Illinois Academy of Science Transactions, Vol. 49, 1956

ACOUSTIC PROBLEMS OF THE FLUTE

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The purpose of this paper is twofold: 1) to describe a physical problem which, though apparently simple and straightforward, has not been entirely solved after extensive investigation; and 2) to describe some of the phenomena observed and some methods used to study them. It has more than purely academic interest, since such methods are useful in many other kinds of work.

Historical Background

Musical instruments of the flute family (including the syrinx or pan-pipe, the Egyptian nay, etc.) are at least as old as our written history; instruments are extant which have been dated as early as 2700 B. C. Many of these were sounded with a reed mouthpiece and some with an embouchure hole in the side, as in the modern flute, or in the end, as in the nay or the shepherd's pipe.

The modern cylindrical flute is almost unique among orchestral instruments in that it is the direct outcome of an intensive investigation begun by Theobald Boehm a century and a quarter ago. He hoped to design an instrument which would be perfect acoustically, making no compromise with the necessities of mechanism. In a detailed study of the construction and characteristics of the instrument, he made and tested more than 300 flutes. His success may be judged from the fact that the Boehm flute of today is dimensionally practically identical with the specifications he set up a century ago, and, as C. Max Champion says (Grove, 1954: 176), "It is not likely that the flute can be further improved, and it remains today a monument to its designer."

Formation of the Musical Tone

In most wind instruments, the source of sound is a mechanical reed, composed of thin, flexible strips of cane or the lips of the player. The principal function of the tube is that of a resonator, strongly reenforcing certain components of the comparatively random sound produced by the reed and thus causing the instrument to sound a tone of a single predominant frequency.

The flute employs no mechanical reed. Instead, a thin jet of air at a high velocity is directed at the edge of the embouchure hole, producing pulses or disturbances having random frequencies over a considerable range. The tube of the flute, with its length adjusted by the opening of certain holes, resonates at and strongly reenforces the desired tone. Through "embouchure adjustment", or the control of size, velocity and direction of the jet of air, the player produces the fundamental (the lowest octave) or the second, third, or even fourth harmonic frequency.

The flue-type organ pipe is customarily used for demonstration of this phenomenon. The textbook descriptions usually point out that: 1) for an open pipe, the wave-length of the note produced is equal to twice the length of the pipe; 2) for a closed pipe, the wave-length is four times the length of the pipe; 3) all tones produced by either open or closed pipe are harmonically related; and 4) that there is always an anti-node or loop at the open end and at the mouth, and one or more nodes distributed at equal intervals along the pipe. This is, however, only an approximation of the behavior of an actual pipe—for many pipes a very rough approximation.

So early a worker as Savart (1823) located the nodes in a speaking organ-pipe by lowering within it a tambourine sprinkled with sand, demonstrating that they were not symmetrically placed with reference to the ends of the tube, and that there was an end-effect (perhaps better described as a diameter-effect). Later workers, including Helmholtz (1885) and Rayleigh (Strutt, 1896) described these phenomena in some detail, giving correction-values of 0.6 times the radius for a straight tube, and 0.82 R for a flanged tube. Most of the early workers considered that the end-effect did not depend upon frequency, but more precise experiments by later workers tend to disprove this.

Organ-builders, in general, seem to hold somewhat different opinions on the subject than physicists or mathematicians. Cavaille-Coll (1860), for example, employed a factor of 1.66 instead of 0.6, and Smith (1911) recommended a factor of 1.0 for some pipes and 2.0 for others. These factors, however, contain an allowance for the partially open upper end of the pipe. The criterion of the organ-builder is "this is the way it sounds best," and this criterion justifiably takes precedence over academic arguments.

The phenomenon of "speaking" causes, in some manner not entirely explained, a further change in the effective length of the tube; that is, the resonant frequency of a blown pipe or flute is not the same as its resonant frequency when excited by an outside source. However, there are several features about the actual initiation of the acoustic vibration that cannot be easily explained, and it is perhaps understandable that many modern textbooks describe the phenomenon in the same manner as did the earliest writers on the subject. Schlesinger (1939) discussed this in considerable detail. There is much evidence disclosing the incompleteness, at best, of this theory, but alternate theories, though better, are still somewhat unsatisfactory.

