Acoustics of the Australian didjeridu

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The didjeridu (or yiraki) of the Australian Aborigines is a very primitive musical instrument, both historically and acoustically. It consists simply of a more-or-less straight small tree trunk or branch, typically between one and two metres long, hollowed out by the action of fire or insects to produce a roughly tapered tube. The inside diameter typically increases from about 30 millimetres at the narrow end, from which the instrument is blown, to about 50 millimetres at the wide end, and the average wall thickness is 5 to 10 millimetres. The bore may expand slightly at the two ends, where it can be easily scraped, and the narrow end is often given a smooth finish, for comfort in playing, by application of a resinous gum. The outside of the instrument is smoothed and painted in geometrical totemic designs, usually in black, white and orange. A didjeridu maker typically spends about two days in shaping and finishing the tube of the instrument and a further two days on the decorative painting.

Because of their origin, no two didjeridus are exactly alike, and the musical quality of an instrument may depend on the smoothness and taper of its bore, on fortuitous perturbations to its cross section, and of course upon the absence of cracks or insect holes in the walls. The factory-made 'didjeridus' sold to tourists bear little resemblance to the true instrument in shape or decorative painting, but a good player can in fact produce a fine authentic sound upon a length of steel water pipe of appropriate diameter!

Table 1 gives the physical dimensions and approximate fundamental pitch of three didjeridus from the Northern Territory of Australia. Instruments A and B are actually by the same maker, and illustrate the extent to which the material available influences the final dimensions. These three instruments are all of the more tonally flexible 'long' variety, and are played in a sitting position with the open end resting on top of the toes. Short instruments about one metre in length are also made, but have less interesting musical qualities.

To play the didjeridu, the musician seals the narrow end against his mouth, blows, and vibrates his lips under appropriate muscular tension as in playing a brass instrument like the tuba. Several resonance modes of the pipe can be excited separately in this way, but the fundamental mode, which typically has a frequency between 50 and 100 Hz (between about G_1 and G_2 in US Standard notation) is the normal basis for the sound. Circular breathing, with the mouth as an air reservoir during inhalation, is used to maintain a continuous drone with a rhythmic pulsation in amplitude and timbre. The player often pronounces syllables, mostly unvoiced, to maintain this rhythm, and one of these standard patterns, 'didjeridu', has perhaps given rise to the Westernised name for the instrument, though this may be a word from a now extinct Aboriginal language. Another such simple pattern is 'ritoru' but much more complex sequences are also used.

In addition to these patterns, the basic sound can be enriched by timbre variations induced by changes in the lip and mouth configuration, and the player may sing while playing to produce rough or smooth beating sounds, sub-fundamental components and animal-like cries. It is the richness of this repertoire of sounds that makes the music of the didjeridu interesting to ethnomusicologists and anthropologists, and that makes its sound, particularly when accompanied by per-

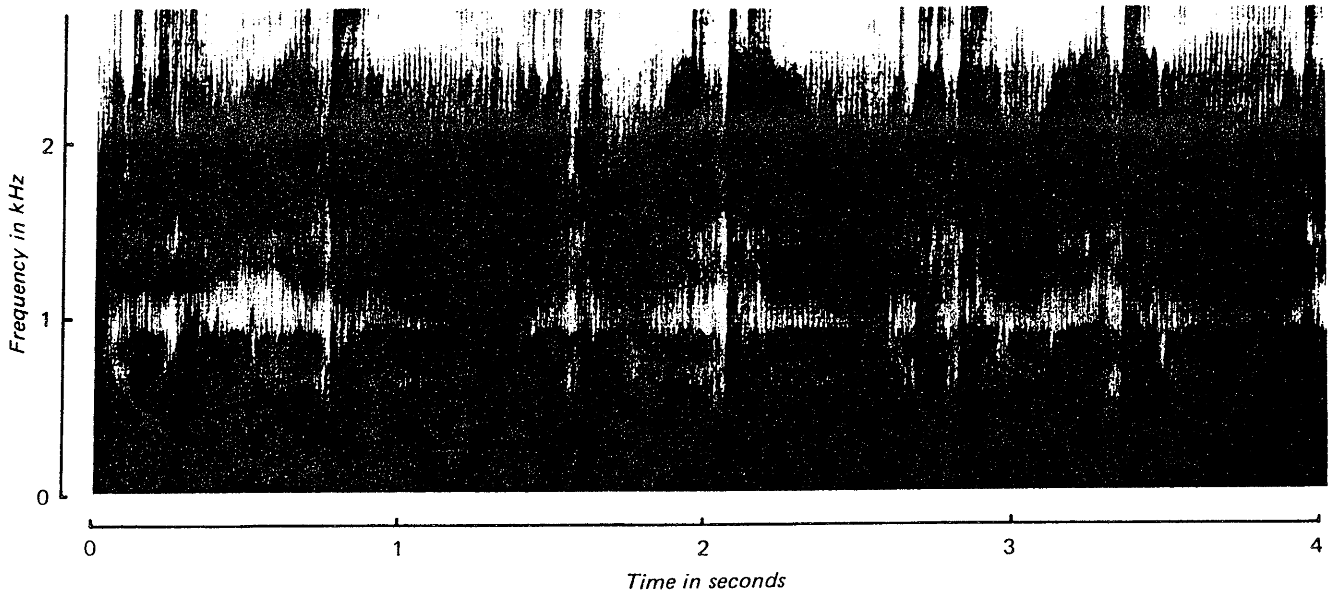
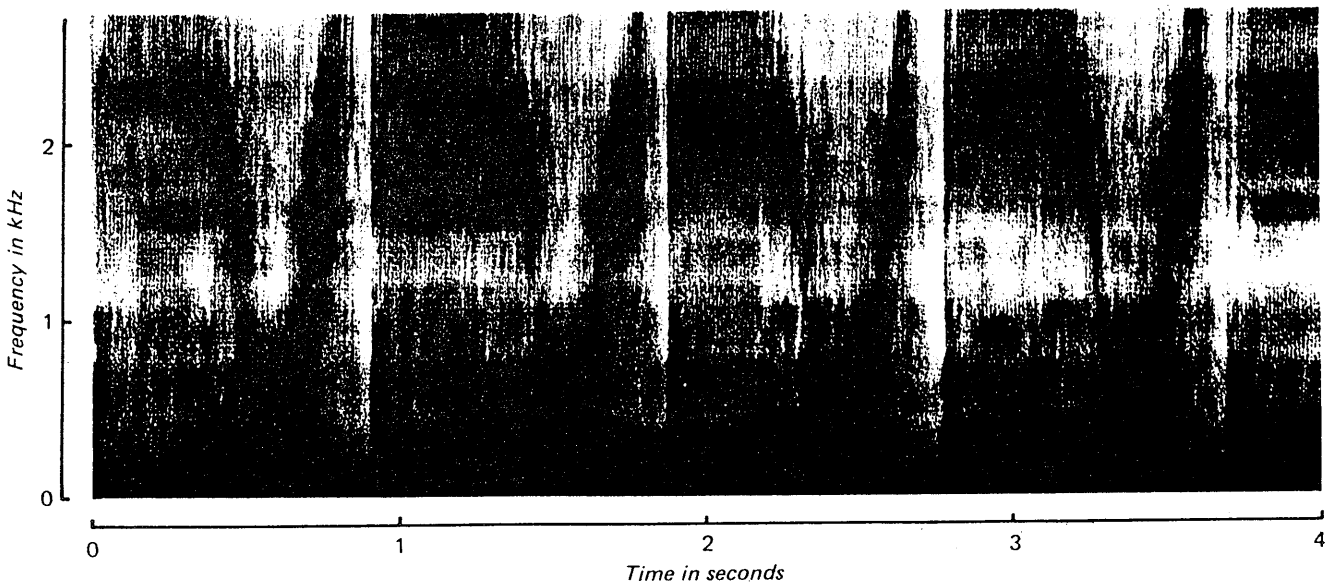


