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INVITED REVIEW

Recent progress in the acoustics of wind instruments

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Abstract: Progress made over the past decade in understanding the mechanisms of sound production in music wind instruments is reviewed. The behavior of air columns, horns, and fingerholes is now fairly well understood, and most recent interest centers on details of the sound generator — the reed in woodwinds, the lips in brass instruments, and the air jet in flute-family instruments. Not only do these generators produce the sound, but they are also largely responsible, through their nonlinearity, for controlling the harmonic content and thus the musical timbre of the instrument, the one major exception being in loud playing on brass instruments where propagation nonlinearities in the air column are also important. Despite considerable progress, there remain important and interesting questions to be answered.

Keywords: Musical instruments, Wind instruments

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1. INTRODUCTION

The aim of this paper is to survey progress that has been made over the past decade or so in our understanding of the acoustics of musical wind instruments, and to look particularly at the important problems that remain. It turns out that these problems all lie in two areas — nonlinear effects and detailed aerodynamics, so that this will be the emphasis of the paper.

The subject of wind instrument acoustics is a large one that has occupied the attention of acousticians from the time of Helmholtz and Rayleigh to the present day. It is not appropriate in this paper to review the whole of this understanding. An up-to-date account with copious references is given in the author's book *The Physics of Musical Instruments* [1], and for this reason few references earlier than about 1990 will be cited here. Two recent articles by Fletcher [2] and by Campbell [3] have paid particular attention to the role of nonlinear phenomena in musical instruments and could be consulted with advantage.

2. THE WIND-INSTRUMENT SYSTEM

It is convenient to think of a musical wind instrument as a system with three components, as shown in Fig. 1. The instrument itself is basically a resonant air column, the acoustic length of which can be controlled by the player by means of valves, slides, or finger holes. Its behavior is basically linear, though, as we shall see, there are exceptions to this statement in the case of brass instruments. The modern form of most instruments has developed gradually over several centuries to give a well-aligned chromatic scale, an efficient fingering system, and an acoustic input impedance that varies smoothly from note to note, giving consistent tone quality. This air column is excited by a highly nonlinear valve controlled by acoustic pressure or flow in its vicinity, and the whole is fed by a steady air flow that must first pass through the player's vocal tract.

It is interesting to realize that, from an energy point of view, the sound output of a musical instrument plays a minor part, and typically represents only about 1 percent of the input power. In the case of wind instruments, a large fraction of the energy is consumed by turbulent and other flow losses in the sound-generation mechanism, and the balance by viscous and thermal losses to the walls of the instrument tube.

The acoustical behavior of wind-instrument bores, either the nearly cylindrical or nearly-conical woodwinds or the more complex flaring horns of brass instruments, has been well understood for many decades. Benade [4] more recently gave particular attention to the finger-holes of woodwind instruments and showed that the open holes, as well as determining the pitch of the note being played, provided a high-pass filter structure that had considerable influence on the tone of the instrument. Harmonics of the played fundamental lying above the cut-off frequency of the finger-hole lattice are not reflected, and so are not re-

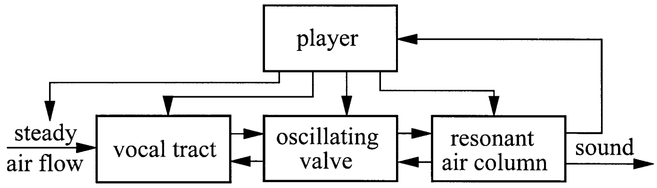

Fig. 1 A wind instrument as a system has three major components: a steady air supply, a highly nonlinear valve to modulate the flow, and a resonant air column of controllable acoustic length. The player's vocal tract may also influence the performance. All components are under the direct control of the player.

inforced in the sound. An instrument with finger-holes small compared with the cross-section of the bore therfore has a "mellow" sound, while an instrument with large tone holes sounds "bright." This is now well accepted, and little further development has occurred.

The horns of brass instruments have similarly been studied and are now well understood. A good modern exposition is that of Benade and Jansson [5].

