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THE WINDS OF MUSIC — ART AND SCIENCE

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ABSTRACT

The acoustics of musical wind instruments is reviewed, with particular reference to traditional instruments of the Western Pacific region. Flute-like instruments, reed-driven instruments, and lip-driven instruments provide a wide variety of musical sounds, and we now have a good understanding of the way in which sound is produced and subtly controlled by the player.

KEYWORDS: musical instruments, wind instruments

INTRODUCTION

While drums are perhaps the oldest of musical instruments, it seems certain that wind instruments rank next in antiquity. The materials for a host of such instruments have always been ready to hand — conch shells, hollow reeds and bamboos, hollow animal bones — and our ancestors seem to have made early use of them. Indeed, some early instruments required even less in the way of materials, for the Australian Aboriginal people were able to fashion a tuneful (and loud!) instrument from a simple leaf sandwiched between two opposing thumbs.

This paper will discuss the acoustics of some of these traditional instruments and relate what is known of them to modern instruments and performance techniques. It is encouraging to see a revival of interest in this subject, and in the music on which it is based. Many technical references could be cited in a review such as this, but to be practical I have listed only one book [1] and two recent review papers [2,3] in which the interested reader can find an extensive bibliography that gives credit to the investigators concerned. There is also a recent encyclopedia that gives a wealth of ethnomusicological detail. [4] Fig. 1 shows sketches of some of the instruments I refer to.

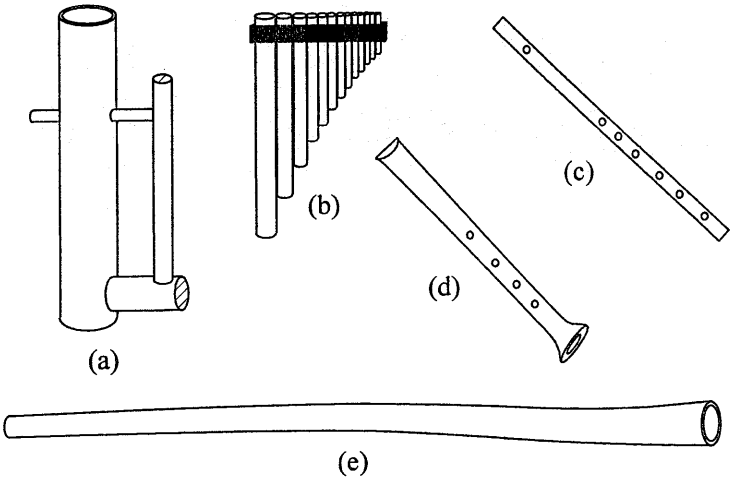

Fig.1 Some traditional wind instruments. (a) the kata batang of Sabah, (b) a set of panpipes, as from the Andes, (c) a side-blown flute, (d) the end-blown shakuhachi of Japan, (e) the didjeridu of Australia.

FLUTE-LIKE INSTRUMENTS

Flute-like instruments consist simply of a volume of air — usually an air column confined in a tube, but sometimes a simple volume confined in a compact cavity with one or more vent-holes — and some means of exciting this with an air jet blown across an aperture. The simplicity is, however, deceptive, and even now the aerodynamics of the jet and its interaction with the air column is only incompletely understood. It is known, however, that an air jet emerging from a flue aperture into an acoustic flow field transverse to the direction of the jet is unstable, and that sinuous waves on the jet grow in amplitude as they propagate away from the flue. It is also known that if such an oscillating jet blows successively into and out of an aperture in a resonator, then its flow will excite the resonator into an oscillation that will interact back with the jet to maintain the waves upon it. This sound generator will work, however, only if the phase relations between jet wave and resonator oscillation are right. It turns out that this requires about half a wavelength of the sinuous disturbance to lie on the length of the jet between the flue and the edge of the resonator aperture, and this puts restrictions upon the blowing pressure as well as upon the geometry.

