133

WOODWIND INSTRUMENTS

NEVILLE H. FLETCHER

1 INTRODUCTION

The woodwind family comprises mouth-blown instruments excited by a single reed in a nearly cylindrical tube (clarinet), a single reed in a conical tube (saxophone), a double reed in a conical tube (oboe and bassoon), or an air jet in a nearly cylindrical tube (flute). Renaissance instruments such as recorders, shawms, and krummhorns and folk instruments such as panpipes and bagpipes are also woodwinds. In all these instruments, except for the panpipes and the drones of the bagpipes, the resonator tube is pierced by tone holes that are closed by the finger tips or by finger-actuated keys to change the pitch of the note. Most instruments are made of wood, with metal keys, but saxophones are always, and flutes now usually, made totally of metal. Surveys of the history[1] and acoustics[2,3] of all these instruments, and more detailed treatments of individual types,[4–7] are available in the literature. Important instruments of the family are shown in Fig. 1.

To understand the acoustics of woodwind instruments, it is convenient to consider first the passive linear behavior of the air column and then the operation of the active nonlinear reed or air jet generator that maintains the resonator in oscillation to produce sound. Reed generators are pressure-controlled valves that present a negative acoustic conductance under appropriate conditions. They therefore drive the air column from a point of maximum acoustic impedance, and the reed end of the tube resonator is effectively stopped. Air jets, on the other hand, are flow-controlled valves that can also present a negative acoustic conductance. They drive the air column at a point of minimum acoustic impedance so that the blowing end of the tube is effectively open. For both flutes and reed instruments, the generator produces a complete and precisely harmonic spectrum based on the fundamental frequency determined by the generator and resonator in combination. Resonances of the air column then serve to shape this spectrum.

2 AIR COLUMN RESONATOR

The fundamental frequency of the note sounded by a woodwind instrument is determined by the mode frequencies of the resonator, usually that of the lowest mode, and these frequencies are varied by opening finger holes to reduce the effective length of the air column. It is therefore important that the mode frequencies of the resonator maintain the same relationship to each other as the resonator is shortened, to give tonal coherence over the playing range. This is possible, in the case of a reed-driven instrument with an impedance maximum at the reed, if the instrument horn is either cylindrical or else conical with the reed at the apex.[8]

In the cylindrical case, adopted for the clarinet family, the modes with impedance maxima at the reed form an approximately odd-harmonic series, with the tube being one-quarter of a wavelength long at the fundamental resonance. This shows up in the radiated spectrum, illustrated in Fig. 2*a*, the very weak second harmonic being the principal timbre characteristic. Because the resonator is not ideally cylindrical, however, its higher resonances are appreciably inharmonic and higher even harmonics of the reed frequency appear. Above the radiation cutoff frequency for the tone holes and open end, whatever the bore shape, there is no reflected wave in the tube and all harmonics are radiated equally. This cutoff is typically between 1 and 2 kHz, depending on the type of instrument.[9]

