

ACOUSTICS OF THE FLUTE

When viewed as a positive-feedback oscillator, with a resonance frequency, energy input and loss mechanisms, the flute displays properties that explain physically how the performer adapts his technique to sound the instrument over its three-octave range.

JOHN W. COLTMAN

IN THE LONG HISTORY of scientific investigation of musical instruments the flute has been given particular attention, primarily because of its apparent simplicity. Yet many of the physical factors that determine its behavior have not been well documented. In my experiments I have tried to look at some of these factors quantitatively, concentrating on a comparison of the passive resonance and blown frequencies of the flute, on the details of the blowing mechanism at the mouth hole, and on the energy conversion and

losses of the instrument when it is regarded as an oscillator with a resonant circuit and nonlinear feedback. It turns out that the momentum and arrival time of waves on the blowing jet determine the loudness and pitch of the sounded note. Details of the flutist's empirically learned technique can be explained in these terms.

Construction and characteristics

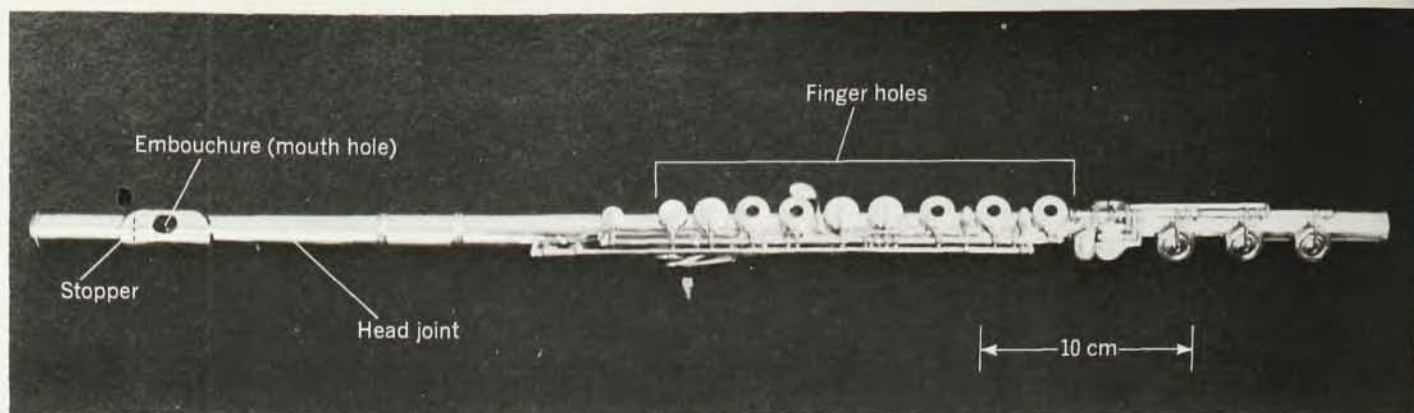
The flute is a member of a family of instruments that includes the piccolo, fife, recorder, organ pipe, ocarina,

shakuhachi, and all sorts of whistles, pan pipes and folk instruments, all of which are set into oscillation through blowing across an orifice. The modern orchestral flute is an essentially cylindrical tube, about two thirds of a meter long and 1.9 cm in diameter (see figures 1 and 2). The lower portion of the tube is pierced laterally with finger holes that can be covered or uncovered at will with a set of keys controlled by the fingers. The upper third of the tube (the head joint) is slightly tapered, diminishing in



FLUTE is blown by directing air stream to strike edge of mouth hole; air column oscillates at sounding frequency.

—FIG. 1



ORCHESTRAL FLUTE, a nearly cylindrical tube about two thirds of a meter long and 1.9 cm in diameter. It is open at both ends, as the mouth hole is not covered in playing. —FIG. 2

diameter to about 1.73 cm at the end. Near the upper end is a somewhat smaller hole, the mouth hole or embouchure, across which the performer directs a small flat stream of breath so that it impinges on the opposite edge of the hole. Shortly above this hole the tube is closed with a cork or stopper.

The essential characteristics of a musical sound are its pitch, loudness and tone color. These correspond to, but are not necessarily identical to, the physical quantities of frequency, radiated power and harmonic content. It is by the time variation of these quantities that the artist produces what is termed music, and his ability to control them determines the musical

value of the results obtained. The flute has a frequency range of three octaves, from C_4 (middle C, 262 Hz) to C_7 (2096 Hz). The various frequencies are produced by alterations in both the fingering and in blowing. The rapidity with which this can be done by a skilled performer is truly astonishing, and the flute is unexcelled for its ability to execute rapid musical passages. Its radiation power is, however, very low, particularly in the lower register, and it is in this respect the weakest of the orchestral instruments. Its tone quality is generally described as "clear and limpid," that is, the sound is less rich in harmonics than that of most other instruments.

We will look at the flute as a simple oscillator, consisting of a resonant circuit and a nonlinear feedback mechanism that converts the direct current of the breath to the alternating current and pressure in the acoustic resonator. We will deal primarily with the fundamental frequency of this oscillation; the question of harmonic content, and therefore of tone quality, is not taken up.