Fig. 1
Sonograph displays of the sound output of didjeridu A while the player pronounces an unvoiced 'didjeridu' with the final 'u' prolonged. Three repeats of the pattern are shown. Vertical gaps in the display correspond to consonants, and horizontal dark bands to the formants associated with the vowels of the articulation pattern. The narrow vertical lines mark the lip vibration frequency (60 Hz).

cussive music-sticks, evocative of the Australian outback. The musical aspects of didjeridu technique have been discussed in detail by Jones (1973) with the aid of recorded examples by Aboriginal musicians, while in another article (Jones 1967) several didjeridu performances are transcribed into standard notation, and performance technique is compared with that of physically related instruments from other cultures. In the present paper we shall be concerned exclusively with acoustical aspects of the topic.

Figure 1 gives a slightly modified Sonagraph display (see Appendix 1) of the sound of didjeridu A when a repeated unvoiced pattern rather like the word 'didjeridu' is being produced by an expert player. The part of the record shown in this case is a little less than four seconds in length, allowing three repetitions of the pattern. The

Fig. 2
Sonograph display of the sound output of a more complex pattern played on didjeridu B. The steeply rising dark bank is associated with a voiced sound at the end of each pattern. Note the closer spacing of the vertical lines corresponding to the higher fundamental frequency of this instrument (80 Hz).



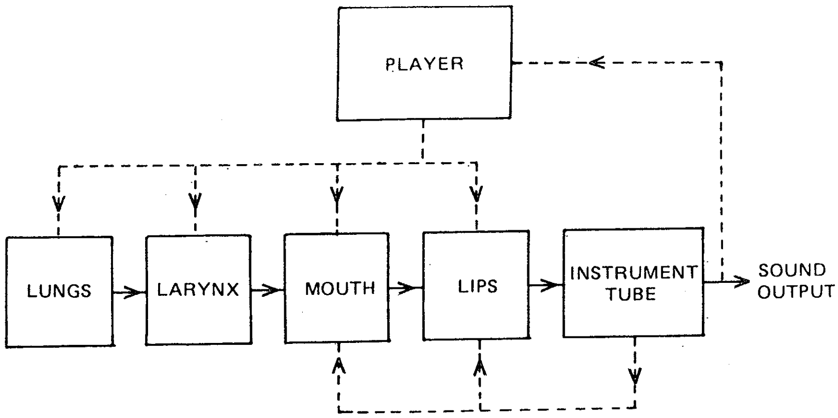


Fig. 3
A system diagram for the didjeridu and its player showing the main forward flow of energy (full lines) and the feedback reactions (broken lines) that control that energy flow.

vertical axis is frequency, extending from zero to nearly three kilohertz, and the extent of the blackening indicates the amount of energy present. The didjeridu analysis shows considerable similarity to the pattern produced by ordinary human speech. The individual lip pulses are just resolved in time as vertical lines and there are shifting formant bands up to about three kHz, reminiscent of the formant bands in voiced speech. There are also gaps in these bands corresponding to articulation. In an analysis such as this, the individual harmonics are too closely spaced in frequency to be resolved.

Figure 2 shows, on the same scale, a more complex pattern in which the last part of each phrase—the narrow rising band—is actually a voiced sound sung above the drone frequency. This is played on instrument B.

Analysis of such patterns is clearly a very complex exercise with which I shall not attempt to proceed very far here. The purpose of the present note is rather to examine the fundamental acoustics of the didjeridu, and of its playing technique, in order to provide a background for such more sophisticated studies of actual performances.

Basic acoustics

The acoustical properties of musical wind instruments have been carefully studied now for more than a century and, building on the fundamental work of Helmholtz (1877) and Rayleigh (1896), we now have quite a good quantitative understanding of the subject. Useful recent reviews have been given by Nederveen (1969), Benade (1976), Smith and Mercer (1979) and Fletcher (1979a), while Kent (1977) has edited a selection of important papers and Hutchins (1978) an easily readable set of reprints from 'Scientific American'.

A convenient approach to the discussion is to divide the system representing the player and his instrument into several parts, as shown in Figure 3. The player's lungs provide an air supply at a reasonably constant pressure, and this passes through the vocal folds of the larynx (which are generally loosely open but may in some cases be vibrating) and the mouth cavity to reach the lips, which are set against one end of the long tube which constitutes the instrument. This tube is a passive resonator with simple acoustical properties, as we shall see presently.

The player's lips themselves, as in modern brass wind instruments, act as a pressure-controlled valve of the type that is forced open by the blowing pressure, in contrast to woodwind reeds which are forced closed by the blowing pressure. For such a lip valve to generate sound in the pipe it is necessary that the blowing pressure should exceed a certain minimum value, that the blowing end of the tube should be a position of maximum pressure amplitude for the wave in the tube (equivalent to a 'closed end' in the simple treatment of pipe acoustics) and that the natural resonance frequency of the lips, as estimated by 'buzzing' them without the tube, should be approximately equal to one of the resonance frequencies of the tube with its blowing end closed. These conditions were recognised long ago by Helmholtz (1877) and have recently been investigated in detail by Fletcher (1979b).