The simplest of the flute-like instruments is a bamboo tube, cut straight across at its open end and sealed at the other end by one of the natural partitions of the stem. The tube is naturally almost cylindrical from the growth habit of the plant. The resonances of such a tube form an odd-harmonic $1, 3, 5, \ldots$ series based upon an odd number of quarter-wavelengths of a sound wave in the tube. If the player blows rather gently, then the wave-speed on the jet is small — actually about half the jet speed — and the fundamental of the pipe can be excited with half a wavelength of jet displacement along the jet. Blowing with higher pressure means a faster jet, so that, at an appropriate pressure, the jet will support a half wavelength of the third harmonic, and the pipe 'overblows' to a pitch that is a musical twelfth above the fundamental. This is rarely used in performance, however, and instead the instrument maker clusters a whole group of pipes together in a row to produce a musical scale of notes. The instrument is generically known as panpipes, though this European name is not really appropriate in the Western Pacific.

Although the pitches of the notes of a set of panpipes would seem to be fixed by the tube lengths, there is in reality a great deal of musical latitude possible, simply by varying the extent of the lip-cover at the open end, and thus changing the 'end-correction' of the pipes. Since these quarter-wave pipes are not very long in any case, it is easy for a skilled player to 'bend' the pitch by more than a semitone (6 percent).

Although the notes of the panpipes are clear and bright when played in the way indicated above, and each is a phase-locked harmonic sound, there is another performance technique that gives a percussively articulated, breathy, and only slightly tonal sound quality. The percussive beginning to the notes is caused simply by the plosive release of breath from the mouth, and the sound quality comes from the use of a broad turbulent air jet which fails to propagate jet waves but excites the pipe essentially by random turbulence noise. The sound output is in the form of narrow-band noise, with successive bands centered on the tube resonances which ae nearly, but not quite, in harmonic relationship. The musical contrast between the two ways of playing is very marked.

The next development was to make a single pipe able to play a range of notes through the use of finger-holes. This involved a switch to an open-ended half-wave pipe and therefore the necessity for the instrument to be about twice as long as before. The most refined development of such a bamboo instrument is the shakuhachi of Japan. An open pipe behaves rather differently from one that is closed, because the jet can blow fully into it without building up a large back-pressure. The end-blown configuration of the shakuhachi then allows particularly efficient excitation of the air column because the momentum flow is in the direction of the acoustic motion. Overblowing to the second mode, which is at the octave, is straightforward and an essential part of the technique. Add to this the freedom of intonation allowed by the large open blowing end, and the musical result has great variety. Despite the pentatonic scale provided by the five finger holes, a skilled player can produce all twelve notes of Western chromatic music over a full two octaves by using forked-fingerings and lip adjustments.

Pacific cultures have also produced side-blown flutes, in which the blowing hole is near one end which is then stopped with a wooden block, giving a geometry like that of the Western transverse flute. The underlying acoustics is similar to that for end-blown flutes, except for the fact that the transverse jet is less able to transfer momentum to the acoustic flow. The blowing hole is also much smaller than in end-blown flutes, so the latitude for pitch variation is smaller. It is the side-blown flute, with the addition of pads and keys, that has become predominant in orchestral and wind-band music. Metal, often silver or gold alloys, has also replaced bamboo or wood, but this of itself makes no fundamental difference to tone quality—it is the geometrical variations in bore shape, finger-hole size and lip support made possible by its use that cause the changes.

Some end-blown flutes have been made with fixed windways, like whistles or like the European recorder, while some Chinese flutes produce an unusual buzzing tone from the nonlinear vibrations of a sheet of tissue paper placed over an extra hole in the upper bore. The variety possible from such an essentially simple instrument is truly amazing.

Technical Details The acoustical behavior of the instrument bore is essentially linear, and interest centers on the way in which the propagation and radiation properties are influenced by small perturbations in bore diameter, introduced purposely by the maker, and by the presence of finger holes which may be open or closed.