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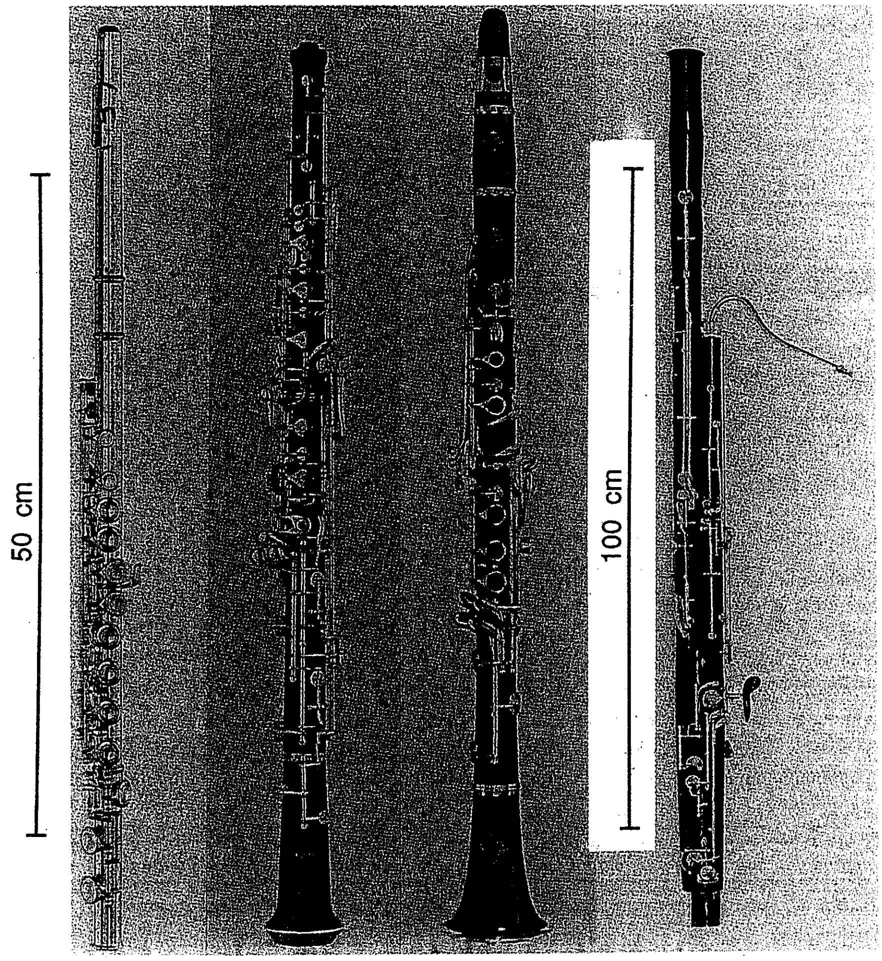

Fig. 1 Flute, oboe (without reed), clarinet, and (to a different scale and in rear view) bassoon. Note the simple integrated keywork of the flute, with one key per finger (except in the foot joint), the small holes and many extra keys in oboe and clarinet, and the large number of keys operated by the two thumbs in the bassoon.

The oboe, bassoon, and saxophone have conical bores for which the tube is half a wavelength long at the fundamental resonance. A conical-bore reed instrument must therefore be nearly twice as long as an instrument with a cylindrical bore to produce the same note—the bassoon is folded to accommodate its 2.6-m length. Because of partial truncation of the cone at the reed end, the acoustic length of the air column is rather greater than the geometric length. There is a further length correction from the acoustic admittance of the reed itself, and this applies also in the case of the clarinet. All harmonics are reinforced in the sound of conical-bore instruments, as shown in Fig. 2*b*.

The input impedance curve of a woodwind instrument with several open finger holes is very complex,[10] and a successful design for a reed instrument appears to depend on achieving a high input impedance at the frequency of at least one of the low harmonics of the note fundamental. This is accomplished by adjustment of tone hole sizes and small variations in bore profile.

In the case of the flute family, the jet generator must be at an impedance minimum for the tube, and the far end is usually open. Bore shapes satisfying the mode-similarity condition can be cylindrical or can have the shape of either flaring or tapering incomplete cones. In each case there is a complete set of harmonic modes, and the fundamental tube length is half a wavelength. There is generally a considerable end correction to be added at the embouchure hole because of its small diameter relative to that of the bore. In a side-blown flute there is also a cavity between the embouchure hole and the stopped end, the size of which is chosen so as to optimize the tuning of the pipe resonances. Before the mid-nineteenth century, flutes had a tapering conical bore and a cylindrical head joint. This geometry is retained in most orchestral piccolos, while the modern flute has a cylin-

