviving instruments in which this key has been modified so that it could also be closed by he left little finger. When, early in the eighteenth century, the long articulated left hand little finger third key became standard, the handedness of the instrument became established, (that is, left hand above the right hand), and this has been retained through to the present.

At this stage of development the instrument could be played over a wide range but many notes of the chromatic scale could not be played satisfactorily. With only a small number of toneholes, the only way to produce the accidental notes was by fork fingering (as on a recorder) [Brindley 1969]♦. The action of fork fingering is to flatten a note by increasing the spacing between the first and second open holes encountered by the sound wave inside the bore. The effective acoustic length is increased but the frequency lowering is usually accompanied by a loss in tone quality. Also, for the clarinet, the flattening effect is less than a semitone, especially for most of the notes in the lower register. In particular, there was no way of achieving an acceptable $F\#_3/C\#_5$ and $G\#_3/D\#_5$ and, as might be expected, the fourth and fifth keys to be added were to obtain these notes.

The extra holes were generally well sized and placed. As a result, the new notes were of better quality than, for example, notes G_3/D_5 for which the tonehole was too small and misplaced to allow it to be covered by the tip of the right little finger. However this feature of the classical clarinet was retained even when up to eight more keys had been added to the basic five.

♦ Benade distinguishes between 'fork-fingering' to flatten a note by closing finger holes below the first open hole and 'cross-fingering' to change to a different register. This distinction has been used here.

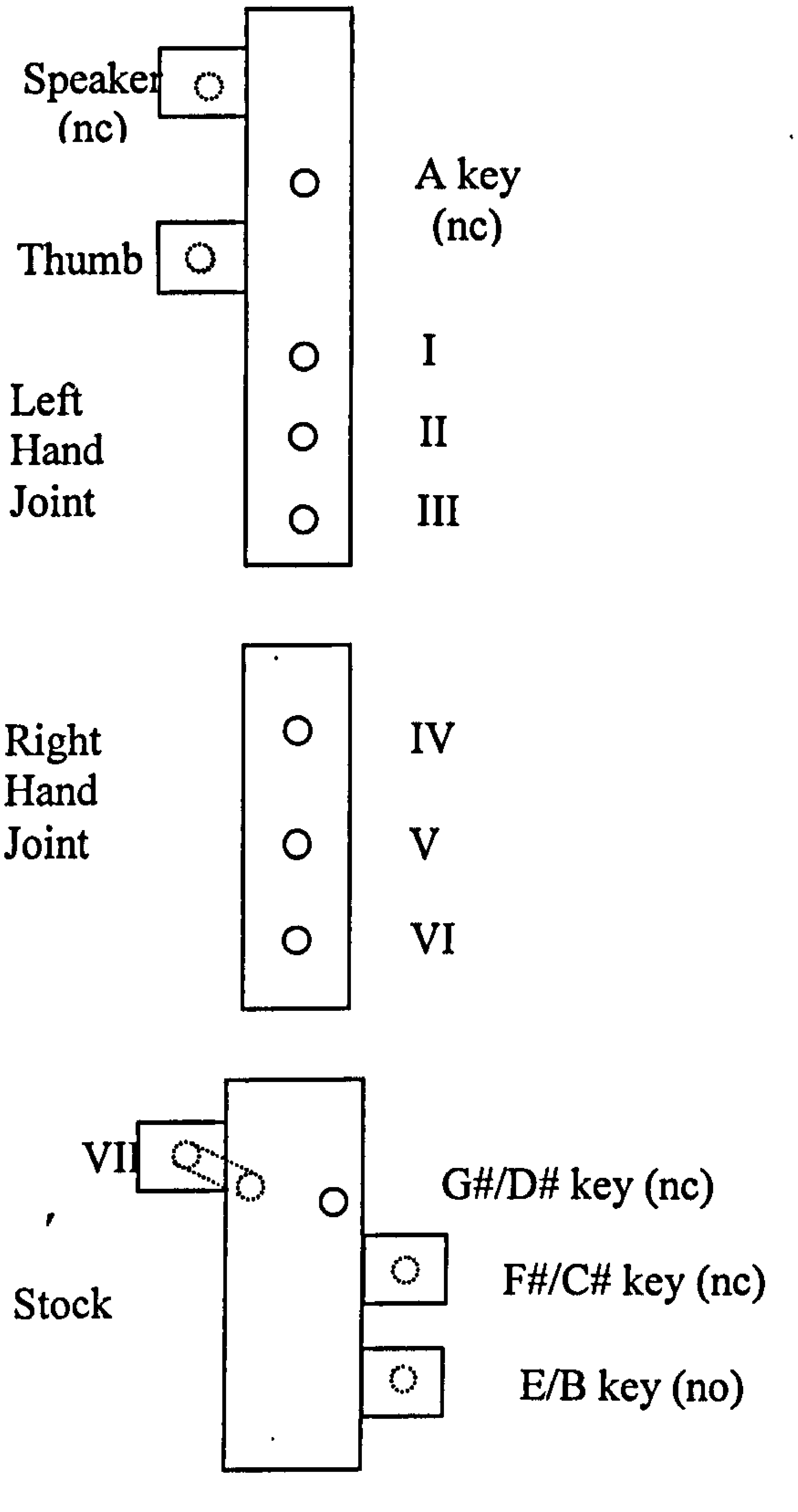
The pattern of five keys was established probably by the third quarter of the eighteenth century and became the basic instrument which is often referred to as the 'Classical' clarinet.[*]

Below is shown a schematic diagram for the tonehole layout of the five-keyed Classical clarinet and a fingering chart compiled from various sources. As well as the basic fingerings, this chart shows some of the alternatives which were employed in attempting to play the unsatisfactory notes on these instruments in tune.

[*] It should be noted that there are extant clarinets from the end of the eighteenth century, especially those of Viennese makers, which are of excellent quality and are well suited to the demands of composers of that time. One of the achievements of today's period instrument players has been the rediscovery of the playing techniques required to achieve musically satisfying performances on either original instruments or good modern copies.

Classical Clarinet Fingering Chart

a) Schematic Tone Hole Layout for the
Five-Keyed Classical Clarinet
nc = normally closed
no = normally open
Mouthpiece at top



b) Basic Fingering Chart for the Classical Five-Keyed Clarinet
Including some Alternative Fingerings
(Clarinet notation)

		E3	F3	F#3	G3	G#3	A3	Bb3	B3	C4	C#4	D4	Eb4	E4	F4	F#4	G4
Left Hand Joint	Sp	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	A	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Th	●	●	●	●	●	●	●	●	●	●	●	●	●	●	○	○
	I	●	●	●	●	●	●	●	●	●	●	●	●	●	○	●	○
	II	●	●	●	●	●	●	●	●	●	●	●	○	○	●	●	○
	III	●	●	●	●	●	●	●	●	●	○	○	●	○	⊙	○	○
Right Hand Joint	IV	●	●	●	●	●	●	●	●	○	●	○	⊙	○	○	○	○
	V	●	●	●	●	●	●	○	○	○	●	○	○	○	○	○	○
	VI	●	●	●	●	●	○	●	○	○	●	○	⊙	○	○	○	○
Stock	VII	●	●	●	○	○	○	⊙	○	○	⊙	○	○	○	○	○	○
	Eb	●	●	●	●	○	●	●	⊙	●	●	●	●	●	●	●	●
	C#	●	●	○	●	●	●	●	●	●	●	●	●	●	●	●	●
	B	●	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

		Ab4			A4		Bb4		B4	C5	C#5	D5	Eb5	E5	F5	F#5	G4
Left Hand Joint	Sp	●	○	○	●	○	○	○	○	○	○	○	○	○	○	○	○
	A	○	●	○	○	○	○	○	●	●	●	●	●	●	●	●	●
	Th	●	●	○	○	●	○	○	●	●	●	●	●	●	●	●	●
	I	○	○	○	○	●	○	●	●	●	●	●	●	●	●	●	●
	II	○	●	○	○	●	○	●	●	●	●	●	●	●	●	●	●
	III	○	●	○	○	●	○	●	●	●	●	●	●	●	●	●	●
Right Hand Joint	IV	○	○	○	○	●	○	●	●	●	●	●	●	●	●	○	○
	V	○	○	○	○	●	○	●	●	●	●	●	●	●	○	●	○
	VI	○	○	○	○	●	○	●	●	●	●	●	●	○	●	●	○
Stock	VII	○	○	○	○	●	○	●	●	●	●	○	○	○	○	○	○
	Eb	○	●	○	●	●	●	●	●	●	●	●	○	●	●	●	●
	C#	●	●	○	●	●	●	●	●	●	○	●	●	●	●	●	●
	B	○	○	○	○	●	○	○	●	○	○	○	○	○	○	○	○

		Ab5	A4	Bb5	B5	C6	C#6		D6		Eb6	E6	F6	F#6	G6
Left Hand Joint	Sp	○	○	○	○	○	○	○	○	○	○	○	○	○	○
	A	●	●	●	●	●	●	●	○	●	●	●	●	●	●
	Th	●	●	●	●	●	●	●	○	○	●	●	●	●	●
	I	●	●	●	●	○	○	○	●	○	○	○	●	●	●
	II	●	●	○	○	●	○	●	○	●	●	●	○	○	○
	III	○	○	●	○	○	○	●	○	●	●	●	○	○	○
Right Hand Joint	IV	●	○	○	○	○	○	●	○	●	●	○	○	○	●
	V	○	○	○	○	○	○	●	○	●	○	○	○	○	●
	VI	●	○	○	○	○	○	●	○	○	○	○	○	○	●
Stock	VII	○	○	○	○	○	○	○	○	●	○	○	○	○	○
	Eb	●	●	●	●	●	●	●	●	○	○	●	●	●	●
	C#	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	B	○	○	○	○	○	○	●	○	●	○	○	○	○	○

○ Open
● Closed
⊙ Optional closed

A comprehensive survey of fingerings for the five-keyed classical clarinet has been assembled by Rice [Rice 1984]

The five-keyed clarinet was characterized by its ability to play well in the clarinet register and above, but many of the fork fingerings in the chalumeau register were ineffective. In particular there was no satisfactory way of fingering the note B_3 in the lower register. It is surprising that this problem was not addressed as a matter of urgency since many composers of the time, including Mozart, required this note to be played. Half-holing with R1 may have been the expedient solution but the double holes commonly found in oboes of the time, as well as in the early three-keyed clarinet, probably by J.C Denner, at theUniversity of California, Berkeley, do not appear to have been applied to clarinets (although they do appear in early basset horns).

By 1800 many clarinets had more than five keys. (The 1776 Supplement to Diderot and Alembert Encyclopėdie had referred to 'recent models' with six keys).

Extra keys were added to the standard set, perhaps at the player's request, essentially as trill keys. Some provided the accidental notes but their placement did little to facilitate the instrument being played in remote keys. By changing from instruments of various pitches the key signature could be rendered down to what was manageable.

The difficulties which arise when a clarinet is required to play in 'remote' keys are a direct consequence of the 'quarter-wave' nature of the instrument. Even today, the twenty five or more toneholes of a modern clarinet, with its sophisticated keywork mechanisms, become difficult to manage as the sharps and flats accumulate.

It is perhaps surprising that the 'Classical' clarinet with its pattern of five basic keys, plus increasing numbers of extra keys, survived so long considering its many deficiencies. Most of the improvements were piecemeal additions of extra keys to a fundamentally unsatisfactory design. Clarinets of this period had rather crude lever-action keys mounted in slots cut in wooden rings turned on the instrument body with brass pins as pivots. As the instrument developed the wooden rings were reduced to 'knobs' which improved the appearance but not the reliability. Wear lead to lateral movement of the keys which, combined with primitive seatings with soft leather pads, caused leaks. The more keys added, the greater the risk of leaks, and hence the reluctance of some players to accept the extra keys.

At the beginning of the nineteenth century, apart from the piecemeal additions of extra keys, various makers throughout Europe were addressing the deficiencies of the Classical clarinet. In particular Simiot of Lyons made significant improvements leading to a nineteen key design by the late 1820s. However Iwan Müller in the second decade of the nineteenth century is today credited with the next significant stage in the development. In essence his approach was to design an acoustically satisfactory set of tonehole positions which would produce a well-tuned, good quality series of chromatic notes over the full range of the instrument. He then devised a keywork system which would achieve all of the required ventings. By employing improved pads, springs, key-mountings and other features, he achieved most of his objectives to the extent that he claimed to have invented the ***clarinette omnitonique***. The rejection of his invention by the Paris Conservatoire proved to be only a temporary set back to this vastly improved instrument.

Müller's design had thirteen keys which allowed legato playing of some note sequences which could not previously be achieved. His original design had two keys for the right thumb (which did not survive), but was quickly improved upon by others (including Sax who added ring keys). These improved designs were the basis of the thirteen-keyed instruments made in Brussels by Eugène Albert after 1850 which became known as 'Albert' or 'Simple' system clarinets.

In the late 1830s the collaboration of Klosé and Buffet produced the so-called 'Boehm' clarinet which is now used worldwide. This has an extremely well thought out and efficient keywork system but the acoustic design of the instrument was also considerably modified [Ridley 1986]. The Boehm clarinet mechanism is designed to permit most note sequences to be played without having to slide the fingers from one key to another as on the Müller-type instrument and its descendents. This was achieved by duplicating the little finger keys to give alternative left and right fingerings and by extensive used of ring-keys for all but one of the fingered toneholes. On lifting a finger from a ringed hole, an up-stream tonehole controlled by the ring is additionally opened for improved venting.

The 'plain' Boehm system (17 keys, 6 rings) is essentially the same today as when first invented. Despite the ingenuity of the key system there are still a few sequences of notes which 'trap' the fingers and require the player to slide from one key to another. Additional keys can be added to remove the problem but at the cost of increasing the weight of the instrument, which is borne mainly by the right thumb. Numerous other 'improvements' to the Boehm system have been championed from time to time but the vast majority of players today (including the author) use plain Boehm system clarinets.

1.2.3 Acoustic Development

For the Bb instrument, the bore sizes have varied in the range 14.35 to 15.3 mm with different national schools of players preferring different bores from time to time[∇]. With the exception of the Denner instruments, early clarinets had small bores and toneholes compared with their modern counterparts. To a first approximation, the fingered toneholes of the 'Classical' clarinet and its predecessors were fairly uniform and small relative to the bore diameter. By the nineteenth century the sizes of the right hand holes was slightly larger than the left, but within each joint the sizes are still roughly uniform. A result of the acoustical approach of Müller and other innovators was that the number of toneholes increased and the tonehole sizes became variable, the trend being to increase with distance from the top. This caused a general raising of the cutoff frequency so that the timbre of the instrument became 'brighter' and closer to that of the modern instrument. Larger toneholes would not necessarily require to be undercut in order to improve the tone quality. However, as will be described in Part 2, the practice continued both as a design feature and as a means of tuning to the present day.

The practice of perturbing the bore from a simple conical or cylindrical geometry has been applied to woodwind instruments since before the invention of the clarinet. In a conical instrument, such as the oboe or baroque recorder, it was discovered empirically that enlarging the bore locally could be used as a means of adjusting the frequency ratios of corresponding notes in different registers to improve the tuning. With a conical bore it is relatively easy to remove material locally by the use of drills and reamers and examples can be found, especially in recorders, where complex bore profiles have been generated as a result of extensive tuning adjustments. Such adjustments, other than a uniform increase in bore size, are more difficult to perform in a cylindrical clarinet bore and no examples of localised bore enlargements (chambering) were found in the bodies of clarinets examined is this study[◊].

Experimental studies of the effects of bore perturbations applied to clarinets were undertaken in the nineteenth century by Cyrille Rose (1830-1903) **[Rendall 1978]**,

[∇] The Oehler system clarinet may be thought of as a more direct descendant of the early instruments than the Boehm clarinet. However because Oehler system instruments are preferred in only a few German-speaking parts of the world, they have not been covered here.

[◊] One example of chambering seen was in a modern mouthpiece for a Boosey and Hawkes model 1010 clarinet.

who was Professor of Clarinet at the Paris Conservatoire from 1876. He worked with Buffet on the effects of 'évasiments', (i.e. cones), in the bore shape at the top and bottom of the clarinet. Subsequently in 1930s Bouasse [**Bouasse** 1929 and 1930] published his comprehensive studies of the acoustics of wind instruments which covered bore perturbations. Benade [Benade and Jansson 1974] applied perturbation theory to woodwind instrument bores. Perturbation weight function curves were developed which determine the relative effects of localised bore perturbations on the frequencies of the different modes.

As stated by Rayleigh [**Rayleigh** 1896] and quoted by Benade [**Benade** 1978]:

"A localized enlargement of the cross-section of an air column (a) lowers the natural frequency of any mode having a large pressure amplitude (and therefore small flow) at the position of the enlargement, and (b) raises the natural frequency of any mode having a pressure node (and therefore large flow) at the position of the enlargement".

Conversely a localised restriction of the bore has the opposite effects. Deviation from the simple cylindrical bore is found in clarinets made during the first half of the twentieth century by Henri Selmer in Paris [**Gibson** 1994]. A linear reversed cone extending from the top of the barrel through all or most of the length of the upper joint is designed to correct the modal ratios.

An alternative approach was devised by Robert Carrée working for Buffet Crampon in 1950. The bore of his 'R13' model has a cylindrical barrel abutting a reversed cone at the top of the left hand joint leading to a smaller diameter cylindrical section which abruptly reduces to the main bore (14.65 mm) comprising the middle third of the instrument. This design overcame most of the problems inherent in tuning small bore clarinets and this model was taken up by many players who had previously favored wider bore instruments. However, there was a tendency for the upper part of the 'clarinet' register to play flat and this was improved in the 'RC' model launched by Buffet in 1975•.

A further refinement in bore perturbation is that currently used by Selmer of Paris and others in which a short reverse cone in the barrel (invented by Mönnig) steps up to a wider bore at the top of the left hand joint which then has a long reversed cone of smaller angle. It would appear that the intention is to produce a venturi effect at the

• 'RC' stands for Robert Carrée

lower end of the barrel preventing the air stream from being disrupted by the cavity formed when the barrel is pulled out for tuning.

Numerous methods have been devised to improve the acoustic behavior of the clarinet by separating out the two roles of the speaker key. (see Section 2.6.1) None have met with much commercial success.

In recent years, the most radical attempt to improve the acoustics of the clarinet was undertaken by Benade. Benade reviewed all of the deficiencies in the normal Boehm system clarinet and their physical causes. He then devised an instrument which he called the 'NX' clarinet in which all of his improvements were incorporated [Benade 1996]. A number of individuals in England and Canada have investigated the possibility of producing the design commercially but at the time of writing examples were not available for assessment.

1.2.4 Clarinets of Different Pitches

From its earliest days the clarinet has been a 'transposing' instrument. Although some of the early two-keyed clarinets were in C, many were pitched in D. Clarinets have been made in a larger range of pitches (and hence sizes) than any other woodwind instruments, from the piccolo clarinet in C to the contrabass in Bb more than three octaves below [Shackleton New Grove article]. As the instrument has developed, Bb has become the most common pitch for the soprano instrument.

There is an easily recognized difference in tone quality between the C clarinet and the Bb or A instrument. The shorter instrument has less of the 'odd-harmonic' characteristic sound at the bottom of the chalumeau register and the desirability of being able to produce this timbre presumably outweighed the inconvenience of having a transposing instrument. However, until the keywork mechanisms had become more efficient, clarinets were made in a range of pitches to cope with the key signature problem, combined with the use of 'corps de rechange' to avoid having to purchase whole new instruments. By the nineteenth century, orchestral parts were scored normally for only C, Bb and A clarinets. It was not until the twentieth century that the orchestral pair of Bb and A instruments became standard with C parts in earlier compositions being transposed on to one or other of the pair. Period performers would now tend to use a C clarinet where this was indicated in the score rather than transpose.

Today the small Eb clarinet is used orchestrally because of its characteristic timbre to achieve particular effects. Likewise the small D clarinet is occasionally called for. Of the lower clarinets only the bass is regularly scored for in orchestras. The alto clarinet in Eb is used mainly in wind bands and clarinet choirs whereas the basset horn is required for some late eighteenth /early nineteenth century repertoire, in particular several of Mozart's works..

The practice of playing 'A' clarinet parts on the extended full Boehm system clarinet is most common today in Italy, but the Spanish clarinetist Manuel Gomez (1859-1922), played all parts on a full Boehm Bb instrument♦.

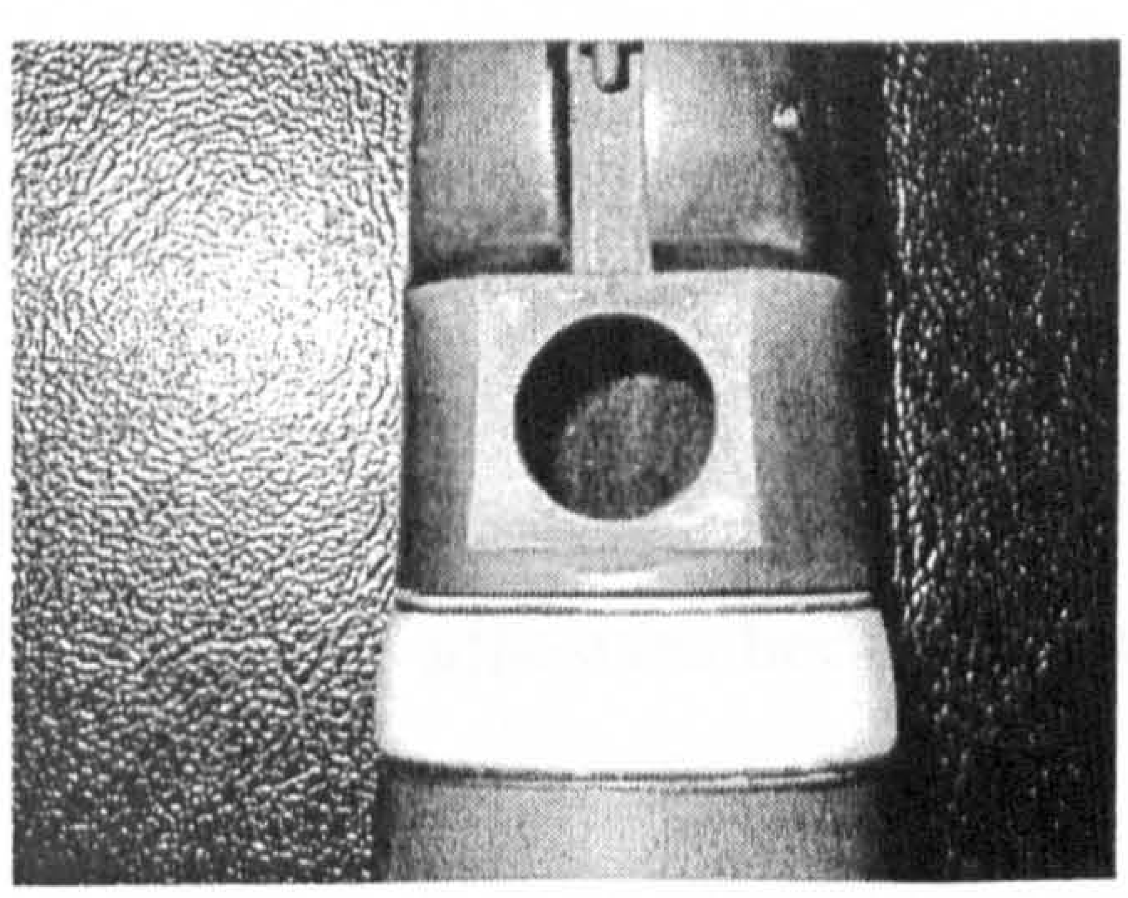
With the exception of one very early 'D' clarinet [CLT097], only soprano clarinets pitched in C, Bb and A have been included in the survey of undercutting which forms Part 2 of this thesis.

♦ Gomez was a member of the Queen's Hall Orchestra in London at the beginning of the twentieth century and became a founder member of the London Symphony Orchestra in 1903 [Weston 1971]

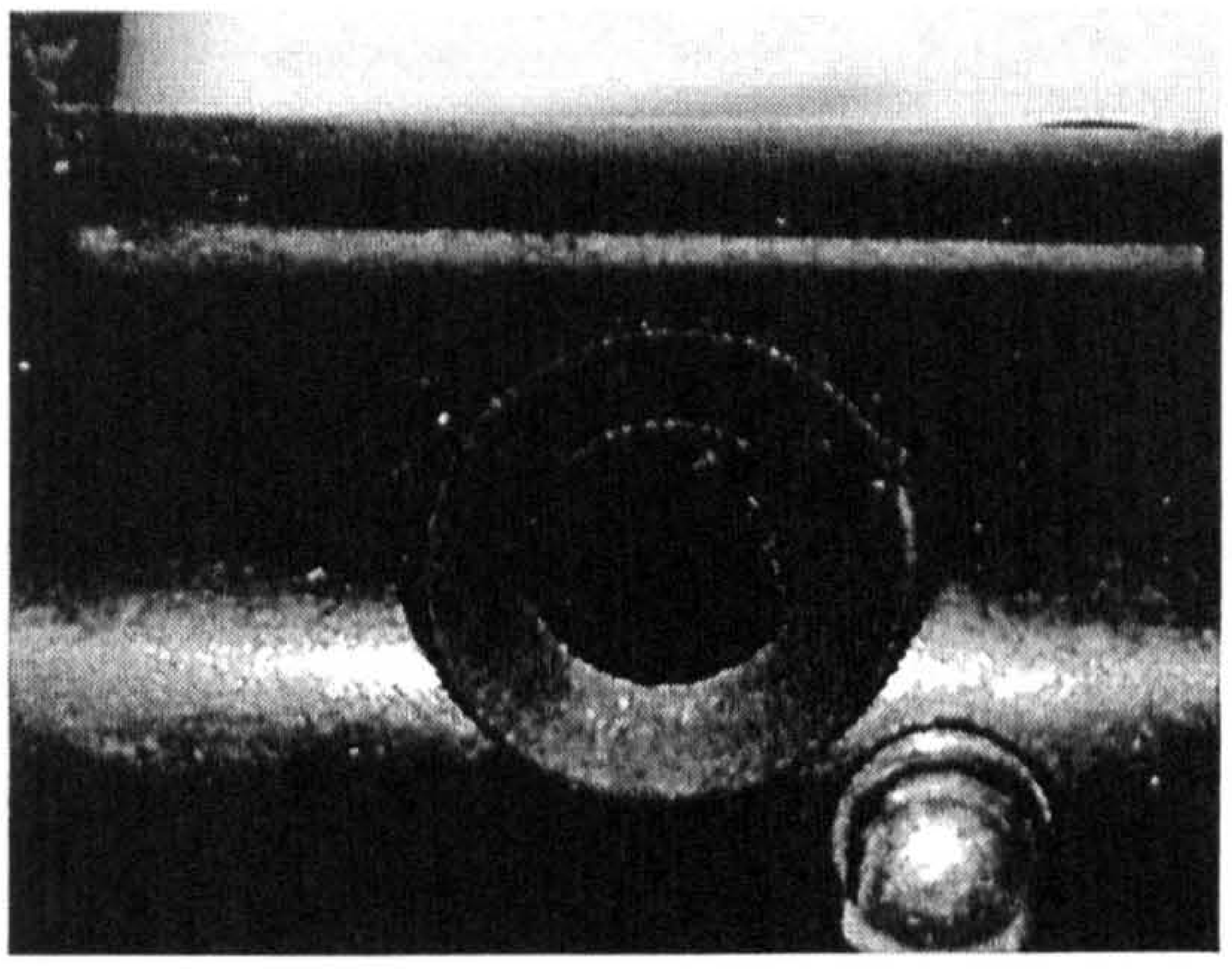
1.3. Toneholes

1.3.1 Types of Toneholes Found in Clarinets (excluding undercutting).

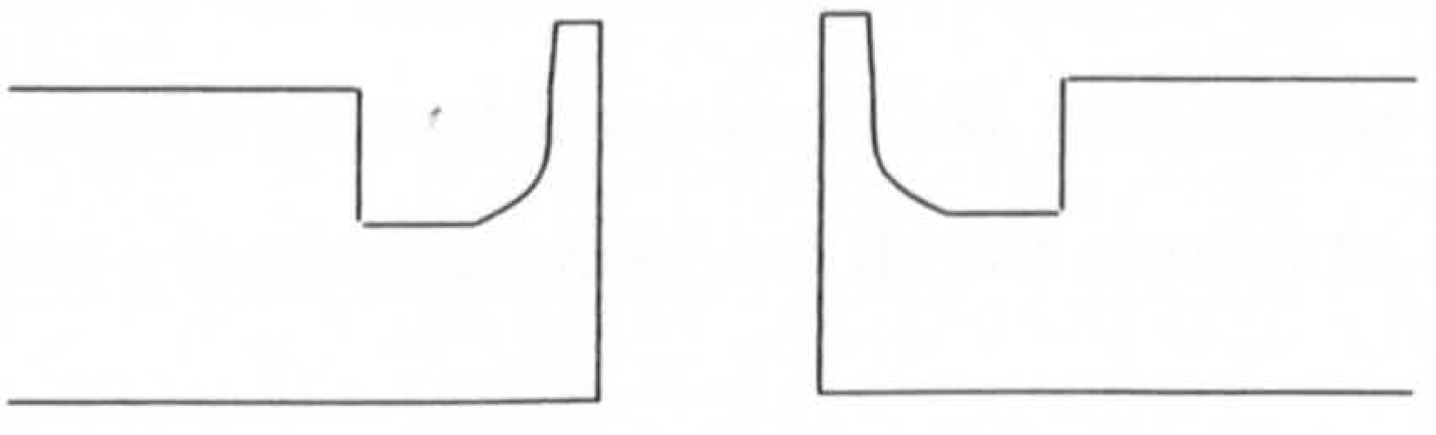
The basic clarinet tonehole is made by drilling a circular hole through the wall of the instrument with its axis perpendicular to, and coincident with, the axis of the bore. The shape of such a tonehole approximates to a right cylinder but its top and bottom surfaces are curved as determined by the local radius of the body tube and the bore respectively. When describing a tonehole the convention is to specify its position by measuring the distance of its axis from a reference plane, usually an end of the joint or an end of the instrument, and measuring the angle of its axis from some fixed direction, say the 'front' of the instrument. The hole itself is specified by its diameter and height. The height is usually taken to be the local wall thickness (the difference between the outer and inner radii of the tube at the hole position). From an acoustic standpoint it is the cross sectional area and height ('chimney' height) of toneholes which are the relevant parameters. The volumes associated with the curved regions can be determined exactly by integration [Keefe 1990] but for the range of hole sizes found in clarinets, the right cylinder approximation is usually sufficiently accurate.
This basic hole geometry presents no problems for fingered holes where, provided the hole is not too big, it is easy to make an air-tight seal with the finger tip. However this is not so for key-operated holes. In early clarinets, keys were made with flaps bent to match the curvature of the body tube and provided with soft leather pads. These were found to be unsatisfactory as any misalignment due to wear in the key mounting or hardening of the leather caused leaks. The difficulty in obtaining a reliable seal increases with the size of the hole and the practice was adopted of filing a flat around the hole exit:



Although not a perfect solution, closure with a flat pad was a significant improvement. Many examples exist where flat and curved top keyed holes occur on the same instrument. Typically the 'between the fingers' keyed holes added to provide trills or alternatives to the forked fingerings have curved tops whilst the rest are flat.
A major improvement in tonehole design was the removal of material surrounding the hole by beveling to create a line seal with the pad:



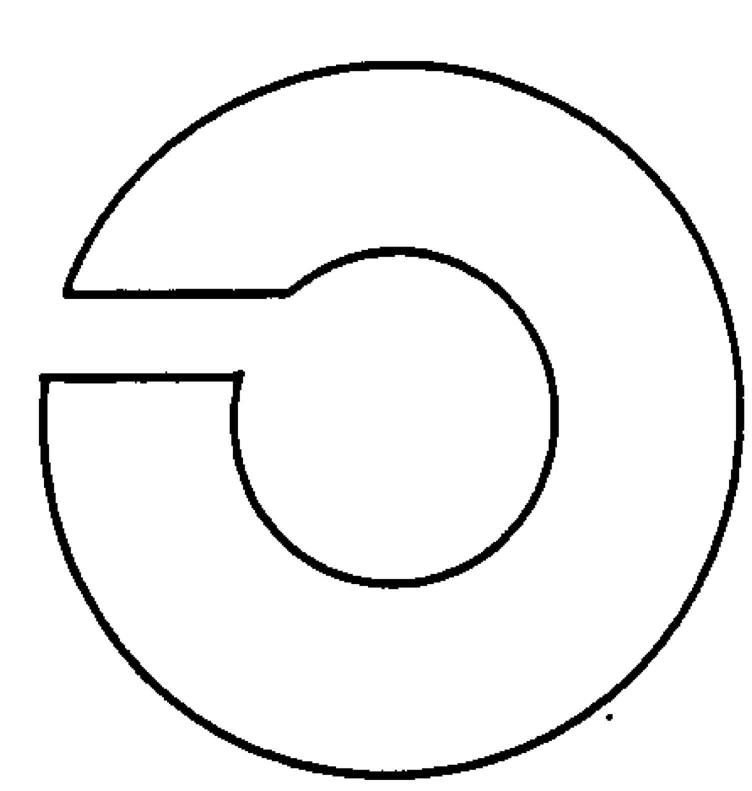
This, combined with improved pad materials and key mounting mechanisms, has produced the highly reliable key closure used on modern instruments. Acoustically the beveling has little effect compared with the plain flat top.
The invention of the ring mechanism surrounding fingered holes requires the flat top of the hole to be raised above the profile of the body of the instrument:



For top-quality wooden instruments, the practice was to leave a raised band of material when turning the outside of the body at the positions of the ringed holes. The ring recess and tonehole were then machined and the top flattened. Finally the surplus wood was chiseled away by hand and the body finished by scraping and sanding to a uniform outline. When reliable adhesives became available this expensive process was largely abandoned in clarinets, especially in the lower price ranges, but some manufacturers, e.g. Yamaha, still retain the integral toneholes in their top-of-the-range models. The alternative technique is to finish the outside of the tube to size, counter-bore to accommodate the ring, and insert a plug of material through which the tonehole is drilled. Because of the thinness of the wall of the insert it is common practice to make it of a homogeneous material, such as ebonite or plastic, in preference to wood and sometimes to improve the fixing by threading the insert and recess before gluing. With this type of tonehole construction great care would need to be taken when undercutting as there is the risk of weakening the joint.

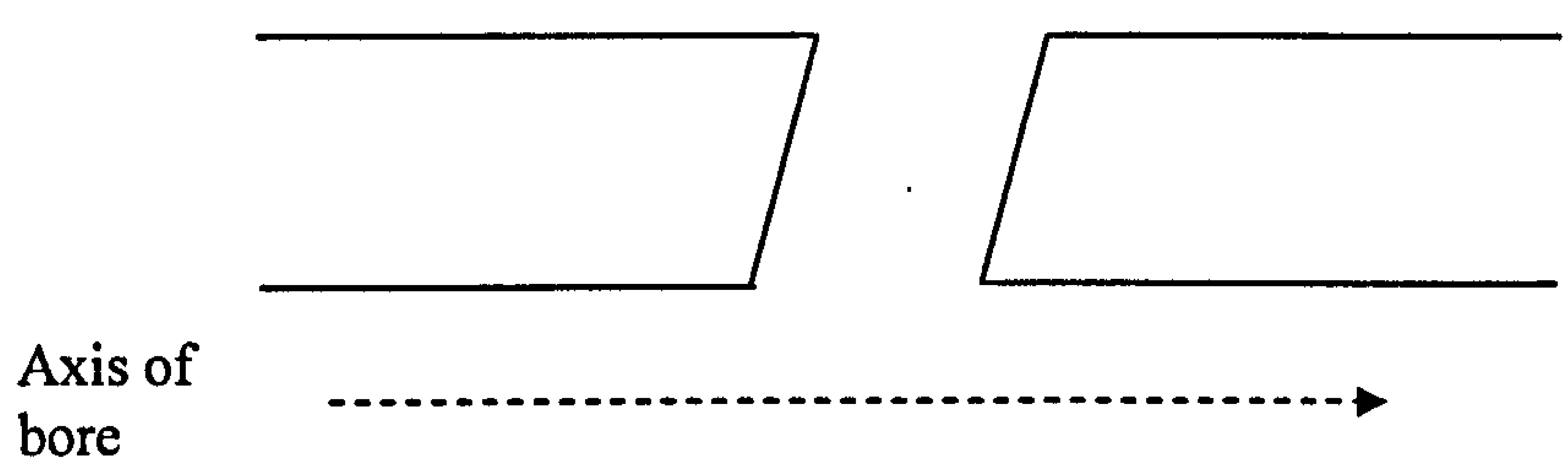
Two additional tonehole geometries are found in most clarinets: thumb holes and register (or speaker) holes. The thumb hole is made from a metal tube which projects slightly into the bore to avoid condensed water running out of it and the end inside the instrument is often radiused to match the bore. The outer end is flat and, in Boehm clarinets, projects past the outside diameter of the body to accommodate a surrounding ring. The tube is normally slightly tapered externally and is pressed into the body up to a shoulder. Sometimes an adhesive is also used or the tube is externally threaded and screwed into the wall. The speaker hole tube, though of smaller diameter, is similarly tapered or threaded, but projects somewhat further into the bore. In the standard Boehm system instrument the geometry and placement of this hole is a compromise as the hole has to act both as a register hole and a tonehole, for which there is a conflict of requirements (see Section 2.6). The tube end is normally flat inside the bore but the outer end is slightly beveled to improve the seal to the pad. The excess length of the tube over that of the wall thickness is acoustically significant in its role as a register hole.

This has covered all of the 'normal' toneholes found in clarinets. There are however variants on these regular geometries to be found, particularly in early instruments. The Figure below shows a hole which has been drilled normal to, but off-axis, to the bore:



Such 'sideways' sloping holes can be defined by measuring the off-set of their axes from the normal to the bore axis. It is not obvious from an acoustic point of view why holes should be displaced in this way, except that displacement produces a small increase in hole ('chimney') height. Holes of this type are found in some modern Boehm clarinets in the left hand joint. Their purpose is to prevent water collecting in the toneholes when the instrument is held in the playing position. It may be that some of the displacements found in early instruments are simply the result of error in manufacture, but this is speculation.

Although oblique holes could be drilled at any combination of angle and displacement, the only other configuration that needs to be considered is as shown below:



Here the axis of the tonehole coincides with the bore axis but the slope may be in either direction, i.e. up- or down-stream. As in other woodwind instruments, in particular the 'wing' joint of the bassoon, this technique is used to bring the hole openings under the fingers to avoid uncomfortable stretches . The most common example is the R4 tonehole in early clarinets. Acoustically this hole is required to operate further down the bore than the little finger of the right hand can reach. The alternative of reducing the size of a normal hole and placing it within the hand span is unacceptable as the tone would suffer even more than with a sloping hole.

With this exception, there is less need to slant toneholes for access reasons in the clarinet than in other woodwind instruments of similar pitch. This is a consequence of the tube responding as a quarter-wave rather than a half-wave resonator. Even for an early open holed basset horn pitched in F, the two sets of three finger holes drilled normal to the axis lie within a hand span of say, 75 mm, (comparable with a tenor recorder).

Occasional examples of sloping holes are found in the right hand finger holes of 'classical' clarinets. Also, in 'C' and higher pitch Boehm clarinets, the hole controlled by the first right hand finger is sometimes is slanted downwards to avoid the socket at the top of the right hand joint. This also moves the pad cup controlled by the rings out of the way of the first finger of the right hand.

Twin holes are less common in early clarinets than in oboes of the same period, but there are examples of twin holes for L3 to give an alternative to a forked $C\#_4/G\#_5$. Some makers even provided a twin hole in addition to a C#/G# key. Typically the hole furthest from the wrist is placed slightly further down the instrument than the other, and the holes may be drilled parallel to each other or, more commonly, radially, so that they merge at the bore or before. The sum of the cross sectional area of the holes is typically similar to that of the equivalent single hole which would be required at the same position.

It has been noted elsewhere [Shackleton chapter in **Lawson** 1995] that it is surprising that only one example can be found where a twin hole has been used to replace R1 finger hole to resolve the difficulty of obtaining well tuned B flat and B natural in the lower register.

Small asymmetries in nominally circular toneholes may be caused by the anisotropic shrinkage which occurs in wood. When a wooden clarinet body continues to shrink after manufacture, the effect on toneholes will be that the dimension measured along the axis of the instrument will remain effectively constant (shrinkage $<0.1\%$), whereas the width will reduce. Whilst detectable by measurement, the effect is likely to be slight and acoustically insignificant in relation to the effect that the equivalent bore shrinkage would have.

A more likely reason for non-circular holes is that adjustments to the hole have been made, either to correct a tuning deficiency of to improve tone quality. Whereas reaming will maintain circularity, filing or cutting may have been applied throughout the whole depth of the hole as an alternative to undercutting. When raising the pitch is the objective, this would be expected to be carried out on the side of the hole nearer to the top of the instrument. It may be possible to detect when this has occurred by detailed visual examination of the hole sides.

The line of intersection of a normal tonehole with the bore is curved in three dimensions. If a contact print were made of a circular tonehole by lining the bore with a photo-sensitive film and exposing it through the tonehole, the image obtained on flattening the film would be an ellipse. The minor semi-axis would be the hole radius and the eccentricity would be determined by the hole radius and the bore radius.

1.3.2 Undercutting of Toneholes

The geometry of the tonehole/bore line of intersection needs to be considered when looking at undercutting

Undercutting can vary from a minimal smoothing-off of the line of intersection of the tonehole and the bore by 'chamfering' the edge, to heavy removal of wall material. Whilst technical drawings of museum instruments usually give accurate dimensions for external features such as keywork and hole sizes and orientations, very little information is usually provided about undercutting. This is probably because of the difficulty of examining it and devising a satisfactory way to describe it quantitatively. Undercutting is typically described only qualitatively, for example 'slight' or 'heavy' or 'undercut towards bottom end only'.

1.3.3 Methods and Tools Used in Undercutting Toneholes

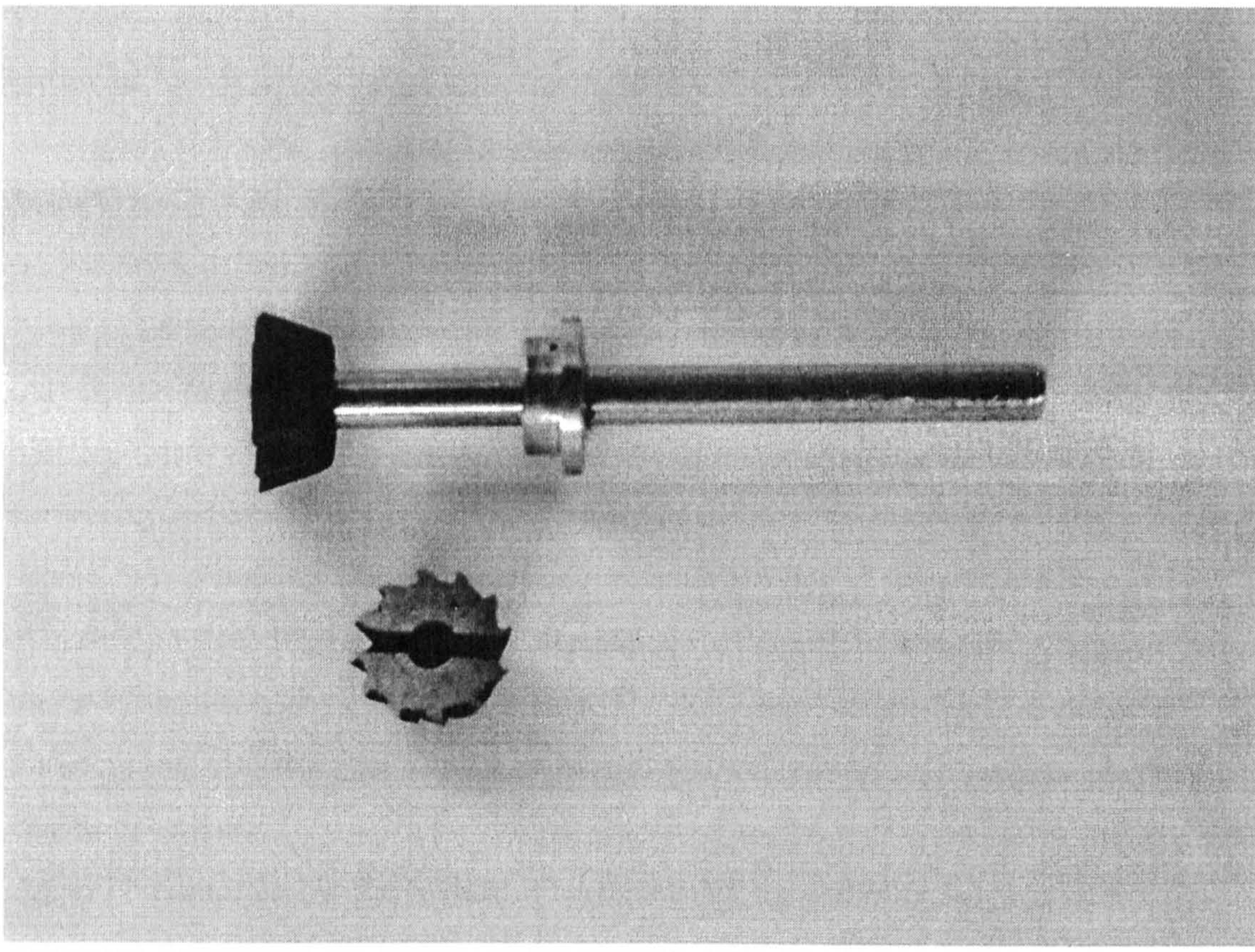
Two methods of undercutting toneholes are employed:

i) free-hand cutting with a file or blade from the outside

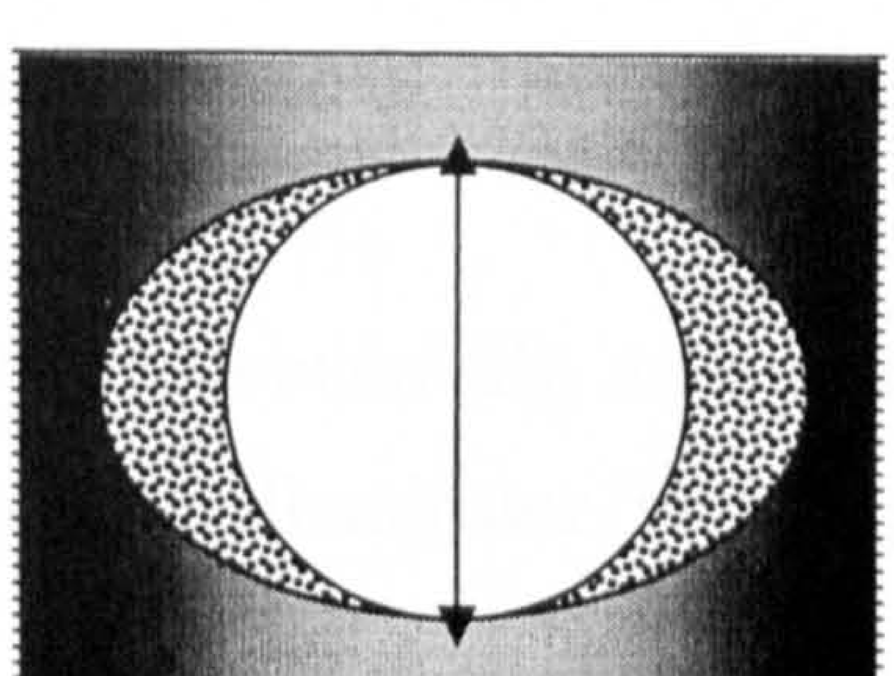
ii) use of a fraise cutting from the inside

In the first method, material is removed with a file or cutting tool inserted through the top of the tonehole and manipulated from outside the instrument. This method allows freedom to generate asymmetrical undercutting where this is judged to be required, for example to sharpen a note in one register relative to that with the same venting in another. This method might to be used when making final adjustments to an instrument.

'Fraise' is the French word for a milling cutter. Fraises used for undercutting toneholes are like reversed countersink tools, but made in two parts. The shaped head (often conical) has a number of cutting edges depending on its size and is threaded through its centre to fit onto a drive shaft.



The head of the fraise is supported on a rod and inserted through the bore of the instrument. When aligned with the hole, the drive shaft is engaged in the fraise and ideally a sleeve is slid down the shaft to centre the tool in the tonehole. The tool is turned and drawn upwards simultaneously to generate the undercut. Because of the shape of the intercept of the tonehole with the bore referred to earlier, the cutting tool will not make initial contact uniformly. This can be pictured by imagining a conical tool being offered up to a round hole in plane parallel wall in which case it will touch all the way round. If the wall is then bent to form a tube, the sides of the hole on a line at right angles to the tube axis will push the tool away from the wall and this part will be cut first. When the depth of cut is sufficient to affect all of the edge of the tonehole, the outline generated on flattening out the wall again will be as shown:



Arrow shows direction of bore axis

This shape can be described explicitly for a conical cutter but will be complex if the profile of the cutter is changed, for example to a 'bell-shaped' cutter.

Fraises are also used 'freehand' to produce asymmetrical undercuts. Normally the fraise is rotated and the instrument body is held in both hands and manipulated to remove material where required.

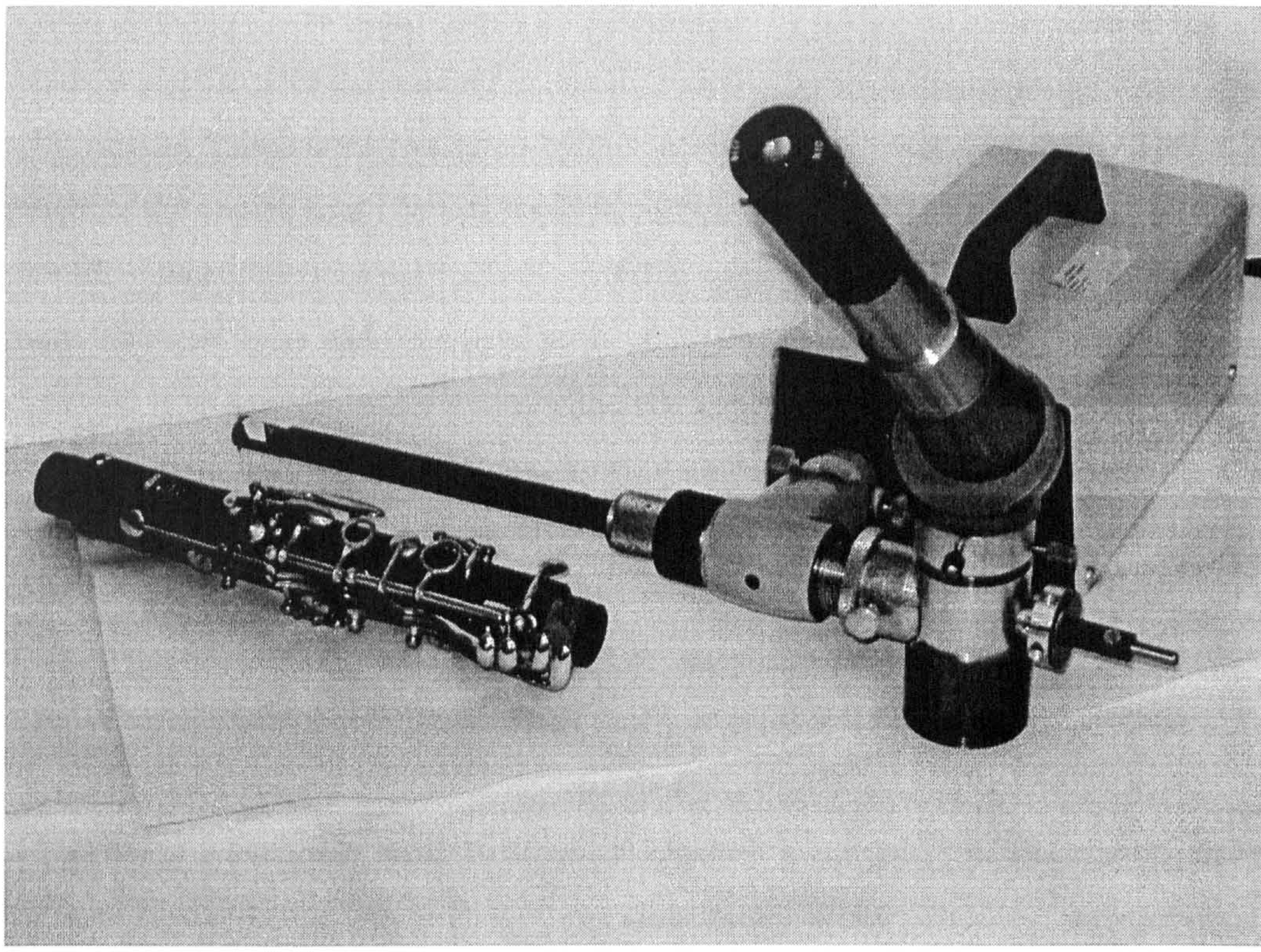
For a given hole and bore size, the geometry of a fraised hole will be determined not only by the form of the fraise, but also by how far it is drawn into the tonehole. In practice this is difficult to measure accurately in an existing instrument, so it is not surprising that even for this symmetric form of undercutting the data available is sparse. When making the experimental toneholes studied in some of the acoustic experiments described in Part 3, an alternative method of defining the degree of undercutting for a given fraise was used. The body was weighed before and after undercutting and, from the known density of the wall material, the volume removed can be calculated.

As will be described in the review of undercutting, the use of fraises has been extensive throughout the history of the clarinet, with hand undercutting only occasionally applied, in some cases subsequently to fraising. Even the earliest eighteenth century clarinets appear to have been undercut with fraises. It is most likely that the use of fraises was well established for the manufacture of other woodwind instruments at the time and therefore to be expected that the technique should be applied to the newcomer to the woodwind family.

1.3.4 Methods of Examining and Measuring Undercutting, Toneholes and Bores

External examination of the open fingered toneholes of a clarinet under good lighting conditions normally reveals whether or not they have been undercut. Internal inspection is however a much better approach as the toneholes can be examined whether or not they are covered with pads, and the shape of the undercutting is much easier to assess.

In order to examine clarinets internally, a purpose-built portable 'Borescope' was constructed with an integral illuminator (requiring a mains electricity supply):



Details are given in Appendix B.

Most of the work was done with a 150 mm long, 12.7 mm diameter probe which was suitable for all Bb and A clarinets from the earliest to modern, and most C clarinets. (High Eb clarinets were not included in this survey). Where metal thumb inserts projected too far into the bore, a smaller probe was used when sufficient access time was available. The probe could be extended to 310 mm to examine clarinets with a single-piece body.

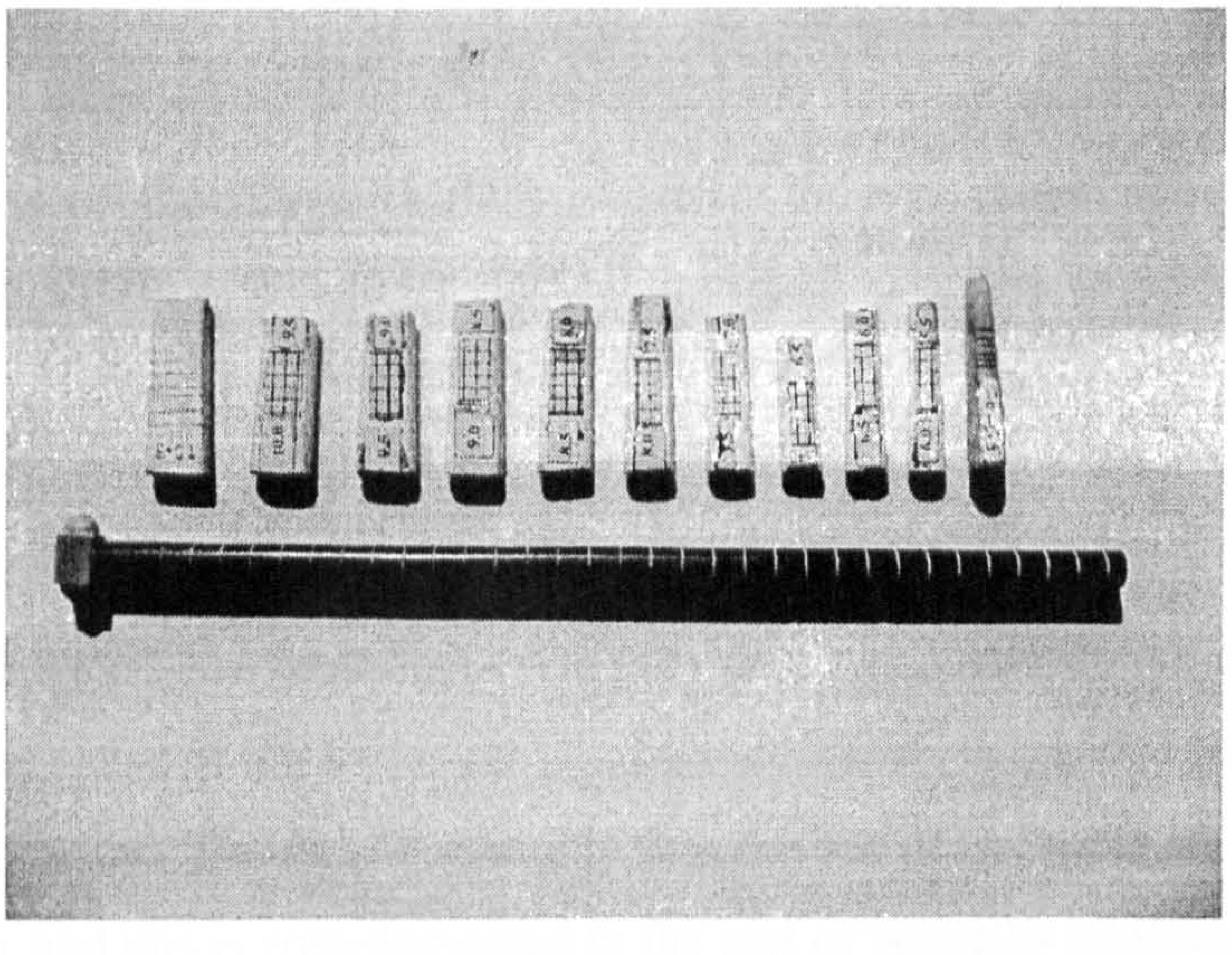
Few objections to the use of the borescope were encountered during the survey. The light source is fan-cooled and sufficiently far away from the clarinet not to cause heating problems and the instrument is nominally 'non-contact'. In practice the probe touches the bore while the clarinet is being manipulated but the probe is smooth and the end was provided with a felt 'buffer' to reduce any risk of marking the bore.

A plain eyepiece was used for general inspection, but this was changed to one with a calibrated graticule when the extent of the undercut along the direction of the bore needed to be measured. This was adequate for most measurements although occasional use was made of a special eyepiece with a cross wire linked to a micrometer when higher accuracy was needed.

Visual inspection was occasionally complemented by taking an impression of the tonehole profile with a moulding material. Initially the semi-angles of undercuts made with conical fraises were measured by this technique but it was found that, with practice, the angles could be estimated to sufficient accuracy by eye. However the moulding technique was particularly useful to measure the tonehole profiles where more than one fraise had been used sequentially, as in some of the eighteenth century clarinets. It was possible to determine the semi-angles of the individual fraises which had been used. Likewise moulds were useful to characterise some of the smooth profiles occasionally found in clarinets from different periods which are most likely to have been hand finished.

Tonehole undercutting is related to the hole size which is in turn related to the bore size. Where possible, bore profiles and tonehole sizes were also measured as part of the survey (see below).

It was not practicable to measure all of the tonehole sizes using the Borescope method outlined earlier as this would be too time consuming. When permitted, measurements of the accessible fingered holes were made using a set of plastic taper gauges. These were inserted into the toneholes until they touched the sides, and the diameter read off from a scale on the gauge. The diameters could be determined to the nearest 0.1 mm. This method was chosen instead of using calipers which might mark the instrument. There is a particular risk in using calipers on raised toneholes surrounded with rings (brille). Here the material is quite thin and vulnerable to fracture. A set of eleven taper gauges was made covering the range 5.0 to 10.5 mm:



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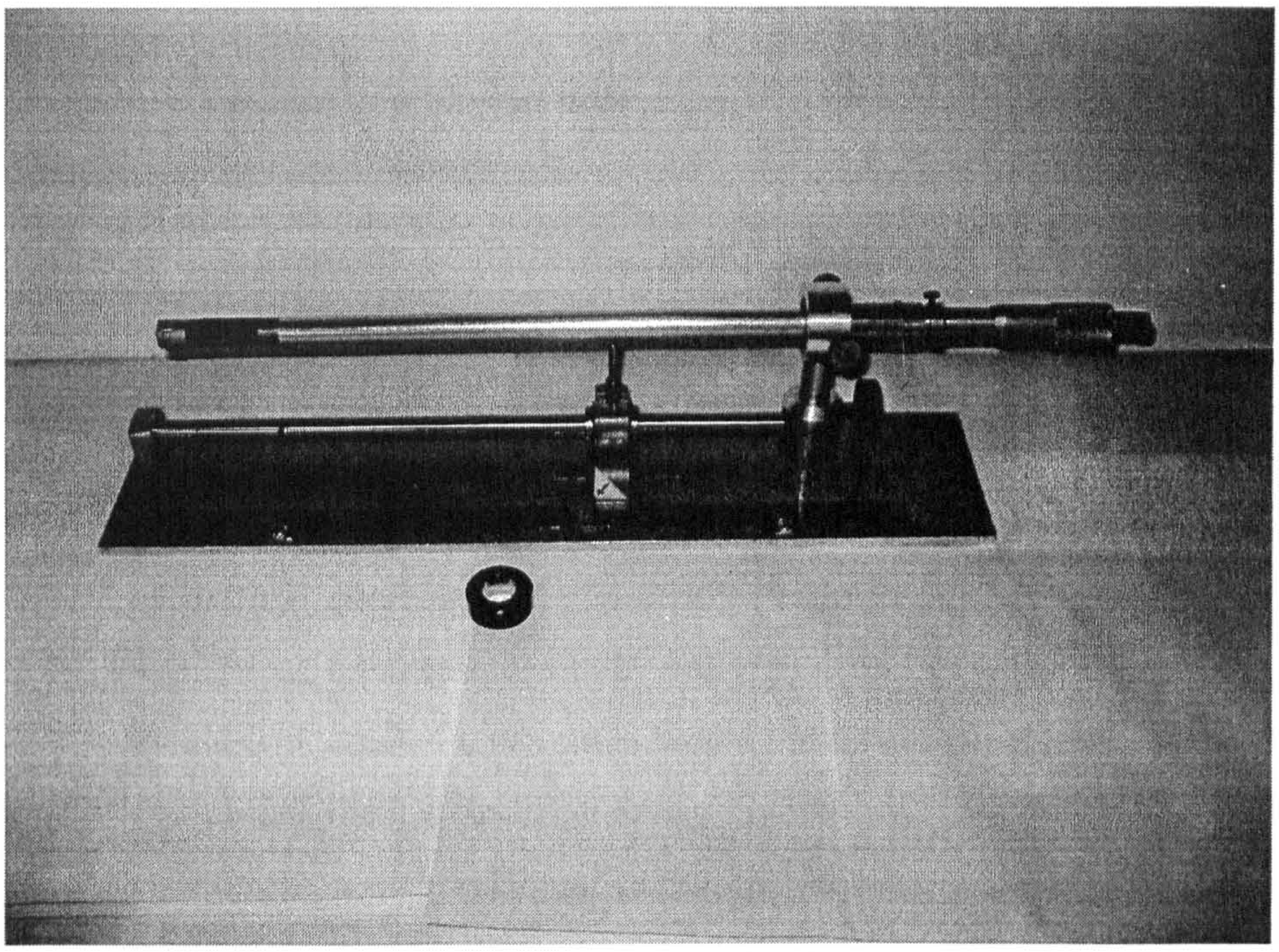


Details are given in Appendix C.

The gauge and its mounting were designed to be portable. This type of instrument is inherently less likely to damage the bore in any way than conventional T-bar type gauges. None of the clarinets examined were marked by the use of this tool.

The question was raised [Shackleton private communication] whether this type of gauge could be used to characterise bores which had become slightly elliptical, as can happen as the result of anisotropic wood shrinkage. Analysis of the problem showed that although in theory enough information can be obtained using this type of gauge to calculate the elipticity, the calculation is very sensitive to small errors and is not reliable. For elliptical bores it is suggested that the three-point bore gauge can still be used but in conjunction with T-bar gauges of the type shown above [Bell and Greenham 2001].

1.3.5 Method of Describing Undercutting.

A legend system has been devised to provide a semi-quantitative description of the extent and shape of the undercutting observed during the survey undertaken in Part 2 as shown below. The most commonly found types of undercutting have been assigned a number and this is complemented in the text or tables by additional information such as cone semi-angle. This method is not exact as there is scope for subjective error but is useful as a means of giving an impression of the nature of the undercutting and for comparisons between instruments.

Legends Used in Undercutting Tables:

0	cylindrical, no undercut, sharp edge
1	cylindrical, no undercut, edge relieved
2	cylindrical, conical undercut laterally, not reaching bore along axis
3	cylindrical, conical undercut laterally, just reaching bore along axis
4	cylindrical, conical undercut extending into wall along axis ~1/4 wall thickness
5	cylindrical, conical undercut extending into wall along axis ~1/2 wall thickness
6	cylindrical, conical undercut extending into wall along axis ~3/4 wall thickness
7	shallow conical undercut (~5 degree semi-angle) through wall thickness
8	moderate conical undercut (~10-15 degree semi-angle) through wall thickness
11	freehand filing
12	'bell' shaped

Asymmetrical undercutting:

u upstream

d downstream

s sideways

sl sloping

ob hole drilled at an angle

o.c. overcut

Part 2 Study of Undercutting in Clarinets from the Eighteenth Century to the Present.