A demonstration can be made with an organ pipe, made of wood, 34 mm. square in cross-section, and 500 mm. long from the languid or block to the open end. Before correction, it is, therefore, one-half wave long for a 344 cps. tone; if an end-correction of 15 mm. is added, the pitch should be lowered. It actually does sound the F♯ below middle C, or 312 cps. If the mouth of the pipe is closed, and it is excited by an external source, it resonates at 339 or 340 cps.—not too far, perhaps, from the theoretical value.

The shape and approximate dimensions of a modern Boehm flute and of the "English flute" of a

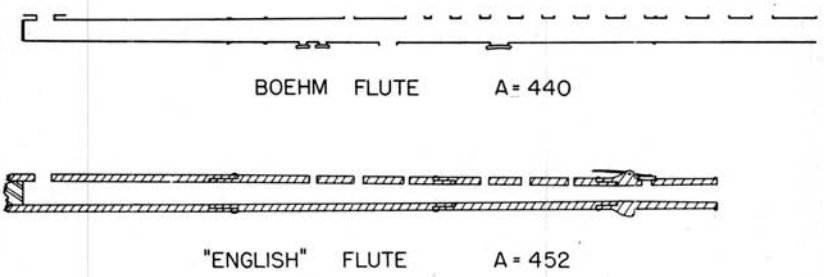

FIG. 1.—Cross-section of modern Boehm flute and of the "English flute." (One-fifth natural size; drawn to scale except for thickness of tube of Boehm metal flute, which is 0.020 inch.)

century ago are shown in Figure 1 which contains cross-sectional drawings, to scale, of these instruments. The inside diameter of the Boehm flute is 19 mm. at the open end, and it is cylindrical for approximately 450 mm. from the open end, tapering in a parabolic curve from this point to a diameter of 17 mm. at the stopper. The drawing shows all the holes, with the three normally-closed ones stopped off with pads. The two nearest the open end are open at all times except for playing the low C and C♯.

The lowest tone this flute sounds is "middle C," or C_4, at 261.6 cps., with all holes closed. Using the commonly-accepted end-correction factor of 0.6 R, the effective tube-length is increased to approximately 625 mm. One-half wave-length is 659 mm., and the standing-wave pattern may be drawn as at Figure 2 A. The tube appears to be "short at the embouchure end" by 34 mm.

The D_5, an octave higher, with a frequency of 587.3 cps. and a wave-length of 587 mm., is sounded with the first hole and the last two holes open, all others closed. Opening the first hole prohibits the formation of a node at that location along the tube (as shown in Fig. 2 A), and the wave-pattern might be drawn as in Figure 2 B, using the 34 mm. value just established as an "embouchure end allowance."

This is not quite as satisfying as the pattern in Figure 2 A, but it is acceptable. But the note D_6, another octave higher, which is fingered by closing the second, third, and fourth holes, must be represented as in Figure 2 C, and a satisfactory physical explanation of this pattern is not at all obvious.

The parabolic taper in the head-joint of the Boehm flute has long been a subject of discussion and dispute; its importance seems quite certain, but the reasons for that importance are obscure. The position of the stopper enters into the picture in a more easily rationalized manner. Normally the stopper is placed a distance from the embouchure hole equal to the diameter of the tube at that point, but its exact location is established by the intonation of the upper register of the instrument. Stopper position has little effect on the tuning of D_4, easily observable effect on D_5, and pronounced effect on D_6. From these and other data it is apparent that the tones in the

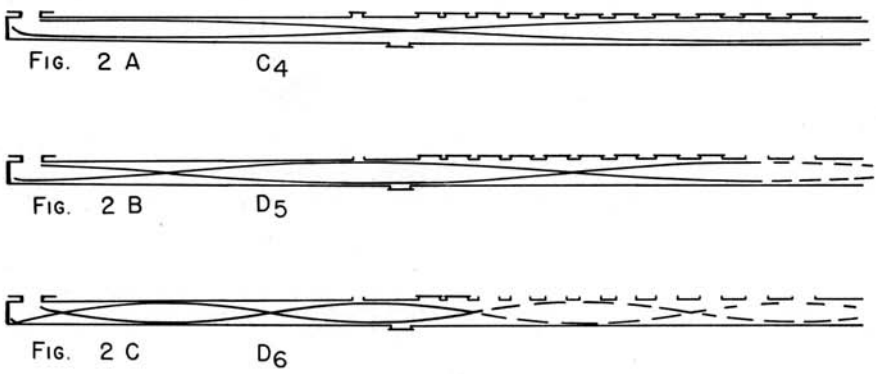

FIG. 2.—Standing-wave patterns within the Boehm flute for the tones C_4, D_5 and D_6.

lower register are governed principally by the lower part of the tube, and those in the upper register by the head-joint, the stopper position, and the embouchure.