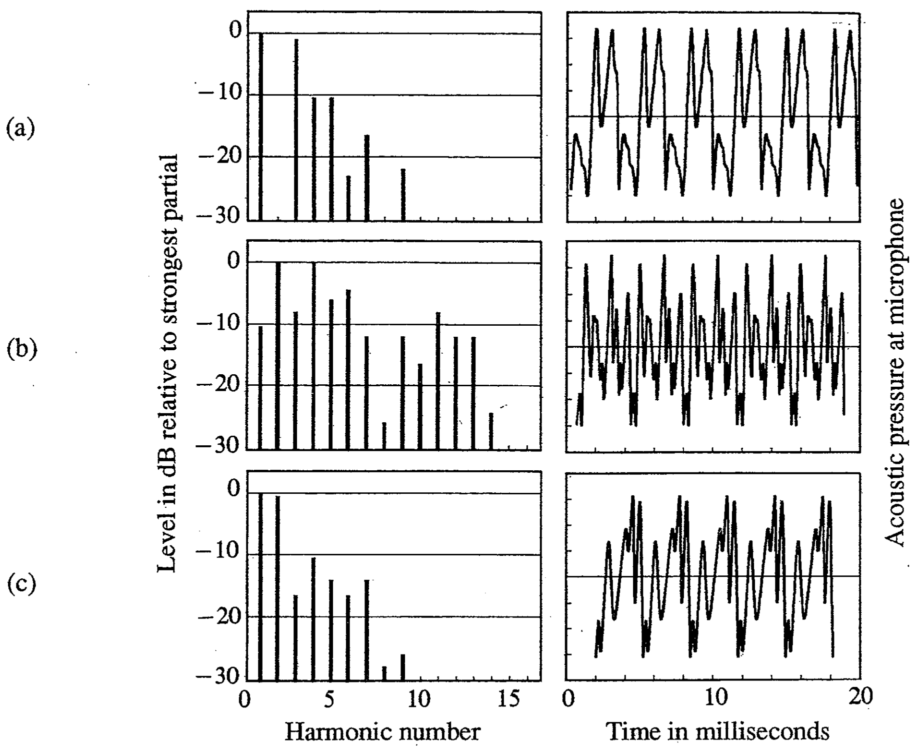

Fig. 2 Waveform and radiated spectrum of the note D4 played with full tone on (*a*) a clarinet, (*b*) an oboe, and (*c*) a flute. Higher notes have less harmonic development for all instruments, and high notes on the clarinet do not have the characteristic missing second harmonic. Waveforms and spectra depend considerably upon the player and the microphone arrangement.

drical bore and a tapering head joint. In each case the arrangement is designed so as to flatten the lowest resonance frequency and so improve response.[11] The spectrum of a typical flute sound is shown in Fig. 2*c*. Upper harmonics are less prominent than in the oboe because of the more gentle nonlinearity, but are still quite well developed, particularly in low notes.

Geometrical details for typical models of common woodwind instruments[2] are given in Table 1. Note the increase in cone semiangle from the bassoon and oboe to the saxophone. This correlates with increasing relative power in the fundamental and low harmonics of the sound because of reduced wall damping and more efficient radiation. The clarinet, oboe, and saxophone all have flaring end sections or bells.

Most woodwind instruments are made from selected hardwood, though saxophones and most flutes are of metal. Acoustic evidence and listening trials[12] suggest that there is no direct influence of the construction material on radiated sound, provided the internal wall is smooth. The amplitude of wall vibrations is in any case very small, and much more affected by wall thickness than by changes in material. More subtle effects such as the influence of material on roughness of bore, sharpness of tone-hole edges, and fit of key pads may, however, be important. There are also questions of ease of machining, surface finish, durability, dimensional stability, and appearance, all of which define particular woods and metals as being specially suitable for instrument making. Plastics can also meet these requirements and are widely used in less expensive instruments.

3 KEY MECHANISMS

The fingering problem for woodwind instruments arises because the number of fingers on a pair of human hands is less than the number of notes in an octave, when semitones are considered. In a simple tone hole arrangement for a flute, oboe, or bassoon, there are six finger holes and one thumb hole to produce the seven notes of a diatonic (white-note) scale by simply opening them in sequence, with a further octave being available by "overblowing" to the next resonator mode, and a few notes above this by using special fingerings. Each semitone step involves reducing the acoustic length of the pipe by about 6%, and each full tone step by about 12%. Finger hole spacing is usually reduced for convenience by using small holes

TABLE 1 Typical Physical Dimensions of Woodwinds

	Musical Range	Tube Length (mm)	Top Diameter (mm)	Bell Flare Diameter (mm)	Cone Semiangle (deg)	Truncation Ratio
Piccolo in C (conical)	D5–A7	262[a]	11	8 → 9	−0.6	—
Flute in C	C4–C7	604[a]	17[b]	19[c]	0	—
Oboe in C	B3–G6	644[d]	3	17 → 37	0.7	0.13
Bassoon in C	B1–C5	2560[d]	4	40[e]	0.4	0.09
Clarinet in B^b	D3–G6	664[d]	14	16 → 60	0	—
Alto saxophone in E^b	D3–A6	1062[d]	12	70 → 123	1.6	0.12