2.1 Introduction.

This part of the project is a survey of the occurrence of undercutting in clarinet toneholes. A large number of clarinets or parts of clarinets have been examined during this project as listed at the end of this Part and these have been grouped into various categories.

Clarinets made before the middle of the eighteenth century are rare and are not readily accessibly for examination. Occasionally measurements made on some of these early instruments are reported but very little information on tonehole undercutting is available from museum drawings and articles on very early clarinets.

Section 2.2 covers early clarinets of the 'Classical' design described in Part 1. Section 2.2.1 contains measurements made on clarinets known to have been made in the second half of the eighteenth century. Because of their relative rarity compared early nineteenth century clarinets, these observations have been recorded in detail for each individual clarinet.

By the start of the nineteenth century the 'Classical' clarinet was well established throughout all of the main European centers and many instruments from this period survive in museums and private collections. Section 2.2.2 covers examples of these instruments which have been examined and in some instances it has been possible to compare clarinets made by the same maker over a time period. A number of the better-known London makers are represented. The instruments studied in this section have up to thirteen keys but retain the most of the characteristics of the classical clarinet (extra keys having been added to the basic instrument).

In Section 2.3, instruments incorporating most or all of the Müller improvements are described. The division between this and the previous section is not clear-cut as, at the beginning of the nineteenth century, many makers as well as Müller were devising improvements to the instrument. However, from the point of view of undercutting this is a convenient method of distinguishing between clarinets with tone placed as in the basic five-keyed pattern to which additional keyed holes have been added, and those in which toneholes have been moved to more acoustically satisfactory positions, for example, the replacement of the oblique right hand little fingerhole with a key-operated hole.

Sections 2.3.2 to 2.3.4 cover clarinets with more advanced keywork systems based on Müller's design. These include the thirteen key 'Simple' or 'Albert' system instruments and other clarinets with more elaborate keywork systems manufactured after the invention of the Boehm system e.g. Clinton and Barrett models. There are also some Barrett-Boehm clarinets which have hybrid mechanisms designed to allow players familiar with the Simple system to benefit from some of the Boehm features. This survey excludes clarinets of the Oehler system developed in Germany but one modern example has been examined and is included here.

Boehm system clarinets are reviewed in Section 2.4, from early examples to those of the present day.

In Section 2.5 the bore profiles of metal speaker tube inserts are examined and discussed.

In Section 2.6 the status of undercutting in the current European manufacturing scene is described. A little information has been obtained from present day commercial clarinet makers about their approach to undercutting and the methods they use to carry it out during manufacture. The paucity of this information is the consequence of commercial confidentiality since undercutting is still performed by hand by most makers even in large scale production. Two of the largest French manufacturers have failed even to respond to requests for information on this topic.

Finally the results of this survey are summarized in Section 2.7.

The key to the legends assigned to the various types of undercutting revealed by Borescope examinations was shown at the end of Part 1.

2.2 Early Clarinets

2.2 1 Eighteenth Century Clarinets.

The numbers of clarinets surviving from the second half of the century is significant but small compared with the numbers of flutes, oboes and bassoons from that period. This is not unexpected as it took until the latter part of the century for the clarinet to find its way across Europe and become generally accepted, so the numbers produced would have been relatively small. Fortunately one museum and two private collectors have made their clarinets from this period available for this survey.

For all of the clarinets described in this section there is good evidence to confirm that they were made before the end of the eighteenth century, either from established makers dates and addresses, method of construction or from other markings on the instruments.

They are listed in approximate date order using the best estimate the date of manufacture where the exact date is not known:

Rottenburgh. 4-Keyed Clarinet in A. c.1760. (Nicholas Shackleton collection). [CLT103]

Description:

This instrument was made in Brussels by Godefried Adrien Rotenburgh, a member of the well known Flemish family firm of woodwind instrument makers. It is marked 'G A Rottenburgh A Bruxelles' with a '*' symbol and is of brown stained boxwood with one ivory ring. This stamp is believed to have been used by Godfridus Adrianus's son Franciscus Josephus, until 1803.

There are three body joints with two brass keys with square flaps on the top joint and two on the bottom joint. The bell is integral with the bottom joint.

The bore of the upper joint varies from approximately 14.85 to 14.45 mm from top to bottom with some distortion. Likewise the right hand joint varies from about 14.85 to 14.75 mm. The outside diameter is approximately 25 mm.

Undercutting:

All of the toneholes are moderately undercut as follows:

Upper joint (wall thickness nominally 5.25 mm). Mostly cylindrical with a ~ 45° 'chamfer' type undercut 1 to 1.5 mm deep, i.e. approximately one quarter of the wall thickness.

Right hand joint (wall thickness nominally 5.1 mm). Deeper conical undercuts with ~ 20° semi-angles extending through three quarters of the wall thickness.

Lower joint. Hole VII drilled sloping, essentially cylindrical. Keyed holes straight sided but opened out sideways slightly on meeting the bore.

The undercutting is fairly symmetrical but it was not possible to determine what type of tools had been used.

It is noted that a flute by the same maker appeared to have been undercut with a rounded fraise tool leaving a dome-shaped profile [Lewis Jones private communication].

P.G.Wietfeld. 2-Keyed Clarinet in D. c. 1765 (Keith Puddy collection) [CLT097]

Description:

This two-keyed clarinet was made by Philip Gottfried Wietfeld of Burgdorf near Hanover in Northern Germany. There were two makers of this name, father and son. The father was born in 1706 and died in 1768 whilst the son lived from 1743 to 1793. Both used the same mark (see below) so it is not possible to distinguish between them. However this is a rare example of a late Baroque clarinet made in the second half of the eighteenth century.

Its construction is unusual. The barrel and/or mouthpiece section have not survived. The upper joint (299mm) has the two keys at the top (first finger and thumb as in Denner examples) and all of the toneholes, including that for the right hand little finger. This is angled downwards through a slightly thickened wall. The bell (156.5 mm) has a narrow flare and is slightly thickened at the top to accommodate the socket. The tenon at the bottom of the upper joint has been shortened. The reason this has been done is not clear as the bell socket has not been adjusted to match. The overall length of the two joints assembled is approximately 439 mm.

Both body sections have the maker's marks, at the top:

• G • / • WIETFELD • (on arc of circle) / ✻ with open circle at centre (sun symbol)/ |

and on the bell abbreviated to:

G W F / ✳ (with open circle at centre) / I (G.W.T according to Langwill)
The bore of the body joint was measured at various points and varies between 12.8 and 12.9 mm. The bore is cylindrical to a good approximation over the whole length, although there is some distortion due to shrinkage. The external body diameter is approximately 24 mm. The tonehole diameters are very small (even for a 'D' clarinet) ranging from 4.7 to 5.65 mm.

The instrument is in good condition and there is no indication, apart from the shortening of the tenon described above, that any modifications to the bore or toneholes have been made since it was manufactured.

This is believed to be the only known example of this type of clarinet construction. The position of the tonehole vented by the thumb key and the external shape confirm that this is a clarinet rather than a chalumeau.

A replica of this instrument has been made (Edward Planas) which plays at A = 415 Hz.

Undercutting:

All of the toneholes are undercut approximately conically through the whole of the wall thickness. An impression was made of the right hand middle fingerhole and the semi-angle was measured as close to 18 degrees. This appears to be representative of all of the toneholes (except for VII which is slanted).

It is not possible to be sure of the method of undercutting, but, despite the narrowness of the bore, the regularity of the profiles favours the use of a fraise tool rather than free-hand work with a file or blade.

Cahusac. 5-Keyed Clarinet in Bb. c. 1785. (Shackleton collection). [CLT099]

Description:

The firm of Cahusac was started near St Clement Danes in London in about 1755 by Thomas Cahusac and later moved to the Strand. The firm is best known for the high quality flutes which they produced but they also manufactured oboes, clarinets, bassoons and violins.

This box and ivory instrument has three body joints. The bore is 14.2 to 14.3 mm to the start of the flare. The bell has a narrow angled conical external shape and is integral with the stock. The nominal wall thicknesses of the left and right hand joints are 5.3 and 4.7 mm respectively

Undercutting:

All of the toneholes are conically undercut with a (measured) semi-angle of approximately 20° extending through most of the wall thickness typically to within 1 mm of the outer surface. Some of the holes show slight enlargement to both sides. The regularity of the cuts indicates that a fraise was probably used but there are no discernible marks to confirm this.

Theodore. 5-Keyed Clarinet in Bb. c. 1785. (Shackleton collection). [CLT104]

Description:

Theodore was French instrument maker working in Paris during the fourth quarter of the eighteenth century. This clarinet is marked with the maker's name and a 'fleur-de-lis' symbol which is not likely to have been used after the French Revolution of 1789. The body is box and ivory and the five brass keys have been plated with silver, much of which has worn away. The bore varies from 15.1 to 15.3 mm.

The bell is integral with the stock. The wall thicknesses of the left hand and right hand joints are nominally 5.0 and 4.9 mm respectively

Undercutting:

The fingered toneholes are conically undercut with a cone semi-angle of approximately 20° through most of the wall (from 5.2 to 5.7 mm thick) leaving a cylindrical section of about 1 mm in height. The third fingerhole has circumferential marks indicating that a rotating (fraise) tool has been used for the undercutting.

The right hand joint has slightly larger angle undercuts with semi-angles measured up to 30° extending over half way through the wall. The middle hole with the smaller angle showed evidence of radial marks indicating the use of a file.

Hale 6-Keyed Clarinet in Bb. c. 1790. (Shackleton collection). [CLT100]

Description:

The inscription 'I Hale Late Collier' is the mark of John Hale who was a well known London flute maker from 1784 to 1804. The sixth key is a long side key on the top joint for trilling on A4 and Bb4 as is usual for London-made clarinets of the time. It is probable that 'Late Collier' refers to Hale having worked for, or been apprenticed to Thomas Collier of whom little is known except that he made the oldest surviving English clarinet which is a five-keyed instrument dating from 1770 (date is marked on the instrument) [Shackleton 1995 Book].

This Hale instrument is of box and ivory in three joints with the bell integral with the stock. As the keys are missing this provided an opportunity to examine more closely the toneholes which would usually be obscured.

The bore is close to 14.4 mm throughout the left and right hand joints and the wall thickness varies from 5.4 to 5.2 mm for these joints.

The diameters of the toneholes in the left hand joint are in the range 5.0 to 5.2 mm which is rather smaller than those in the other clarinets examined here. The right hand joint has toneholes with diameters of 5.6 to 5.9 mm.

As in several other examples of clarinets of this period made in London, a sixth key has been provided on the tip joint to allow trills to be played starting on the notes at the top of the chalumeau range.

Undercutting:

Despite the small size of the toneholes in the upper joint, the undercutting is quite moderate, being roughly conical with (measured) angles of around 15° extending half way or a little more through the wall thickness which is nominally 5.4 mm.

The right hand joint has toneholes with diameters of 5.6 to 5.9 mm and these are similarly undercut to those in the upper joint , i.e. 15° but slightly larger for hole VI (~20°).

The transition from cone to cylinder has been smoothed to some extent in the fingered holes.

As in all clarinets of this pattern the hole for the right hand little finger (VII) is drilled obliquely through the thickened part of the wall and is essentially not undercut.

Of the holes closed by keys, the side B hole is very narrow at 3.7 mm and the top A hole is cut at 15° slightly deeper than the fingered holes. At the bottom the holes are likewise cut at 15 to 20° through one half to three quarters of the wall thickness.

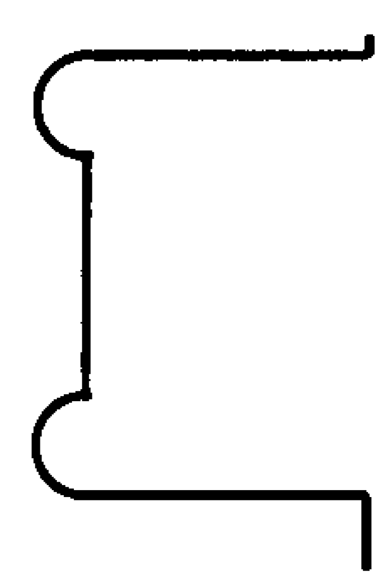
Doleisch 5-keyed clarinet in Bb. 1793. (Shackleton collection). [CLT102]

Description:

This instrument is made of boxwood and horn with brass keys and was made in Prague. Again the bell is integral with the bottom joint.

A symbol in the form of a circle of dots is stamped below the maker's name on the top joint. The date '1793' is stamped on the lower joint[±].

The wooden 'rings' on the top and middle joints are rectangular in section with decorative trims:



but the ring at the top of the bottom section is the normal smooth swelling and the lower rings have been cut back to form 'knobs'.

The bore is nominally 14.0 mm and 14.4 to 14.3 mm and the wall thickness 6.8 and 5.8 mm in the left and right hand joints respectively.

The fingered tonehole diameters are very small, ranging from 5.4 to 5.7 mm in the top joint and 5.8 to 6.2 mm in the other joints.

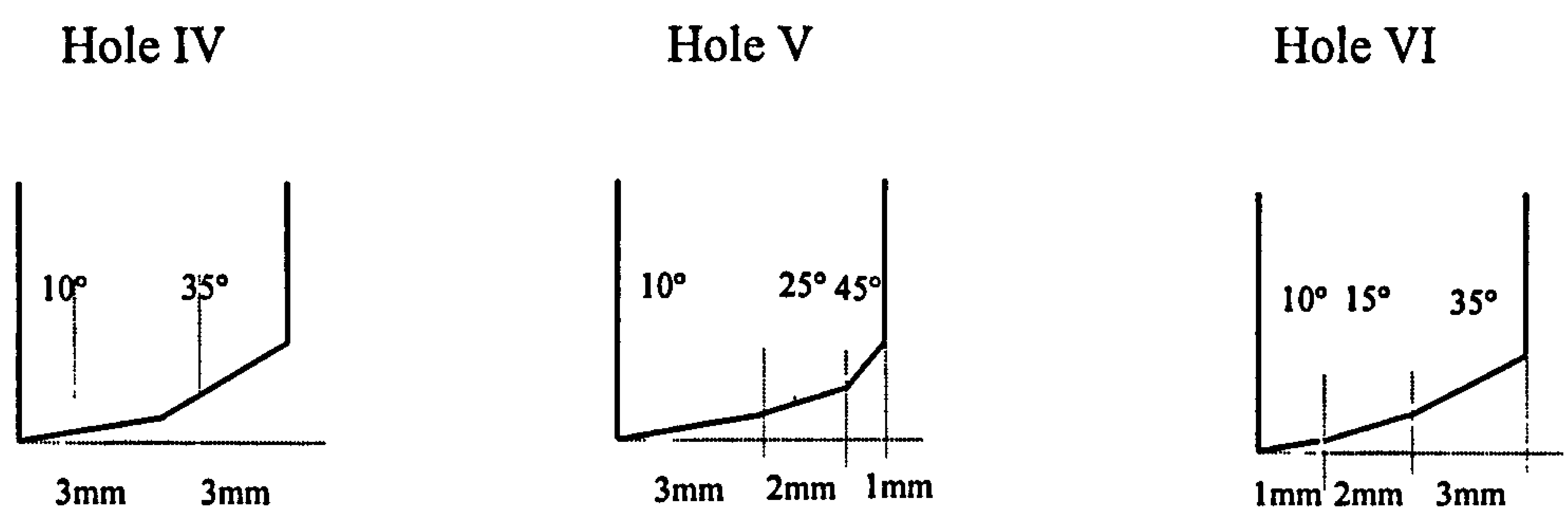
Undercutting:

The undercutting throughout is irregular. Starting at the top:

'A' keyed hole - Undercut asymmetrically to the sides and downstream extending only a short distance into the wall.

[±] A 9-key basset-horn by the same maker in the Royal College of Music Museum has : a crown mark / DOLEISCH /PRAG /and either one or three six-pointed stars, with the date '1803' stamped in addition on the 'book' only. The rings are also made of horn.

Thumb and fingerholes I to III - Undercut asymmetrically to the sides and upstream also extending only a short distance into the wall except for hole III which has a deeper undercut.
Right hand holes IV to VI - Two or three stage undercut i.e. a shallow cone followed by wider angle cuts extending the holes to both sides.
Estimates of the angles were made on the upstream side of these three holes by taking an impression with the following results (wall thickness approximated to 6 mm):



The edges between the separate cuts are sharp and well defined.
Close examination of the imprints on the moulding material used to make the impressions revealed traces of radial marks on the widest portion of the undercuts indicating that the final stage of the enlargement has been made with a file.

Miller 6-Keyed Clarinet in Bb. c.1795. (Shackleton collection) [CLT101]

Description:
This is a box and ivory instrument with brass keys by G Miller who worked in Cornhill, London from 1775 to 1799. It has the features of the standard 'classical' clarinet, namely three main body joints with a separate bell, which indicates that it was made towards the end of the century. In the early years of the nineteenth century Miller is known to have produced clarinets for Clementi & Co.
The bore is nominally 14.4 mm in the top joint and 14.5 mm in the right hand and bottom joints. The wall thickness is nominally 5.6 mm. The flare in the bottom joint only extends some 20 mm up from the bottom, roughly the length of the tenon.
The tonehole diameters range from 5.25 to 5.55 mm in the top joint and 5.7 to 5.8 mm in the right hand joint.

Undercutting:

All of the open toneholes are lightly undercut (except VII). The thumb hole is undercut at a shallow angle (~5°) through the whole wall thickness and the other fingerholes in the top joint are cut approximately through half the thickness at about 10°. The cuts in the right hand joint are slightly deeper and wider at about 15° with similar shapes for the keyed holes of the bottom joint. As is usual the right hand little fingerhole (VII) is sloping and without undercut.

The top keyed 'A' hole is unusual in that it is almost cylindrical with only a minimal widening at the bore end. No deliberate undercutting seems to have been made.

Cahusac, Thomas 6-key Clarinet in Bb. Royal College of Music Museum, London Exhibit No.450 [CLT053]

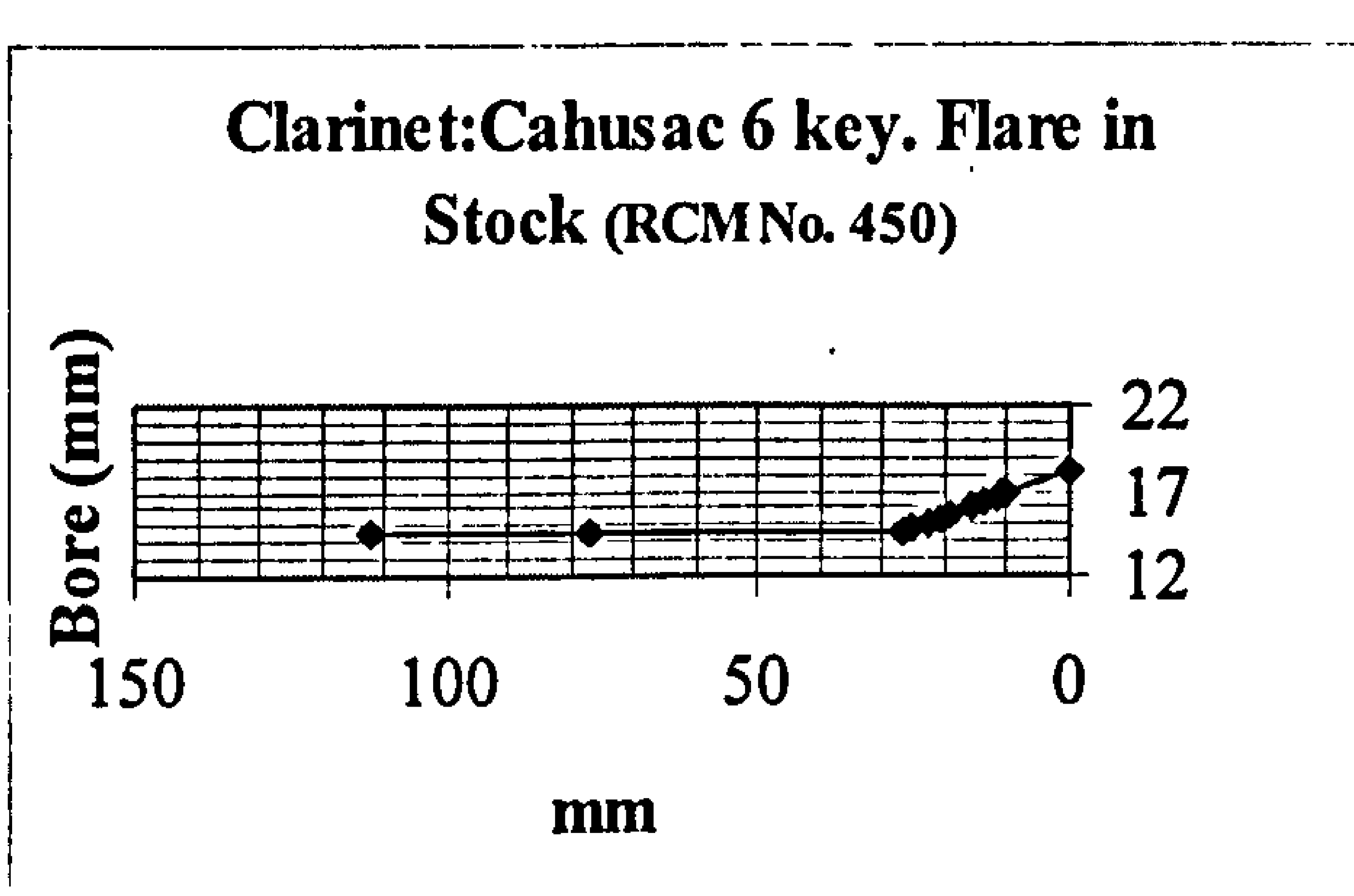
This box and ivory clarinet has brass keys with square flaps. The sixth key is a side B trill as is usual for London-made clarinets of the period. As well as the maker's name, the instrument is stamped 'B' indicating the pitch as Bb, and with the address 196 Strand, London. Thomas Cahusac is known to have worked there from 1794 to 1798 so an estimated date of 1796 is proposed. From 1800 this address was used by his son W M Cahusac.

Measurements showed the following:

Top joint: Bore nominally 14.35 mm. Finger tonehole diameters ~ 5.9-6.6 mm. Wall thickness ~5.4 mm. Upper toneholes slightly elongated along axis.

Right hand joint: Bore ~14.4-14.6 mm. Lower tenon compressed. Finger tonehole diameters ~ 6.6-7.0 mm, some with slight elongation as above. Wall thickness ~5.8 mm.

Stock: Bore ~14.5 mm with sharp transition to a conical flare as shown below:



Undercutting:

All of the toneholes examined in the left and right hand joints have symmetrical conical undercuts through at least half of the wall thickness indicating that a fraise tool was used. Typically the ratio of the total extent of the undercuts measured along the direction of the bore axis to the diameters of the toneholes is 1.41 with a spread of 1.33 to 1.50. The semi-angle of the undercut cone is estimated to be ~20°-25°.

The toneholes in the stock, excluding the G/D hole which is typically cut obliquely and cylindrically, have shallower undercuts with broader angles. The ratio as defined above for the C#/G# hole is 1.53.

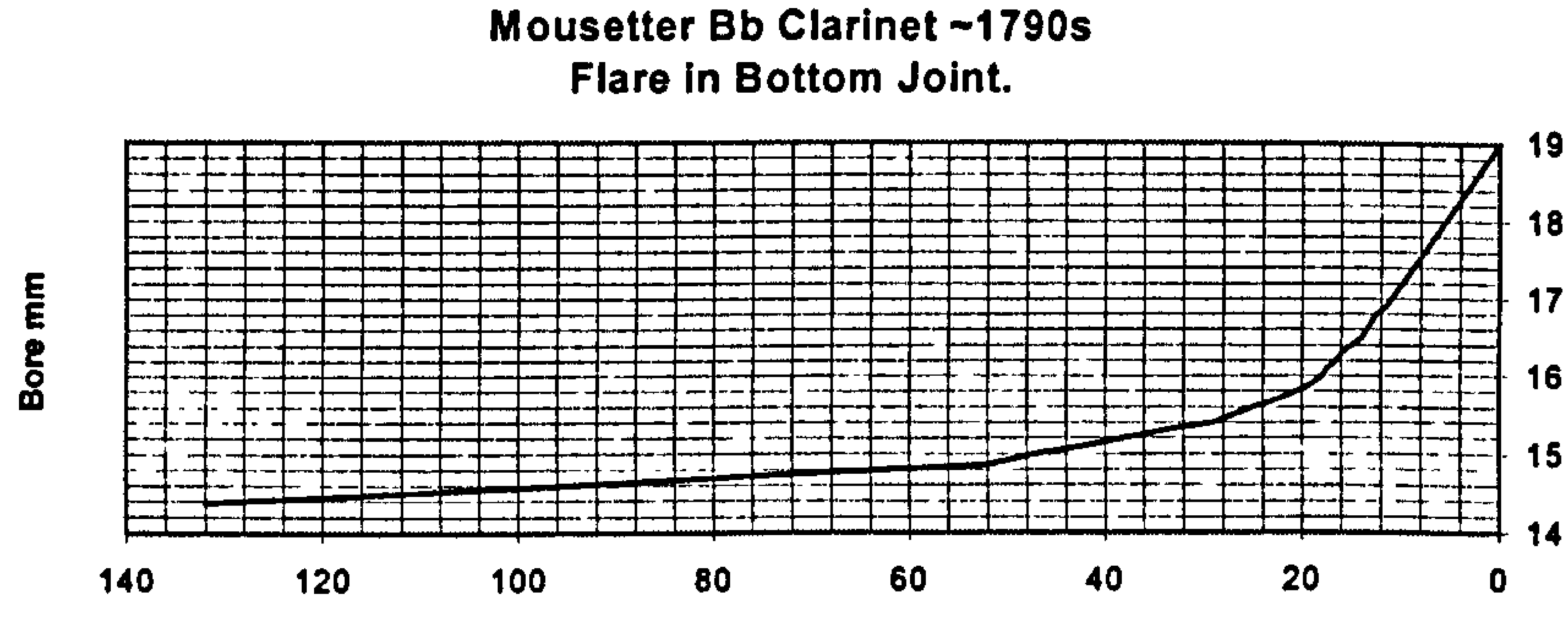
Mousetter 5-Keyed Clarinet in Bb. (Keith Puddy collection) [CLT098]

Description:

This is a five-keyed instrument dating from the 1790s. It is stamped 'Mousetter A Paris' at the top and lower down with the mark 'P' which is probably an incompletely stamped 'B' to indicate the pitch.

Like the Baumann clarinet [CLT105] in the Shackleton collection which is described later, the two left hand little finger key touch pieces are extendible to accommodate a longer 'corps de rechange' middle joint when the instrument is converted to an A clarinet.

Both tenons in the upper joint constrict the bore but away from these regions the bore ranges between14.40 and14.48 mm. The bore in the right hand joint is slightly larger in the range 14.50 to 14.57 mm. The minimum bore in the stock is ~14.3 mm and the flare starts high in the joint, increasing smoothly and merging with a cone over the lower 15 to 20 mm as shown in the measured profile below. This is not typical of the period as there is usually an abrupt transition from cylinder to cone in this region (see Cahusac [CLT053 above]).



Undercutting:
All of the fingered toneholes are doubly undercut with a small angled undercut followed with a wider angled cut. The undercutting is rather irregular indicating that the enlargements have probably been carried out free-hand either by holding the body against a rotating fraise or with a round file. An indication of the extent of the undercutting along the bore axis direction is shown in the Table at the end of this section (from borescope graticule measurements).

2.2.1.1 Discussion

With some exceptions, including the very earliest Denner instruments, the bore sizes of eighteenth century clarinets tend to be smaller than in present day instruments. For instruments pitched in Bb the bores are mostly in the range 14.0 to 14.5 mm, (14.5 mm is typically the bore of a modern 'C' clarinet). The tonehole diameters are also significantly smaller and the open fingered holes tend to be of similar sizes over the length of the instrument rather than increasing in diameter with distance from the top as generally occurs in modern designs. This is necessary if forked fingerings are to be used.

The measured bore and tonehole sizes for the instruments studied (excluding the Wietfeld [CLT097]) are tabulated below:

[CLT] →	Rottenburgh 103	Cahusac 099	Theodore 104	Hale 100	Doleisch 102	Miller 101	Cahusac 053c	Mousetter 098
~ date	1760	1785	1785	1790	1793	1795	1796	1790s
Nominal .Bore	14.4-14.8	14.2	15.1-15.3	14.2	14.0-14.4	14.5	14.3-14.6	14.3-14.6
Thumb	5.85	?	5.9	5.0	5.4	5.3	6.0	5.6
I	5.9	5.7	5.8	5.1	5.5	5.55	6.6	6.0
II	6.3	5.75	5.8	5.2	5.7	5.25	6.0	6.3
III	5.8	5.6	5.8	5.2	5.4	5.25	6.3	6.2
IV	7.0	6.1	6.1	5.9	6.2	5.7	6.6	6.4
V	6.6	6.1	6.0	5.85	5.9	5.8	7.0	6.2/6.0
VI	6.1	5.9	5.6	5.65	5.8	5.7	6.5	6.2/6.0
VII	6.0	~5.2	5.9	4.7	6.2	5.9	7.0	6.2

The descriptions of the undercutting found in the individual instruments was obtained by use of the borescope and from impressions taken from some of the toneholes using a moulding compound.

It is apparent that there is variety in the style and extent of undercutting applied by the different makers.

Of the oldest instruments, the Rottenburgh 4-keyed clarinet [CLT103] from about 1760 shows different types of undercutting in the left and right hand joints. (Also the bore of the right hand joint is slightly larger than the left raising the possibility that the work was split between craftsmen). The enlargements of the upper joint holes are wide angled extending through only about one quarter of the wall (approximately 5.3 mm thick) whereas in the lower joint the undercutting extends through most of the wall (~5.1 mm) with an estimated cone angle of 20°. The bottom keyed holes are mainly parallel sided with some enlargement to both sides. From the estimates of the extent of the enlargements along the direction of the axis it appears that the volume of material removed is greater for the right hand fingerholes than for the left.

In contrast the Wietfeld [CLT097] D clarinet of a similar date, with its uniform bore throughout the single piece body, has not only similarly sized toneholes but they have all been similarly undercut.

Comparisons can be made between the four clarinets made in London between 1785 and 1795. From the tables it can be seen that the earlier Cahusac [CLT099] and Hale [CLT100] instruments both have nominal bores of 14.2 mm and the Miller [CLT101] has a slightly larger bore of 14.5 mm. The Hale has the smallest toneholes in the range 5 to 6 mm for the fingered holes and the Miller holes are on average slightly larger and more uniform ranging from 5.2 to 5.8 mm. The corresponding holes in the Cahusac lie between 5.6 and 6.1 mm, that is, larger on average but more uniform in size than the other two instruments.

In this comparison the Miller has the least undercutting with cone angles in the range 5° to 15° tending to increase down the length of the instrument, the undercutting in the right hand (lower) joint extending further through the wall thickness than in the upper joint.

The Hale, with the smallest toneholes, has slightly more pronounced undercutting with angles of typically 15° extending half way or more through the wall with some smoothing of the shape having been carried out. This is probably a combination of the use of a fraise and hand finishing with a file.

The Cahusac with the largest toneholes also has the heaviest undercutting with 20° cones extending through most of the wall thickness.

The other factor which needs to be taken into account is the actual wall thicknesses. These are:

	Cahusac	5.3 mm LH joint, 5.1 mm RH joint
	Hale	5.4 mm LH joint, 5.2 mm RH joint
and	Miller	5.6 mm both joints

The Cahusac has a slowly tapering body shape which was probably created for aesthetic rather than acoustic reasons.

Although the Miller has the thickest wall it also has the least undercutting and the thin walled Cahusac the heaviest.

The absence of undercutting in the top 'A' hole of the Hale clarinet is most likely the result of a careless omission rather than a design feature.

Of the Paris-made instruments, the top joint of the Theodore [CLT104] clarinet has moderate angle undercuts extending through most of the wall and in one of them there are traces of circumferential scratches making it likely that a rotating cutter has been used, whereas in the lower joint one of the shallower angled wider cuts shows radial marks pointing to the use of a file or knife. This is perhaps an illustration of the craftsman who finished the instrument having the freedom to choose his own method of achieving his objective.

The other French instrument by Mousetter [CLT098] and the Doleisch [CLT102] example from Prague both have undercuts with complex profiles. In the Mousetter an initial shallow cone is followed up with a wider angle cut which has left rather irregular shapes where the hole meets the bore. This could be the result of using a rotating fraise freehand or the use of a round file to finish. The Doleisch has holes made in two or possibly three stages. The sharp edges in the tonehole sides between the cuts indicate that different angle fraises have been used, but when taking the impressions it was noticed that there are faint radial marks on some portions of the wider angle cuts. Also the final enlargements of the right hand fingerholes in particular are asymmetrical, being heavier upstream than down. This can be seen clearly in the table of borescope measurements. The most likely explanation is that two or more fraises were used to achieve a regular shape and then the holes were enlarged upstream only with a hand file.

The other unusual feature of this clarinet is the pronounced oval shapes of the lowest two holes (long axis parallel to the bore) which are also regularly undercut. Clearly this must have been performed with a file or a knife followed by smoothing with a file. Within the dimensional limits found within this small sample, the need to undercut does not appear to have been determined by the height and diameter of the toneholes. In contrast, these observations indicate that the style of undercutting adopted by an individual maker was a matter of choice aimed at achieving a particular characteristic sound for that maker's instruments.

The clarinet came into existence at about the beginning of the eighteenth century, and it is not surprising that all of the surviving specimens were made by firms already producing woodwind instruments. As a consequence the materials, manufacturing methods, and key mechanisms currently in use would have been applied to the new type of instrument. (One feature peculiar to the clarinet is the metal tube projecting into the bore to act as the speaker vent which is present in all but the earliest instruments). It is therefore to be expected that the tonehole sizes and shapes used in clarinets of this period would have been influenced by the current practice for flutes, oboes and bassoons, and this would include routine undercutting of what would be considered small diameter toneholes relative to the bore size compared to modern design.

All of the instruments discussed above, with the exception of the Wietfeld D clarinet, have the right hand little fingerhole drilled obliquely so that it vents the bore at a point below the finger position. To increase the magnitude of the flattening effect, the wall is thickened with a turned ring which also is used to pivot the lower joint keys. Typically the physical length of this tonehole is about 15 mm compared with about 6 mm for the other fingerholes. This hole is drilled as a straight cylinder and any undercutting is carried out to the sides only (and occasionally downstream). This is because any enlargement upstream would raise the pitch of the associated notes (G_3/D_5) which would counteract the objective of sloping the tube i.e. flattening the notes. Undercutting this hole with a knife or file is in any case restricted because of its depth. A fraise tool would also be difficult to employ as it is only ideally suited to cutting normal holes.

2.2.2 'Classical' Clarinets from 1800 onwards.

In this section, undercutting in classical pattern clarinets made in the nineteenth century is explored. The number of keys range from five to thirteen but all retain to a large extent the 'classical' features.

2.2.2.1 Five and Six Key Classical Clarinets

Fourteen five- and six-keyed clarinets from this period have been examined. All but one of the six key clarinets has the side B as the additional key. The exception is the Baumann instrument made in Paris which has a C#/G# cross key. 'Classical' clarinets continued to be made long after the design had been superseded but the instruments selected here can all be shown to have been made in the early part of the century, either from details revealed by the maker's mark [Langwill 1993], or from the style of their construction.

Nineteenth Century Five- and Six- keyed Classical Clarinets

[CLT] ↓	Pitch	Bore	Keys	Maker	Estimated Date	Lower Joint
017	Bb	13.6	5	Goulding and Co	Early 19 C	Stock
030	Bb	13.9	5	Goulding and Co	Early 19 C	Stock
052	C	14.0	5	Astor and Co.	Early 19 C	Stock
055	Bb	14.1	5	Cramer	1805	Stock
001	Bb	14.1	6	G Astor & Co London	1801-7	Stock
003	Bb	14.1	6	Goulding London	1806-8	Stock
004	C	13.5	6	Goulding London	1806-8	Stock
010	C	13.5	6	C Otten London	1820	1 piece
011	C	13.4	6	G C Payne London	1808-35	1 piece
016	A	14.1	6	U	~1810	Stock
034	Bb	14.0	6	Goulding and Co. New Bond St	1804-11	Stock
054	Bb	14.4	6	Clementi and Co.	Early 19 C	Stock
092	C	14.3	6	Baumann a Paris	Early 19 C	Stock
105	Bb	14.5	6	Baumann a Paris	~1800	Stock

The following Table shows that, as described in Part 1, the open fingerholes of the top joint are small and of similar sizes whereas those in the right hand joint are, on average, slightly larger but similar to each other. The hole covered by the right hand little finger is drilled obliquely through a thickened wall section which also provides the mount for the left hand little finger lever keys.

Tonehole Diameters 5-key

[CLT]	Th	I	II	III	IV	V	VI	VII
017	6.2	6.0	6.0	5.9	6.9	6.5	6.9	-
030	5.8	5.8	5.8	5.8	7.5	7.4	7.2	7.3
052	-	5.5	5.6	5.8	6.9	6.9	6.9	-
055	5.9	5.7	6.0	5.9	6.3	6.2	6.2	5.7

Tonehole Diameters 6-key

001	6.9	6.0	6.1	5.9	Missing			6.6
003	6.2	6.0	6.2	5.9	7.0	6.7	6.8	6.8
004	5.9	5.7	5.7	5.8	6.6	6.6	6.6	6.8
010	5.7	6.5	6.2	6.1	6.7	6.6	6.7	6.4
011	6.2	6.5	6.1	6.2	6.9	7.0	7.0	6.7
016	6.2	6.4	6.5	6.2	7.0	7.1	6.9	-
034*	6.10	6.00	5.90	-	7.32	7.04	6.86	7.15
054	5.6	5.9	5.9	5.9	6.6	6.7	6.7	6.5
092	5.8	5.7	5.9	5.8	6.1	5.9	5.8	-
105	5.9	5.7	5.7	5.9	6.4	6.4	6.0	7.0

* Speaker hole diameter 3.3 mm

Undercutting 5-key

[CLT]	Speaker	A	Thumb	I	II	III	IV	V	VI	VII	Ab	C#	E
017	M	-	-	8	8	8	8	8	8	-	7	7	7
030	M	-	D*	D*	D*	D*	5	5	5	-	3(s)	0	0
052	M	-	5/6^	5/6^	5/6^	5/6^	5/6^	5/6^	5/6^	-	2s	0	0
055	M	-	6	5†	6	5†	5	5	4/5	-	-	-	2s

Undercutting 6-key

[CLT]	Speaker	B	A	Thumb	I	II	III	IV	V	VI	VII	Ab	C#	E
001	M	12	-	12	12	12	12	Missing			-	5	5	4
003	M	-	-	D*	12	12	12	12	12	12	-	4	0	0
004	M	-	-	-	12	12	12	12	12	12	1s	8	8	8
010	M	4	u†	-	6	6	6	7/8	5^	5^	-	6	3	3
011	M	-	-	12	8	8	8	8	5	6	-	4	5(s)	4
016	M	-	*d	-	12	12	12	12	12	12	o.c.	6	8	8
034	M	-	-	-	12	12	12	12	12	12	-	-	7+4	7+4
054	M	-	-	6	5	4/5	4	5	6	6	-	6^	6^	5
092	M	-	5	6w	6	6	5	6	5/6	5/6	-	5	5	5/6
105**	M	-	6	5	6	6	6	6	5	5	-	(s)	6	5

* D = Doubly undercut (5°/20°) † = filed asymmetrically ‡ = hole plugged

** sixth key is C#/G# ^ = shallower angle ~ 10° o.c. = overcut

w = wax added s/u/d = cut sideways/upstream/downstream

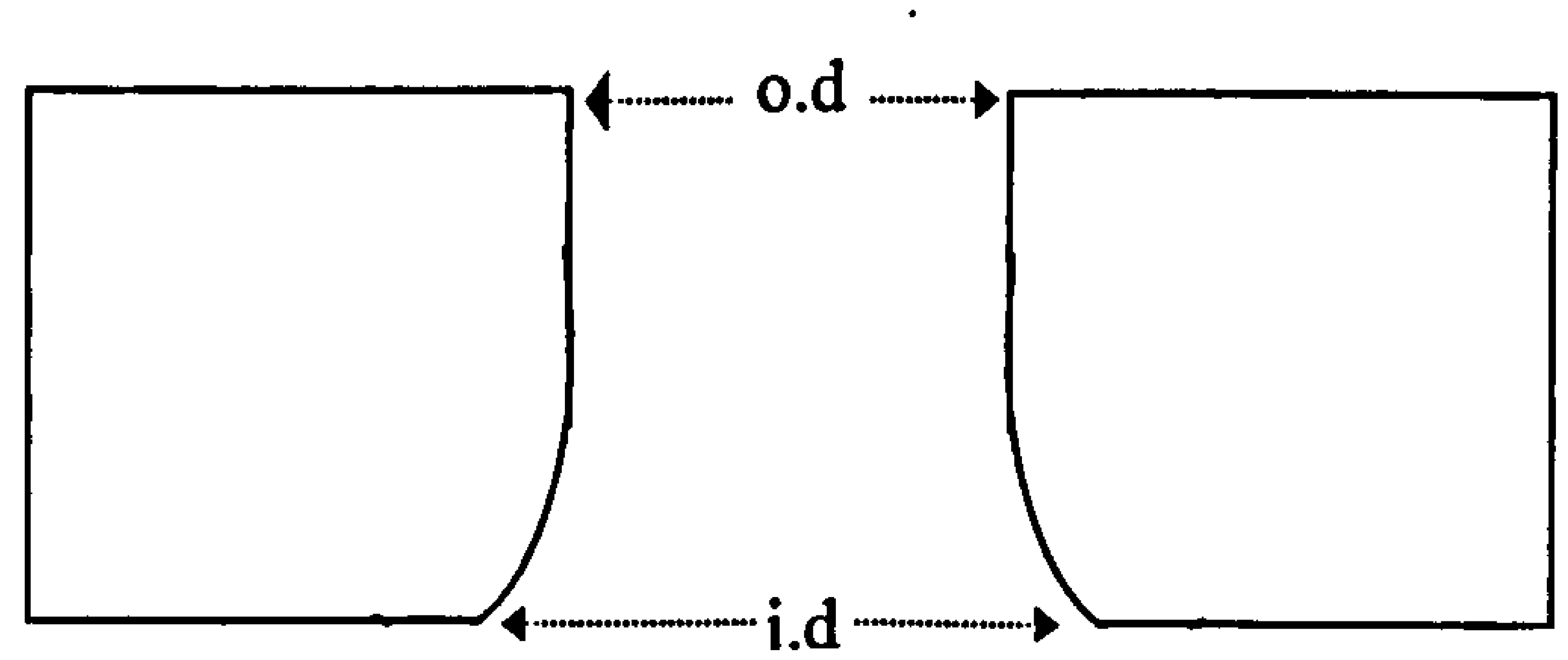
The earliest of the Goulding clarinets, [CLT017] and [CLT030] have the 'Goulding & Co." stamp which was used for a few years from about 1800. The example in the Boosey and Hawkes Museum [CLT017] is in poor condition with considerable distortion of the joints due to shrinkage. The toneholes appear to have been undercut in two stages for the most part, first with a conical fraise followed by a beveling at the intersection with the bore which was probably done with a file. A similar pattern is found in the Kneller Hall example [CLT030] but here the second cut appears to have been made with a larger angle cone cutter to give a more distinct change in angle at approximately one quarter of the way through the wall thickness.

All three of the six-keyed Goulding instruments from a slightly later date have toneholes which have been opened out towards the bore with 'bell' shaped flares: The surface finish of the flares is fairly smooth and the shapes appear to be regular. One of these clarinets [CLT034] was examined in detail to assess the consistency of this type of undercutting. Close examination indicated that cone shaped fraises had probably been used to generate the shapes initially followed by smoothing to approximate to a smooth flare.

The borescope was then fitted with the measuring eyepiece as described in Part 1 which has a cross-wire driven by a micrometer mechanism. With this device it was possible to make accurate measurements of the extent of the bell-shaped flares at the bore end of the toneholes measured along the axis of the instrument. Details of the data obtained from this clarinet are shown in below:

Goulding Six-Keyed Clarinet [CLT034]

Borescope examination showed that all of the fingered toneholes had been undercut to form a smooth flare as illustrated here:



The measurements were compared with the tonehole sizes as measured externally and the results expressed as percentage increases in diameter.

Fingered Holes

Hole	o.d. (mm)	i.d. (mm)	% increase (linear)
Thumb	6.10	9.10	49.0
I	5.84	8.37	43.3
II	6.00	8.71	45.2
III	5.90	7.99	35.4
IV	7.32	10.71	46.3
V	7.04	9.86	40.0
VI	6.86	9.69	41.3

Hole VII is bored obliquely with no undercut (diameter 7.15 mm)

Keyed holes:
Similar shapes to fingered holes except where stated.

Hole	o.d. (mm)	i.d. (mm)	% increase (linear)
Speaker	3.38	3.30 (M)	0
Side B	5.60	7.48	33.6
A	5.78	8.26	42.9
G#/D#	11.4	14.9	30.7
F#/C#	7.02	8.64	23.0
E/B	11.7	Mainly upstream u/c (~1.2 mm)	

Whilst the undercutting of the fingered holes is fairly symmetrical, there are some irregularities in the keyed hole shapes, indicating that the undercutting tool may have been hand-held.

An unusual feature of this clarinet, not found in any of the other five- and six-keyed Goulding clarinets examined [CLT003, 004, 017 and 030] is the enlargement of the bore at the lower end of the stock. The enlargement extends past the lowest hole (F3/C5) and matches the bore at the top of the bell. This is probably an attempt to improve the frequency ratio for these notes and is an early example of a bore perturbation in this region. Clarinets of this period normally have a fairly abrupt transition from the cylindrical to conical bore just above the bell, (see the Casuhac clarinet [CLT053] in Section 2.2.1), as is perpetuated to the present day in German-style clarinets.

As noted above, it appears that a combination of conical fraises and smoothing was used to generate the bell shaped profile rather than a profiled cutter. Whichever technique was used, the uniformity and extent of the undercutting show that this is a design characteristic rather than attention being given to individual toneholes to improve tuning.

Similar features were found in a six-keyed Bb clarinet by G Astor and Co. of London [CLT001] from this period of which only the top joint survives and in an unsigned 'A' clarinet [CLT016] as listed in the Tables above. The unsigned instrument was made to accommodate a 'London' pattern mouthpiece indicating that it too was manufactured in London. This raises the possibility that these makers might have out-sourced the wooden body parts.

With all of the examples described so far the intention of the makers appears to have been to reduce the sharpness of transitions in the tonehole shape by progressive or smooth enlargement of the holes.

The other Astor clarinet [CLT052] which is in C has shallow-angle conical undercuts extending from half way to three quarters way through the wall thickness.
The Cramer five-keyed example [CLT055] was difficult to assess because the toneholes had accumulated a thick layer of dust. However it was noted that the first fingered hole of the left hand had been opened up with a file asymmetrically, presumably to correct the tuning, whereas the rest showed fairly uniform undercutting.
The six-keyed clarinets by the London makers Otten [CLT010], Payne [CLT011] and Clementi [CLT054] all had toneholes which had been undercut with shallow angled cones extending well through the wall thickness and, in some cases, to the full depth of the wall.
Two examples of French-made six-keyed clarinets were examined, both by Baumann of Paris: [CLT092] and [CLT105]. Both have cross C#/G# keys as the sixth key. Their basic undercutting was similar, extending typically between half and three quarters way through the wall thickness with shallow angle cone shapes. In addition to the normal undercutting the second instrument had been heavily hand undercut in the right hand and stock sections to create irregular shaped enlargements.
This instrument has long lever keys on the stock for the left hand little finger that can be extended to accommodate 'corps de change' sections when altering the pitch to 'A' (as the Mousetter 5-keyed clarinet, [CLT098], described earlier.

2.2.2.2 More than Six Keys

The clarinets examined in this section were made during the first half of the nineteenth century and retain most of the classical clarinet features, but have had extra keys added to the basic design as defined in Section 2.1 previously. All but the Grenser instrument [CLT107] were made in London.
Most of them are boxwood with ivory rings and have brass keys mounted in wooden 'knobs' which are integral with the body. The exceptions are three of the clarinets by Key. The 'C' clarinet [CLT006] has an ebony body and the two Bb clarinets [CLT007 and CLT108] are made from cocus wood. All three have silver keywork.

CLT	Pitch	Keys	Maker	Bore	~ Date
027	Bb	8	Cramer London	14.25-14.5	1800
031	Bb	8	Bilton London	13.65	1825
005	C	9	Key London	13.5-14.1	1815-56
107	Bb	10	H Grenser Dresden	14.4	1810
006	C	11	Key London	13.9	1815-56
002	C	12	Bilton London	13.7	1840
029	Bb	12	Blackman London	13.7	1820s
106	Bb	13	Cramer and Key	13.8	1805-07
009	A	13	Key London	15.1	~1820
008	Bb	13	Key London	14.0	~1825
007	Bb	13	Key London	14.1	1832
108	Bb	13	Key London	14.4	1834

Dealing with the London-made instruments first:

The eight-keyed Bb example by Cramer [CLT027] has a long tenon 'London' pattern mouthpiece. The lower section is made as a single piece. All of the toneholes examined have been conically undercut with an estimated angle of 20°, the cut extending approximately half way through the wall. The undercutting is quite uniform throughout.

The Bb Bilton example [CLT031], also with eight keys made two decades later, is of similar construction to the Cramer but with a tenon on the top of the barrel and round brass key flaps seating on holes with raised rims. The bore is narrower but the undercutting in the top joint is similar to that of the Cramer. The fingerholes in the lower joint are cut slightly deeper whilst the lowest holes have 'crescent' cuts to the side indicating light use of a fraise tool which did not touch the bore all the way round.

The second Bilton clarinet in C [CLT002] has twelve keys, two of which are in saddles and may be later additions. The barrel has been shortened and all of the toneholes have been undercut with considerable variation in the depths and shapes of the undercuts. Clearly at some time an attempt has been made to sharpen the pitch of this instrument which would account for this variation. Interestingly the fingered toneholes at the top of the right hand joint, IV and V, have been undercut sideways and downstream but the up-stream edges are close to perpendicular to the bore axis. It is possible that this was the result of an attempt to improve the lower register B/Bb tuning problem and that the cross-keys on the lower joint were later additions.

The first of the Thomas Key examples [CLT005] has nine keys with round flaps, still block-mounted, except for the upper joint F key which is mounted in a saddle. The thumb and speaker holes are not metal lined. This instrument is unusual for the period because the front fingerholes of the top joint are not undercut. The thumb hole and the right hand fingerholes are tapered, narrowing towards the outside, with an angle estimated at 5°. Only the lowest hole has a conventional conical cut. The keyed G#/D# hole is like the lower fingerholes but has additionally been irregularly enlarged to the side with a file. This type of taper cut is unusual compared with contemporary clarinets but does have some similarity with the early six-keyed Miller instrument [CLT101] made in London at least twenty and possibly fifty years earlier.

The second Key clarinet [CLT006] in ebony and ivory would have been a more expensive instrument. It started life with probably nine silver keys mounted in blocks with 'pincushion' shaped flaps engraved at the corners. Extra keys have been added in saddles to the left hand joint to give a high C and throat G#. Subsequently two of the keys (cross Eb and right hand cross Bb) have been removed and the holes plugged. All of the open fingered holes have a 'bell' shaped profile whilst the holes at the top of the instrument have shallow straight-sided tapers. The enlargement of the holes at the bore is quite small and the profile of the shaped holes is similar to that found in one of the Goulding clarinets [CLT034] described in detail in the preceding section.

The clarinet made by Blackman [CLT029] in the 1820s has twelve 'saltspoon' keys and has been conically undercut throughout. A feature of this instrument is that the top fingered holes of both joints have been drilled sloping downwards towards the bore without undercutting, whereas all of the other fingered holes are cut normally with moderate conical undercutting. This has the effect of making the fingerhole spacing more uniform but the maker's intentions are not clear.

The rest of the London instruments, all by Cramer and Key and Thomas Key have thirteen keys, but some are believed to be later additions.

First the clarinet by Cramer and Key [CLT106]:

Cramer had acquired a reputation for making high quality bassoons and clarinets early in the nineteenth century [**Langwill** 1993]. This clarinet, made in1806 or 1807, predates Müller's inventions but has a key to replace the oblique hole for the right hand little finger. This key is hinged at its lower end and the touch piece has a hole drilled through the pad. Depressing the key with the hole covered gives F/C, whilst pressing the key with the hole uncovered produces an alternative F#/C#. All of the toneholes are undercut with shallow angle cones extending through the wall except for the C#/G# cross-key which is heavily cut to one side only. Despite the sophistication of the right hand little finger mechanism, the flaps on the cross keys are curved to match the body, as found in other less advanced instruments made at this time

The remaining four examples of clarinets by Thomas Key [CLT009], [CLT008], [CLT007] and [CLT108] were made in the 1820s and 1830s. Key's partnership with Cramer ended in 1807 and he then made woodwind instruments marked with his own name until 1855.

The A clarinet, [CLT009] was owned by the English clarinettist, Henry Lazarus. This has an F/C key but hinged at its top end. The bore of this clarinet is exceptionally large for this period (15.1 mm). According to Rendall this instrument was made in about 1820 but keys were added and the bore enlarged at a later date. Weston [**Weston** 1977] notes that the two rings for holes V and VI mounted on an axel rod between metal posts were added for Lazarus. This clarinet also has beveled pad seatings and metal tonehole liners not extending to the bore to improve the seal. All of the holes are undercut but some have quite small cone angles estimated at ~10°. It is not known whether this undercutting is original or was adjusted when the bore changes were made, presumably to Lazarus's instructions.

In the other clarinets by Key, there is evidence that this maker has opted by-and-large to restrict the undercutting to the basic fingered toneholes leaving the 'accidental' holes as drilled. This occurs even in what were presumably more expensive instruments [CLT007] and [CLT108] with cocus wood bodies and Hall-marked silver keys. The first of these (1832) has one metal lined tonehole whilst the second (1834) has metal liners throughout for the pad covered holes. Again the liners stop short of the bore and light undercutting has been applied to only a few of these holes.

Finally there is the ten-keyed Grenser Bb clarinet [CLT107]. This was made in Dresden in about 1810 and has brass keys with rectangular flaps. All of the toneholes have been undercut with small angle cone shapes most extending well through the wall thickness. Several of the holes showed a bias towards downstream undercutting with one of the lower holes additionally enlarged sideways. Fingered holes IV and VI in the right hand joint have been back-filled with wax, again probably in an attempt to improve the tuning in this problematical region.

Although thirteen keys allow all notes of the chromatic scale to be played and trills to be executed, these are still essentially 'classical' clarinets and only work efficiently in 'home' keys.

Clarinets with 8 to 12 keys:

CLT	Keys	Bore mm		Speaker	Side B	A	Thumb	Side F/F#	I		II	Front Eb	III	C#/G#	IV	V		VI		VII	F#/C#	F/C
027	8	14.25-14.5	D																			
			u/c				5		5		5		5		6	5		5				
031	8	13.65	D				5.5		6.1		6.3		5.8		7.2	6.4				6.5		
			u/c			4	5		5 (ob)		5		5		6	6		6		ob	3	3
005	9	13.5-14.1	D				6..3		6.4		6.4		6.1		7	7		7.1				
			u/c	0	0	0	7		0	0	0	0	0		7	7		7	7+ 11	0+ 11	11s	3
107	10	14.4	D				5.7		6.0		6.0		5.9		6.6	6.5		5.6		6.2		
			u/c	M		4	M	7	6/8		5 ob	0	4/5	3	4	5	6	6	s+s	0	3/4	4

Clarinets with 8 to 12 keys:(continued)

CLT	Keys	Bore mm		Speaker	Side B	A	Ab	Thumb	I	II	Front Eb	III	C#/G#	IV		V		VI		VII	F#/C#	F/C
006	11	13.9	D					6.0	6.5	6.1		6.0		6.9		6.8		63.9				
			u/c	0	7	7	7s (sl)	0	12	12		12		8/12 sl		12		12		5 s	5	6
002	12	13.7	D						6.2	6.0		5.8		6.8		6.4		6.4				
			u/c	M	5	475	5	4	4 s	7	4	8	4	5 s	4	5 s	3/4	6	3/4	0 s+s	5	4
029	12	13.7	D						6.3	6.0		5.9		6.5		6.5		6.8		6.9		
			u/c			5		4	0 sl	4		5		0 sl		5		6		0 ob	5	5

Clarinets with 13 keys

CLT	Keys	Bore mm		Speaker	Side B	A	Ab	Thumb	Side F/F#	I	II	Front Eb	III	C#/G#	IV		V		VI		VII	G/D key	F#/C#	F/C
106	13	14.1	D					6.1		6.3	6.0		6.1		7.2		7.0		7.1					
			u/c	M		7	8	8	8	8	8	8	8+s	0+ s	7	7	7	7	7	5 10°		2	4	4
009	13	15.1	D							6.6	7.1		6.9		7.5		7.6		8.3					
			u/c	M	4	4	4	5	3/4	5	12	4	4/5	4	4		6		5	4		0 sl	4	0
008	13	14.0	D					5.8		6.3	6.3		6.35		7.4		7.1		7.5		7.2			
			u/c	M	0+1	0	0	8	0	3	12	0+1	12	0	8+2	4	8+2		7+3	6+3	3		3	3
007	13	14.1	D					6.0		6.3	6.0				7.4		6.8		7.8		7.1			
			u/c	M			5	0	0	8+5	8+5	0	5	0	6		6		12	3	0 sl		3/4	¾
108	13	14.4	D					5.7			6.25		6.2				7.0		7.4					
			u/c	M		0	0	0	0	7sl	7	0	7	0	6/7	M	5		5	M	sl+d		3/4	3/4

2.3 Clarinets Incorporating Müller-type Improvements
(excluding Boehm System)

2.3.1 Early Müller-type Clarinets

Three examples of clarinets from the second quarter of the nineteenth century which are based directly on Müller's original *'clarinet omnitonic'* design were examined. These are in box and ivory with brass keys mounted between pillars. The oblique right hand little fingerhole has been replaced by a correctly sized and positioned hole operated by a right hand little finger key. Two of these clarinets have a right hand thumb key although they have different actions. In the Stenger instrument the thumb key is for Ab/Eb whereas in the Guerre it opens the F#/C# tonehole.

[CLT]	Pitch	Keys + RH thumb	Maker	Bore (mm)
169	Bb	13	Godfroy Aine (Paris)	14.8/14.65
168	Bb	14+1	Guerre, Georges (Paris)	14.7
167	Bb	12+1	Stengal (Beyreuth)	14.7

The table below shows the tonehole sizes of the fingered holes in comparison with those of a typical 'classical' clarinet and an Albert system clarinet which was developed later. The Müller-style instruments have been listed according to the best estimate of their manufacture date:

Style	[CLT]	(Putative) Date	Maker	Keys	Tonehole Diameters (mm)						
					Th	I	II	III	IV	V	VI
Classical	034	1804-11	Goulding	6	6.1	5.8	6.0	5.9	7.3	7.0	6.9
Müller	169	1818	Godfroy	13	6.5	6.5	6.5	6.5	7.0	6.9	6.9
	168	(1835)	Guerre	15	6.9	6.0	6.4	6.3	7.3	6.3	7.2
	167	(1850)	Stenger	13	7.0	6.9	7.0	6.9	7.4	7.2	7.4
Albert	151	1862-66	Albert	12	6.9	6.8	7.1	7.1	7.9	7.6	8.3

Whilst Müller's chromatic key system removed the need for small toneholes to allow fork fingerings, [Shackleton Chapter in **Lawson** 1995] it appears that other makers copying the key system did not take immediate advantage of this freedom to improve the venting.

The Albert clarinet shown for comparison [CLT151], made in the 1860s, has on average larger holes than the Stenger but also has a larger bore of 15.2 mm.
The undercutting of these Müller-style instruments is of particular interest to this investigation.
The Godfroy instrument [CLT169] has all of the main fingerholes undercut with 10° to 20° semi-angle cones extending ¼ to ½ way through the wall thickness. The thumb hole is not metal lined and has been undercut downstream and to the side. Of the key-operated holes, only the low G_3/D_5 hole is similarly undercut, the rest being not undercut or with a slight 'chamfer', and the two lowest holes show the usual lateral 'crescents'. It is interesting to note that the right hand joint has still been made in two parts: a section with the fingered holes and a 'stock', as in some of the early classical clarinets.
The second French instrument by Guerrre has similar but slightly heavier undercutting of the main holes but the keyed holes range from no undercutting to 20° semi-angle cones extending half way through the wall. It is noted that there is a long flare in the right hand joint of this clarinet, similar to that found in later French instruments.
The Stengler has narrower conical cutting in most of the main holes, (cone semi-angle ~10°), except for the lowest two in the right hand joint (cone semi-angle ~20°). In contrast to the French instruments, the key operated holes are all undercut with wider cones (typically 20°). The $C\#_4/G\#_5$ hole appears from its irregular shape to have been adjusted by hand.

2.3.2 Mid 1800s Thirteen Key Examples

The keys for the right thumb in Müller's original design proved unpopular and were soon discarded. A number of clarinets from the mid 1800s which include Müller-type features are listed below:

[CLT]	Pitch	Keys	Date	Maker
091	Bb	13	~1840	Buffet a Paris
090	C	13	~1850	Lefevre a Paris
012	Bb	13	Pre 1850?	U France?
023	Bb	13	~1850	Boosé London
019	Bb	13*	1855-71	Clinton and Co

* brille added later

Two early French examples by Buffet [CLT091] and Lefevre [CLT090] have similar undercutting to each other. It appears that conical cutters with a cone angle of about 20° have been used throughout and the cutters have been drawn well into the wall thickness. In the Buffet, three of the fingered holes have also been slightly overcut, but there is no evidence of this in the Lefevre. The Buffet shows signs of additional hand working with a file, which may have occurred after manufacture. There is evidence of slight overcutting, merging smoothly with the undercut, to form a smooth profile. In both instruments the keys are supported on brass posts and the pad cups are domed. On the Lefevre the posts have mounting plates which are attached to the boxwood body by two or four screws.

The third example listed [CLT012] is unsigned but has features which are characteristic of French manufacture. The undercutting shows a similar pattern to the Buffet and Lefevre and the keywork is similar except that the right hand F/C key has its fulcrum at the end. This suggests that it might have been made at a slightly earlier date than the others (see [CLT106] above).

The Boosé boxwood Bb clarinet [CLT023], with silver keys mounted on posts with elaborate silver mounts, was made for the 1851 Exhibition and, according to Brymer [**Brymer** 1976], "plays superbly". All of the he left hand joint holes are neatly conically undercut but the right hand joint is only partially cut. Fingered holes IV and V are cut about three quarters of the way through and merge smoothly to the cylindrical part to give almost a 'bell' shape.

The Clinton and Co clarinet [CLT019], in cocus wood with shallow-domed brass keys, was made some time between 1855 and 1871 but with a brille added later. This clarinet is lightly undercut throughout with rather wider angle cones than usual (estimated cone angle 30° particularly for the left hand fingered holes). A consequence of use of a wider angle cutter is that there is extensive sideways cutting. The first right hand fingerhole, IV, has been lined with black wood or ebonite and subsequently doubly-undercut with a 20° followed by a 30° cone angle

Clarinets with 13 keys

CLT	Keys	Bore mm		Speaker	Side B	Side Bb	A	Ab	Thumb	Side F/F#	I		II	Front Eb	Side Eb	III	C#/G#	IV		V		VI		VII	G/D key	F#/C#	F/C
091	13	14.8	D						7.1		6.45		6.2			6.9		6.9		6.4		7.0					
			u/c				5	5	5	5/6	6		oc sl	6+4	-	6	6	5		5/6 oc		6 oc			4 wide	3/4	2/3
090	13	14.0	D					'	6.25		5.9		6.0			6.25		6.6		6.45		6.7		-	4+6		
			u/c	M			5	3/4	5	4 u	6		6	6		5/6	2/3	6	5	6	4	5/6		-		4	3
012	13	14.6	D						7.7		7.5		8.3			8.4		9.3		7.9		9.6					
			u/c		?		4+1		M	?	5+1		5+1	?		5+1		6/12		12	6	5/12			?	2	4
023	13	14.3-14.5	D																								
			u/c	M	4		2-45°	4		2	5		5			5	5	6/12	0	6/12	0	0	0		6	0	5
019	13	15.0	D						5.6		6.5		7.5					5.6		7.7		8.3					
			u/c	M	?		4	5	5	4/5	4		4	4		4	4	5+6	4 4	4	2	4	5		6	5	4

2.3.3 Albert or Simple System Clarinets:

The Albert or Simple system clarinet was developed in the mid 1800s by Eugène Albert in Brussels. He devised a keywork system which combined most of Müller's improvements with Sax's right hand 'brille' key. Instruments made by Albert and his relations were prized for their high quality.