Finger holes, of course, are used to change the acoustic column length and thus the pitch of the note being played, and for this there is a trade-off between finger-hole diameter and position along the bore. Such a trade-off has traditionally been used to bring finger holes

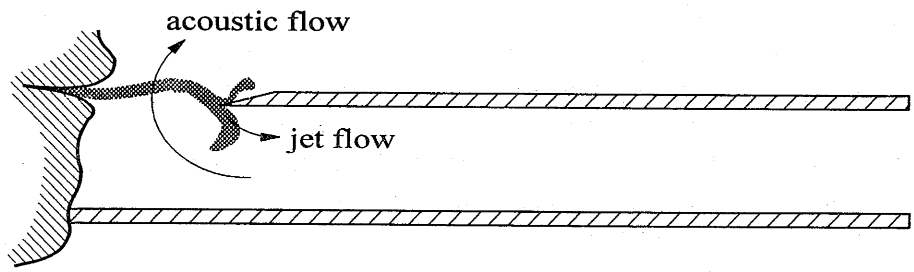

Fig.2 Excitation of a flute-like instrument by an air jet. The phase relation between the acoustic flow out of the instrument mouthpiece and the flow of the deflected jet into the instrument is important.

within easy reach, but it also has an effect on the overall sound of the instrument—finger holes that are much smaller than the instrument bore reduce high-frequency resonances of the air column and so give the instrument a mellow sound, while large finger holes give a bright sound. The diameter of the holes also influences radiation efficiency, so that small holes lead to a quieter sound than large holes. In modern flutes, the finger holes are provided with padded keys, so that they can be made nearly as large as the instrument bore, giving a bright clear sound. The mechanism associated with these keys also allows their number to be increased so that there is one hole for each or the 12 chromatic semitones in the octave. For traditional instruments, only fingers are used, and generally not all of these, which restricts the number, size, and position of the holes. While this can be seen as a disadvantage in modern music, it has the feature of giving a different sound quality to certain "cross-fingered" notes, and of allowing finger slides and other devices that add subtle musical interest to performances of music written with the characteristics of the particular instrument in mind.

Much acoustical interest has been concentrated on the way in which the air jet from the player's lips interacts with the air column to excite and maintain the sound. Essentially this air jet is unstable to transverse displacements, and these are imposed upon it by acoustic flow through the instrument mouth-hole. If the mouth-hole acoustic flow velocity is $v \sin \omega t$, then this displaces the jet by an amount $-(v/\omega) \cos \omega t$ everywhere along its length except at the opening in the player's lips, where displacement is prevented. This is nearly equivalent to keeping the jet center-line fixed and displacing the lip orifice by an amount $(v/\omega) \cos \omega t$. This local transverse displacement grows exponentially as it propagates along the jet, giving a growing transverse wave for which the wave velocity can be shown to be about half the airstream velocity of the jet. Formally, this transverse wave can be written

$$y(x,t) = \frac{v}{\omega}\left[-\cos \omega t + \cosh \mu x \cos\left(\omega t - \frac{x}{u}\right)\right] \tag{1}$$

where x measures distance along the jet from the lip aperture, u is the wave speed on the jet, and μ is a growth coefficient which is greatest when the wavelength of the jet wave is about 5 times the jet thickness. These waves can be visualized using aerodynamic techniques such as schlieren photography.

At the further edge of the instrument mouth hole, the jet impinges on a sharp edge, and its transverse motion means that it blows successively into and out of the instrument bore. The transfer of volume flow and of momentum from the jet to the tube oscillation can reinforce that oscillation provided that the phase relationship is correct. Detailed analysis shows that for this to be achieved, there must be about one-half of a transverse wavelength of the jet disturbance along the jet length. This, in turn, fixes the required blowing pressure, since this determines the jet speed and so the wave speed along it. The process of mixing of the jet with the acoustic flow in the pipe is very inefficient, and further energy is lost by viscous and thermal effects near the tube walls. The overall efficiency for sound production of less than 1% is, however, typical of nearly all musical instruments.

All this means that the player must adjust blowing pressure and lip position for each note so that the phase condition is approximately fulfilled. Detailed studies of performance technique carried out on skilled players confirm these predictions in detail. To alter the loudness of the sound, the player simply increases the area of the lip opening while maintaining blowing pressure constant. All this does not mean, however, that the player is rigidly constrained in playing technique, but rather that small and subtle adjustments to lip position and blowing pressure can achieve artistic effects that make the performance musically satisfying.