[a] To center of embouchure hole.
[b] Head taper to embouchure hole.
[c] Cylindrical tube.
[d] To tip of reed.
[e] Uniform cone.

placed rather closer to the generator end than this simple proportion would suggest. This device is taken to an extreme in the bassoon, which has tone holes drilled at an angle through thick wood to bring them within reach of the fingers. The diameter and placing of the tone holes can be slightly varied to achieve optimal tuning in the two octaves.[9] In this simple fingering system, semitones are produced by closing one or more holes below the first open hole to increase the acoustic load and lower the pitch.

Musical developments in the eighteenth and nineteenth centuries required greater facility and tonal evenness for chromatic semitones, and extra keys, normally standing closed, were provided for this purpose between the original tone holes. Further keys added below the normal bottom note also served to extend the range downward. This device was essential in the clarinet, which overblows to the twelfth rather than the octave and must therefore have a basic fingering range of a twelfth, leaving four diatonic and three chromatic notes to be filled in between the two six-finger registers. Clarinets, oboes, and bassoons still retain small open finger holes, with many supplementary keys, as shown in Fig. 1, and incorporate some coupling mechanisms borrowed from the flute, as discussed below. These reed instruments are generally made of selected hardwoods, tradition dictating different wood for different instruments, though plastic materials are sometimes used in cheaper instruments. The saxophone, invented by Adolphe Sax in the mid-nineteenth century, has a clarinetlike single reed, a wide conical bore, and very large tone holes with a key mechanism related to that of the flute, though the fingering is somewhat different. Saxophones are almost always made of metal.

The flute, which in baroque times had a tapered conical body with a cylindrical head, was redesigned in the mid-nineteenth century by Theobald Boehm. His initial design retained this bore shape, but his revised model of 1847 used a cylindrical body, with a head joint tapering slightly toward the mouth hole, and with large tone holes placed in acoustically appropriate positions.[4,9,13] This arrangement required large padded keys to cover the tone holes and a mechanism of axles and clutches connecting all keys to give the player control. Boehm designed an elegant and enduring mechanism for this purpose. Many of his later flutes were made of silver rather than of wood. These changes increased greatly the acoustic power and tonal uniformity of the flute and are universally used today. Modern flutes are usually made of silver (typically 925 fine), gold (typically 14 carat) or even platinum, the alloy composition being chosen to give good strength, appearance, and manufacturing properties. Any acoustic difference between flutes made of these different materials is much less significant than the differences introduced by variations in head taper design, acoustic absorption of the key pads, and adjustments to the embouchure hole introduced during hand finishing. Student instruments are usually made of a cheaper cupronickel alloy with silver plating.

As well as changing the frequency of the resonator modes, the tone holes also have an influence on the tone quality of the instrument. While some of the sound is radiated from the first open tone hole, much of it, particularly the harmonics of higher frequency, propagates along the remainder of the bore and is radiated from open tone holes and from the open end, giving a rather complex directional characteristic.[14] The lattice of open tone holes along the lower part of the bore acts as a filter and modifies the upper part of the radiated spectrum.[9] The size of the tone holes is, of course, partly determined by the diameter and cone angle of the instrument tube, but small variations are possible in the design of instruments of one type. Small tone holes reduce the radiation of higher frequency components and make the instrument less bright than do large tone holes.[8]

The musical ranges of the more common members of the woodwind family are shown in Table 1. In addition there is a cylindrical version of the piccolo, and alto flute in G, and a bass flute in C, as well as a less common small flute in E$^\flat$. The oboe family is augmented by the oboe d'amore and cor anglais, both of which have a globular rather than a flaring bell, and there is a contra-bassoon an octave below the normal bassoon. The clarinet family has a high-pitched member in E$^\flat$ and an additional orchestral version in A, as well a lower pitched alto clarinet in F and bass clarinet in B$^\flat$. The saxophone family contains as many as six members, with a high soprano in B$^\flat$ and several larger relatives.