With this general explanation and the diagram of Figure 3 in mind, we can see that the pipe resonator can interact back upon the player's lips and mouth cavity, thus modifying their vibration behaviour. More than this, the player himself can listen to the acoustic output and purposely modify all the sub-systems of the sound-producing chain to obtain desired variations in sound quality.

We shall consider some of these more detailed effects later. For the moment we note simply the general level of sound output and acoustic efficiency of a typical didjeridu. Measurements gave a sustainable maximum sound pressure level of about 90 dB (relative to the standard reference of 20 micropascals) at one metre distance. This corresponds to a total radiated acoustic power of about ten milliwatts, since the radiation is nearly non-directional except for the highest components of the sound. Measured blowing pressure (see Appendix 1) for this loudness was about two kilopascals (20 centimetres water gauge) and air flow rather less than one litre per second, giving a pneumatic power input of nearly two watts and implying a total efficiency of rather less than one percent. These figures are generally similar to those measured by Bouhuys (1965) for brass instruments, the maximum loudness of the didjeridu being comparable with that of a low note played on a trumpet. The low efficiency for conversion of mechanical power to sound power is typical of all musical instruments. In the case of wind instruments it is caused mainly by viscous and thermal losses to the tube walls and by turbulent losses in the air flow between the player's vibrating lips.

Tube modes and harmonics

We have already mentioned that the tube oscillations that couple most strongly to the player's lips are those with a pressure maximum at the lip end. The resonance modes of the tube corresponding to these oscillations are the same as those for the tube if it were to be closed by a rigid stopper at the blowing end.

From elementary theory we know that, if the tube is a simple cylinder, then these resonances occur for frequencies f_n for which the length L of the tube (ignoring a small 'end correction') is an odd number of quarter wavelengths for sound in air. If v is the speed of sound in air, then the tube is one quarter of a wavelength long at a frequency $f_1 = v/4L$, so that the resonance frequencies are $f_n = (2n-1)f_1$ where $n = 1,2,3\ldots$ These resonance frequencies are thus those of odd series $f_1, 3f_1, 5f_1\ldots$

It is not quite so well known that, if the tube is a complete cone, then the resonance frequencies are $f_n' = 2nf_1$ where again $n = 1,2,3\ldots$ In this case the resonances are those of the even series $2f_1, 4f_1, 6f_1\ldots$ which is just the same as a complete series based upon $f_1' = 2f_1$. It is for this reason that a clarinet, which has an essentially cylindrical tube, overblows to a second mode which is a musical twelfth above the first mode (a frequency ratio of 3:1) while an oboe, which is about the same length but conical, has a first mode that is an octave higher than that of the clarinet ($2f_1$ instead of f_1) and overblows to the octave (a frequency ratio of 2:1).

The didjeridu is intermediate between these two cases. The bore expands roughly conically away from the blowing end, but the apex of the cone is missing. It is therefore not surprising that the resonances lie somewhere

Table 1

Physical characteristics of three didjeridus

Identification	*A*	*B*	*C*
Origin	Arnhem Land	Arnhem Land	(?)
Length (cm)	159	144	149
Small diameter (mm)	31	26	30
Large diameter (mm)	36	60	40
Wall thickness (mm)	10	10	6
Fundamental frequency (Hz)	60	80	64
Fundamental pitch	B_1	E_2	C_2

in between those for a cylinder and for a complete cone of the same length. This behaviour is discussed in more detail in Appendix 2. Here it will suffice to point out that, for a given tube length, the pitch of the fundamental rises as the flare of the tube increases. This is exemplified by instruments B and C of Table 1. B is only three percent shorter than C but its fundamental frequency is 25 percent higher because of its greater flare.

Actually the pitch of all the tube modes rises as the flare increases, but the fractional rise in the higher modes is less, so that the frequency ratios are compressed. Thus in instrument C the mode frequencies are in the ratios 1:2.8:4.5:6.3 for the first few resonances. Each of these modes can be sounded separately by an experienced player, and the measured frequencies are in good agreement with those calculated according to the method given in Appendix 2. The second mode, incidentally, requires increased lip tension and a blowing pressure of four to five kilopascals (40–50 centimetres of water) compared with one to two kilopascals for the first mode.

In actual playing, the lowest mode is used almost exclusively, with just occasional isolated leaps to the second mode. For instrument A this leap is nearly a musical twelfth but falls short of this by about a semitone for instrument C, and by about a whole tone for the much more flared instrument B.

It is important here to understand the distinction between the frequencies f_n of the resonant modes of the pipe and the frequencies of the components present in the steady sound. When the normal drone is being played, the fundamental frequency in the sound is f_1 and this is accompanied by harmonics at exact integer multiples $2f_1$, $3f_1$, $4f_1\ldots$ of this frequency. This can be verified from the fact that the sound wave form, as in Figure 4, remains essentially the same from one cycle to the next. The overblown sound is similarly based upon the second resonance f_2, and its sound contains components with frequencies $f_2, 2f_2, 3f_2\ldots$

The vibrating lips of the player, even though they move in a simple and nearly sinusoidal fashion, generate a considerably distorted air-flow wave form because of the nonlinearity of the relationship between pressure and flow through the small lip opening. This behaviour has been investigated in some detail for conventional brass instruments by Backus & Hundley (1971) and more recently by Elliott & Bowsher (1982). The vibration frequency of the lips is ordinarily close to the frequency f_1 of the fundamental pipe resonance, but there is no necessary relation between high harmonics nf_1 generated by the lips and the frequencies f_n of higher pipe resonances. When a lip-generated harmonic does coincide with a pipe resonance, however, it is reinforced. Since the tube of the didjeridu is not far from cylindrical, the tube resonances are separated in frequency by a little less than $2f_1$, and there is therefore a tendency for an alternation in the intensity of harmonics. The second and fourth harmonics are thus weak relative to the first, third and fifth, as can be seen later in Figures 7 and 8, though in the higher parts of the spectrum it is sometimes the even harmonics that are reinforced.

We might therefore expect that the exact relationship between the mode frequencies, and thus the flare of the pipe, might be of considerable importance to the tone of the didjeridu, as is the case with modern wind instruments (Benade 1966), but this does not seem to be obviously so. Certainly

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different didjeridus have rather different sound, but they vary so much in other features that no clear quality criterion emerges.

Timbre variation

One of the most striking features of skilled didjeridu playing is the extent of timbre variation possible without changes of pitch or loudness. Such variations have much of the character of changes in spoken vowel sounds and enhance the brilliance and variety of the sound during even a single sound-pattern repeat. To make the nature of this timbre variation clearer, we now examine it for isolated steady notes.