Resonance modes

The frequency of the emitted sound is approximately that of one of the resonance modes of the tube. As a first approximation we may consider the flute to be a cylindrical tube open at both ends, so that it will resonate at frequencies such that 1, 2, 3 . . . half wavelengths fit in the tube. The lowest mode has a maximal acoustic current (volume velocity) at each end and a single pressure maximum in the center. The next higher mode is approximately one octave above this, with two pressure maxima inside the tube. The length of the tube is de-

termined by keeping closed the finger holes in the upper portion of the instrument, leaving all those below a certain point open, effectively terminating the tube at a point near the first open hole. It is necessary to provide finger holes only in the lower half of the instrument. These suffice to produce the notes in the first octave; the performer can then, by suitable alterations in lip configuration and blowing pressure, force oscillation in the second mode, and repeat the process of successively shortening the tube as the scale of the second octave is ascended. The third octave could be similarly achieved using the fourth mode, but as now several half wavelengths can fit within the tube pressure nodes occur at points near finger holes, and the performer can vent one or more of these nodes to prevent relapse into a lower mode. Thus fingerings for the third octave resemble those of the first two, but generally are more complex.

Such a rough description suffices for a general understanding of what is going on but is far from adequate for design purposes. To be musically acceptable the pitch of an instrument should be determinable within about five cents. (A cent is 1/100 of a semitone, a frequency increment of about six parts in 10 000.) Although the performer has some control over the emitted frequency, he must start with the natural resonance of the tube-and-hole system, and the perfection of intonation is highly dependent on the proper placing of the finger holes. This subject was first scientifically attacked by Theobald Boehm¹ who invented, about 1847, the modern flute that bears his name. The subject of finger-hole placement has been dis-



As well as being director of Mathematics and Radiation at the Westinghouse Research Laboratories in Pittsburgh, John W. Coltman collects flutes. He pursues the research described here as a hobby, with experiments carried out in his basement "with home-made equipment and a very modest budget." He took his PhD at the University of Illinois in 1941 and has worked in microwave-tube development and electronic imaging. He is now responsible for the departments of mathematics, computer sciences, quantum electronics, applied physics and undersea technology at Westinghouse.

cussed theoretically by E. G. Richardson² and will not be taken up here except to present some quite precise measurements of the degree to which a single sample of a modern instrument approaches the desired perfection. These measurements show that some compromise has been found necessary to obtain the wide range. Certain deficiencies have been pointed out by Robert Young,³ and the variation in designs by different manufacturers suggests that work is still to be done for the best compromise.

Our interest here is directed at the deviations from the first-order treatment that are caused by the taper of the head joint, the variable coverage of the mouth hole by the performer's lip, variations in the velocity of sound in the tube, and the blowing mechanism itself. In particular we want to know how the sounding frequency is related to the passive resonance frequency of the system.

Frequencies: resonance and blown

I have made a series of measurements⁴ of the passive resonance frequencies of a flute with the stopper replaced by a small condenser microphone that gave a measure of the internal acoustic pressure developed at the mouth hole. The lower half of the flute was enclosed in an acoustically "dead" enclosure, which also contained a small loudspeaker driven by an external oscillator. Appropriate keys were

closed as desired with spring clips, and a plastic cover partially closed the mouth hole to simulate the coverage of the lips. Each simple resonance curve obtained in this way for microphone pressure as a function of frequency has a maximum that determines accurately the passive resonance frequency for a given fingering and mode.

Figure 3 shows in black the results of these measurements. Plotted there are the deviations, in cents, from the frequencies of the A440 equal-tempered scale. The chief feature of the curve is the trend from very flat at the lower frequencies to quite sharp at the upper frequencies. There are also irregular departures from this smooth progression. The progressive sharpening of the passive resonance frequencies is, as we shall see later, an intentional and desirable effect. The irregularities, however, are undesirable; in general they result from forced compromises in tone-hole position.

The major contributor to the sharpening trend is the taper in the head joint, which has been discussed at some length by Arthur Benade and J. W. French.⁵ They point out that a tapered section on a cylindrical tube (or similarly a straight section on a conical tube, as in the old-style flute) has the effect of "stretching" the octave, that is, the second mode of such a system is somewhat sharper

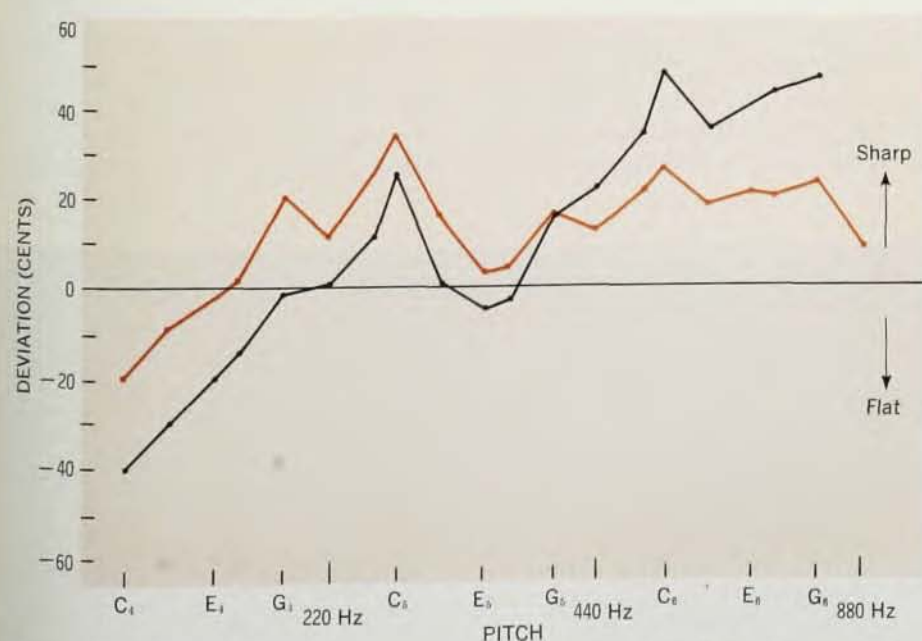
than just twice the frequency of the fundamental. Comparisons of my measured points with their values calculated for a tapered-head cylinder verifies the expected trend, but I found irregular departures⁴ caused by the cavities formed by the closed finger holes, and by the structure below the first open hole.

