sound. The use of a sophisticated computer to generate the numbers offers the electronic musician almost limitless creative scope.

However the numbers are generated, they must be turned into a continuous analogue signal before a loudspeaker can realize their musical potential as sound. This process is carried out by a digital-to-analogue converter (DAC). In principle the output of the DAC is a series of steps rather than a smoothly varying signal (Figure 2.22), but the musical significance of this 'staircase effect' is negligible provided that suitably high values of resolution and sampling frequency are chosen.

3

Woodwind Instruments with Reeds

3.1 ACOUSTICAL PRINCIPLES

A reed woodwind instrument consists essentially of a tube, considerably longer than its widest diameter, with a single or double reed at one end. We saw in Chapter 2 that such an instrument is a member of the aerophone family, since the pitches at which it sounds are determined by the properties of the air column confined within the tube.

The tubes used in practical woodwind instruments fall into two categories: approximately cylindrical, and approximately conical. We start by discussing the acoustical consequences of using a reed to excite an exactly cylindrical or conical tube, before considering the musical consequences of the deviations of real instruments from these idealized shapes.

Basic acoustics

When a note is sounded on a clarinet or oboe, a complex interaction takes place between the reed and the standing waves in the air column. Standing waves which have pressure antinodes at the reed cooperate to pump up the amplitude of the reed vibration, which in turn modulates the air flow so as to increase the amplitudes of these standing waves. As the standing waves grow, more energy is lost as heat to the walls of the tube, or radiated as sound. When the instrument is radiating a stable note of constant loudness, a balance has been achieved in which the energy input is equal to the rate of loss.

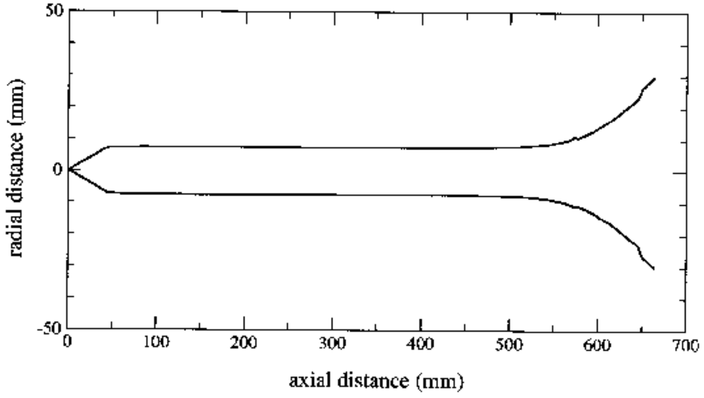
The requirement that standing waves should have pressure antinodes at the reed makes the blown end of the tube behave as though it were closed. Our discussion in Chapter 2 then leads us to expect that a clarinet-like cylindrical tube, with one end effectively closed by the reed, will have natural mode frequencies which are the odd members only of a harmonic series (see Figure 2.3). For example, a B♭ clarinet with all the side holes closed has a set of natural modes with frequencies close to 147 Hz, 440 Hz, 735 Hz, etc. These are 1, 3, 5 . . . times the first mode frequency of 147 Hz.

When the lowest note on the clarinet (sounding D_3) is played, the reed locks into vibration at a frequency of 147 Hz. The resulting variation of the air flow into the instrument contains all harmonics of 147 Hz, not just the odd ones. The reception afforded to odd and even harmonics by the air column is however very different. Each odd harmonic of the exciting air flow is in tune with a natural mode of the air column, and happily enters into the mutual back-scratching arrangement already described. The even harmonics, in contrast, find no helpful air column resonances at their frequencies, and therefore make only a weak contribution to the radiated sound.