At the other end of the system is the air supply provided by the player. Most early work simply assumed a constant blowing pressure in the player's mouth, this pressure being adjusted to suit the note being played. While this assumption is adequate for an initial understanding and modeling of the instrument, it is now recognized that the player's vocal tract should be considered to be an acoustic system in its own right, and that its resonances can have a significant effect on the behavior of the whole instrument. Several studies, which are mentioned later, have examined this problem.

The central part of the system is, of course, the sound-generating mechanism provided by the reed-valve in woodwind instruments, the lip-valve in brass instruments, and the air-jet generator in flute-family instruments. It is here that most of the subtleties of the system reside, for the valve involves both mechanical and aerodynamic influences, and the couplings between them are generally highly nonlinear. It is to these matters that most of the present paper will be devoted.

Once the complexities of this generator have been understood, it is possible to model the whole system using a time-domain formalism developed by McIntyre, Schumacher and Woodhouse [6] and applied explicitly to reed-driven woodwind instruments by Schumacher [7]. This approach allows the calculation of both steady-state and transient behavior and thus, in principle, the complete behavior of the instrument. Alternative approaches, such as that of harmonic balance, which can treat only the steady state, have been discussed in detail by Kergomard [8]. The one limitation to all these treatments is that the air column behavior is assumed to be linear, an assumption that is violated for loud playing on brass instruments, as we shall see.

3. PRESSURE-CONTROLLED VALVES

In both reed-driven and lip-driven wind instruments, the heart of the generating mechanism is a pressure-controlled oscillating valve. It is helpful to consider this first in a generalized way. On the simplest model, the valve can operate in one of three configurations which can be defined by a couplet (σ_1, σ_2), where $\sigma_1 = +1$ if positive static pressure in the player's mouth tends to open the valve and $\sigma_1 = -1$ if this pressure tends to close it. The symbol σ_2 has the same implication for pressure in the instrument mouthpiece. The configuration $(-,+)$, found in the reed valves of woodwinds, is like an inward-swinging door, the $(+,-)$ configuration is like an outward-swinging door, and $(+,+)$ is like a sliding door.

If p_0 is the pressure in the player's mouth and p that in the instrument mouthpiece, then the motion of the valve is described by an equation of the form

$$m\left[\frac{d^2x}{dt^2} + \alpha\frac{dx}{dt} + {\omega_0}^2(x - x_0)\right] = A(\sigma_1 p_0 + \sigma_2 p) \quad (1)$$

where m is the effective moving mass of the valve, A is its effective flap area, x_0 its static opening, α its damping, and ω_0 its natural frequency. The volume flow U through the valve is given by a Bernoulli equation of the form

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

where W is the width of the valve aperture and ρ is the density of air. Together these two equations provide the groundwork for our discussion.

It is hardly necessary to point out that these equations are oversimplified. In particular, it should be recognized that the pressure p_0 in the player's mouth is not constant, but depends upon the balance beween inflow from the lungs, outflow through the reed opening, and displacement flow caused by motion of the reed itself. It can be shown [9] that the phase of the mouth-pressure oscillations is such as to add positive damping to woodwind-type valves of configuration $(-,+)$, thus smoothing their frequency response, and to add negative damping to lip valves of configuration $(+,-)$ or $(+,+)$, thus giving a very sharp resonance in their response and indeed allowing them to vibrate autonomously even in the absence of an instrument tube. Various other refinements will be mentioned later.

4. REED-DRIVEN WOODWINDS

Of all the reed-driven woodwinds, the clarinet has received most attention. The reason for this is its relatively simple geometry — a nearly cylindrical tube, and a pressure-controlled valve consisting of a simple flat cantilever reed closing an aperture in a mouthpiece that is almost a simple extension of the tube. The reed valve, as in all common woodwinds, is of the type $(-,+)$. In addition, it has proved to be a good initial assumption that the natural frequency of the reed is very high, so that (1) takes the simple form $x = KA(p_2 - p_1)$ where $K = \rho/\omega_0{}^2$ is the effective compliance of the reed in response to a pressure difference across it. The flow equation (2) then has a simple quasi-static form, shown as the full curve in Fig. 2. The slope of this curve is the acoustic admittance $\partial U/\partial p$ presented by the reed to the bore of the instrument, and it is clear that this quantity is negative only over the region TC of the curve. The generator thus requires a threshold blowing pressure $p_0(\mathrm{T})$, corresponding to point T, before it will generate sound, and this pressure is just one-third of the pressure $p_0(\mathrm{C})$ required to completely close the valve at point C.