The frequencies produced when the flute is sounded by blowing are not the same as those shown in the black curve of figure 3. A careful set of sounding-frequency measurements on the same flute are plotted as the colored curve in figure 3. They show the same irregularities as the passive frequencies, but the general sharpening trend is much less. This curve approaches much closer to the zero-deviation line throughout the scale. Two kinds of causes produce the difference between the two curves; those that represent alterations in the natural resonance frequency of the system, and those that belong to the blowing and sounding mechanism itself.

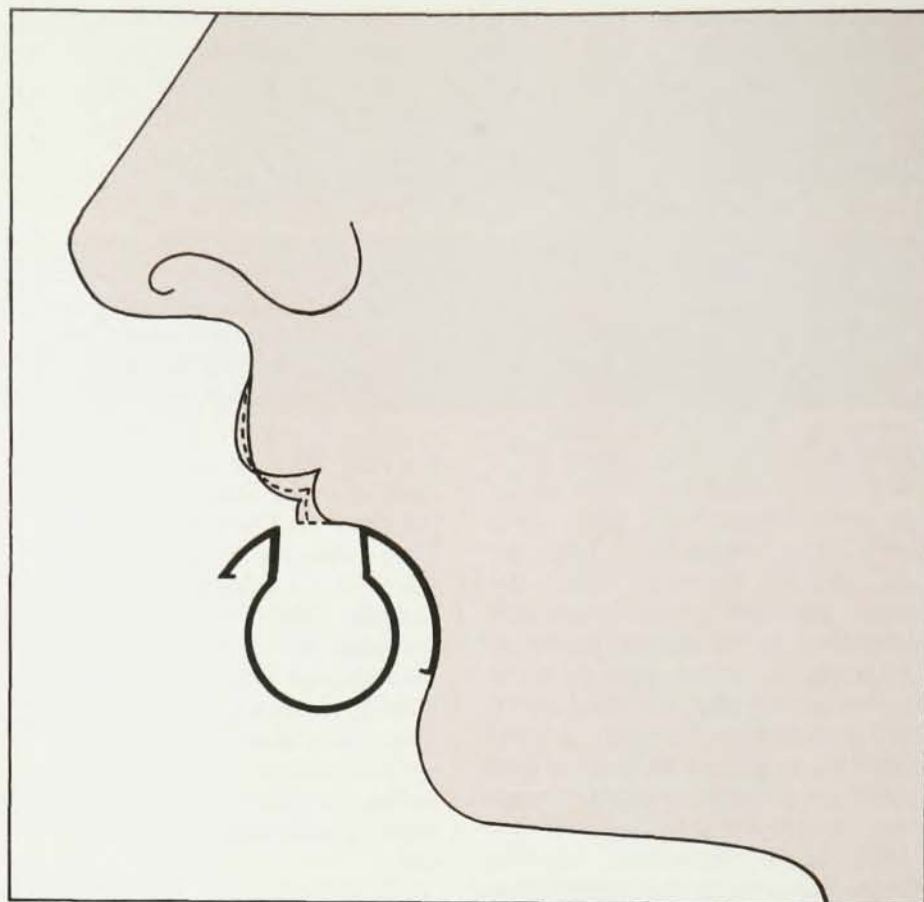
Alteration of the natural resonance

The resonance frequencies of the system when blown may differ from those measured in the enclosure because of changes in the amount by which the lips close off the mouth hole and alterations in the velocity of the sound in the tube. The performer's breath, which has a different composition and temperature from the air in the flute measured cold, causes the velocity change. Surprisingly the carbon-dioxide content of the breath (about 2.5%) is significant, reducing the velocity of sound by an amount that flattens the notes by about 12 cents. The temperature in the flute varies from about 26.5°C at the upper end to 25.8°C at the lower end, when played in an ambient temperature of 21°C. With these values, and including the effect of water-vapor content, we can calculate the sharpening effect to be from 17 to 19.5 cents.

The remaining discrepancy between resonance and sounding frequencies can be wholly accounted for by the variation in mouth-hole coverage by the performer's lips. Photographs, from which the sketches of figure 4 were made, show that the lips are progressively pushed forward as the scale is ascended, and the concomitant increase in inductance of the mouth hole accounts for the remaining



RESONANCE FREQUENCIES of the flute shown as deviations from the equal-tempered scale. In black is the passive resonance frequency obtained by driving the cold instrument by an oscillator and loudspeaker. Colored line shows frequencies produced by blowing, with noticeable reduction in the deviation. —FIG. 3



LIP POSITIONS at the mouth hole. This sketch shows the change in lip-to-edge distance for C_1 (withdrawn) through E_5 to C_6 (advanced). —FIG. 4

frequency difference. As a final overall check the flute was arranged in its enclosure so that the passive resonance frequency could be measured with the lips in position and so soon after playing a given note that the air temperature and composition had little time to shift. The frequency differences found were only a few cents, both positive and negative, and do not follow any particular trend.

The mean of the set is about +2 cents, and we conclude that in normal playing the sounding frequency is very close to the actual resonance frequency of the system. We see also that the purpose of the taper in the head joint is to counteract the effect of the pushing forward of the lips.