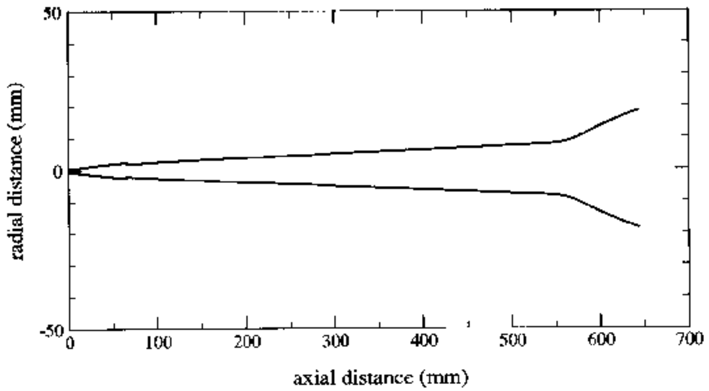
For oboe-like instruments with a conical bore, the natural mode frequencies form a complete harmonic series (see Figure 2.6). Odd and even harmonics of the exciting airflow thus receive an equally favourable response from the air column, and we should not expect to find any bias in favour of odd harmonics in the spectrum of the radiated sound.

The shapes of real woodwind instruments

A real clarinet differs in many ways from the ideal cylinder which was assumed in the foregoing discussion. Figure 3.1 shows the measured bore profile for a typical B♭ clarinet. Although the main part of the tube is cylindrical, there is a noticeable narrowing towards the reed end and a pronounced flaring out at the open end. Nor is a real oboe a perfect cone: Figure 3.2 illustrates a typical bore profile, consisting of several conical sections with different tapers and a final flaring bell. There are also the side holes; even when these are all closed they constitute a series of additional volumes spaced along the tube.



3.1 Internal bore profile of a B♭ clarinet. The complicated inner geometry of the mouthpiece is here replaced by a cone with the same cross-sectional area. Note the difference in axial and radial scales

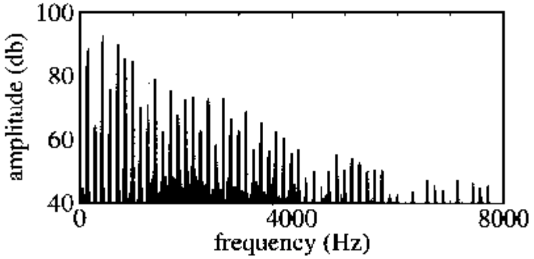


3.2 Internal bore profile of an oboe. Note the difference in axial and radial scales

As a result of these divergences, the natural mode frequencies of real woodwind instruments show small but significant departures from the exact harmonics predicted by the idealized theory. This does not mean that the frequency spectrum of a steady woodwind note will contain inharmonic components: the regular periodic vibration of the reed ensures that a set of exact harmonics is injected into the tube. But the strength of each harmonic in the radiated sound will depend on how close it is in frequency to one of the natural modes of the tube.

The vibration frequency of the reed tends to adjust so that several of the low harmonics are as close as possible to natural modes of the air column. The resulting build-up of a set of strong standing waves is sometimes called a 'cooperative regime'. By altering the blowing pressure and the way that the reed is squeezed by the lips the player can vary the reed frequency to a considerable extent. Since this will move some harmonics closer to air column resonances and others further away, such 'lipping' of the note will alter the timbre as well as the pitch.

An ideal cylindrical clarinet should give a note with only odd harmonics. To what extent is this true of a real clarinet? This question is answered by the measured spectrum shown in Figure 3.3. We can see that the 2nd and 4th harmonics are certainly much weaker than the 1st, 3rd, and 5th, but by the time we get to the 10th harmonic we find that it is much stronger than the surrounding odd components. The reason for this reversal of the expected pattern is that the natural modes have by then got so out of tune that the fifth mode, which should have boosted the 9th harmonic, is in fact in tune with the 10th harmonic.



3.3 Frequency spectrum of a note D_3 (sounding pitch) played on a B♭ clarinet

Overblowing

On most woodwind instruments it is possible by a suitable adjustment of blowing pressure and lip control to make the reed vibration lock onto the second natural mode of the air column, instead of the first. This adjustment is described as 'overblowing'. On a conical bored instrument like the oboe the second mode is an octave above the first, so the pitch of the note will rise an octave on overblowing. Further overblowing will make the reed frequency jump to that of the third natural mode, a twelfth above the first. On a cylindrical instrument like the clarinet overblowing will raise the pitch immediately by a twelfth, since this is the interval between the first and second natural modes.