[CLT]	Pitch	Keys	Date	Maker
151	Bb (HP)	12	1862-6	E Albert
152	Bb (HP)	12	1871-1901	E Albert
032	Bb	13	Late 19th C?	Gisborne Birmingham
033	A	13	1890-99	Dan Godfrey's Sons
026	Bb	13	~1930	Buffet Crampon

The first two clarinets listed, [CLT151 and 152] were made by Eugene Albert of Brussels. These are early examples of 'Albert System' or 'Simple System' clarinets which became very popular and co-existed with Boehm system instruments in England and many other parts of the world until the middle of the twentieth century. Both are high pitched (HP) and were intended for army band use, one having the stamp of the Band of the Royal Artillery on it. Both were imported to London by Chappel.
The first example [CLT151] has the * E Albert A Bruxelles* stamp on the bell and both the 'Jullien' and 'Chappel' stamps elsewhere, both at 214 Regent Street. The name Jullien is inverted.
This is an exceptionally wide bore Bb instrument (nominally 15.2 mm) with large toneholes cut through a wall thickness of typically only 6.2 mm. Despite this, the majority of the toneholes are undercut with rather narrow cones (semi- angles estimated as 10°, depth varying from one quarter to three quarters of the wall thickness). It was noted that in addition to this undercutting the upper portions of the toneholes are slightly tapered (~5°), widening towards the bore.
The second later example [CLT152], with a more modest bore of 15.0 mm and similar wall thickness, also has large-sized toneholes. About half are not undercut but the fingered holes mostly have shallow conical undercuts (~5°) extending through the whole wall thickness. The second and third fingerholes (II and III) slope upstream slightly.

By the time these clarinets were made, the demand for band instruments would have been quite large and these might therefore be considered to be 'mass produced'. Despite this, attention has been given to shaping the toneholes and the selective nature of the work suggests that instruments were given individual attention before leaving the factory.

The types of undercutting in the Gisborne Bb [CLT032] and the Dan Godfrey's Sons A [CLT033] clarinets are similar: both are extensively undercut with the cones extending through the full wall thickness. The cone angles in the latter are estimated at 15° compared with an estimated 20° in the Gisborne.

The last clarinet in this group [CLT026], is a Buffet Crampon Simple system dating from the 1930s. This has a large bore (15.1mm) and the fingerholes, especially in the left hand joint are moderately undercut throughout.

Albert System Clarinets

CLT	Keys	Bore mm		Speaker	Side B	Side Bb	A	Ab	Thumb	Side F/F#	I		II	Front Eb	Side Eb	III	C#/G#	IV		V		VI		VII	G/D key	F#/C#	F/C
151	12	15.2	D						6.9		6.8		7.1			7.1		7.9		7.6		8.3		8.3			
			u/c	M	4°		4	s4		4	4		s6	4		6	3	3	4	4	3	3			0	0	3
					10° cones throughout but in addition toneholes I-III; V & VI have a slight taper (~5°).																						
152	12	15.0	D						7.4		7.1		7.2			7.1		7.0		7.7		8.3					
			u/c	M	0		0		0	0+ 3s	7 5°		7 5°	0 s		7 5°		0 s	5 10°	10° +5°		10° +5°	3 10°		0		3 10°
032	13	14.8	D																								
			u/c	20° cones through wall thickness																							
033	13	14.d	D																								
			u/c	15° cones through wall thickness																							
026	13	15.1	D						7.1 7.6		7.9		7.4			7.5		7.2 7.3		8.5		8.6					
			u/c	M	4	4	2	2	7		4 15°	4	5 20°	2*		4 20°	3			4		4	0		2	2	0

* ring Eb

2.3.4 Advanced and Hybrid Keywork Systems based on the Albert Design.

The final examples included in this Section are non-Boehm clarinets with more elaborate keywork systems.

[CLT]	Pitch	Key system	Date	Maker
013	Bb	Clinton/Boehm	1905	Boosey and Co
014	A	Clinton/Boehm	1905	Boosey and Co
021	C	15/5rBa/Boehm	Pre 1925	S Quilter
024	Bb	Barrett	Pre 1930	Boosey and Co
025	A	Barrett	Pre 1930	Boosey and Co
044	Bb	Oehler	Modern	Clemens Wurlitzer

These comprise a pair of Barrett action models [CLT024] [CLT025], a hybrid Barrett/Boehm [CLT021], and a pair of Clinton/Boehms [CLT013] [CLT014], all made in the first half of the twentieth century, plus a modern Oehler system clarinet by Clemens Wurlitzer [CLT044].

The Clinton/Boehm pair [CLT013] [CLT014] by Boosey and Co. are made in ebonite with one-piece bodies. This type of mechanism, with Clinton top and Boehm bottom joints, were made for players familiar with the Albert system fingering, who did not wish to learn the Boehm left hand fingerings. Again these are wide bore clarinets with minimal (small angle) undercutting.

The Quilter hybrid Barrett/Boehm in C [CLT021] has a Barrett action left hand joint and Boehm system right. The undercutting is shallow angled (~10°) and light, especially in the right hand joint. Again, when normallised to Bb, the bore is large (equivalent to ~ 15.2 mm), and this is consistent with minimal undercutting.

The Boosey and Co. Barrett action pair has large bores (comparable with the Boosey and Hawkes '1010' model which came later). The undercutting in both of these instruments is light and some holes, especially in the A, are not undercut. Removal of material is restricted to the region at the bore with no excursions into the depth of the toneholes. This type of undercutting is typical of large bored instruments as will be shown later in Boehm models.

Finally, there is one example of a modern Oehler system by Clemens Wurlitzer [CLT044]. The instrument examined was the Bb of a pair, both with 14.55 mm bores. The left hand joint had been heavily reworked subsequent to manufacture in an attempt to improve the tuning with double cone cuts in the fingered holes. However the right hand joint was as manufactured with little or no undercutting.

Comment: As noted in Section 1.2.3, this study has concentrated developments leading to the Boehm system clarinet. However there is currently interest in clarinets of the early Viennese makers and the development of the Oehler system.

Non-Boehm Clarinets with Advanced Keywork Systems

CLT	Keys	Bore		Speaker	Side B	Side Bb	A	Ab	Thumb	Side F/F#	I		II	Front Eb	Side Eb	III	C#/G#	IV		V		VI		VII	G/D key	F#/C#	F/C
013	Clinton/ B	15.2	D						7.0		7.5		8.8			7.2		7.1		cov .		8.2 5		-			
			u/c						o.c.		5		0			0		4		0		4	3	-		4	0
014	Clinton/ B	15.2	D						7.7		7.4 5		8.6			7.2		8.1		cov .		8.0		-			
			u/c						5		?		2			8		0		6		4		-			
021	Bar/B	14.3	D						6.5		6.8		7.0			6.9		7.5		7.5		8.5		-			
			u/c	M	8	0	5 10°	5 10°	0		5 10°		5 10°	8		5 10°		4		4		4	3	-	3	3	3
024	Barrett	15.2	D																								
				M	4		3/4	4			3	4	2		4	3/4	4		3	2	3/4 0	0	0		0	0	0
025	Barrett	15.2	D																				-				
			u/c	M	5		4	4	4 5°		4 45°	0	4 5°	0	0	0 s +11	0	0	0	8		8	-		0	0	0
044	Oehler	14.55	D																								
											8		8/5			8/5		0		0		0					

2.4 Boehm System Clarinets

2.4.1 Early Examples – Nineteenth Century

The 'Boehm' clarinet which resulted from Buffet and Klosé's collaboration from around 1839 to1843 as described earlier had required a major rearrangement of the positions and sizes of the toneholes. With relatively large bore sizes and freedom to choose tonehole sizes this would have been an opportunity to eliminate undercutting if its sole purpose (other than post-manufacture tuning adjustments) had been simply to cause a small hole to behave acoustically as a larger one. Unfortunately the whereabouts of the prototype instruments is unknown, but the first production clarinets were made by Auger Buffet, known as Buffet Jeune, a nephew of Louis-Auguste Buffet the inventor, who had formed his own instrument making business in 1830. Clarinets with the Buffet Jeune mark are rare but fortunately there was an example in the Shackleton collection which could be examined*.

The clarinets described below are believed to be in date order as deduced from their marks and other features such as the keywork styling.

[CLT]	Mark	Pitch	Estimated Date
109	A Buffet J^ne^ Paris	C	Pre 1850
111	Buffet Crampon	A	Pre 1850
110	Buffet Crampon	A	Pre 1850
113	Buffet Crampon & Cie	Bb	1859-1885
114	Buffet Crampon & Cie	C	1859-1885
018	Buffet Crampon 'Approved J Paske' 'Lazarus'	A	Pre 1872

* It is known that the Buffet Jeune stamp continued to be used after the Buffet Crampon mark appeared in about 1844. (Buffet had married Mlle Crampon in 1836). In 1850 the name 'Buffet-Crampon, F Tournier et P. Goumas successors' also appeared when the firm took on new partners but later in 1859 became 'Buffet-Crampon & Cie. The firm was sold to P.Evette & E.Schaeffer in 1885, but retained the Buffet-Crampon & Cie name. In that year they began marking their clarinets with serial numbers.

The Table at the end of this section shows the diameters of the easily accessible holes, together with indications of the types of undercutting observed in these early Buffet Boehms.

A Buffet Jne Paris In C. [CLT109]
Bore 14.9-15.0 mm
Date: pre 1850

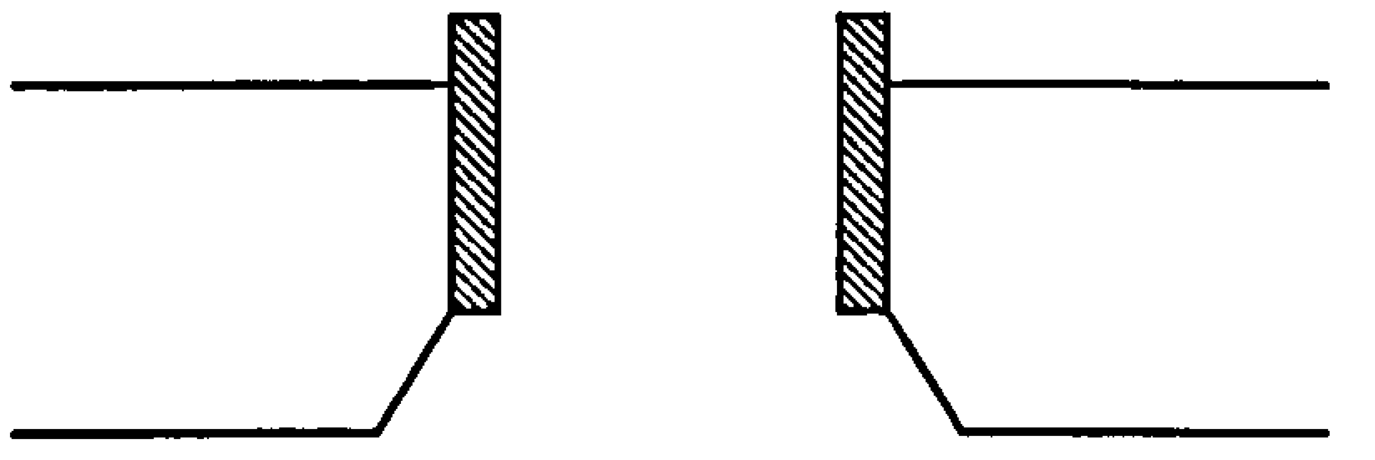
This is a boxwood clarinet with brass 'saltspoon' keys. Most of the keys have riveted steel springs, except for needle springs on left and right hand ring keys. The bore is slightly constricted at the tenons of the top joint. The bottom joint has been shortened at the lower end only, presumably to correct a tuning problem. The tonehole for top hole on lower joint (operated by ring keys), is drilled obliquely to move the pad cup up the instrument, presumably to give more space for the right hand first finger as this is a C clarinet.
Undercutting:
Borescope examination revealed that all of the toneholes are lightly undercut conically, in most cases extending between 'just touching' and half way through the wall thickness. The regularity and shape of the undercutting indicates that a conical fraise tool was use. The extent of the undercutting make it probable that it was carried out during manufacture rather than later but, to provide more confidence in this conclusion, a number of other early Buffets from the Shackleton collection were examined.

Buffet Crampon in A. [CLT111].
Bore 14.85 expanding to 15.0 mm at top (but with some compression at the tenon).
Date: pre 1850.

The instrument has a blackwood body with brass 'saltspoon' keys. This clarinet has several unusual features in its mechanism. On the left hand joint there is no side Eb/Bb key for the right hand first finger. A third ring on the upper joint operates a pad within the second finger ring. Fork Eb/Bb vents through a pair of holes whose pads are coupled together. Brass sleeves form chimneys for holes with ring keys. There is no 'link' between the left and right hand joints. Also the layout of the four right hand little finger keys is unconventional, the E/B key being displaced downwards. The number of unusual keywork features of this clarinet suggests that this was an early experimental design.

Undercutting:

This clarinet is lightly undercut throughout. The 'ringed' fingered toneholes in the RHJ are lined with brass sleeves but the wood is cut back as shown here:



This provides evidence that the undercutting was carried out at the time of manufacture since the brass sleeve is an original feature of the construction. The undercutting must have been done prior to inserting the sleeve as this has a squared off end.

Buffet Crampon in A [CLT110]

Bore 15.0-15.1 mm top joint, 14.95-15.0 mm bottom joint. Barrel bore ~15.15 mm.

Date: Pre 1850.

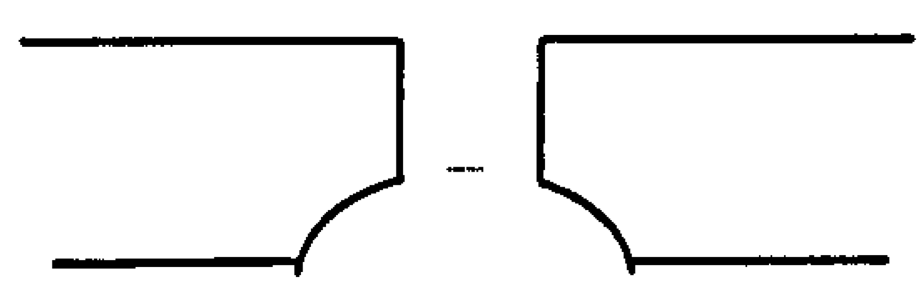
This instrument has a blackwood body with nickel silver 'saltspoon' keys. The thumb hole has an integral raised external wooden chimney. The throat 'A' tonehole has been plugged and re-drilled slightly further down the body. Only the ring keys have needle springs. The top three side keys for the right hand first finger are pivoted on a single steel mounted on a metal 'channel' screwed to the body. This clarinet is believed to be of a slightly later date than [CLT111] above.

Undercutting:

Examination of the bore again showed conical fraise undercutting throughout, but with more of the holes cut further through the wall thickness. The cone semi-angles were estimated to be approximately 20°. The middle fingerhole of the left hand joint (II), with the deeper undercutting, appears to have been enlarged by hand-filing, as traces of the file marks remain.

Buffet Crampon & Cie Clarinet in [CLT 113]
Bore 14.8-14.85 mm expanding to 15.1 mm at top.
Date: 1859-1885. Bb (Pre Serial numbers).

This clarinet has a blackwood body with nickel silver keywork. The barrel is integral with top joint. Other French makers such as Martel Frères (see next section) and Millereau & Cie also made clarinets of this design through to the early decades of the twentieth century. Apart from leaf springs on the C#/G# and right hand little finger F#/C# key, the keywork design of this clarinet is very similar to current 'plain Boehm' clarinets.
Undercutting:
Most of the toneholes are conically undercut but with a small angle estimated to be about 10° just clearing the bore all round. The small hole for the first finger of the left hand (I) appears to have had extra work done on it to leave a dome-shaped profile:

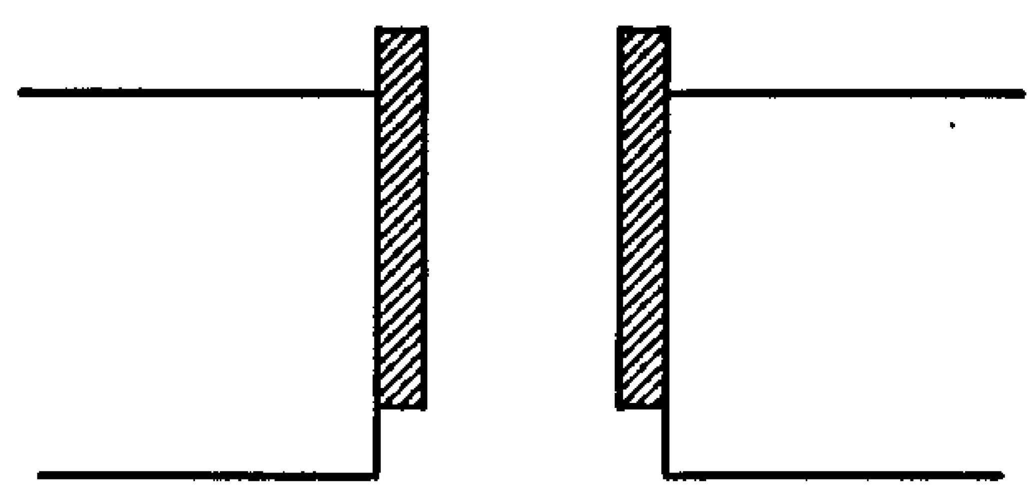


This type of enlargement is occasionally found in modern Boehm clarinets as a means adjusting the F_4/C_6 twelfth which tends to be flat in the chalumeau register. This hole is used as an additional register vent for the third mode and above and is therefore made as small as possible without restricting its role as a normal tonehole.

Buffet Crampon & Cie Clarinet in C Pre Serial numbers. [CLT114]
Bore 14.7 mm expanding to 14.9 mm at top.
Date: 1859-1885 (Pre Serial numbers)

Boxwood with brass keys. Possibly a cheaper model. Barrel integral with top joint as [CLT113] above.
Undercutting:
Again the undercutting is light. The tonehole at the top of the lower joint (operated by ring keys) is drilled obliquely to avoid the socket. Brass sleeves form chimneys

for holes with ring keys. The sleeves are cut square at the bore end and stop just short of the bore. Unlike the examples described for [CLT111] above, these holes are not undercut but, because the sleeves are square ended, there is a ‘pseudo-undercut’ where the sleeve does not reach the bore:



Buffet Crampon Clarinet in A. [CLT018]

Bore 14.9 mm

Marked ‘Approved Pask’ and ‘Lazarus’[∅]

Date: 1859–1885 (1870 according to Brymer) Pre Serial numbers

Cocus wood body with separate barrel. Speaker tube at front but does not project into bore.

Undercutting:

As shown in the Table below all but the lowest four and one other hole are moderately undercut with considerable variation in the degree of undercutting. As well as cones of different angles there are holes with asymmetrical shapes indicating the use of a fraise followed by hand working.

Considerable effort appears to have been employed in adjusting this instrument, but one of the hand finished holes has an area of damage where a splinter has broken out during the work.

[∅] John Pask was an instrument maker in London from 1840 until 1872. This was the only soprano Boehm clarinet in Lazarus's large collection and was sold by his executors by auction in 1895, the year of his death. However he also owned a Boehm basset horn stamped by Pask made in the 1850s. Rendall [**Rendall** 1978] suggests that this was French-made as no Boehms clarinets or basset horns are known to have been made in London at such an early date.

Early Buffet Boehm System Clarinets. Comparison of Tonehole Sizes and Undercutting

CLT	Pitch	Bore mm		Speaker	Side B	Side Bb	A	Ab	Ring I	Thumb	Side F#	I	Ring 2	II	Front Eb	Side Eb	III	C#	Rings	IV	B/F#	V	VI	G#/D#	G/D	F#/C#	F/C
109	C	14.9-15.0	Dia.									5.3		7.2			9.1			9.2		7.8	9.5				
			U/C								0	5	3	2	3	3	5	0	obl.	3	5	2	5*	5	6	3	2
111	A	14.8 5	Dia.									5.1		cov.			8.9			838		7.7	8.8				
			U/C							M		3/4		3	3		3	3	5	3	3	3	3	5	3/ 4	3	3
110	A	15.0 nom	Dia.									8.0		5.5			10.2			8.8		8.2	9.2				
			U/C							7	4	5		6	2	3	4	4	5	3	5	3	4	5	3	2	3
114	C	14.7	Dia.																	8.5		7.6	9.6				
			U/C								4	M	3/4	M			M		0 obl.	M	3/4	M	M	2	2	0	2
113	Bb	14.8	Dia.									5.1		7.0			8.1			7.9		7.7	8.9				
			U/C							M	3/4	4 (d)	3/4	3/4	3/4	3/4	3/4	0	3/4	3	3/4	4	4	2	2	2	3
018	A	14.9	Dia.							8.0		4.9		6.8			7.6			8.2		8.0	9.0				
			U/C		4	4/5	4	0	4	M	8/1 1s	4	-	3	6	4	4- 11 20°	6	4	4-5°	4	3	3- 11	0	0	0	0

2.4.1.1 Summary

The six nineteenth-century Buffet clarinets examined all showed moderate undercutting of the majority of the toneholes. There is evidence that this was undertaken during manufacture.

Apart from devising a highly successful keywork system, Buffet and Klosé worked out suitable combinations of tonehole sizes and positions to provide acoustically satisfactory ventings for all notes within the range of the instrument. The fact that undercutting was employed suggests that they were striving to achieve a result which could not be achieved with pitch-equivalent straight-sided toneholes. Evidence of hand adjustments, presumably to correct tuning deficiencies, has been seen but it is not possible to tell if these were made at the time of manufacture or later.

2.4.2 Twentieth Century

2.4.2.1 From 1900 to 1930

2.4.2.1.1 Boehm System Clarinets by Martel frères

Of particular interest are Boehm clarinets made from the start of the twentieth century until the First World War by the French company Martel frères of Mantes, near Paris. Some of these instruments were imported into England by W H Hawkes and Son where they gained a good reputation for their responsiveness and ease of playing, combined with a characteristic tone quality. They were sought after by many leading players of the time.

Two pairs of clarinets bearing the Hawkes stamp but made by Martel have been examined.

The instruments are all stamped:

Excelsior Sonorous Class
Hawkes and Son
Denman Street
Piccadilly Circus
London

with a cross symbol above and below, followed by a **4-digit** serial number.

The name Martel does not appear on the instruments but one example has been reported [J Miley personal correspondence] of a Martel clarinet now owned and played by an amateur clarinettist in Dublin with the Hawkes mark additionally stamped 'H M' - presumably to indicate 'Hawkes Martel'. It has been generally assumed that their exceptional qualities were achieved by the extensive use of heavy undercutting.

The first pair, with serial numbers 2093 (Bb) [CLT095] and 2096 (A) [CLT096], were owned by the famous English clarinettist Frederick Thurston (1901-53) who played on them from probably before 1920 until some time in the early 1930s when he changed to Boosey and Hawkes '1010s'. The serial numbers would indicate that these were made at the turn of the century so they would appear to have been acquired second-hand by Thurston [Greenham 2001].

The second pair, with serial numbers 4590 (Bb) [CLT093] and 3983 (A) [CLT094], was owned by the clarinettist Frank Hughes who lent the A instrument to Reginald Kell (1906-81) to use for his 1937 recording of the Brahms Clarinet Quintet and probably also the Mozart Quintet and Concerto. These clarinets were bought by Sydney Fell and are now in the possession of Keith Puddy. They date from the 1910s. All four instruments now have replacement barrels but one of the 'Kell' barrels survives. The bores of these clarinets were measured as 14.95 mm for the Bb instruments and 14.85/14.9 mm for the As. Both Bb clarinets have a slight reverse cone above the speaker hole (to ~15.10 mm at the top) but the A's remain parallel (ignoring some tenon shrinkage in the Thurston A). This apparent slight bore perturbation is almost certainly the result of wear and age rather than being a design feature. The bore of the surviving barrel measures approximately 14.9 mm diameter but is distorted especially at the top. The flares in the bottom joints were measured and found to be very similar.

Playing tests made by the author on the 'Kell' pair confirm that these clarinets are exceptionally responsive and the effect, from the player's point of view, is that less effort is required to play these instruments than is customary with 'normal' clarinets. Unfortunately the basic tuning of these instruments is poor, especially in the high register. To play these Martel instruments in tune requires considerably effort from the player, even to the extent of 'half-holing' some fingerings to flatten notes (confirmed by Keith Puddy). It is remarkable to note that Reginald Kell gained his celebrity not only from his characteristic tone quality, which included vibrato, but also by the accuracy of tuning he achieved. Kell set new standards of tuning at a time when one eminent player claimed that some notes were physically impossible to play in tune on the clarinet[⊖].

Examination of the Toneholes (Borescope):

i) Top Joint

In all four instruments the toneholes above the first ring-operated key were found to be moderately undercut with a small angle cone extending effectively through the wall

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[⊖] From reminiscences of the bassoonist Gwydion Brooke quoted in the notes accompanying the transfer from 78s to CD of Kell's 1937 recording of Brahms Clarinet Quintet. (Testament SBT 1001).

thickness. The open fingerholes are more extensively conically undercut and, although not identical, the undercutting follows a similar pattern for all of the instruments as tabulated here:

	Thurston	Kell	Thurston	Kell
	Bb 2093	Bb 4590	A 2096	A 3983
[CLT] →	095	093	096	094
Hole	Undercutting			
Ring 1	2			
Side F#	4/5		3	
I	5	5	4+5	5
Ring 2	4		4	4
II	5	4 (20°)	3	3/4
Front Eb	5		3	
Side Eb	5		4	
III	4	6 (10°)	4	5
C#	to one side		to one side	

Cone angles were measured for a few holes by taking an impression with a moulding material.

To estimate the magnitude of the undercuts, the holes were measured along the axis of the bore using the borescope with a calibrated graticule in the eyepiece. To estimate the consistency of the undercutting, the ratio of the extent of the undercut along the bore to the hole diameter was calculated. The results for the three left hand fingerholes are tabulated below:

	Thurston	Kell	Thurston	Kell
	Bb 2093	Bb 4590	A 2096	A 3983
[CLT] →	095	093	096	094
I	1.50	1.52	1.64	1.53
II	1.28	1.32	1.29	1.28
III	1.21	1.27	1.29	1.24

This shows that the left hand joint undercutting is consistent for the four instruments indicating that the pattern of undercutting has been carried out systematically rather than as piecemeal attention to selected holes. For comparison, the ratios for the same fingerholes measured for a modern Yamaha Model CX [CLT137] are I: 1.26, II: 1.14 and III: 1.10. This illustrates the heaviness of the undercutting in these Martel instruments compared with a present day design.

ii) Bottom Joint

The right hand joints are likewise heavily undercut with wide cone angles extending at least half way through the wall. There is however one example of extreme undercutting. The side tonehole for the key operated by the third finger of the right hand (alternative B/F# key) in the A instrument of the 'Kell' pair [CLT094], has gross undercutting to one side extending round to the front of the instrument. This reaches to within a few millimeters of the enlargement of the R1 hole. This does not occur in the corresponding instrument of the 'Thurston' pair and appears to be a drastic attempt to cure a tuning problem.

It is of interest that the Louis Company set up in Chelsea, London by the clarinettist Charles Draper (Thurston's teacher), which operated in the 1920s and 30s, not only copied Lorée oboe designs but also sold clarinets which are believed to be copies of Martels. These are sometimes referred to as 'false Martels'. It is also reported (K P) that there are Martel instruments which have had their markings filed away and the Louis stamp then added. These instruments presumably come from the early days of Louis' existence.•

After inspecting the pairs of 'Hawkes ' Martels described above, an opportunity arose to examine a clarinet in the Shackleton collection made in the early years of the twentieth century marked with Martel's own stamp [CLT112]. This instrument is a Bb plain Boehm in Blackwood with nickel-silver keywork, and is unusual in that the 'barrel' is integral with the top joint which is stamped:'Martel frères à Mantes', but there is no serial number. This instrument bears a striking resemblance to a pre-serial number 'Buffet Crampon et Cie' Bb clarinet [CLT113], also in the Shackleton collection. For example, there are leaf springs on the C#/G# and right hand little finger

• The Louis factory was destroyed during WW II and subsequently the name was sold to Rudall Carte which in turn was acquired by Boosey and Hawkes in 1955.

F#/C# keys. Borescope examination of this Martel showed that all of the toneholes are conically undercut but with a small cone angle estimated at approximately 10 degrees. Most of the undercuts extend less than a quarter of the way through the wall thickness. The exceptions are hole I, where the undercut extends about half way through and in the lower joint the hole for cross B/F# key, in which a narrow angle (~2 degree) cone is cut through the whole of the wall thickness. Some of the cuts indicate that a fraise with a slight dome shape has been used rather than a straight cone.

The overall pattern of undercutting is very similar to that seen in the Buffet Crampon instrument [CLT113] made at the same time or possibly a little earlier which, from its appearance, could well be its twin.

Although it is likely that this Martel slightly pre-dates the 'Hawkes' Martels, it is clear that there is a significant difference in the degree of undercutting. Could the heavy undercutting characteristic of the imported models be the work of Hawkes rather than Martel?

It is possible that these clarinets were manufactured by Martel to play at A=435 Hz, a standard current in France at the time. This is almost 20 cents lower than A=440 Hz which was the new 'low pitch' standard in London. This difference is too much to eliminate satisfactorily simply by the use of a shorter barrel or shortening the upper joint as this would have a disproportionate sharpening of the throat notes. However it is quite possible that Hawkes attempted to retune the instruments by comprehensively undercutting the toneholes and in so doing bestowed on them their unique playing characteristics, but still with imperfect tuning as commented on earlier. This is consistent with the observed overall uniformity of the pattern of undercutting, together with additional enlargement of individual holes for further tuning adjustment[◊].

A simple system high Eb clarinet [CLT156] with Martels stamp, once the property of Frederick Thurston, now also in the Shackleton collection, has had its mouthpiece shortened to raise the pitch. This instrument was again made at the beginning of the twentieth century, further supporting the premises that Martel was working to a lower pitch.

[◊] Note: The clarinet stamped 'Martel' [CLT112] in the Shackleton collection does indeed play below A = 440 Hz. However this clarinet pre-dates the 'Hawkes Martels' so this merely supports rather than confirms the proposition outlined above.

One pair of Louis clarinets [CLT 149 and 150] from the mid 1920s was examined. These were stamped: Louis & Co. Makers. Chelsea London. 'Approved by Charles Draper' - and are plain Boehm but with rollers on the top row of the right hand little finger keys. The bores were close to 14.75 mm and all but the lowest toneholes had been conically undercut through most of the wall thickness at about 10°, and then finished with a 20° cone just touching the wall. The bottom four holes were cut laterally to form 'crescent' shapes. There was also evidence of hand tuning adjustment with a file and some in-filling of holes with a black wax. These are top quality instruments noted for their evenness of response. The use of two cone angles suggests that an attempt was being made to approximate to a flare profile.

2.4.2.1.2 Examples of other Early Twentieth Century Boehms.

One clarinet of special interest from the early years of the twentieth century is the full Boehm to low Eb [CLT015] made by Boosey and Co. for Manuel Gomez. According to Weston this clarinet was made in about 1900 [**Weston** 1977] but the serial number (17543) indicates 1907.

This has a single-piece cocus wood body with a minimum bore of approximately 15.1 mm. There is some enlargement of the bore at the top of the body where a metal tuning sleeve has been incorporated. The barrel is metal lined with a bore of 15.25 mm. The mechanism includes a fifth side trill key for the right hand first finger, (for G#) and an extra cross key between fingerholes IV and V. There is also an additional 'long Bb' fork fingering option[r].

The single-piece body made examination of the undercutting more difficult and required the use of an extension tube to the Borescope. However it was clear that none of the toneholes had been undercut where they meet the bore. In fact all of the open fingerholes had been slightly overcut to form a shallow angle cone through the wall thickness. Some of the covered holes showed slight variations from cylindrical possibly caused by hand finishing for a smooth surface. This is an early example of a non-undercut Boehm clarinet by a London maker.

This instrument can be compared with a plain Boehm also made by Boosey and Co. a few years later in 1914 [CLT022], with the serial number 21005. This has a

[r] An illustration of this clarinet is shown in Brymer's book [**Brymer** 1976] but is incorrectly labeled in the original edition.

conventional two-piece body made of ebonite with a minimum bore also of 15.1 mm with no significant perturbation at the top.
Again none of the toneholes closed with pads are undercut but the open fingered holes are lightly undercut, the cone shape extending at most a quarter of the way through the wall thickness. Furthermore these holes are also slightly overcut as in the Gomez's clarinet.

[CLT]		Bore mm	Thumb	I	II	III	IV	V	VI
015	Boosey	15.1	7.05	4.8	8.5	8.0	9.3	9.2	9.9
022	Boosey	15.15	6.7*	4.6	6.8	7.0	8.5	8.4	8.5

* no metal insert

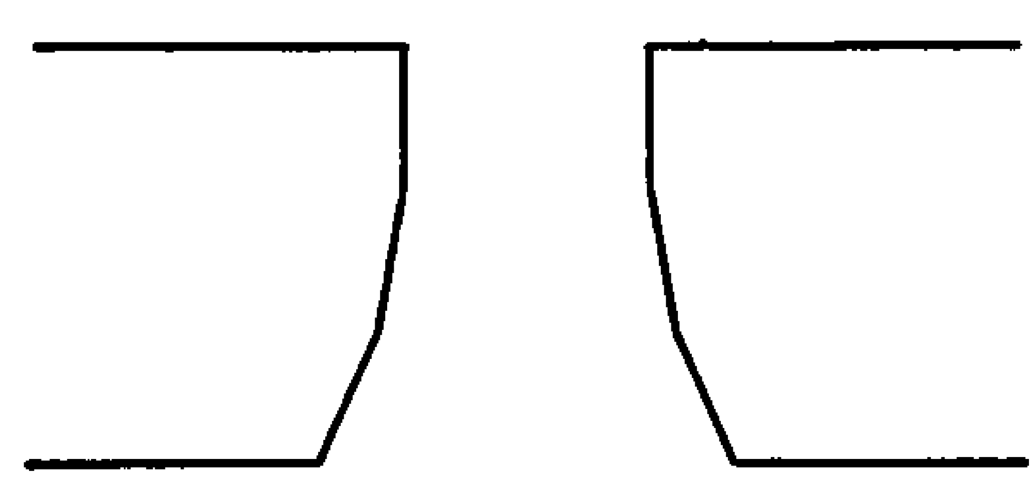
The relatively light use of undercutting in these early twentieth century Boehms is consistent with the large bore sizes which were being used by Boosey and other manufacturers at that period.

Several other Boehm system clarinets made in the 1920s were looked at. These included a pair made by E.J. Albert [CLT048 & 049], a Leblanc Bb [CLT047], two Selmer pairs [CLT045 & 145 and CLT154 & 155], a Selmer Bb [CLT 165], and a Buffet A [CLT046]. The first Selmer pair and the Buffet were all made in 1928 according to their serial numbers and the second Selmer pair before 1926 when the Selmer logo changed.
These Selmers were typical of the instruments which were so highly rated by the profession during the between-war years. Borescope examination confirmed that the toneholes were cut straight into the bore with no undercutting. Extensive playing tests were carried out on the earlier pair [CLT154 & 155] (AH, NS and ACG) which confirmed that these instruments, especially the Bb, deserve their good reputation. As well as having a fine tone, these clarinets show an even response over the range. The bore profile for the upper joint of the Bb of the pair showed a striking similarity to the 'polycylindrical' design created by Robert Carrée for the Buffet R13 clarinet some thirty years later. However the bore of the A of the pair was a plain cylinder.

Following this unexpected discovery, more Selmers from this period were examined, [CLT 161, 162 and 163], but none had this type of bore perturbation. It is not possible to determine whether the bore of the Bb [CLT154] had been made polycylindrical at the time of manufacture, possibly as an experiment, or whether the bore had been reamed out later. In either case the result is a fine example of a non-undercut top-grade clarinet.

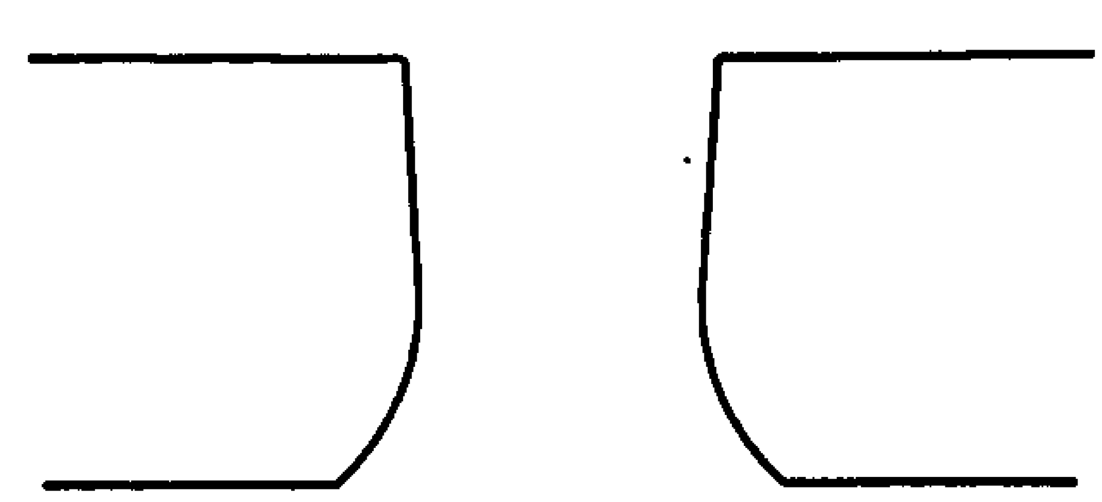
The pair of E.J Albert Boehms [CLT048 and 049] were made by Joseph Eugène Albert, a son of Eugène Albert who developed the thirteen-keyed 'Albert' system. These instruments were stamped 'Imported by Heyworth of Blackpool'. Most of the holes were conically undercut but the intersections had been smoothed to give a slightly rounded profile especially in the fingered holes of the right hand.

The fingered holes of Leblanc 'Dynamique' Bb [CLT047] were undercut with the exception of the middle right hand hole. The undercutting was quite heavy with a 'double angle' profile indicating the use of two fraise tools:



The majority of the keyed holes had no undercutting

The 1928 Buffet 'A' [CLT046] had all of the holes undercut with a smooth profile with slight overcutting as well:



A slightly later Buffet Bb [18540] from the 1930s had more conventional conical undercutting, slight and moderate in the left and right hand joints respectively.

These high quality instruments, all from the 1920s and early 1930s show the divergence in approach to undercutting by the major manufacturers of the period. Almost the complete spectrum of tonehole profiles is demonstrated in this small sample.

2.4.2.2 Mid to Late Twentieth Century and Contemporary Boehms.

The Major Manufacturers:

2.4.2.2.1 Boosey and Hawkes (1930-85)

Boosey and Hawkes was a major producer of clarinets in the UK supplying mainly Simple and Boehm system instruments in a range of grades from student to professional models. For the purpose of this study attention has been given primarily to the '1010' or 'Symphony' model first produced in the early 1930s.This was the most expensive clarinet they produced and was intended for professional use. Failure to control the consistency of this model damaged Boosey and Hawkes' reputation when production was restarted after World War II

The other top-grade post-war model, the '926' or 'Imperial' was designed to have no undercutting, and this has been confirmed by examining a number of examples. Checks have also been made on some of the cheaper models which were based acoustically on the '926' design, for example the 'Emperor' model.

A number of 1010s from the 1930s have been examined, including ones played by celebrated British clarinettists, and these are compared with various post-war examples The design specification for the bore of the 1010 model was set at 0.600 inches (15.24 mm). Bore measurements made during this study show that whilst the pre-war examples are all close to specification, allowing for slight shrinkage, the majority of the post war examples are oversized. The problems associated with this model are well known and it is clear that lack of control of the bore size as revealed here was a major contributory factor.

As would be anticipated for a large bore design, the tonehole undercutting is generally light and confined to the junction of the hole with the bore rather than extending up into the toneholes. The exception is the first example tabled, [CLT041] which is the A of the pair played by the famous English clarinettist Frederick Thurston. This is probably one of the earliest of the '1010s' produced. It is highly likely that great attention was given to the final adjustment of this instrument and the slight hole enlargements through the wall thickness are probably the result of careful hand-tuning, as this pattern of undercutting is not found elsewhere.

Most of the other pre war 1010s listed all belong to, and have been used by, well known English professional clarinettists. One unusual exception [CLT153] (not tabulated), is an ebonite 1010 with a bore of 15.26 mm partially sleeved with nickel silver and highly polished internally. The instrument is also marked 'LP'•. This clarinet plays very sharp with a standard mouthpiece and barrel, despite having had copious amounts of nail varnish applied to the insides of the toneholes, obscuring the (moderate) undercutting. Ebonite clarinets were often made for army band use. According to the serial number one of the 1010s examined [CLT166], may have been started pre- and completed post-WWII. The undercutting of the toneholes is minimal.

The post war sample shows that fraise tools have been used essentially to bevel the bottom edge of the toneholes. In some of the clarinets examined, particularly [CLT146] dating from 1964, the workmanship is poor, the fraise leaving a rough and chipped finish.

The exception is the last example tabled [CLT143] which, according to its serial number, must have been one of the last of this model to be made. This instrument was in the Boosey and Hawkes Museum. All of the toneholes are very neatly undercut with ~20° cones. In the lower joint the fingered holes all have an identical symmetrical lateral (crescent shaped) cuts produced with a fine finish. This high standard of workmanship was not observed in any other of the post-war examples examined.

The table below shows the diameters of the open fingered holes of pre- and post-war '1010'clarinets:

• 'LP' on a Boosey and Hawkes clarinet may indicate 'London and Paris' whereas the acronym normally stands for 'Low Pitch'

CLT	S.No.	Date	Thumb	I	II	III	IV	V	VI
041	30255	1932	7.65	5.0	6.2	7.3	8.2	8.1	9.2
089	32088	1935/6	7.8	5.1	7.0	8.0	8.7	8.1	8.7
088	32536	1936	7.7	5.0	6.8	8.0	8.5	8.2	9.5
166	35279	1939/45?	7.8	4.7	6.5	8.0	7.8	7.7	9.1
146	250667	1964	7.7	5.3	6.8	8.0	8.7	8.4	9.7
143	539123	1980?	7.6	4.9	6.8	8.1	7.7	8.2	9.7

Boosey and Hawkes 1010 Model

Pre War

CLT	Pitch	Bore mm	Date	Speaker	Side B	Side Bb	A	Ab	Ring I	Thumb	Side F#	I	Ring 2	II	Front Eb	Side Eb	III	C#	Rings	IV	B/F#	V	VI	G#/D#	G/D	F#/C#	F/C
041	A	15.22	1932	M						M		8s	8+ 4	8s	8	5	8	0	4	8	8+ 3	8	8	0	0	0	0
115	Bb	15.20	1935	M						M		4	0/7	0/7	2/3	4/5	0/7	4/5	5	8	0/7	3	3	0	0	0	0
089	Bb	15.24	1935/6	M						M		3/4s	3s	3	2/3	3	0	3	4	3	w	4	4	2+ w	3+ w	3+ w	2+ w
088	Bb	15.24	1936	M		4	3s	3	3/4	M	4	3s	3/4	3	3	3	3	3	2	3	3	3	3	0	0	0	0

Boosey and Hawkes 1010 Model

Post War

CLT	Pitch	Bore mm	Date	Speaker	Side B	Side Bb	A	Ab	Ring I	Thumb	Side F#	I	Ring 2	II	Front Eb	Side Eb	III	C#	Rings	IV	B/F#	V	VI	G#/D#	G/D	F#/C#	F/C
146	Bb	15.24 *	1964	M	-	-	-	-	-	-	Minimal undercutting in top joint. Bottom joint essentially not undercut																
147	A	15.25	1964	M	-	-	-	-	-	-	Minimal undercutting in top joint. Bottom joint essentially not undercut																
073	Bb	15.37	1974	M	4	4	4	3	4	M	3	4	3/4	3	3	3	3	M	3	2	2	2	0	3	3	0	0
074	A	15.37	1975	M	Obstructed by metal liner to C#/G# tonehole													M	3	3	3	3	0	3	3	3	3
079	Bb	15.30	1979	M	3	3	3	3	3	M	3	0	0	3	3	3	4	M	3	3	3	3	3	3	3	3	3
080	A	15.44	1979	M	0	0	0	0	3	M	0	0	3	3	0	0	3	M	3	0	0	0	0	3	3	3	3
143	Bb	15.24	1981	M	2	2	-	-	-	M	4	4	3/4	2	3	3	2	M	2	2	2	2	2	2	2	2	2
159	Bb	15.24	1981	M	Obstructed by metal liner to C#/G# tonehole													M		2		2	2				
160	A	15.24	1981	M	Obstructed by metal liner to C#/G# tonehole													M		2		2	2				

* 15.28 at top

Six examples of Boosey and Hawkes '926' Imperial clarinets have been examined, confirming that these instruments are not usually undercut. Details of these clarinets are shown in the following Table:

Boosey and Hawkes '926' Imperial Clarinets

[CLT]	Pitch	Bore	Date	Details	Tonehole diameters.		Serial No.
					LHJ	RHJ	
050	Bb	15.0	Late 1930s or post war	Possible prototype for '926' Model launched post WWII. A few undercut holes	-	-	36578
036	Bb	15.0	1953	LHJ only	5.4-8.4	-	89836
035	Bb	15.0	1956	Chromium plated nickel silver keywork.	5.36-8.54	8.55-9.7	120763
116	A	15.0	1956	Paired with [CLT035]	5.36-8.54	8.55-9.7	120774
117	Bb	15.0	1959	Standard model with silver plated keys	5.36-8.54	8.55-9.7	150441
118	A	15.0	~1960	Paired with above [CLT117]	5.36-8.54	8.55-9.7	179373

The first clarinet listed does not bear the '926' mark but is believed to be a prototype made in the late 1930s or, more likely, soon after World War II when Boosey and Hawkes resumed production. The divide between the upper and lower joints is further down the instrument than in the 926s, with the first tonehole of the lower joint cut through the socket and tenon as found in some earlier Boosey clarinets. Only the two alternative holes for Eb/Bb in the top joint are undercut and in the bottom joint the fingerholes V and VI are lightly undercut laterally only. Apart from this the instrument is not undercut.

Boosey and Hawkes used the acoustic design of the 926 as the basis for some of their cheaper clarinets, for example the 'Edgware' and Emperor' models.

Two pairs of Edgwares [CLT068 and 069; 082 and 083] and one pair of Emperors [CLT057 and 058] were checked and, as expected, no undercutting was found.

One example of the Boosey and Hawkes '2-20 Series [CLT128] made for the American market incorporating design features advocated by Reginald Kell was also found to have no undercutting. This has an intermediate bore size of 14.85 mm with a reversed cone in the left hand joint expanding to15.15 mm at the top.

In the 1980s Boosey and Hawkes acquire Buffet Crampon and ceased production of all of their own models.

2.4.2.2.2 Buffet Crampon

A total of six modern Buffet Crampon clarinets have been examined for undercutting. Three are R13 models from various years of manufacture [CLT051, 077 & 078] and a fourth clarinet (top joint only) is marked 'Evette Master Model made by Buffet Crampon' [CLT131] (top joint only). This stamp was applied to instruments from the R13 production line which had been rejected for appearance by quality control (for example non uniformity of the wood staining), but which were otherwise to the R13 specification. In addition one 'S1' model from the 1970s [CLT039], and a recent 'Elite' model [CLT081] were examined. The results are shown in the Table below.
All of the examples are lightly conically cut typically at 20°, no more than half way through the wall, except for the Evette 'Master Model' [CLT131]. This has shallower angle cuts ranging from 5° to 10° which only extend up to a quarter way through the wall typically.
It is of interest to compare these undercuts with that found in a Buffet Crampon 'A' clarinet made in 1928 [CLT046]. Whereas in the modern instruments all of the undercutting has been achieved with conical fraises, typically with cone semi-angles of up to 20°, the 1928 toneholes all show a smooth rounded profile as illustrated here:

Apart from the smoothness of the undercut profile it was clear that, at least in the open fingered holes which could be observed from the outside, overcutting had also been applied, merged with the undercutting to form a smooth profile. This type of bore profile has not been seen in post war clarinets but a number of similar examples can be found in clarinets made before the middle of the nineteenth century (see, for example, the Goulding six key clarinet [CLT034] and the Buffet thirteen key clarinet [CLT090] from circa. 1840). In the next Section a contemporary pair of French Selmer clarinet has been examined for comparison.

Modern Buffet Crampon Boehm System Clarinets

CLT	Pitch	Bore mm		Speaker	Side B	Side Bb	A	Ab	Ring I	Thumb	Side F#	I	Ring 2	II	Front Eb	Side Eb	III	C#	Rings	IV	B/F#	V	VI	G#/D#	G/D	F#/C#	F/C
051 R13	Bb	14.65	U/C	M			0	0		M	2	5		3	3		0		4/5	4/5	4/5	4/5	4/5	4/5	4/5	4/5	4/5
077 R13	A	14.65	U/C	M	4	4	4	4	5	M	4	5	5	3	5	4	4	4	5	4	5	4	4	5*	5*	5*	5*
078 R13	Bb	14.65	U/C							As [CLT077]																	
131 Evet	Bb	14.65	Dia.	M	4 5°	4 10°	4 5°	3 10°	3 5°	M	0	4 5°	4 5	3 5°	3 5°	4 5°	4 5°	4 5°	Missing								
039 S1	Bb	14.65	U/C									5	5	4	3/4	3/4	0	3/4		4	0	0	0	0	3/4	4	4
081	Bb	14.65	Dia.																								
Elite			U/C									4	5/6	3	3/4	4/5	3	6	3/4	3	5	3	4	4	4	5	4

* wide angle cone

2.4.2.2.3 Selmer (France) and Selmer (USA)

In addition to the Selmer pair made in 1928 [CLT045 & 145] described in Section 2.4.2.1.2, six further examples of Selmer (France) clarinets were examined during this survey. Two 'Series 9' Bb examples [CLT038 &062] were found to have no undercutting, except for slight symmetrical lateral enlargement of the lowest holes. However the 'A' clarinet, [CLT 063], paired with [CLT 062] was found to have the bottom tonehole asymmetrically undercut to one side only. This is almost certainly an attempt to improve the F_3/C_5 twelfth by sharpening the fundamental, a common problem not always resolved by the flare design in the lower joint.
The pair of 'Series 10S' [CLT064 &065] were found to be selectively undercut with a similar pattern for the two instruments (see Table). To a first approximation, the open fingered holes are left uncut whereas most of the pad-covered holes have been undercut by varying degrees. Benade warns about the problems that this hybrid approach can create [Benade 1960], but these instruments appear to be satisfactory. One example of a Selmer Recital model [CLT059], probably from the 1980s, was found to have the upper joint fingered holes undercut but those in the lower joint not. Only some of the keyed holes were undercut. This mixed pattern is similar to that found in the Buffet S1 model [CLT039] described in the preceding Section.

Selmer 10S and Recital Models

[CLT]	Pitch	Bore mm		Speaker	Side B	Side Bb	A	Ab	Ring I	Thumb	Side F#	I	Ring 2	II	Front Eb	Side Eb	III	C#	Rings	IV	B/F#	V	VI	G#/D#	G/D	F#/C#	F/C
064	Bb	14.5	Dia.									-		-			-										
			U/C									4/5	5	0	4	4	0	0	0	0	0	0	0	0	0	0	5
065	A	14.5	Dia.									~5		6.2			7.8			-		-	-				
			U/C									3	4	0	3	3	3	0	0	0	0	0	0	3	3	2	2
059			Dia.																								
			U/C									5	6	6	0	0	6	0	0	0	0	0	0	3-4 5°	3-4 10°	3-4 10°	3-4 10°

The American Selmer clarinets are best known in the UK for their Bundy and Console student clarinets and to a lesser extent for their 'Signet' models.

An early wooden Bundy model [CLT124], and a number of the later plastic versions were examined [CLT119-123], and none are undercut. Likewise examples of plastic Signet and wooden Signet 'Special' right hand joints [CLT139] were found to have no undercutting.

Two Selmer Console models dating from the 1960s or 1970s were examined. The first, with a wooden body [CLT132], is comprehensively undercut. All but one of the lowest holes have been carefully cut with a shallower cone angle than usual (estimated at 10°), the cutter having been drawn at least half way through the wall thickness except for the large holes at the bottom which have the usual 'crescent'shapes

Conversely the plastic bodied instrument [CLT133], which may be slightly more recent, has no undercutting.

A cursory comparative playing test of these instruments indicated that the plastic version sounded rather harsh and lacked uniformity over the range, i.e. it behaved like a cheap student clarinet whereas the wooden undercut clarinet sounded rather restrained and more uniform, if anything lacking projection.

This is an example of the same model name being used for instruments of completely different tonehole design. In view of the effort put into the earlier wood version it may be that this was a more expensive model originally and the model name was retained for the later low-priced plastic versions. These instruments both bear the Selmer logo currently used by the American Selmer Company but are marked 'London' and 'Foreign'. It is probable that they were manufactured in Europe, but not necessarily in France.

Of the current Selmer (USA) plastic bodied clarinets the CL200 and CL300 series all have undercut toneholes according to the Selmer sales literature. The CL300 has the smallest bore at 14.55 mm and is claimed to produce a "dark" tone. The wider bore 1400 model has non-undercut toneholes and is claimed to produce the "brightest" tone whereas the 1401 model with undercut toneholes and intermediate bore size is described simply as "a good all-around playing clarinet".

2.4.2.2.4 Leblanc.

Six examples of Leblanc's more recent models have been examined for undercutting [CLT066, 067, 072, 129, 134, and 140]

Two student plastic 'Normandy' models, [CLT129] and [CLT140], a plastic 'Vito' Resotone 3' [CLT134] and an intermediate 'Noblet Artiste' model [CLT072] had none of their toneholes undercut.

A Leblanc 'Dynamic' [CLT067] clarinet with a wooden body was found to have all but one of the open fingered holes undercut to various depths with 20° cones, the exception being hole V, the right hand middle fingerhole, which was not undercut. The pad-covered holes, on the other hand, were not undercut except for the four at the bottom which were uniformly lightly undercut. The heavy undercutting of the left hand first fingerhole was biased to one side, a device used by tuners attempting to improve the F_4/C_6 twelfth. Leblanc do not release the dates corresponding to their serial numbers but this model is believed to have first been made in about 1958 and this example is probably from that period. The undercutting pattern is summarized in the Table below.

This pattern of mixed tonehole geometries is indicative of a production line model which has been hand finished by a specialist technician as the final step in the manufacturing process.

One example of a brand new 'Opus' model was looked at [CLT087]. This is the most expensive of the current Leblanc range and was on display in a London showroom. All of the toneholes are undercut, the heaviest undercutting being at the top of the instrument as shown in the Table below. Whilst the right hand joint undercutting had been carried out to produce a smooth finish, the toneholes in the left hand joint all had an unfinished appearance with marks from the fraises evident. In fact in the first fingered open hole it appeared that the fraise had been allowed to stop rotating whilst in contact with the wood, throwing up chips which were still present. It was possible to count the number of teeth (12) on the fraise tool which had been used

These observations were subsequently raised with a representative of the Leblanc firm who acknowledged that this was the result of a production problem. Despite entrusting the undercutting of their top grade clarinets to a single experienced craftsman in the factory and a policy of replacing the fraises on a regular basis, the quality control inspection had not been sufficiently stringent, allowing this instrument to reach the retailer. Unfortunately it was not possible ascertain whether or not the imperfect processing had affected the performance of the instrument by carrying out a playing test.

One Leblanc basset-clarinet in A was examined [CLT066]. Basset-clarinets made a re-appearance in the last decades of the twentieth century, primarily for the performance of the Mozart works descending to low C, although some contemporary composers have now also written works for them. Many basset-clarinets are made from standard instruments which have been converted by extending the lower joint and adding the extra toneholes and keywork. However this example was purpose-made with matching serial numbers on the top and bottom joints. It is not a new instrument and is probably one of Leblanc's early basset examples. Again a random mixture of straight-sided and undercut toneholes was found with evidence of teeth marks left by the fraise in one of the toneholes. Only a small numbers of these models would have been manufactured and hand tuning and finishing would be expected.

Leblanc Clarinets

CLT	Pitch	Bore mm		Speaker	Side B	Side Bb	A	Ab	Ring I	Thumb	Side F#	I	Ring 2	II	Front Eb	Side Eb	III	C#	Rings	IV	B/F#	V	VI	G#/D#	G/D	F#/C#	F/C
067	Bb	15.0	u/c	-	-	-	-	-	-	M	-	4s	0	3	0	0	3	0	0	5	-	-0	3	2	3	3	3
087		14.65	u/c	-	-	-	-	-	-	M	5s*	5*	-	5*	5s*	5	4*	4*	4	4	4/5	4	4	3	3	2	2

* tooth marks from fraise tool visible and raised wood ‘chips’ present in some holes

2.4.2.2.5 Yamaha

The Japanese firm Yamaha began producing woodwind instruments in the final quarter of the twentieth century. As newcomers to the field they were able, from the outset, to incorporate the best available acoustic recipes as the starting point for developing their own designs. It appears the Yamaha clarinets dating from the 1980s were not undercut but all of their current models are produced with undercut toneholes. Yamaha make a distinction between their standard and intermediate models, which are described as having undercut straight sided toneholes, and their professional models which have undercut tapered toneholes. According to their publicity data the undercutting on the top grade models is carried out by hand. The term 'tapered' is ambiguous as it does not define which end of the hole is larger but from the models examined it appears that the holes are larger at the outside than at the bore (i.e. overcut).

The bore sizes of the Custom series differ. The CS was the first of the series to be made and is acoustically similar to the Buffet R13 (bore 14.65 mm) with moderate undercutting. The SE model is similar to the Buffet RC with a larger bore than the CS. The AE has a longer taper in the bore than the R13 and small lightly undercut toneholes. This is claimed to have some of the sound qualities associated with large bore instruments, such as the Boosey and Hawkes '1010's, but with more resistance to blowing. The CX model is similar to the CS but with inserts for the toneholes with rings.

In the late 1990s the CSV and SEV versions of the CS and SE models were introduced in which the tonehole overcutting was featured as well as undercutting.

A few examples of Yamaha clarinets were examined to confirm the details of the undercutting. Samples of YCL-34 II [CLT138] and YCL-CX [CLT137] wooden top joints were found to have been conically undercut (cone semi-angle ~20°) with good consistency between samples. One pair of AE clarinets was examined [CLT157 and 158] made in the 1990s. In the Bb the lowest four open fingered holes were not undercut whilst, with one exception, the rest had been lightly undercut with 20° cones. The depths of cut ranged from just reaching the intersection with the bore to approximately one quarter of the wall thickness. All of the toneholes of the A of the pair were similarly undercut throughout. In both clarinets the toneholes closed by the second ring key on the upper joint had been deeply undercut with a narrower cone (through approximately three quarters of the wall thickness in case of the Bb but less in the A).These instruments were purchased as new and have not been adjusted subsequently. This is almost certainly an example of the manufacturer incorporating selective undercutting into the design to narrow the E_4/B_5 and probably also the F_4/C_6 twelfths.

Some Small Scale Manufacturers

2.4.2.2.6 Howarth of London

Howarth used to import clarinets from France to be stamped with their mark but they now manufacture their own models in the UK. Only one Howarth clarinet was examined [CLT086], a new S2 model selected at random from those on display in their London showroom.

All of the accessible toneholes had been neatly conically undercut leaving a smooth finish to the wood. The undercutting was quite uniform in the top joint extending on average a third of the way through the wall thickness and became shallower towards the bottom. The observed undercutting matched the criteria described by Jon Steward who was involved in the design of the model.

2.4.2.2.7 Peter Eaton

The background to these British-made clarinets can be found in an interview with Peter Eaton published in an issue of the Clarinet and Saxophone Society of Great Britain [Vol. 24 No.2 1999 pp16-19].

In brief, Peter Eaton in the 1980s collaborated with Ward and Winterbourne to produce hand-made clarinets based on the pre-war Boosey and Hawkes 1010 design but with somewhat thicker walls. After Boosey and Hawkes ceased clarinet production in 1984, he acquired their tools and materials and continued to develop his large bore 'Elite' model. With new 1010s no longer available, this was taken up by a number of professional players who still preferred the wide bore instrument sound.

In 1990 a smaller bore 'International' model was introduced which allows a standard mouthpiece to be used, rather than the special mouthpiece necessary for the 1010 bore design.

Peter Eaton makes extensive used of hand undercutting [personal communication] during the final stages of tuning and voicing, including the use of more than one fraise tools of different angles per hole, especially in the larger toneholes at the bottom of the instrument, aiming to achieve a smoother profile.

Relatively small numbers of Peter Eaton clarinets are in circulation but two pairs of the International model were located [CLT075 & 076; 060&061] and their undercutting assessed. The minimum bore of these instruments was in the range 14.75 to 14.8 mm. The undercutting in all four instruments has been applied to all of the toneholes with the majority of the conical cuts just reaching the bore or extending not more than a quarter of the way through the wall thickness. Larger cone angles are evident in the lowest holes where more than one cutter has been used. The lowest hole in one of the instruments had been further enlarged as it showed some asymmetry.

2.4.2.2.8 Louis Rossi (Chile)

All Rossi clarinets have one-piece wood bodies and there is a choice of bore types:

i) American bore

Central section bore = 14.65 mm. Upper body reversed cone formed from three cylinders with top diameter of 14.8 mm. Reversed cone barrel

ii) French bore.

Central section bore = 14.6 mm

Upper body reversed cone with top diameter of 14.9 mm. Completely cylindrical barrel with 14.9 mm bore.

iii) English bore based on B & H 1010s

Parallel 15.2 mm bore.

iv) Viennese bore.

Based on the large bore Koktan clarinets owned by Leopold Wlach.

Some toneholes are lined with hard plastic to ensure good seal with the pads but the lining does not extend to bore.

The undercutting of an un-numbered pair made with the English style bore were examined [CLT070 & 071]. In both instruments the undercutting is light but there is little correspondence between the patterns in the two instruments as illustrated in the following Table. These are hand made clarinets and it can be assumed that the Rossi's final finishing adjustments result in this variability.

Louis Rossi Clarinets

CLT	Pitch	Bore mm		Speaker	Side B	Side Bb	A	Ab	Ring I	Thumb	Side F#	I	Ring 2	II	Front Eb	Side Eb	III	C#	Rings	IV	B/F#	V	VI	G#/D#	G/D	F#/C#	F/C
070	Bb	15.2	u/c	-	-	-	-	-	-	-	-	-	-	0	3	0	3	0	3/4	0	4	3	3/4	3/4	3	3	2/3
071	A	15.2	u/c	-	-	-	-	-	-	-	-	-	-	4	4	3/4	3	3	3	0	0	3	3	0	3	3	3

2.4.2.3 Miscellaneous Boehm System Clarinets Examined

During the undercutting survey several Boehm system clarinets (mostly cheaper instruments), were encountered which were un-marked. Also there were brand-named models but without the manufacturer's name (e.g. 'Pennant'), and clarinets by less familiar makers. For completeness these are all listed here but attention will be given only to those of particular interest.

One of the clarinets played by a well known professional Hungarian clarinettist (who requested that he should not be identified here) was examined [CLT040]. This Bb instrument with a bore of 14.9 mm is one of a pair made by Frank Hammerschmidt of Bergau, in Germany. The original barrel which matched the bore of the top joint had been replaced with one with a narrower bore (14.6 mm). All of the left hand joint holes had been slightly undercut whilst none of the right hand holes had any significant undercutting. At the request of the player extensive adjustments to the toneholes had been made by Hammerschmidt over a period of years subsequent to manufacture. For example the third left hand finger tonehole had been angled so that it now slopes downwards towards bore and black wax had been added at the bore end. Likewise wax had been added to several of the holes, especially in the left hand joint, to correct tuning imperfections. Hammerschmidt produces relatively small numbers of clarinets and routinely collaborates with the players to carry out these types of hand adjustments

The other instruments encountered are listed below:

The first Table shows the non-undercut clarinets, mostly cheaper models designed for student use, and the second Table shows the undercut models. All but the American 'Artley' were made in France, including examples by Cabart and Marigaux, both well known makers of oboes, but who also produced clarinets in smaller quantities.

In general the undercut examples are somewhat better quality instruments produced for the intermediate player rather than the beginner.

