Basic Clarinet Acoustics

– Stephen Fox

It is useful for clarinettists to know something of the scientific basis of how a clarinet works, on a slightly deeper level than the superficial descriptions given in general clarinet books, both for practical reasons (for example, understanding and solving tuning problems) and just for intellectual satisfaction. This article will attempt to give a brief sketch of some aspects of this large and subtle subject.

Basics of sound production

Sound is produced and sustained in any wind instrument through cooperation between two distinct but connected entities: a cavity containing air in which sound resonates (the body), and a sound wave generating device (the reed and mouthpiece of a clarinet, the player's lips and mouthpiece in the case of a brass instrument, etc.).

Sound waves in a clarinet are generated by the reed beating against the mouthpiece lay at a certain frequency, which is controlled primarily by the resonance of the air inside the body and secondarily by the embouchure of the player. Since the motion of the reed is non-sinusoidal, *harmonics* (exact whole number multiples of the reed's beating frequency) are also produced.

When the sound waves pass through the air inside a cavity, there are certain *modes* or patterns of vibration of the air at which standing waves are possible, or in other words certain frequencies at which the sound waves reinforce each other as they bounce back and forth from end-to-end of the cavity; these are the *resonance frequencies* of the cavity. These frequencies depend on the shape of the cavity, and in general can be in any numerical relationship; they will not necessarily be harmonic (in whole number multiples). For the cavity to function properly as the body of a wind instrument, though, they must be at least close to harmonic.

A tone is thus produced when the set of frequencies generated by the reed/mouthpiece and the set of resonance frequencies of the air inside the body are aligned; the beating frequency of the reed is dictated by the dominant resonance of the body, and the harmonics of the reed vibration attempt to find further resonance frequencies to excite. How effectively this collaboration takes place (in other words, how close to harmonic the resonance frequencies for that note are) determines the strength, stability, clarity and ease of response of the note.

Most of the energy in the sound waves is eventually dissipated by friction with the bore and at various edges and obstacles inside the instrument. A small amount, however, leaks out through the tone holes and through the bell, producing the sound that we hear.

The resonance frequencies of a woodwind instrument are determined both by the shape of the bore and by the tone holes, some of which will be open and some closed when a given note is fingered.

In order to give harmonic resonance frequencies, the bores of woodwinds are roughly either cylindrical (clarinet, flute) or conical (oboe, bassoon, saxophone). Since the bore of a clarinet is approximately a cylinder with the reed end closed and the bottom end open, in the simplest approximation the resonance frequencies should be the odd numbers of a harmonic series (e.g., 100Hz, 300Hz, 500Hz…). However, the tone holes (both open and closed), as well as frequency-dependent end effects at the reed and bell, modify the resonance frequencies considerably. This must be compensated for by alterations in the shape of the bore.

A sound wave travelling down a woodwind bore will be reflected back from a point at a certain distance, the *open hole end correction*, below the highest open tone hole. Higher frequencies travel further past the open hole (the length correction is longer); we could say that higher frequency waves "see" the hole as being smaller than lower frequency waves. Thus in any woodwind, the second and higher registers will tend to be flat, unless this is counteracted by changes in the bore shape. Above a certain frequency, known as the *cutoff frequency*, the waves ignore the tone holes completely and travel all the way down to the bottom end.

In addition, the closed tone holes make the bore behave as if it were both enlarged in diameter and stretched lengthwise slightly; this must also be taken into account when designing an instrument.

Characteristics of a purely cylindrical clarinet

Consider a clarinet (Boehm system) with a completely cylindrical bore of, say, 15.0 mm diameter, right from the top of the mouthpiece bore down to the bottom end.

When playing such an instrument, the first observation is that tone projection is uneven; overall it is rather muffled, but the notes sounded with the full length of the clarinet (bottom E and middle B) are much stronger. This leads to the first modification of the bore, the addition of a bell. The bell acts as an efficient radiator of sound into the room, particularly the high frequencies; and since the bell acoustically approximates a length of tubing with a row of open tone holes, the tone of the bell notes now matches that of the rest of the scale.