Overblowing is greatly assisted by the opening of a small vent-hole near a pressure node of the desired higher mode. Figure 2.6 shows that in a conical tube complete to the apex, the second mode has a pressure node half-way along the tube. In a realistic oboe, which is more like a cone with the sharp end cut off, this pressure node is nearer to the reed end. What would be the effect of opening a vent-hole at the node? If the second mode alone were activated there would be no variation in pressure at the position of the vent-hole; opening the hole would then have no effect, since both inside and outside there would be constant atmospheric pressure. The same argument applies to the fourth mode, and in fact to all the even modes; opening the vent-hole should have no effect on these modes.

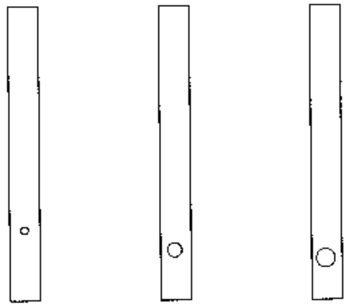
On the other hand, the first mode is trying to maintain a significant pressure variation at the vent-hole. Opening the hole will have two effects on this mode: the amplitude of the standing wave will decrease, and the frequency will shift upwards. There will be similar changes in the amplitudes and frequencies of the other odd modes.

With the vent-hole open, the second mode is stronger than the first, which encourages the reed to lock onto the second mode frequency. This tendency for the sounding note to jump an octave is strengthened by the fact that the odd-numbered mode frequencies are shifted by varying amounts and are no longer capable of supporting the original cooperative regime. In contrast, the fourth mode frequency is unaffected by the opening of the vent key, allowing a cooperative regime based on the second and fourth modes to stabilize the vibration of the reed at the higher frequency.

Side holes and scales

It is possible to make music using only the notes obtainable by overblowing a tube of fixed length. To play an approximation to a diatonic scale, however, it is necessary to overblow to the eighth mode and beyond (see Figure 1.13). Although this technique is commonplace in brass instruments, it is rarely used on woodwind instruments. Instead, a set of holes is provided along the side wall of the tube. To play the lowest note on the instrument all of the side holes are closed, either directly by the fingers or via a system of keys, levers, and pads. Opening the lowest side hole reduces the effective length of the vibrating air column and raises the pitch of the note. Successively opening higher side holes raises the pitch further, in a series of steps which can be made to correspond to any desired scale by suitable positioning of the holes.

The pitch obtained by opening a particular hole depends not only on the position of the hole but also on its diameter. All three tubes shown in Figure 3.4 will sound the same note, since the shortening effect of each hole is the same. The tube on the right has a hole with a diameter almost as big as that of the tube. Opening such a large side-hole is roughly equivalent to sawing off the section of tube beyond the hole; a pressure node is created just below the hole position. The tube in the middle has a somewhat smaller side-hole, and the effective pressure node is some distance below the hole. The tube on the left has an even smaller hole, and the distance from hole to effective pressure node is even greater. The ability to compensate for the shifting of a hole by altering its diameter is very useful to the designer of woodwind instruments.



3.4 Three cylindrical tubes, open at both ends, each with a single side hole. The tubes have the same effective (or sounding) length

On most modern woodwind instruments the use of side-holes is coupled with the overblowing technique previously described to provide a musical compass of several octaves. The oboe, for example, sounds the note $B^\flat_3$ when all its holes are closed. By successively opening side holes a chromatic scale up to C_5 can be played. This part of the instrument's compass is described as the low register; for all of the low register notes, the reed vibrates at a frequency close to that of the first mode of the air column.

There is no further hole which can be opened to give the next chromatic note, $C^\sharp_5$. To sound this note, most of the side-holes are closed again to give the fingering for $C^\sharp_4$; the opening of a vent hole causes the instrument to overblow to the octave above, thus achieving the desired pitch. The chromatic scale from $C^\sharp_5$to C_6 is obtained in this way by overblowing from the low register. Since the vent-hole should be at the pressure node of the second mode, there should ideally be a separate vent-hole for each note. In practice, a small perforation opened in the pad covering the highest side-hole is used to vent the notes from $C^\sharp_5$to $E^\flat_5$; a vent-hole further up the tube is opened by the 'bottom octave key' for the notes E_5 to $G^\sharp_5$; and an even higher vent is opened by the 'top octave key' for the notes A_5 to C_6. The notes from $C^\sharp_5$ to C_6 constitute the upper register of the instrument, in which the reed frequency is close to that of the second mode of the air column.