4 REED GENERATORS

The reed in a woodwind instrument is a pressure-controlled valve that is closely coupled to the air column resonator, which determines its vibration frequency. Reeds are made from thinned and carefully shaped cane. A single reed, bound against an aperture in a mouthpiece, is shown in Fig. 3*a* and double reeds in Figs. 3*b*, *c*. All are of the type that is blown closed by steady pressure in the mouth and have natural resonance frequencies well above the playing frequency. If the blowing pressure is p_0, the pressure in the mouthpiece of the instrument p, and the opening distance of the reed x, then the volume flow U into the instrument is determined by Bernoulli's law and has the approximate form

$$
\begin{aligned}
U &\approx (2/\rho)^{1/2} W x (p_0 - p)^{1/2} \\
&\approx (2/\rho)^{1/2} W[x_0 - C(p_0 - p)](p_0 - p)^{1/2}, \qquad (1)
\end{aligned}
$$

where ρ is the density of air, x_0 is the static opening of the reed, W is its width, and C is proportional to its elastic compliance. The form of this relation is shown in Fig. 3*d*, the reed being closed and the flow zero to the right of *B*. Details are slightly different for a real instrument because of mouthpiece curvature in single reeds and reed arch in double reeds, so that the closure is not abrupt but more as indicated by the broken curve. Slight modifications can be made to Eq. (1) to take account of more complex reed geometry.[15]

In a linear small-signal approximation, the acoustic admittance presented to the resonator is $Y = -\partial U/\partial p$, and can be found as a real conductance by differentiating Eq. (1), provided the frequency is much less than the resonance frequency of the reed. This conductance is negative in the *AB* region of the curve, above a blowing pressure p_0^* that is sufficient to reduce the reed opening so that $x < 2x_0/3$. The blowing pressure p_0 is therefore set by the player to an operating point *O* close to that shown on the curve, where $x \approx x_0/3$. When the reed is treated in more detail as a mechanical vibrator,[16] its acoustic conductance for $p_0 > p_0^*$ has the form shown in Fig. 3*e*. This is negative at all frequencies below the reed resonance, so that the reed can act as an acoustic generator at these frequencies when coupled to a resonator of sufficiently high *Q*, the oscillation frequency being determined largely by the resonator. There is a negative conductance valley just below the reed resonance frequency f_R, but this does not dominate the behavior as it does in organ reed pipes, largely because the woodwind reed is damped by the player's lips, giving a broad low peak, while an organ pipe reed is clamped by a metal wire and has a high *Q*.

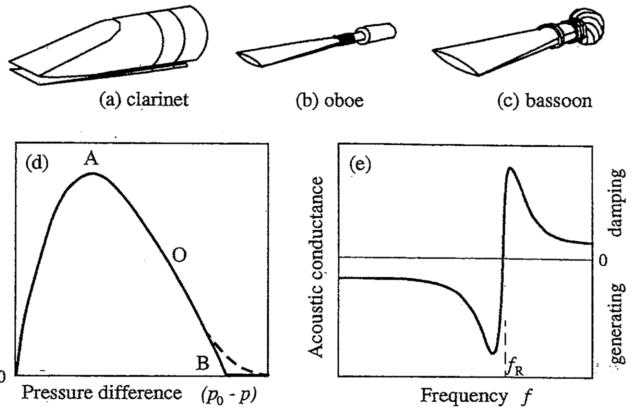

Fig. 3 (*a*)–(*c*) Reeds of the clarinet, oboe, and bassoon, to a similar scale. (*d*) Static flow curve for a reed generator; the operating point is set near *O*. (*e*) Acoustic conductance as a function of frequency for blowing pressure near the point *O*; f_R is the resonance frequency of the reed.