Such a clarinet will always tend to have a certain general tuning deficiencies:

- bottom E and F will be flat (wide twelfths between the first and second registers);
- the region around A to B in the low register will be sharp, and/or the corresponding E to F# region in the second register will be flat (narrow twelfths);
- most likely the high B to C region will be sharp (wide twelfths).

These are characteristics with which we are all familiar from playing older or lesser quality clarinets, and which cause much grief to clarinet designers and makers. What are the reasons for these problems, and what can be done about them?

The narrow twelfths in the middle of the scale are caused by the flattening effect of the tone holes through increased open hole end correction at high frequencies, as discussed above; later we shall see how this is corrected.

The wide twelfths at the bottom and (possibly) the top of the scale result from the behaviour of the speaker hole, as described below.

Effects of the speaker hole

The speaker hole is located ideally for one point in the scale (around A/E or Bb/F); in this region, the pitch of the second register note is independent of the characteristics of the speaker hole, and in fact is the same whether or not the speaker hole is open. Toward the top and bottom of the scale, however, the fact that the register hole is misplaced leads to the upper register notes being pulled sharp. This can be demonstrated on any clarinet by playing the second register, closing the speaker key and listening for the change in pitch.

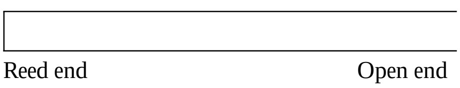
The degree of widening of the twelfths at the ends of the scale increases with the size of the speaker hole. Thus the problem is exacerbated by using the speaker hole also as a tone hole for throat Bb. On clarinets with a separate or supplementary tone hole for throat Bb, the speaker hole can be considerably smaller, and the tuning between the first and second registers is noticeably improved.

Bore perturbations and tuning the registers

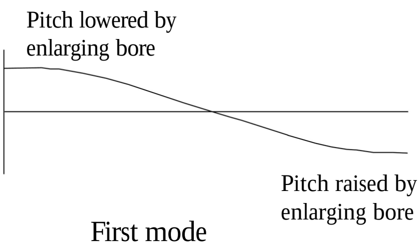
If a woodwind instrument has a bore that is basically cylindrical or conical, but the bore is slightly enlarged or reduced over part of its length (this is called a *bore perturbation*), the resonance frequencies are modified according to the following principle:

A localised *enlargement* of the bore *lowers* the frequency of vibration of modes which have *high* pressure in the region of enlargement, and *raises* the frequency of modes having *low* pressure in that region. A *contraction* of the bore has the opposite result.

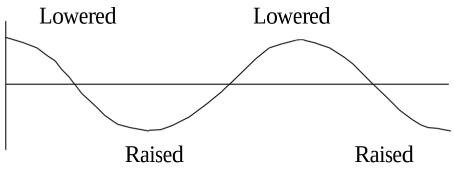
In a clarinet, the lowest mode of vibration has high pressure towards the reed (closed) end, and low pressure towards the bell (open) end of the air column; so enlarging the bore in the *upper* part will *lower* the pitch of the fundamental mode, while enlarging the bore in the *lower* part will *raise* it. The second mode (on which the second register is based) has a pressure node one third of the way down the air column, giving two regions where enlarging the bore will lower the pitch and two regions where it will raise the pitch:



Air column for a particular note



First mode



Second mode

By examining these so-called *perturbation weight functions* for each note of the scale, it can be deduced whether the first, second, third, etc., resonance frequencies of each fingering are raised or lowered by enlarging or reducing the bore at various points. This knowledge can be used to design a clarinet bore that plays the different registers as much as possible in tune with each other. All of the variations in diameter seen within the bore of a clarinet can be explained with reference to this principle.

We can experiment informally with this process by placing something - a sliding ring, a lump of modelling clay, etc. - inside the bore of a clarinet at different places and measuring the changes in intonation; the qualitative effect of enlarging the bore at a certain point can safely be assumed to be the opposite of the effect of reducing the bore at the same place.