Miscellaneous Boehm System Clarinets Examined

Non-Undercut Toneholes

CLT	Pitch	Maker	Details	LHJ	RHJ	Bore	Date	S. No.
020	Bb	Jean Martin	Twentieth century French make	-	-	14.7	?	
037	Bb	U	Cheap plastic student model, probably made in China. Serial no on RHJ only.	5.6-8.8	8.5-9.5	15.0	~1970s	J5269
042	Bb	C Zinzi & C	Full Boehm made in Italy by Orsi. Found in the basement of the Royal Society of Musicians. (Zinzi is not listed as a clarinet maker in Langwill). Wood.	-	-	14.65	20th C	-
126	Bb	Pennant (USA)	Wood	5.5-8.6	8.8-10.1	14.8	Post WW2	W3865
127	Bb	Jean Barre	French made. Ebonite body with un-plated nickel silver keywork	5.3-8.2	8.0-9.9	14.85	?pre WW2	5009
128	Bb	B&H 2-20	Incorporating Reginald Kell design features for American market.	5.0-8.2	8.6-9.5	14.85 Rev. cone	1960-65	242705
135	Bb	Rene Dumont	'Artist' model made in France. Wood.	5.5-8.5	8.7-9.4	15.05	Post WW2	15223
136	Bb	Kraftsman	American make. RHJ only. Die cast keys. Wood	-	8.8-10.3	15.2	Post WW2	906080
142	Bb	Rudal Carte	'Super Graduate' model. made by Boosey & Hawkes. Wood	5.4-8.5	8.3-9.6	15.1	Pre 1955	546917
144	Bb	The Pedlar Co USA	Intermediate grade instrument with silver plated keywork. RH ring keys fitted close to body with B/F# key passing over the ring axel. Made in Elkhart USA. Wood	5.4-8.2	8.3-9.2	14.95	Post WW2	P18303

Miscellaneous Boehm System Clarinet Examined

Undercut Toneholes

CLT	Pitch	Maker	Details	LHJ	RHJ	Bore	Date	S. No.
043	Bb	Marigaux	Made in France by Strasser, Marigaux & Lemaire. Best known as oboe makers but also made significant numbers of clarinets. Wood	5.5-8.3	8.1-9.7	14.85	1974	1334
130	Bb	M Dupont	Generic name for French-made clarinets imported into USA by Sears Roebuck & Co. Wood.	5.0-8.6	7.9-9.6	14.65 rev cone	Post WW2	12750
056	A	F Baron	French made. Wooden body with ebonite barrel	-	-	14.9	Mid 20th C	
084	Bb	'Musical'	New York import from France. Higher quality model. Wood	-	-	14.75	Post war?	-
085	A	Cabart	French maker specialising in oboes. Wood.	-	-	14.75	Post war?	-
125	Bb	Artley (USA)	Various '18S'model. Plastic.	5.0-7.8	7.7-9.4	14.5	Post WW2	

2.5 Speaker Tube Bore Profiles

2.5.1 Introduction.

The dual role played by the speaker vent (or register hole) presents design conflicts. The hole must cause the instrument to play efficiently in the second mode (clarinet) register when opened in conjunction with most of the fingerings used for the low register notes, but must also act as a tonehole to produce Bb_4 when opened with the A_4 key.

To produce a speaker action, the hole is normally placed at one third of the acoustic length of A_3 (or thereabouts) from the top of the instrument, to give an accurately tuned E_5. The hole is made larger than ideal for a good speaker action in order to perform the tonehole role. The effect of having a single somewhat oversized register hole in a plain (unperturbed) cylindrical bore is that the twelfths above and below A_3/E_5 is too wide. Until the middle of the twentieth century, clarinets were typically made with the 'bell' notes in tune in the clarinet register and consequently flat in the chalumeau register. The flat notes tended to rise in pitch when played at low dynamic levels, but at louder levels it was not always possible to raise the pitch enough by increasing the pressure on the reed via the embouchure. (This problem was solved in Euler System clarinets by adding an extra thumb-operated key on the bell, which could be opened to sharpen the low register bell notes). Above A_3/E_5, the instrument is much more responsive to lip pressure and tuning corrections can be achieved, to some extent, by embouchure control.

Many clarinets made before and during most of the twentieth century had uniform cylindrical bores from the top of the barrel to the bell flare, one well-known example being the Boosey and Hawkes 1010 model, introduced in the early 1930s. Other manufacturers attempted to reduce the tuning deficiencies of strictly cylindrical bore instruments by making the bore of the barrel slightly conical, the diameter being larger at the top than at the bottom (reversed cone). Examples can be found in wider-bore Leblanc clarinets from the early part of the twentieth century.

In the first half of the twentieth century Henri Selmer in France successfully made instruments in which the reversed cone was extended through most of the length of the top joint as well as the barrel. Various manufacturers adopted this pattern using different cone lengths. Some restricted the cone to the bore above the speaker key whilst others extended it through the whole of the top joint. Occasionally the perturbation was extended into the lower joint (for an example the clarinet marked M Dupont [CLT130]).

In 1949 Robert Carrée, working for Buffet Crampon invented the 'polycylindrical' bore. Here the upper and lower joints are cylindrical but the bore of the upper joint is slightly larger than that of the lower. Today all top-range clarinets by the well-established major manufacturers have some kind of bore perturbation aimed at overcoming the tuning problems associated with a single dual-role speaker key.

Even to design a hole to work only as a speaker presents a conflict in requirements. At low playing levels, an acoustically resistive hole is needed to reduce the amplitude of the fundamental mode below that of the second order mode so that a shift to the upper register occurs. At louder playing levels, where the higher-order modes are strong, a reactive hole is required to shift the fundamental mode frequency upwards sufficiently that it can no longer cooperate with the higher-order modes. (see Benade's special clarinet) **[Benade1978** p 456]. The reactive hole, which relies on the inertia of the mass of air contained within it, is closer to the Bb tonehole requirement than the resistive hole which relies on friction, and this is the type of register hole which is found in actual clarinets.

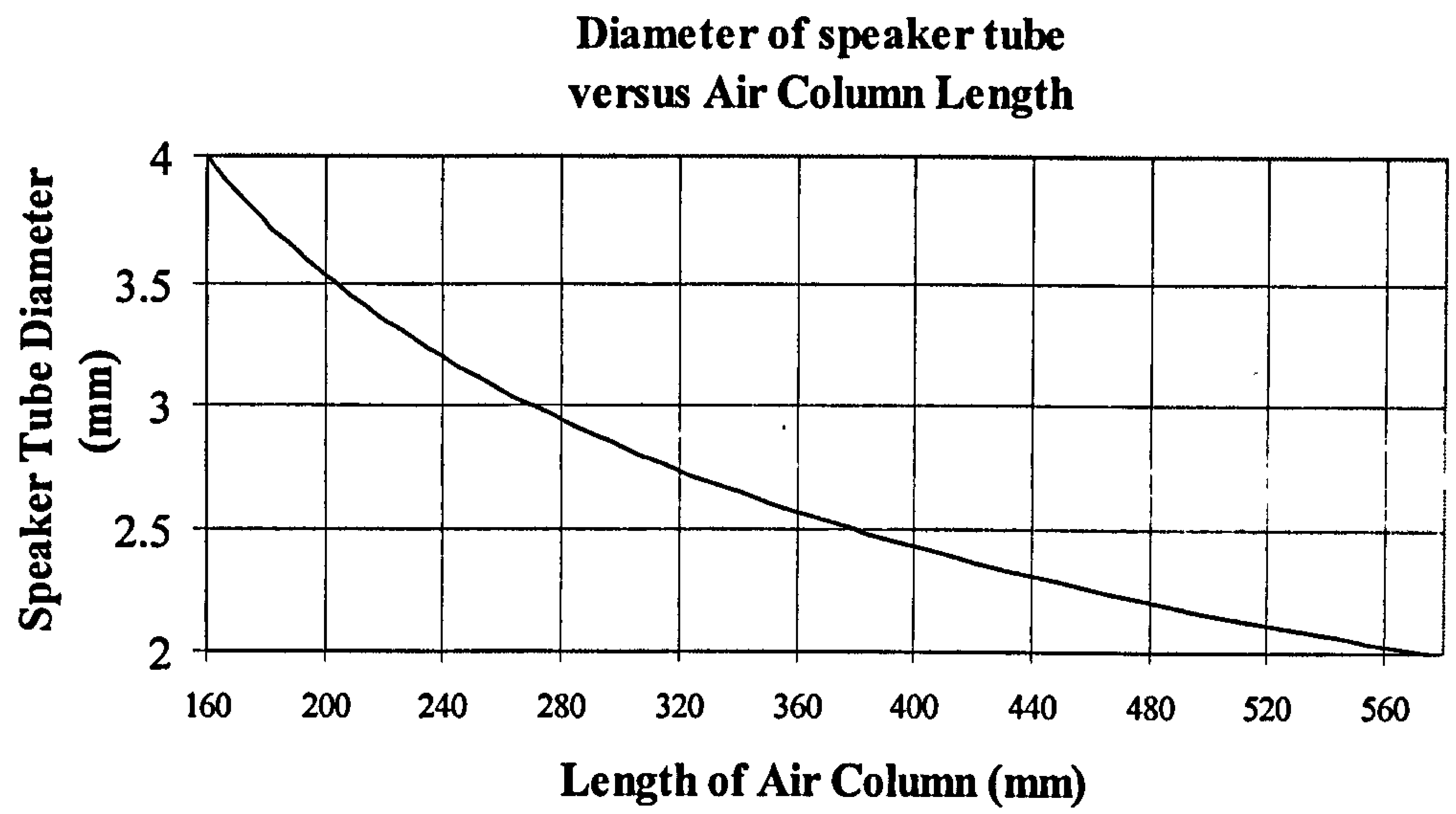
For cylindrical air columns Benade gives an expression relating the radius, (b), and effective length, (t_e), of a register tube to the acoustic length, (L), of the air column to be changed to the second mode, and the radius of the cylinder, (a) :

$$\left(\frac{b}{a}\right)^2 \cdot \left(\frac{L}{t_e}\right) = 0.757$$

The effective length, (t_e), is related to the physical length of the register tube, (t), by the approximation:

$$t_e \approx t + 1.5b$$

Assuming a clarinet bore of 15 mm diameter and a speaker tube physical length of 12 mm, one can plot Benade's optimum speaker tube bore diameter as a function of air column length, (i.e. quarter wavelength), as follows:



Assuming the speed of sound to be 346 m/s in warm moist air, the quarter wavelength for concert G_3 (196 Hz, A_3 on the Bb clarinet) is:

$$\lambda/4 = 346/196 \times 4 = 0.4413 \text{ m or } 441.3 \text{ mm}$$

From the graph this corresponds to an optimum speaker tube bore of approximately 2.3 mm. As will be seen in the following section, this is somewhat smaller than the bores normally used, which are typically slightly larger than 3 mm.

If the same calculation is done for the air column corresponding to concert A_3 (220 Hz, B_3 on the Bb clarinet) the quarter wavelength is 393.2 mm and the optimum bore becomes 2.45 mm.

These lengths cover the range over which perfect twelfths might reasonably be set by placing the hole at one third of the length from the top of the air column without causing unacceptable widening of the twelfths above and below.

Speaker vents are normally made as small metal tubes which are either slightly tapered externally and pushed into a matching hole drilled through the body or, in some modern instruments, externally threaded and screwed in.

In the modern Boehm instrument, the speaker vent is placed at the back of the instrument and roughly half its length projects into the bore. The now obsolete 'Simple System' clarinets usually had the speaker tube at the front with a curved key wrapped half way round the body to allow its operation by the left thumb. This pattern can be also be found in some Boehm system instruments, notably those made by Buffet Crampon around the beginning of the twentieth century.

Traditionally players have accepted Bb_4, formed by opening the A key and speaker keys together, as the weakest note on the clarinet and instead use the side Bb key in conjunction with the A key when this is possible, especially if a sustained solo Bb is required. The technique of closing fingerholes further down the instrument ('shading'), sometimes used to enhance the timbre of G_4, is less effective when applied to Bb_4. This technique relies on advantageously altering the acoustic filtering of the toneholes below the sounding note. Notes at the top of the chalumeau register, the so-called 'throat notes', lack timbre essentially because the bore is oversized relative to their air column lengths in this part of the instrument.

Larger instruments such as the bass clarinet need to have two speaker vents spaced apart to allow all of the second mode notes to play satisfactorily. These may be operated as separate keys by the left thumb in the 'manual' models, or in the automatic models work from a single touch piece. The automatic mechanism is linked to the lower part of the instrument and when (usually) the right hand third finger is raised, the venting switches from the lower to the upper speaker vent with the speaker key depressed. Even for these instruments the lower speaker vent still acts as the Bb tonehole. However the lower of the vents can be made larger than the upper as it only provides the register role for five or six semitones above the break, and so produces a better throat Bb than in the soprano instrument.

Speaker tubes with a simple cylindrical bore can be found in clarinets from the 'classical' pattern through to twentieth-century Boehms. Invariably the speaker tube is squared off at the bore end and profiled at the other end to form an air-tight seal with the pad. The tube projects typically 5mm or more into the bore according to the length of the tube.

2.5.2 Undercutting in Speaker Tubes.

Speaker tube are not usually considered when discussing tonehole undercutting, but in this investigation the bore profiles of a number of speaker tubes have been examined. They are demountable and they are made separately, unlike the normal toneholes which have to be drilled and undercut *in situ*.

Because speaker tubes project into the top joint and have small bores, the use of the borescope is ruled out. To measure the bore profiles the tubes were first removed from the instruments. This is a simple procedure involving first removing the speaker key and then pressing the tube out using a specially shaped tool, or unscrewing it with a thin walled box spanner of suitable size. Calibrated pin gauges with diameters in steps of 0.025 mm were then inserted at the wider ends and the bore profiles constructed by measuring the depth of insertion, knowing the lengths of the pin gauge and the speaker tube.

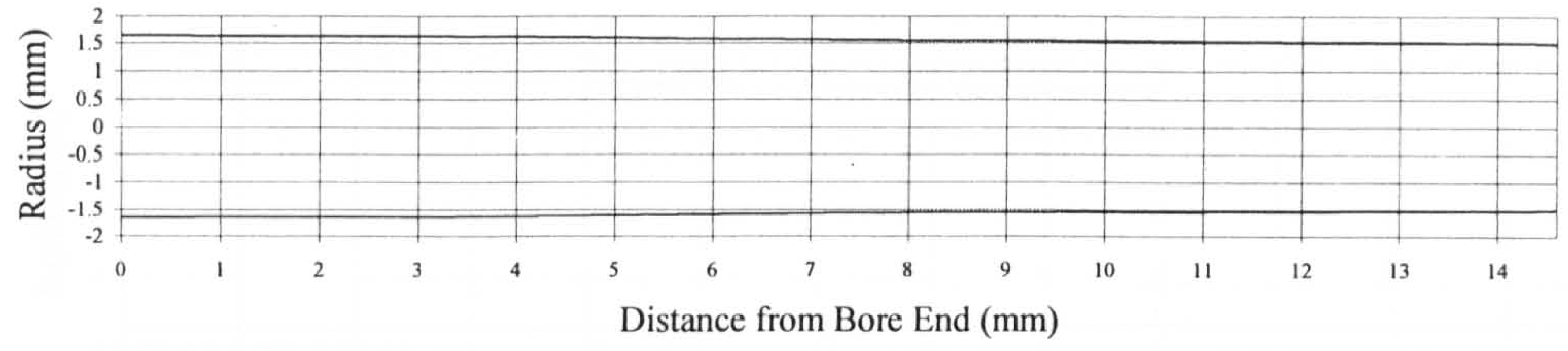
Examples of cylindrical bore speaker tubes measured during this study are tabulated below:

CLT	Maker	Model	Serial No	Tube length mm	Bore mm
034	Goulding & Co.	6-key		11.86	3.30
036	Boosey and Hawkes	926	89836	11.62	3.18
035	ditto	926	120763	11.63	3.15
116	ditto	926 (A)	120774	11.75	3.16
117	ditto	926	150441	11.75	3.13
118	ditto	926 (A)	179373	11.67	3.13
128	ditto	2-20	242705	13.66	3.23
132	Selmer	Console	-	11.62	3.05
127	Jean Barre (France)		5009	12.43	3.20
144	Harry Pedlar Co. (USA)		P18303	11.00	3.20

This shows that in clarinets with simple cylindrical-bore speaker tubes, the bores are made some 25 percent larger in diameter than the register-role theoretical requirement, in order to accommodate the tonehole role.

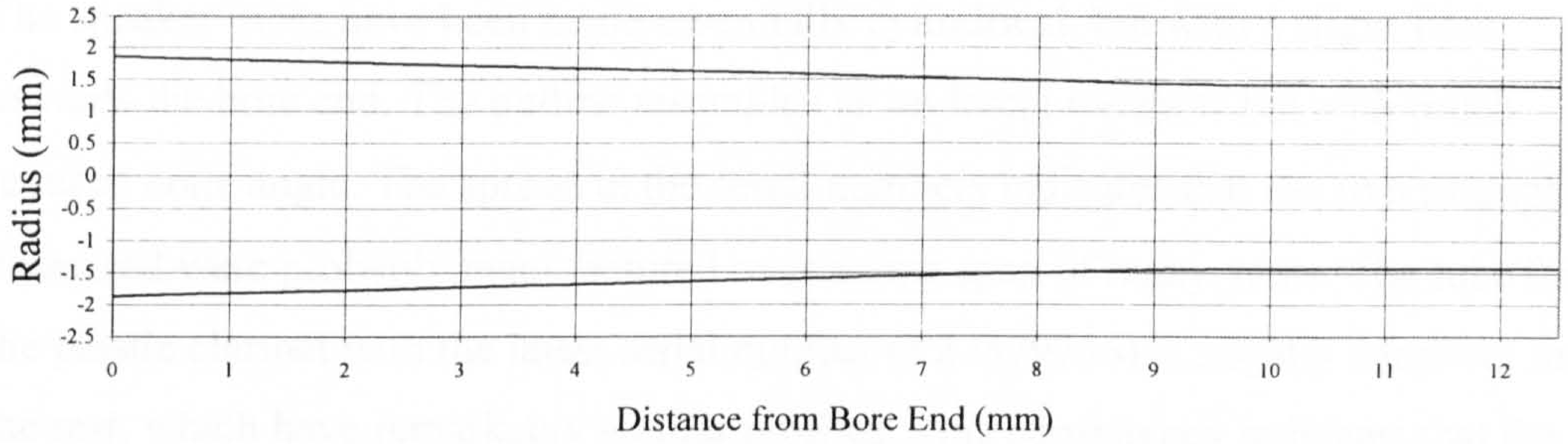
An example of slight conical undercutting has been found in the speaker tube of a Selmer (Paris) Series 9 model clarinet manufactured in the 1950s. This model has a plain cylindrical bore of nominally 14.85 mm diameter and, like the Boosey and Hawkes 926 model of 15.0mm bore, the toneholes are not undercut. The bore of the speaker tube, which is unusually long (14.6 mm), changes from 3 mm nominal at the outside end to 3.25 mm at the inner end:

Selmer (Paris) Series 9. Unnumbered
Speaker Tube Bore Profile



A number of examples have been found in more modern instruments where the bore of the tube has been more extensively undercut. In a sample of two Yamaha Model 34II clarinets examined, the speaker tubes have a short parallel section slightly under 3 mm in diameter at the outer end which then expands to 3.7 mm as a regular cone towards the bore. The cone semi-angle is 2 degrees:

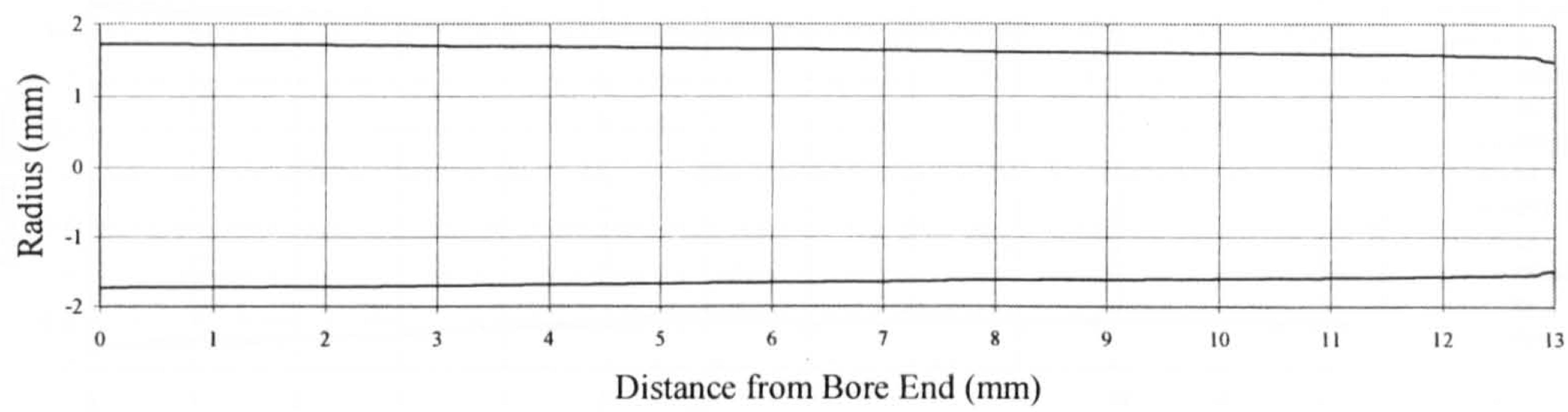
Yamaha Model 34 II (sample 2)
Speaker Tube Bore Profile



Measurements were also made of register tubes from Yamaha CX clarinets. These are top-of-the-range models, intended for professional use. The bore profiles were found to be identical with those measured for the cheaper 34 II model.

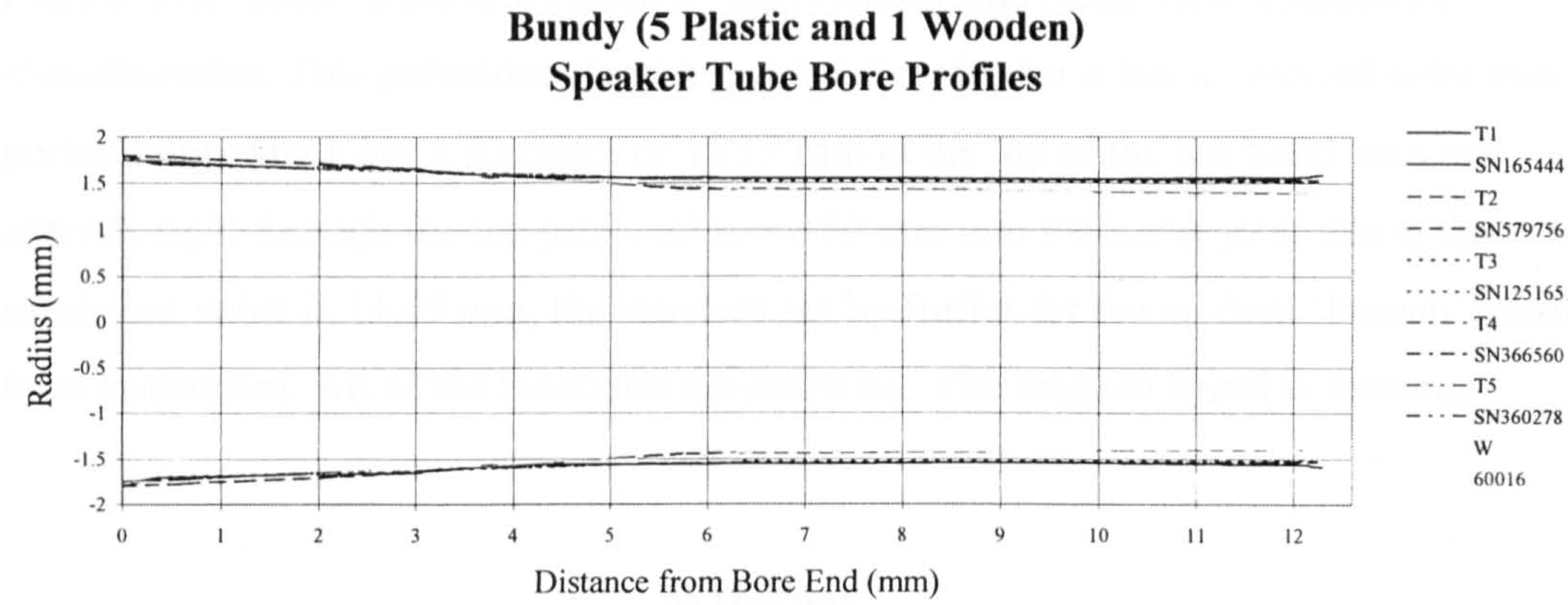
Another example of a near-conical undercut was found in the speaker tube of a Vito 3 Model clarinet made in America by the Leblanc Corporation:

Vito Resinite 3 (Leblanc)
Speaker Tube Bore Profile



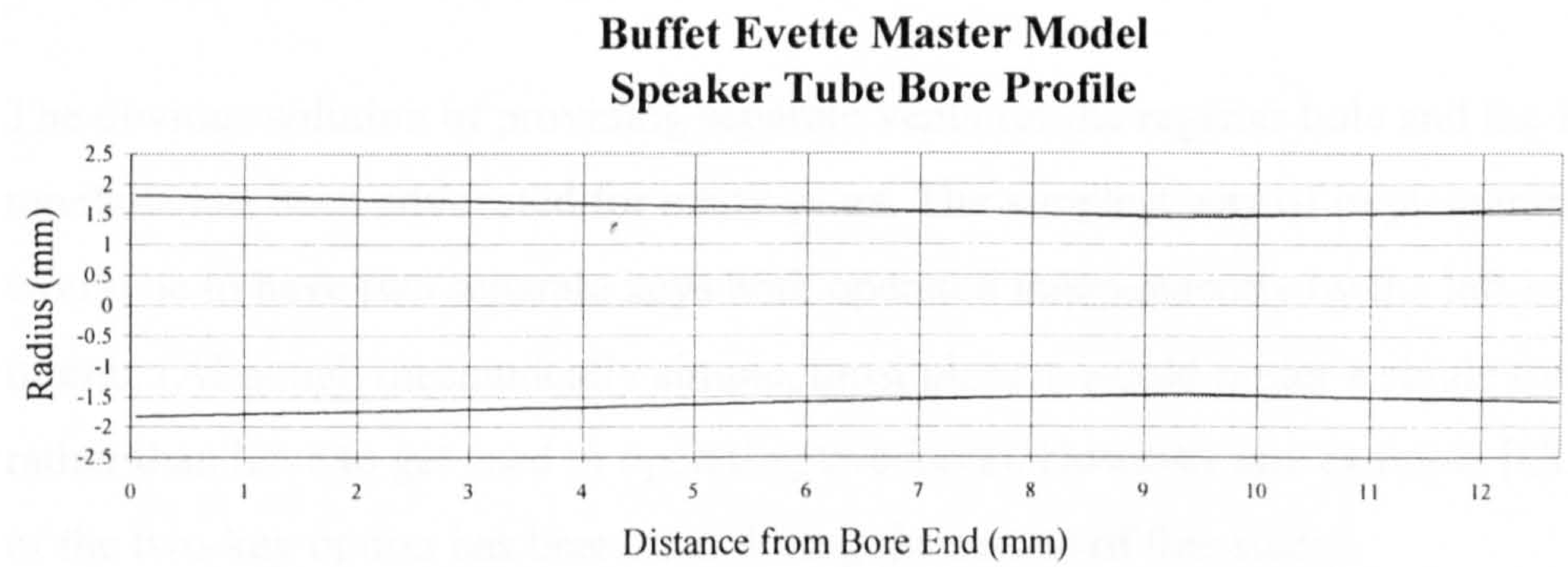
Here the cone has a slight concave shape and pinches in slightly as it reaches the outside. These are lower priced clarinets not intended for professional use.

A different type of bore perturbation was found in a set of five Bundy plastic clarinets. These are cheaper instruments manufactured in America by the Selmer Company. The top joints are stamped with serial numbers but the maker's name has worn off. The make can however be clearly identified by comparison with other Bundy clarinets. The speaker tubes have been made essentially cylindrical, but with a slight flare towards the bore end. The outline resembles an undercut tonehole but with much reduced cone angle. The spread in the serial numbers indicates that the five examples measured were probably manufactured over a time span of many years. The tube from the plastic clarinet with the latest serial number (T2 /579756) is slightly narrower than the rest, which have remarkably similar profiles. This consistency indicates that the undercutting is a design feature rather than a chance enlargement due to the method of manufacture.
These plastic clarinets were used for the playing experiments to be described in Section 3.4.



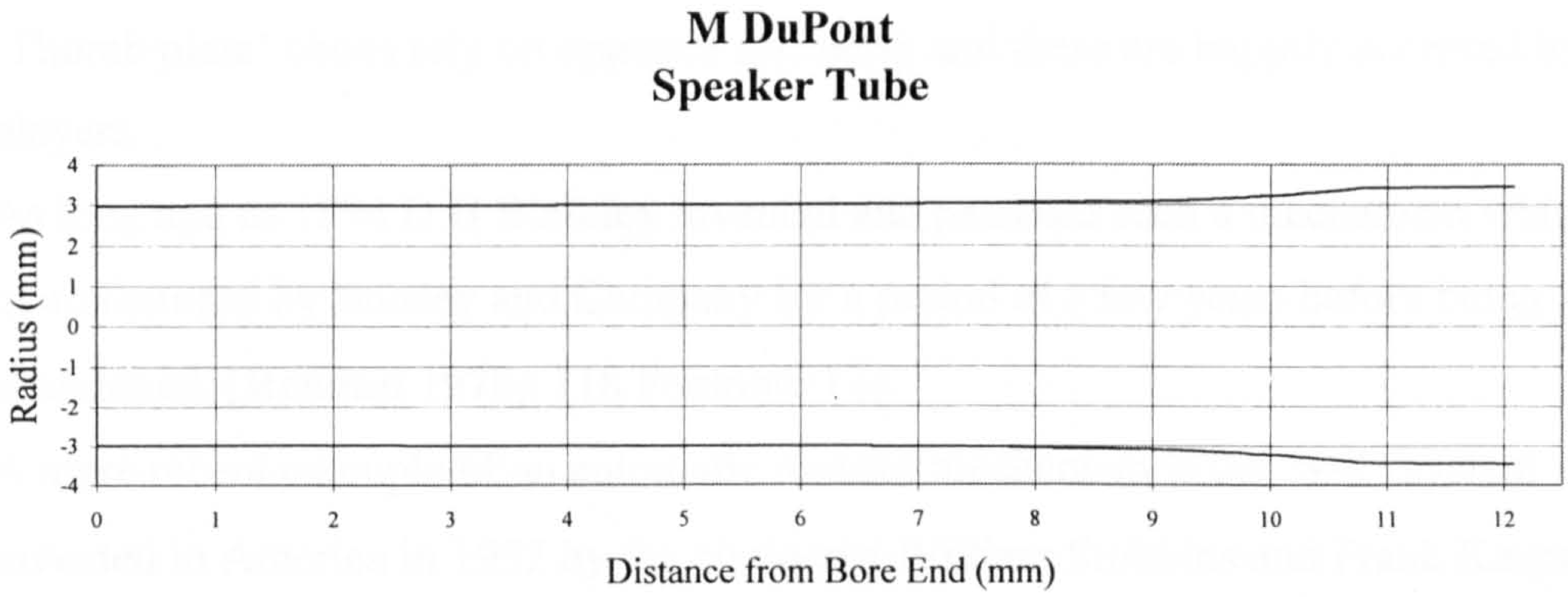
The speaker tubes from the wooden Bundy instrument referred to above (91009) and the most recent plastic example (579756), have similarly bore profiles, 2.80 mm at the narrowest part. This compares with an average figure of 3.06 mm for the earlier plastic examples. It is not known if the same sequence of serial numbers was used in both wooden and plastic models.

A combination of undercutting and 'overcutting' was found in an Evette 'Master Model' made in France by the Buffet Crampon Company. The speaker tube starts at 3.6 mm diameter at the bore end, reduces to about 2.9 mm three quarters of the way along and then expands up to 3.1 mm at the outside:



One example has been found of a speaker tube which has been 'overcut', the bore increasing towards the outside over half its length. This was in a wooden clarinet marked 'M DUPONT', of unknown date of manufacture, but probably made after the Second World War. M DUPONT is a generic brand name used by the Sears Roebuck mail-order company in America which they applied to clarinets they imported from

France. The maker is not known but it was probably one of the large established manufacturers. This particular clarinet is interesting in that it has a reversed cone bore perturbation which has a diameter of 15.15 mm at the top of the left hand joint and extends right through the top joint and some 50 mm into the lower joint where the minimum value is 14.65 mm, the standard set by Buffet for the modern 'French' small bore instrument. All of the toneholes are undercut. The original barrel is missing.



The tube is parallel at the bore end with a diameter of nominally 3 mm and half way along begins to flare to almost 3.5 mm at the outer end.

2.5.3 Discussion.

The obvious solution of providing separate vents for the register hole and the Bb_4 tonehole has been advocated for many years. The simplest way of implementing this would be to have two separate keys both operated independently by the left hand thumb. (Although mechanically simple, most players would prefer a single touch piece rather than have to get used to operating two keys). However one example [CLT028] of the two-key option has been seen during the course of this study.

Various automatic systems, such as used for the two or three octave keys on the oboe, have been applied to the clarinet. Essentially the hole for the speaker action is made smaller and moved up the instrument from the usual position, and a larger tonehole provided for the throat Bb. The size and placement of the tonehole depends on whether it is intended to be opened with or without the speaker hole open at the same time, (i.e. the speaker hole only open for high registers, and either speaker plus tonehole or tonehole alone open for Bb). Both versions have been tried. In either version some kind of mechanical linkage has to be provided so that the automatic mechanism can tell from the fingering whether the note Bb or the speaker action is intended. This is frequently a link to the A key, but other keys such as the thumb ring can also be used. In most of these mechanical arrangements, opposed springing is involved, which is perceived by some players as being difficult to keep in adjustment. This is one of the reasons that none of these improved speaker mechanisms have been adopted as the standard by clarinet manufacturers. This appears illogical since all Conservatoire and 'Thumb plate' oboes rely on opposed springing and these are happily accepted by players.

As long ago as 1894 D H Blaikley invented and patented such a mechanism which was manufactured by Boosey and Company for a period of a few years before being abandoned. [**Rendall** 1978p 118 Footnote 12].

A more recent example of an automatic register mechanism is the 'S-K' system invented in America in 1952 by the clarinetist William Stubbins and Frank Kaspar[⊕]. This version is of the type in which both holes are open for throat Bb. In the example given in their US Patent 2508550 (May 1950), the position for the register hole relative to the top of the joint (18 mm) is misleading as 'from the top of the upper joint' should read 'from the shoulder of the upper tenon of the top joint'. This would make the distance from the top of the joint 37 mm, the figure stated in Stubbins' book [**Stubbins** 1974]. The correct figures are:

For a nominal 15 mm bore clarinet:

Top Register hole:	Diameter	2.69 mm.	Dist from top	37mm
'Resonance' hole:	Diameter;	4.22 mm.	Dist from top	87 mm

The register hole diameter is now much closer to Benade's theoretical value but the displacement upstream from the position typically found in conventional dual-role speaker tubes is small, about 2 mm. However, small displacements along the axial direction are significant in this region of the bore. For example, it has been found that in some Buffet Model R13 'A' clarinets the note A_5 was difficult to start. When Buffet introduced their 'RC' and 'Festival' model 'A' clarinets, the speaker tube positions were moved upstream relative to the R13s by approximately 2 mm, which removed the

[⊕] not 'Kalmus' as incorrectly stated by Brymer [**Brymer** 1976] problem. The R13s could be corrected by shortening the length of the speaker tubes by as little as 0.5 mm, but this carries the risk of sharpening the upper register right hand notes.

Many other automatic register hole mechanisms can be found in which the extra hole is opened as well as, or instead of, the speaker hole, and a few of these mechanisms have been incorporated in production clarinets, usually as 'special order' models. One exception is the Mazzeo mechanism which was widely available in America. From about1960, Selmer marketed the 'Mazzeo' model clarinets[±]. Mazzeo invented a range of modifications to the Boehm system clarinet including a mechanism which releases the speaker key from its dual role. Minimal extra keywork is required and, when disconnected, the instrument can be played as a standard Boehm system. When set up, pressing the lower ring on the left hand joint or any of the right hand rings opens the hole operated by the side Bb trill key to produce A_4. When the normal A_4 key is opened as well, a good Bb_4 is produced as when using the side key option with a conventional Boehm. Closing the covered thumb hole overrides the ring keys action and closes the side hole. The advantages of this mechanism are that the first finger and thumb of the left hand stay close to their hole positions and do not need to reach up to work the A and speaker keys respectively for the throat notes. The fingers are then better placed for the notes immediately over the break: and the speaker hole can be reduced in size as it is no longer need as a tonehole. The drawback for players accustomed to the standard system is that 'shading' the throat notes (by closing any of the left hand fingerholes), causes the side hole to open, with unfortunate results. Also it is difficult to make a clean transition from the clarinet register to the throat 'A' if the conventional key is used (from force of habit), rather than one of the rings.

According to Weston [**Weston** 1989], more than 13,000 Mazzeo clarinets were sold by Selmer. Brymer [**Brymer** 1976], whilst acknowledging the problems for established Boehm players, is an enthusiast for the Mazzeo system, saying that it may take a generation of players before it is generally adopted. However there is no sign of this happening, a quarter of a century after Brymer made this prediction.

A cheap Selmer Bundy non-undercut clarinet with the Mazzeo register mechanism was examined [CLT148]. It was found that the register hole size and position were as in the standard Boehm model, so no advantage had been taken of the scope for improving the tuning of the twelfths.

[±] Rosario Mazzeo was bass clarinettist in the Boston Symphony Orchestra from 1939 to 1966

The examples described above of under- and over-cutting of speaker tubes show that manufacturers consider the register tube to be are area of potential improvement. Their objective can be presumed to have been to find a profile which is better than a simple cylindrical tube at satisfying the conflicting requirements outlined above. The variety of shapes discovered indicates that their approach was probably in most cases intuitive, rather than being based on physical principles. However Yamaha now claim to design their instruments using acoustic principles, so there may be an acoustic justification for employing conically undercut speaker tubes rather than other patterns which have been described above.

Whilst a plain cylindrical speaker tube can operate successfully as register changer within the limitations described above, it has been commented on in discussions with clarinetists that the tone quality of the note Bb_4 in modern cheap, mass-produced clarinets with profiled register holes tends to be better than that produced by some older clarinets with plain tubes, including some of the more expensive models. Although not conclusive, this suggests that the motivation for redesigning the speaker tubes was to achieve a better-sounding Bb_4, rather than to improve the register action.

The design of the speaker tube is a crucial and important feature of a clarinet. Even to provide an efficient speaker action with a single register hole requires compromise, and the difficulty is added to when the hole has to play a tonehole role as well. 'Undercutting', in the sense of abandoning the plain cylindrically-bored speaker tube, appears to have become quite common practice in present day clarinet manufacture. Despite the advocacy of many leading players and experts, the separation of the speaker and tonehole roles as a standard feature of the clarinet seems to be no nearer to realisation than it was fifty years ago.

2.6 The Commercial Scene Today - Manufacturers Use of Undercutting in Production.

Approaches have been made to several clarinet manufacturers asking for information on their use of undercutting in past and present models. Of those who responded, none could provide information about models no longer in production. However, some were prepared to provide information about their use of undercutting in current models and the techniques used in production to achieve it. At the time of writing, information had been obtained from three European manufacturers. These have not been referred to by name, to preserve commercial confidentiality.

i) Small-scale producer (< 100 clarinets p.a.). Hand-made instruments. (Sub-contracted keywork).

Instruments are routinely undercut using conical fraises as part of the manufacturing process, with the amount of material removed and the angle of cone increasing towards the bottom of the instrument. Most holes undercut with 20 degree, cones but two fraises of 35 and 45 degrees used for the lowest holes, (below hole VI). These holes are enlarged in this way to approximate to a 'flare', and the adjustment is claimed to be done as part of the tuning procedure, to improve the twelfths in this region of the instrument. It is not clear whether providing a larger hole initially would achieve the same effect.
This manufacturer commented that the overall characteristics of the instrument are determined primarily by the bore dimensions and hole positions and undercutting is an additional parameter which can then be applied to further improve the playing characteristic of the instrument.

ii) Medium-scale producer (< 1000 clarinets p.a.). Factory production.

All toneholes are conically fraised during production, the depth and tool angle being specified. Semi-angles in the range 15 to 25 degrees are used, the holes at the top being cut slightly deeper and with a smaller angle than those at the bottom. The depth of undercutting was aimed at one quarter to one third of the wall thickness. However undercutting is still a hand operation and all of the clarinets produced are undercut by the same person in an attempt to reduce variability. Undercutting tools are replaced according to a maintenance schedule as part of the quality control. Where adjustments to the toneholes are required to be made after manufacture this is done as a hand-controlled process, using a cutting tool rotated in a lathe head. By omitting a guide sleeve, the operator can rotate the instrument about its axis to achieve a partial cone, cut to one or both sides of the hole. Again this is used to correct tuning deficiencies.

iii) Large-scale manufacturer (> 1000 clarinets p.a.). Factory production.

This manufacturer stated that both undercutting and overcutting were used extensively in their 'professional' models, and that dome- and cone-shaped undercuts were used, depending on the model. Overcutting was deemed to be a feature which has a significant beneficial effect on the behavior of an instrument. Again in production, undercutting is a hand process, and it was acknowledged that this is the cause of appreciable variability within instruments made to the same specification. The lifetime of an undercutting tool is restricted to forty operations before it looses its cutting edges.

A representative of this firm commented that at present the reproducibility achieved in the manufacture of clarinets does not approach that achieved by (metal) flute manufacturers. Some of the shortfall is simply a consequence of trying to achieve precision mechanical engineering in wood as opposed to metal, but much of the variability found in practice arises from the final hand processes used even in relatively large-scale production.

There is a conflict between the manufacturer's wish to be able to replicate an excellent instrument by control of the manufacturing processes and his wish to sell instruments which can legitimately be described as 'hand finished by skilled craftsmen'. Even if perfect reproducibility could be achieved, there would still be room for hand finishing. Skilled players will ask for excellent instruments to be hand adjusted to meet their personal requirements arising from their individual embouchures, styles of playing, and their expectations of the way the instrument should behave.

2.7 Summary of Undercutting Survey.

The survey of undercutting of clarinet toneholes described in the preceding sections has covered clarinets ranging from the eighteenth century to current models. The data obtained show that undercutting has been applied to clarinet toneholes throughout the history of the instrument, not solely as a means of correcting the tuning of individual notes, but as a characteristic feature of the tonehole design. In fact, straight-sided toneholes without undercutting, apart from cheap mass-produced student models, appear to be restricted to some top grade models produced by certain manufacturers from about the start of the twentieth century.

Extensive use of fraising tools has been found. The most commonly used fraise tool shape is a simple cone shape. The semi-angle of the cone can vary from about 5 degrees up to about 45 degrees, but the most frequently used angles are from 10 to 20 degrees, with 20 degrees commonly used in modern instruments.

Evidence that a fraise has been used rather some other method of enlargement can often be deduced from the characteristic shape a rotating cutter produces. On drawing the tool up into the tonehole, the first points of contact are lateral and, provided the tool is centered and its shape and size is matched to the hole, two crescent-shaped cuts are made at either side of the hole. As the tool is drawn further up, the crescents enlarge and merge as material is removed from all round the hole. By contrast, undercutting with a file or small blade usually results in material being removed upstream and/or downstream of the hole unless a deliberate attempt is made to cut sideways. Freehand use of rotating fraises is not uncommon and can produce selective lateral cutting but uniformity of the shape of the cut may still be apparent. After examining large numbers of toneholes via the borescope it is possible to deduce with some confidence the undercutting technique used. Impressions taken of the sides of a tonehole with a moulding compound have been used to measure angles but, with practice, accurate estimates of cone angles can be made by use of the borescope alone.

Fraises had already become well established in the manufacture of woodwind instruments by the time clarinets began to appear, and it is therefore not surprising that there is extensive evidence of their use in early clarinets where symmetrical cutting was required. Where undercutting is made asymmetrically (e.g. upstream, downstream or to the sides), hand cutting with a knife or file may have been preferred, and some evidence of this has been seen. However, it appears that it was good practice to leave the cut surface of the toneholes with a smooth finish and, as a consequence, with a few exceptions, evidence of whether a file or blade was used has been removed. Considerable variation in undercutting profiles was found in the limited number of eighteenth century clarinets examined here, different makers producing different shapes.

By the time that 'Classical' pattern clarinets were being made in substantial quantities from about the start of the nineteenth century there appears to a considerable degree of standardization in the design, at least within instruments made in similar locations. Bore sizes for the soprano clarinets pitched in C, Bb and A are typically around 14 mm and the hole sizes are about 6.0 mm and 6.7 mm for the fingered holes in the left and right hand joints respectively. The holes were routinely undercut with reasonable uniformity within a given instrument and there is occasional evidence of additional hand working.

From the examination of eighteenth and nineteenth century clarinets there is evidence that manufacturers sought to avoid sharp edges by beveling. Several examples have been found where two fraises of differing angles have been used in the same hole to form an undercut tending towards a more rounded profile. Several examples were found where this smoothing is taken a step further by generating 'bell'-shaped profiles. The uniformity of the extent of the bell flares determined by measurements suggests that these smooth profiles may have been cut with a form tool. Whereas a cone cutter can be used for a range of tonehole diameters within limits, a bell-profiled form tool is much more restricted in its application. To achieve a perfectly smooth transition from a cylindrical hole to a flare requires the tool profile to match the hole size, although in practice some tolerance would be allowable. Because of the relative uniformity of the hole sizes within each joint found in classical clarinets, it is possible that only one or two bell-profiled tools might have been required to carry out all the undercutting

As discussed in Part 1, a major problem with the 'classical' clarinet and its predecessors was the inability to produce a satisfactory 'B' in the chalumeau register. With The first right fingerhole (R1) closed, the note is flat; but it is very sharp with R1 open and R2 and R3 closed. It is surprising, therefore, that there is little evidence in the instruments examined of selective undercutting of these holes in an attempt to improve matters, either during or after manufacture. Although informed composers of the period tried to avoid this note, this deficiency continues to be a source of frustration today for players of period instruments.

From before the start of the nineteenth century, extra keys were being added to the basic classical instrument initially, to make trills possible or to avoid using forked fingerings which gave unacceptable tuning especially in the chalumeau range. Instruments with eight to thirteen keys from the first half of the nineteenth century have been studied. Examples were found where the fingered toneholes used for the 'home' keys of the instruments continue to be carefully undercut, whilst less attention has been given to the 'extra' toneholes, many of which are simply drilled through the body wall and left uncut.

In the second decade of the century, Müller's improved clarinet design was being taken up by players and copied by other manufacturers. This dispensed with the need for small toneholes as fork fingerings were mainly eliminated. It appears that in the following decades some of the manufacturers of clarinets using Müller's design did not in fact take the opportunity to fully enlarge the tonehole sizes. A modest progressive increase has been found throughout this period in French and German instruments, and the practice of undercutting the toneholes continued.

The invention of the 'Boehm' system clarinet, with its acoustically proportioned and placed toneholes, would have provided a further opportunity to eliminate the costly process of undercutting if it were true that an undercut tonehole can be replaced by an exactly acoustically equivalent hole of slightly larger diameter. The fact that Buffet Crampon continued to undercut indicates that, even though good quality clarinets can and have been made without undercutting, there is some property associated with undercutting which is desirable to players or listeners.

By the 1860s, Albert was producing large volumes of ergonomically designed thirteen (and later fourteen) keyed 'Simple' system clarinets, with large bores and tonehole sizes. However, his early examples examined here showed that light but extensive undercutting had been carefully applied to all of the toneholes, even though these were probably less expensive instruments, intended for military band use. It appears that the holes were first tapered and then further undercut with narrow-angle fraises. Again this suggests that the intention was to vary the profile gradually, tending towards a rounded outline.

When, in the mid and late twentieth century, clarinets began to be manufactured by mass production methods and large numbers were made intended for the student or beginners market, undercutting was omitted as the process was too expensive to apply, irrespective of its acoustical merits. Many of these instruments had insurmountable tuning problems, but these were associated more with the use of inappropriate bores and hole placements than with lack of undercutting.

However, some twentieth-century makers produced relatively wide-bored clarinets, intended for professional use, with no undercutting, (for example some pre-war Selmers, and Boosey and Hawkes post-war 926 'Imperial' model).

Today none of the large French manufacturers produce wide-bored (~15 mm) Boehm models, and the smaller-bored designs predominate. In general these are undercut even for some of the cheaper models.

Particular attention has been given in this survey to Boehm system clarinets made by Martel in the early years of the twentieth century. These were highly prized by professional clarinettists for their playing quality and are heavily undercut. The possibility has been raised that the undercutting may have been carried out by Hawkes, who imported the instruments to raise the pitch from A=435 to 440 Hz. As a result, these became extremely free playing clarinets but still with unsatisfactory tuning when playing at A = 440 Hz..

Today clarinets are produced in large numbers using modern techniques (e.g. numerically controlled machines) and the undercutting is specified in the design. However, it known that undercutting is still be carried out as a skilled manual finishing process by some manufacturers. An important factor here, which manufacturers are reluctant to divulge, is whether the instruments are simply hand undercut without appraisal or tested by playing whilst being undercut. The later procedure is known to have been applied to top-grade instruments made in England in the middle of the twentieth century[ℵ].

To conclude, this survey has confirmed that undercutting of toneholes has been employed in the manufacture of clarinets throughout the lifetime of the instrument. Its use appears to have been largely empirical, and to some extent arbitrary, in the absence of a sound acoustical basis for its use.

[ℵ] for example Frederick Thurston was engaged as a consultant by Boosey and Hawkes to approve the final hand-adjustments made to their highest quality clarinets.

2.8 Table of Clarinets Examined
(excluding tonehole undercutting data)

Key: Column

1. Clarinet reference number quoted in text as [CLT***]
2. Source of instrument. See: Source key following table.
3. Museum/Owner's reference number.
4. Nominal pitch of instrument.
5. Number of keys or key system. A=Albert (13/14 key); B= 'Plain' Boehm; C=Clinton; O=Oehler; FB= Full Boehm, Bm=modified Boehm; Ba=Barrett; E= Euler
6. Maker/place of manufacture if known. U= unsigned.
7. Details of construction and comments.
8. Left Hand Joint. Range of fingered tonehole diameters (mm).
9. Right Hand Joint. Range of fingered tonehole diameters (mm).
10. Indication of nominal bore (mm).
11. Date of manufacture. '~' indicates best estimate from available evidence.
12. Serial number.
13. ✓ indicates that the flare in the lower joint was measured.

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
001	B&H	BH300	Bb	6	G Astor & Co London	Box and ivory. Square brass keys. Some mounting rings trimmed to 'knobs'. RHJ missing. .Side B key.	5.8-6.9	-	14.0	~1801-7	-	-
002	B&H	BH302	C	12	Bilton London	Box and ivory. Round brass keys, two in saddles, possibly later additions.	5.8-6.2	6.4-6.8	13.7	~1840	-	✓
003	B&H	BH306	Bb	6	Goulding London	Box and ivory. Square brass keys. RHJ and stock in one piece.	5.9-6.1	6.5-7.0	14.1	1806-08	-	✓
004	B&H	BH307	C	6	Goulding London	Box and ivory. Square brass keys. C (stuck to RHJ). Incorrectly labelled as in Bb in museum list. Side B key missing and hole plugged.	5.6-5.9	6.6	13.5	1806-08	-	✓
005	B&H	BH308	C	9	Key London	Box and ivory. RHJ and stock in one piece. Round domed brass keys in knobs/one in saddle.	5.9-6.4	6.9-7.0	13.5/ 14.1	(1815-56)	-	-

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
006	B&H	BH309	C	11	Key London	Ebony and ivory. Square ('pin cushion' shaped) silver keys. Two keys missing (front Eb and RH cross Bb) removed and holes plugged. Two added keys in saddles.	5.9-6.4	6.8-6.9	13.9	(1815-56) ~1830	-	✓
007	B&H	BH310	Bb	12	Key London	Cocus and ivory. Round silver keys with Hallmarks 0f 1832. Rollers on LH B & C# keys	6.0-6.4	6.8-7.8	14.1	1832	-	✓
008	B&H	BH311	Bb	13	Key London	Pair owned by Lazarus Stained box and ivory. Round slightly domed brass keys in knobs/rings and three saddles.	5.7-6.4	7.0-7.5	14.0	~1825 (Weston)	-	✓
009	B&H	BH312	A	13	Key London	Paired with above.	6.5-7.1	7.4-8.5	15.1		-	✓
010	B&H	BH314	C	6	C Otten London	Box and ivory. Square brass keys. RHJ and stock in one piece.	5.5-6.5	6.4-6.7	13.5	~1820	-	✓
011	B&H	BH315	C	6	G C Payne London	Box and ivory. Square brass keys. RHJ and stock in one piece. 'London' pattern m/p. Thick walled bell.	6.0-6.5	6.7-7.0	13.5	1808-35	-	-
012	B&H	BH316	Bb	13	U France?	Box and brass. Domed brass keys on pillars. Riveted steel springs. Metal thumb rest.	7.5-8.4	7.8-9.6	~14.6	~1850	-	-
013	B&H	BH320	Bb	C/B	Boosey & Co. London	One-piece ebonite bodies. Played by George Clinton. Details of hybrid key system described by Rendall	7.0-8.8	7.1-8.3	15.2	~1890 (S.No. indicates later date)	16314	-
014	B&H	BH321	A	C/B	Boosey & Co. London	Paired with above.	7.2-8.6	7.9-8.1	15.2	See above	16315	-
015	B&H	BH322	Bb	FB	Boosey & Co. London	One-piece cocus wood body. Specially made for Manuel Gomez with additional keys. Metal faced m/p with cord grooves.	7.1-8.6	8.9-10.0	~15.1	1907	-	-
016	B&H	BH323	A	6	U	Box and ivory. Square brass keys. . 'London' pattern m/p made by Wood. Separate stock.	6.1-6.5	6.9-7.1	14.1	~1810	-	-
017	B&H	BH324	Bb	5	Goulding and Co	Box and ivory. Square brass keys. M/p and bell missing. Separate stock. Badly compressed tenons. Stock oval.	5.7-6.0	6.5-6.9	13.2-13.6	~1800	-	-
018	B&H	BH326	A	B	Buffet Crampon	Cocus wood including m/p. Sp/key vent at front Metal lining at top of RHJ. Allegedly owned by Lazarus Marked 'Approved by J Pask' and 'Lazarus'.	4.9-7.6	8.2-9.0	14.9	pre 1872	-	-

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
019	B&H	BH327	Bb	13*	Clinton and Co	Cocus wood including m/p with shallow domed brass keys. Knobs and saddles. Modified: *brille* added later and insert on IV tonehole	5.6-7.7	5.6-8.3	14.95	1855-71	-	-
020	B&H	BH328	Bb	B	Jean Martin	Example of twentieth century French Boehm system clarinet with no undercutting throughout.	-	-	14.7	?	-	-
021	B&H	BH331	C	15/5rBa/ B	S Quilter	Cocus and brass. M/p, barrel and bell missing. Hybrid: LH Barrett, RH Boehm Metal lined top of LHJ. Short conical flare in lower joint.	6.5-7.0	7.5-8.5	14.3	1890-1925	-	-
022	B&H	BH335	Bb	B	Boosey and Co	Early English Boehm with ebonite joints. S/No 21005.Bottom of LHJ lined with brass M/p, barrel and bell missing.	6.7-7.0	8.4-8.5	15.15	~1914	-	-
023	B&H	BH336	Bb	13	Boosé London	Boxwood. Silver keys and pillars on ornate mounts. No ring on lower joint. Exhibited at 1851 Exhibition	-	-	14.3-14.5	~1850	-	-
024	B&H	.BH337	Bb	Ba	Boosey and Co	Blackwood body with nickel silver key-work on pillars. Played professionally.	-	-	15.2	Pre 1930	-	-
025	B&H	BH338	A	Ba	Boosey and Co	Paired with 024 above Metal liner in top of LHJ. Top hole of RHJ cut through tenon	-	-	15.2	Pre 1930	-	-
026	B&H	BH339	Bb	13	Buffet Crampon	Albert System with metal speaker tube not projecting into bore. Top hole of RHJ cut through lower tenon of LHJ	7.1-7.9	7.2-8.6	15.1	~1930	-	✓
027	KH	KH64	Bb	8	Cramer London	Box and Ivory. 2 keys missing. '2' stamped above Cramer. Integral stock indicating early date (J.B.Cramner) 1799-1805). Possibly extra keys added?	-	-	14.25-14.5	~1800	-	-
029	KH	KH71	Bb	12	Blackman London	Box and Ivory. Brass 'saltspoon' keys in knobs. 'London' pattern mouthpiece. Upper fingered tonehole on both joints cut obliquely.	5.9-6.3	6.5-6.9	13.65	~1820	-	-
030	KH	KH74	Bb	5	Goulding and Co	Box and Ivory with square brass keys. Maker's name and 'London' on bell. Earliest mark used by Goulding.	5.8 – uniform	7.2-7.5	13.9	~1800	-	-

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
031	KH	KH75	Bb	8	Bilton London	Box and Ivory with round brass keys. Barrel has tenon on top with socket in mouthpiece. Keyed toneholes have raised rims.	5.5-6.3	6.4-7.2	13.65	1825	-	-
032	KH	KH339	Bb	13	Gisborne Birmingham	Keys mounted on pillars with two rings on RHJ.	-	-	14.8	? late 19th C	-	-
033	KH	KH441	A	13	Dan Godfrey's Sons	Blackwood Simple System with two rings on RHJ. Made by Harry Godfrey who was formerly employed by Gautrot Aîné in Paris	-	-	14.5	1890-99	-	-
034	LGU	LG7	Bb	6	Goulding and Co. New Bond St	Box and Ivory with square brass keys mounted on rings and knobs. 'London' pattern mouthpiece.	5.8-6.1	6.7-7.3	14.0	1804-11	-	✓
035	ACG	AG 1	Bb	B	Boosey and Hawkes	'Imperial' 926 Model. Chromium plated nickel silver keywork. Made in Edgware, London	5.36-8.54	8.55-9.7	15.0	1956	120763	✓
036	ACG	AG 2	Bb	B	Boosey and Hawkes	'Imperial' 926 Model. LHJ only	5.4-8.4	-	15.0	1953	89836	-
037	ACG	AG 3	Bb	B	U	Cheap plastic student model, probably made in China. Serial no on RHJ only.	5.6-8.8	8.5-9.5	15.0	~1970s	J5269	
038	ACG	AG4	Bb	Bm	H Selmer Paris	'Series 9' Model. 7-ring model but no articulated C# or low Eb. No serial no.	5.7-8.7	8.4-10.0	14.85	1960s	-	-
039	GL	GL1	Bb	B	Buffet Crampon	'S1' Model. Played professionally. Slight reversed cone in LHJ	-	-	14.65	1976	167142	-
040	ANON	AN1	Bb	B	F Hammerschmidt Bergau	Hand-finished clarinet in Cocobolo wood with gold plated keys. Used professionally in Eastern Europe. Slight reversed cone in LHJ	5.5-7.1	7.7-9.5	14.85	Late 20th C	-	-
041	TK	TK1	A	B	Boosey and Hawkes	One of the first '1010' Models made. Played by Fredrick Thurston. Pair with Bb S.No.30256 –split and now restored.	5.0-7.65	8.1-9.22	15.22	~1932	30255	✓
042	TK	TK2	Bb	FB	C Zinzi & C	Full Boehm made in Italy by Orsi. Found in the basement of the Royal Society of Musicians. (Zinzi is not listed as a clarinet maker in Langwill)	-	-	14.65	20th C	-	-
043	CB	CB1	Bb	B	Marigaux	Made in France by Strasser, Marigaux & Lemaire. Best known as oboe makers but also made significant numbers of clarinets	5.5-8.3	8.1-9.7	14.85	1974	1334	✓
044	JP	JP1	Bb	O	Clemens Wurlitzer	Oehler System made in Wernitzgrün, Austria. LHJ heavily reworked by hand to correct tuning	-	-	14.55	1930s	15400	-

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
045	JP	JP2	Bb	B	Selmer Paris	Example of 1920s non-undercut Selmer	-	-	-	1928	8313	-
046	JP	JP3	A	B	Buffet Crampon	Example of 1920s fully undercut Buffet	-	-	-	1928	721	-
047	JP	JP4	Bb	B	Leblanc	Example of 1920s Leblanc with some holes undercut and some not.	-	-	15.15	1920s	828	-
048	JP	JP5	Bb	B	E.J.Albert	Example of undercut Boehm made by Albert of Brussels from 1920s/1930	-	-	15.0	Late 1920s/1930	-	-
049	JP	JP6	A	B	E.J.Albert	Paired with above	-	-	15.05	Late 1920s/1930	-	-
050	JP	JP7	Bb	B	Boosey and Hawkes	Possible prototype for '926' Model launched post WWII. A few undercut holes	-	-	15.0	? late 1930s or post war	36578	-
051	JP	JP8	Bb	B	Buffet Crampon	Recent 'R13' Model. Less undercutting than in earlier example of this model (see below)	-	-	14.65	Late 20th C	8142601	-
052	RCM	326C/1	C	5	Astor and Co.	Box and Ivory with square brass keys	5.5-5.8	6.9	~13.6	Late 19th C	-	✓
053	RCM	RC450	Bb	6	Thomas Cahusac	Box and Ivory with square brass keys	5.9-6.6	6.4-7.0	14.4-14.6	Late 18th C	-	✓
054	RCM	RC451	Bb	6	Clementi and Co.	Box and Ivory with square brass keys. Original boxwood mouthpiece.	5.6-5.9	6.5-6.7	~14.4	Early 19th C	-	✓
055	RCM	RC326C/2	Bb	5	Cramer	Box and Ivory with square brass keys	5.7-6.0	5.7-6.3	~14.2	1805	-	✓
056	TWH	CL028	A	B	F Baron	French made. Wooden body with ebonite barrel	-	-	14.9	Mid 20th C		-
057	TWH	CL150(i)	Bb	B	Boosey and Hawkes	Emperor model. Mass produced middle grade model introduced after WW2 based on '926' design	–	–	15.1	1960/70s	521693	-
058	TWH	CL150 (ii)	A	B	ditto	Emperor. Paired with above	-	-	15.08	1960/70s	516452	-
059	TWH	CL154	Bb	B	Selmer Paris	'Recital' model	–	–	~14.6	? 1980s	C9162	-
060	TWH	Cl203(i)	Bb	B	Peter Eaton	'International' model. Contemporary English maker	-	-	14.8	? 1980s	S143	-
061	TWH	Cl203(i)	A	B	Peter Eaton	Paired with above	-	-	14.75	? 1980s	S131	-
062	TWH	CL212(i)	Bb	B	Selmer Paris	'Series 9' model. See also C36 above			14.8	1960/70s	5629	-
063	TWH	CL212i(i)	A	B	Selmer Paris	'Series 9'. Paired with above			15.0	1960/70s	-	-
064	TWH	CL224(i)	Bb	B	Selmer Paris	'Series 10S' model.	-	-	14.6	1980s	F1997	-
065	TWH	CL224(ii)	A	B	Selmer Paris	'Series 10S'. Paired with above			14.6	1980s	D9391	-
066	TWH	CL229	A	Bm	Leblanc France	Basset-clarinet as manufactured by Leblanc in Paris. Extra RH little finger and R thumb keys for basset notes	-	-	14.7	? 1980s	110	-
067	TWH	CL232	Bb	B	Leblanc France	'Dynamic' model	-	-	15.0	From 1958	40108	-

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
068	TWH	CL237(i)	Bb	B	Boosey and Hawkes	'Edgware' model Post Emperor. Mass produced middle grade model introduced after WW2 based on '926' design	-	-	15.0	Mid 1980s	266113	-
069	TWH	CL237(ii)	A	B	Boosey and Hawkes	'Edgware'. Paired with above	-	-	15.0	1988	305308	-
070	TWH	CL248(i)	Bb	B	Louis Rossi	Contemporary Chilean maker. Small scale production professional instruments. Single piece bodies. 'English' model based on B&H 1010	-	-	15.2	1980/90s	–	-
071	TWH	CL248(ii)	A	B	Louis Rossi	Paired with above	-	-	15.2	1980/90s	-	-
072	TWH	CL254	Bb	B	Leblanc	'Noblet Artiste' model. Student clarinet	-	-	14.6	1980s	891663	
073	TWH	CL259(i)	Bb	B	Boosey and Hawkes	'1010' Model. Post war With 'Acton vent' Oversized bore.	-	-	15.37	1974	387849	
074	TWH	CL259 (ii)	A	B	Boosey and Hawkes	'1010'. Paired with above. Also Acton vent' and oversized bore.	-	-	15.37	1975	415768	
075	TWH	Cl261(i)	Bb	B	Peter Eaton	'International' model. See C61	-	-	14.8	? 1980s	S127	
076	TWH	Cl261(i)	A	B	Peter Eaton	'International'. Paired with above	-	-	14.8	? 1980s	S130	
077	TWH	CL269(i)	Bb	B	Buffet Crampon	'R13' model. Earlier example than C51 above	-	-	14.65	? 1970	458885	
078	TWH	CL269(ii)	A	B	Buffet Crampon	'R13'. Paired with above	-	-	15.2	? 1970	454674	-
079	TWH	CL3249(i)	Bb	B	Boosey and Hawkes	'1010' Model. Post war Bore close to specified size.	-	-	15.30	1979	488525	-
080	TWH	CL324i(i)	A	B	Boosey and Hawkes	'1010'. Paired with above. Bore close to specified size.	-	-	15.44	1979/80	496898	-
081	TWH	CL838	Bb	B	Buffet Crampon	'Elite' model. Redesigned Wood cut away and hole positions moved.	-	-	14.65	Recent	379371	-
082	TWH	CL237(i)	Bb	B	Boosey and Hawkes	'Edgware' model Post Emperor. See CLT068 above	-	-	14.92	mid 1980s	551690	-
083	TWH	CL237(ii)	A	B	Boosey and Hawkes	'Edgware'. Paired with above		-	15.1	mid 1980s	543463	-
084	TWH	CL952	Bb	B	'Musical'	New York import from France. Higher quality model	-	-	14.75	Post war ?	-	-
085	TWH	CL953	A	B	Cabart	French maker specialising in oboes.	-	-	14.75	Post war ?	-	-
086	TWH	SR1	Bb	B	Howarth	'S2' model. Latest Howarth design (current), made in England. Brand new.	-	-	14.73	1990s	2104	-
087	TWH	SR2	Bb	B	Leblanc	'Opus'. Model. Brand new.	-	-	14.65	1990s	77074	-
088	KP	KP1	Bb	B	Boosey and Hawkes	'1010' Model. Pre-war. Ebonite body. Need long barrel to tune correctly.	5.0-8.0	8.15-9.5	15.24	1936	32536	-