If the analysis is refined by using the full equation (1), then there is a favored oscillation regime at a frequency that is just below the reed resonance frequency ω_0 by an amount close to $\alpha/2$. The metal reeds of reed pipes on an organ operate, in fact, in this regime, because their Q values are high, giving a pronounced peak in reed response

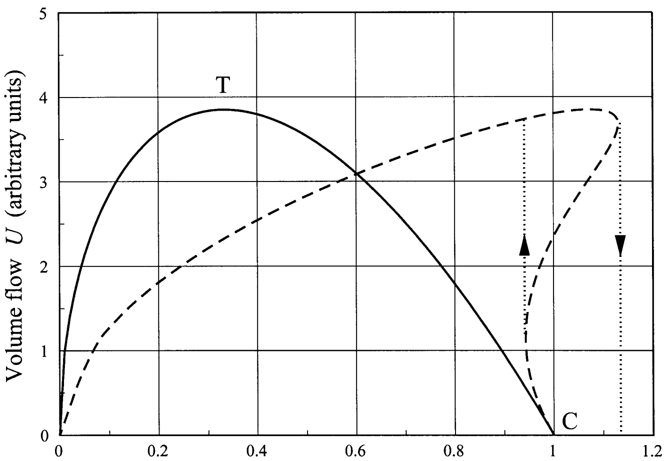

Fig. 2 Quasi-static volume flow U through a $(-,+)$ reed as a function of the pressure difference across it, measured in terms of the closing pressure of the reed. The full curve is for a simple single reed, for which the acoustic resistance, as seen from the instrument, is negative when the curve slope is negative. The broken curve is for a double reed with a significant flow resistance, in which case the reed tends to oscillate around the path shown with dotted lines.

and a sounding frequency that is controlled largely by the reed, rather than the pipe. The reeds of woodwinds, on the other hand, are strongly damped by the players lips and normally operate at frequencies well below their resonance, giving a flat frequency response and a sounding frequency that is controlled predominantly by the pipe resonator. The numerical approach of Schumacher [7, 10] then gives a relation between the flow U and the pressure p in the instrument mouthpiece of the form

$$p(t) = Z_0 U(t) + \int_0^\infty r(t')[Z_0 U(t-t') + p(t-t')]\,dt' \quad (3)$$

where Z_0 is the characteristic impedance of the instrument tube and $r(t')$ is the Fourier transform of the reflection function $r(\omega)$ at the mouthpiece. Further refinements have been made by allowing for the mass-load provided by the air in the flow channel of the valve, and for the volume displaced by motion of the reed itself.

The oscillating flow generated by the reed, and thus the loudness of the resulting sound, is controlled primarily by the compressive pressure applied by the player's lips, which can reduce the magnitude of the static opening x_0. The blowing pressure is also slightly reduced for soft playing. The result is that, for soft playing, the operating point moves towards the peak of the curve at T. When the fact is taken into account that a cylindrical bore preferentially reinforces odd harmonics of the pressure (because $p = Z_{\mathrm{in}} U$ where Z_{in} is the input impedance of the tube at the mouthpiece end) then the pressure oscillations are nearly symmetrical about the operating point, with the result that the reed does not approach the closed configuration C and the flow waveform becomes increasingly simple. This contrasts with very vigorous playing, in which the reed closes once in each cycle, generating strong higher harmonics. In a conical-bore single-reed instrument such as the saxophone, of course, all harmonics are supported by horn resonances, the waveform is not symmetrical, and the reed is easily induced to beat against the mouthpiece in moderately loud playing.