Figure 4 shows two examples of the sound pressure waveform recorded with a non-directional pressure microphone about one metre from the open end of the didjeridu (see Appendix 1). The upper waveform shows a normal loud and resonant sound played on instrument A. The fundamental period is shown by the distance between the major downward spikes (about 17 milliseconds, corresponding to a frequency of 60 Hz) but it is clear that much of the energy is concentrated in a vibration with about seven or eight times this frequency and that there is also a spread of energy to much higher frequencies, as shown by the irregular shape of the waveform in each period.

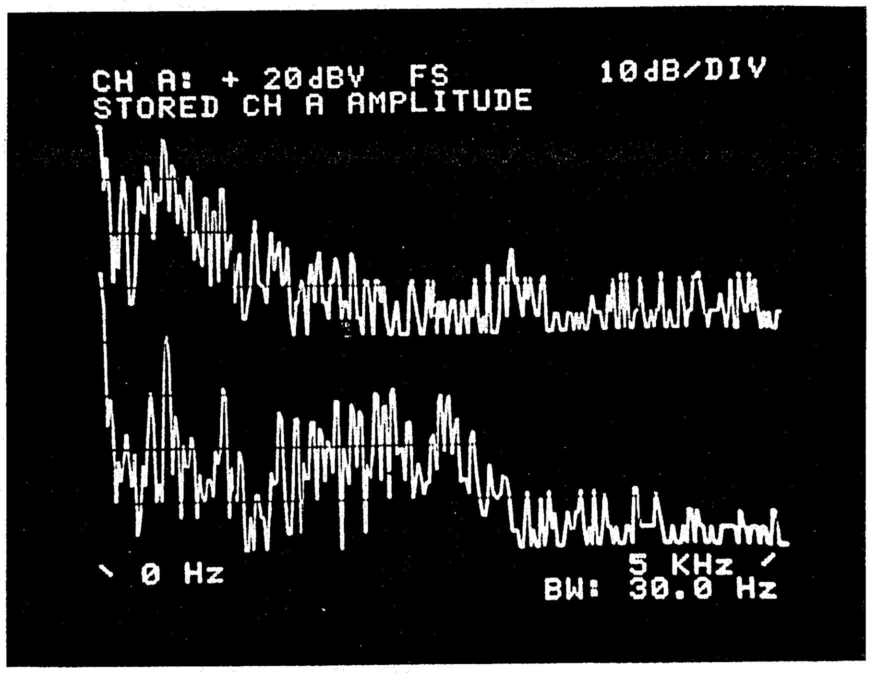


Fig. 5
Frequency spectra of the two sounds whose waveforms are shown in Figure 4. The frequency range is 0 to 5 kilohertz in each case. Note the formant band near 500 Hz in each trace and the additional formant near 2 kHz in the lower trace.

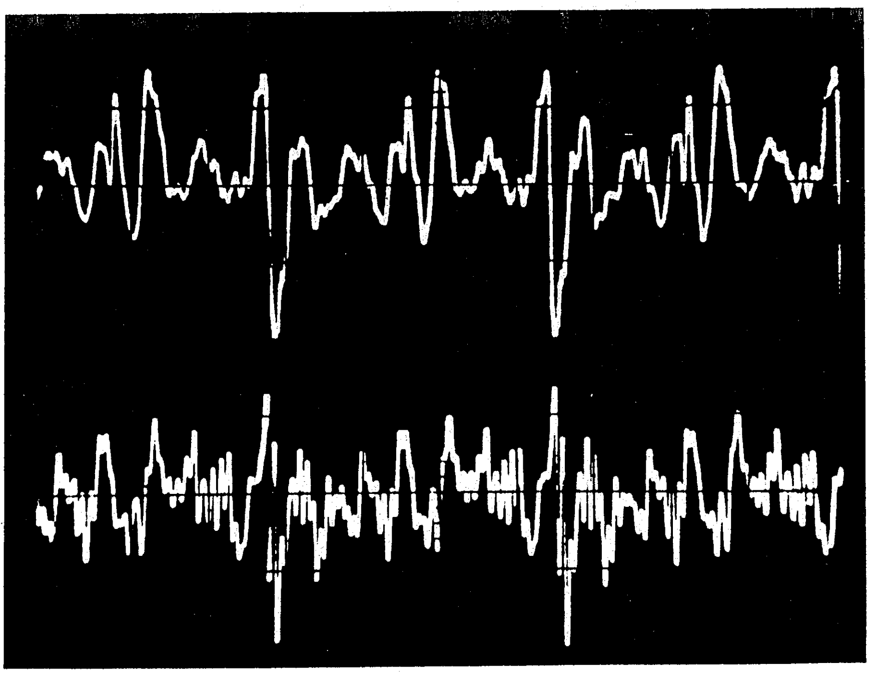


Fig. 4
Pressure waveforms of the didjeridu B sound for two different mouth positions. Upper trace: a normal bright sound; lower trace: a sound with a pronounced high-pitched ring. The trace length is 50 milliseconds in each case.

The upper trace of Figure 5 gives the general shape of the sound spectrum for this note (see Appendix 1). The individual harmonics are not very well separated, for this is not the aim of this particular illustration, but there are in fact about eight peaks between each of the scale divisions, corresponding to the 60 Hz spacing of the harmonics of the fundamental. More important is the general shape of the curve, which rises to a peak at about 500 Hz—the eighth and ninth harmonics as expected from the waveform.

This analysis is carried out, of course, on the radiated sound rather than on the sound wave inside the tube, and this accounts for the very small amplitude of the 60 Hz fund-