It is surprising that the sounding frequency is so close to the resonance frequency, as it is well known that in

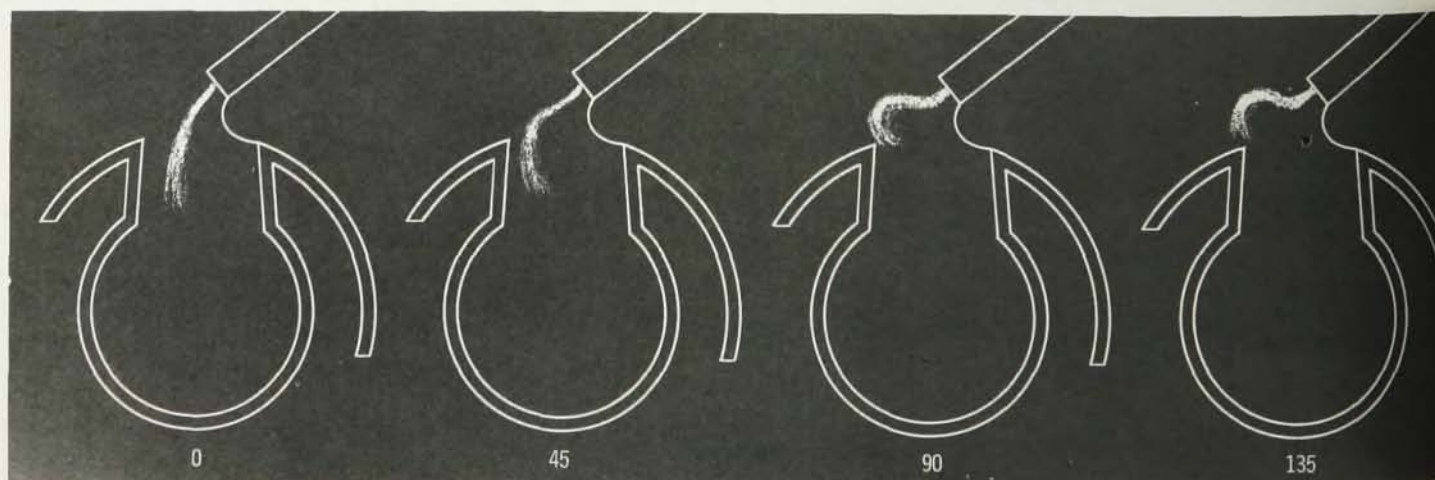
flutelike instruments with fixed whistle mouthpieces large frequency variations arise from changes in blowing pressure. The variation in lip-to-edge distance turns out to be important for preventing these frequency shifts; it is also the chief means by which the flutist controls the mode, or octave, in which the flute will sound.

Acoustic losses and radiation

Before discussing the sounding mechanism we will look briefly at an important property of the resonant system, the energy loss. The energy in the oscillating system may be dissipated by several mechanisms, of which the most important are viscous and thermal losses at the tube walls. The viscous losses occur in the boundary layer, where the particle velocity drops from that of the air column to zero at the wall.

Thermal losses occur here also, and are caused by the temperature drop across the boundary layer as heat is conducted to and from the walls on compression and expansion of the air. The thermal and viscous effects are very closely related and may be expressed by a single formula in which an effective viscosity accounts for both frictional and thermal losses.⁶ For smooth tube walls the losses are independent of the tube material. For a given acoustic current the loss in a halfwave resonant column varies inversely as the cube of the diameter and inversely as the square root of the frequency.

A loss mechanism that may be almost as important is the resistance associated with the end apertures. Here turbulence gives rise to nonlinear losses for which, as the acoustic current is increased, the power losses go

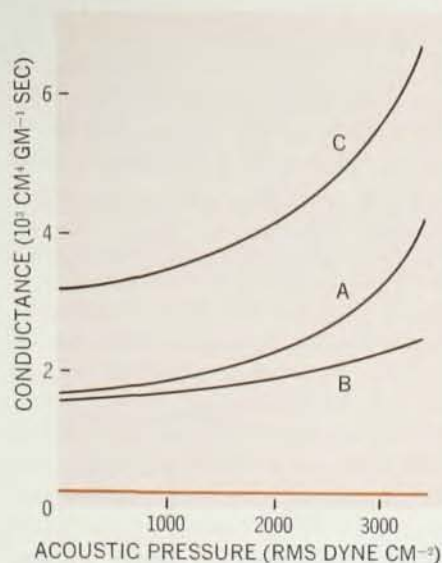


SMOKE-LADEN JET viewed stroboscopically, for frequency 437 Hz, blowing pressure 0.5 in. water, acoustic current $130 \text{ cm}^3/\text{s}$

up more rapidly than the square of the current.⁷ In the flute these losses are most serious at the mouth hole, where the particle velocity is high. At normal playing amplitudes this loss can be quite large.* Figure 5 shows the conductance of a flute as a function of the oscillation pressure, measured at the velocity node. The data represent the conductance of the two halves of a flute on either side of the velocity node; curve A looking up the tube toward the mouth hole, and curve B looking down the tube toward the keys. The total conductance, curve C, is the sum of these two. The total power dissipated at any point on the curve can be calculated by multiplying this conductance by the square of the acoustic pressure at the node.

If the resistances were linear, the curves would be constant, that is, straight lines parallel to the pressure axis. The small-signal values where the curves intercept the zero-pressure axis represent the viscous and thermal losses. As the oscillation strength increases the additional nonlinear effects come into play. The loss factor at nominal playing pressure (about 2200 dynes/cm² for the G of figure 5) is half as large again as for small signals, and most of this nonlinearity occurs in the head joint. This is one of the nonlinear processes that brings the flute oscillator to a steady-state amplitude.