Kobata and Idogawa [11] have shown experimentally that clarinets, artificially blown, can exhibit bifurcations and even transitions to chaotic behavior — the hallmarks of highly nonlinear systems. This has been discussed also by Kergomard [8], and the behavior in phase space has been studied by Keefe and Laden [12] and by Wilson and Keefe [13]. Barjau and colleagues [14, 15] have undertaken a similar study but using a different approach to modeling the instrument. Multiphonic sounds, which may not be chaotic, can also be generated through the nonlinearity of the driving mechanism. Such multiphonic sounds are of limited musical interest, except in very "modern" music, but are important for the information they reveal about the underlying behavior of the reed generator.

Another development of importance is the extension of the analysis to double reeds such as those found in the oboe and bassoon. The whole subject is complicated by the fact that the instrument bore is conical, rather than cylindrical [16], but here we concentrate simply on the reed generator. In double-reed instruments, the reed essentially continues the conical bore to its apex, and so has a very narrow passage for air flow. This results in a considerable aerodynamic flow resistance in series with the reed valve itself, so that equation (2) must be modified by replacing the downstream pressure p on the reed by the quantity $p - RU^2$, where R is the flow resistance of the channel. The consequences of this were pointed out by Hirschberg [17], who showed that it leads to the complex curve shown with a broken line in Fig. 2. If the flow resistance is sufficiently large, then the curve is multivalued as a function of the mouthpiece pressure p, with the result that oscillations lead to a type of switching behavior in which the reed is either nearly fully open or fully closed, as shown by the dotted loop. This behavior means that there are sharp interruptions in the flow and a consequent generation of large energy in the higher harmonics of the waveform. While the amplitude of the flow, and thus the loudness of the sound, can be varied by lip pressure applied to change the equilibrium opening x_0 of the reed, this does not change the switching behavior of the reed, with the result that sound quality in double-reed instruments remains nearly the same for both loud and soft playing, in contrast with the behavior of single-reed instruments.

The aerodynamics of reed-valves is a topic that has received rather little attention, except for the work of Hirschberg and his colleagues [17]. Most theories of valve operation use a simple equation for Bernoulli flow through the valve aperture, and neglect such features as flow separation and vortex generation, despite the fact that it is well known in practice that the detailed shape of a valve aperture can have a significant effect upon its vibrational behavior. While the practice of simply ignoring these effects, or of allowing for them by using a simple parameter such as a flow contraction factor which replaces x in equation (2) by Cx where typically $0.5 < C < 1$, is a reasonable beginning, it is clear that a complete understanding will require much more careful attention to aerodynamics.

There has also been increasing recent interest in performance technique. Clinch *et al.* [18] have shown how the properties of the player's vocal tract can modify playing behavior in clarinet and saxophone. This is a subject of continuing interest, though relatively little has been published. In principle, the problem can be addressed by using an additional Schumacher-type equation to describe the pressure in the player's mouth and its interaction with vocal-tract resonances. An intriguing study of the role of the vocal folds in wind-instrument performance has been made by Mukai [19], who found that professional players of all types of wind instruments tend to adduct their vocal folds to a nearly closed configuration during playing. Researchers in various laboratories are following up this conclusion on greater detail.

There have also been studies of blowing pressure in reed instruments, as functions of pitch and loudness, by Fuks and Sundberg [20]. They find that, in the clarinet, blowing pressure is nearly constant across the pitch range, and is about 2–3 kPa for soft playing and 4–6 kPa for loud playing. Saxophone players use similar pressures for soft playing, but can use pressures up to 8 kPa for extremely loud playing in the middle register. Pressures for bassoon and oboe playing rise somewhat with both pitch and loudness, with an extreme near 12 kPa for very loud and very high playing on the oboe. Double-reed instruments are, however, very economical in their use of air, the oboe requiring as little as $100\,\mathrm{cm^3 s^{-1}}$ for moderate playing.