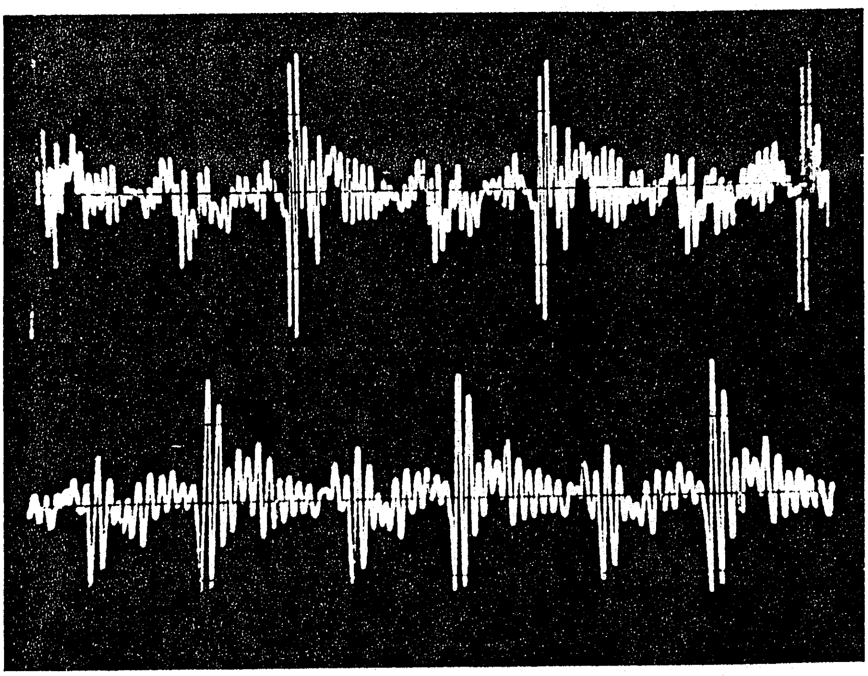


Fig. 7
The waveforms of sound from the same didjeridu (B) played aso as to emphasise two different high-frequency oscillations. The frequency of this upper component is higher for the upper than for the lower trace. The trace length is 50 milliseconds in each case.

amental. Low frequencies require large radiators if they are to couple efficiently to the air, and the open end of the didjeridu, like that of the bassoon, but unlike the tuba, is very small compared with the fundamental wavelength. The higher frequencies are less important in the internal oscillation of the air column, but, because of the greater efficiency with which they are radiated, they predominate in the sound that is heard.

Returning now to the lower trace in Figure 4, we see that it is similar in general outline to the upper trace but has superposed on this a large component of very high frequency sound, represented by the closely spaced wiggles. This is the waveform associated with production of a ringing nasal sound by appropriate adjustment of mouth shape and tongue position. The lower part of Figure 5 shows the frequency spectrum of this waveform and we see that there is a large hump in the distribution corresponding to a concentration of radiated energy in the frequency band from about 1300 to 2800 Hz. By analogy with the vocal case we might call this a formant band and say that it is centred around 2000 Hz. It is probably appropriate to describe this as the second formant and associate a first formant with the peak already noted near 500 Hz.

The location of these formants and the way in which they can be varied by the player constitute important features of the sound of a well played didjeridu. To illustrate this further, we show in Figure 6 two traces in which the player has consciously varied the tone quality by variation of mouth and tongue position. Both traces show the closely spaced high frequency oscillations characteristic of a prominant formant, but the spacing of these is much closer in the upper than in the lower waveform.

Figures 7 and 8 show the frequency analyses of these sounds, this time on a more expanded scale than in Figure 4 so that the individual harmonics are all clearly resolved. Both spectra show the first formant at about 500 Hz but the second formant is centred around 2100

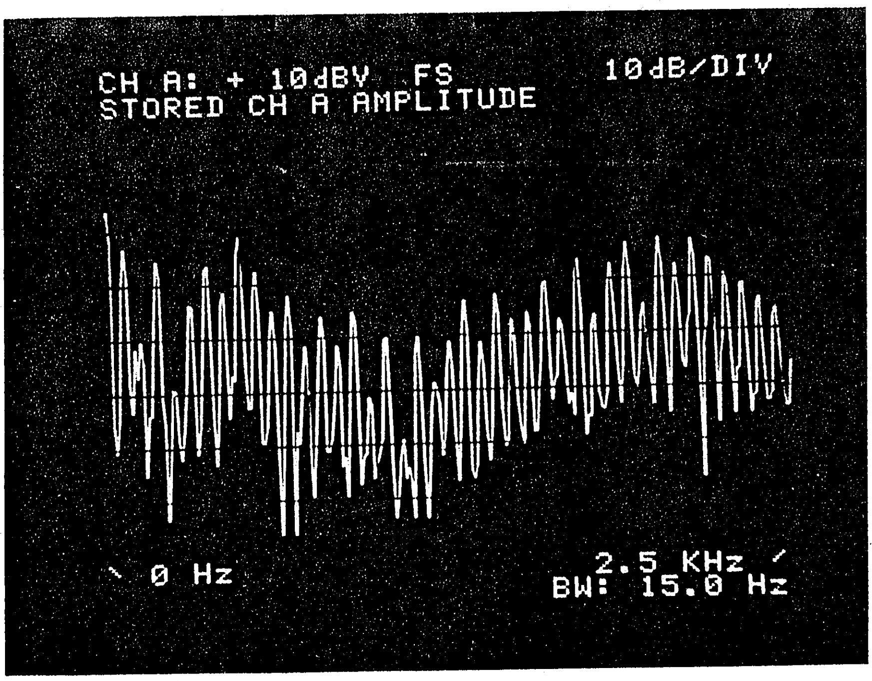


Fig. 6
Frequency analysis of the upper trace of Figure 6, showing a pronounced formant band centred around 2.1 kHz. Note that the resolution in this spectrum is higher than in Figure 5, the frequency range being 0 to 2.5 kHz. Note also the relative weakness of the second and fourth harmonics in the spectrum.

Hz in Figure 7 and around 1400 Hz in Figure 8. This corresponds exactly with what is seen in Figure 6. More careful analysis may indeed recognise the two humps in Figure 8 as being separate formants, but we shall not concern ourselves further with this now.

The exact mechanism by which variation in the player's mouth shape changes the location of the formant is a matter of some subtlety, as we explore briefly in Appendix 3. The formants are not the same as those associated with vowel sound (see for example the paper by Sundberg in Hutchins 1978), since these involve the whole vocal tract. Rather they seem to be more closely analogous with the mouth resonances determining pitch during whistling, though again the analogy is not exact. It suffices for the present to note that the formant is associated with a resonance of the mouth cavity and that, as is to be expected, its frequency rises as the most effective mouth volume is reduced by movement of the tongue. Effects of this type in woodwind instruments have been commented upon by Coltman (1973) and by Clinch et al. (1982).

Voiced sounds

As was mentioned earlier, voiced sounds constitute an important extension of the repertoire of the didjeridu, not generally as long notes but rather as syllables within a repeating phrase. To produce a voiced sound, the player simply sings while playing the didjeridu in a normal manner. The open throat associated with singing seems to inhibit simultaneous production of a high formant of the type discussed in the previous section so that this is normally not present in voiced sounds.