The smallest dissipation mechanism is, disappointingly, the radiation of acoustic power as sound. The radiation resistance of a small source is a function only of the frequency. The flute under most circumstances has two radiation sources—the open end and the mouth hole. Some interference occurs between these two but



ACOUSTIC LOSS FACTOR (expressed as a conductance) as a function of the oscillation pressure, looking up from the velocity node (a) and down (b). Curve C is the sum of these two. Colored line shows radiation losses. —FIG. 5

the effects are not large at low frequencies; for our purposes we may simply sum the power lost from each. The radiation losses at 440 Hz, again expressed as a conductance, are plotted as the colored line in figure 5. From these values we find that the ratio of acoustic power radiated to total acoustic power dissipated, the resonator efficiency, is about 3.5% at 440 Hz. Insufficient measurements have been made to obtain the resonator efficiency at other frequencies, but if we ignore the nonlinear effects a comparison of radiation and boundary-layer losses indicates that the resonator efficiency should rise as the 5/2 power of the frequency, as the cube of the tube diameter, and should be inversely pro-

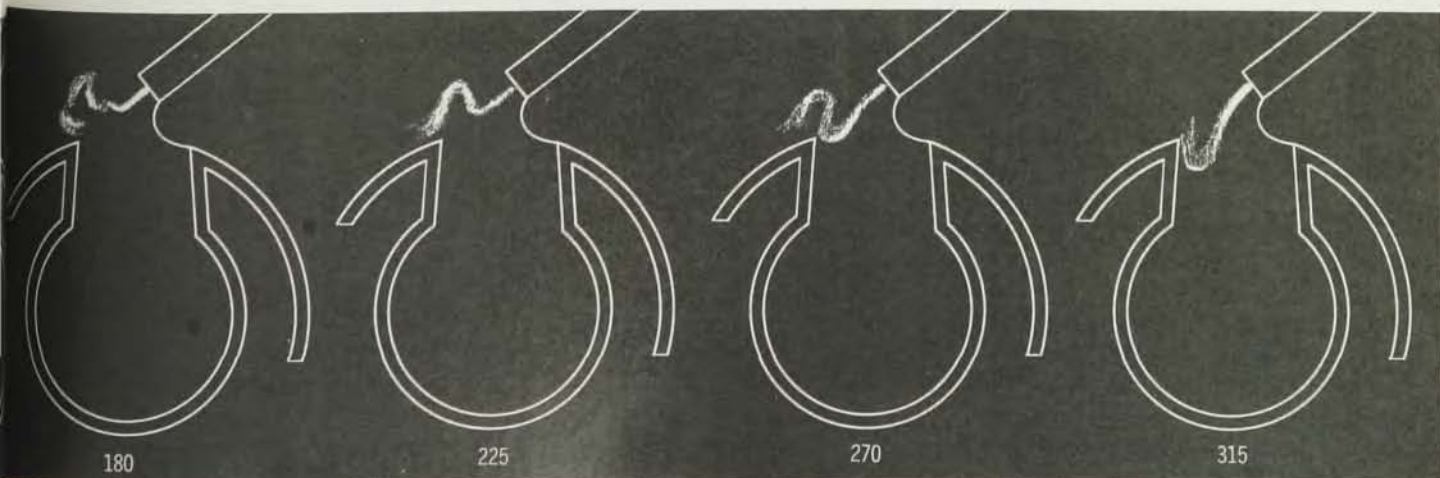
portional to the number of quarter wavelengths.

The blowing mechanism

The mechanism by which the oscillations are maintained has been the subject of a certain amount of confusion and disagreement. Stroboscopic pictures obtained by B. Z. Carrière,⁹ who injected steam into the air jet of a very large organ pipe, provide a general picture of what is going on. Carrière showed directly that the jet stream was directed into the tube during most of one half cycle and out of the tube during the other half. The jet is not deflected like a reed but takes up a sinuous motion of growing amplitude that leads eventually to a set of beautifully formed spirals or vortices. These waves, which may arise as a result of instabilities in the jet independent of the presence of a splitting edge or acoustic feedback, have received a great deal of attention in the literature of fluid mechanics.^{10,11} In the flute the mouthhole edge interrupts the stream before vortices are well formed.

I have carried out similar experiments to observe these effects in dimensions more typical of the flute at known values of amplitude and phase. With an artificial lip on the flute head I injected cigarette smoke into the center of the jet stream. Sketches made from observation with a synchronized strobe light are shown in figure 6. Blowing-volume rate and pressure, and the oscillation amplitude while these sketches were made, were typical of the flute sounding A440 *mezzoforte*.

Be careful when interpreting these pictures: They are simply "snapshots" of the position of smoke parti-



sec, and particle amplitude 0.14 cm. Maximal current leaves hole for phase angle 90 deg (third picture).

—FIG. 6

cles at a given instant. We should not infer that individual smoke particles follow a path that looks like these traces, nor that the air that does not contain smoke is motionless.

The pictures obtained here exhibit the same features as those given by G. Burniston Brown.¹¹ They show an amplitude of lateral motion far