5. LIP-DRIVEN BRASS INSTRUMENTS

The horn of a brass instrument has a shape that is designed to give a series of impedance maxima at the input end with a frequency progression like $0.7, 2, 3, 4, 5, \ldots$. The lowest resonance is not used in normal playing, but each of the higher resonances is supported by a series of further resonances that are in closely harmonic relationship to it. The gaps between the resonances are filled-in with the aid of slides or valves that increase the length of the cylindrical part of the basic tube. The mouthpiece cup provides an auxiliary resonance that emphasizes the impedance peaks in the normal playing range of the instrument. The formalism of Schumacher [7], discussed above, can be used to model the interaction of the instrument air column with the pressure-driven lip generator and, as before, most current interest centers on the operation of this generator.

The vibrations of a brass-instrument player's lips are much more complex than those of a simple reed, but can be analyzed to a first approximation in the same manner, using equations (1) and (2). There is, however, a great difference between the configuration and dynamics in the two cases. Thus, while the reed in a woodwind instrument is driven closed by the blowing pressure, the lips of a brass player are driven open by this pressure. It is not immediately clear, however, whether the lips are driven open like swinging doors, in a $(+,-)$ configuration, or sideways like sliding doors in a $(+,+)$ configuration. We return to this question later. The important thing is that the acoustic effect of the player's mouth cavity is to provide a negative damping to the lip motion in either case, so that the effective Q value for the lip oscillation is very high [9, 21]. This means that the resonance frequency of the lips, rather than the acoustics of the air column in the instrument horn, primarily determines the sounding frequency, though in actual playing the two frequencies are brought into close agreement. Because the lips operate at very nearly their resonance frequency, their motion is normally closely sinusoidal, without an appreciable time spent in the 'closed' configuration. This has long been known from stroboscopic observations.

In the absence of experimental data, the motion of a brass-player's lips might equally well be described in terms of a $(+,-)$ or a $(+,+)$ valve. Recently, however, several experiments have thrown light on this question. Yoshikawa [22] carried out an experimental study with strain gauges attached to a trumpet player's lips, while Copley and Strong [23] used stroboscopic methods for a trombone player. Both studies concluded that the player has a good measure of control over the effective vibration mode, but that generally the longitudinal $(+,-)$ behavior is dominant at low frequencies and the transverse $(+,+)$ behavior at high frequencies.

Adachi and Sato [24] investigated the problem theoretically by modeling the behavior of lips with two degrees of freedom, longitudinal and transverse. The results from the calculation support the experimental observations and show, moreover, that the pitch of the note produced depends a little upon which mode of oscillation is dominant. This gives the player additional control over intonation. In the lower range, where the $(+,-)$ mode is dominant, the playing frequency is a little above the resonance of the lips and a little above the horn resonance, while these frequency shifts are reversed for higher horn modes where the motion is primarily that of a $(+,+)$ valve.

More recently, Ayers [25] has demonstrated the existence of traveling waves on lip-like elastic structures, and has suggested that this is the basic form of motion of brass-players' lips. This motion is very similar to that found in human vocal folds during phonation, and requires at least a two-mass model for each lip, as used by Ishizaka and Flanagan in 1972 to model the human vocal folds. If the model is also to incorporate the two types of motion studied by Adachi and Sato, it will need to be more complex still. In all these cases, it goes almost without saying that a more sophisticated evaluation of pressure forces acting upon the lips is required than the simple approximation on the right-hand side of equation (2), and it is also necessary to consider flow separation in detail.

It is well known that brass instruments, particularly trumpets and trombones, are able to produce incisive sounds with very high levels of upper harmonics. The mechanism underlying this has been obscure, but has recently been clarified by Hirschberg *et al.* [26] In very loud playing, the acoustic pressure level in the bore of a trumpet or trombone has been measured to be as high as 175 dB, or about 20 kPa. This is about one-fifth of normal atmospheric pressure, and is so large that wave propagation is nonlinear, and generates shock waves. In these waves there is steepening of the advancing wavefronts and transfer of energy from lower to higher harmonics. The development of shock waves is greater in instruments such as the trumpet and trombone, which have long sections of cylindrical bore, than in the more mellow-toned instruments with longer sections of quasi-conical horn.