A further extension of the compass of the oboe (up to A_6 is required by some orchestral parts) is provided by overblowing so that the reed locks on to the third or fourth mode of the air column. This region is described as the high register.

Similar techniques are used on the other reed woodwinds, although the detailed methods of venting vary considerably. In instruments of the clarinet family the second mode is a twelfth above the first, and the low register of the instrument must span this pitch interval. The side-holes therefore continue further up the tube than is necessary on a conical instrument. The relationship between fingering patterns in first and second registers is also less straightforward: a fingering which gives, say, C_4 in the low register of a clarinet will give not C_5 but G_5 in the upper register.

Tables showing patterns of finger-holes and keywork for several currently used and historically important models of woodwind instruments are given in Appendix 2.

Cut-off frequency

Up to this point we have assumed that opening a particular pattern of side-holes on a woodwind instrument reduces the effective length of the air column by the same amount for all its modes of vibration. This is an oversimplification. The effect of an open hole on a wave travelling down the tube depends very much on whether its frequency is above or below a critical value known as the cut-off frequency. If the wave frequency is much below the cut-off, the wave is reflected just below the highest open hole, as described above. As the frequency approaches cut-off, the point of reflection moves further down the tube. If the frequency is above the cut-off value, the wave is not significantly reflected by the open side-hole, but continues on to the lower end of the tube.

The cut-off frequency depends on the diameter and depth of the open side-holes, and on their spacing. The pattern of open holes changes with the note being played, and in general there will be a different cut-off frequency for each fingering pattern. An instrument with large side-holes will have higher cut-off frequencies than an otherwise similar instrument with smaller holes.

Altering the cut-off frequency has a profound effect on the timbre of the instrument. Below the cut-off frequency, the strong reflection gives powerful natural modes corresponding to the shortened tube length. Above the cut-off, we find much weaker modes corresponding to the complete length of the tube. Usually an instrument is proportioned so that the first few modes are below cut-off, and these strong low-frequency modes provide the cooperative regime which stabilizes the reed vibration. The higher harmonics of the exciting airflow lie above the cut-off; the absence of strong modes in this frequency region means that in the internal spectrum of the instrument these high harmonics are much lower in amplitude than the harmonics below cut-off. Raising the cut-off frequency will boost the strength of some of these high harmonics, giving the instrument a brighter timbre. Carrying this process too far will make the sound unacceptably harsh.

The cut-off frequency also affects the fingering of notes in the high register. A note in the low register normally has a fundamental frequency well below the cut-off frequency; since a wave at this frequency is totally reflected at the highest open hole, it is unaffected by the opening or closing of holes much further down the tube. In contrast, the waves which determine the pitch of a high register note may have frequencies above the cut-off, in which case they will run on to the end of the tube. The pitch can then be altered by closing one or more of the lower holes, a technique known as cross-fingering. Because the standing wave patterns above the cut-off frequency are complicated, the effect of cross-fingering can be surprising—sometimes closing an additional hole will make the pitch rise instead of fall.

Radiation of sound

We have seen that in the internal air column of a woodwind instrument harmonics below the cut-off frequency are liable to be much stronger than those above cut-off. In the sound radiated by the instrument, this bias towards low-frequency components is partly offset by the fact that in general high frequencies are radiated more efficiently than low frequencies. This 'treble boost' in the radiation process means that the sound heard by a listener is much brighter than the sound which is picked up by a microphone inside the instrument.