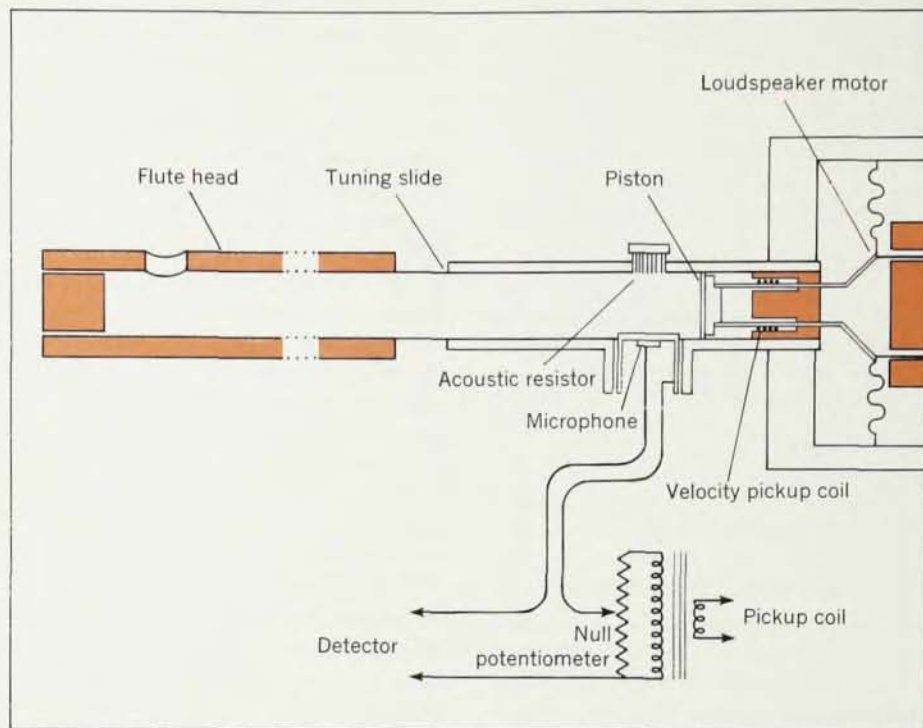
greater than the amplitude of the exciting sound-particle motion at the jet, and a velocity of propagation of the disturbance that is less than half the velocity of the issuing stream. A jet can propagate a disturbance with reduced velocity and rapid amplification because of action at the boundary layer between the moving

and still air. Simplistically a slight deviation of the boundary from a straight line results in a tendency for it to be "rolled" between the moving and still layers, so that the deviation grows in size and simultaneously progresses forward at about half the velocity of the jet. Brown¹¹ and H. Sato¹⁰ offer a fuller description and discussion of this rather complex set of phenomena. For our purposes it will suffice to point out that the action important to sound generation in the flute takes place under conditions of strong excitation of the jet and short travel distances, so that only the very early stages of vortex formation are involved. Thus, many of the intricacies and subtleties of the larger subject of jet instability do not bear on our case.

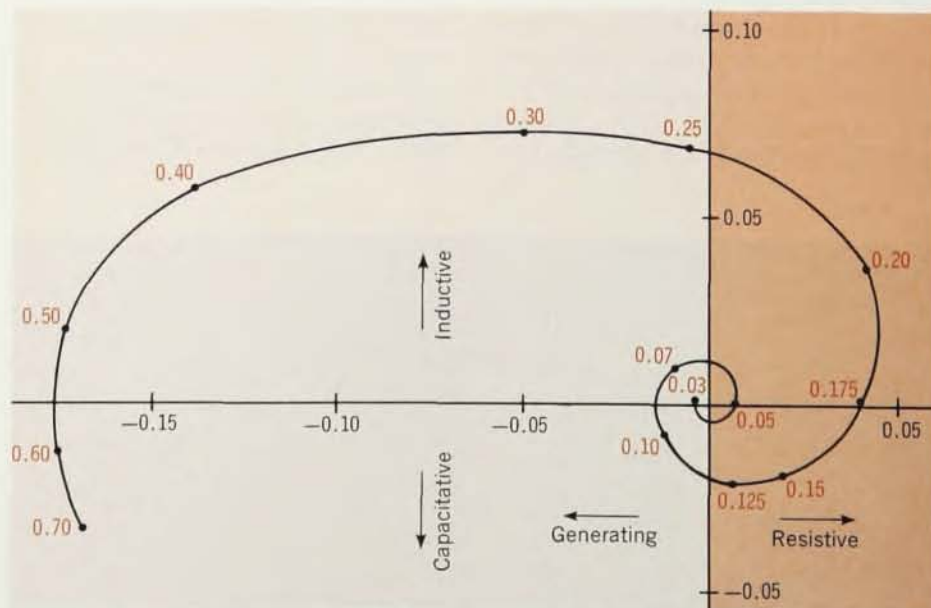
Measurement of impedance

The apparatus shown in figure 7 examines in detail the manner in which this oscillating jet interacts with the acoustic wave. A cylindrical flute head with its sliding tuning joint mounted on a short length of pipe represents the upper half of a flute resonating in a quarter-wave mode. At the position of the velocity node a massive piston, sealed with a thin rubber membrane, terminates the tube. The piston is driven at the desired frequency by a loudspeaker motor, and a pickup coil enclosed in a small magnetic yoke provides a measure of the piston velocity. Near the closed end is a low compliance microphone. Opposite this is a variable acoustic resistance consisting of a bundle of very small glass capillaries that could be closed off with a rubber pad. The microphone gives a measure of the oscillation pressure, and it could also be connected, as shown, to a null circuit to measure the ratio of acoustic pressure to acoustic current. Thus the real part of the impedance looking up the tube can be read from the potentiometer. This impedance can always be made real, either by shifting the frequency or changing the tube length at the tuning slide. Adjustment of the acoustic resistor ensures that the tube is too lossy to go into self-oscillation when the jet of air is blown across the mouth hole.

By comparing tube lengths and potentiometer readings for null output with and without the blowing jet, and with the usual transmission line equations,¹⁰ the effective impedance of



ACOUSTIC IMPEDANCE MEASUREMENT. Piston and loudspeaker motor drives the flute at the position of the velocity node; low-compliance microphone near the closed end measures oscillation pressure or (when connected as shown through null detector) ratio of acoustic pressure to acoustic current. Acoustic resistor is adjusted to make tube too lossy for self-oscillation. —FIG. 7



COMPLEX ACOUSTIC IMPEDANCE of the jet as seen from inside the tube at the mouth hole. Colored numbers show blowing pressure (in. water), and the dark colored areas represents resistive (lossy) condition. Parameters are: acoustic current, $28 \text{ cm}^3 \text{ sec}^{-1} \text{ rms}$; frequency, 440 Hz; jet area, 0.072 cm^2 . —FIG. 8

the jet as seen from the acoustic circuit at the plane of the mouth hole can be measured. In view of the nonlinear nature of many of the effects, the word "impedance" is used here in a restricted sense, as its value is not independent of the acoustic current. At any given oscillation level, however, it has a specific value, which when multiplied by the known acoustic current at the plane of the mouth hole will give the induced back pressure.