Note that the flow curve of Fig. 3*d* is nonlinear, so that exact harmonics of the basic reed motion appear in the flow into the resonator.[17] The reed can respond to several mode frequencies of the resonator, and behavior is complicated by the conductance peak just below the reed resonance. As with most highly nonlinear systems, the oscillation usually locks into a single periodic regime with high harmonic development. This is facilitated if the resonator has several resonances in approximately harmonic relationship (i.e., with frequencies in the ratios of small integers[10]). If there is no pipe resonance close to the frequency of a particular harmonic of the reed fundamental, as in the case of the second harmonic for a cylindrical clarinet pipe, then the reed flow at that frequency does not produce an appreciable acoustic pressure, and the radiated harmonic partial is weak. Figures

2*a*, *b* show waveforms and spectra of typical midrange notes on a clarinet and an oboe, illustrating the high harmonic content.

5 AIR JET GENERATORS

An air jet emerging from the windway of a recorder, as in Fig. 4*a*, or from a flute player's lips, as in Fig. 4*b*, is unstable against the influence of transverse acoustic flow, which produces a sinuous disturbance that propagates along the jet at about half the jet speed and grows exponentially in amplitude. If the jet strikes against the edge of a resonator a small distance away from the flue, then flow of the jet into the resonator excites oscillations of the air column that act back upon the motion of the jet. The mechanism by which the jet drives the pipe combines the effect of injecting a volume flow at a position just inside the end correction, where there is a small acoustic pressure, and injecting momentum, and thus pressure, at a position of large acoustic flow.[18]

The phase of the coupling determines whether or not oscillation can be maintained, and this depends on the length of the jet from lip aperture to resonator edge, on the jet speed or blowing pressure, and on the mode frequency of the resonator.[19] The acoustic conductance presented by the jet to the resonator has the form shown in Fig. 4*d* as a function of the parameter

$$\delta = 2lf[\rho/(2p_0)]^{1/2}, \qquad (2)$$

where p_0 is the blowing pressure, l the jet length, and f the sounding frequency. The parameter δ is essentially equal to the propagation phase shift, measured in wavelengths, for transverse waves on the jet. Only the principal negative minimum, labeled O, near $\delta = \frac{1}{2}$ is used in normal playing. The player adjusts blowing pressure and lip position to place this minimum near one of the mode frequencies of the resonator, which then sounds.

The velocity profile across a planar jet has approximately the bell-shaped form $v_0 \operatorname{sech}^2(y/w)$, where y is the coordinate across the jet, w is the jet half-thickness, and v_0 is the centerplane velocity. The flow into the resonator mouth is then

$$U \approx \tfrac{1}{2}U_0[1 + \tanh(y_0 + y)], \qquad (3)$$

where y is now the time-varying displacement of the center plane of the jet, as deflected by the acoustic flow, y_0 is the static offset of this plane relative to the plane of the sharp edge of the resonator, both measured in units of w,

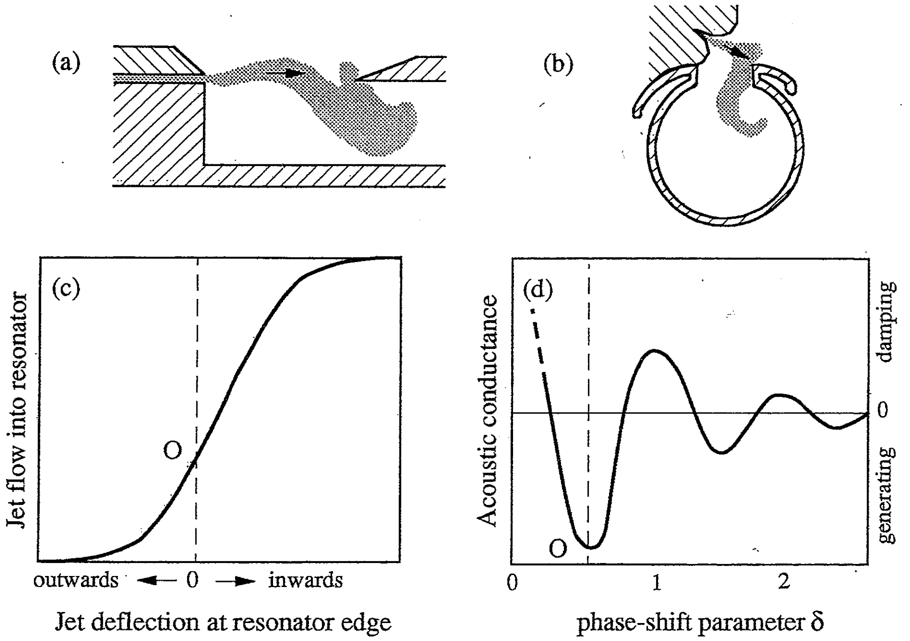

Fig. 4 Sinuous waves on a jet emerging from (*a*) the windway of a recorder and (*b*) the lips of a flute player. (*c*) Flow characteristic for an air jet generator with static jet position *O*. (*d*) Acoustic conductance of an air jet generator; the jet speed operating point *O* is set near the principal minimum.