In principle any note at all can be sung while playing, since there is very little back-coupling to the larynx from the vibrations of the lips or of the air column in the instrument. This is illustrated by omission of any such feedback coupling from the diagram in Figure 2. In practice the most usually voiced note is a major tenth (frequency ratio 5/2) above the pipe drone note. For reasons that will be discussed presently this produces a powerful sub-octave sound which is particularly effective. Gliding voiced sounds and high falsetto shouts are, however, also used to mimic the cry of animals or birds such as the brolga.

Since the vocal folds vibrate nearly independently of the rest of the system, their effect in a voiced note is essentially to modulate the flow of air to the mouth so that, instead of being steady, it consists of a train of pulses with frequency f_0 equal to the vocal fold vibration frequency. Because of the sharpness of each air puff, which is inherent in the nature of the motion of the larynx, the air supply to the mouth then contains components of all frequencies mf_0 where $m = 1,2,3\ldots$

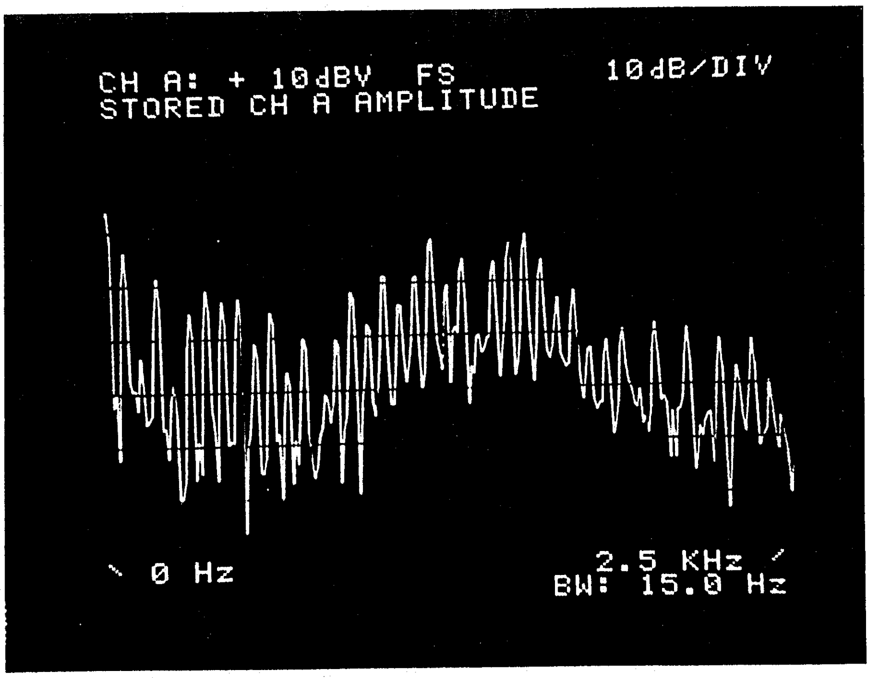
Because the motion of the larynx is relatively rapid and the reservoir of the mouth allows a reasonable blowing pressure to be maintained at all times, the lips continue to vibrate at their natural frequency f_1 in co-operation with the tube air column, and generate their harmonic spectrum of frequencies nf_1, where $n = 1,2,3\ldots$

With both these mechanical vibrators acting in series as shown in Figure 3, the resulting sound will contain components of all the combination frequencies $mf_0 \pm nf_1$ with all possible integer values of n and m. This is commented upon briefly in Appendix 4.

We now see the significance of singing a just major tenth above the drone note f_1, for then $f_0 = 5f_1/2$ and the combined sound will contain the sub-octave $f_1/2$ (for $m = 1$, $n = 2$) and all its harmonics. We actually expect the frequency component $f_1/2$ to be very weak, both because it is produced by a non-linear process and because it is very inefficiently radiated, but this is not significant to the audible result.

Figure 9 shows the frequency spectrum of a voiced note of this type produced on instrument B. Note that the frequency scale is expanded still further to resolve clearly the low frequency peaks. The first strong peak is the drone fundamental $f_1 = 80$ Hz, while the fundamental of the sung note is the next strongest peak which has fre-

Fig. 8
Frequency analysis of the lower trace of Figure 6 showing a formant band centred around 1.4 kHz. Other notes are as for Figure 7.



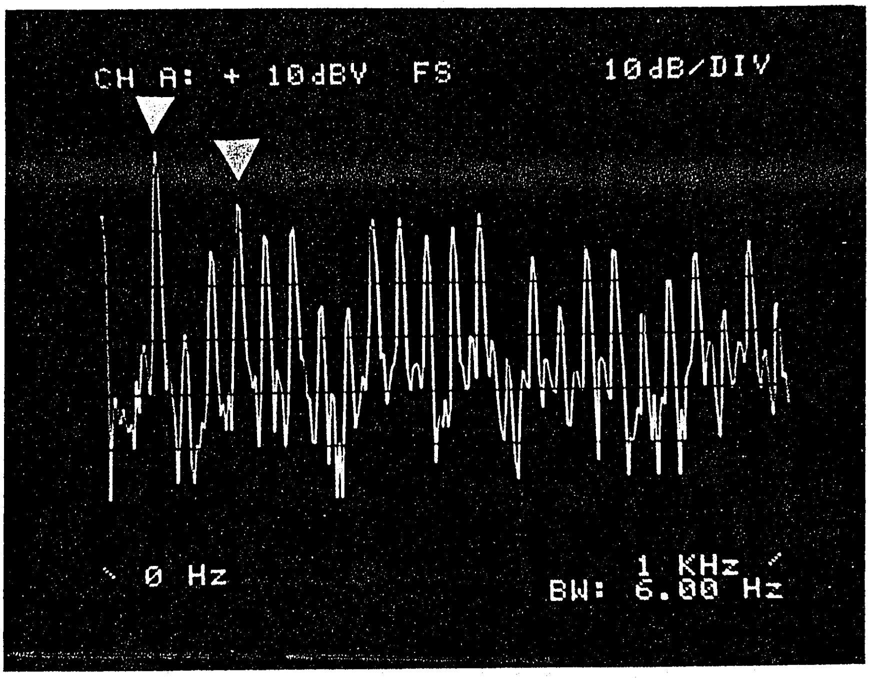


Fig. 9

Frequency analysis of the sound produced by didjeridu A while a note is being sung a major tenth above the drone pitch. The fundamental components of these two notes are indicated by arrows. Note that the frequency resolution is still further increased and the range extends now only from 0 to 1 kHz.

quency $f_0 = 200$ Hz. Between these peaks lie two smaller peaks: one at 160 Hz which is $2f_1$ and a lower peak at 120 Hz which is $f_0 - f_1$. It is debatable whether or not one of the peaks below 80 Hz is the sub-octave $f_0 - 2f_1$ at 40 Hz, but it seems that this is lost in the noise. The important thing however is the existence of the combination tones with both n and m non-zero, and the orderly progression of peaks with a separation of 40 Hz. The human auditory system interprets this as a solid sound based on the sub-octave 40 Hz as fundamental (Terhardt 1978).