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
089	KP	KP2	Bb	B	Boosey and Hawkes	'1010' Model. Pre-war Still played professionally	5.1-8.0	8.05-8.7	15.24	1935/66	32088	-
090	KP	KP3	C	13	Lefevre a Paris	Box and Ivory. Domed brass keys in pillars with mounting plates screwed to body. Threaded steels	5.9-6.3	6.6-6.7	14.0	~1850 or later	-	✓
091	KP	KP4	Bb	13	Buffet a Paris	Box and Ivory. Domed brass keys in pillars with mounting plates screwed to body.	6.2-7.1	6.4-7.0	14.8	~1840	-	-
092	KP	KP5	C	6	Baumann a Paris	Box and Ivory. Square brass keys Separate stock	5.7-5.9	5.8-6.1	14.25	Early 19th C	-	
093	KP	KP6	Bb	B	Martel	Stamped 'Hawkes and Son. Imported from France. These instruments became highly sought after by professional players.	5.0-7.8	7.4-8.5	15.0	1900-14	4590	✓
094	KP	KP7	A	B	Martel	Paired with above. Used by Reginald Kell for his 1930s recordings	4.7-7.6	6.5-8.8	14.9	1900-14	3983	✓
095	KP	KP8	Bb	B	Martel	See above. One of pair played by the English clarinettist Fredrick Thurston until the early 1930s	5.1-8.0	7.5-9.0	14.95	1900-14	2093	✓
096	KP	KP8	A	B	Martel	Paired with above	4.6-7.7	7.4-8.7	14.85	1900-14	2096	✓
097	KP	KP9	D	2	P.G.Wietfelt	Boxwood with square brass keys. Single piece body with long bell section. Replica has been made which plays at A=415Hz	4.55-4.64	5.1-5.6	12.8 - 12.9	Second half 18th C	-	-
098	KP	KP10	Bb	5	Mousetter a Paris	Box and Ivory with square brass keys	5.6-6.3	6.2-6.4	14.4	Late 18th C	-	
099	NS	NS1	Bb	5	Cahusac London	Box and Ivory with square brass keys. Integral stock	5.6-5.8	5.2-6.1	14.2	~1785	-	-
100	NS	NS2	Bb	6	Hale London	Box and Ivory with square brass keys. Integral stock	5.1-5.2	4.9-5.9	14.15	~1790	-	-
101	NS	NS3	Bb	5	Miller London	Box and Ivory with square brass keys. Separate stock.	5.25-5.55	5.7-5.9	14.4	~1795	-	-
102	NS	NS4	Bb	5	Doleisch Prague	Box and Horn with square brass keys. Integral stock Date stamped.	5.4-5.7	5.8-6.2	14.0	1793	-	-
103	NS	NS5	A	4	G A Rottenburgh	Dark brown wood with one Ivory ring. . Integral stock	5.8-6.3	5.0-7.0	14.45	~1760	-	-
104	NS	NS6	Bb	5	Theodore	Box and Ivory with square brass keys. Integral stock	5.8-5.9	5.6-6.1	15.0	Pre 1789	-	-
105	NS	NS7	Bb	6	Baumann a Paris	Box and Ivory with square brass keys. Separate stock.	5.7-5.9	6.0-7.0	14.5	~1800	-	-

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
106	NS	NS8	Bb	13	Cramer and Key	Box and Ivory with rectangular brass keys.	6.0-6.3	7.0-7.2	14.1	1805-07		
107	NS	NS9	Bb	10	H Grenser Dresden	Box and Ivory with rectangular brass keys.	5.7-6.0	5.6-6.5	14.4	~1810		
108	NS	NS10	Bb	13	Key of London	Box and Ivory with hallmarked silver keys. Four saddles.	5.7-6.3	7.0-7.4	14.4	1834	-	-
109	NS	NS11	C	B	Buffet Jeune	Boxwood with brass saltspoon keys. Early Boehm example.	5.3-9.1	7.8-9.5	15.0	~1850	-	-
110	NS	NS12	A	B	Buffet crampon	Blackwood with brass saltspoon keys.	5.5-8.0	8.2-9.2	15.0	Pre1859	-	-
111	NS	NS13	Bb	Bm	Buffet crampon	Blackwood with brass saltspoon keys. Novel keywork features. Possibly experimental design.	5.1-8.9	7.7-8.8	14.8	Pre 1859 (earlier than above)	-	-
112	NS	NS14	Bb	B	Martel Frère	Stamped' Martel' c.f. Hawkes imported Martels Barrel integral with top joint (see below)	5.1-8.2	7.9-9.0	14.95	Pre 1914	-	-
113	NS	NS15	Bb	B	Buffet Crampon et Cie	Barrel integral with top joint. Some toneholes lined with brass sleeves.	5.1-8.1	7.7-8.9	14.8	1859-85	-	-
114	NS	NS16	C	B	Buffet Crampon et Cie	Barrel integral with top joint. Some toneholes lined with brass sleeves.	-	7.6-9.6	14.7	1859-85	-	
115	TK	TK3	Bb	B	Boosey and Hawkes	Pre war '1010' used professionally. 'LP' after S.No .signifying 'London and Paris' model	-	-	15.2	1935	31185	-
116	ACG	AG5	A	B	Boosey and Hawkes	Imperial '926' model paired with [CLT035]				1956	120774	-
117	ACG	AG6	Bb	B	Boosey and Hawkes	Imperial '926' model silver plated keys				1959	150441	-
118	ACG	AG7	A	B	Boosey and Hawkes	Imperial '926' model paired with above				? 1959	179373	-
119	ACG	AG8	Bb	B	Selmer Bundy (USA)	Plastic student model (used for playing tests)	5.6-8.4	8.5-9.6	15.05	Post WW2	125165	-
120	ACG	AG9	Bb	B	Selmer Bundy (USA)	Plastic student model (used for playing tests)	5.6-8.4	8.56-9.7	15.05	Post WW2	165444	-
121	ACG	AG10	Bb	B	Selmer Bundy (USA)	Plastic student model (used for playing tests)	5.5-8.46	8.78-9.7	15.05	Post WW2	366560	-
122	ACG	AG11	Bb	B	Selmer Bundy (USA)	Plastic student model (used for playing tests)	5.6-8.4	8.5-9.8	15.05	Post WW2	579756	-
123	ACG	AG12	Bb	B	Selmer Bundy (USA)	Unnumbered top joint only	5.6-8.4	-	15.05	Post WW2	-	-
124	ACG	AG13	Bb	B	Selmer Bundy (USA)	Older wooden version	5.6-8.4	8.6-9.7	15.05	Post WW2	91009	-
125	ACG	AG14	Bb	B	Artley (USA)	Various '18S'model. Plastic undercut examples	5.0-7.8	7.7-9.4	14.5	1980s	various	-

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
126	ACG	AG15	Bb	B	Pennant (USA)	Wooden body without undercutting	5.5-8.6	8.8-10.1	14.85	Post WW2	W3865	✓
127	ACG	AG16	Bb	B	Jean Barre	French made. Ebonite body with un-plated nickel silver keywork	5.3-8.2	8.0-9.9	14.85	? pre WW2	5009	-
128	ACG	AG17	Bb	B	Boosey and Hawkes	'2-20' model made for the American market incorporating Reginald Kell design features including reversed cone in LHJ	5.0-8.2	8.1-9.5	14.85	1960-65	242705	-
129	ACG	AG18	Bb	B	Leblanc	'Normandy' model made in USA. Plastic body with 'in-line' trill keys.	5.2-8.3	8.0-9.2	14.85	Post WW2	9210	-
130	ACG	AG19	Bb	B	M Dupont	Generic name for French-made clarinets imported into USA by Sears Roebuck & Co. Wood body.	5.0-8.6	7.9-9.6	14.65 rev cone	Post WW2	12750	-
131	ACG	AG20	Bb	B	Buffet Crampon	'Evette Master' model. R13 'seconds' rejected for cosmetic rather than acoustic faults.	5.2-7.8	7.6-9.1	14.65	1960s	D25392+ C5347	-
132	ACG	AG21	Bb	B	Selmer (USA)	'Studente Console' model. Wood. (USA logo but marked' London Foreign')	4.9-7.7	7.3-8.7	14.95	1960s	-	-
133	ACG	AG22	Bb	B	Selmer (USA)	'Console' model. Plastic. As above	-	-	-	1960s	-	-
134	ACG	AG23	Bb	B	Leblanc	'Vito Reso-Tone 3' model. Plastic	5.3-8.2	8.0-9.3	14.9	1980s	-	-
135	ACG	AG24	Bb	B	Rene Dumont	'Artist' model made in France. Wood.	5.5-8.5	8.7-9.4	15.05	Post WW2	15223	-
136	ACG	AG25	Bb	B	Kraftsman	American make. RHJ only. Die cast keys. Wood	-	8.8-10.3	15.2	Post WW2	906080	-
137	ACG	AG26	Bb	B	Yamaha	Samples of 'CX' model top joints. Wood.	-	-	-	1980s ?	-	-
138	ACG	AG27	Bb	B	Yamaha	Samples of '34II' model top joints. Wood.	-	-	-	1980s ?	-	-
139	ACG	AG28	Bb	B	Selmer (USA)	2 Samples of 'Signet' model RHJs Both wood. Not undercut.	-	8.6-9.7	14.8 14.9	Post WW2	-	-
140	ACG	AG29	Bb	B	Leblanc	'Normandy' model made in USA. RHJ only. Plastic body	-	-	-	-	-	-
142	B&H	BH247	Bb	B	Rudal Carte (made by B&H)	'Super Graduate' model.	5.4-8.5	8.3-9.6	15.1	Pre 1955	546917	✓-
143	B&H	BH248	Bb	B	Boosey and Hawkes	'1010' model with Acton vent. Metal sleeved C#/G# tonehole.	4.9-8.1	7.7-9.7	15.24	1981	539123	✓
144	ACG	AG31	Bb	B	The Pedlar Co USA	Intermediate grade instrument with silver plated keywork. RH ring keys fitted close to body with B/F# key passing over the ring axel. Made in Elkhart USA	5.4-8.2	8.3-9.2	14.95	Post WW2	P18303	✓

1	2	3	4	5	6	7	8	9	10	11	12	13
CLT	Source	Ref	Pitch	Keys	Maker	Description	LH	RH	Bore	Date	Ser. No.	Flare
145	JP	JP9	A	B	Selmer Paris	Example of 1920s non-undercut Selmer. Paired with [Clt 045] serial no. 8313	-	-	-	1928	8618	-
146	AC	AC1	Bb	B	Boosey and Hawkes	'1010' model post war	5.3-8.0	8.4-9.7	15.24-15.28	1964	250667	-
147	AC	AC2	A	B	Boosey and Hawkes	'1010' model post war	-	-	15.25	1964	244967	-
148	ACG	AG31	Bb	BMazzeo	Selmer (USA)	Plastic Bundy model with Mazzeo system	5.6-8.4	8.6-9.8	14.05	1960s	526433	-
149	EP	EP1	Bb	B	Louis	Allegedly based on Martel model by Charles Draper	5.3-8.1	7.7-9.0	14.75	1921	119	-
150	EP	EP2	A	B	Louis	Matched pair with above	5.2-8.0	7.8-9.0	14.90	1921	118	-
151	NS	NS17	Bb	12	E Albert	High pitch. Imported by Chappel with Jullien marking.	6.8-7.1	7.6-8.3	15.2	1862-66	-	-
152	NS	NS18	Bb	12	E Albert	High pitch. Imported by .S.A.Chappell	7.1-7.4	7.0-8.3	15.0	1871-1901	-	-
153	NS	NS19	Bb	B	Boosey and Hawkes	Ebonite pre war '1010' Marked 'LP' but plays sharp.	-	-	-	1937-8	33934	-
154	NS	NS20	Bb	B	Selmer (Paris)	Excellent example of non-undercut quality instruments	-	-	14.88	1920s	6208	✓
155	NS	NS21	A	B	Selmer (Paris)	Paired with above	-	-	-	1920s	7227	✓
156	NS	NS22	Eb	13	Martel	Barrel shortened to raise pitch	-	-	-	~1900 ?	-	-
157	JB	JB1	Bb	B	Yamaha	Model AE. Integral tonehole inserts.	-	-	-	1991	01050	-
158	JB	JB2	A	B	Yamaha	Model AE. Integral tonehole inserts.	-	-	-	1999	01012	-
159	LF	LF2	Bb	B	Boosey and Hawkes	Post-war 1010	-	-	-	1981	551535	-
160	LF	LF3	A	B	Boosey and Hawkes	Post-war 1010	-	-	-	1981	505244	-
161	NS	NS23	Bb	B	Selmer (Paris)	1920s 'K'series	-	-	14.95	1920s	2298	-
162	NS	NS24	Bb	B	Selmer (Paris)	~1930 'L' series. 'RI' – Radio Improved	-	-	15.0-	~1930	L406	-
163	NS	NS25	A	B	Selmer (Paris)	as above	-	-	14.9	~1930	L***	-
164	JP	JP9	Bb	B	Buffet	1930s light u/c LHJ, moderate u/c RHJ	5.4-7.5	7.7-9.1	14.85	1930s	18540	-
165	JP	JP10	Bb	B	Selmer (Paris)	Not undercut	5.2-8.9	8.1-9.6	14.75	1920s	4601	-
166	JP	JP11	Bb	B	Boosey and Hawkes	1010 model made immediately before WWII	4.7-8.0	7.7-9.1	15.24	1939/45	35279	-
167	NS	NS26	Bb	12+1	Stengal (Reyreth)	Muller pattern with RH thumb key	6.9-7.0	7.2-7.4	14.65	2nd Q 19C	-	-
168	NS	NS27	Bb	14+1	Guerre, Georges (Paris)	Muller pattern with RH thumb key	6.0-6.9	6.3-7.3	14.7	2nd Q 19C	-	-
169	NS	NS28	Bb	13	Godfroy Aine (Paris)	Muller pattern without RH thumb key	6.5	6.9-7.0	14.8-14.65	2nd Q 19C	-	-
170	NS	NS29	Bb	B	Buffet (Paris)	Ebonite body. Register hole at front.	5.3-8.0	8.1-10.0	14.9	1930	4675	-

Source key.

Code	Owner/ Location
AC	Alison Carter. Privately owned. St Albans
ACG	Author. Middlesex
ANON	Anonymous. International soloist. Hungary
B&H	Boosey and Hawkes Museum formerly in Edgware
CB	Clare Byrn. Hertfordshire
EP	Dr Edward Pillinger. Middlesex
GL	Gordon Lewin. Middlesex
JB	Joy Bell. St Albans
JP	Prof. John Playfair. London
KH	Kneller Hall Museum. Twickenham
KP	Keith Puddy. London
LF	Les Fielding. St Albans
LGU	London Metropolitan (formerly Guildhall) University
NS	Prof. Sir Nicholas Shackleton. Cambridge
RCM	Royal College of Music Museum. London
TK	Dame Thea King. London
TWH	Howarth of London. Clarinet manufacturer and retailer. London

Part 3 Acoustic Measurements of the Effects of Undercutting and Playing Tests

3.1. Introduction.

Whilst the mechanism of the Boehm system clarinet has remained essentially unchanged, the acoustic quality has by and large progressively improved, especially in the second half of the twentieth century. This is due in some part to a better understanding of the physical processes taking place in the instrument and in particular of the effects slight bore perturbations have on tuning. Makers now have a better basis for design which can complement the empirical approach traditionally used.

As well as the bore shape there are many other factors which contribute to the acoustic quality of a clarinet. These include the mouthpiece design, the tonehole sizes and positions relative to the bore size (which determine the cut-off frequencies) and the internal surface finish. When studying the effects of undercutting, any interactions with these factors must be considered.

The data collected in Part 2 shows that makers throughout the history of the clarinet have invested considerable time and expense in undercutting toneholes. In the absence of a model to explain the exact effect undercutting has on the behavior of the instrument, undercutting has been carried out empirically, even to the present day. The fact that instruments highly regarded by players have been made without undercutting raises questions about the significance of its role in the overall design.

Against this background, a number of experiments have been devised to test some important aspects of undercutting under conditions which are controlled, as far as it is possible.

The first section examines the effects of undercutting a single hole. This process is well known as a means of adjusting the frequency ratios between registers in woodwind instruments. In particular the effects of asymmetrical cutting are investigated.

The second section describes experiments to determine whether low-power acoustic input impedance spectra can detect changes in mode alignment as a result of undercutting. Improved mode alignment should result in a more responsive instrument, and this method of final adjustment was traditionally used empirically by skilled technicians. Benade enthusiastically endorsed this technique (he called it 'sweetening' a clarinet) and implied that impedance spectra could be used to monitor its application. In the experiments described in the final section, a number of clarinettists were invited to play clarinets which had been specially prepared. One had sharp-edged, non-undercut toneholes; one was conventionally undercut; and the third had had all of the internal edges at the tonehole intersections with the bore smoothed off. The players' responses to these instruments were recorded and the results analysed.

3.2 Pitch Effects of Undercutting a Single Hole

3.2.1 Objective

On the Boehm clarinet, the first left-hand fingerhole is the first open hole for the notes F_4 (at the top of the chalumeau register) and, with the register hole open, C_6 (at the top of the clarinet register). Because of the acoustically unsatisfactory placement and size of the register hole for these notes, there is a tendency in some clarinets for the interval between these notes to be wide, (i.e. greater than a twelfth), in most cases because F_4 is flat. In the Boehm design this hole is deliberately made small as it also serves as a secondary register hole for the fifth harmonic notes (i.e. $C\#_6$ upwards).

When the lower note is flat, clarinet repairers commonly selectively undercut, or increase the undercutting of this hole, in an attempt to narrow the interval. Often this undercutting is performed asymmetrically, with the aim of raising the pitch of the lower note whilst minimising pitch rise of the upper note. Some clarinet technicians claim that sideways asymmetrical undercutting is an effective means of achieving this objective. Examples of this type of adjustment were observed during the survey, (e.g. [CLT067]).

Whereas there is a physical argument which can be used to predict that upstream and downstream undercutting will have different effects, **[Nederveen** 1998] there is no clear reason why lateral undercutting should be effective. Hence this experiment has been devised to measure the effects on pitch of undercutting this hole in various ways.

3.2.2 Experimental Clarinet (EC1).

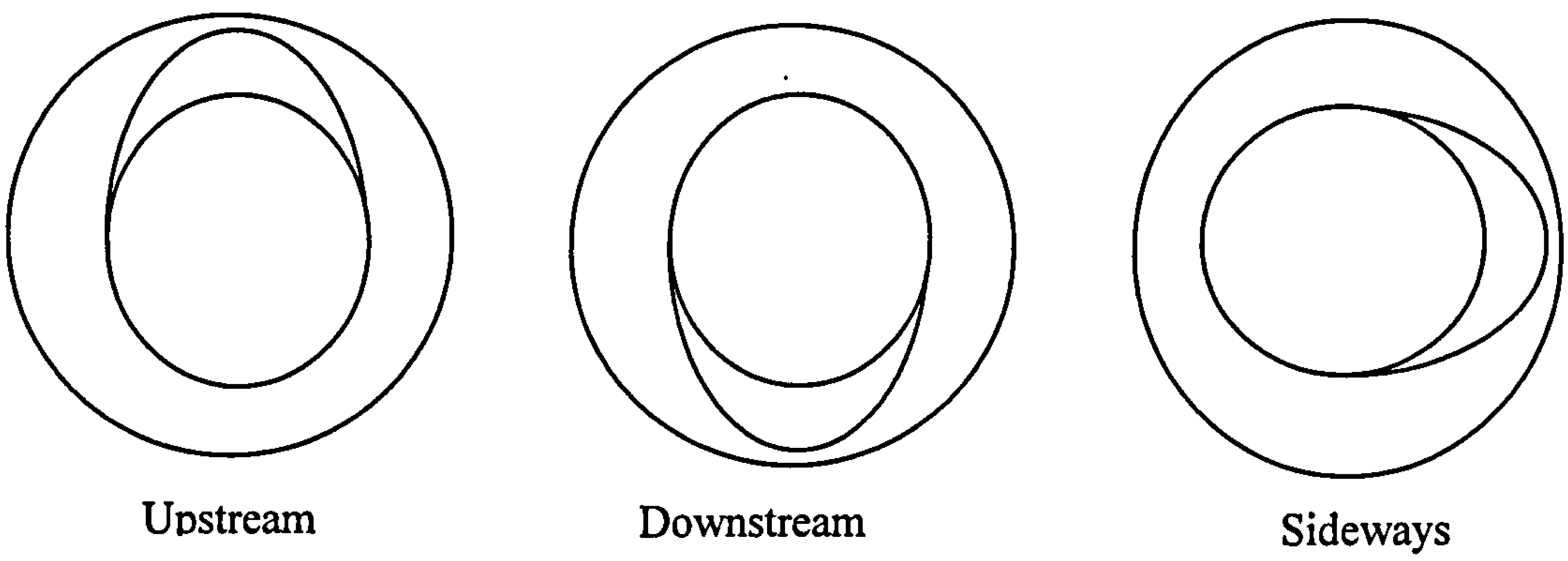
An experimental clarinet (EC1) was constructed using the top joint of a Yamaha 34 II Boehm system clarinet in which the left-hand, first-finger tonehole of was removed by counter-boring so that alternative replacement toneholes could be inserted. A set of five Delrin inserts was prepared, all with the same hole diameter and chimney height as the original tonehole but:

1) asymmetrically undercut upstream only
2) asymmetrically undercut downstream only
3) straight sided
4) asymmetrically undercut to one side only

5) symmetrically undercut with a 20° semi-angle fraise through ~ one third of wall thickness

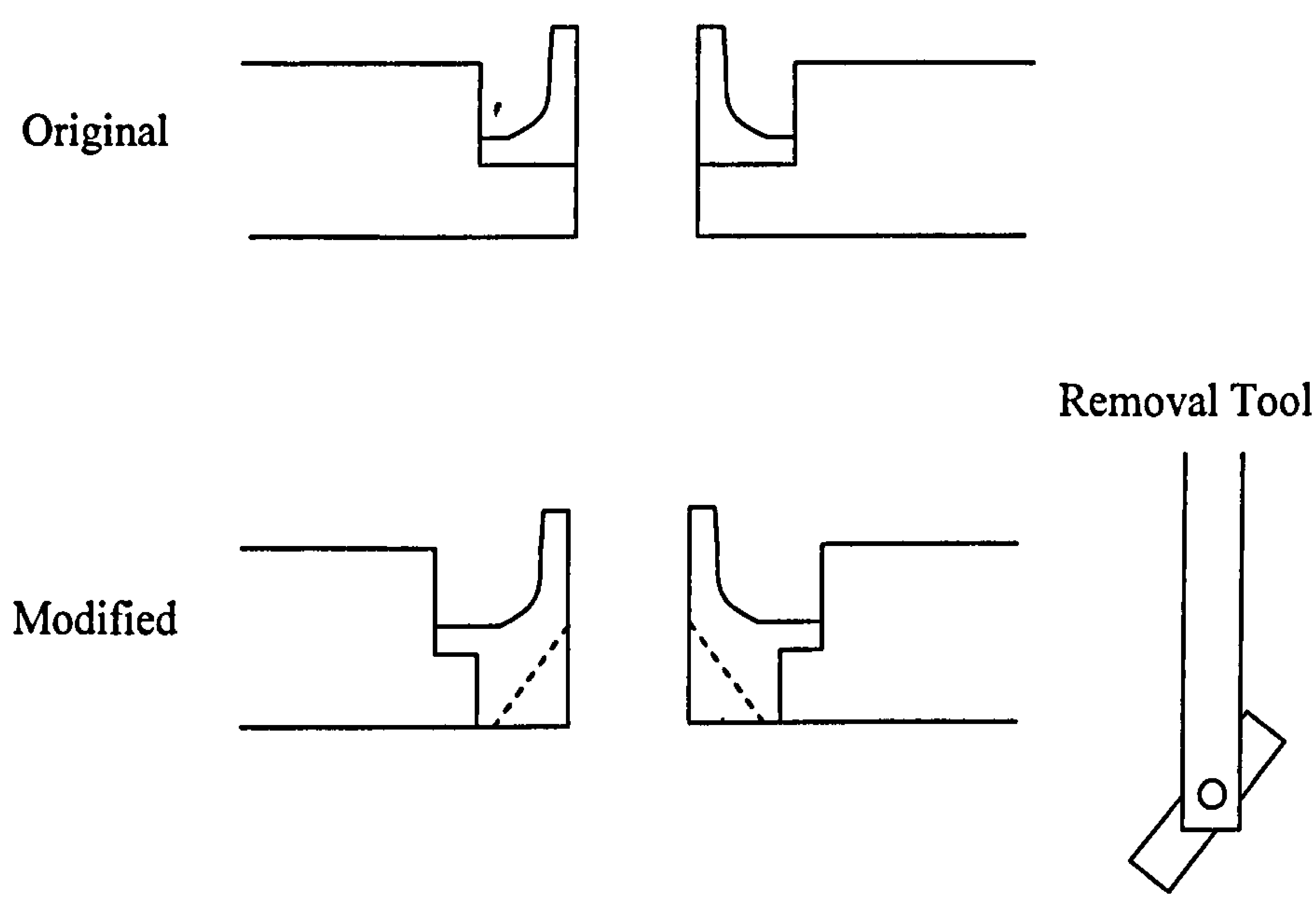
Equal amounts of material were removed from the upstream, downstream and sideways inserts (1, 2 and 4), equivalent to approximately 8.5 % of the cylindrical hole volume. A spread within ± 2% was achieved. The material removed with the fraise (5), represented approximately 50% of the original hole volume, i.e. approximately six times the volume removed in the asymmetric undercuts.

Target Shapes for Asymmetrical Undercutting:



The volumes were calculated from the known density of Delron (1.42 g/cm^3) and the weight changes on undercutting.

The original and modified tonehole are shown below:



The inserts form an air-tight push fit into the counter-bore and the inner end of each insert was cut in situ with a bore reamer, to match the bore profile accurately.

The ring key for the first fingerhole, (operated by the thumb ring for F_4 and C_6), was removed, and the associated tonehole closed with a pad attached to a specially made key, closed with a spring. This avoids having to remove three keys in order to change inserts and saves considerable time. Each insert was scribed with an indexing mark to assist alignment with the bore axis. A tool with a swivel bar was constructed to aid removal of the plugs as shown in the sketch above..

The Yamaha top joint was attached to a compatible bottom joint (EXP R F10711) and a Boosey and Hawkes conical pattern bell attached.

3.2.3 Pitch Measurements under Playing Conditions.

The task of playing the notes F_4 and C_6 and measuring their frequencies appears at first sight to be trivial. In reality, there is a considerable degree of pitch flexibility for both notes, especially the upper, and an experienced player, after having established the lower note, will attempt to play the upper note 'in tune' relative to the lower.

To avoid this complication it was decided to perform the test using an 'artificial mouth' to play the instrument.

Initially the artificial mouth designed and constructed for the study of mouthpiece characteristics [**Pillinger** Thesis 2000] was tried, and a number of minor modifications were made to it to improve the reproducibility. Having carried out some initial tests with this equipment, it was decided to construct a new artificial mouth designed specifically for this and subsequent experiments.

The basic construction remained the same (including the artificial tongue) but the following features were added:

(i) A mirror was attached to the rear wall of the enclosure to make it easier to check the parallelism between the reed and the artificial 'lip'.

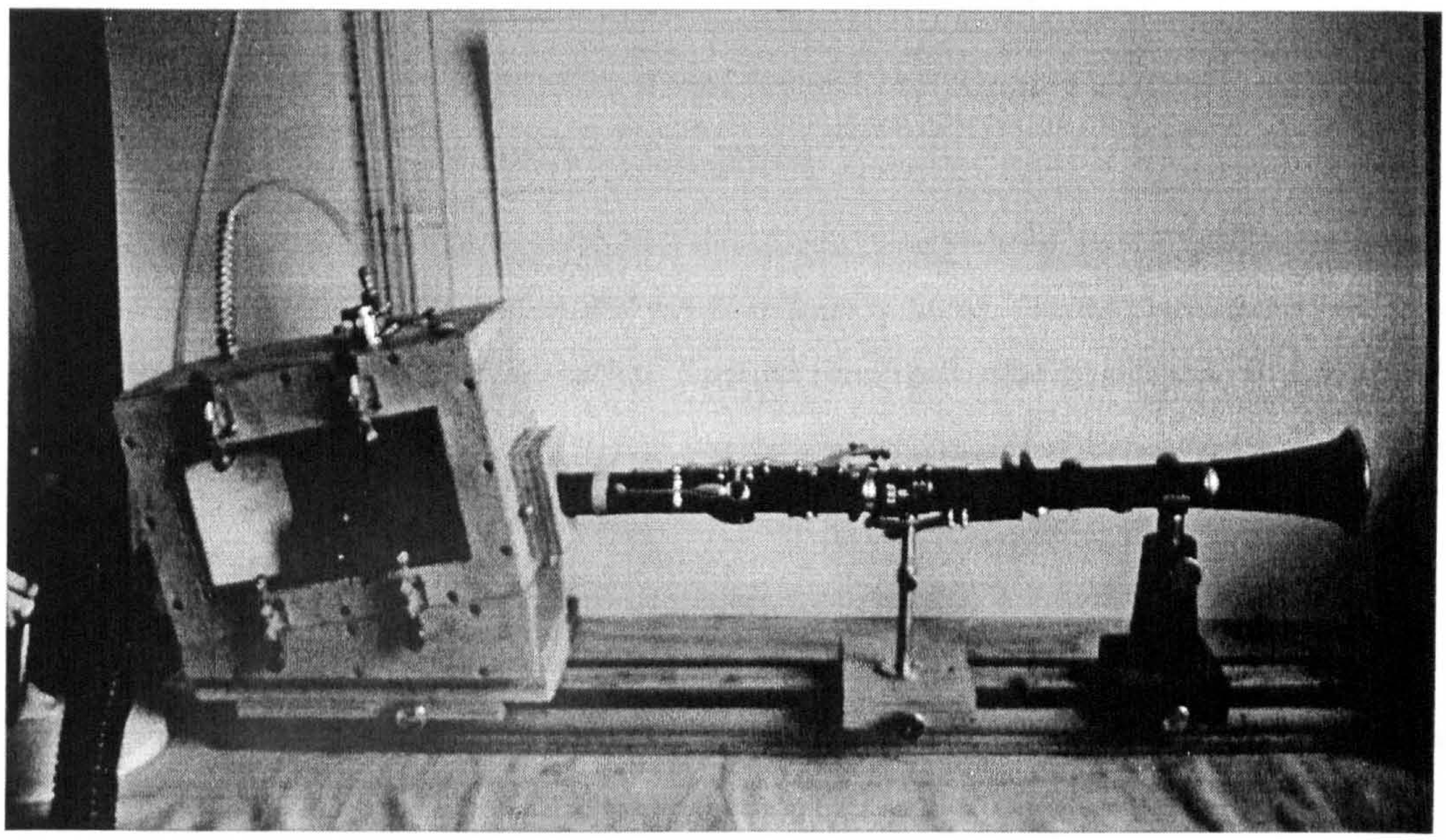
(ii) The air supply was adjusted with a needle valve so that finer control of the pressure in the enclosure could be achieved.

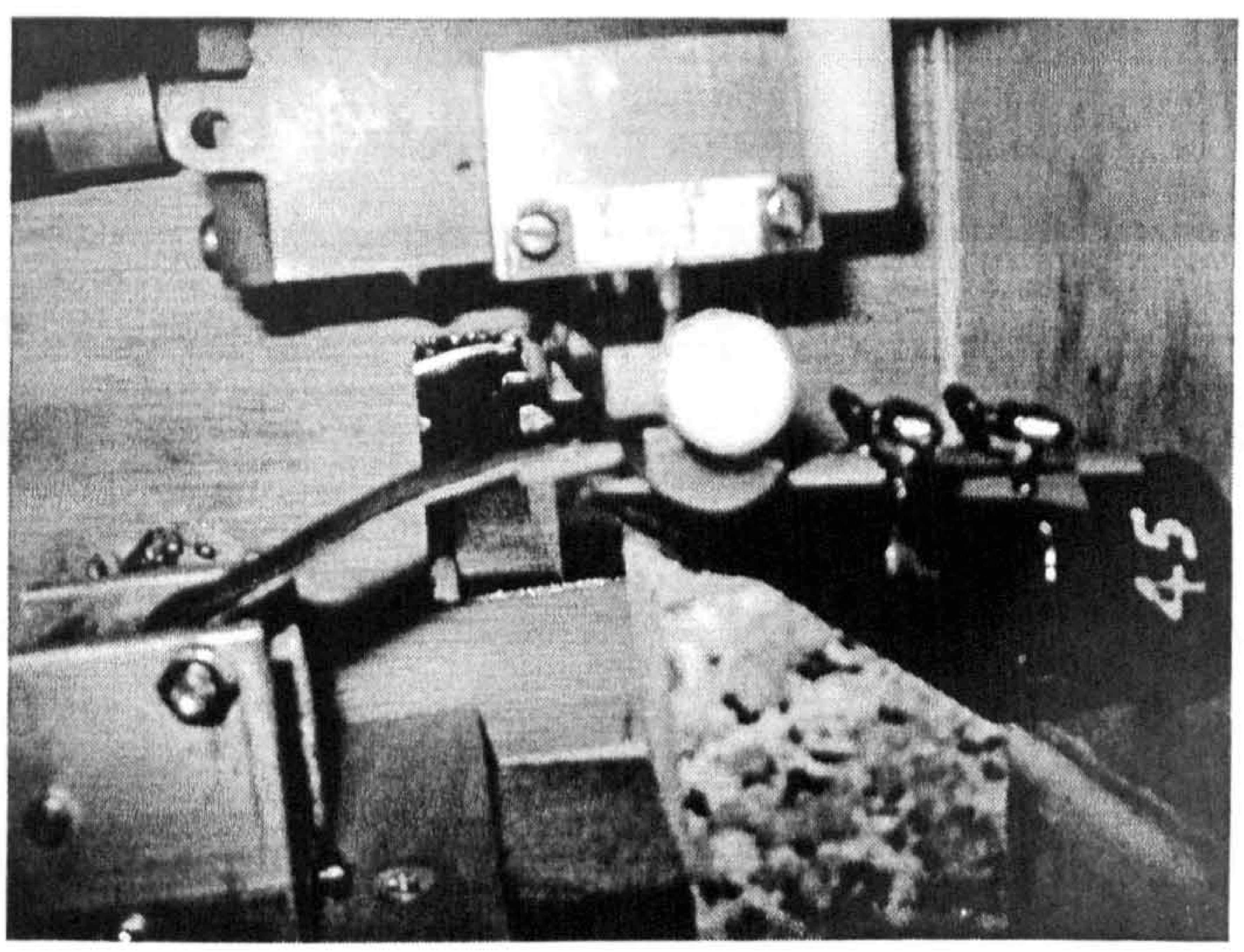
(iii) The artificial lip was mounted on a micrometer-driven x-z manipulator for accurate positioning..

(iv) The enclosure was tilted (~8°) so that, with the clarinet horizontal, the point of contact of the lip was perpendicular to the axis of the manipulator, which was aligned with the enclosure (see Photographs). Small adjustments of the distance of the lip from the mouthpiece tip can then be made without causing large changes in lip pressure.

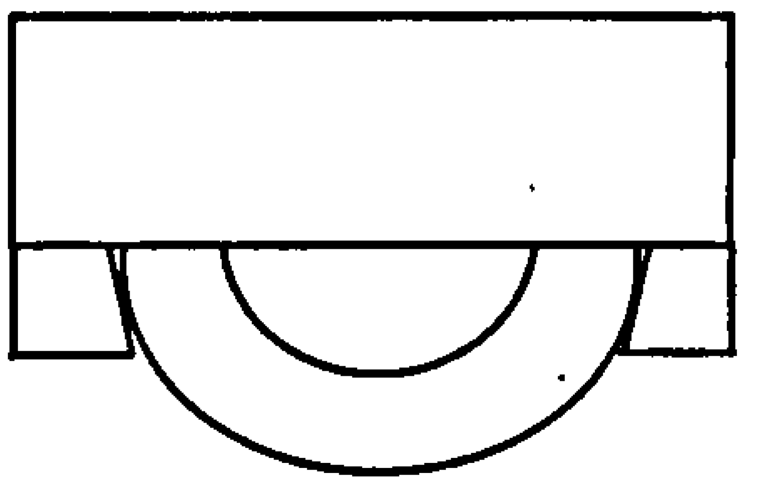
(v) A baffle with an acoustic absorber was added to the chamber to reduce blower noise transmitted through the hose, and to distribute the air flow evenly within the chamber.

(vi) The enclosure was mounted on a sturdy cast iron optical bench. The clarinet was then supported rigidly with two adjustable supports clamped to the bench. This was necessary to allow the plugs to be removed and inserted without disturbing the 'artificial embouchure'.





The apparatus was found to be critically dependant on the shape and material of the artificial lip. After some experimentation, good results were achieved with a cast plastic sheet material with a Shore A hardness of 20, clipped into a metal channel attached to the manipulator:



Pitch measurements were made with a Korg Model DT1 Tuning Meter operating in 'Slow' mode. The meter was calibrated against digitally synthesised sine waves and was found to be accurate. In practice it was found to be possible to measure the frequency to within +/- one cent with this meter.

The method used was to set up a mouthpiece and reed and establish settings of lip pressure, lip position and mouth pressure which gave good 'clarinet' quality sounds for both notes at a moderate '***mf***' dynamic. Natural reeds gave the best sound but needed to be wetted and subsequently dried out during the course of long measurements. As in the Pillinger work, a satisfactory solution was to use a soft 'Plasticoat' reed. This is a natural reed coated with a black plastic material which plays when dry.

With each insert in place, three pitch measurements were made: G_3, and the test notes F_4 and C_6. G_3 uses a longer tube length and its pitch was used to monitor any drifts due to temperature variations or other causes occurring during the measurement time. In practice it was found that the range over which G_3 varied was only 3 cents, but the measured frequencies of the test notes were adjusted to correct for this measured drift.

A comparison was made between results obtained with the reed stopped by the artificial tongue whilst the inserts were exchanged, and with the reed vibrating continuously throughout the experiment. It was found that both techniques gave similar results but that the spread in measurements was slightly larger when the reed was stopped. Hence the latter technique was adopted in the results given below.

3.2.4 Results.

The results shown are averaged values for five complete cycles of exchanging the set of tonehole plugs, corrected to constant G_3 pitch (as described above). The results were obtained during a continuous series of measurements, with the reed vibrating continuously. The 'embouchure' was maintained constant throughout and the pressure stayed constant at 12.0 inches of water (30 mbar). The intensity was assessed subjectively as *mezzo forte* in playing terms. Note pitches are shown as cents deviation from equally tempered notes, based on A = 440 Hz

The plugs (as identified in Section 3.2.2) were cycled in the order: 3 – 4 – 5 – 1 – 2

Cycle	F_4	C_6	Spread (twelfth +cents)
1	-2	+7	+9
	-6	+10	+4
	+21	+21	0
	+9	+11	+2
	+3	+10	+7
2	+2	+7	+5
	+3	+8	+5
	+21	+21	0
	+8	+13	+5
	+6	+10	+4
3	+2	+8	+6
	+3	+9	+6
	+20	+21	+1
	+10	+12	+2
	+3	+10	+7
4	0	+7	+7
	+3	+9	+6
	+19	+20	+1
	+8	+12	+4
	+4	+9	+5
5	-2	+6	+8
	+2	+8	+6
	+19	+20	+1
	+9	+10	+1
	+5	+11	+6

Effect on twelfths:

Plug	1 Up	2 Down	3 Not u/c	4 Side	5 Cone
Ave cents	+2.8	+5.8	+7.0	+5.4	+0.6

Effects on Pitch:

F4

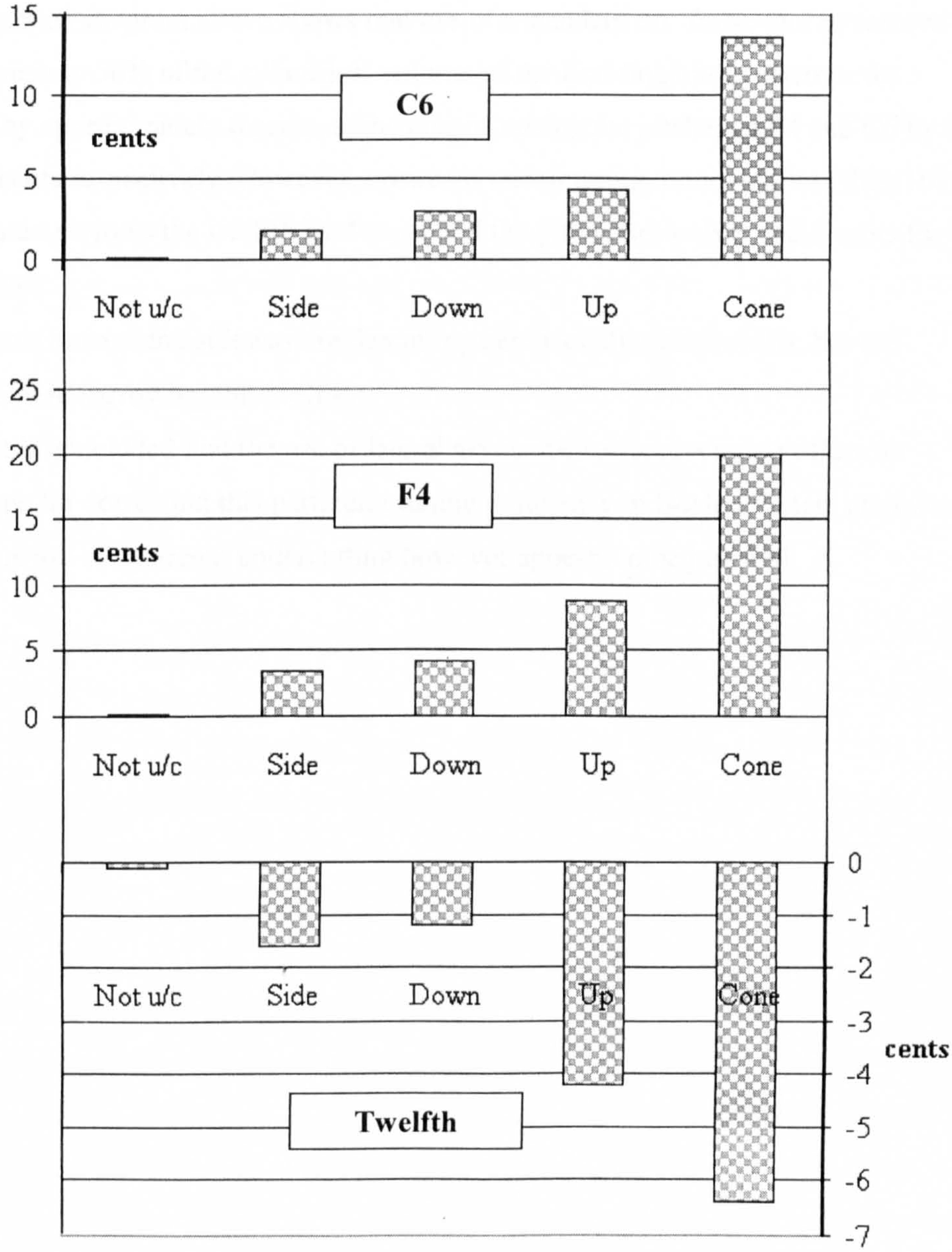
Plug	1 Up	2 Down	3 Not u/c	4 Side	5 Cone
Ave cents	+8.8	+4.2	0	+3.4	+20

C6

Plug	1 Up	2 Down	3 Not u/c	4 Side	5 Cone
Ave cents	+11.6	+3.0	0	+1.8	+13.6

Summary of asymmetrical undercutting:

Effects of Undercutting First Left-Hand Fingerhole



Finally the acoustic input impedance spectra were measured for the note F_4 These results are given later in Section 3.3.4.

3.2.5 Conclusions

The summary diagram above shows that use of a standard 20° fraise tool to remove approximately 50% of the cylindrical volume of the first fingerhole narrows the twelfth by approximately 6 cents, at the cost of raising the pitches of F4 and C6 by 20 and 14 cents respectively. However, upstream undercutting, removing less than 10% of the volume narrows the twelfth by 4 cents and the pitch rises only 9 and 5 cents for these notes.

Both down stream and sideways undercutting cause smaller pitch shifts, but are ineffective in narrowing the twelfth.

Hence it is concluded that the use of lateral asymmetrical undercutting offers no advantage for correcting this particular tuning deficiency in Boehm system clarinets. Judicious use of upstream undercutting however appears to be justified.

3.3 The Effect of Undercutting on Mode Alignment

3.3.1 Objective.

The objective is to establish whether undercutting causes changes in the mode alignment, and whether this can be detected by measuring acoustic input impedance spectra at low drive levels. The 'regimes of oscillation' described by Benade would occur more readily if, as a result of undercutting, the modal ratios were shifted closer to the simple harmonic relationships or, to a lesser extent, if the impedance peaks were significantly broadened. The effect on the player would be that the instrument would feel more responsive, a claim often made for clarinets which have been adjusted by a skilled craftsman. If impedance spectra show mode alignment effects, this would provide a useful technique for monitoring the process of undercutting as it is applied to an instrument.

3.3.2 Measuring Acoustic Input Impedance of a Clarinet.

The theory of acoustic impedance was outlined in Section 1.1.2.5. It can be measured in the time or frequency domain, and notionally either technique should give identical results. In practice, one approach is usually preferred to the other, either because theoretical approximations can be avoided or because of some restriction which arises when making measurements. Methods of measuring input impedance were comprehensively reviewed by Benade [Benade and Ibisi 1987], and by others more recently.

Ideally a source should generate a volume velocity signal which is constant over the frequency range being investigated, and the impedance of the source should be very much greater than that of the instrument being measured. If the pressure is measured with a microphone placed as close as possible to the source end of the instrument, the impedance is then simply the ratio of the pressure to the volume flow measurements, and plots of input impedance versus frequency can easily be constructed. Constant volume velocity is normally achieved by the use of a feedback mechanism. Typically the sound generator is attached to a cavity with a second microphone monitoring the pressure. The pressure signal is fed back to the amplifier driving the generator to maintain the sound pressure level in the cavity constant over the frequency range. The cavity is connected to the instrument being measured by a high-impedance capillary designed so that its impedance is constant over the frequency range. Annular capillaries are commonly used to meet this requirement. Techniques based on this principle have been refined to measure impedances of wind instruments to high accuracies.

In his review, Benade advocated the use of a very simple experimental arrangement, ideally suited to clarinets, which dispenses with the feedback loop. A piezoelectric resonator bonded to a thin flexible metal disk forms the sound source. The disk is bonded with a flexible adhesive to the end of a tube of similar bore to a clarinet which has a small microphone embedded in the side wall close to the source. The other end of the tube terminates in a socket which fits on to the top of the instrument being measured.

For this study an impedance-measuring head employing this technique has been constructed for use with clarinets. The volume of the head is equivalent to that of the mouthpiece and barrel which it replaces. (Details of this impedance measuring head and its associated circuitry are given in Appendix E).

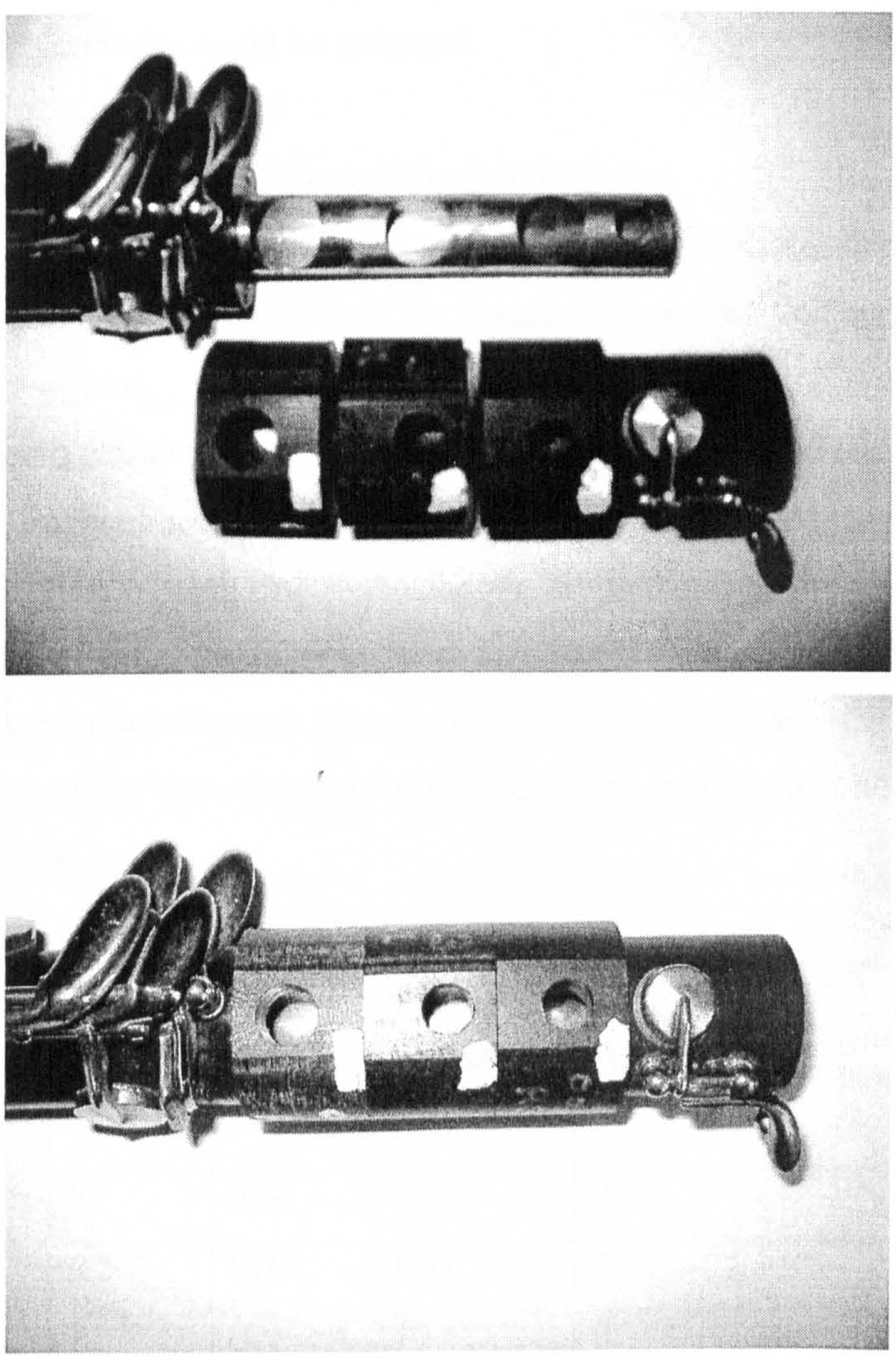
The head can be driven sinusoidally using a swept frequency (frequency domain measurement) or with a maximum length sequence of pulses (time domain measurement). Details of the measurement methods, software and limitations of the techniques are also given in Appendix E.

The device can be calibrated by attaching it to a plain cylinder whose impedance characteristic can be accurately calculated theoretically, and corrections can then be applied to the measured response if required. Where relative rather than absolute impedance measurements are required, as in the present study, this correction can be omitted. Appendix E also includes details of a number of tests to check that the impedance measuring head was operating satisfactorily, which were performed before carrying out the experiments described below.

3.3.3 Experimental Clarinet (EC2)

To assess the effects of undercutting toneholes, they should be part of a clarinet-type structure. Because of the complicated interactions which occur in real instruments it was decided to confine the investigation to measuring the effects on the impedance spectra of modifying a few adjacent holes. This allows comparisons to be made between holes with and without undercutting both upstream (closed holes) and downstream (open holes) of the first open hole.

A second experimental clarinet was constructed (EC2), in the toneholes for the first three fingers of the right hand can be changed by rotating sections of the tube wall. In the experimental section, the bore is formed by a thin-walled brass tube with over-size 'windows' cut at the positions of the toneholes. Sections of body wall, each having toneholes of different shapes drilled through them, fit over the tube. The toneholes are brought into action by rotating the sections to align them with the holes in the brass tube. The toneholes can then be closed externally with the fingers, and the instrument can be attached to the impedance measuring head, or played normally or mechanically, as required. Details of its construction are given in Appendix F.



Experimental Clarinet EC2 with rotating tonehole rings

With a mouthpiece and barrel attached, it was found that the instrument could readily be played over the entire normal range, using either a Yamaha CX or a Buffet Evette 'Master Model' (R13 bore) top joint. Because of the bore perturbations described in Appendix F there are a few tuning imperfections, but the overall pitch is close to A=440Hz when either top joint is used. The clarinet is deemed to be sufficiently representative of a standard Boehm clarinet for acoustic measurements made on it to be meaningful.

3.3.4 Results

Before making measurements on undercutting, extensive checks were made, as described in Appendix E to confirm that the equipment was operating correctly, and that repeatable results could be obtained.

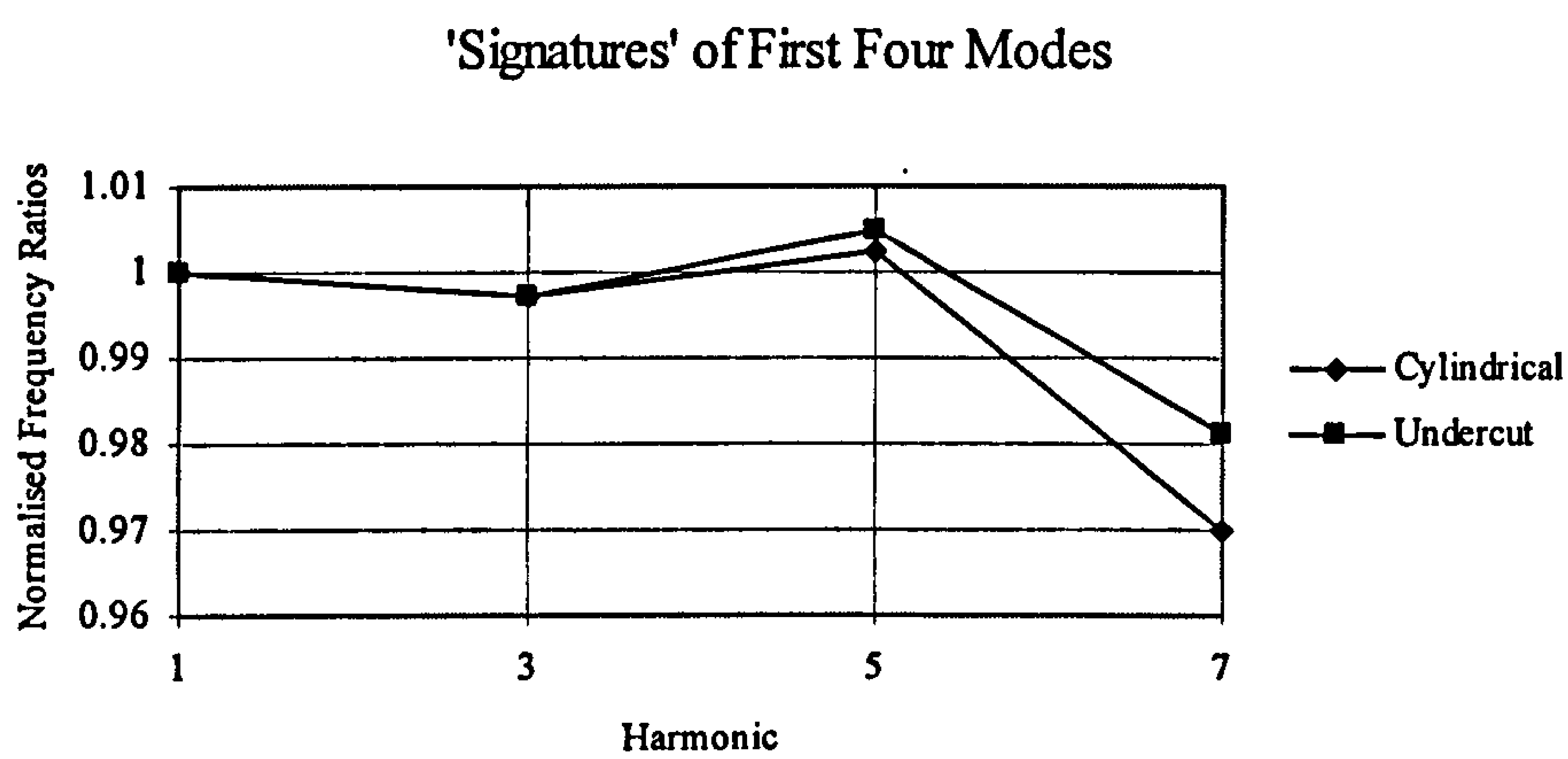
3.3.4.1 Undercutting Two Adjacent Open Toneholes.

These measurements were made in the frequency domain (Audio RTA software) with the Buffet top joint.

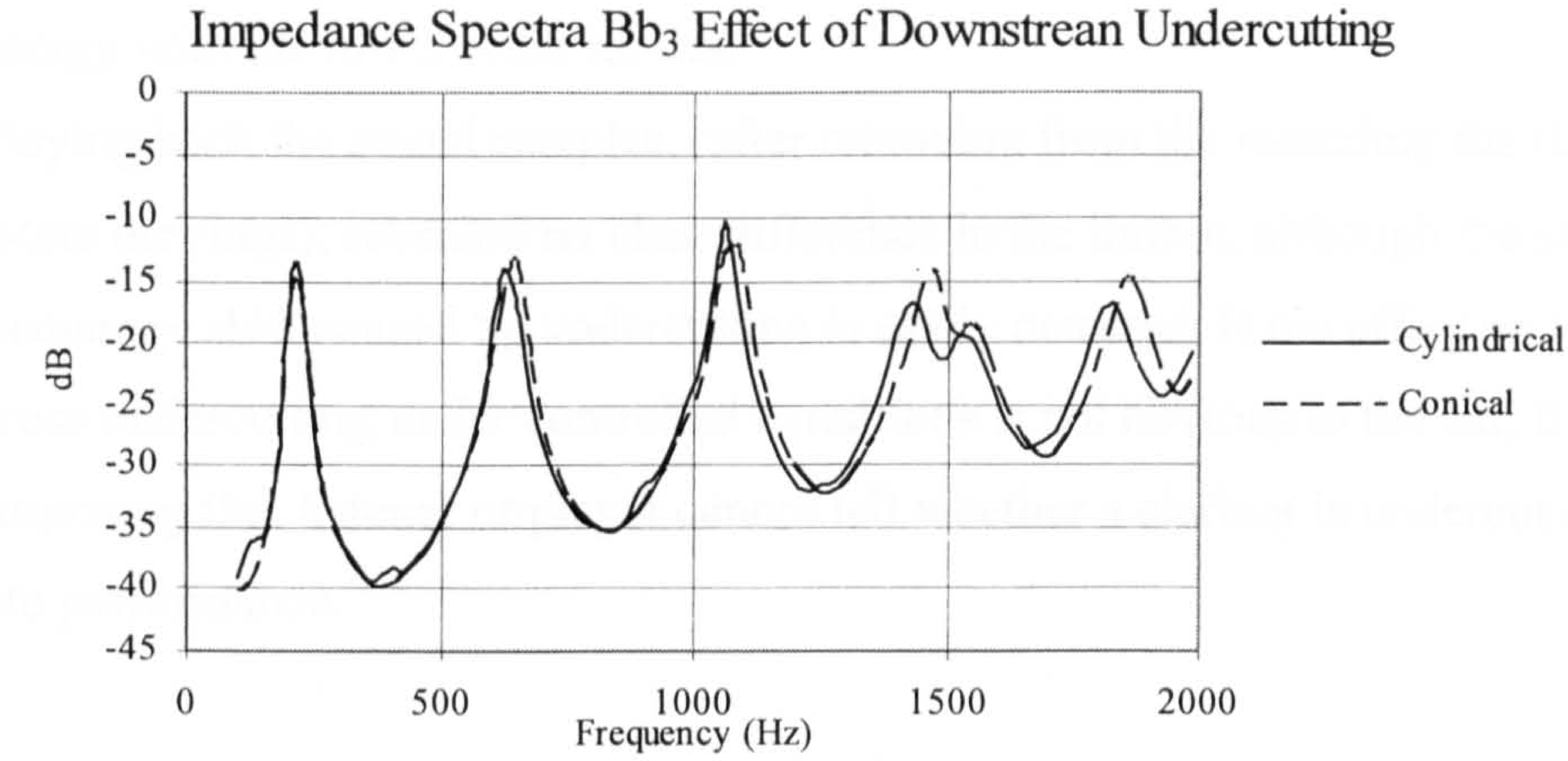
On the Boehm clarinet, Bb_3 is obtained by closing all left-hand and the first of the right-hand-fingered holes. Three rotatable rings were prepared for the right hand joint of EC2. One hole of each ring replicated the original and, in the second and third rings, second holes of the same diameter were machined, which were then undercut. Conical undercuts were made through the whole of the wall thickness, which expanded to the full diameter of the bore at the junction. This is the maximum cone which can be accommodated.

Position	Ring Number	External diameter mm	Hole A Angle °	Hole B Angle°
R1	009	8.42	0	-
R2	020	8.51	0	11.5
R3	021	10.41	0	8.0

Impedance scans were made covering the first four impedance peaks (up to the cut-off frequency). The spectrum with the cylindrical holes in place was measured first, and then the undercut holes were immediately rotated into place for the comparative measurement. Ten sets of results were obtained and the frequency ratios of the harmonics to the fundamental calculated. These ratios were then divided by the harmonic number to produce a 'signature' for the note. (Perfect alignment would have a flat signature, with all values equal to 1). The averages of the ten sets of readings were calculated and plotted, as shown below:

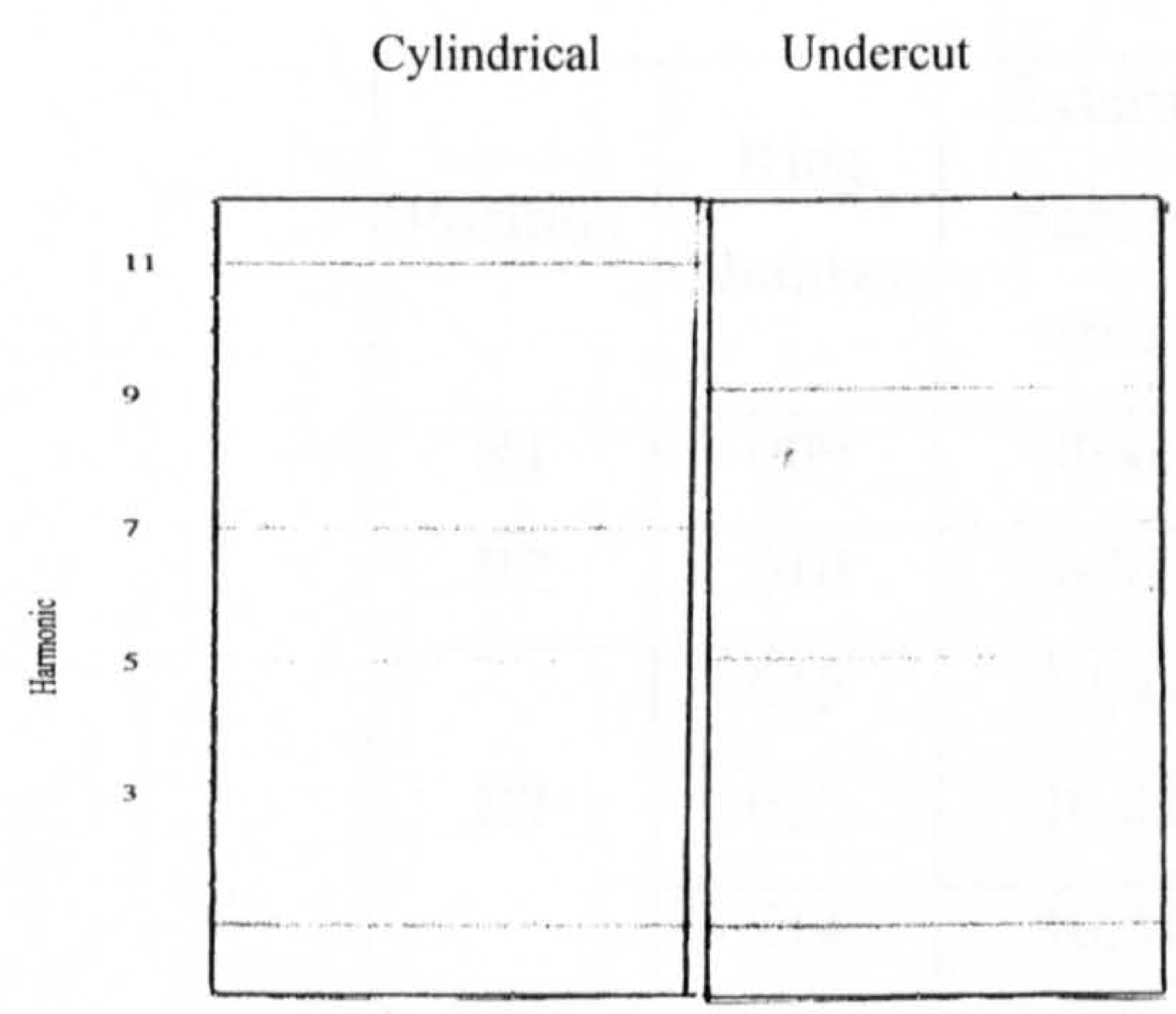


These signatures include the volume of the measuring head, but this is constant throughout. It appears that this gross undercutting has no effect on the mode alignment of the third harmonic. However a small effect is seen at the fifth harmonic, and there is a larger effect at the seventh. If it is assumed that for the instrument alone the ratios decrease with increasing mode number, these results indicate that undercutting would be tending to improve the alignment of the higher modes. However this result must be treated with caution because the seventh mode impedance peak occurs in the region of 1450Hz, which is close to the cutoff frequency.