and U_0 is the steady volume flow of the jet. This nonlinearity, shown in Fig. 4*a*, is softer than that of a reed generator, so that the relative strength of high harmonics is less.

6 TIME-DOMAIN ANALYSIS

While physical understanding of woodwind instruments is most easily expressed in terms of frequency components, numerical simulation and calculation is best carried out in the time domain. For such calculations, the reed or air jet generator is described by differential equations, and the air column resonator in terms of a reflection function that is related to the Fourier transform of its acoustic input impedance. Such numerical calculations give quite good agreement with experiment for both transient and steady states for both the clarinet[20] and the flute[21] but are limited at present by the reliability with which the generator, and particularly the airflow, can be understood and modeled.

7 PERFORMANCE PARAMETERS

In reed instruments, the major parameters available for adjustment are the blowing pressure p_0 and the static reed opening x_0, which is set by lip pressure. Little variation in p_0 is possible if the operating point O in Fig. 3*d* is to remain near the center of section AB. From Eq. (1), the magnitude of the negative conductance at O is proportional to $x_0^{1/2}$, the flow range AB to $x_0^{3/2}$, and the pressure range AB to x_0. Changes in lip pressure to alter the static opening x_0 can therefore be used to change the acoustic excitation magnitude and instrument loudness. Increase in the negative conductance for loud playing ensures that more of the nonlinear curve is sampled, and so increases relative harmonic content. This increase in harmonic content is more important than absolute power level in determining musical impact in loud playing.

For the clarinet and saxophone, the normal blowing pressure is 3–4 kPa for soft playing and 5–7 kPa for loud, with little systematic change with pitch through the compass. In double-reed instruments, the blowing pressure increases steadily with pitch and with loudness, ranging from 4 to 12 kPa for the oboe and from 1.5 to 6 kPa for the bassoon. Average acoustic output power varies with the pitch of the note played, but is typically a few milliwatts for all woodwind instruments. The dynamic range[22] of the oboe and the bassoon for a skilled player is typically 20–30 dB, varying somewhat with the pitch of the note played. The clarinet has a dynamic range of up to 40 dB over most of its playing compass. Conversion efficiency from pneumatic to acoustic power is typically 0.1–1% for reed instruments, being higher at higher power levels.

In flute instruments[19,23] the blowing pressure is determined by jet phase matching requirements, as discussed in relation to Eq. (2), and increases approximately linearly with the frequency of the note played, from about 0.3 kPa for C_4 to 2 kPa for C_7, an accompanying reduction being made in jet length for high notes by pushing the lips forward. The loudness is controlled by the total jet flow, which is varied primarily by changing the aperture between the player's lips. Average acoustic power output is again typically a few milliwatts, but the dynamic range is only about 20 dB for low notes and less than 10 dB for very high notes. Acoustic conversion efficiency is typically about 1%, depending on pitch and loudness level. Again the harmonic content increases at loud playing levels. More subtle changes in timbre can be effected by changing the direction of the air jet and hence the operating point O in Fig. 3*c*. If O is set to the inflection point of the curve, then even harmonics are suppressed and odd harmonics reinforced, while for other jet directions particular even harmonics can be emphasized.[24]

In reed instruments the player's mouth cavity is closely coupled to the reed, so that its acoustic properties can have a significant influence on sound production.[25] Analysis shows that the vocal-tract impedance is effectively in series with the impedance of the instrument as presented to the reed but, because the peak impedance of the vocal-tract resonances is low compared with that of the instrument tube resonances, the vocal tract has only a relatively small effect on the frequency and amplitude of the sound produced. It is necessary, however, to adjust mouth configuration to make the low notes on the bassoon sound at all, and mouth configuration has a significant influence on tone quality in all reed instruments. In the case of flutes the mouth cavity is only weakly coupled to the instrument air column, and vocal-tract effects are much smaller, except insofar as they affect the flow, shape, and turbulence of the air jet.