Another way of looking at this effect is shown in Figure 10 which is the radiated pressure waveform for the same note. The effect of the vocalisation is to alter the shape of every second peak so that the repetition time of the waveform is doubled. If the human auditory system processes the signal to determine the repetition rate, then theresulting perception will be based on 40 Hz as the fundamental.

The auditory effect of such a voiced note is very striking and the sound is rather like that of a 16-foot pedal reed stop on a pipe organ. If, instead of a just major tenth, the player sings a perfect fifth above the pipe drone, a sub-octave effect is also produced, but tends to be less pronounced because the note to be sung is rather low in pitch and therefore can be sung only softly.

Conclusion and acknowledgments

I have set out to analyse in some detail just a few of the better defined aspects of didjeridu performance technique. To these should be added all the varieties of articulation, from simple consonants to a rolled tongue, and all the varieties of added vocal sounds (Jones 1967, 1973).

To attempt any detailed acoustical analysis of these effects, however, would be of no great assistance to the musicologist, for their variety is great and their interest lies largely in their

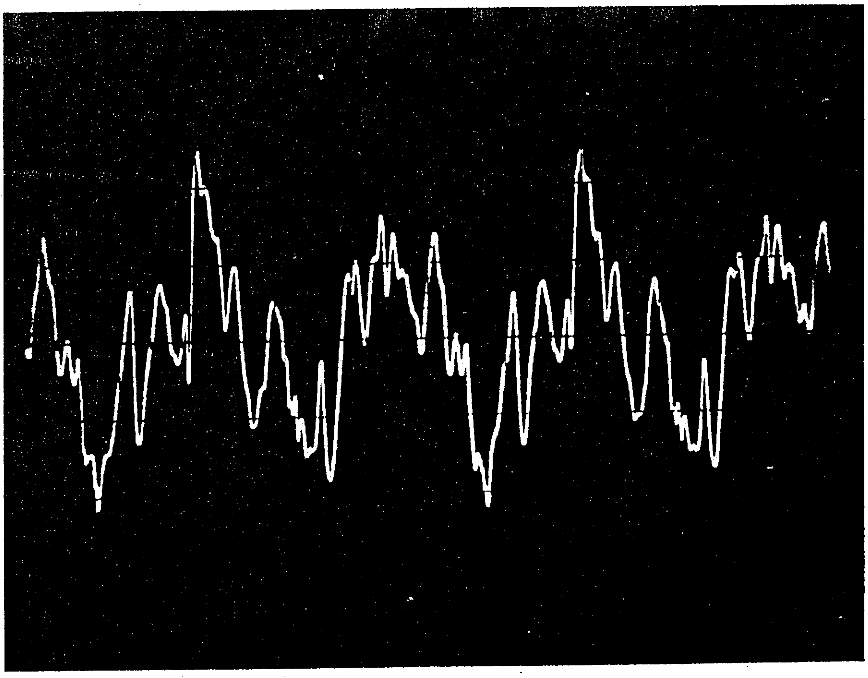


Fig. 10

The pressure waveform associated with the voiced sound analysed in Figure 9. The trace length is again 50 milliseconds. Note that every alternate peak of the drone note is modified in shape by the effect of the sung note, so that the repetition time of the pattern is twice as long as for an unvoiced drone.

musical use. What I have tried to do, however, is to lay a firm acoustical foundation upon which can be built a more detailed musical discussion of particular aspects of performance.

The didjeridu is clearly a simple and undeveloped musical instrument from a technological viewpoint, but its musical repertoire is varied. The performing techniques applied to it in Australia show an amazing number of subtle variations that rival and sometimes surpass the achievements of other peoples who possess comparable instruments.

I am most grateful to Trevor Jones of the Department of Music at Monash University, who demonstrated and played most of the examples that I have analysed. Our work in musical acoustics at this University is supported by the Australian Research Grants Committee.

APPENDIX 1. Technical notes

(a) In recording the sound of a didjeridu or similar low-pitched instrument for later analysis, it is advisable to use an omnidirectional microphone which is sensitive to the acoustic pressure. The reason is that directional microphones operate at least partly on the acoustic pressure gradient and therefore emphasise the low part of the frequency spectrum if they are relatively close to the source. A condenser microphone of good quality is preferred and for these measurements a Neumann U87 microphone was used, though a Bruel and Kjaer microphone would have been even better.

No environment is absolutely ideal to characterise the sound unless measurements are made with different microphone placings. Our measurements were compromised by using a microphone position one metre from the end and on the axis of the instrument, in a normally furnished room.

(b) The analyses in Figures 1 and 2 were made from the tape-recorded sounds using a Kay Sonagraph. The tape was played back at twice the recording speed, thus doubling the analysed record length and halving the frequency range. The wideband filter was used, giving an effective band width of 150 Hz for the original signal.

(c) Detailed waveform analyses like those of Figures 4, 6 and 10 are most easily carried out using the 'single-shot' facility on a storage oscilloscope. Most major manufacturers supply such instruments. (We used a Tektronix model 5115).

(d) Frequency analyses like those of Figures 5, 7, 8 and 9 are most easily carried out using a spectrum analyser operating by means of a Fast Fourier Transform process, since the data sample is collected in a fraction of a second. Many manufacturers market such instruments. (We used a Hewlett Packard model 3582A). Other types of analysers take much longer to complete their analysis and generally require the use of a tape loop.

(e) Measurements of blowing pressure can be conveniently made using a small bourdon-tube pressure gauge with a full-scale reading of say 600 millimetres water-gauge (six kilopascals). A soft plastic tube about one millimetre in diameter, of the type used as a surgical cannula, is connected to the gauge and inserted into the mouth cavity (non-surgically!) through the corner of the player's lips.

An estimate of the air-flow rate during playing can be made by measuring the vital capacity of the player's lungs (for example by blowing into a water-filled container) and then by noting the maximum time for which a note can be played at a given loudness.

(f) Measurements of radiated acoustic power can be made with a standard sound-lever meter. Measurement should be made in a non-reverberant environment and relatively close to the instrument to avoid reflections, and should be averaged over several directions. A 'flat' frequency response should be used on the meter if total radiated power is to be measured, but an 'A-weighted' level corresponds more closely to what is heard, since this filter characteristic is designed to approximate the behaviour of the human ear.