REED-DRIVEN INSTRUMENTS

Instruments driven by a vibrating reed-valve also have their origin in the hollow stems of bamboos or reeds. If the tube is split at one end, thinned, and bound nearly closed with thread, then it can be used as a double reed. The vibrations of the reed are controlled by the acoustic pressure inside the tube and it can be shown that the system will go into spontaneous oscillation at the quarter-wave frequency of the tube provided that the natural frequency of the vibrating tongues is much higher than that of this tube resonance, and that the blowing pressure is great enough to nearly half-close the reed aperture. Although air flow enters through the reed, this end must be an acoustic pressure maximum for it is this pressure that controls the reed vibration. As in the flute instruments, finger holes in the tube wall can be used to vary the resonance frequency and thus the pitch of the note produced. Because nearly all natural cane tubes are nearly cylindrical, these reed instruments all overblow by a musical twelfth if a means of excluding the lower resonance can be found. This is an inconveniently large interval, however, and almost inevitably leaves a gap in the middle of the scale unless mechanical keys are employed, as in the modern clarinet. For this reason, most traditional instruments limit their playing to the lower octave of their range.

While a double reed seems the natural symmetrical arrangement to use, it is also possible to split the tube asymmetrically and thin just one side, blocking the end of the other as a sort of mouthpiece as in the modern clarinet. Such a single-reed instrument has one significant acoustic difference from a double reed instrument — the air passage past the reed is wide because of the hollow mouthpiece, while in a double reed the passage between the two constricted reed flaps is long and narrow. The result turns out to be that a single reed can be made to vibrate without beating against the mouthpiece, thus producing a mellow sound as in the modern clarinet, while a double reed always beats closed in each cycle, producing an incisive tone like the medieval shawm, now moderated to the modern oboe.

There is, of course, one other significant difference between these traditional instruments and the modern oboe, bassoon, or saxophone, and this is that the latter have conical rather than cylindrical bores. For a given length of instrument, this raises the pitch by an octave and causes the overblowing to be to the octave rather than the twelfth. A narrow double reed clearly fits well onto the narrow end of such a conical bore, and only the saxophone uses a broadened mouthpiece with an enclosed cavity and a single reed. Although such conical horns were used for lip-driven instruments, as will be discussed below, no plant produces a hollow stem of this shape. Development of such instruments therefore had to await the use of more sophisticated tools than those needed for their cylindrical cousins.

Among all these reeds coupled to acoustic resonators that determine the vibration frequency, there is just one 'free-reed' instrument in which the reed vibrates at its own natural frequency. This is the gum-leaf instrument of the Australian Aborigines. As mentioned before, it consists simply of one of the tough narrow leaves of a Eucalypt tree sandwiched between the opposed thumbs of the hands. When blowing pressure is applied, the leaf is deflected by Bernoulli pressure and executes a torsional vibration that opens and closes the flow aperture at a frequency that is twice the torsional oscillation frequency, this frequency itself being controlled by adjusting the longitudinal tension on the leaf. There are modern instruments based upon free reeds, but none of which I am aware use torsional vibrations in this way.

Technical Details In all except 'free-reed' instruments, the natural frequency of the reed is very much higher than the frequency of the note being played. This means that the reed operates in a quasi-static manner, with its opening x being proportional to the pressure difference across it. If the blowing pressure is p_0 and the pressure inside the instrument mouthpiece p, then the volume flow U of air into the instrument is given by

$$U = \left[\frac{2(p_0 - p)}{\rho}\right]^{1/2} Wx \tag{2}$$

where ρ is the density of air and W is the width of the reed. If x_0 is the unpressured opening of the reed, then under the pressure difference $p_0 - p$ it closes to

$$x = x_0 - K(p_0 - p) \tag{3}$$

where K is the elastic compliance of the reed under applied pressure. Putting these two equations together gives a flow curve of the shape shown in Fig. 3. The acoustic conductance of the reed, as viewed from inside the mouthpiece, is $-dU/dp$, and this quantity is negative, causing the whole system to oscillate spontaneously, for blowing pressures p_0 greater than that corresponding to point T on the curve. This pressure is just one-third of the pressure required to completely close the reed against the mouthpiece at point C.