Examination of the spectra indicates that undercutting may have caused a very slight increase in the cutoff frequency, but the difference is exaggerated because of the drive amplitude dependence on frequency at constant drive voltage (see Appendix E).

The experimental clarinet was attached to the artificial mouth and sound samples recorded for Bb_3, first with R2A and R3A in position (cylindrical), followed by R2B and R3B (undercut). The samples were Fourier transformed and are displayed below as sonograms. The intensity of the plots has been adjusted to reveal only the differences in the strengths of the harmonics:



The sonograms indicate that undercutting the first open and next downstream holes enhances the fifth harmonic. Above the cutoff frequency which, by calculation and as indicated by the impedance plots, is close to 1.5 kHz, the ninth harmonic is enhanced by the undercutting and the seventh and eleventh are reduced. The harmonics associated with these peaks are not reflected back at the open hole and so do not share energy with the lower order modes.

Playing back the sound samples, (after removing from the recording the time it takes to rotate the rings), revealed no clear difference in the timbre, although the slight frequency shift caused by undercutting is easily detected. If the effect on timbre of gross undercutting under controlled conditions is not obvious to the ear, it is not surprising that listener or player cannot tell whether a clarinet is undercut or not in real life performance.

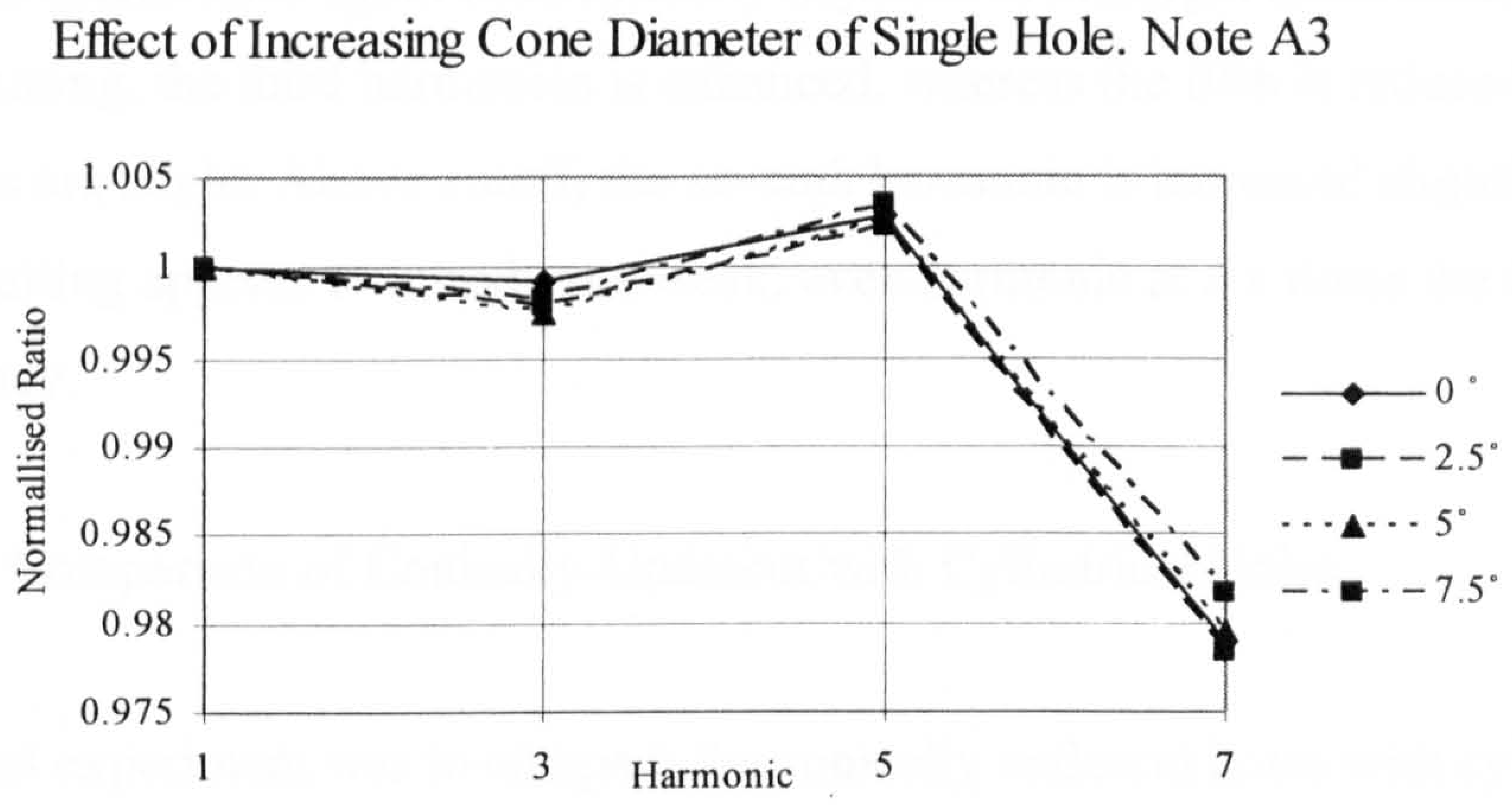
3.3.4.2 Undercutting First Open Hole Only.

For this experiment, note A_3 was used, which requires the first two right hand fingerholes to be closed. Here the measurements were made in the time domain (WinMLS software). The first objective was to measure the effect on mode alignment when the first open hole is progressively opened up by conically undercutting the whole wall thickness, up to the maximum possible.

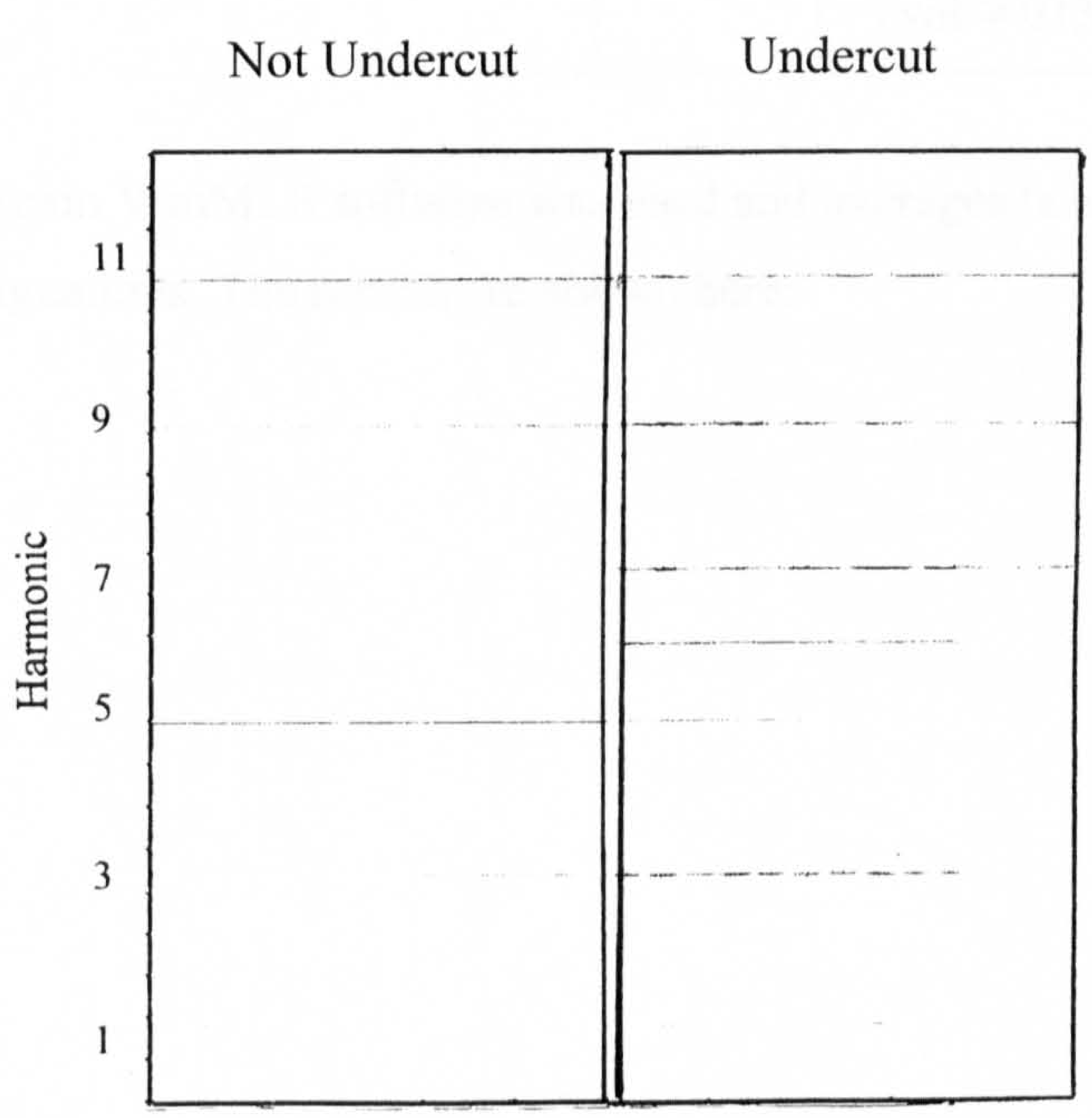
Rings were chosen with normal holes in positions R1 and R2. Three rings were made for position R3 with pairs of holes: one cylindrical, as the original, and the other with different cone angles, as shown in the table:

Position	Ring Number	External diameter mm	Hole A Angle °	Hole B Angle°
R1	009	8.42	0	-
R2	010	8.51	0	-
R3	012	10.41	0	2.5
	013	10.41	0	5
	014	10.41	0	7.5

Averages values were again calculated and plotted as normallised frequency ratios, as in the preceding experiment. The results are shown below:



The 'signature' shows a similar characteristic to those for note B_3, but the overall effect on mode alignment is marginal, with only a small effect at the seventh harmonic, compared to undercutting two adjacent holes maximally, as seen previously.
For less radical undercutting of the type normally found in practice, this indicates that undercutting a single hole has no major effects on the alignment of the impedance peaks, at least when excited at these low drive levels. The experimental clarinet was again attached to the artificial mouth and sonograms made to compare the sound spectra under playing conditions. The cylindrical non-undercut is compared here with the 5° conical hole.



The sonograms have again been intensity adjusted to highlight differences. After undercutting, the third harmonics is enhanced, whereas the fifth is reduced but the changes are slight. Above cutoff, the seventh harmonic is increased slightly. Also the undercutting appears to introduce a weak, even harmonic at six times the fundamental frequency.

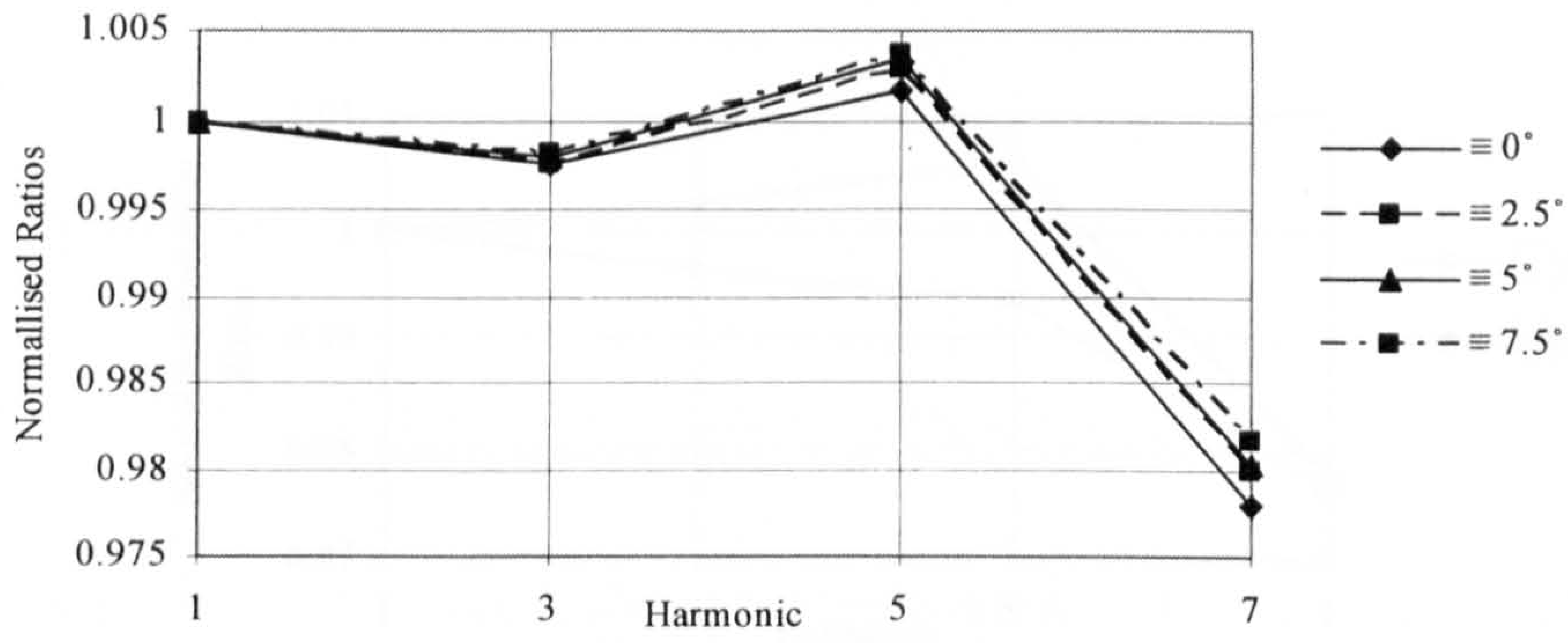
3.3.4.3 Comparison of Conically-Undercut with Cylindrical Holes

The next experiment was to compare the conically undercut holes with cylindrical holes of larger diameter than the original. Ideally these should have the same acoustic admittance as the conical holes with increasing angles but, for the present purposes holes of equivalent volume were used as a near approximation. By weighing the rings before and after machining, the volumes removed could be matched and the diameters used are shown below.

<table>
<tr><th rowspan="2">Position</th><th rowspan="2">Ring Number</th><th colspan="2">External diameter mm</th></tr>
<tr><th>A</th><th>B</th></tr>
<tr><td rowspan="2">R3</td><td>015</td><td>10.41</td><td>10.95
(vol ≡ 012B)</td></tr>
<tr><td>016</td><td>11.30
(vol ≡ 013B)</td><td>11.80
(vol ≡ 014B)</td></tr>
</table>

Again WinMLS software was used and averages taken to obtain the data for the signatures. The results are shown here:

Cylindrical Holes with Equivalent Volumes



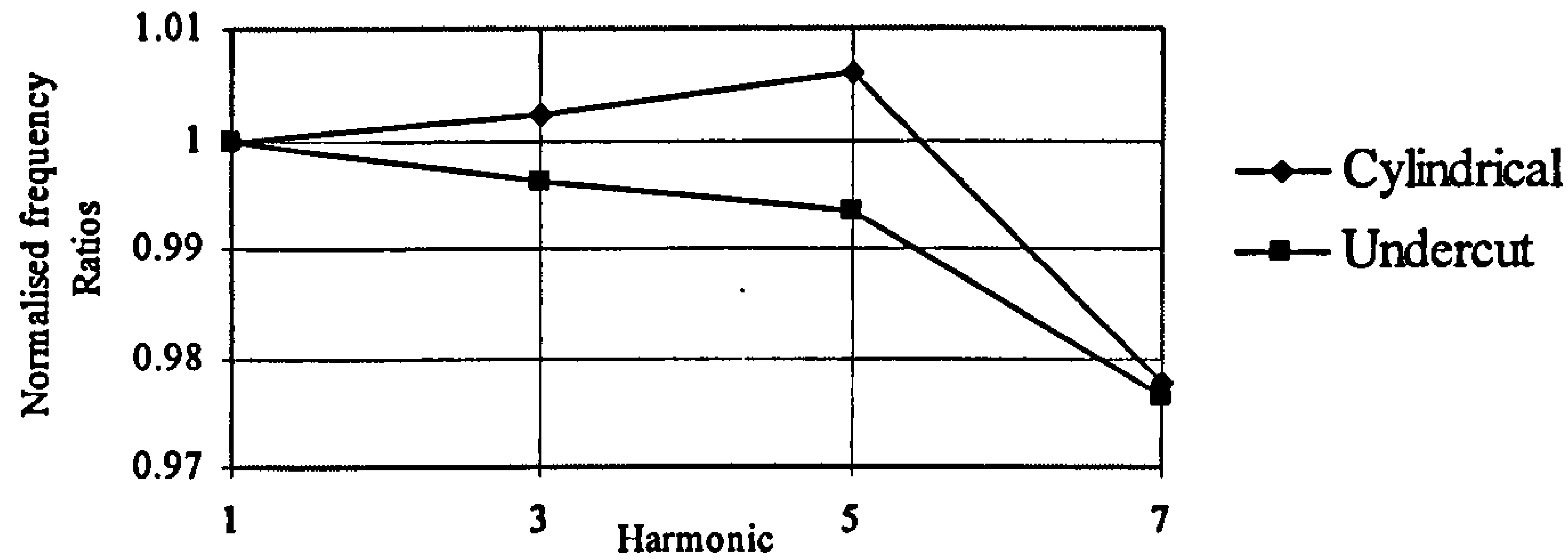
The results are very similar to those measured for the conical holes, with only marginal improvements in mode alignment at the higher harmonics.

3.3.4.4 Undercutting Upstream of the First Open Tonehole

Note A_3, with the first two right hand holes closed, was again selected. In this experiment each ring had two holes, one cylindrical, as the original, and the other with the same external diameter but maximally conically undercut through the wall thickness. The two closed holes contribute a 'dead space' which acts as a small, localised bore enlargement in the vicinity of the end of the effective tube length
The ring details are shown below:

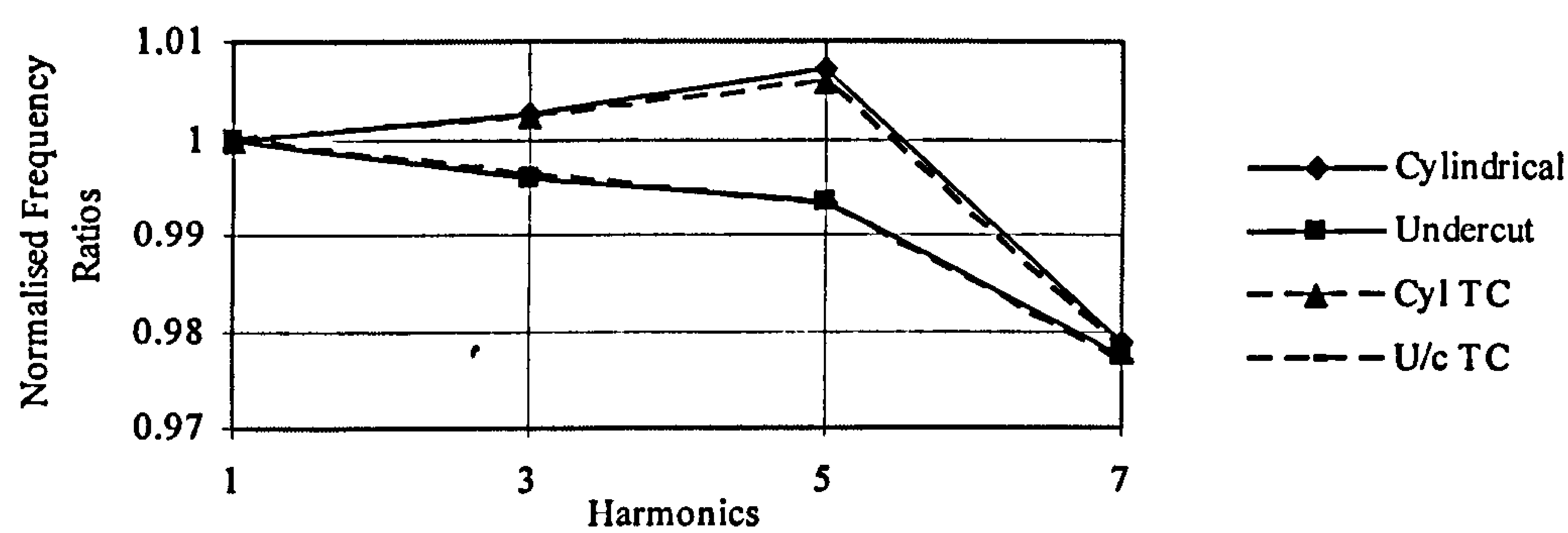
Position	Ring Number	External diameter mm	Hole A Angle °	Hole B Angle°
R1	022	8.42	0	15
R2	020	8.51	0	11.5
R3	021	10.41	0	8.0

Signatures: Holes Upstream of First Open Hole
Note A3



Measurements were made in the frequency domain, and the data plotted are the averages from ten sets of measurements. Because the ambient temperature was observed to be changing significantly during the experiment, the measured frequencies were standardized to 20°C before averaging. In fact, when the averaged temperature-corrected data is compared with the uncorrected as shown below, the differences are negligible.

Signatures with and without Temperature Correction
(TC = adjusted to 20°C)



Hence, even when the ambient temperature is changing significantly, provided the frequencies being compared are measured sequentially and averages of sufficient numbers of data sets are taken, temperature corrections can be omitted.

The bore perturbation resulting from the closed-hole dead space affects both the third and fifth harmonics, lowering the ratios in each case..

Comparison of sonograms made, (using the artificial mouth), with and without the upstream undercutting revealed no significant differences in the distribution of energy within the harmonics. This experiment highlights the potential hazard of applying heavy undercutting to individual toneholes as notes further down the instrument may be adversely affected.

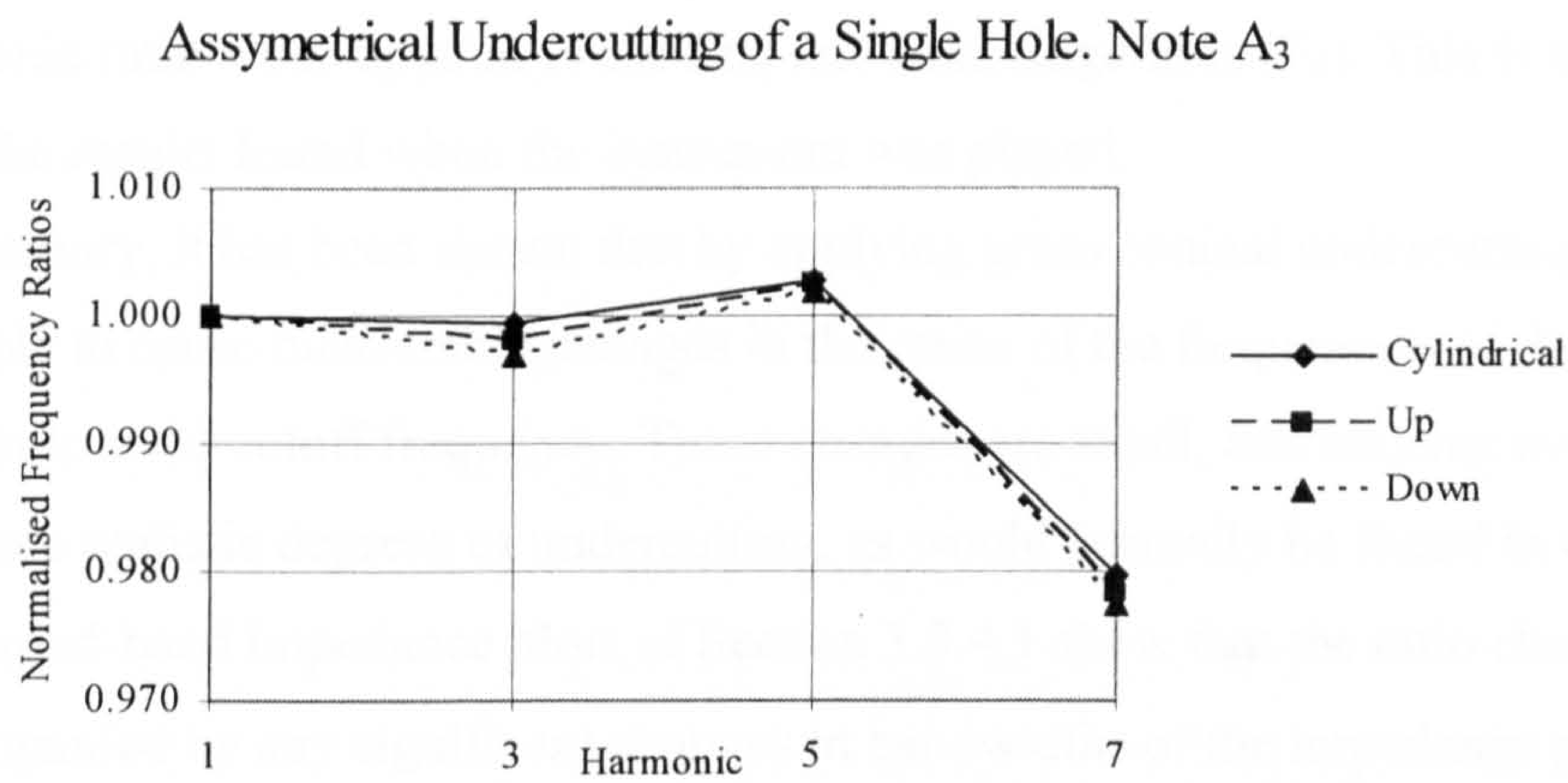
3.3.4.5 Effect of Asymmetrically Undercutting a Single Hole

These measurements were made on the Experimental Clarinet 1 (EC1) to complement the results shown in Section 3.2. It was demonstrated that under playing conditions, the twelfth interval between F_4 and C_6 can be narrowed by undercutting, and in particular by undercutting asymmetrically upstream only. Clarinet EC1 was attached to the impedance head and the spectra for F_4 measured with different tonehole profiles inserted. The ratios of the frequencies of the third harmonic to the fundamental were calculated for the different inserts, as shown on the table:

Insert No	Undercut	Ratio
3	Cylindrical	2.98
4	Sideways	2.98
2	Down	2.97
1	Upwards	2.96
5	Cone	2.96

As noted previously, actual values of the measured ratios include effects from the geometry of the impedance measuring head, but these are constant throughout. The results show the same trends as in the playing experiments: i.e. upward and conical undercutting narrow the modal ratios whereas sideways cutting is ineffective. However, the differences are not great in relation to the measurement uncertainties, and these results should be treated as indicative only.

A further attempt was made to detect changes on mode alignment from measured impedance spectra when the undercutting is applied asymmetrically. A ring was made for the third right-hand finger position, which was asymmetrically undercut along the direction of the axis at 7.5°, and its length was reduced. By adding a spacer, it was possible to reverse the asymmetrical ring to make the undercutting either up or downstream, whilst keeping the position of the hole centre constant. Measurements were made in the time domain, and the results of multiple measurements averaged. The signatures obtained are shown below:



According to this experiment, both up and downstream undercutting slightly reduce the third harmonic ratios, with no effect at the fifth. It appears that this moderate degree of undercutting has only a marginal effect on the mode alignment.

3.3.5 Summary of Mode Alignment Experimental Results.

Comparisons of measured impedance spectra obtained from toneholes with no undercutting with those from holes with heavy conical undercutting have revealed only small changes in the modal frequency ratios.

When two adjacent open holes are grossly undercut, this causes no change in the mode alignment of the third, a small change in the fifth (~¼%), and a larger change in the seventh harmonic (~1%); the mode alignment is improved.

When the first open hole alone is undercut with cones of increasing semi-angle, the largest cone angle causes marginal shifts, with a slight increase in the misalignment at the third harmonic, and a small (~½%) improvement in the seventh. The changes are, however, small, and of the same order of magnitude as the measurement uncertainties. At smaller cone angles the effects are insignificant.

Heavy undercutting of the first open tonehole and two toneholes upstream of it shows worsening of the mode alignment, especially at the fifth harmonic (~1½%). The third harmonic changes in the same sense to a lesser extent and the seventh is unaffected. In this situation the closed holes act as localised bore enlargements, and the changes are consistent with perturbing the bore.

Asymmetrical upstream and downstream undercutting showed no significant shifts when applied to the third right-hand fingerhole (A_3), but a slight narrowing of the third harmonic ratio when applied to the first left-hand fingerhole (F_4). This is consistent with the results found when the instrument was played.

In summary, it has been shown that by applying gross conical undercutting it is possible to cause measurable changes in the ratios of the frequencies of the impedance peak below the cutoff frequency. These changes are small, and become even smaller for more realistic degrees of undercutting, as would normally be found in clarinets.

The broad-band impedance plots of Section 3.3.4.1 show that the ratio changes are not accompanied by any significant changes in bandwidths of the impedance peaks, or in the cutoff frequency, although this may be marginally raised by undercutting.

The question remains whether such small changes, which mainly affect only the higher orders of the collaborating modes, would be perceptible to the player. This is difficult to test in an experimental clarinet in which only a few holes are modified, and further experiments on this subject are described later. Considering the way in which the standing waves collaborate at the reed, it is only those modes whose impedance peaks exceed a critical level, corresponding to unity gain, which interact at the reed. The distribution of energy within the harmonics varies with the strength of the fundamental [**Worman** Thesis 1971], and as the playing level drops, the higher-order peaks fall below this level, which accounts for the change in timbre with dynamic. Hence any minor changes in alignment of these higher peaks up to the cut-off frequency would only manifest themselves to the player at high dynamic levels, if at all. In view of the small magnitude of the mode alignment changes, it is likely that, under playing conditions, there are other processes occurring which are sensitive to undercutting, and that these may have a greater contribution to the way the instrument feels to the player.

From a practical standpoint, the results from these experiments indicate that impedance spectra alone cannot be used to monitor progress when undercutting an instrument.

3.4 Playing Tests

3.4.1 Objective

It is commonly perceived that top quality clarinets have undercut toneholes whilst lower quality or 'beginner' clarinets do not, and indeed this is usually true. But instruments for professional use have at various times been produced without undercut toneholes, for example the pre-war Selmers, the post-war Boosey and Hawkes 926 Imperial model, and the Selmer Series 9 model, none of which are normally undercut. As observed in Part 2, some Boosey and Hawkes 1010 models have minimal undercutting in the form of chamfering of the edges at the tonehole/bore intersection. This suggests that instruments with and without undercutting may have distinct characteristics, which appeal to different groups of people. The fact that manufacturers of clarinets undertake the expensive procedure of undercutting the toneholes implies that they believe that undercutting achieves either a tone quality or playing characteristic which is desirable.

Various claims are made, mainly by manufacturers and players rather than by listeners, for the effects that undercutting has on the playing characteristics of a clarinet. As would be expected for such a subjective topic, these claims are not always consistent, and are sometimes contradictory.

In practice it is difficult to make objective comparisons between undercut and not undercut clarinets. Invariably there will be other differences between instruments. For example, clarinets may have different bore sizes and profiles, as well as different tonehole sizes and positions, all of which can influence the playing characteristics in addition to any effects caused by undercutting.

A test has therefore been devised to see whether experienced clarinettists could detect by playing any differences between clarinets and without undercutting, but which are otherwise physically identical, (i.e. same bore profile, hole sizes and positions, body material and internal finish). Comments made during the test would be noted and analysed to see if a consensus could be established which qualified the differences as perceived by the testers.

A third clarinet was included in the experiment, again initially identical to the other two, but with all of the edges where the toneholes meet the bore having been carefully smoothed off to form a rounded profile. The amount of material removed is minimal, so it is debatable whether or not this should be referred to as an 'undercut' clarinet. It is referred to here as the 'smoothed' clarinet.

This clarinet was included in the experiment with the intention of testing claims that removing all sharp edges from the inside of the instrument improves the 'feel' of the instrument to the player. This effect has been referred to in the literature [Keefe Benade] and the practice of smoothing is practiced by a number of clarinet repairers and players.

3.4.2 Preparing the Clarinets

An auction lot of damaged clarinet parts was purchased which included a selection of plastic upper and lower body joints, all of the same design[∇]. The left hand joints were marked only with serial numbers but the right hand joints were unmarked. All of the pieces were measured for bore profile, tonehole sizes and positions, and the intersections of the toneholes with the bore examined. It was found that none of the toneholes were undercut, and the holes had been machined to form a sharp edge at the bore.

Of the five top joints available, it was found that the two with the lowest serial numbers had cylindrical bores of 15.0 mm throughout, whereas the more recent three showed a slight conical enlargement from this diameter, starting at about the position of the register hole. Clearly a design change had been made at some time, presumably to improve the tuning of the twelfths. It was decided to use the latter three top joints, which were matched to three of the five bottom joints from the batch.

Details of the bore, and sizes and positions of the tonehole of three instruments, as assembled, are shown in Appendix G.

The auction lot also included an old (1950s?) wooden Bundy clarinet, manufactured in the USA by the Selmer Company [CLT124]. This had identical key work to the plastic bodies; for example, the throat A key is closed with a needle spring rather than the usual leaf spring, thus identifying the make and model of the plastic test clarinets. Furthermore, a plastic Bundy Mazzeo system clarinet [CLT148] has the same keywork design, apart from the Mazzeo additions, thus confirming the maker and model. The Bundy logo on the Mazzeo top joint is made as a transfer stuck to the body rather than embossed. Most of the logo had worn off which explains why the test bodies appear to

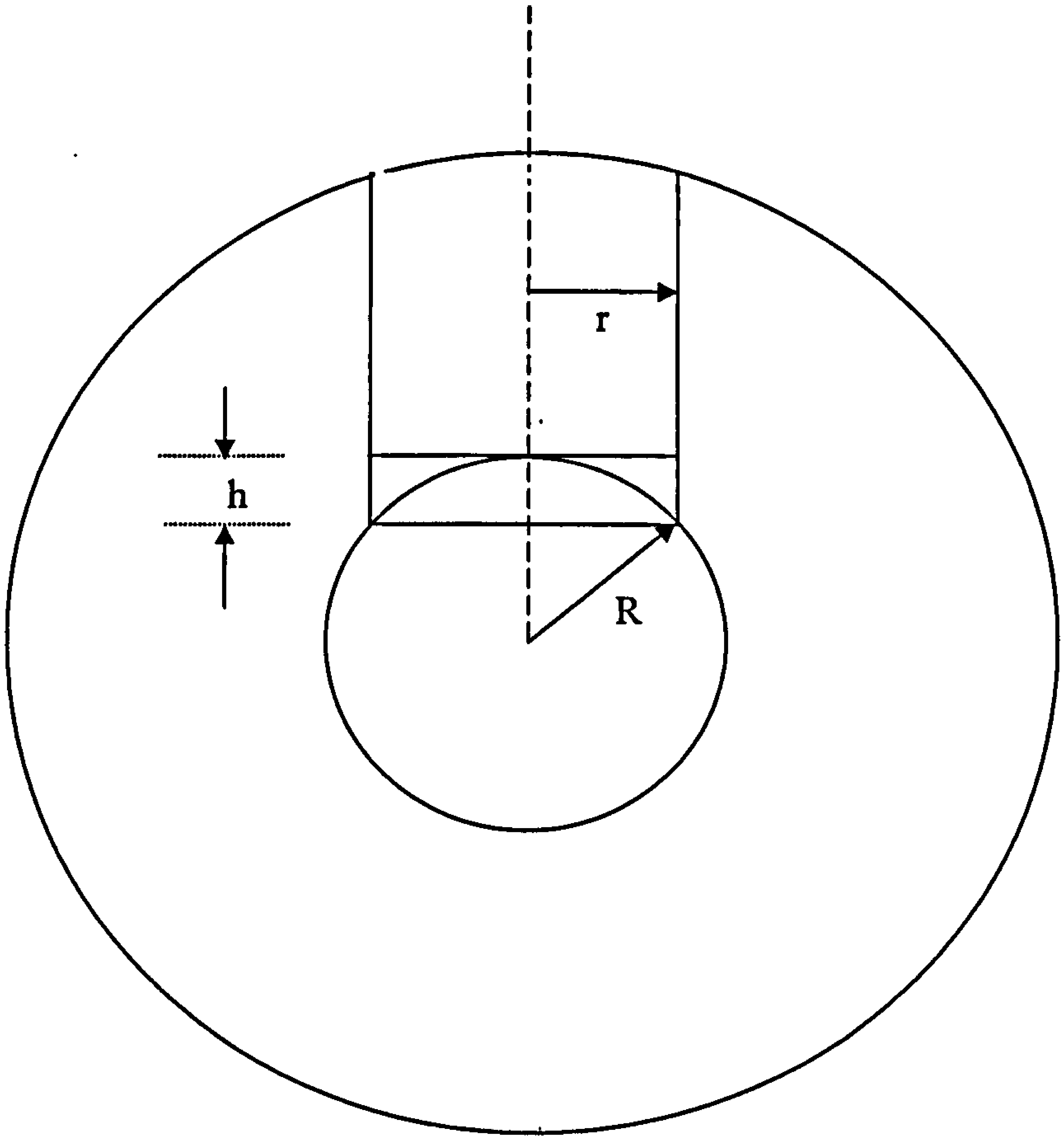
[∇] The auction lot originated from a music store and it is likely that the cost of repair had been deemed uneconomical be unlabeled. This proved to be an advantage in the tests as the participants were not prejudiced in any way by recognising the make and model.

Having selected the bodies for the test instruments, they were then carefully restored. This involved repairing damaged tenons and replacing missing posts and keys (salvaged mainly from the other Bundy bodies in the auction lot). Where necessary, new pads, corks and springs were fitted to put the instruments in good playing order[◊]. A set of plastic bells was purchased from various sources and a Bundy plastic barrel obtained which fitted all three instruments. Before any modifications to the toneholes were made, the instruments were played by the author to confirm that they all responded similarly. Furthermore the low-power acoustic input impedance spectra were measured for selected notes across the chalumeau register (A_3, C_4, E_4 and G_4). The 'signatures', as defined earlier, were plotted and found to be similar for the three instruments.

Borescope examination revealed little difference between the instruments where the toneholes meet the bore. The bores were all highly polished and there is little sign of use, apart from the loss of the logo transfer. The combination (T2+12B) was selected as the control (Green clarinet) as it was estimated to have the sharpest tonehole edges. Combination (T4+14B) was chosen for undercutting (Red clarinet) using the following procedure:

A set of multi-teethed fraises was made to cover the range of tonehole sizes. After assembling the drive rod and guide sleeve through one of the toneholes and attaching the fraise, the body was held horizontally in a specially made jig mounted on an X-Y positioning table attached to a drill press stand. The body was then positioned accurately so that the fraise tool was exactly aligned with the tonehole. For each hole the amount by which the tool needed to be raised until it just begins to cut all round the tonehole was calculated using the known tonehole and bore sizes (see Figure below).

[◊] The thumb rests were moved up by ten millimetres to improve the right hand position



$$h = R - SQRT(R^2 - r^2)$$

Height of cut needed before undercutting into the wall all round

To this distance was added one third of the wall thickness (taken as the difference between the body external radius and the bore radius). The drill press was fitted with a reversed depth gauge so that the extent of undercutting could be accurately controlled. Care needed to be taken not to burn the plastic through machining at too high a rate. This procedure was applied to all of the toneholes, using an appropriately sized fraise tool.

The remaining combination, (T5+11B), had smoothing applied (Yellow clarinet). Achieving smooth tonehole edges proved to be difficult. The recommended procedure of smoothing the edges with a fine abrasive cloth supported on the end of a cotton wool bud was found to be ineffective, due to the hardness of the plastic body material. After trying various methods on a spare body part, an effective technique was found. A length of synthetic cord of approximately 4 mm diameter was tied to form a knot, too large to pull through the hole to be smoothed. The knot was then 'dressed' with a rouge-in-wax polishing compound, and the cord threaded through the hole with the knot inside. The free end of the cord was clamped in the chuck of a pillar drill and the body held so that the knot was pulled up against the internal edge of the tonehole, while the cord was rotated by the drill. The irregular shape of the knot ensured that the whole of the end of the tonehole became smoothed over. It was not possible to measure the radius of curvature achieved, but this was estimated as small since very little of the wall material was removed by this method. The hole nearest the bottom of the left hand joint can be reached with the tip of a little finger. It is easy to detect by touch the difference between the sharp edge in the control clarinet and the smoothed edge.

After the clarinets had been modified, the key work was reassembled and the instruments leak-tested and checked by playing.

Before conducting the playing experiment, the low-power acoustic impedance 'fingerprints' were re-measured for the same notes originally measured, and the results compared. No significant differences were found.

Finally the instruments were marked with coloured labels as indicated above, namely:

GREEN: as-received instrument with sharp tonehole edges (Control).

YELLOW: smoothed tonehole edges.

RED: fully undercut, with 20° semi-angle cones through approximately ⅓ of wall thickness.

3.4.3. Experimental Protocol

It was apparent from the author's own preliminary playing tests that the differences created by undercutting and smoothing are detectable but rather subtle, and would probably not be appreciated by an inexperienced player. It was therefore decided to restrict the testing to professional, semi-professional and experienced, high-grade amateur players. For the purposes of this experiment the distinction between professional and semi-professional is loosely defined as:

Professional – Players who have trained as musicians and now earn their living playing the clarinet and/or teaching the clarinet, or have retired from the profession;

Semi-professional – Those who play and/or teach professionally but also have some other occupation.

The identities of the players do not appear in the results, but their status as defined above is shown. The names of the players do however appear in the acknowledgements section.

For consistency, and to try to eliminate possibilities of biasing the results, the following protocol for conducting the tests was applied:

(i) The players were encouraged to use their own mouthpiece and reed. Occasionally it was necessary for the barrel normally used with the player's mouthpiece to be used, instead of the one provided, when the mouthpiece tenon would not fit the barrel. It has been noted in the Table of results when this occurred.

(ii) The players were asked to disregard any tuning irregularities inherent in the clarinets or introduced by using an unmatched mouthpiece (and barrel).

(iii) The instruments were assembled by the author at the start of the tests to discourage the players from examining them too closely.

(iv) The clarinets were referred to only by their colour codes until the test was complete.

(v) The author explained that he would not respond positively or negatively to any comments made by the players, but would simply record the comments.

(vi) The players were asked to 'warm up' and familiarise themselves with all three instruments in quick succession initially, rather than to concentrate on any one instrument from the start.

(vii) Initial reactions were noted where opinions were offered before the players spent longer times comparing the instruments.

(viii) At appropriate times, the more considered comments were noted and these were read back to the players to allow opinions to be changed, if requested, and to agree the wording.

(ix) No time limits were imposed

(x) When the players felt that they had completed their assessments they were asked to rank the clarinets in order of preference and to 'grade' the quality in terms of playing characteristics (rather than quality of materials or construction).

(xi) Selected players were asked whether the individual clarinets appeared to have undercut toneholes or not.

3.4.3.1 Notes on the Protocol.

Points (i) and (ii): The advantage of having the players use their own mouthpiece and reed with which they were familiar is deemed to heavily outweigh any resulting tuning problems. In practice it was found that the clarinets played well in tune when using mouthpieces of the Boosey and Hawkes 926 design. This is as expected because the Bundy test clarinets have the same bore as the 925, (i.e. 15.0 mm). The mouthpieces used ranged from Buffet R13 design (small bore) to Boosey and Hawkes '1010' type (wide bore) but whilst some of the players commented on the effects of tuning, especially around the throat notes, none indicated that this disturbed their assessments of the playing characteristics.

Point (v): This is probably the most important of the procedures to observe, and most difficult to apply strictly in practice. It is a part of human nature to expect a response to comments, especially when the effects being sought are subtle and the subject is consciously or subconsciously trying to produce the 'right answer'. The temptation to 'lead' the player had to be rigorously resisted, especially with the later tests, where the author had accumulated a body of test data from which a trend was becoming apparent. Occasionally players would ask "What do you want me to do now?" This was an opportunity to check that each clarinet had been played legato and staccato at all dynamic levels, but otherwise prompting was kept to a minimum.

Points (vi) – (viii): It was observed by the author that, as a player, one adapts to an unfamiliar instrument over a relatively short spell of playing. Generally the instrument 'improves' with time during this initial period: i.e., one adapts one's technique to suit the instrument. It was with this in mind that the players were asked to change instruments fairly quickly, at first, to note their initial reactions if they were offered. A number of players revised their opinion of an instrument, rating it better than originally thought after more prolonged playing. Comments such as "I could get to like this one" were made. One slight problem was encountered in that once a player had decided which of the three was the 'best', they were somewhat reluctant to return to the others.

Point (x): Ranking the instruments was straightforward for most players. However there were instances where different clarinets were preferred for a particular attribute, (e.g. easiest staccato response for Green; best tone for Yellow).

Point (xi): The only players who were asked if they could detect the presence or absence of undercutting were those who were known to have had experience of playing these different types of instrument. For example, some players regularly change their clarinets throughout their careers and others have the opportunity to try out clarinets of different types, as used by their students. Even so, they are not necessarily aware of the undercutting state of the different models.

3.4.4 Results of Playing Tests.

The comments made by the players have been tabulated below.

3.4.4.1 Test Results Table.

Player reference	Usual Instrument	Mouthpiece used for test	Barrel used for test	Test Clarinet			Additional comments
				GREEN	YELLOW	RED	
1(SP)	Buffet R13	Pomerico (glass) R13	R13	Slightly more resistant than YELLOW. Can be made to play with good sound but YELLOW preferred. Best staccato response. Articulation easiest on GREEN.	Most flexible. Best tone quality. Best dynamic range. Good staccato response but slightly less than GREEN. YELLOW makes best sound.	Initial reaction: 'Stuffy' feeling. Marginally less responsive to staccato playing. May be 'freer' in response but tone not as good when established	Overall differences are not large.
2(A)	Buffet R13	R13	R13	Smoothness to legato playing very slightly less than YELLOW. Preferred tone quality.	Smoother response than GREEN. Not much to choose between YELLOW and RED, especially for legato playing.	Similar (or possibly slightly better) response to slow tonguing to YELLOW. Rated best for fast tonguing.	All three rated as good instruments. No large differences. Would buy any of them. Might choose RED for a beginner.
3(A)	B&H 1010	1010	1010	Least responsive. Not as easy to control dynamic range as on YELLOW.	Best response to legato and staccato playing. Good dynamic range.	Slightly less 'free' than YELLOW. Not easy to control over dynamic range.	Overall preference for YELLOW but differences between all three are not large.

Player reference	Usual Instrument	Mouthpiece used for test	Barrel used for test	Test Clarinet			Additional comments
				GREEN	YELLOW	RED	
4(SP)	Louis (1920s)	B&H 926 style with tip openings: (i) 1.1 mm (ii) 1.25 mm (iii) 1.27 mm	Bundy	Not liked. Expressions: "stuffy", woolly" and "resistant" used, but quite even. "Cotton wool" feel. Not responsive to staccato.	(ii) Crispest and brightest. (iii) Slightly uncontrollably. (i) Still crisp with good tone quality. Lighter tone, lively and with good staccato response (similar to RED).	(i) Plays better with this lay. More refined tone, smoother but less 'open' than YELLOW. (ii) Slightly less smooth with darker sound than YELLOW but not so dynamic. Good staccato response similar to YELLOW.	Would choose YELLOW to play on. Slightly 'wild' but controllable and with more character. Best range of tone qualities available. Not happy with GREEN. RED improved with playing (on 1.25 tip) and could be as good as YELLOW on familiarisation. Suggested that GREEN was not undercut, YELLOW undercut and RED possibly partially undercut.
5(A)	F Wurlitzer	Wurlitzer	Bundy	Most even especially for RH notes. Best for staccato. Projects best. First choice.	Also projects well but less controllable than GREEN. Second choice overall.	Second best for staccato playing. Least liked of three	Perceived as 'cheap' instruments because of the quality of the key work. Uneven response in different registers for different instruments. No strong indications as to which might be undercut bur YELLOW suspected as being undercut.

Player reference	Usual Instrument	Mouthpiece used for test	Barrel used for test	Test Clarinet			Additional comments
				GREEN	YELLOW	RED	
6(P)	Period	Selmer (1920s)	Bundy	Less flexible. Rather 'straight' sound. Projects quite well on throat notes.	Feels flexible and more even throughout the instrument. YELLOW sound preferred. More 'body'.	Bright sound particularly in the upper register. Would project well but tone quality rather harsh. Too 'open' on throat notes. Larger dynamic range than YELLOW.	Would choose YELLOW overall although it has somewhat less projection than GREEN and RED. RED second choice. GREEN third.
7(A)	Various pre-war	(i) 926 style (ii) Hite-modified	Bundy	(1) Preferred instrument. Less open than RED. Less 'tight' than YELLOW. Has good 'feel'. (ii) Still OK but now not as good as YELLOW	(i) Plays evenly with more 'confined' tone. High notes 'thin'. Possible OK for small room use i.e. chamber music. Good in piano, less so in forte playing. (ii) Now preferred instrument	(i) Plays fairly evenly with good response. 'Broader' sound than YELLOW. Good for forte playing. Large hall instrument i.e. Symphony Orchestra use. Difficult to control in piano. (ii) Now too open and brash	Clear differences recognised between the three. Using mouthpiece (i): RED instrument was reckoned to be undercut. (confident) GREEN possibly undercut (not sure). YELLOW possibly not undercut (not sure).
8(P)	B&H 1010	1010	1010	Not as responsive as YELLOW. Rated 4/10 overall.	Good even response. Very clear with no 'stuffiness'. Tested in remote keys. Played easily. Rated 9/10 overall.	Response somewhere between GREEN and YELLOW. Rated 6/10 overall.	Intonation acceptable on all three. YELLOW rated as a professional grade instrument. The clarinets were also tried with a 926 mouthpiece which appeared to improve all of the instruments but with the same results.

Player reference	Usual Instrument	Mouthpiece used for test	Barrel used for test	Test Clarinet			Additional comments
				GREEN	YELLOW	RED	
9(P)	Buffet S1	Custom (glass)	Bundy	Not comfortable. 'Closer' feel than YELLOW.	Preferred instrument. Uniform over range and free blowing. Faster response –more immediate. Good instrument. Would be good for jazz.	More 'resistance'. Perhaps somewhat more 'pitch focussed'. Some non-uniformity in loudness between notes, e.g. top BB louder. Generally open feel. More focussed.	Very little difference between YELLOW and RED both rated good quality acoustically. Responsive over whole range. Reasonable quality instruments.
10(P)	B&H 1010	1010	Bundy	Not responsive. Very restricting. 'Straight' sound which could not easily be varied. Much effort needed to produce variety of sound. Hard edge to sound. Good characteristic however is that it plays well in piano.	First choice. Even response. Plays easily. Projects well. Greater range of dynamics. Would cope with playing in large orchestra. High notes play readily. Not quite so easy to control piano playing as GREEN.	Very 'narrow' sound. Not quality sound. Could project with RED. Bordering on instability at top. Upper register notes feel insecure. Free-flowing in chalumeau, becoming 'stuffier' over break, then unstable at top. Rather thin sound.	YELLOW rated as good instrument – professional grade. RED feels like a beginner's instrument. GREEN also lower quality, slightly better than RED. Thought YELLOW might be undercut but not confident to judge.
11(P)	B&H 1010 + others	Louis (1920s)	Bundy	Second best but close to YELLOW. Legato not as good as YELLOW. Good stability in high register – second to YELLOW.	Plays best of three. Good enough to play professionally. Good legato in piano playing. Stability in high register better than RED.	Least preferred instrument. Slightly 'stuffy'. Stability in high register not as secure as YELLOW.	All are free-playing instruments. Differences between the three are not great. Could get used to playing any of them. Rated YELLOW as undercut. Possibly GREEN undercut? –not sure.

Player reference	Usual Instrument	Mouthpiece used for test	Barrel used for test	Test Clarinet			Additional comments
				GREEN	YELLOW	RED	
12 (P)	Buffet DGs	James Pyne (Ohio USA) Clarion Model	Bundy	Initial response: Second choice. Bottom register more 'stuffy' than YELLOW. Notes under break not as 'clean'. Not as 'clear' a sound as YELLOW.	Initial response: First choice. Rounder sound. Has 'ringing' quality. Most 'resonant' of three. Nice instrument.	Initial response: Third choice. 'Stuffier' at bottom. 'Thinner' sound – not 'round'. Not as 'broad' a sound. More erratic than GREEN or YELLOW. Adequate upper register but more 'ordinary' sounding.	Would be prepared to play on YELLOW for a concert. No opinions on whether instruments were undercut or not.
13(P)	B&H 1010	1010	Bundy	Least liked. Hard work. Not responsive. Ruled out on all counts	First choice but sound harder to focus than with RED. Most even and free response. Would chose YELLOW if required to select one for a performance. 'Artistic' choice – more scope for expression.	Easier to focus. Not as 'wide' as YELLOW. Ease of response good but overall second choice (but close) to YELLOW.	All three clarinets felt restricted compared with 1010s. Thought perhaps YELLOW is undercut but not confident.
14(P)	Leblanc Concerto/ B&H 1010	Selmer C85/120	Bundy	Least liked. Would not 'sing'. Not responsive. Rejected as significantly inferior to RED and YELLOW.	Second choice just behind RED. Similar to RED but slightly less 'voice' quality. Slightly less 'open' sound.	Best on first reaction and subsequent testing. 'Even' over range. 'Voice' like quality.	No opinion on undercutting. Rated as free-playing clarinets. RED and YELLOW rated as up to intermediate level instruments.

Player reference	Usual Instrument	Mouthpiece used for test	Barrel used for test	Test Clarinet			Additional comments
				GREEN	YELLOW	RED	
15(SP)	Yamaha Custom	Jean Hite	Bundy	Similar to RED but slightly freer playing and not as restricted at bottom. Fairly stable in top register. Marginally preferred to RED as sound is more 'as expected'. Noticeable inferior to YELLOW.	Preferred clarinet. Freer than RED and GREEN. More responsive. Stable. Flexible. Sound is what player is used to.	Least liked. 'Stuffy' at bottom of range. More resistance. Sound less focussed than YELLOW and feeling of instability at top of clarinet register.	All relatively free playing. Marked preference for YELLOW but little difference between GREEN and RED. YELLOW rated as only middle range instrument because sound is 'unsophisticated' No opinion on whether undercut.
16(P)	Selmer recital	Dan Johnston 'W'	Bundy	Slightly 'stuffy' but with more clarity in articulation than RED. Not as even as YELLOW. Second choice but close to RED	Best instrument on initial reaction – confirmed by further playing. Uniform and even. Good articulation.	Least liked. 'Stuffy'. Not even (but good around throat noted and at top of clarinet register). Articulation moderate.	YELLOW rated as an intermediate clarinet. Rated significantly better than RED and GREEN which were of similar (lower) quality. Believed YELLOW to be undercut.
17(A)	Buffet RC	Selmer C85/120	Bundy	Less open than YELLOW. More uniform than RED	Good tone. Projects well. Good dynamic range. Tone quality even. 'Open' feeling. Can penetrate.	Rather uneven. Some notes not projecting well. Tone quality not very even	Rating: 1 YELLOW clearly superior, then 2. GREEN and 3. RED. No opinion on whether undercut or not.
18(P)	B&H 1010	1010	Bundy	Least liked on initial test. Uneven tone quality. Some notes very uneven and 'stuffy', e.g. low F and A poor c.f. middle C rated good. Better quality than RED at top of clarinet register.	Best quality. Even tone, easy to blow. Clear initial first choice. Feels 'safe' at top of clarinet register.	Second choice. 'Uncomfortable' feeling at top of clarinet register. Top C has poor tone quality.	YELLOW clear first choice because of its even playing throughout the range. No opinion on whether undercut.

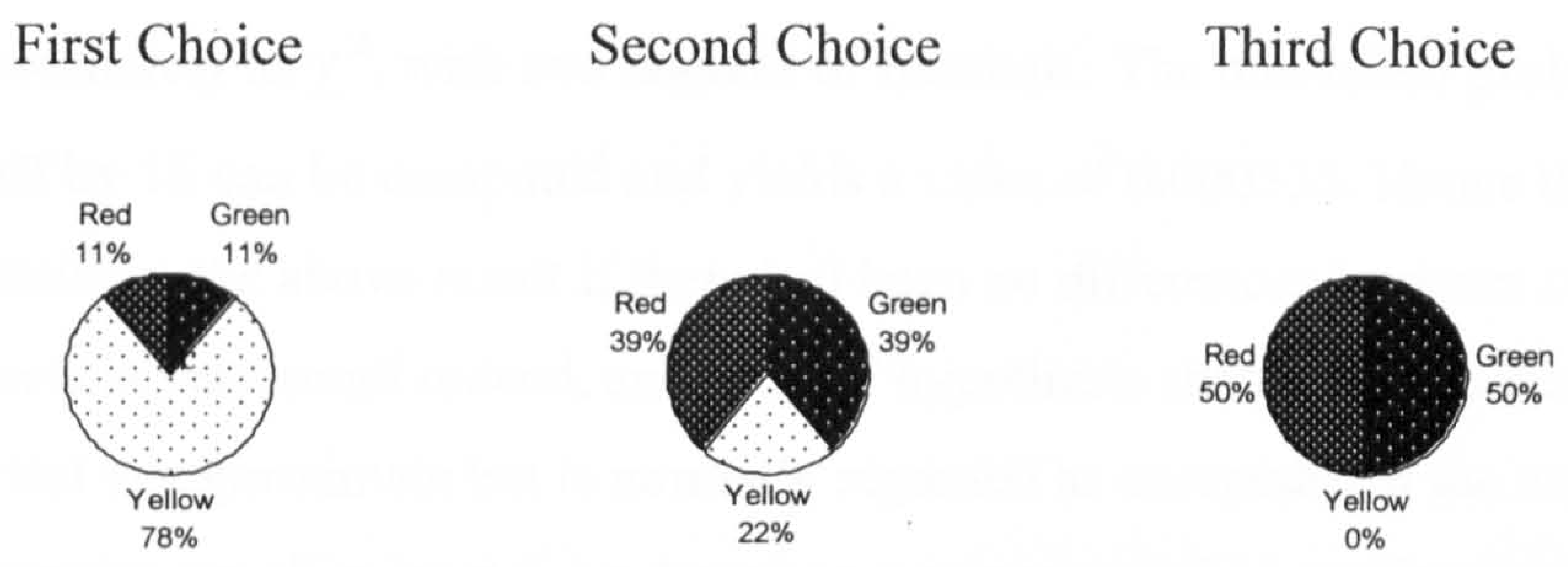
3.4.4.2 Analysis of the Results

Of the eighteen clarinettists who took part in the experiment, ten were classed as professional, three as semi-professional and the remainder amateur. All used their own mouthpieces but only four used their own barrels.

All of the players could detect differences between the instruments, but the subjective assessment of the magnitude of the differences varied considerably from player to player (see later comment). Most of the players expressed an opinion about which would be their first choice, and ranked the three instruments in order of preference. Where an order of preference was not definite, for example where good qualities were observed in different instruments, a judgement has been made by the author based on the overall comments made. The ranking of the clarinets was as follows:

Player	First choice	Second choice	Third choice
1	Y	G	R
2	R	Y	G
3	Y	R	G
4	Y	R	G
5	G	Y	R
6	Y	R	G
7	G	Y	R
8	Y	R	G
9	Y	R	G
10	Y	G	R
11	Y	G	R
12	Y	G	R
13	Y	R	G
14	R	Y	G
15	Y	G	R
16	Y	G	R
17	Y	G	R
18	Y	R	G

From the results the following pie-charts were constructed:



A majority of players (78%) chose Yellow as their preferred instrument. The number of results obtained allows statistical testing of the ranking to be carried out, at least as far as the first choice is concerned. If one considers the frequency with which a particular clarinet is made first choice, a simple but approximate 'Chi-squared' (χ^2) test can be applied. If there were no differences between the clarinets (the 'null' hypothesis) and if N tests were carried out independently by different players, the expected frequencies of each clarinet appearing in first place would be the same, (i.e. N/3).

For a total of 18 tests the expected frequency would be:

$$18/3 = 6 \text{ times}$$

i.e. for the hypothesis that the instruments are the same, the expected frequencies of the instruments appearing in first position would be equal (6).

It was found, however, that:

Green was ranked first	2 times
Yellow	14 times and
Red	2 times

The test statistic X^2 is expressed as –

$$\Sigma \frac{(\text{Observed - Expected})^2}{\text{Expected}}$$

$$= \frac{(-4)^2 + (8)^2 + (-4)^2}{6} = 16$$

Under the null hypothesis, the test statistic X^2 would be distributed approximately as χ^2, with two degrees of freedom. The one-tailed probability cut-off by 16 can be computed and yields a value of 0.000335. Hence the chance of obtaining the above result if there had been no differences between the clarinets is very small indeed, and the null hypothesis should be rejected.
This test is approximate but is normally regarded as acceptable if the expected frequencies are all at least 5, i.e. based on a minimum of 15 results. In the present application, however, it is possible to replace the χ^2 approximation by an exact calculation. As Yellow appears to be better than Red or Green, it is necessary to calculate the probability of obtaining the observed result or any other result which more strongly favour Yellow. Under the null hypothesis the probability of obtaining 14 <u>or more</u> first choices for Yellow out of 18 results is:

$$\sum_{r=14}^{18} \left(C_r^{18}\right)\left(\frac{1}{3}\right)^r\left(\frac{2}{3}\right)^{18-r} = 0.0001457$$

As there are three clarinets, the probability of any one of them achieving this many first places is three time this figure, namely 0.0004372 i.e. a 1 in 2287 probability of obtaining this result by chance.
The exact probability (0.00044) is slightly larger than the approximate one based on χ^2 (0.00034) but leads to the same conclusion. Such a low figure indicates that it is highly probable that the Yellow clarinet is of higher quality than Red or Green.

It is interesting that all but one of the professional and semi-professional players made Yellow their first choice. Those who chose otherwise, whether amateur or professional, put Yellow as their second choice. Amateur players found more difficulty in detecting and describing the differences they found, and were generally less confident in their responses. Unsurprisingly the professional players coped well with the instruments and could, within limits, overcome any deficiencies they detected.

This method of ranking is not amenable to a simple statistical test for the second and third choices since the quality of the instruments relative to each other was not quantified by the players (e.g. scored out of ten). An examination of the players' comments is necessary to reveal the characteristics of the clarinets. The attributes ascribed to the clarinets will now be discussed:

Green

Lack of response was a common feature in the comments. This was also expressed by the use of the words "resistant", "woolly", "close", "stuffy", "hard work" and "restricting".

Generally players did not feel comfortable with this clarinet. One of the two players who initially made this their first choice subsequently relegated it to second choice on changing to a different mouthpiece. The other player chose it for its staccato response and projection. However this player stated that he was not comfortable with any of these instruments. This problem arose partly because he did not normally use plain Boehm system instruments, and also he felt uncomfortable with the keywork, which is of lower quality than that with which he is familiar.

The response to staccato playing was not consistent, two players rating it good and one bad.

The good characteristics noted for this clarinet were 'smooth legato' (one player) 'plays well in piano' (one player) and 'good stability/good quality in high register (two players).

Yellow

Most players rated this as a good instrument and a majority (78%) rated this as their first choice.

The positive attributes described included:

Flexibility.

Legato response

Staccato response

Evenness (smoothness)

Tone quality

Dynamic range
Stability
Clarity
Projection

These are all qualities which one would expect from a top-quality clarinet, intended for professional use. That these could be found in a cheap student instrument with only minimal modifications came as a surprise to the participants at the end of the experiment, not to mention the author. Several of the players found it difficult to accept that the clarinet started life as a mass-produced student model, costing at most a few hundred dollars.

The attributes have been listed in the approximate order of prominence in which they appear in the comments. The only negative comments concerned the projection and, possibly, stability. One player felt that the instrument might not project through a large orchestra and one commented that it was harder to 'focus' than Red.

Red

Although the pie-charts indicate that this clarinet fared similarly to the Green, analysis of the comments shows that some players rated it as closer to the Yellow in its characteristics than to the Green. Others assessed it as similar to Green, with Green and Red both of significantly lower quality than Yellow. The instrument appears to be more variable in its response over the registers, with some unevenness between notes. One player applied the term 'erratic'. Several players recognised the feeling of instability, especially in the upper register, but the projection here was rated as good.

Only two players gave Red as their first choice. One player qualified this by saying that he might choose it as a first instrument for a beginner. The other player rated it as only marginally superior to Yellow.

3.4.4.3 Discussion of the Playing Test Results

The original objective of this experiment was to compare the playing characteristics of clarinets with and without undercut toneholes. The third instrument, with smoothed edges to the toneholes, was included rather as an afterthought. Whilst the author was gathering data for this thesis, two professional clarinettists with international reputations mentioned that they had applied this type of smoothing to brand new clarinets, either for their own use or for pupils. Benade also referred to the technique ("sweetening"), and a possible explanation for the change in 'feel' brought about by the smoothing has been described in the literature [Keefe 1983]. The undercutting experiment therefore provided an opportunity to assess the effects of the process under reasonably well controlled experimental conditions.

The control clarinet, with sharp-edged toneholes, behaved somewhat better than expected for a cheap student instrument, in that the tuning was found to be very good (although the players were asked to discount tuning discrepancies from their appraisals). This is probably attributable to the top joint bore flare described previously, which was not present in the joints of the same model with lower (earlier) serial numbers. Most players however recognised this clarinet's limitations and classified it as a cheap student model.