This jet impedance was experimentally determined for a large variety of operating conditions. An effective way to present the results is to show a trace of the jet impedance in the complex plane as the blowing pressure is varied, holding the blowing geometry and the oscillation level constant. Such a trace is shown in figure 8. The coordinates are impedance values relative to the characteristic impedance of the cylindrical tube. A positive real value (resistance) represents energy loss, a positive imaginary value an increased inductance, a negative real value an energy gen-

erator, and a negative imaginary value a capacitance. Each point on the curve represents the effective impedance of the jet itself for the blowing pressure indicated.

Variation of impedance with pressure

The impedance ascribable to the jet is a smooth, well behaved function of blowing pressure over the entire range. Its magnitude decreases monotonically as the pressure is reduced, and its phase, which is determined by the arrival time of a disturbance on the jet, rotates clockwise over more than two complete cycles. Starting at the outer edge where the blowing pressure is about 0.56 inches of water, we see the impedance is real and negative; such a condition would overcome the losses in the tube if the artificial resistance were removed, and would result in oscillation at large amplitude at the natural resonant frequency of the tube. At a higher blowing pressure the impedance has a capacitive component that will make the frequency sharp. At lower blowing pressure (0.3 inch), the inductive

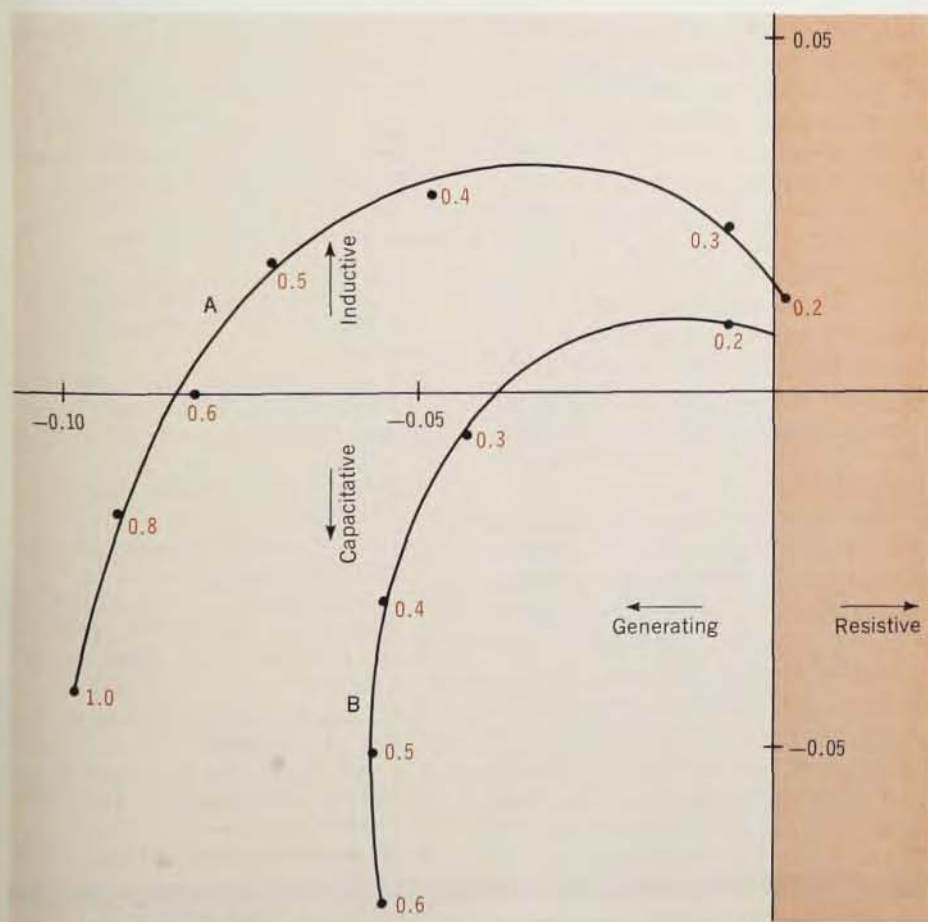
effect makes it go flat, and the real component is less negative, that is, it could not generate so much power. At a pressure of about 0.25 inch the phase crosses into the positive real domain—the jet now represents a loss mechanism and could not possibly sound the flute.

Though the jet impedance varies smoothly with blowing pressure, spiralling around the origin while its magnitude decreases monotonically, it represents a possible sound-generating mechanism only when it lies in the negative half plane. These pressure regions are the distinct oscillating regimes mentioned by many authors; they represent, for each successive turn of the spiral, one additional sinusoidal wave on the jet between the point of issuance from the lip and the splitting edge. Only the outermost portion of the spiral, representing one half wave in this distance, is used in playing the flute.