The player has various parameters of the system, apart from the finger holes, under control. The blowing pressure is more or less independent of the pitch of the note being played, but there is a fair range of variation possible and this allows delicate control of sound quality, and particularly of whether or not the reed closes completely each cycle—a process called "beating" which sharpens the edge of the waveform and increases the content of high harmonics in the sound. Actually double reeds always beat, a circumstance that gives oboes and bassoons their characteristic sound quality, as noted before. To make the sound softer, the player increases lip tension so that the reed opening x_0 is decreased, and with it the whole curve, as shown with a broken line in the figure.

LIP-DRIVEN INSTRUMENTS

The third class of wind instruments is that in which the pressure-controlled valve is the lips of the player. This valve differs from that of reed-driven instruments in that it is forced open by the pressure in the player's mouth, while reed valves are forced closed. This has very important consequences, since, while a reed valve can act as an acoustic generator at any frequency below its natural resonance, a lip valve can do so only in a narrow frequency

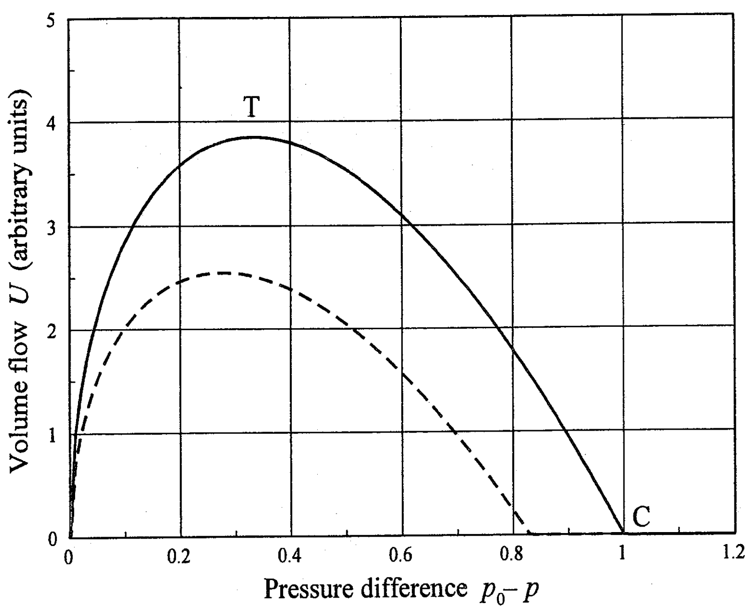

Fig.3 The volume flow U through a reed valve blown with a mouth pressure p_0 when the pressure inside the instrument mouthpiece is p.

range near to that resonance. In playing a lip-driven instrument, therefore, the player must continually adjust lip muscle tension to ensure that the lip frequency matches that of the note it is desired to produce.

The other peculiarity of lip-driven instruments is that, with only a few exceptions that I will return to in a moment, the resonant air column has been derived from an either an animal horn or a sea shell, with the result that it is roughly conical in shape. An exception to the use of horns or shells is the bamboo trumpet *kata batang* of Sabah in Malaysia, which uses four bamboo tubes of increasing diameter, ingeniously arranged, to produce a stepped quasi-conical bore as shown in Fig. 1. From the acoustical properties of a conical horn, it follows that the mode frequencies are in a simple harmonic progression $1, 2, 3, \ldots$. Modern brass instruments have complex bore shapes that produce well-aligned resonances with relative frequencies $0.7, 1, 2, 3\ldots$, the lowest resonance not being used in playing.

Because most natural horns are short, this limits their repertoire of notes to the first two or three resonances, producing at most a limited sort of bugle call. Indeed, most conch-shell horns can produce only the fundamental. This limitation is offset by the loudness of the sound produced, which is a function of the high blowing pressure and the relatively large flow of air. long narrow horns, as found in metal trumpets adn modern horns, allow sounding of modes as high as the sixteenth.