According to some players the undercut clarinet (Red) performed almost as well as the Yellow, but attention must be drawn to the caveat referred to earlier when planning the experimental procedure.

The main problem with the experiment is that that the undercutting had to be applied to an extant instrument, whose design had presumably been optimised to work without undercutting. The immediate effect of undercutting would be to raise the average pitch of the notes by, say, some 20 cents, although not uniformly for all notes. This is not a major problem in that, as state above, tuning was not a criterion for assessing the playing characteristics, and could in part be corrected by adjusting the barrel. The absolute pitch of the instrument as a whole was immaterial. In practice some participants noted the tuning effect but only in the throat note region, and they were not troubled by it. What is more difficult to assess is the potential for excessive undercutting to produce instability, especially in the upper registers. This effect is occasionally referred to in the literature but the exact cause is not fully understood. About a third of the players alluded to an awareness of instability in the upper register, but none thought this to be sufficiently serious to condemn the overall performance.

Six of the players used the expression 'stuffy' to describe the Red clarinet, particularly in the lower register. This is exactly the expression used by Keefe [Keefe 1983], who attributes the problem to excessive undercutting.

An alternative approach would have been to start with a clarinet with identical bore and tonehole positions but with slightly smaller diameter toneholes [Nederveen et al.1995] such that, on completing the undercutting, the pitches of all the notes would match those of the control. To prepare joints in this way was not feasible, particularly as it would not be possible to replicate the finish of the bore. The finish on the available parts is a smooth reflecting surface, achieved from an injection moulding process. The risk of over-venting the toneholes by undercutting seems to have been justified, as the Red instrument was deemed by most players to be almost as good as Yellow and markedly superior to the Green.

The results for the Yellow clarinet are surprising. The small amount of material removed during the smoothing process means that this is still essentially a non-undercut clarinet. However the effect has been to upgrade a good student model to an instrument which several highly experienced professional players rated as good enough to use in a performance.

One point of interest is that some players were of the opinion that the differences between the instruments were quite small, whilst others recorded strong preferences. Curiously, some of the players who noted only small differences then went on to rate the Yellow as a top-quality clarinet. If both statements were true then the control must a very good instrument. This apparent conflict may arise from the very subjective nature of the experiment. It is possible that those who could only detect small differences subconsciously exaggerated the good qualities of their first choice as they felt they needed to 'pass' the test. Unfortunately it was outside the scope of the experiment to persuade those who felt they would be happy to perform in public on the Yellow clarinet actually to do so. However the weight of evidence indicates that the Yellow clarinet has sufficient good attributes to distinguish it from the control, and is rated by many players to behave similarly to the Red.

To explore this point a little further, the author has played the Yellow clarinet for prolonged periods and compared it to his own Boosey and Hawkes 926 Imperial Bb clarinet (using the same mouthpiece and reed). This is a good comparison as both instruments have the same nominal bore. Yellow does appear to play very well, but on changing back to the 926, which has been exclusively played by the author for over 45 years, certain subtle differences become apparent. Again this is complicated by the inferior keywork of the Bundy, which affects fast passage work, but the impression is that the tone quality of the Yellow is different from the 926. In the author's opinion it is less refined. Again this is no more than a personal opinion, biased by a long familiarity with a particular instrument.

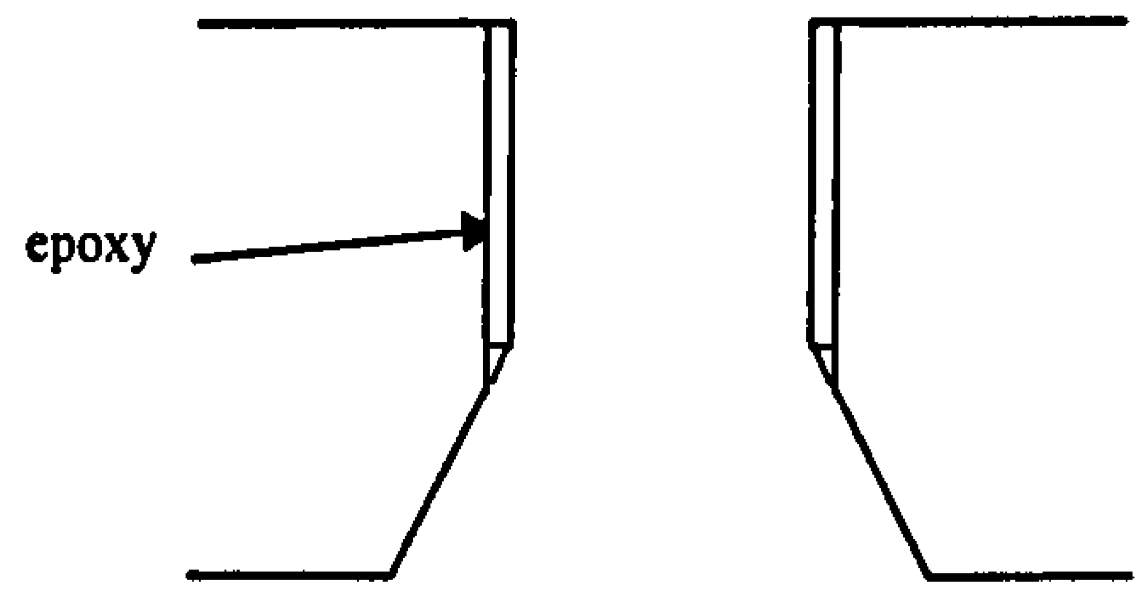
It would perhaps be fair to summarise the results from smoothing the tonehole edges by stating that smoothing has eliminated many of the deficiencies found in the student model. Of particular note is the improvement in the evenness of response to both legato and staccato playing. The resulting instrument shows many of the attributes associated with a top-grade professional model clarinet. It might be speculated that if the smoothing process was applied to a top quality non-undercut, clarinet this might produce an instrument of exceptional quality.

A question sometimes asked is whether clarinets need to be 'played in' from new. There is a general belief, based on anecdotal evidence, that clarinets whether undercut or not, improve as a result of being played from when they are new. Manufacturers always recommend that new wooden clarinets should always be carefully dried out after use, to reduce the risk of the wood splitting. (In practice clarinets appear to split in an unpredictable manner if there is sufficient internal stress in the wood, even when they have been conscientiously dried out every time after use). Drying is normally achieved by dragging a 'pull-through'- a piece of absorbent material attached to a cord - through the bore. It is likely that this often repeated use of a pull-through causes a slight rounding of the tonehole edges in addition to any rounding which may have already occurred if the manufacturer has polished the bore. Hence it may be the polishing and rounding action of drying the clarinet which causes a beneficial effect as demonstrated in the experiment, rather than playing it. If this effect is real then it might be expected that the benefit will be greatest in clarinets without undercutting. Benade [**Benade** 1976] has referred to the elimination of sharp edges in the context of the effects of wall material on the playing properties of wind instruments. Benade points out that for rigid walls, changing material may result in geometrical differences because different materials require different fabrication methods or may machine differently. It is easy erroneously to attribute the change in playing characteristic simply to the change of material, rather than the shape changes that this has brought about. However, geometrically identical rigid tubes which have different porosities at the bore surface will have different damping, and hence different playing pitches. According to Benade, frequency differences may be as much as 20 cents. (This is in agreement with the differences observed between wood and ebonite pre-war Boosey and Hawkes 1010 models in this study).

3.4.5 Secondary Experiment: Infilling of Undercut Toneholes (Red Clarinet)

As described above, the undercutting of the Red clarinet was applied to an instrument whose toneholes sizes had (presumably) been optimised by the manufacturer. The instrument might therefore be considered to be over-vented as a result of the undercutting. Apart from the obvious pitch rise, the characteristic behaviour of an excessively undercut clarinet is reported to be a loss of stability, particularly in the upper (clarinet) register. Some of the testers commented on a perceived lack of stability in this region.

In an attempt to resolve this possible complication, a secondary experiment was planned after the main playing experiment had been completed. This involved reducing the diameters of the straight sided parts of the Red clarinet toneholes whilst leaving the undercutting as before. This was achieved by painting layers of nail varnish onto the cylindrical parts of the walls.



The amount of material added was aimed at restoring the tuning to the original pitch of the non-undercut instrument. A number of iterations was required with the instrument being played and checked for tuning at each stage (using a tuning meter).
Three of the original testers were then asked to make a direct comparison between the modified undercut clarinet (Red) and the smoothed tonehole (Yellow) clarinet.

3.4.5.1 Results of Retesting.

The observations of the testers and those of the author are tabulated below, using the same tester's reference numbers as before.
All of the players found in general little difference between the modified Red and the Yellow clarinet. After infilling the toneholes, Red has become, by a narrow margin, the first choice for the reasons stated in the Table. The subjective nature of the test is demonstrated by the way in which Yellow has been 'down-graded' when compared with the 'improved' Red, even though no alterations had been made to it between the tests.
The previous results indicated that both smoothing and undercutting can be used to improve the quality of a clarinet as perceived by the player. However, this additional small-scale experiment demonstrates that care must be taken when applying undercutting to toneholes which have already been optimised for size and position. Apart from the obvious sharpening effect, excessive undercutting produces an effect which some players describe as a feeling of instability in the upper part of the clarinet register. By contrast, a clarinet of the same design can be improved to a similar extent by rounding and smoothing all internal sharp edges. The process involves removal of a minimal amount of material and appears to have no adverse side effects.
It is concluded that smoothing and judicious undercutting can both improve the quality of a clarinet as perceived by the player, and that the sharp edges at the intersections of the toneholes with the bore are a factor in limiting the performance of cheap mass produced clarinets. The question of whether smoothing or optimal undercutting is a better technique cannot be answered because of the many factors, both objective and subjective, involved in judging the quality of a clarinet.
It is noted that a conical fraise tool can leave 'sharp' edges at the bore and tonehole junction,and a slight rounding and smoothing in these regions may well have additional beneficial effects. Makers who have used bell-shaped fraises or more than

one conical fraise in a hole and have then merged the cuts to generate a smooth profile may well have been aiming at achieving this.

This experiment suggests that the nature of the air flow in the region of the toneholes has a readily detectable effect on how the instrument feels to the player. Under normal playing conditions air flows in the vicinity of toneholes reach levels at which turbulence may begin [Keefe 1983] and the associated energy losses may be the cause of the negative effects experienced by the players. Experiments and theoretical models on toneholes, for example [Keefe 1982a and 1982b], support this explanation, but are not sufficiently detailed to include edge sharpness detail. A better understanding of the air flow phenomena is likely to be revealed by flow visualisation techniques, such as Particle Image Velocimetry currently being employed at the University of Edinburgh.

Player reference	Mouthpiece	Barrel	Test Clarinet		Additional comments
			YELLOW	RED	
4	B&H926 1.1 mm tip opening	Bundy	As before feels easy to play. Slightly more resistance on some notes and therefore not quite as even compared to modified RED. Slightly less refined tone than RED at high dynamic level,	Very even and easy to play. Slightly more 'alive' and 'sweeter' tone. Retains tone quality to higher dynamic than YELLOW.	Very difficult to distinguish between clarinets now. Quality has converged. Both rated as good instruments. RED has particularly good LH clarinet register and tone is refined overall. Very even throughout. Becomes first choice now.
18	B&H 1010	Bundy	YELLOW felt to be slightly less responsive than RED	Good sound now at top of clarinet register. Feels stable and 'comfortable' to play..	Both rated as good. Difference between RED and YELLOW now slight. Difficult to choose but RED now first choice.
10	B&H 1010	Bundy	Big chalumeau sound with possibly more resistance. Projection more restricted than RED. Throat notes now thought to be bright and quality not as good as RED. Upper registers less even and sound 'thin' c.f. RED. Less overall projection than RED	Easy blowing in chalumeau with good projection. Throat notes now preferred to YELLOW. Instability at top of clarinet register removed. Feels good now. Extreme register comfortable. Projects well overall.	Differences not great except in throat region where RED is definitely preferred. RED now first choice. (noted that it might be more suitable for an experienced player than a beginner).
Author	B&H926 0.9 mm tip opening	Bundy	Still happy with overall response of the instrument.	Instability in top of clarinet register no longer felt. Improved tuning.	Very difficult to chose between instruments now. Would be happy to use either as a 'spare'.

3.5 Right Hand Fork Fingerings for a Classical Clarinet: Effects of Undercutting

3.5.1 Objective

It has been noted earlier that the five- or six-key 'classical' clarinet, from the late eighteenth and early nineteenth century, has small toneholes so that fork fingerings can be more effectively used to play chromatic scales.

The survey found that all of the clarinets of this pattern had toneholes which had been undercut, and many examples were seen where considerable care had been employed when carrying out the process. Systematic undercutting was routinely applied to enhance the tone quality and volume of the sound as well as to adjust tunings of individual notes.

In this section the objective is to determine how the ability to fork finger depends on tonehole size and undercutting. Do undercut small holes retain more of the ability to fork finger effectively in comparison with larger holes, which produce a similar tone quality and volume?

3.5.2 Equipment and Instrument Used.

These experiments were based on a six-keyed classical clarinet by the London maker Goulding [CLT034]. The London pattern mouthpiece by T Wood with the clarinet had been damaged and repaired but was not playable. It was replaced by a modern replica by Brian Ackerman and 'Black Master' reeds by Vandoren were used. (These are for modern German style clarinets and match the Ackerman mouthpiece reasonably well).

It should be noted that this combination of reed and mouthpiece is acceptable for the present purposes since only pitch changes are being considered rather than changes in tone quality.

The experiments were made with the instrument blown naturally (by the author) and with the artificial mouth, as described earlier in Section 3.2 but fitted with a smaller replacement barrel to match the Goulding. As the reeds are of natural cane they had to be kept moist when artificially blown, and a fine mist of water droplets was sprayed into the enclosure as required.

Frequency measurements were made with a Korg Model DT-1 Digital Tuner and a Brüel and Kjær 2238 Mediator was used to measure sound pressure levels. The sound level meter was set to the built-in default parameters (Range 30-110dB, Broadband, Frequency Weighting A). Digital recordings were made using a Labtec Verse-704 microphone connected via a sound card to Sound Forge 4.5 software with Sound Forge 4.0 Spectrum Analysis plug-in. Measurement were made in a quiet domestic environment, ≤40 dB(A), with clarinet and microphone positions constant throughout. The microphone was placed approximately 500mm from the right hand joint, at 30° to the axis of the clarinet.

The overall tuning of the Goulding clarinet was first assessed by playing over a three octave range: E_3 to E_6. There is some scope for pitch flexibility when played with a soft reed, but for this experiment the aim was to play with a constant embouchure, avoiding the temptation to 'bend' the notes to improve tuning. The fingerings used were those described by Baines [**Baines** 1957]. The pitch meter was set to A_3=440Hz and deviations are in cents from the equally tempered scale based on this. The clarinet is in Bb and clarinet notation has been used in the Table.

Chalumeau			Clarinet		
Note	cents		Note	cents	
E_3	-12		B_4	-5	
F_3	-20		C_5	-15	
$F\#_3$	-11		$C\#_5$	-12	
G_3	-10	-10	D_5	-10	-10
$G\#_3$	-30		Eb_5	-30	
A_3	-20	-20	E_5	-15	-15
Bb_3	+6 (●○●)		F_5	0	
B_3	-70 (●○○)		$F\#_5$	+5	
	+40 (○●●)				
C_4	-18	-18	G_5	-10	-10
$C\#_4$	+30 (○/●●●)		$G\#_5$	-5	
D_4	-25	-25	A_5	-10	-10
Eb_4	+5		Bb_5	+5	
E_4	-30	-30	B_5	-10	-10
F_4	-20		C_6	-10	
$F\#_4$	+70				Ave -11
G_4	-20				≈ 438z
$G\#_3$	+40 (T +A key)				
	+20 (Spkr only)				
A_4	-15				
Bb_4	-15				
		Ave -20	$C\#_6$	-10 (th. Only)	
		≈ 435Hz	D_6	-10 (A key only)	
			Eb_6	-20	
			E_6	-10	

This playing assessment, carried out under normal playing conditions, indicates (from the open hole basic notes) that the clarinet plays at lower than present day pitch, possibly intended as A=435Hz, with the upper register rather sharp (~438Hz) relative to the lower. (The length of the instrument is the same as that of a modern Bb clarinet pitched at A=440Hz with a 15 mm bore diameter, but the smaller bore will produce a lower pitch). However changes to the bore profile caused by shrinkage since manufacture will probably have affected the tuning. Using the first finger of the right hand produces a very flat B_3 (-70 c), and adding the third finger forms a slightly sharp Bb_3 (+6 c). The alternative fingering shown for B_3 is also unsatisfactory (+40 c). For this clarinet, half-holing might be necessary.

The right-hand joint of the Goulding is a short section with a socket reinforced with an ivory ring at the top and a tenon at the bottom, with just the three open fingerholes for the right hand. These were examined in Part 2 and the extent of the undercutting was measured. For these experiments, two replicas of the right hand joint were made in pear wood, having different sizes and shapes of toneholes drilled at the same positions as in the original.

The first (RJ1) has the toneholes with the same diameter as the outside of the original but straight sided (not undercut).

The second (RJ2) started as RJ1 but the toneholes were progressively enlarged by 10% steps of the cross sectional area again with no undercutting.

The experiment was designed to estimate what size of straight-sided holes would produce the same volume and tone quality as the original undercut holes and then determine the effectiveness of fork fingering (B_3 to Bb_3) for the two situations.

3.5.3: Enlarged Cylindrical Holes Compared with Undercut Holes.

The experiment was performed with the instrument blown both with the artificial mouth and naturally. When using the artificial mouth, the measurements were made, as far as possible, under constant conditions. Where interruptions occurred (e.g. when the holes in RJ2 had to be enlarged), the same pressure in the mouth chamber was set. With the right hand joint removed, the intensity of the chalumeau note produced was measured and, if necessary, adjusted to its previous value by making a small adjustment of the lip micrometer (movement normal to the reed). This measurement is independent of the right hand joint and it was found that minimal adjustments were needed as the sound level stayed within a few dB of target throughout.

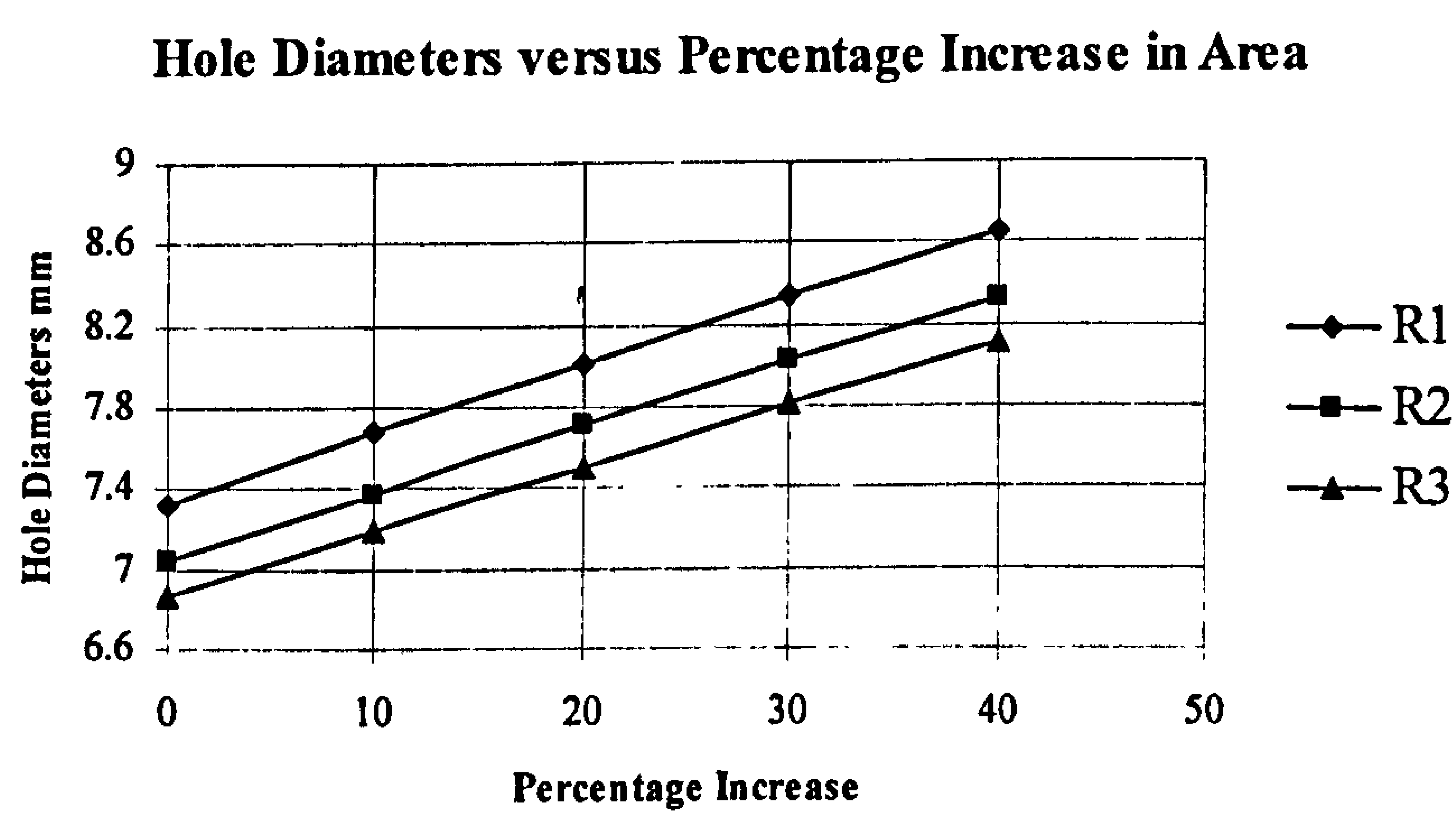
Considering first the original clarinet:

The chalumeau notes controlled by the right hand were played first using the artificial mouth at a forte level (14.5 inches water pressure), and the tunings and sound levels measured. Closing the first right hand finger-hole produces a very flat B_3 (-78 cents relative to A=440Hz, -58 cents relative to chalumeau average pitch). This is a few cents flatter than when played naturally. Making a forked Bb_3 with the third finger lowers the pitch by 20 cents, in good agreement with naturally blown measurements of the initial assessment but the loudness and tone quality are noticeably affected. Adding the little finger lowers the pitch by a further 16cents (total 36 cents) with a further reduction in loudness and quality.

Similar measurements were made with the register hole open (clarinet register) but these were more difficult as there was a tendency towards instability when blown artificially. This may have been due to not optimising the artificial lip for the smaller reed and mouthpiece. This instability was less evident when testing modern clarinets.

The original right hand joint was next replaced with RJ1 (same external diameters and positions but straight cylindrical holes) and the difference was immediately apparent. As anticipated, apart from lowering the pitch, the notes sounded quieter and of lower quality. Blown artificially under the same conditions, B_3 became 98 cents low or 78 cents relative to chalumeau average pitch, and making a third finger fork lowered the pitch by 32 cents (c.f. 20 cents originally). Adding the little finger (i.e. closing hole VI), lowered the pitch a further 10 cents making a total of 42 cents, (c.f. 36 cents). Again measurements were made in the clarinet register, and the same problem with instability was found.

This right hand joint was retained and a second replacement joint, RJ2, attached. In this the toneholes were enlarged by 10% in cross sectional area (RJ2 10%) as described above and the same pitch measurements carried out. The process was repeated twice more (RJ2 20% and RJ2 30%)



The results on pitch are shown below (in cents) in comparison with the first measurements

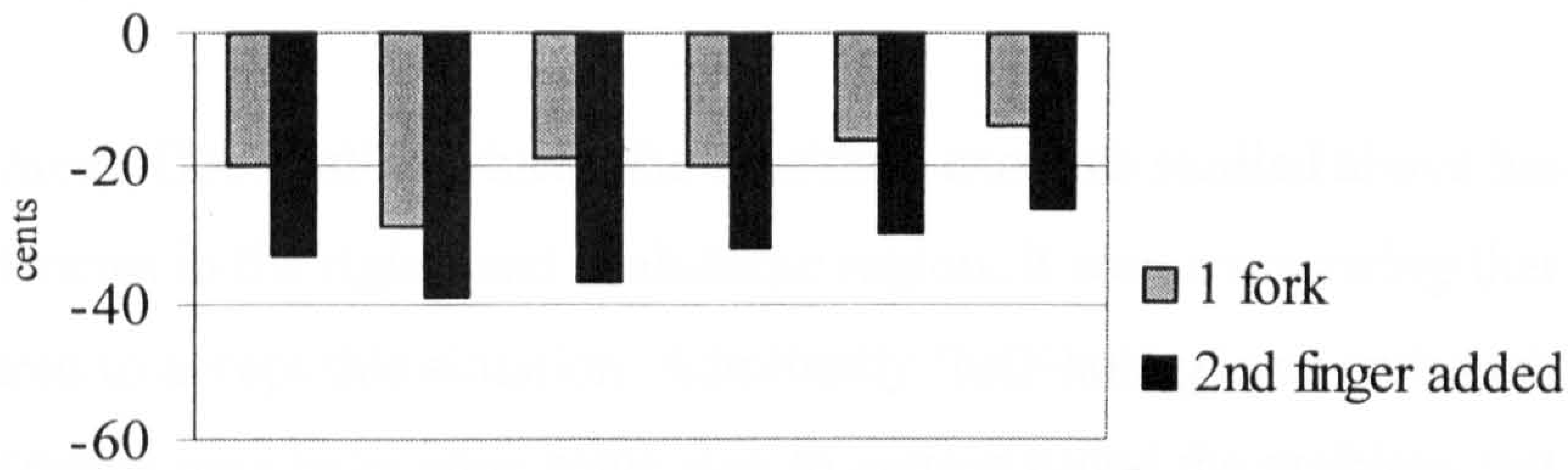
(A_3 concert=440Hz):

Note	Blown	Original		RJ1	RJ2+10%	RJ2+20%	RJ2+30%	Rj+40%
C_4	Naturally	-30	-30	-50	-30	-20	-21	-20
	Artificially	-30		-45	-35	-20	-18	-20
B_3	Naturally	-70	-78	-95	-80	-78	-70	-70
	Artificially	-78		-98	-86	-70	-70	-70
Bb_3(●o●)	Naturally	+6	+8	-20	0	+5	+15	+14
	Artificially	+2		-30	-3	+7	+12	+18
B_3(●o●●)	Naturally	-16	-5	-30	-20	-8	0	0
	Artificially	-18		-40	-20	-5	0	+7
A_3	Naturally	-20	-15	-40	-30	-22	-17	-22
	Artificially	-21		-40	-30	-14	-12	-12

In general there is good consistency between pitches obtained by blowing naturally or artificially. Average values are shown below:

	Original	RJ1	RJ2+10%	RJ2+20%	RJ2+30%	RJ2+40%
C_4	-30	-48	-33	-20	-21	-20
B_3	-75	-96	-83	-74	-70	-70
Bb_3(●o●)	+5	-25	-2	+6	+14	+16
B_3(●o●●)	-13	-35	-20	-6	0	+4
A_3	-19	-40	-30	-18	-15	-17

The flattening effects on B_3 of adding a single fork finger and then a second finger as a means of producing Bb_3 were extracted from this data and are shown graphically below:



	Original	RJ1	RJ2+10 %	RJ2+20 %	RJ2+30 %	RJ2+40 %
1 fork	-20	-29	-19	-20	-16	-14
2nd finger added	-33	-39	-37	-32	-30	-26

This shows that, in the chalumeau register, as expected, if the original undercut holes were replaced with non undercut holes of the same external diameter, the flattening effect of fork fingering is increased (by 9 cents for a single fork). If the cylindrical holes are increased in cross-sectional area by 10-20%, the ability to fork finger is roughly the same as for the original undercutting. Surprisingly, if the enlargement is increased to 30%, then 40%, the flattening effect is reduced by only a few cents. However this takes no account of the volume and tone quality produced by the different arrangements. This proved difficult to measure experimentally, and a mainly subjective approach had to be employed, supported by measurements where possible. The volume of sound was significantly reduced with joint RJ1. This was immediately apparent to the ear and could be confirmed by SPL measurements. Tone quality was markedly inferior. Subjectively, it was assessed that it was not until the holes had been enlarged by 30% or more that the volume was restored to that of the original instrument. Loudness measurements were not sufficiently reliable to confirm this as the measurements were not carried out in an ideal environment.

It was found that when the holes were increased in area by 40%, the forked notes became unstable and of poor quality. The instability manifested itself when played naturally and it was noticed that when artificial blowing was used, the range of settings for which all of the notes could be sustained became very narrow.

The quality of sound using any of the cylindrical hole arrays was assessed as being slightly inferior for normally fingered notes, and more noticeably inferior for the forked ones. Examination of sonograms confirmed that the notes produced by the experimental holes, whilst showing some similarities to each other, were dissimilar to those produced by the original joint.

3.5.4 Digression: Attempt to Sharpen B_3 by Heavy Upstream Undercutting.

Like most 'Classical' clarinets, the Goulding example studied above has severe tuning deficiencies in the right hand chalumeau region. It seems surprising that players were prepared to accept this situation. Admittedly 'half-holing' and embouchure adjustments may have gone some way to getting round the problem, but at the cost of tone quality, which is equally unsatisfactory. It was therefore decided to see what would happen if the middle hole of a standard joint was grossly asymmetrically undercut upstream, leaving its position and external diameter unchanged.

The third replica joint, RJ3, was prepared initially as RJ1 without undercutting and its tuning measured. The middle hole was then enlarged, as described above with a sloping upstream cut at approximately 45° to the normal and the joint re-tested (blown naturally).

Note	cents			
	Original	As RJ1	Hole 2 Cut Upstream	Hole 2 Cut Upstream. 1&3 bell-shaped
C_4	-30	-50	-50	-30
B_3	-75	-96	-70	-70
Bb_3(●○●)	+5	-20	+15	+22
B_3(●○●●)	-13	-30	+5	+8
A_3	-19	-40	-40	-21

This drastic undercutting has raised the pitch of B_3 by ~26 cents (still 50 cents flat relative to A=435 Hz), but adding a single fork finger now causes only 15 cents flattening, compared to 24 cents in RJ1. The comparable figures on adding a second figure causes an additional 10 cents flattening, both before and after undercutting.

To make a valid comparison with the original joint, Holes 1 and 3 need to be undercut as in the original. This was carried out with a fraise combined with filing to replicate, as far as possible, the original profiles, and the joint was re-measured. With all three holes undercut, the tuning of the normally fingered notes C_4 and A_3 was brought close to the original, but the heavy asymmetrical undercutting of Hole 2 raised the pitch of B_3 by only 5 cents. The flattening effect on adding a single fork was reduced from 30 to 8 cents, and with a second finger added, from 38 to 22 cents.

This *ad hoc* experiment illustrates the ineffectiveness of undercutting to resolve the B_3/ Bb_3 tuning problem in clarinets of the 'Classical' pattern.

3.5.5 Summary of Experiments on the 'Classical' Clarinet Right-Hand Joint.

The undercut toneholes in the right hand joint of a 'Classical' clarinet have been replaced with cylindrical holes of various sizes, and the flattening of note B_3 caused by adding one or two forked fingers has been measured. It was found that a cylindrical hole of the same diameter as the original showed a greater flattening effect, as expected. As the hole sizes were increased, the holes were equivalent in this respect when the cross-sectional areas had been increased by 20 to 30%. Further enlargement to 40% continued to show the flattening effect but the amount was reduced. Even at 40%, adding one finger flattened the B by 14 cents compared with 20 cents for the original undercut holes. Loudness was assessed to be similar at about 30% enlargement, but this was only a subjective estimate.

The tone quality produced over the range of cylindrical hole sizes was perceived to be of inferior quality to that produced by the original undercut holes. Even when the enlargement had restored the loudness, the tone quality was perceived to be poorer than the original sound. Different sonograms were obtained but it was not possible to quantify the differences.

This experiment is not conclusive because of the parameters which have not been quantified and, furthermore, only one example of a period clarinet was used. However, the results indicate that the statement: 'undercut toneholes are acoustically equivalent to straight sided toneholes' is not strictly true and may explain why the practice of undercutting continued after tonehole size constraints had been removed. It is noted that the differences between straight sided and undercut toneholes for a narrow-bore clarinet are far more evident than with the large bore instruments used in the playing tests.

Part 4 Summary and Conclusions.

The survey of tonehole undercutting was carried out on clarinets made from the eighteenth century to the present day. Examples were sought which represent the main-stream development of the instrument through to the modern Boehm system clarinet which is played universally today. The objective of the survey was to discover the extent to which undercutting has been applied through the development of the clarinet. It was not known at the outset whether undercutting in the period before clarinets were mass-produced was part of the inherent design, or whether its use was mainly as an adjustment technique to correct tuning or other acoustic deficiencies. Examination of the earliest available clarinets from the second half of the eighteenth century has revealed that, in general, undercutting was applied, at least to the fingered holes used for the basic scales of the instrument, during manufacture, and that fraise tools were commonly used rather than hand filing. Subsequent adjustments, either by fraising or filing individual holes for adjustment purposes, were seen only occasionally. Examples were found where up to three conical fraise tools of increasing angle had been used sequentially in the same hole, to create a shape approximating to a flare. This is a difficult and time-consuming procedure, and indicates that makers had discovered empirically that the elimination of abrupt shape changes was beneficial to the instrument's behaviour. Later examples were also found where smooth 'bell'-shaped flares had been produced.

By the beginning of the nineteenth century the clarinet had to a large extent become standardised. Although some of these instruments had many keys, they were basically constructed as the five key instruments from the previous century. Of the early nineteenth century clarinets examined, all were extensively undercut, with again examples of flare shapes found in some of the major toneholes. In general the undercutting applied to these fingered holes has been more carefully executed than in the keyed holes. Quite frequently the less important keyed holes were found to be given a nominal 'chamfered' finish, or occasionally left without undercutting, although exceptions to this were found.

In the second decade of the nineteenth century Müller developed an improved clarinet design which provided good ventings for all notes of the chromatic scale, with larger and better placed toneholes, together with a more efficient keywork system, eliminating the necessity to fork finger. Early examples of Müller-type clarinets were sought in the survey in order to determine what effect these changes had on the use of undercutting. It was found that, despite a progressive increase in bore and tonehole sizes, the practice of undercutting was still carried out. The same was found when looking at early clarinets made by Eugene Albert of Brussels, who further refined Müller's improvements to produce the highly successful 'Simple System'. Furthermore, early examples of Boehm system instruments made by Buffet were all found to be extensively undercut, despite having optimally-sized and positioned toneholes.

Clearly, undercutting is not simply a technique used as a device for improving the sound of early, acoustically unsatisfactory instruments. It is a time consuming and therefore expensive process, but makers continued to apply it as the clarinet evolved. In fact the survey confirmed that it was not until the twentieth century that completely non undercut Boehm system clarinets were introduced (by Henri Selmer). From about the 1920s good quality clarinets with relatively large bores (~14.9mm), mainly Boehm system, co-existed with and without undercutting.

As part of the survey, examples of Boehm system Martel clarinets from the beginning of the twentieth century were examined. Martels were highly regarded by professional players, and the examples looked at had been played by eminent clarinettists in the 1920s and 30s. Heavy undercutting was found which, it is believed, contributes to the ease of playing of these instruments, but their tuning is unsatisfactory. It is suggested that heavy undercutting had been applied after manufacture in an attempt to raise the pitch from Continental A=435 to A=440 Hz. In so doing, instruments had acquired their unique qualities but the overall tuning was compromised.

Attention has been given to the '1010' model introduced by Boosey and Hawkes in the 1930s. This has an exceptionally wide bore (15.24 mm) and was intended to be their top quality model for professional use. Good pre-war examples of were examined and found to have moderate but variable undercutting. It is known that these instruments were hand adjusted on an individual basis, and this appears to have been undertaken successfully. Post war examples were also found to have variable undercutting, but the process does not appear to be controlled. This, together with lack of bore consistency, probably contributed to the poor reputation some examples of this particular model eventually acquired.

Even though mass-production techniques are nowadays applied to clarinets, one large manufacturer still employs a skilled technician who has sole responsibility for carrying out the final undercutting. However, modern numerically controlled machines have the capability of carrying out the process. The survey indicates that another of the large manufacturers appears to have automated the process by this route, although this cannot be positively confirmed because of commercial confidentiality.

With modern manufacturing methods, even some of the cheaper student models are now being undercut, whereas traditionally these were made with plain toneholes, to reduce the cost.

This survey gives a picture of the way in which undercutting has been applied to the clarinet throughout its history and raises questions about the effects it produces. A number of experiments were carried out (Part 3), to test and quantify some of these effects.

The first experiments were devised to measure the effect of various types of undercutting of the first left hand finger toneholes. In the Boehm clarinet the F_4/ C_6 interval is sometimes too wide, and when this occurs this first hole is adjusted to improve the twelfth. An artificial mouth for maintaining a constant embouchure and an experimental clarinet in which tonehole inserts could be substituted were used for the measurements. Conventional conical undercutting narrowed the interval but markedly raised the pitch of both notes. Asymmetrical undercutting upstream was a more effective technique in that similar narrowing could be achieved with less overall sharpening. However, lateral cutting, as advocated by some clarinet technicians, was found to be ineffective.

A second experimental clarinet was made in which part of the body comprised rotatable sections with different toneholes which brought into play. An acoustic impedance head was constructed which was used to measure the input impedance. The aim was to determine whether the measured impedance spectra would detect changes when one or more toneholes were changed by undercutting and, in particular, whether undercutting could bring about better mode alignment. The impedance peaks in a clarinet appear at intervals which are not exact whole odd number multiples of the fundamental frequency. The closer the peaks are to exact numbers, the more readily they will couple to the harmonics generated by the reed, and this would make the instrument feel easier to play.

In order to visualise changes in mode alignment, the frequencies of the impedance peaks were divided by the fundamental frequency and then by the harmonic number. When plotted against the harmonic this produces a 'signature' which would ideally be flat if the alignment was perfect.

Applying progressively increasing conical undercutting to the first open hole produced only a small change in the signature. However, undercutting the first and second open holes caused the signatures to diverge at the higher harmonics, the ratio change being of the order of 1% at the seventh harmonic. This is only a small difference, and at low playing levels the higher harmonics would be of insufficient strength to take part in the regeneration mechanism. This suggests that any differences resulting from undercutting perceived by the player are a consequence of processes other than simple mode alignment. Sonograms were recorded in both experiments which showed slight changes in the relative strengths of the harmonics on undercutting, but the changes were not perceptible to the ear.

Two closed holes upstream of an open hole were shown to act as a localised bore perturbation, when undercut.

In order demonstrate these effects it was necessary to make cone undercuts of the maximum size achievable, (i.e. intercepting the bore tangentially). The undercuts found in practice are invariably much more moderate, and consequently the measured changes would be even less, as was also demonstrated.

Asymmetrical upstream and downstream undercutting caused no significant signature changes for the right hand notes, but indicated a slight reduction in the third harmonic ratio when applied to the first left-hand fingerhole, in line with the playing tests.

The conclusion from these experiments is that it is unlikely that the alignment changes on undercutting are of sufficient magnitude for them to be sensed by the player, and impedance scans are not a suitable tool to monitor with confidence the progress of undercutting.

In the next set of experiments, a number of professional and good amateur clarinettists were invited to compare three specially prepared clarinets. Unknown to the testers, these were three cheap student instruments which originally has straight-sided toneholes throughout. Before the tests, one of the clarinets was conventionally undercut and another had all sharp internal edges (where the toneholes meet the bore) slightly rounded and smoothed. The tests were conducted to a strict protocol, designed to prevent the players being influenced in any way.

The control clarinet was recognised by most of the testers for what it is – a cheap student model. Surprisingly a clear majority selected the smoothed clarinet as their first choice and some even described it as playing like a top quality professional model. The undercut clarinet was deemed to have good qualities but was thought not to be as good overall as the smoothed. Sufficient numbers of players took part that a statistical analysis of the results could be made.

On reading the comments it was noticed that some of the players had experienced a feeling of insecurity when playing the undercut clarinet at the top of the clarinet register. This can be symptomatic of an instrument which has had too much undercutting applied. It was realised that if the hole sizes of the original instrument had been optimised then any undercutting would be detrimental to its overall behaviour. The cylindrical portions of the undercut toneholes were therefore reduced in diameter and the clarinet re-tested against the smoothed one by a small group of the original testers. These now unanimously rated the undercut as marginally superior to the smoothed.

The results of this experiment strongly suggest that the 'cheap' qualities of the student instrument are associated with the presence of sharp edges at the ends of the toneholes. Improvement to the feel of the instrument can therefore be brought about by undercutting and by smoothing, a process which removes only a nominal amount of body wall material

It should be noted that these changes occurred in well designed instruments which, although intended for the student market, could be played in tune. It is not suggested that a bad instrument could be turned into a good one by applying these changes; rather that a well designed clarinet can be made to feel like a good quality one by carrying out a relatively simple smoothing process.

The final experiments examined one of the tuning problems inherent in clarinets of the 'Classical' design. The right hand joints of clarinets of this pattern have three holes which have no satisfactory ventings to produce good-quality, well-tuned B_3 and Bb_3. The note produced by adding one finger gives a B_3 which is unacceptable flat, whilst a two- or three-finger fork is very sharp. Fingers 1 and 3 usually give a slightly sharp Bb_3, which is better tuned on adding one more finger, but at the cost of tone quality. The objective was to test whether replacing the small undercut holes with larger cylindrical holes, giving the same volume and timbre, would reduce the effectiveness of fork fingering.

An original six-keyed Goulding clarinet from the early nineteenth century was used for these tests, blown normally and artificial. A set of replacement right-hand joints was made in which the holes could be modified. It was found that cylindrical holes with cross sectional areas approximately 20% greater than the originals, (based on the external diameters), behaved similarly to the original in terms of the ability to fork finger. However it proved difficult to measure when the volume and timbre matched. From a subjective assessment the holes needed to be enlarged by 30% or more to match volume. None of the enlargements replicated the tone quality as judged by ear or from sonogram plots. It seems that the makers were using undercutting to combine the ability to fork finger with the production of a particular tone quality and volume, which non-undercut holes cannot achieve.

As a digression an attempt was made to sharpen B_3 obtained with one hole closed by grossly undercutting the middle hole upstream. Only a small amount of sharpening was achieved, at the cost of losing some of the flattening on adding the third finger and also causing instability.

These experiments have demonstrated that the effects of undercutting are complicated and subtle. As stated above, in early clarinets with small bores, undercut toneholes appear to generate tone quality which cannot be produced by cylindrical holes. However, in modern wider-bore instruments, the differences are small. Few listeners can tell whether a clarinet is undercut or not, and most players are unable to tell by playing. It is probable that differences between players using identical instruments may be greater than those brought about by undercutting.

Undercutting a single hole is potentially hazardous as, when closed, this acts as a bore perturbation for lower notes, and the effect on the third harmonic alignment has been demonstrated. Excessive undercutting can produce a sense of instability to the player whilst it may also yield a feeling of ease of blowing as in the Martel instruments.

In general only minor changes in mode alignments result from undercutting when the air column is excited at low drive levels, and the system behaves essentially linearly. The smoothing experiment indicates that, under playing conditions, non-linear processes are occurring at sharp tonehole edges. There may be a transition occurring from steady to turbulent flow in these localities and the associated energy dissipation may be what is sensed by the player.

Whilst testing clarinets the phenomenon of 'streaming' from the first open tonehole was observed when playing in the chalumeau register. If a clarinet is blown as when playing, but the note is not started, there is only a small outflow of air from the first open tonehole. The total flow is distributed between all of the open holes and the bell. When the note is struck, there is a strong flow from the first open hole, which drops markedly on opening the register key. This phenomenon has been described by Keefe [Keefe 1983] in the context of woodwind instruments.

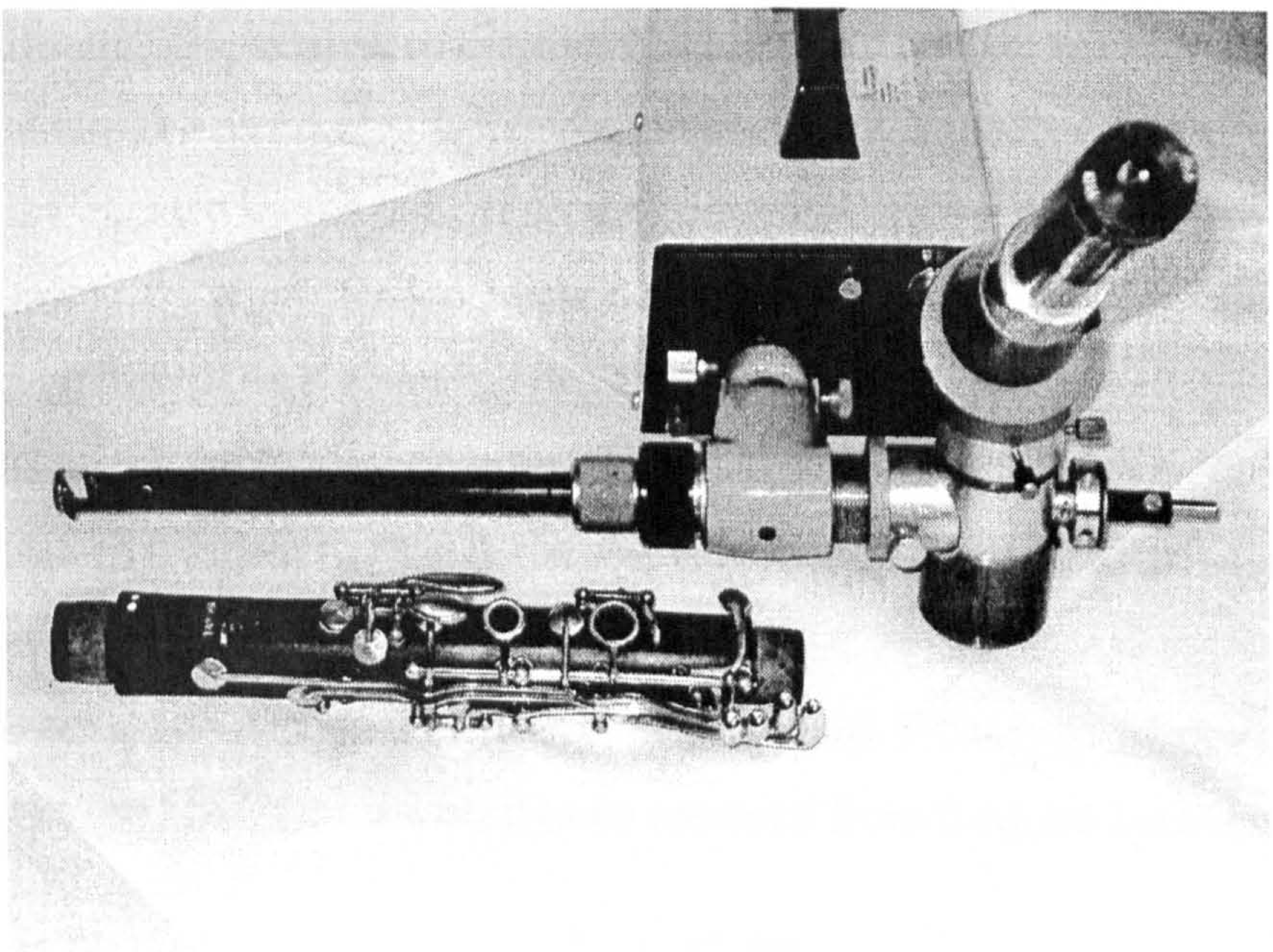
When an energetic acoustic wave travels along a tube, friction at the walls causes the air to vibrate rotationally, whilst away from the wall it vibrates irrotationally. This sets up a driving force known as Reynolds stress which enhances flow in the boundary layer in the direction in which the wave is propagating. The return flow is along the axis and vortex loops are established. When the boundary layer flow encounters a discontinuity, such as at the end of the tube or at a tonehole, the flow is directed out of the hole and streaming results. Recent experiments show that the mechanism is sensitive to the sharpness of edges [Skulina D.J 2003]. It is suggested that current studies of tonehole lattices [Skulina D.J et al. 2002] using Particle Image Velocimetry (PIV) to visualise fluid flows might be extended to examine the effects of changes to the bore/tonehole intersections, such as smoothing and undercutting. Ideally the measurements should be made under conditions corresponding to those encountered during normal playing, which could be achieved by using an artificial mouth. This would also replicate the flow of air through the instrument as normally provided by the player's breath.

Appendix A: Octave Notations and Frequencies (Equally Tempered A_4=440Hz)

Standard	Piano	Organ	Helmholtz	Hz	Clarinet	
					Bb	A
C_3	C_{28}	C	c	130.81	D_3	
				138.59		E_3
D_3				146.83	E_3	F_3
				155.56	F_3	
E_3				164.81		G_3
F_3				174.61	G_3	
				184.99		A_3
G_3				195.99	A_3	
				207.65		B_3
A_3				220.00	B_3	C_4
				233.08	C_4	
B_3				246.94		D_4
C_4	C_{40}	C^1	c'	261.62	D_4	
				277.18		E_4
D_4				293.66	E_4	F_4
				311.12	F_4	
E_4				329.62		G_4
F_4				349.22	G_4	
				369.99		A_4
G_4				391.99	A_4	
				415.30		B4
A_4				440.00	B_4	C_5
				466.16	C_5	
B_4				493.88		D_5
C_5	C_{52}	C^2	c"	523.25	D_5	
				554.36		E_5
D_5				587.32	E_5	F_5
				622.2	F_5	
E_5				659.25		G_5
F_5				698.45	G_5	
				739.98		A_5
G_5				783.99	A_5	
				830.60		B_5
A_5				880.00	B_5	C_6
				932.32	C_6	
B_5				987.76		D_6
C_6	C_{64}	C^3	c'''	1046.50	D_6	
				1108.73		E_6
D_6				1174.65	E_6	F_6
				1244.50	F_6	
E_6				1318.51		G_6
F_6				1396.91	G_6	
				1479.97		A_6
G_6				1567.98	A_6	
				1661.21		B6
A_6				1760.00	B_6	C_7
				1864.65	C_7	

Appendix B: Borescope

The internal inspection instrument referred to as a 'borescope' was constructed from a Vision Engineering Type 100 Inspectoscope. In its original form this tool was a simple telescope with a choice of extension tubes with side windows at the far end and a selection of sloping mirrors set at 30, 45 or 60° to the axis. This has been modified to make it more suitable for examining clarinets by adding an extra mirror and prism to bend the optical path, first through 90°, then through a further 45°. In this form the instrument can be set up on a table, with its eyepiece at head height, and the clarinet joint to be inspected held in the hand to the side. A fan-cooled quartz-iodine light source has been added to replace the original tungsten filament lamp.
Various probes up to 300 mm can be attached and the instrument focussed by adjusting the position of the eyepiece. Probe tubes of 12.7 mm (1/2 inch) are suitable for most clarinet work but occasional use was made of a narrower probe of 9.5 mm (3/8 inch) diameter for small bore instruments and to reach past thumb tube inserts and other obstructions such as tonehole liners projecting into the bore.
For general observation, a plain eyepiece was used but, when estimates of size were required, this was changed to an eyepiece fitted with a graticule. The graticule could be calibrated against a steel rule to give a measurement accuracy of about 0.02 mm. Higher accuracy could be achieved by using a special eyepiece with a micrometer controlled crosswire, but this level of precision was not required in the undercutting survey. It did however prove useful for checking some of the parts used in the experimental clarinets.



Appendix C. Bore Micrometer.

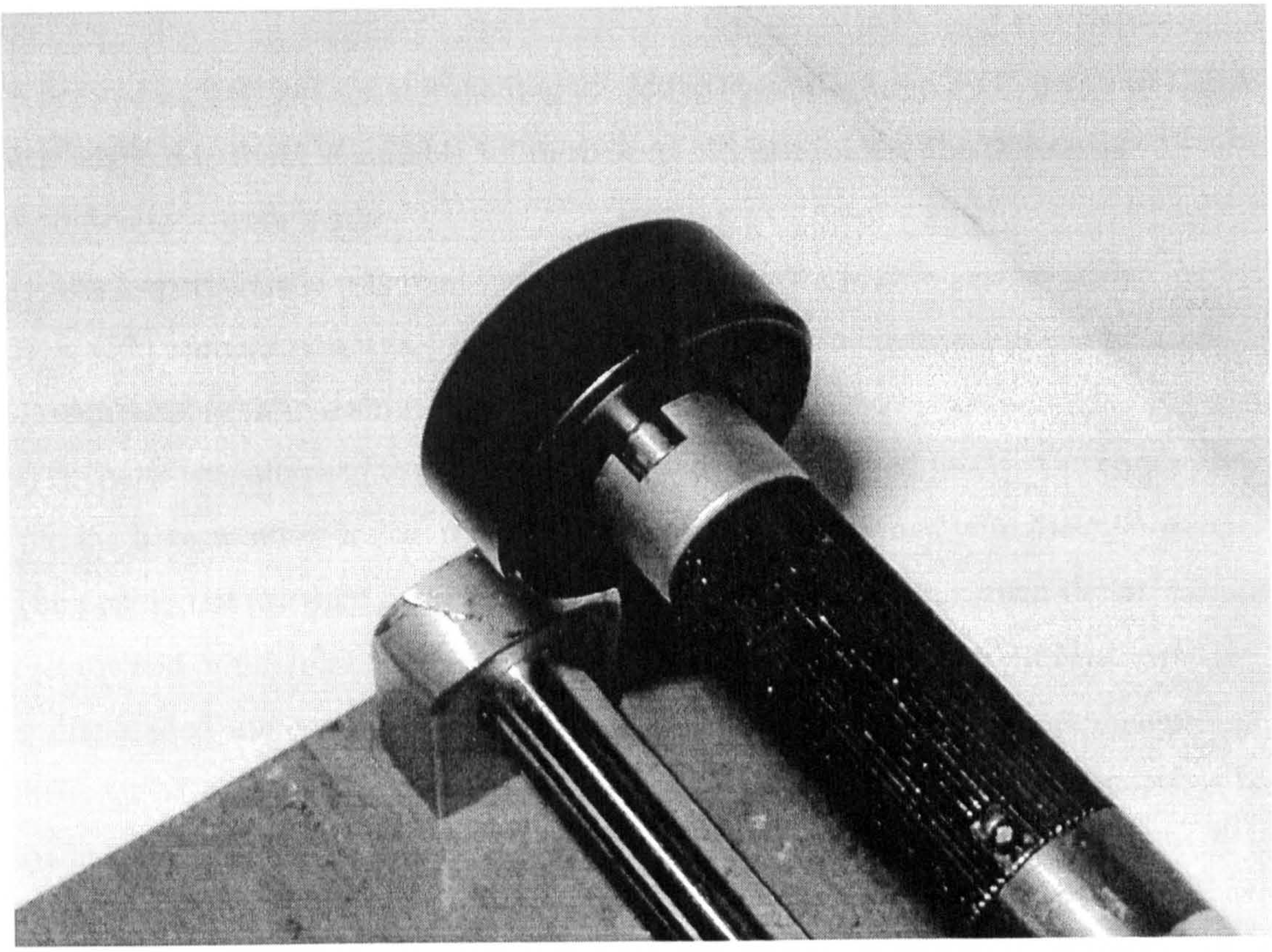
A Mitutoya Holtest (Type II) three-point internal micrometer was acquired and adapted to measure the bores of clarinet joints. The following modifications were made:

A 205 mm long extension section was made to fit between the measuring head and the micrometer drum. The 'reach' of the instrument is approximately 240 mm.
The original Imperial micrometer drum was replaced by a Metric drum with a reversed scale covering the range 12.5 to 16.9 mm.
A stand was constructed so that the extended micrometer is held horizontally. A vertical rod running on a rail parallel to the gauge with a pointer and scale was fitted to indicate the distance of the measuring head from the end of the joint.

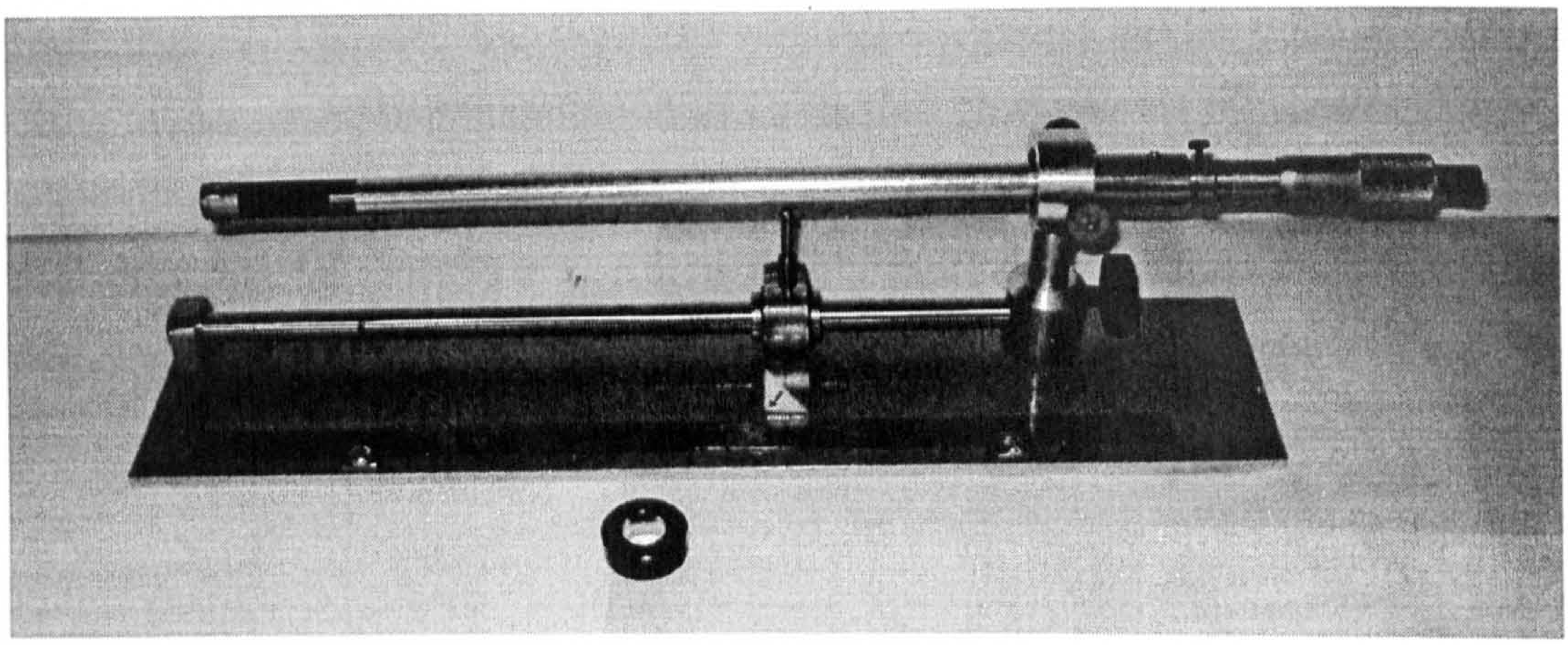
In this type of bore gauge, turning the micrometer drum propels a conical taper between three 'anvils' set at 120 degree to each other in the measuring head, pushing them outwards to make contact with the bore. The instrument is calibrated with a standard internal ring gauge and is direct reading. When the micrometer drum is wound back the anvils are retracted by springs.
To measure the bore of a clarinet joint, the anvils are first retracted. The joint is then held horizontally and slid over the measuring head so that the anvils are at the position where the bore is to be measured. The micrometer drum is then slowly rotated until the anvils make contact with the bore and the diameter read directly from the micrometer drum. A slipping clutch mechanism is provided so that the force at the anvils is limited and constant. The vertical rod is slid along to make contact with the end of the instrument. The position at which the measurement is made, relative to the end of the joint, is indicated by the pointer on the horizontal scale. The anvils are retracted and the measurements repeated at a new position.
The usual technique is to make bore measurements at approximately equal steps along the axis, using the horizontal scale as a guide. However, if the bore is changing rapidly, it is more convenient to change the diameter setting by equal decrements and measure the insertion length, as with a fixed diameter type gauge.
An advantage of this instrument over conventional T-bar type gauges is its speed of use since the head does not need to be removed from the joint between measurements.

The lightly-sprung slipping clutch mechanism on the micrometer drum ensures that damage to the bore does not occur through excessive pressure. The micrometer can be read to 0.01 mm and the accuracy is estimated to be +/- 0.02 mm. Also, if the instrument is used in the first method described above, the anvils approach the bore normally on making contact, with no sliding motion. Hence the risk of marking or damaging the bore is further reduced. The anvils provided by the manufacturer are made from hardened polished steel to achieve the optimum accuracy. If required they could be replaced with copies made from a suitable plastic material, but with possibly some loss of accuracy.

A disadvantage of the three contact point measurement is that it is only suitable for circular bores. Badly distorted bores would need to be measured with traditional T-bars. Modern clarinets made from suitably selected and processed African Blackwood are not normally prone to serious warping. A detailed discussion of the use and limitations of this type of bore gauge has been published [Bell and Greenham 2001]



Head with Internal Ring Gauge in place for calibration



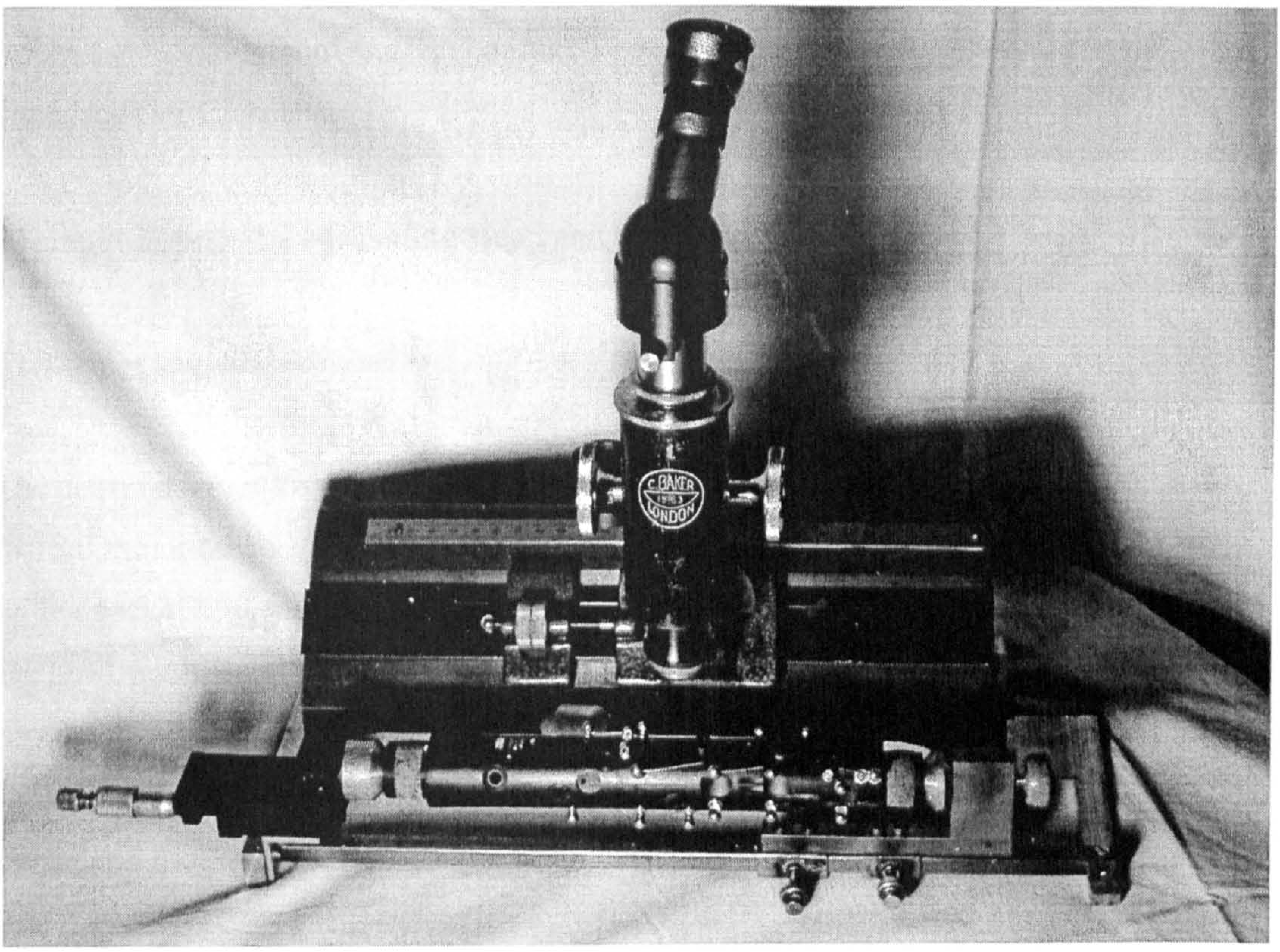
Three Point Bore Gauge assembled with calibration ring in foreground

Appendix D. Travelling Telescope used for Tonehole Measurements

A heavy cast iron industrial travelling telescope (manufactured by C Baker of London) was adapted to make it suitable for measuring clarinet joints. The following modifications were made:

1) The Imperial scale was removed and replaced with a Metric vernier scale.
2) A 45° prism section was added to the optics so that the instrument can be used comfortably from a sitting position.
3) A frame was attached to provide cone supports for clarinet joints. The cones project into the bore at either end so that the joint is accurately aligned with the microscope. The position of the right hand cone can be finely adjusted with a micrometer screw so that the end of the joint coincides exactly with the scale zero. The left hand cone is spring loaded and can be moved along a rail and then clamped to accommodate different joint lengths (from approximately 30 to 300mm), and measurements can be made over 250mm.The frame was designed with sufficient clearance that keywork can be left on the instrument if desired.