REFERENCES

1. A. Baines, *Woodwind Instruments and Their History*, Faber and Faber, London, 1967.
2. C. J. Nederveen, *Acoustical Aspects of Woodwind Instruments*, Frits Knuf, Amsterdam, 1969.
3. N. H. Fletcher and T. D. Rossing, *The Physics of Musical Instruments*, Springer Verlag, New York, 1991.
4. P. Bate, *The Flute*, Norton, New York, 1979.
5. P. Bate, *The Oboe*, Norton, New York, 1975.
6. L. G. Langwill, *The Bassoon and Contrabassoon*, Norton, New York, 1966.

7. F. G. Rendall, *The Clarinet*, Williams and Norgate, London, 1954.
8. A. H. Benade, "On Woodwind Instrument Bores," *J. Acoust. Soc. Am.*, Vol. 31, 1960, pp. 137–146.
9. A. H. Benade, "On the Mathematical Theory of Woodwind Finger Holes," *J. Acoust. Soc. Am.*, Vol. 32, 1960, pp. 1591–1608.
10. J. Backus, "Input Impedance Curves for the Reed Woodwind Instruments," *J. Acoust. Soc. Am.*, Vol. 56, 1974, pp. 1266–1279.
11. A. H. Benade and J. W. French, "Analysis of the Flute Head Joint," *J. Acoust. Soc. Am.*, Vol. 37, 1965, pp. 679–691.
12. J. Backus, "Effect of Wall Material on the Steady-State Tone Quality of Woodwind Instruments," *J. Acoust. Soc. Am.*, Vol. 36, 1964, pp. 1881–1887.
13. J. W. Coltman, "Acoustical Analysis of the Boehm Flute," *J. Acoust. Soc. Am.*, Vol. 65, 1979, pp. 499–506.
14. J. Meyer, *Acoustics and the Performance of Music*, Verlag Das Musikinstrument, Frankfurt am Main, 1978.
15. J. Backus, "Small-Vibration Theory of the Clarinet," *J. Acoust. Soc. Am.*, Vol. 35, 1963, pp. 305–313.
16. N. H. Fletcher, "Excitation Mechanisms in Woodwind and Brass Instruments," *Acustica*, Vol. 43, 1979, pp. 63–72.
17. N. H. Fletcher, "Nonlinear Theory of Musical Wind Instruments," *Appl. Acoust.*, Vol. 30, 1990, pp. 85–115.
18. N. H. Fletcher, "Jet Drive Mechanism in Organ Pipes," *J. Acoust. Soc. Am.*, Vol. 60, 1976, pp. 481–483.
19. J. W. Coltman, "Sounding Mechanism of the Flute and Organ Pipe," *J. Acoust. Soc. Am.*, Vol. 44, 1968, pp. 983–992.
20. R. T. Schumacher, "Ab Initio Calculations of the Oscillations of a Clarinet," *Acustica*, Vol. 48, 1981, pp. 71–85.
21. J. W. Coltman, "Time-Domain Simulation of the Flute," *J. Acoust. Soc. Am.*, Vol. 92, 1992, pp. 69–73.
22. J. Meyer, "Zur Dynamik und Schalleistung von Orchesterinstrumenten," *Acustica*, Vol. 71, 1990, pp. 277–286.
23. N. H. Fletcher, "Acoustical Correlates of Flute Performance Technique," *J. Acoust. Soc. Am.*, Vol. 57, 1975, pp. 233–237.
24. N. H. Fletcher and L. M. Douglas, "Harmonic Generation in Organ Pipes, Recorders and Flutes," *J. Acoust. Soc. Am.*, Vol. 68, 1980, pp. 767–771.
25. P. G. Clinch, G. J. Troup, and L. Harris, "The Importance of Vocal Tract Resonance in Clarinet and Saxophone Performance—A Preliminary Account," *Acustica*, Vol. 50, 1982, pp. 280–284.