An important exception to the use of conical bores is in the case of the didjeridu of the Australian Aboriginal people. This instrument, which has been in use for thousands of years, consists simply of the small trunk of a Eucalypt tree, hollowed out by termites, cut to a length of about 1.5 m, and with the narrower blowing end coated with beeswax for playing comfort. The bore has, indeed, a small flare, but the mode frequencies are only a little compressed from those of a simple odd-harmonic series. Because of the length of the tube, the fundamental frequency is around 70 Hz, and is produced as a pulsating drone because of the technique of 'circular breathing' used to sustain the sound. Such a sound would be rather dull, but in practice it is embellished by imposing upon it a variety of vocal effects.

Some are produced by modifying the geometry of the vocal tract, rather as in alkoomi or 'harmonic singing', so as to produce a prominent formant variable over the range 1.5–2.5 kHz. Others involve singing, either as a tone with a frequency such as 3/2 or 5/4 times that of the drone of the instrument in order to produce sub-harmonics by nonlinear interaction, or as sharp vocal utterances to mimic the cries of birds or animals. These devices are made effective through the fact that the instrument has no mouthpiece cup, as in a modern brass instrument, so that the player's vocal tract is rather closely coupled to the instrument air column.

In due course, many cultures developed the art of metal working to the extent that brass tubes could be produced, thereby extending the length of the lip driven instruments. It was universally recognized that a flaring bell at the end of the instrument increased the sound power, and most instrument makers refined the shape so that the frequencies of the upper modes were brought into approximate harmonic alignment, making it possible for a skilled player to produce a variety of pleasing horn calls. Narrow flaring horns several meters long, as in the 'natural' trumpet or 'natural' horn, allowed a nearly complete scale to be played using the 8 th to the 16 th modes, and valves or slides were ultimately introduced to fill in the gaps between the lower modes. Most cultures also found that attachment of an appropriately shaped mouthpiece cup improved both playing comfort and also the quality of the sound.

Technical Details As noted above, a lip-valve is blown open by mouth pressure and can oscillate only in a narrow frequency range quite close to its natural resonance. A pair of lips constitute a very flexible structure, of course, and this lip vibration may involve sideways, in-and-out, or even wave-like motion. All of these are possible, and can be used by the player for fine control of pitch and tone quality.

While playing low-pitched instruments softly does not place any great physiological demands on the musician involved, the same is not true of very vigorous playing of high notes. Analysis of the behavior of a lip valve shows that the blowing pressure must increase with the pitch of the note being played, essentially because the mouth pressure must be great enough to overcome the extra lip tension required to raise the natural resonance frequency. Th amplitude of lip vibration, and also the flow of air through the lips, are both controlled by blowing pressure and increase as mouth pressure is increased. All these factors mean that to play a high note very loudly requires a high blowing pressure. Measurements on trumpet players show that the blowing pressure can be very high indeed, 20 kPa being common and pressures up to 25 kPa having been repeatably measured on some players. When it is recalled that a common systolic blood pressure of 140 mm Hg corresponds to a pressure of only 19 kPa, we can see that the physiological stress can become extreme.

Because it is common to require brass instruments to be blown very loudly, it is no longer possible to treat the instrument tube as a linear device. Indeed internal sound pressures as high as 175 dB, or about one-tenth of an atmosphere, have been measured. Such high pressures in a narrow nearly-cylindrical tube lead to the formation of shock waves which sharpen the propagating waveform and transfer energy from low to high harmonics. It is this mechanism that gives trumpets and similar instruments their extremely incisive tone quality.

MATERIALS

There is a long tradition among musical instrument makers about the materials from which their instruments should be made. In the case of bells, gongs and drums, the argument is inescapable—the material has a very great influence on frequency for a given geometry, and upon internal damping. For stringed instruments the case is also established, though the details are more complex. The vibrating string, as primary source of the sound, is a very inefficient radiator because of its small diameter, and must communicate its vibrations to some larger body that then generates sound waves in the air. The resonance characteristics of this larger structure, the body of the instrument, are then superimposed upon the initial string vibration spectrum, and these resonances depend very significantly upon material properties as well as upon geometry.

Of course, the choice of material is also dictated by tradition and by available technology. Bells can be made of bronze or of iron, but bronze is much easier to melt and cast using simple technology than is iron. Bronze bells and iron bells have a slightly different sound, too, but tradition makes us prefer one or the other. Violin top-plates are made of spruce, which is light and has highly anisotropic elastic properties. Other timbers, or even synthetic materials, can certainly be used, but the instrument then sounds rather different.