The French clarinet bore

A typical modern French style clarinet bore can be represented schematically (with differences in bore diameter exaggerated) like this:

The effects on tuning of each region are the following:

1. The mouthpiece bore affects both the overall pitch and the balance between the top and bottom of the playing range. It is usually conical (tapering towards the top), more rarely cylindrical.

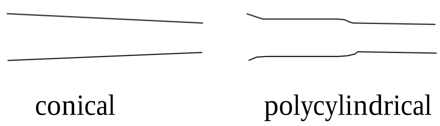
It is essential to use a mouthpiece with the correct bore size and shape for a given clarinet. A mouthpiece with a bore smaller than ideal will play sharp up to about A in the second register, then flat above that; one with an oversize bore will behave in the opposite way, flat up to the same point and sharp above. (This is rather a moot point when discussing modern equipment from major manufacturers since virtually all mouthpieces currently made have essentially the same bore, but it is crucial to consider it when dealing with historical instruments, and clarinets with now-uncommon bore sizes.)

2. The barrel bore affects the tuning of the upper part of the second register and the lower altissimo notes; these are sharpened if the barrel bore is enlarged. It also exerts a disproportionately large effect on the playing feel and resistance of the entire range of the instrument.

Current French style clarinets most often have a reverse conical shape (tapering towards the bottom) in the barrel bore.

3. The top part of the upper joint, most importantly in the region of the speaker hole, is enlarged to bring the middle twelfths into tune.

This expansion is generally either conical - tapering towards the bottom, over either the top part of the joint or in some cases the entire joint - or “polycylindrical”, i.e., with a cylindrical upper section larger than the main bore:



4. The lower joint has a long, gradually flaring expansion from around the Ab/Eb tone hole down to the bottom. This functions to narrow somewhat the wide twelfths at the bottom of the scale caused by the oversized and misplaced speaker tube; as we know, however, this is not completely effective (bottom F in particular is usually still uncomfortably flat on most clarinets).

A point worth emphasising is that it is the *difference* in bore size between the central section and the speaker hole region that controls the tuning of the middle twelfths; it is *not*, as is often erroneously stated, the size of the bore by itself. Much misunderstanding is caused by comparing the intonation of large bore clarinets with no upper joint expansion (for example, the Boosey & Hawkes 1010) with that of small bore instruments with a large amount of upper joint expansion (most recent French style clarinets); it is really the *shape*, not the *size*, of the bore that is being compared.

In the main, the evolution of clarinet bores in recent decades has taken place by keeping the bore of the mouthpiece and the diameter of the top end of the upper joint more or less constant, and altering the bore shape by making the central bore diameter smaller. A large bore clarinet *can* be built to be just as well in tune as a small bore clarinet, though in practice most are not.

The German clarinet bore

The bore of German clarinets has fewer departures from a cylinder than that described above. Most notably, the bottom end does not have the long flare of the French clarinet; it is cylindrical down just above the bell tenon with a sudden expansion into the bell (sometimes there is no expansion at all, merely a jump into the bell bore). Traditionally there is very little expansion in the upper joint, though in recent years there has been a movement towards conical upper joints.

The differences in tone and playing feel between French and German clarinets are caused largely by the shape of the lower joint bore. The mainly parallel bottom end leads directly to the greater clarity and tonal centre or focus of the German clarinet, especially on the lowest notes, accompanied by some loss of brilliance. (Somewhat smaller tone holes on the German clarinet also contribute to these differences.)

Tone holes and cutoff frequency

The tone holes of a chromatic woodwind instrument are, simplistically speaking, positioned so as to terminate the tube acoustically at each semitone of the scale. In order to give constant tone colour and resistance throughout the scale, the holes need to be smallest at the top of the tube, larger further down. In contrast with the rationally designed tone hole lattice of, for example, the flute, the tone holes of a clarinet are an apparent hodgepodge of varying diameters, depths and spacings; this is reflected in some inhomogeneity in the scale, though acoustically the system is not as irregular as it looks.

The pitch of a given note depends on the location of the tone hole principally involved in producing that note and on its open hole end correction (the distance the sound waves travel beyond the hole before bouncing back). The end correction varies with a number of characteristics of the hole: its diameter, the spacing between it and the next hole, its depth, and the height of the pad over it. The note is sharpened by enlarging the hole, moving the next hole closer, reducing the depth of the hole or raising the pad; it is flattened by doing the opposite.