Playing technique has mostly been examined only in general terms, but Fletcher and Tarnopolsky [27] have recently published the results of a study of several experienced trumpet players. They found distinct differences in blowing pressures used, which correlated with the sturdiness of the player's physique. The greatest measured blowing pressure, for high notes played extremely loudly, was 25 kPa, which is greater than normal systolic blood pressure and likely to cause physiological distress, even for a very sturdy player. The study also showed a progression of threshold blowing pressures related linearly to the frequency of the note being played, and provided further support for the shock-wave theory.

6. FLUTE-FAMILY INSTRUMENTS

Instruments of the flute family are excited by entirely aerodynamic means without any mechanical influences apart from instrument and lip geometry. The general features of the excitation mechanics have long been understood, and date back to Lord Rayleigh's work on the instability of laminar jets. Essentially, the flow from the player's lips (or from the instrument flue) is acted upon by a transverse acoustic flow through the embouchure hole of the instrument. This interaction induces a wave-like disturbance on the jet which grows as it propagates towards the lip of the instrument mouth. Upon striking this lip, the flow divides, and the amount that enters the bore of the instrument depends upon the deflection of the jet at that instant. This entrant flow then acts upon the air column, both by volume injection and by momentum transfer, to further excite the original tube oscillation.

The major difficulty with understanding this mechanism is the phase shifts involved. There are three of these, the phase difference between the acoustic flow through the instrument mouth and the deflection that it excites upon the jet, the phase delay for propagation along the jet, and phase shift involved in the interaction of the jet flow with internal acoustic waves in the pipe. In total these must sum to 2π for the feedback loop to close. Most of these matters were worked out some time ago by the combined efforts of Coltman, Elder and Fletcher, and result in a coherent theory that gives reasonable agreement with experiment [1]. If the acoustic displacement in the mouth aperture of the instrument is $z\cos\omega t$ and x measures distance along the jet from the aperture in the player's lips, then the wave on the jet is fairly well described by the equation

$$y(x,t) = z\left[\cos(\omega t) - \cosh(\mu x)\cos\left(\omega t - \frac{x}{u}\right)\right] \quad (4)$$

where the wave velocity u is about half the jet speed. The first term represents simple convection of the jet in the acoustic flow, while the second shows a 'negative-displacement' disturbance initiated at the aperture and growing exponentially with a coefficient μ. More detailed studies of jets have shown that this growth coefficient μ has a maximum value for waves with wavelength about 5 times the jet thickness and falls to zero when the wavelength is less than about 1.5 times the jet thickness, so that there is an optimal jet geometry for the generating mechanism. The phase shift of the jet deflection clearly depends upon jet length and velocity, and thus on blowing pressure. It turns out that the phase-closure requirement for the whole instrument demands a propagation phase shift or about *pi*, or about half a wavelength, along the jet.

Clearly, however, this description of the jet neglects many important details. Sinuous wave propagation is certainly a nonlinear phenomenon, and for large amplitudes the wave breaks up into a series of vortices moving along with the jet. The assumptions that go into the equation (4), are also a considerable oversimplification from an aerodynamic point of view [17, 28], although reasonable on other grounds. Many of these questions can be settled only by detailed experiments such as those of Thwaites and Fletcher. The most recent studies by Nolle [29] suggest that, despite certain reservations, a relatively simple theory of jet wave excitation and propagation is probably adequate.

The interaction of the jet with the flute tube is also a complex matter, and has so far generally been treated by sweeping all the aerodynamic interactions into a simple 'mixing region' in which the flow becomes uniform and momentum balance is satisfied. The result is a relation between the volume flow U_{p} induced in the pipe and the jet flow U_{j} into it, of the form

$$U_{\mathrm{p}} = \frac{(V + j\omega\Delta L)\rho U_{\mathrm{j}}}{S_{\mathrm{p}}Z} \quad (5)$$

where V is the jet speed, ΔL is the end-correction at the embouchure hole, S_{p} is the pipe cross-section, and Z is the impedance of the flute tube and embouchure hole in series. It is in the mixing region that most of the energy loss takes place, the efficiency of energy transfer from the jet to the pipe oscillation being about $(S_{\mathrm{j}}/S_{\mathrm{p}})^{1/2}$, where S_{j} is the cross-section of the jet. This efficiency is typically of order 1 percent.