When we consider wind instruments, the story is much less clear. The primary vibrating element is the enclosed air column, and it is the oscillating flow of this out through the end of the instrument, or through finger holes, that generates the radiated sound waves. To a first approximation, the solid structure of the instrument serves simply to define the geometry of the air column, and so has no effect at all. The wave impedance ρc of the material from which it is made is typically several thousand times that of air, and its circular cross-section gives it very great rigidity, so that its vibration amplitude, though measurable, is extremely small.

There are exceptions to this generalization, however. I have already mentioned Chinese flutes in which there is an extra hole in the head joint that is covered by thin tissue paper and produces a buzzing vibration. Obviously the properties of this tissue have a significant influence on sound output. We might also note that flat sheets of material lack the rigidity that is conferred by circular geometry. If a wind instrument were to be made with rectangular cross-section and thin walls, then these walls would vibrate easily, like the top-plate of a guitar, and their vibrational properties would certainly influence the sound. The only instances of square cross-section wind instruments that I know are the wooden pipes used for some of the ranks of a pipe organ, and here the wall thickness is so great that the pipe is quite rigid.

The properties of the material from which it is made can also directly influence instrument geometry, and this in turn can have a significant effect on sound quality. For example, cylindrical metal walls can be made quite thin—only a few tenths of a millimeter—and strengthened with terminating rings, while the walls of an instrument made from wood can scarcely be less than a few millimeters in thickness if they are to have adequate strength. These geometrical restrictions, and others like them, influence the shapes of blowing holes, finger holes, and bore terminations, with consequent small audible effects.

There are also other direct ways in which the wall material can influence the instrument performance. The radiated sound power is typically less than 1 percent of the input power, as we have already noted. Most of the loss occurs in the energy transfer from the player's breath to the instrument air column vibrations, but there is then a further loss from the air column to the walls by viscosity and thermal conduction. If the walls are rough or porous, these losses can be increased considerably over those for perfectly smooth walls. If the structure has extremely sharp edges, for example around finger holes, then there may also be aerodynamic losses through turbulence. All these affect the sound and playability of the instrument.

Finally, and very importantly, the available technology determines the way in which materials can be shaped and therefore limits the possibilities for an instrument of given shape. Bamboo is most convenient because it is already hollow, and its use defines the tradition for instruments such as the shakuhachi. Fine-grained wood can be bored and turned to produce instruments with simple shapes, and is widely used. Instruments of the trumpet family, however, almost demand the use of metal, because of the need for long narrow tubes that can be bent to a convenient compact shape. Precious metals such as gold or silver would be excellent, but are too expensive for anything larger than a flute; modern materials such as stainless steel would also be fine, but are too difficult to work, even with modern technology. The obvious compromise, which has indeed been available for more than 2000 years, is the conveniently workable, relatively cheap and durable copper-zinc alloy brass. Its only drawback is its tendency to tarnish, so that it requires a protective plating or varnish layer.

Argument continues among musicians and instrument makers about the merits of different metals and their effect on tone quality. Such rigorous tests as have been conducted, however, have failed to find any such consistent differences. The variation between two instruments of the same metal and nominally identical design often exceeds the difference between either of these and a similar instrument crafted from a different metal. But a professional musician who has spent a large amount of money on a gold flute will not admit, even to himself, that a silver flute can sound just as good!

CONCLUSION

The construction and playing of wind instruments has an immensely long history in the Western Pacific region, as in most other parts of the globe. The instruments that were developed centuries or even millenia ago still survive in many countries, and are now beginning excite interest, not simply for their historical value but also for their unique contribution to the repertoire of modern musical sound.

The physical mechanisms underlying sound production and control in most of these instruments are now well understood, although certain detailed puzzles remain. There is certainly much in this fascinating field to keep researchers occupied for many years to come, and their discoveries will help us both to understand the years of craft tradition that go into making these instruments, and to make their manufacture more reliable. We may also hope to understand more of the technique that goes to make an expert performer, and perhaps be able to help a little in improving the sound and playability of the instruments themselves.

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