Measurements can be made in one dimension only along the axis. The telescope has a fixed focal length, and a rack and pinion mechanism is provided to focus cross wires in the eyepiece on features at different heights. With good illumination it is possible to place the cross wire on a feature, such as the edge of a tonehole, with a repeatability of better than +/- 0.02 mm. Measurement with this equipment has the great advantage of being 'non-contact' and therefore ideal for its role. However the instrument weighs approximately 8 kg and is therefore not easily portable. Other faster methods of measuring tonehole sizes and positions may be more convenient where such a high degree of accuracy is not necessary.



Clarinet Top Joint Supported between Cones

Appendix E. Equipment and Techniques Used to Measure the Acoustic Input Impedance of Clarinets.

E1. Input Impedance Measuring Head and Circuits.

E1.1 Input Impedance Head

The acoustic input impedance head was made from a black-filled Nylon rod bored out to 15.0 mm diameter, similar to the bore at the top of modern Boehm system clarinets, with a socket at one end to fit a clarinet upper tenon as shown below. The other end of the head was turned down to form a narrow rim at the bore, to which the driver was cemented with a flexible silicone room temperature vulcanising adhesive. The length of the head was calculated so that the enclosed volume is similar to that of a normal barrel and mouthpiece, including a small correction for the reed compliance.

The driver is a Ceramic Bender (RS Part No. 228-1605) comprising a polarised piezo-electric ceramic disk bonded to a thin metal disk of larger diameter. Electrical connections were made by soldering fine wires to the outer silver electrode and to the metal plate. The ceramic is polarised perpendicular to its major faces so that, when an alternating electrical voltage is applied to the electrodes, the normal fundamental mode of vibration will be radial dilation. However, because one side of the ceramic is rigidly attached to the metal disk, the motion will be transformed into a to-and-fro movement of the centre of the disk along its axis. The disk then acts like a miniature loudspeaker set on the axis of the head. For a Lead-Zirconate-Titanate (PZT) transducer, the displacement of the centre of the disc along the axis of the head is typically 1 micron per volt applied. The resonant frequency of the selected transducer is approximately 4.4 kHz. The seal fixing the disc to the tube tends to damp the third harmonic of the radial dilation mode.

The microphone is a miniature electret type, 6 mm in diameter, obtained from Maplin Electronics. This has a built-in field effect transistor (FET) which requires a DC voltage which is normally supplied by the sound card. A counter-bored hole was drilled in the side wall of the head as close as practical to the driver end. The microphone was then inserted with its face flush with the bore and held in place by an O-ring pressed into the recess to form an air-tight seal.

An end cap is fitted to the head to protect the piezo-electric driver and to absorb sound radiated from its back face. Wires from the driver and microphone are brought out to a terminal block mounted on the head.

E1.2 Driver Amplifier.

The voltage levels available at the Line Out port of the sound card (Creative Labs AWE 32) are insufficient to drive the ceramic bender directly. It was found by experiment that peak-to-peak levels of up to 15 volts were required to achieve adequate sound pressure levels in the head.

A single stage amplifier was constructed with switchable voltage gains of +20 to +40 dB in 5 dB steps. The circuit diagram is shown in below. The static capacitance of the piezo-electric ceramic exceeds the limit recommended for the Op Amp and a 2k 0hm resistor has been placed in series with the output to provide a minimum load should the reactance go to zero on being driven at resonance.

The +/-15 volt rails are derived from a +5 volt DC supply via isolated DC-to-DC converters.

E1.3Microphone Amplifier.

A fixed (~ +40 dB) gain amplifier circuit was constructed using an Analog Devices Type OP213 single rail dual Op Amp. The circuit diagram is shown below. One of the amplifiers is used to provide a DC supply for the FET incorporated in the microphone. The values of the input and output capacitors were chosen so that in combination with the output impedance of the sound card Line Out and 10k ohm load resistance respectively, the low frequency 3 dB points are below 10 Hz.

E1.4 Operation.

The amplifiers are designed to be connected to a PC sound card which operates in full duplex mode.

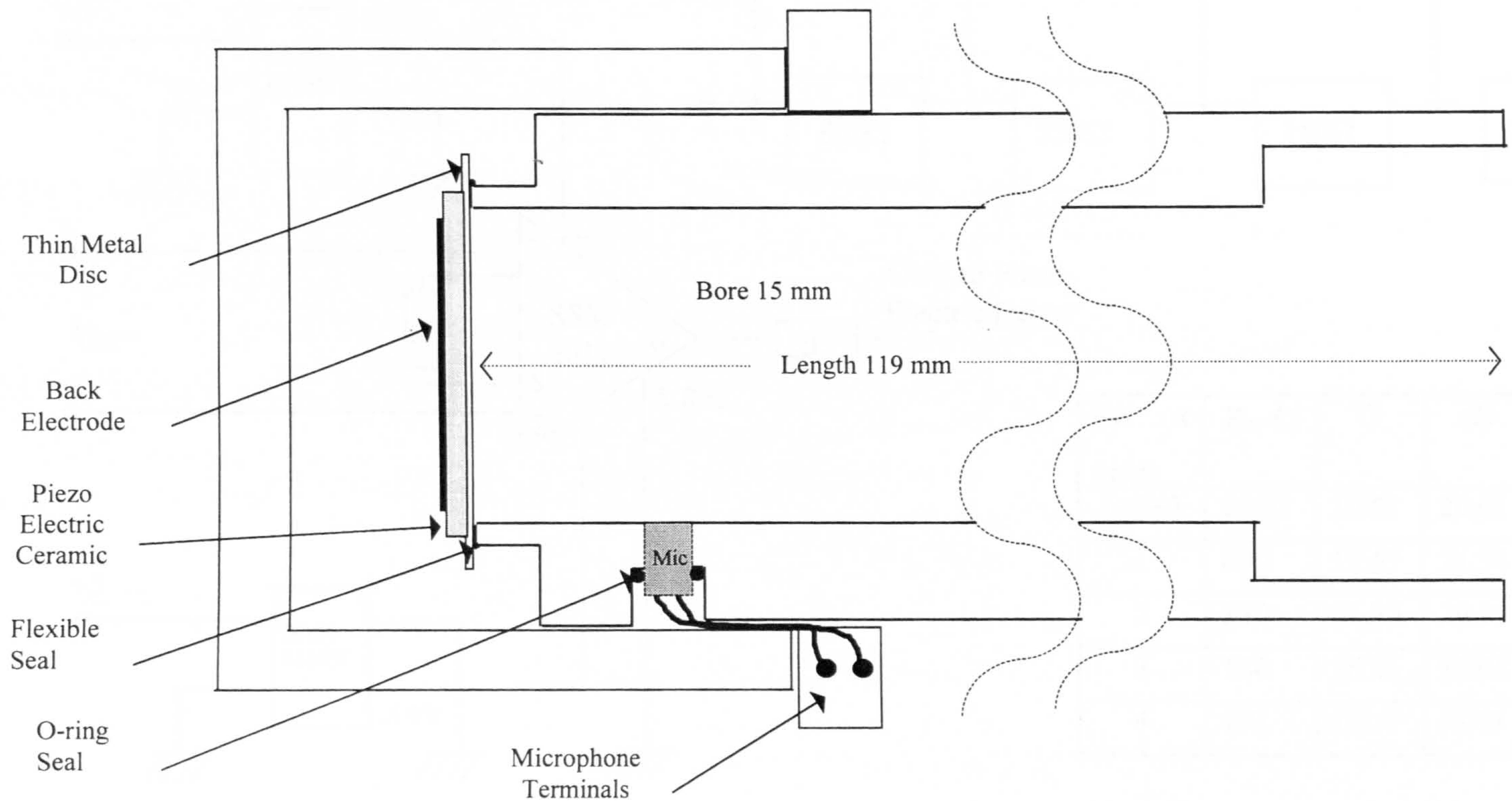
The head will operate from near DC to beyond the resonant frequency of the ceramic bender (~4.4kHz) as claimed by Benade [Benade 1987] and confirmed here by experiment. No effect is seen on the spectra when passing through the resonance of the ceramic driver because of the high level of damping.

Below resonance, for constant drive voltage amplitude, the velocity amplitude of the surface of the disc is directly proportional to the frequency. This has the effect of enhancing the apparent amplitudes of impedance peaks with increasing frequency. If required, the system could be normalised by adding a -6 dB filter/octave in the drive circuit. In the present work this has not been included as the enhancement makes it easier to determine peak frequencies for comparing frequency ratios before and after changes are made. Likewise the absolute amplitude levels are of less interest than relative changes.

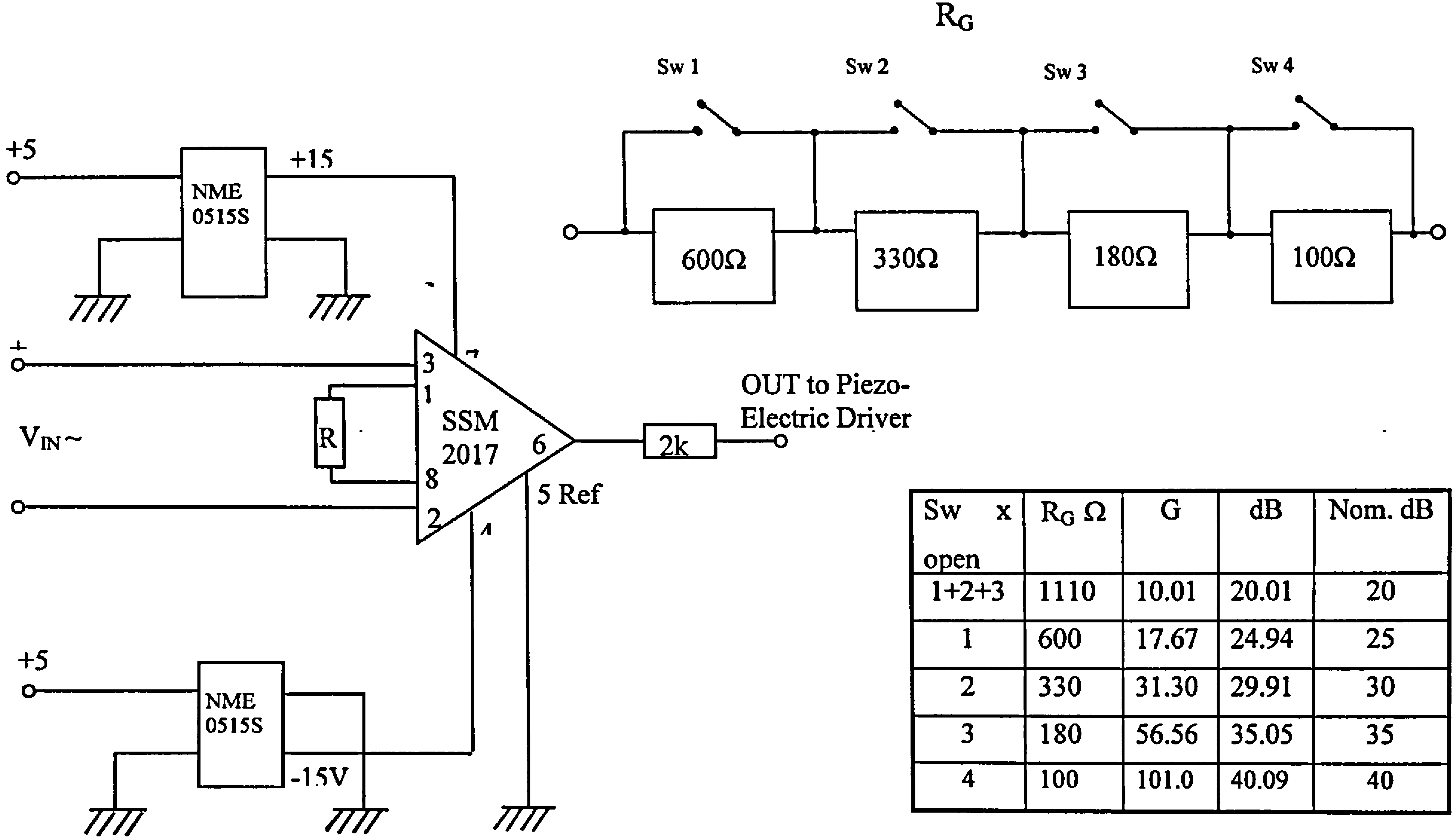
For drive levels up to +/- 15 volts, the air displacement, without normalisation of the drive, will approach the threshold of playing under blown conditions (pianissimo playing). This is confirmed by applying a slowly varying swept signal which is just audible initially and becomes easily audible as the sweep approaches about 1 kHz. Sound pressure levels measured outside the clarinet under test are only 10 to 20 dB above the background level.

Acoustic Input Impedance Measuring Head:

(not to scale)

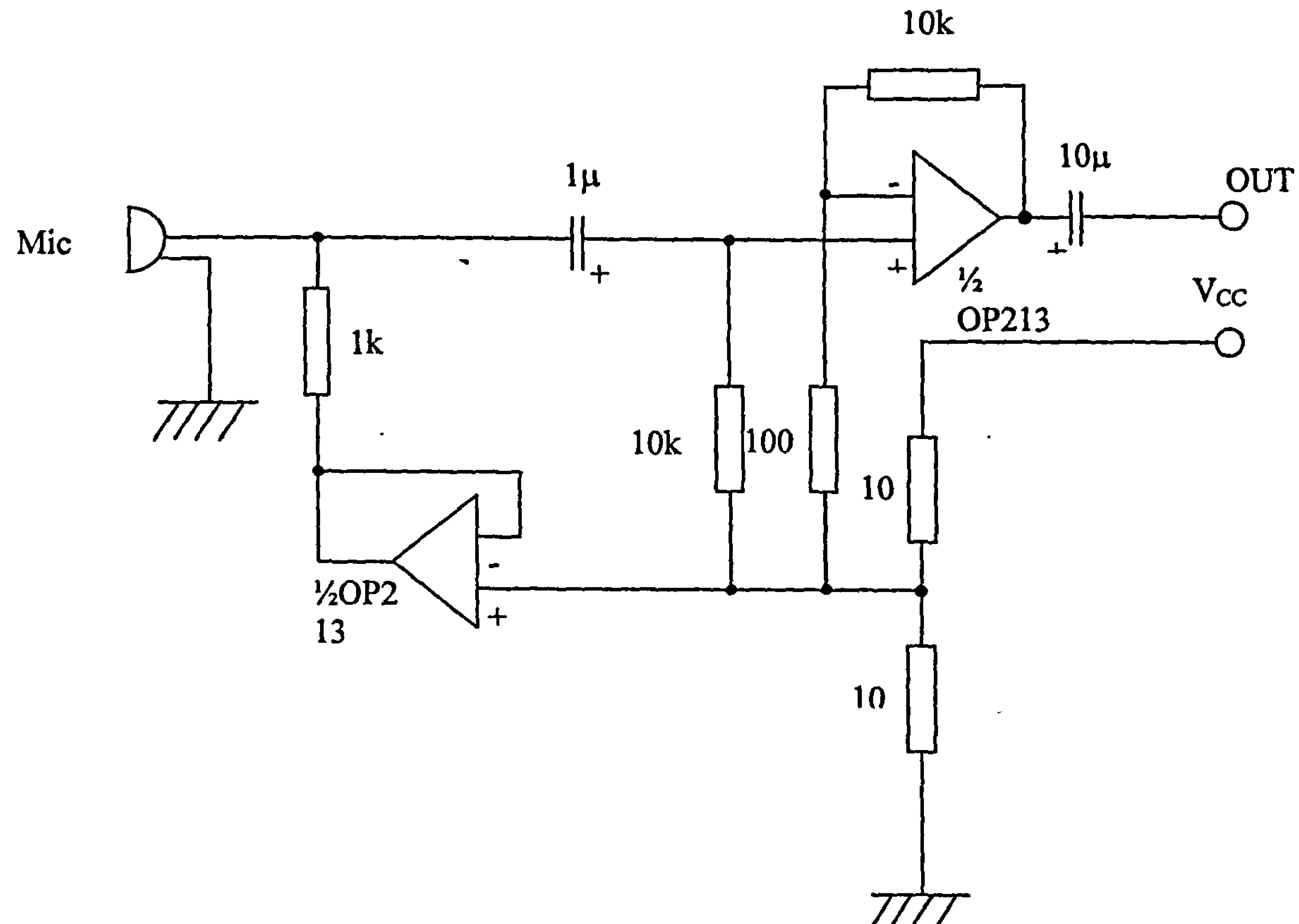


Piezo-electric Driver Amplifier



Sw x open	R_G Ω	G	dB	Nom. dB
1+2+3	1110	10.01	20.01	20
1	600	17.67	24.94	25
2	330	31.30	29.91	30
3	180	56.56	35.05	35
4	100	101.0	40.09	40

Microphone Amplifier Circuit:



E2 Software:

E2.1 Frequency domain measurements AudioRTA software.

The software provides an on-screen signal generator and response analyser. A digitally synthesised sine wave can be swept over a frequency range up to 20 kHz and the analyser has a narrow band notch filter which is synchronised to the generator. The response of the system under test is displayed as an on-screen trace to which smoothing can be applied.
Running the program in 'Slow Sweep' mode using the maximum time span (60 seconds) will produces a spectral scan showing all of the air column impedance peaks. However a maximum of 180 sets of data can be recorded, irrespective of the measurement range and hence the resolution is inadequate to measure accurately the peak frequencies. (The author of the software was unwilling to develop a higher resolution version). This problem was overcome by using the broad sweep to identify the approximate frequencies of the impedance peaks and then each peak was scanned separately to enhance the resolution.
Various methods were tried for establishing the exact frequencies of the peaks. Even when scanning a single peak, readings from the screen display were not sufficiently accurate for this study. However the raw data from which the display is generated can be accessed and this was transferred to an Excel worksheet. Selecting peak values from the tabulated data is not satisfactory even after applying smoothing because of random noise. The most reproducible results were obtained by plotting each peak over a restricted range (minimum of 20 data pairs symmetrically about the peak) and then applying a second-order polynomial trend line as provided within Excel. The equation of the trend line can then be displayed and its first derivative set to zero for the maximum frequency.
A disadvantage of measuring each peak separately is that any temperature changes during the measurements cause frequency changes. For small temperature drifts, when measuring frequency ratios normalised to the fundamental, this problem can by minimised by re-measuring the fundamental immediately before or after measuring each higher response. Repeating the measurements and using averages of the ratios increased the measurement accuracy confidence

Occasionally the temperature drift was considered to be large enough to cause a problem and the frequencies were then temperature corrected, but for most of the measurements it was found that this was not necessary provided the procedure described above was followed and sufficient data was used for averaging.

E2.2 Time domain measurements. WinMLS software.

Pulse reflectometry can be used to measure the impedance characteristics of wind instruments in the time domain. Typically an acoustic impulse is created at the mouthpiece end of the instrument which travels through the air column and is partially reflected wherever there is a change in the impedance. The pattern of reflections received at a microphone placed at the input end of the instrument is referred to as the input impulse response. From this data the input impedance of the instrument can be calculated by applying the appropriate algorithm.
Although simple in concept, there are considerable practical and theoretical difficulties in applying pulse reflectometry. One complicating factor is reflection of the returning signals at the source end which may be detected again at the microphone before all of the reflected signal from the instrument has been collected. A practical method of overcoming this problem is to connect the pulse generator to the instrument via a 'source tube' whose length is sufficient to delay the source reflection appearing at the microphone until the signal measurement is complete. A greater difficulty arises from the conflicting requirements for a pulse which is sufficiently short to generate the highest frequency component required to characterise the instrument, but which also contains sufficient energy to achieve a high signal to noise ratio. The ratio of peak to average power (crest factor) is high in a pulse and clipping of associated circuitry can readily occur even when the average pulse power is low. It is the average power level which determines the signal-to-noise ratio. Furthermore, the long collection time required to acquire low frequency information results in vulnerability to noise intrusion.
With the advent of digital techniques, various methods involving the use of repetitive pulses and averaging to improve the signal to noise have evolved, the penalty being longer measurement times. One technique which is particularly applicable to acoustic measurements in the time domain makes use of a class of pseudo-random binary sequences known as 'maximum length sequences' (MLS).

The mathematics of maximum length sequences is complicated but, in essence, a MLS has the special property that the cross-correlation function of itself with the returned signal from the system to which it has been applied is the impulse response of the system. The auto-correlation function of an MLS signal produces the impulse signal. Algorithms can then be applied to transform the measured pulse responses into the frequency domain.

The advantages of this type of measurement technique are its relative immunity from external noise and that the signal-to-noise ratio can be improved by increasing the number of sample averages. Furthermore, any temperature fluctuations which occur during the measurement period affect all components of the measured response equally so that frequency ratios in the frequency domain are unaffected.

A software package, WinMLS, was acquired which was designed to measure room acoustics and the impulse responses of resonant structures such as the bodies of stringed instruments, and it was found that it could be used with the impedance head constructed for this work.

Screen displays again do not provide sufficient accuracy but the frequency domain data pairs can be extracted from the program and treated as described above to determine the peak frequencies.

E2.3 Comparison of AudioRTA and WinMLS

Both software programs were used successfully in this experimental study and within the measurement accuracy gave identical frequency measurements.

As explained above the time domain approach has the advantage of insensitivity to temperature changes during the measurement period but in practice it was found that the measurements were more difficult to perform as the program was sensitive to slight disruptions to the fed-back signal used to monitor the continuity of the data gathering.

In theory the measured bandwidths are dependant on the choice of windowing applied to Fourier transform to the frequency domain but the effect was found to be small in practice.

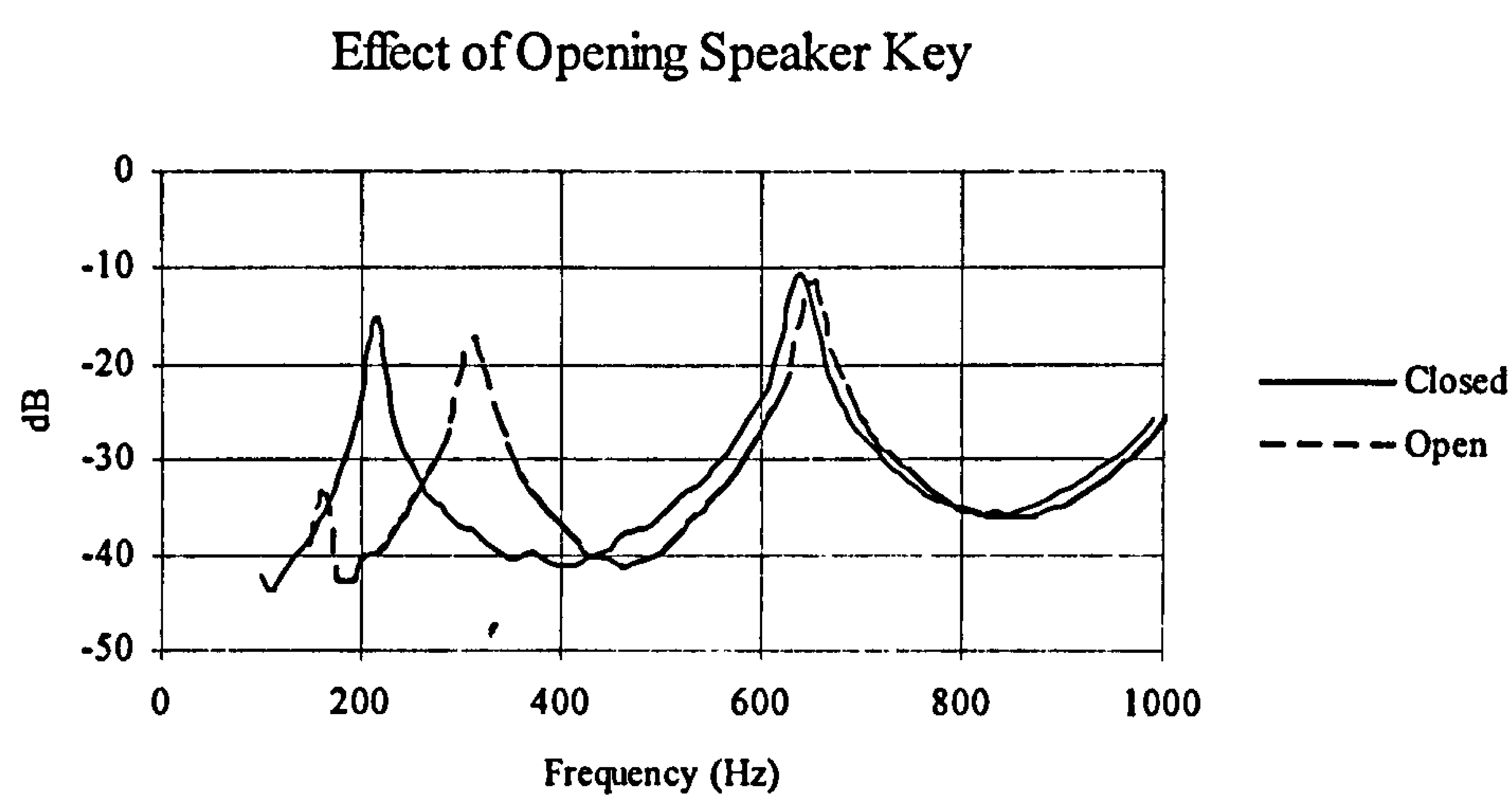
Most of the data gathering was made using the frequency domain approach because of its ease of use, reliability and simplicity, despite the temperature problems, which could be overcome by judicious choice of measurement sequences and averaging of repeated runs.

E3 Testing the equipment:

Before making experimental measurements a series of checks was made (frequency and time domain measurements) to confirm that the equipment was working satisfactorily. First a 1 meter long tube with a 15.8 mm bore (nearest available size to a clarinet bore) with no side holes was attached and its impedance measured. The spectrum showed peaks at the anticipated frequencies and the average response was reasonably flat.

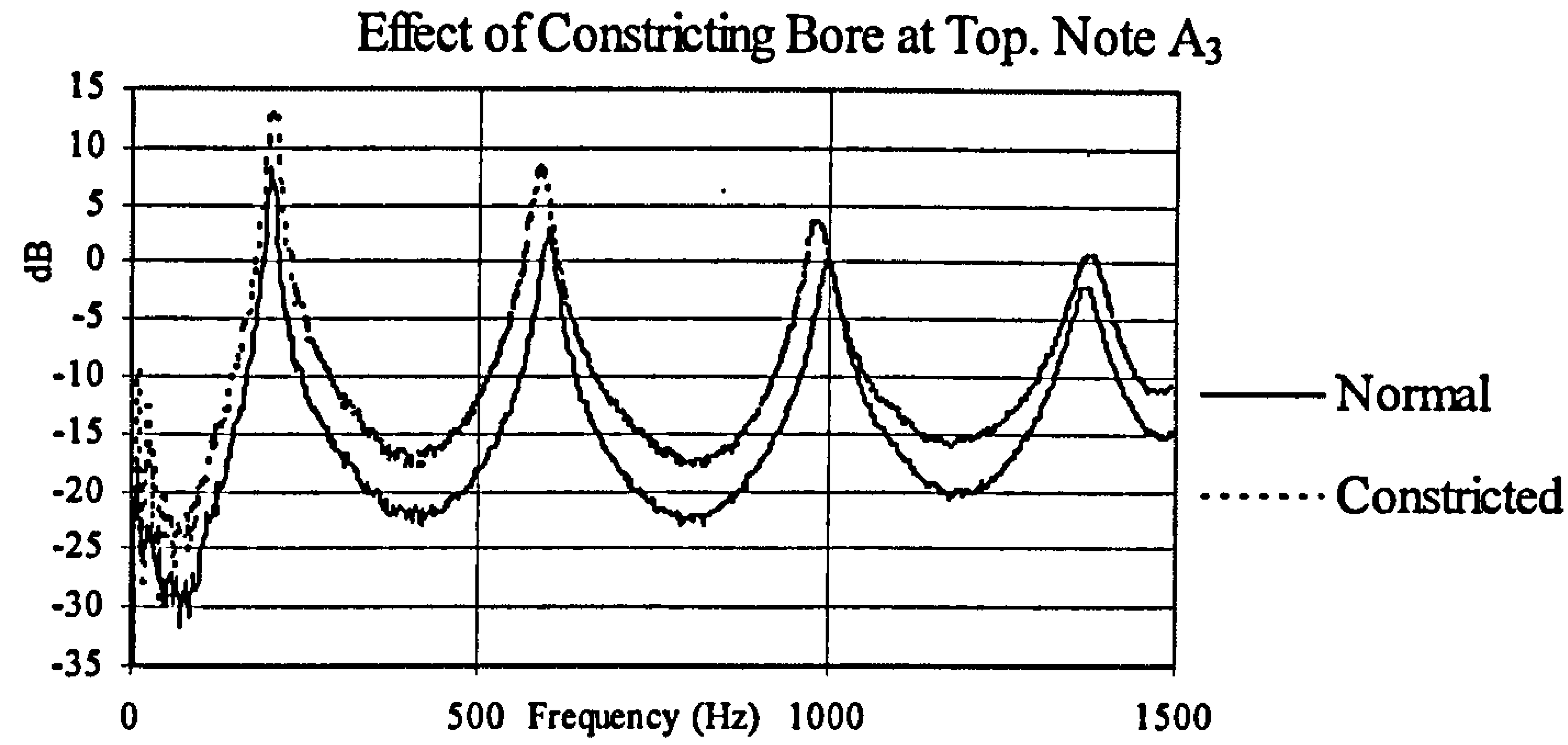
This plain tube was then terminated with a tonehole lattice and attenuation appeared at the expected cut-off frequency (~1.5kHz).

A Boehm system clarinet was then tried and the spectra of several notes recorded. Again the peak frequencies appeared at the anticipated frequencies. When the speaker key was opened, the fundamental response shifted to a higher frequency as expected.



The drive level applied to the ceramic disc was stepped up incrementally and the wave form monitored to check the clipping level of the drive amplifier. Up to this level no significant frequency shifts in the response patterns appeared. All subsequent measurements were made at a level just below that at which amplifier clipping set in (+/- 15v applied to the ceramic).

Finally the bore of a Boehm clarinet was perturbed at the top end by reducing the diameter with a ring of moulding compound. The third and fifth harmonic peaks were shifted to slightly lower frequencies, and the seventh harmonic moved to a slightly higher frequency in line with perturbation weight function predictions.



From these preliminary tests it was concluded that the impedance measuring equipment was operating satisfactorily.

Appendix F. Experimental Clarinet EC2: Construction Details

A badly damaged modern Boehm system right hand joint made of African Blackwood was acquired whose upper socket had been split beyond repair (the joint was marked with the serial number 010944 but no maker's name). The positions and sizes of the toneholes were measured using the traveling microscope (see Appendix D). The bore was measured with the long-reach three-anvil bore micrometer (see Appendix C) and the external diameter of the body at the positions of the toneholes was measured with vernier calipers. The joint was then cut perpendicular to the axis approximately mid way between the third open fingerhole (R3) and the next hole down (closed by A flat/E flat key and the damaged section discarded.

The top of the remaining part of the joint was reamed out past the first open tone to form a tight fit to a length of thin-walled brass telescopic tubing. The tubing was pressed into the body and the A flat/E flat tonehole cut through the brass. The fit was sufficiently tight that no adhesive was necessary. Sets of three of annular rings in various plastic materials were machined and reamed to fit closely over the projecting tube, one for each of the right hand fingers.

The rotating sections were made with a slightly larger outside diameter than the original body so that flats could be machined to give the same tonehole heights as the originals. These had flat-topped inserts projecting above the body outline to make them level with the ring keys ('brille').

By adding a spacer ring to the body below the R3 ring it was possible to make the lengths of all three finger rings the same. A top section was made having one tonehole closed with a pad (replacing the hole normally operated by the right hand ring mechanism), and the top socket. This hole can be opened with a key for the left hand little finger to produce the normal venting for C_4/G_5 if required. It is also necessary to open this key when fingering D_4/A_5 to achieve the correct venting. The brass tube was then finished to length and the apertures for the toneholes cut through and enlarged to allow for undercutting of the tonehole. When assembled the overall length, tonehole positions and chimney heights are the same as in the original body. The dimensions are shown in the sketch below.

In order to achieve the correct tuning and cut-off frequencies it is necessary to retain a mechanism for controlling the four toneholes downstream from R3. Two have normally closed pads and two normally open with pads above them. The joint was therefore fitted with a set of four keys to be operated with the right hand little finger as on a normal Boehm system instrument. However the three replicating (lever) keys for the left hand little finger were omitted due to the difficulty of mounting them across the rotating sections.

The replication of the original joint is not perfect in two respects:

i) The bore of the brass tube is less than the bore of the original joint (14.42 compared with 15.03 mm).This is the best match which could be found using commercially available telescopic tubing.

ii) The normally-closed tonehole and key operated by R3 finger to give an alternative B natural/F sharp (cross-key) has been omitted as it almost at the same position as the R2 tonehole.

The slightly smaller bore in fact matches quite well to available French style left hand joints (~14.6 mm bores) and the discontinuity at the lower end (14.42 to 15.03 mm) is tolerable as this is close to the flare leading to the bell.

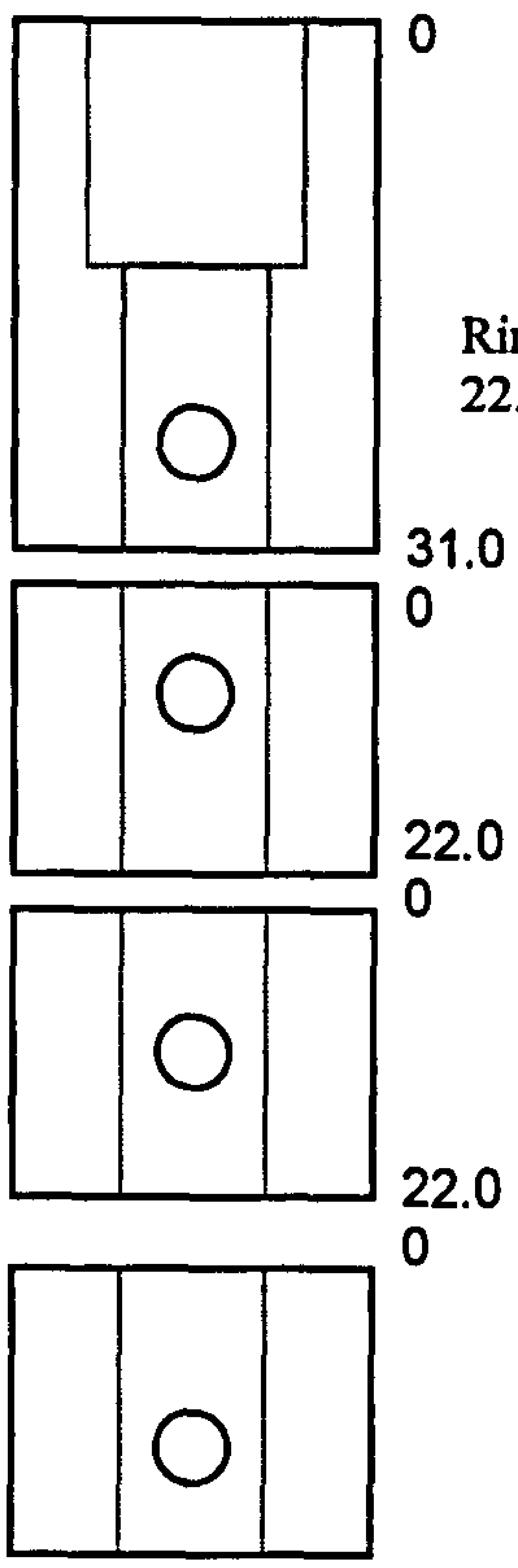
When assembled it is possible (using the additional left hand little finger key when called for) to provide the normal ventings for the whole range of notes for the standard Boehm clarinet with the exceptions of those which use the cross key provided for the alternative B natural / F sharp.

An advantage of the arrangement described above is that toneholes of different geometries can be compared either by playing the instrument or by measuring input impedance spectra whilst the conditions remain steady. The time between measurements can be made very short so that the effects of temperature change are minimized. This is particularly important when measuring in the frequency domain as discussed in Section 3.3.3.2.1.,

The experimental joint was attached to a Yamaha Model YCLCX or a Buffet Evette Master Model (R13 bore profile) top joints. The bell was turned from African Blackwood and was based on the Boosey and Hawkes 926 conical design, but made slightly longer. A photograph in Section 3.3.3 shows the complete assembly.

Experimental Tonehole Sections

Reamed to slide over 15.06 mm Brass Sleeve. O.D. = 35.1mm
Flats machined to achieve original chimney height (1.6mm removed)



Socket 15.6 mm deep. Diameter 22.1

Ring key hole. Diameter 7.33 mm.
22.97 mm from top of section

R1 Hole Diameter 8.42 mm.
8.55 mm from top of section

R2 hole. Diameter 8.51 mm
11.02 mm from top of section

R3 hole. Diameter 10.41 mm
12.86 mm from top of section

Appendix G. Bundy Test Clarinets. Hole Positions measured from top of LHJ joint and Diameters (mm)
Deviations from Average Distance from Top and Average diameter are shown as Dl and Dd respectively.

	T5+B11		T4+B14		T2+B12		Average		T5+B11		T4+B14		T2+B12	
	l	d	l	d	l	d	l	d	Dl	Dd	Dl	Dd	Dl	Dd
Speaker key	38.94	3.08	38.95	3.1	38.39	2.78	38.76	2.99	0.18	0.09	0.19	0.11	-0.37	-0.21
Side tr to B	49.32	5	49.39	5.06	48.91	4.94	49.21	5	0.11	0	0.18	0.06	-0.3	-0.06
Side tr to Bb	75.4	6	75.6	5.92	74.97	5.9	75.32	5.94	0.08	0.06	0.28	-0.02	-0.35	-0.04
A key	85	6	85.09	5.94	84.37	5.94	84.82	5.96	0.18	0.04	0.27	-0.02	-0.45	-0.02
Ab key	97.06	5.64	97.12	5.6	96.44	5.6	96.87	5.61	0.19	0.03	0.25	-0.01	-0.43	-0.01
Ring 1	112.98	5.48	113.13	5.46	112.51	5.42	112.87	5.45	0.11	0.03	0.26	0.01	-0.36	-0.03
Thumb	122.83	8.02	122.9	8.04	122.46	8	122.73	8.02	0.1	0	0.17	0.02	-0.27	-0.02
F# key	125.46	5.64	125.57	5.62	125.02	5.64	125.35	5.63	0.11	0.01	0.22	-0.01	-0.33	0.01
I	135.34	5.56	135.66	5.6	134.89	5.58	135.3	5.58	0.04	-0.02	0.36	0.02	-0.41	0
Ring 2	153.54	5.44	153.75	5.5	153.22	5.44	153.5	5.46	0.04	-0.02	0.25	0.04	-0.28	-0.02
II	168.76	7	168.8	7	168.45	7.1	168.67	7.03	0.09	-0.03	0.13	-0.03	-0.22	0.07
Side Eb key	172.53	6.34	172.58	6.36	172.42	6.36	172.51	6.35	0.02	-0.01	0.07	0.01	-0.09	0.01
Front Eb key	173.54	6.36	173.67	6.34	173.37	6.34	173.53	6.35	0.01	0.01	0.14	-0.01	-0.16	-0.01
III	191.5	8.44	191.63	8.42	191.51	8.42	191.55	8.43	-0.05	0.01	0.08	-0.01	-0.04	-0.01
C# key	201.92	5.52	202.21	5.58	202.07	5.62	202.07	5.57	-0.15	-0.05	0.14	0.01	0	0.05
Ring key	230.98	8.44	231.32	8.6	231.19	8.54	231.16	8.53	-0.18	-0.09	0.16	0.07	0.03	0.01
IV	246.45	8.82	246.83	8.94	246.75	8.82	246.68	8.86	-0.23	-0.04	0.15	0.08	0.07	-0.04
Cross B key	248.9	7.4	249.24	7.36	248.89	7.38	249.01	7.38	-0.11	0.02	0.23	-0.02	-0.12	0
V	272.12	8.52	272.47	8.54	272.38	8.64	272.32	8.57	-0.2	-0.05	0.15	-0.03	0.06	0.07
VI	295.38	9.64	295.55	9.78	295.65	9.7	295.53	9.71	-0.15	-0.07	0.02	0.07	0.12	-0.01
G# key	327.82	11.24	328.09	11.26	327.9	11.4	327.94	11.3	-0.12	-0.06	0.15	-0.04	-0.04	0.1
G key	352.81	12.58	352.93	12.66	352.99	12.7	352.91	12.65	-0.1	-0.07	0.02	0.01	0.08	0.05
F# key	387.05	12.3	387.17	12.38	387.1	12.4	387.11	12.36	-0.06	-0.06	0.06	0.02	-0.01	0.04
F key	419.9	11.2	420.19	11.3	420.2	11.6	420.1	11.37	-0.2	-0.17	0.09	-0.07	0.1	0.23
								Average D=	-0.01	-0.02	0.17	0.01	-0.16	0.01

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RONALD BELL AND ADRIAN GREENHAM

The Use and Limitations of a Three-Point Bore Gauge for Measuring Woodwind Instrument Bores

Three-point bore gauges are mechanical devices which are capable of measuring circular bores to high accuracy. They are used in many industrial applications, particularly in inspection and calibration. Sets of gauges are available to cover diameters from 6 to 300mm. As an example, a single three-point bore gauge which is useful for the clarinet measures over the range 12 to 16mm with an accuracy of 0.002mm. The way these gauges operate is straightforward. The gauge head has three 'anvils' which are housed in rectangular slots at 120° to each other so that they can move only radially. The anvils are usually made from hardened steel, tungsten carbide or a ceramic, but could be made of a plastic if desired. The outward facing surfaces are curved cylindrically to make a line contact with the bore being measured. In the simplest type of design, the anvils are pushed outwards by a cone attached to a micrometer and when the cone is withdrawn, the anvils retract under the action of small leaf springs so that they stay in contact with the cone. By choosing a cone semi-angle of 26° 34', whose tangent is ½, the change in diameter of the circle enclosing the anvils equals the distance moved by the cone. Thus a standard type of micrometer head can be used but with a scale engraved on the drum which gives the diameter of the bore directly. Most manufacturers now also offer digital displays with electrical outputs for logging the readings. The reach of a gauge can be increased by inserting one or more extension pieces between the head and the micrometer. Internal ring gauges are normally supplied with the gauges for calibration.

The three anvil gauge is particularly useful in measuring the bores of clarinets where it has a number of advantages over other types of measuring tool. By retracting the anvils, the head can reach past constrictions such as compressed tenons or tone hole inserts (though not speaker tubes which normally project too far into the bore). At the position to be measured the anvils are expanded to make contact with the bore. The head tends to be self centring and it is easy to detect by feel when a true contact has been made. By using the slipping clutch mechanism normally provided on the micrometer drum, the force which is applied to the anvils can be limited so that the pressure at the contacts does not mark the bore. It is easy to set this pressure to an acceptable level by changing the strength of the spring in the clutch mechanism, bearing in mind that where the bore is conical, for example the flare at the bottom of the lower joint of a clarinet, the anvil then makes point contact and the pressure is increased. A particularly important advantage of this tool is the speed of use since it is not necessary to withdraw the device from the instrument between readings.

For studying soprano clarinet bores, a light jig has been constructed to support the gauge horizontally so that the joint can be held in one hand and the micrometer operated with the other. The end of the joint touches a rod attached to a carriage which slides parallel to the axis of the gauge. The carriage has a pointer traversing a ruler so that the distance of the gauge head from the end of the joint can be read off directly. The gauge used was a 12 to 16mm Mitutoyo Holtest (Type II) Series 368 with a custom-made extension piece giving a reach of 250mm. This arrangement has been found to be convenient and quick to use and covers all but the widest part of the flare leading to the bell for which T-bar gauges have been used to complete the measurements.

The question has been asked whether this type of three-point gauge could be applied to out-of-round bores. Oval bores may be the result of anisotropic wood shrinkage which has occurred after the instrument has been made. It is usual to assume that the bore becomes elliptical with the minor and major axes of the ellipse being determined by the directions of maximum and minimum shrinkage respectively. Karp[1] has demonstrated that if the ratio of the shrinkage rates for the wood is known, it is possible to reconstruct the original bore from measurements of the ellipse's axes. Now if an equilateral triangle i.e. the points of contact of a three-point gauge, is rotated in an ellipse so that the apices remain on the ellipse at all times, it is found that the size of the triangle varies periodically. There are six maxima and six minima per rotation. The maxima occur when any one of the apices coincides with a minor axis and the minima when one of the apices is on a major axis. It may be noted that during rotation the centres of the ellipse and the triangle are not coincident. Appendix 1 gives a mathematical analysis of the situation and Appendix 2 shows how the axial dimensions of the ellipse can be calculated from these maximum and minimum measurements.

In practice it is not too difficult to find these maximum and minimum readings provided care is taken that the longitudinal axes of the joint and the gauge stay parallel. Whereas the accuracy of measurement in a perfectly circular bore is potentially that of the gauge, namely 0.002mm for the type described above, an unexpected and unfortunate phenomenon occurs when the bore is elliptical. This is outlined in Appendix 2 where the Table shows the ratio of the maximum and minimum bore gauge measurements

[1] Karp C. 'Woodwind Instrument Bore Measurement', *GSJ* XXXI, May 1978, pp.9-28

for different axial ratios. It can be seen that a small error in the measurement leads to a relatively large error in the calculated ratio. In practice, if the ellipticity is approximately constant over the length being measured, the maximum gauge reading (which is the easiest to detect) may be measured at a series of points along the bore. Then if the axial ratio is subsequently measured at a few points by other means, e.g. T-bar measurements, the data may be combined to define the bore with reasonable confidence.

To summarise, three-point bore micrometers offer a number of advantages when measuring woodwind instrument bores of circular or near circular cross section. These tools are accurate, portable, quick and safe to use. They are more expensive than some other measuring tools but not prohibitively so if the simple micrometer drum type is purchased. For near cylindrical instruments such as the clarinet a single gauge may be sufficient to cover the required range. Caution must be used when attempting to characterise elliptical bores with this type of tool. Theoretically the 'maximum fit' and 'just able to rotate' gauge readings give sufficient information to allow the ellipse's major and minor axes to be calculated explicitly as has been shown below but, due to an unfortunate gearing effect, small measurement inaccuracies may lead to relatively large errors in the calculated values of the axial dimensions.

Appendix 1

THE BEHAVIOUR OF A THREE-POINT BORE GAUGE IN A TUBE OF ELLIPTICAL CROSS-SECTION

The radial extremities of the three anvils in this type of gauge form an equilateral triangle. When placed in a tube of circular section the size of the biggest triangle that can be accommodated is independent of the angular position of the gauge: the centre of the triangle is at the centre of the circular cross-section and the three anvils remain in contact with the bore if the gauge is rotated. When placed in an elliptical bore however, the extent to which the anvils can be extended until they each make contact with the bore depends on the angular position of the gauge with respect to the principal axes of the ellipse. Moreover the centre of the triangle will not be at the centre of the ellipse.

If an equilateral triangle, ABC, is constructed inside an ellipse, then the following three equations apply:

$$(x_2 - x_1)^2 + (y_2 - y_1)^2 = S^2$$
$$(x_3 - x_1)^2 + (y_3 - y_1)^2 = S^2$$
$$(x_3 - x_2)^2 + (y_3 - y_2)^2 = S^2$$

where the coordinates of A, B are C are (x_1, y_1), (x_2, y_2) and (x_3, y_3) respectively and S is the length of the sides of the triangle.

Now the three apices of the triangle lie on the ellipse, so for each apex the value of the y-coordinate can be described in terms of its x-coordinate and the semi-axial lengths of the ellipse, a and b, using the equation of the ellipse:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$$

This yields three equations with three unknowns as follows:

$$(x_2-x_1)^2+\left[b.\sqrt{1-\left[\frac{x_2}{a}\right]^2}-b.\sqrt{1-\left[\frac{x_1}{a}\right]^2}\right]^2=S^2 \qquad (1)$$

$$(x_3-x_1)^2+\left[b.\sqrt{1-\left[\frac{x_3}{a}\right]^2}-b.\sqrt{1-\left[\frac{x_1}{a}\right]^2}\right]^2=S^2 \qquad (2)$$

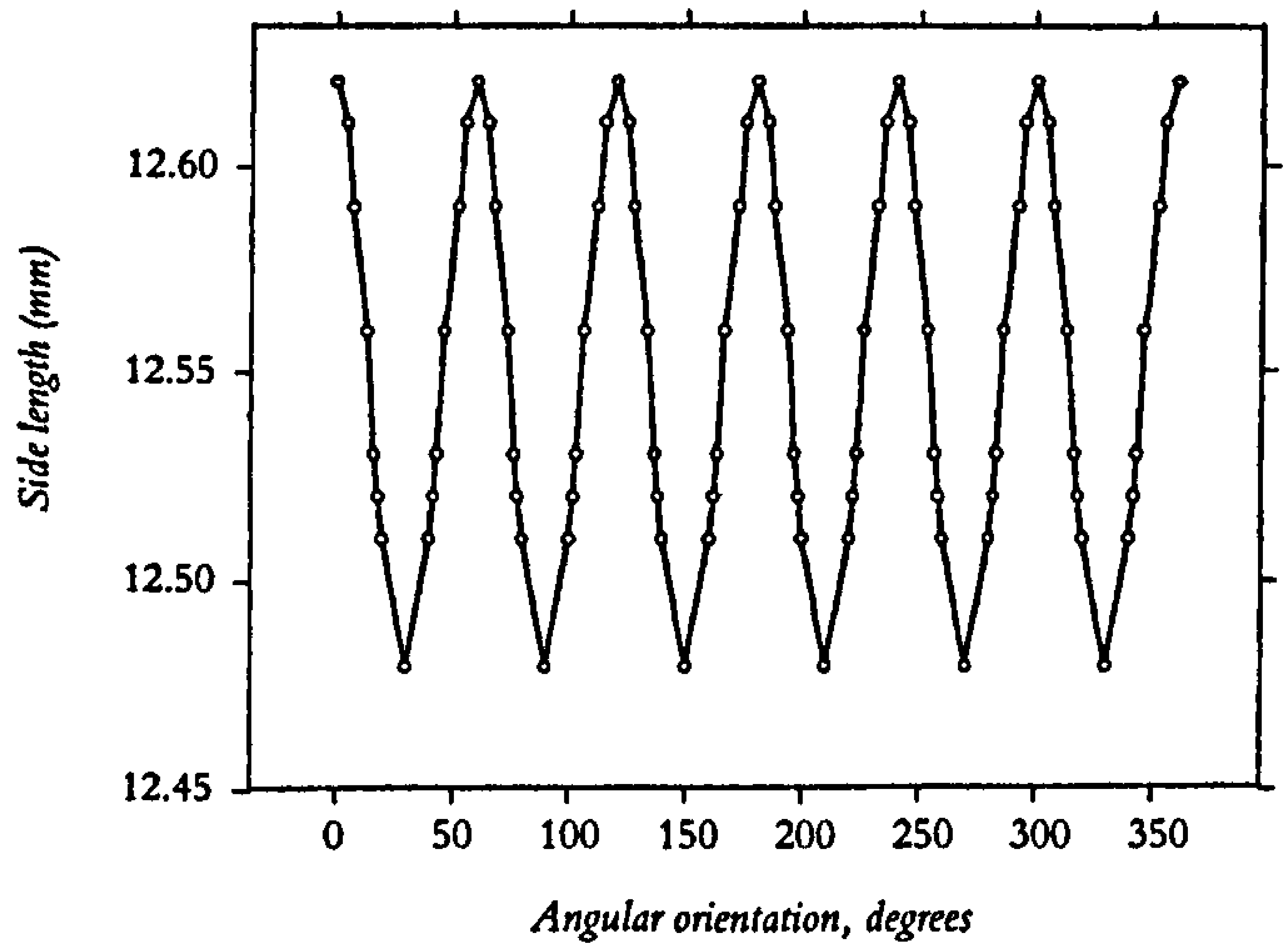
$$(x_3-x_2)^2+\left[b.\sqrt{1-\left[\frac{x_3}{a}\right]^2}-b.\sqrt{1-\left[\frac{x_2}{a}\right]^2}\right]^2=S^2 \qquad (3)$$

Inserting values of x_1, a and b, the quantities x_2, x_3 and S may be obtained by solving the three equations. This is conveniently performed numerically using a computer software package such as 'Mathcad'. Care must be taken to specify the sign before each square root.

A typical set of results for an ellipse with semi-axes equal to 9.1 and 6.35 mm is shown in the graph of Figure 1. Note that six maxima and six minima occur as the triangle is rotated through 360 degrees. The maxima correspond to an orientation of the triangle where one of its apices is on a minor axis of the ellipse; the minima to where one of the apices is on a major axis. But notice that the zero on the y-axis has been heavily suppressed because the ratio of the maximum to the minimum values is only about one percent for an elipse with the ratio a/b equal to 1.43.

A three-point bore gauge is designed to read out directly the diameter of the circle which circumscribes the equilateral triangle. Hence a gauge used on the elliptical section in the above example would give values that showed exactly the same pattern of six peaks and six minima but each 'diameter' reading would be 1.155 times the S-value.

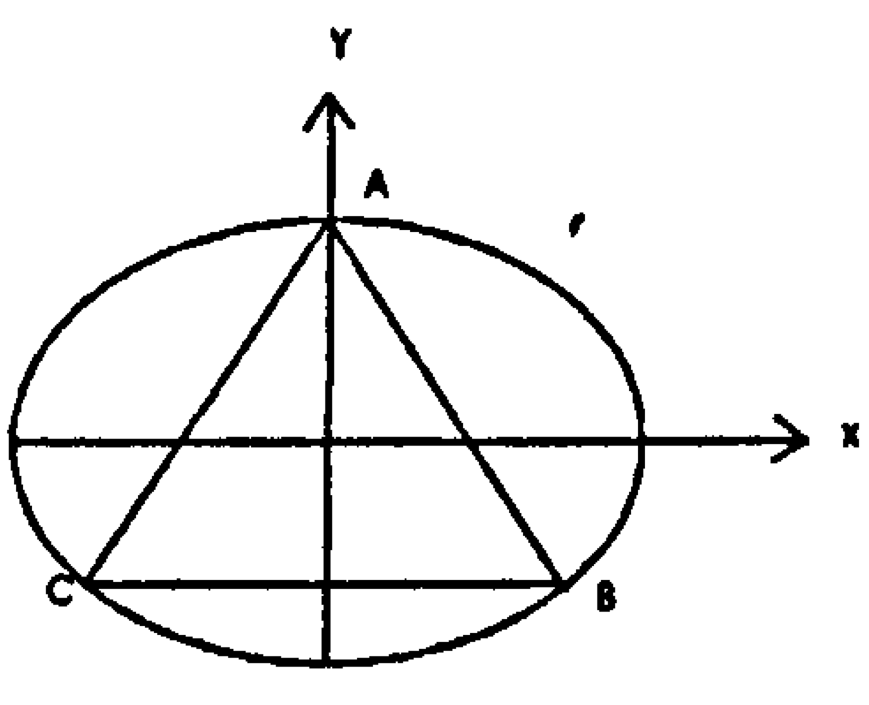
Figure 1. *Maximum equilateral triangle size vs its orientation in ellipse*



Appendix 2

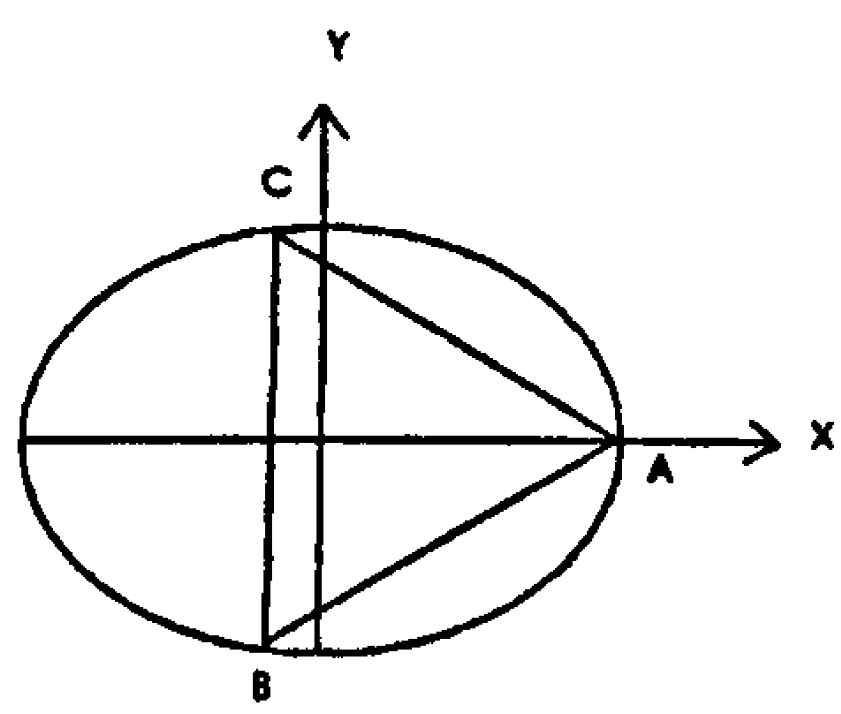
DETERMINATION OF THE LENGTHS OF THE PRINCIPAL AXES OF AN ELLIPTICAL CROSS-SECTION

In Appendix 1 it was shown that the three-point bore measurement instrument gives a maximum reading when one of the anvils is located on a minor axis of the ellipse (Figure 2) and a minimum reading when an anvil is on a major axis (Figure 3). This observation provides a method for determining the values of the major and minor axes.



Side length S_1

Fig 2



Side length S_2

Fig 3

When an apex is situated on the minor axis, $x_1 = 0$, $y_1 = b$ and $x_2 = -x_3 = S_1/2$
Inserting these into equation (1) gives:

$$S_1 = \frac{4.\sqrt{3}.a^2.b}{3.a^2 + b^2} \qquad (4)$$

Similarly, when an apex is on a major axis of the ellipse, $x_1 = a$, $y_1 = 0$

Also $y_2 = 0.5S_2$. Inserting these into equation (1) yields:

$$S_2 = \frac{4.\sqrt{3}.a^2.b}{a^2 + 3.b^2} \qquad (5)$$

Given measurements with the three-point gauge from which the triangle sizes may be derived, the equations (4) and (5) may be solved to give separate values of a and b.
If it is required to know only the ratio a/b, these two equations may be combined to give one equation:

$$x^3 - 3.\frac{S_1}{S_2}.x^2 + 3.x - \frac{S_1}{S_2} = 0 \qquad (6)$$

where $x = a/b$.

To illustrate the way that S_1/S_2 varies with the axial ratio the following table has been drawn up:

S_1/S_2	a/b
1.02	1.547
1.01	1.412
1.002,	1.222
1.001	1.172
1.0002	1.097
1.0001	1.076
1.00002	1.044
1.00001	1.035

Given that the gauge may be read to 0.002mm, this means that in a bore of about 15mm the smallest ratio of the two S values that could be detected is 1.0001. This corresponds to an a/b ratio of 1.076, but note that an error of only 0.01% in the measurement gives an error in a/b of over 2%. The reason for this is that the three-point gauge effectively measures a kind of weighted average of the lengths a and b, or to put it another way, the equations are 'ill-conditioned' to the task of providing accurate values of a and b from measurements of S.

Adrian Greenham

Thurston's Clarinets

Frederick Thurston was first taught the clarinet by his father who played thirteen-keyed 'simple system' instruments. The photograph on page 4 shows Frederick Thurston as a boy playing what appears to be a simple system clarinet. When he became a student at the RCM his teacher, Charles Draper, would certainly have encouraged him to change to the Boehm system if he had not already done so.

For the early part of his career, Frederick Thurston played clarinets manufactured in France by Martel Frères. From about the beginning of the twentieth century to the First World War, Martel clarinets were imported into England by Hawkes, later to form part of Boosey and Hawkes. Thurston's pair were lightly stamped on the top joint with a 'cross' symbol, then Excelsior / Sonorous / Class / Hawkes and Son / Denman Street / Piccadilly Circus / London followed by the serial numbers 2093 on the Bb and 2096 on the A. The name Martel does not appear on the instruments. They were probably made at about the turn of the century.

They are 'plain' Boehm system with bores just under 15 mm. The bore of the Bb instrument has a slight 'reversed cone' above the speaker hole whereas the A is cylindrical. The reversed cone is probably the result of wear and age rather than a design feature. In the bottom joints the flares start at about the third hole up (G/D venting) and increase smoothly to the join with the bell in typical French style.

Martel clarinets were highly rated in the profession and many eminent players owned them. Reginald Kell used a Martel 'A' clarinet for his famous 1930s recording of the Brahms Quintet, but surprisingly he borrowed the instrument from its owner, Frank Hughes, just for the occasion.

The responsiveness and easy playing qualities of these Martel clarinets is quite remarkable. Stories of players queuing up to acquire Martels when their owners retired may be apocryphal but it is true that some of these instruments were handed on several times within the profession.

What makes these clarinets special? A look at the inside of the Thurston instruments shows that, like other Martels from that period, the tone holes have been heavily undercut, far more so than in modern designs. (This is the process of enlarging a tone hole where it meets the bore without changing its external size). This is not the place to discuss the physical acoustics of undercutting but there is strong evidence to suggest that this accounts for their special qualities. Unfortunately accuracy of tuning was sacrificed in the process. To play these instruments in tune over the full dynamic range requires major embouchure and fingering adjustments from the player.

Thurston was still using his Martels when he was appointed principal clarinet of the BBC Symphony Orchestra formed in 1930. Playing standards were rising and visiting conductors were demanding greater accuracy of intonation from woodwind sections. Against this background Thurston soon changed to the recently launched Boosey and Hawkes '1010' clarinets. They were a 'matched pair' with serial numbers 30255 for the Bb and 30256 for the A. The B & H numbering system from that time is a little hazy but they were probably made in about 1932 and are early examples of what later became the 'Symphony' model.

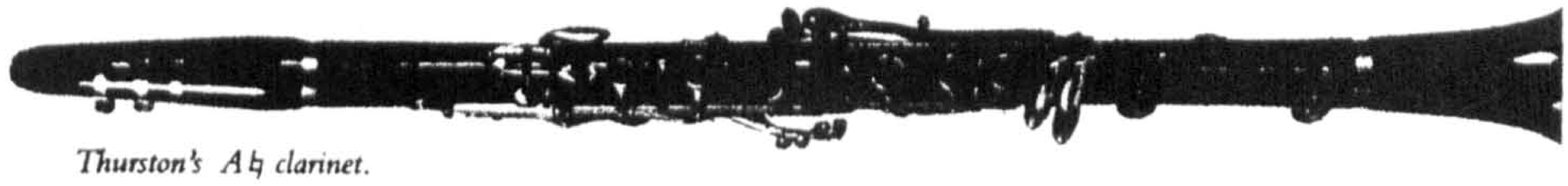
The 1010s were designed with a bore of 0.600 inches, (15.24 mm) which is uniform from the top of the barrel to the start of the flare. They required special mouthpieces with nominally cylindrical bores to achieve good tuning of the twelfths.

Thurston's pair were again plain Boehm system. The 'A' instrument has survived with its bore still very close to the original specification and most of the tone holes are lightly conical undercut through most of the wall thickness. Some of the pads are showing their age but the instrument can still be played with good intonation and a fine tone. When Frederick Thurston died in 1953 Thea King continued to play these 1010s until the mid 1970's, but soon after they stopped being played regularly, more than forty years after manufacture, a bad crack opened up in the top joint of the Bb instrument which has now been repaired.

After the Second World War, with Thurston's encouragement, Boosey and Hawkes re-established production of the 1010s but ran into design and quality control problems as has been well discussed. Thurston was at that time a consultant to the firm and tested their top-of-the-range clarinets. Many years ago I was told by a member of Boosey and Hawkes staff that when Thurston found a clarinet which he considered to be of exceptional quality, he marked it with a cross somewhere close to the thumb rest (using his pen-knife!). I have yet to see an example or meet anyone who can confirm this story.

In the late 1940s, Boosey and Hawkes launched the 926 Imperial with its more modest bore (15 mm) and straight sided tone holes. They gave Fredrick Thurston a presentation pair in the hope that he would become their champion but, he was not comfortable with them and stayed with his pre-war 1010s for the rest of his career.

The author would like to thank Peter Eaton, Keith Puddy and Dame Thea King for their help in preparing this article



Thurston's A♮ clarinet.

I have no complaints whatsoever with the second grade instruments, because I realise that they are made for those who are not concerned to have the very best, and perhaps do not care greatly whether they produce an artistic sound. But I am concerned with the top line instruments, which are at present nothing like so good as the pre-war job. I ~~believe~~ that you are ~~now~~ getting out some instruments ~~which~~ on the ~~same~~ lines as the pre-war clarinet, which is of course good news. I think it is important that ~~somebody~~ should ~~vet every instrument which goes out~~, to make sure that ~~it is~~ as perfect as possible, and so that if the instrument is brought back, a complete answer can be given by playig it over to the dissatisfied customer.

I do not want you to think from this that I am disparaging any of your staff, who have always listened to me with great respect. Nor do I want you to think that this is a roudabout way of asking you for a job! I shall be satisfied enough if my little piece has convinced you that nothing but the best is good enough for the poor devils who have to blow down the clarinet and who have enough to think of without the clarinet getting too much in the way! As a practical suggestion, I should like to say that after a good deal of thought I am convinced that the instruments

Part of a draft letter to Geoffrey Hawkes (see page 22).

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