The oscillating jet flow U_{j} depends upon the deflection (4) and the geometry of the embouchure hole. This geometry also determines the jet flow into the pipe. Although much of this theory is linear, the interception of the jet by the lip of the pipe is certainly not, for the jet flow saturates of goes to zero when the jet blows entirely into or outside the lip of the embouchure hole. In addition, the jet itself has a velocity profile that also contributes to nonlinearity in the flow, and the undeflected jet mid-plane may not line up with the lip of the embouchure. These effects together are responsible for the increase in upper harmonics in the sound at high playing levels and for the sensitive way in which tone quality can be controlled by altering jet width and direction. The results of studies made some time ago by Fletcher and Douglas show good agreement between theory and experiment.

Despite the general success of this theory, there are still many features that demand more detailed aerodynamic explanation. A beginning was made on such an explanation by Howe [30] many years ago and has been followed up by Hirschberg and his collaborators [17]. The problems involved are so formidable, however, that no complete treatment has yet been produced. In many cases organ pipes are the preferred instruments to study because of the simplification of their fixed geometry.

Playing technique on flutes and related instruments has also been the subject of study, principally by Coltman and by Fletcher [1]. Players use techniques that are in accord with the expectations of the theory outlined above. To match phases correctly, it is necessary to use a particular combination of blowing pressure and jet length for each note, the jet length decreasing and the blowing pressure increasing steadily with the pitch of the note to be played. Pressures are quite low, ranging from 200 Pa for low notes to about 2 kPa for very high notes. Loudness is controlled largely by varying the lip opening, and thus the total flow of air in the jet.

7. TRANSIENTS

Most of the discussion above has been in terms of the steady sound of an instrument, but it is widely known that this is only part of the story. Indeed the attack transient is one of the most characteristic features of instrumental sound, and it is very difficult to identify musical instruments from recordings in which the attack transient has been removed.

Fortunately, the method of analysis of sound production outlined above is adequate to treat time varying phenomena in general and attack transients in particular. There are, however, some reservations that must be placed upon this assertion. It assumes that the time variation of some controlling parameter, such as the air pressure in the player's mouth or the air flow from the lungs or lip tension, is specified, and that no new phenomena enter. This covers many interesting cases, and in particular vibrato, which is generally induced by a rhythmic variation in mouth pressure, perhaps controlled by vocal-fold motion [19]. Mention should, however, be made of some exceptions.

The most important and interesting of these is the attack transient in flute-like instruments. This was investigated some time ago, for the case of organ flue pipes, by Fletcher and by Nolle, and a recent study has been published by Castellengo [31]. Various mechanisms that are not present in the steady sound contribute, among them the generation of edge tones by the jet, the excitation of evanescent transverse modes in the pipe, and excitation of pipe resonances by jet turbulence. There is much still to be learned of this subject.

8. CONCLUSIONS

The past few decades have seen the development of a generally satisfactory set of theoretical treatments of sound generation and playing technique in musical wind instruments. Work over the past decade has built upon this understanding and has allowed us to understand many details of harmonic generation, and thus the characteristic timbre of instruments, and the way in which this varies with loudness or under the control of the player.

Along with this increased understanding has come the realization that some of the standard treatments, though practically useful, conceal within their broad formulation a considerable ignorance of aerodynamic fundamentals. It seems likely that work in the immediate future will seek to remedy these deficiencies in understanding. This is likely to prove important, not just for the satisfaction of producing a detailed model, but also for the light it may shed upon instrument design and playing technique.

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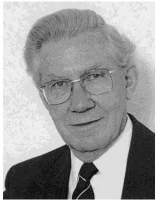

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