APPENDIX 2. Passive tube acoustics

The tube of the didjeridu varies in cross-section along its length and thus belongs to the family of configurations called horns, which have been extensively treated in the standard acoustics literature (Morse 1948, Young 1960, Kent 1977). It is an adequate first approximation to take the didjeridu tube to be a simple truncated cone, and we can then use either the general development set out by Morse or the briefer and more specific treatment of conical tubes given by Nederveen (1969:20–24). It will be sufficient here to give the results of the simplest version of Morse's analysis which applies to tubes of small taper.

If the diameter of the tube at the blowing end is d_0 and the diameter at the larger open end is d_1 then we can define a taper parameter g by the relation

$$g=(d_1-d_0)/d_0.$$

Clearly g goes to zero for a cylinder, since then $d_1=d_0$, while g becomes very large for a nearly complete cone, for which d_0 is very much smaller than d_1.

We further note that the acoustic length L' of the tube is greater than its physical length L because of an 'end correction' at the open end. To a very good approximation

$$L'=L+0.3d_1.$$

Now, if v is the speed of sound in air, then it can be shown from the analysis given by Morse that the frequencies f_n of the resonances with the blowing end closed (or, more technically, the frequencies for which the acoustic impedance, and therefore the pressure, is a maximum at the blowing end) are given by

$$f_n \approx [(2n-1)^2+(8g/\pi^2)]^{1/2}(v/4L')$$

provided that g is less than about 0.3. Clearly the correction term involving the taper parameter g raises the frequencies of all the resonances slightly in comparison with those of a simple cylindrical pipe, but has a larger effect on the low than on the high resonances.

This analysis applies only for small values of g. Nederveen's more general discussion shows that the mode frequencies f_n appear as the solutions of the equation

$$2\pi fL'/v=n\pi-\tan^{-1}(2\pi fL'/gv)$$

with $n=1,2,3\ldots$ This equation must, however, be solved numerically for particular values of L^1 and g.

In a real instrument the tube is rarely of precisely conical form, so that it is worthwhile to note the effects of various perturbations that may exist in its bore.

Firstly the bore is not usually exactly round but rather roughly elliptical. This has no effect on the calculations outlined above provided that for the diameters d_1 and d_0 we use effective values which give the correct cross-sectional area for the tube. This rule is appropriate also for more irregular shapes.

More importantly, we have already noted that some instruments have an extra flare at the open end and perhaps even at the blowing end. In addition there may be fortuitous variations along the length of the pipe. The general rule for interpreting the effects of such perturbations on the tube mode frequencies is that, for a given mode, the frequency is raised if the bore is expanded near a velocity maximum and lowered if it is expanded near a pressure maximum (and conversely for a contraction of the bore, see Benade (1976:473–80) for a more detailed discussion).

In relation to the first two modes of the didjeridu, which are all that really concern us here, this means that a flare (enlargement) at the open end raises the frequency of both modes, while a flare at the blowing end lowers both made frequencies, the pitch change (relative frequency change) being about the same for each mode. However, an expansion of the bore about one-third of the length away from the blowing end will raise the frequency of the second mode, and an expansion about two-thirds of the way from the blowing end will lower it, while in both cases the frequency of the first mode will be very little affected.

APPENDIX 3. Formant mechanism

It is not yet possible to give a complete explanation of the mechanism of production of formant bands in the didjeridu, if only because the effects of mouth volume even on the basic mechanism controlling lip vibration are only now beginning to be understood. What happens, however, seems to be essentially as follows.

The player's lips vibrate in a more or less sinusoidal fashion at a frequency f_1 that is determined by the moving mass of the lips and the elastic forces exerted by the lip muscles. This frequency f_1 must be close to the first resonance of the tube (with the lip end effectively closed) if there is to be co-operation between lip and tube vibrations and hence a loud and stable sound.

Because the lips are essentially a simple oscillator, they respond hardly at all at any frequency other than near their resonance, but they are still able to generate harmonics in the air flow into the tube, even if the blowing pressure is exactly constant. This arises partly because the flow through the lip opening varies as the square root of the pressure difference across it and partly because, for vigorous motion, the lips may actually close for part of their cycle, completely cutting off the air flow.

When the finite volume of the mouth cavity is taken into account, two more effects enter. In the first place, the blowing pressure is no longer constant but varies during the vibration cycle in such a way as to assist the lip motion—this is why it is possible to buzz the lips without the presence of a resonating tube. In the second place, there is developed a particular resonance effect in the mouth, called a Helmholtz resonance, which causes the air flow to be very large for pressure excitations at frequencies near this resonance. This resonance frequency varies inversely with the square root of mouth volume and directly with the linear dimensions of the opening between lips or teeth (if we make some other simplifying assumptions). Of course the geometry of the mouth is rather complex so that some of our statements cannot be made very specifically, but we know that when whistling between the lips or teeth we excite a similar resonance, and it is not difficult to vary its frequency between about 500 and 2000 Hz, largely by moving the tongue to adjust effective mouth cavity volume. The didjeridu player does something very similar when exciting a selected formant band, all frequencies near the cavity resonance being similarly emphasised. With the complex geometry of a real mouth, there may indeed be several resonances with which formant bands can be associated.

APPENDIX 4. Voiced sounds

The air-flow waveform coming from the vibrating vocal folds contains harmonics of the fold vibration frequency f_0 which behave with time t like $\cos 2\pi m f_0 t$, where m is an integer. Similarly the air-flow waveform generated by the vibrating lips contains harmonics of the lip vibration frequency f_1 which behave like $\cos 2\pi n f_1 t$, where n is also an integer.

If the air flow were to enter the instrument tube separately from each of these two sources, then we could simply add the separate flows, giving frequency components at mf_0 and nf_1. However, this is not what happens. Instead, the already pulsating flow from the vocal folds passes through the vibrating lips and the two effects are multiplied rather than added—a process that would be termed amplitude modulation in radio engineering. (Actually the interaction is rather more complex than this, but we neglect the further complications here.)

Now from elementary mathematics

$$\cos 2\pi m f_0 t \times \cos 2\pi n f_1 t = \tfrac{1}{2}\left\{\cos 2\pi(mf_0+nf_1)t + \cos 2\pi(mf_0-nf_1)t\right\}$$

so that the resulting flow entering the instrument contains components at all the frequencies $mf_0 \pm nf_1$ for any integer values of m and n.

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