As mentioned previously, the cutoff frequency (of a particular tone hole or of the instrument in general) is the frequency above which sound waves ignore the open tone holes. This is an important value, which can tell us a lot about the character of an instrument, since it is a quantitative measure of tonal “brightness” or “darkness”; a high cutoff frequency gives a sound which we describe as bright, a low cutoff frequency a dark tone.

Large tone holes (relative to the bore), short hole spacing, shallow holes and high pads give a high cutoff frequency; small holes, wide hole spacing, deep holes and low pads give a low cutoff frequency.

The lower the cutoff frequency, the more serious is the flattening of the upper resonance frequencies relative to the fundamental. Fork fingered notes, with large spacing between open holes (e.g., low B on the Boehm system clarinet or low Bb on the simple system clarinet), or notes produced by abnormally small tone holes (e.g., low C#), have much lower cutoff frequencies than fully vented notes; this explains why these fingerings are especially troublesome, with “strange” tone qualities and a tendency to be sharp in the low register and/or flat in the upper registers.

The degree of undercutting (also referred to as *fraising*) of the tone holes has a significant influence on the personality of a clarinet. An undercut hole has roughly the same effect on pitch as a large hole with respect to the low register, but has the lower cutoff frequency of a smaller hole, giving a darker tone colour and relatively flatter pitch in higher registers. Modern French style professional clarinets, in general, have fairly heavily undercut tone holes, in the interests of dark tone and flexibility of pitch.

Further reading

Of the numerous books available in English on musical acoustics, the following are recommended:

Arthur Benade: *Fundamentals of Musical Acoustics* (revised edition Dover, 1990; original edition 1976). An indispensable guide to all aspects of musical acoustics by a physicist who was also a clarinettist and instrument maker; written for the layperson in readable and almost entirely non-mathematical form, though with simple formulas allowing practical calculations.

Hermann Helmholtz: *On the Sensations of Tone* (Dover, 1954; original edition 1863). In spite of its age, still a standard (if rather heavy going) text on the physics and psychology of music.

Ernest Ferron: *The Clarinet Revealed* (International Music Diffusion, 1996). Though it suffers somewhat from being translated into English from French, contains much valuable information on the functioning of the clarinet and also on repair techniques.

Cornelis J. Nederveen: *Acoustical Aspects of Woodwind Instruments* (Frits Knuf, 1969). Very mathematical and really aimed at physicists, though some insight can be gleaned by the layperson.

Lee Gibson: *Clarinet Acoustics* (Indiana University Press, 1994). Contains useful observational information and opinions on different types of clarinets, though not scientifically authoritative.

It is hoped that this will help clarinettists understand a little about how their instruments function and why they are designed the way they are.

– Stephen Fox combines the backgrounds of instrument maker, musician and scientist.

Born in England, raised in western Canada and currently based in Toronto, he began his university studies in physics, achieving a Masters degree with a thesis in theoretical plasma physics from the University of Saskatchewan, before deciding to concentrate on music and receiving a degree in clarinet performance.

An active performer, he plays clarinet, saxophone and historical clarinet in orchestral, chamber and commercial music settings in the Toronto area, and has presented recitals in Norway and Finland as well as across Canada..

In addition to being a woodwind repairer and restorer known across North America, he is one of a handful of independent clarinet builders in the Western Hemisphere, designing and producing both modern clarinets and reproduction historical instruments; his clarinets are currently used by professional musicians in the fields of symphonic music, period instrument performance, jazz and Klezmer in Britain, the Netherlands, Scandinavia, the U.S.A. and Canada. He also spends part of each year in Europe, teaching woodwind instrument making at the Musikk Instrument Akademiet in Sarpsborg, Norway.

Stephen Fox
242 Ashlar Road
Richmond Hill, ON
Canada L4C 2W6
tel/fax +1 905-737-7263
internet www.sfoxclarinets.com
email <steve@sfoxclarinets.com>