The directional pattern of the radiated sound depends on frequency; once again, the cut-off frequency is a crucial parameter. A component with frequency much below the cut-off is radiated with equal strength in all directions; such a uniform directional pattern is described as isotropic. Practically all the sound energy is radiated from the highest open hole. A component whose frequency is close to the cut-off is radiated in a complex pattern, with the strongest radiation occurring along a fairly wide cone whose central axis is that of the tube. For components with frequencies much above the cut-off, the sound is radiated most strongly down the tube axis. The varied nature of these directional patterns poses a tricky problem for the recording engineer, trying to position a microphone so that one frequency region will not be favoured at the expense of another.

3.2 HISTORICAL DEVELOPMENT

Many of the most primitive instruments known are of the reed type because of the simplicity with which they can be made. Every child knows, for example, that by stretching a blade of grass between cupped hands and blowing across the edge, a loud and quite varied buzzing sound can be produced. A crude form of reed instrument, which produces a squawk when placed in the mouth and blown strongly, can be made simply by splitting the end of a dry length of reed. Little is known about the earliest origins of reed instruments, but it is not unreasonable to assume that techniques such as these were used for the imitation of natural sounds and the accompaniment of religious ceremonies.

Pictorial representations of reed instruments date back as far as 3000 BCE, and the remains of Sumerian silver reed instruments found in the course of excavation in the Royal Cemetery of Ur have been dated at about 2500 BCE. These are cylindrical bore instruments with three side-holes, probably designed to play whole tone scales. Single reed instruments are frequently depicted in Egyptian tomb paintings of the Old Kingdom (around 2200 BCE); double-reed instruments do not seem to have appeared in Egypt until the time of the New Kingdom (around 1500 BCE).

Further developments were made by the ancient Greeks, whose wind instruments were characterized broadly as either aulos (reed) or syrinx (flute). An aulos usually took the form of two pipes, each fitted with a reed and typically about 50 cm long, held one in each hand, usually at a divergent angle, and played together. Players are often depicted wearing a form of halter which covers the cheeks and the outer lips, being held on with a strap around the back of the head. One possible function of such an arrangement is in helping to maintain the pressure in the mouth and to stop the cheeks from bulging. There appears to be convincing evidence that both single- and double-reed versions of the aulos were constructed. Writings of the ancient Greek philosophers tell us that a good deal was known at that time about the art of producing suitable reeds and the mechanics of blowing them.

Rather similar to the aulos was the Roman tibia, dating from around 500 BCE. This was usually made of metal, although sometimes hardwood or even ivory was used, and it incorporated a number of technical refinements which increased its flexibility. For example the side-holes could be opened or closed by means of metal bands, thus allowing the instrument to be preset to play in one of a number of modes. Tibias were used, often by groups of players, to accompany social and ceremonial events ranging from the preparation of food to the engagements of gladiators in the arena.

After the fall of the Roman empire the European tradition of reed instrument-playing seems to have almost completely died out. There is no evidence that knowledge of the classical reed aerophones contributed to the reappearance of double-reed instruments in Europe around the end of the first millennium CE. The catalyst for this development was almost certainly the growing military, political, and social interaction between Islamic and Christian civilizations, which led to the spread into Europe of conical reed instruments already in common use in North Africa and the Near East.

Shawms

The term shawm is used generically to describe a conical bored double-reed instrument. Although no shawm made in Europe before the sixteenth century is known to have survived to the present, images of this type of instrument are found in late twelfth-century manuscripts, and documentary evidence for the use of shawms in Europe is found from the thirteenth century onwards. The shawm is blown in a similar manner to a modern oboe except that the reed itself is held almost entirely inside the player's mouth. Frequently the reed is mounted in a cylindrical wooden holder known as a pirouette. The lips of the player can rest against the front face of the pirouette while maintaining some control of the reed at its base. The use of the pirouette makes it easier to play loudly for long periods of time without lip fatigue setting in, and also protects the player's mouth from damage in the event of the instrument being knocked.

The earliest European shawms were small instruments playing in the soprano range. By the end of the sixteenth century shawms were being made in a range of sizes from the sopranino down to the great bass. The body is generally wooden. Figure 3.5(b) shows a twentieth-century reconstruction of a tenor shawm similar to that illustrated by Michael Praetorius in the *Syntagma Musicum*, published in the early seventeenth century. Pirouettes are not normally used on the bass and great