An examination of the rate of rotation of the impedance vector around the origin reveals that the propagation velocity of a wave on the jet is about 0.4 times the initial air velocity. I have obtained similar values¹² from stroboscopic ciné films of a smoke-laden jet in an oscillating field in agreement with those measured by Brown¹¹ and calculated by Sato.¹⁰

For oscillation the jet impedance must have a negative real component as least as large as the real (loss) component of the tube impedance, which is determined by the losses discussed earlier. The phase of the jet impedance is thus of great importance to the strength of the oscillation, as well as to the resultant frequency. This phase is determined by travel time, that is, not only by the jet velocity, but also by the lip-to-edge distance. Figure 9 shows two spirals like that of figure 8. Curve A was obtained with a 7-mm lip-to-edge distance; curve B, with 5 mm. The major effect of changing this spacing is to rotate the spiral in the plane. The two conditions are very different from the standpoint of the flutist. With a 7-mm spacing (curve A) he could achieve a large power input, and no frequency pulling, with a blowing pressure of 0.6 inch of water. With a 5-mm spacing (curve B) the same blowing pressure would produce less than half the power and would raise the pitch of the sound almost half a semitone.

The importance of phase is even



ACOUSTIC IMPEDANCE of the jet for two lip-to-edge distances: 7 mm (curve A) and 5 mm (curve B). Colored numbers show blowing pressure (in. water) and the other parameters are as defined for the previous figure except for acoustic current at the mouth hole, which is here $74 \text{ cm}^3 \text{ sec}^{-1} \text{ rms}$. —FIG. 9

more apparent when such curves are plotted for successive modes of the resonant pipe. Proper lip spacing for the lowest frequency throws the curve for the next higher frequency mode almost entirely into the nongenerating half-plane. For a shorter lip spacing the upper frequency shows favorable phases, while the impedance for the lower one lies in the lossy half-plane. Thus it is through variation of the travel time of a jet wave across the mouth hole that the flutist exercises his choice of the mode that will sound. The development of this technique, perhaps the most difficult task for the aspiring flutist, apparently consists of achieving mastery of that combination of lip distance and air velocity that will assure a jet-wave travel time of about half a cycle at the desired frequency.

Magnitude of the driving pressure

Multiplication of the measured jet impedance by the known acoustic current at the plane of the mouth hole gives the oscillating acoustic pressure generated by the jet. Experimentally we find this acoustic pressure, which is the driving force maintaining the oscillation of the resonant circuit, to be roughly proportional to the blowing pressure. It is of interest to see if we can account theoretically for the magnitudes found, as these values, together with the losses and the radiation efficiency previously discussed, determine the power of the sound that the instrument produces.

A steadily blowing stream of air exerts a thrust, or force, given by the mass flow times the stream velocity. From Bernoulli's law relating velocity, pressure and density, we find this force to be $2Ps$, where P is the blowing pressure and s the area of the aperture from which the stream is issuing. If such a stream blows into the open end of a long can of cross sectional area S the air stream will be slowed to zero velocity, and the reaction force will develop in the can a pressure approximately equal to $2Ps/S$.

We may look at the situation in the flute as very similar, except that the stream flows into the chamber only during one half of the cycle, and we are interested in the alternating component of this chopped force. We are somewhat at a loss, however, to decide what area to divide the force by to get the pressure. If the jet stream enters the narrow mouth hole

and proceeds well into the flute tube before stopping, we should use the area of the flute tube. If it is slowed greatly while traversing the mouth hole length, we should use the mouth hole area. Experiments¹² on the static pressure built up by a jet blowing into a can with constricted necks of varying lengths show that considerable interaction does take place right at the entrance aperture. We may expect then that the oscillating acoustic pressure will be somewhat larger than $P s/S_T$ where S_T is the tube area, but less than $P s/S_H$, where S_H is the mouth-hole area. Plots of more than 40 measurements, taken under a wide variety of conditions, do indeed give values lying between these limits. We see from the above relation that the flutist, although compelled to adjust the blowing pressure P to fit the phase condition, has at his disposal an independent parameter, the lip aperture area s , with which he can control sound power.

Efficiency of sound production

The process of exerting a force on a moving object, the vibrating air column, with a much quicker air stream that must slow down and mingle with it, is necessarily inefficient. Mathematically we calculate a generating efficiency, defined as oscillating power developed divided by breath power expended, about equal to the ratio of the acoustic particle velocity to the jet-stream velocity. In practice this turns out to be quite low, about 2.4% when sounding A440. This efficiency must be multiplied by the circuit efficiency (the ratio of radiation loss to total loss) to obtain the overall sound-generation efficiency. Thus we find for A440 an overall efficiency of 8×10^{-4} .

The situation is quite different as we go to higher frequencies. Consideration of the mathematical expressions for viscous loss, radiation resistance, acoustic pressure generated and change of blowing pressure with frequency⁴ tells us that the radiated power should rise as the fifth power of the frequency if the lip-aperture area were kept constant and the tube length continually shortened. Neither of these last two conditions are, of course, met over the entire range of the instrument.

Higher and louder

Studies over a much wider range of conditions would fill in the picture of

flute behavior. Nevertheless the few that have been made give us a good understanding of the fundamentals. We see that the blowing mechanism can force the flute flat or sharp compared to resonance, depending on the arrival phase of the amplified jet disturbance. The performer can, however, stay near resonance and at the same time keep required pressure changes at a minimum by shortening the lip-to-edge distance as frequency is increased. In general, a proper phase of arrival for a desired note automatically excludes the possibility of oscillation in an undesired mode.

The blowing pressure the flutist must use is set by the phase condition and must rise with frequency. The acoustic power generated also rises with pressure, but it can be independently modified by varying the area of the lip aperture.

The generating efficiency is low because the fast moving jet colliding with the slowly moving vibrating air passes on its momentum but dissipates most of its energy. The radiation resistance is low compared to the viscous resistance, but rises rapidly with frequency; because pressure also goes up, the sound power level mounts very rapidly with frequency.

And that is why, as the band crescendos into the grand finale, the flute player abandons his instrument and pulls out of his pocket a piccolo.

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