There is no question that the player exercises very great influence over the formation of tones through embouchure adjustment or that, for the practised player, this adjustment is made without conscious effort. Accurate description of these adjustments is difficult, and the technique is correspondingly difficult for the student to learn. One of the reasons for beginning the present work was the hope of devising some useful techniques for teaching the flute.

MEASUREMENT WITHIN THE FLUTE

In physical science, it is almost invariably the case that the act of making the measurement, or of applying the measuring instrument, will so disturb the conditions as to impair the investigation. This is especially true of the study of the flute; nearly any procedure that may be tried will change the operating conditions considerably.

To study the formation of the acoustic vibration, a simple flute was constructed of glass; it possessed only two holes, the embouchure hole and a single hole for fingering. The method of Kundt (1866) was first employed, using lycopodium powder, but even this light material seriously damped the vibration. Smoke and stroboscopic illumination were little more useful. The experimental difficulties in setting up a Schlieren system for this study are considerable, but some work has been successfully begun on this project, and it is to be continued.

Electric resistance strain gauges, mounted on the metal body of the flute, disturbed the mechanical vibrations appreciably, as indicated by perceptible changes of timbre of certain tones. The actual strains produced are small, although the internal pressures are high enough to be surprising to a person who has not played the flute and observed the often pronounced vibration of the flute tube and the closed keys.

Toepler and Boltzman (1870) measured pressure differences of the order of magnitude of three pounds per square inch in a sounding organ pipe, and it seems probable that corresponding pressures exist in the flute.

In a first attempt to survey the standing-wave pattern within the bore of the instrument, a probe less than one-tenth inch in diameter and carrying a pressure-sensitive pick-up (later, a velocity-sensitive element) was inserted from the open end. Excellent records were obtained, but the data were of negligible value, since the presence of the probe greatly affected both pitch and tone quality of the instrument. This was not unexpected, since this is an old method of changing the pitch of an instrument and is known to be unsatisfactory in many respects. The hot-wire anemometer element, responding to velocity alone and capable of extremely high sensitivity, can be so mounted as to cause little error from volume displacement; but, because it dissipates an appreciable quantity of heat while in operation, it introduces a new group of disturbing factors.

A desirable method would be to attach a large number of pressure pick-ups at intervals along the tube (attaching small-bore tubes through the side of the flute body for this purpose) so arranged that their presence would not appreciably disturb the characteristics of the instrument. The procedure seems quite feasible though expensive.

The quality and fit of pads is extremely important with regard to ease of playing, particularly in the lower register. Poorly fitting, leaky, porous or spongy pads all introduce difficulty. A demonstration of the effect of such leaks was arranged by carefully corking all the holes in an easy-playing flute, then opening a very small aperture in the first hole. It was shown that if this hole was covered with a 1/32-inch thick plastic cap, perforating this cap with a hole 0.020 inch in diameter completely destroyed the low D_4 of the instrument, sounding the octave, D_5, instead. Leaks in other locations produce corresponding adverse effects.

External Acoustics of the Flute

It is relatively easy to measure frequencies, amplitudes and phase differences in the area near but outside the instrument, although the presence of external reflecting objects, and the interference of the multiple sources of sound of the flute, are occasionally confusing. These are simple problems, however, compared to those connected with measurements within the instrument.

As a source of orchestral sound, the flute presents some practically unique characteristics. Brass instruments emit their sound almost entirely from the bell, the other woodwinds partially from the bell and partially from open holes near the bell. For most tones, the flute presents two separated sources—the embouchure, from which more than half the energy is radiated, and the open holes near the end of the flute, from which most of the remainder is radiated. Octave or speaker holes emit little sound compared to the others.

This fact makes possible an interference phenomenon which can seriously affect the tone of the flute, so

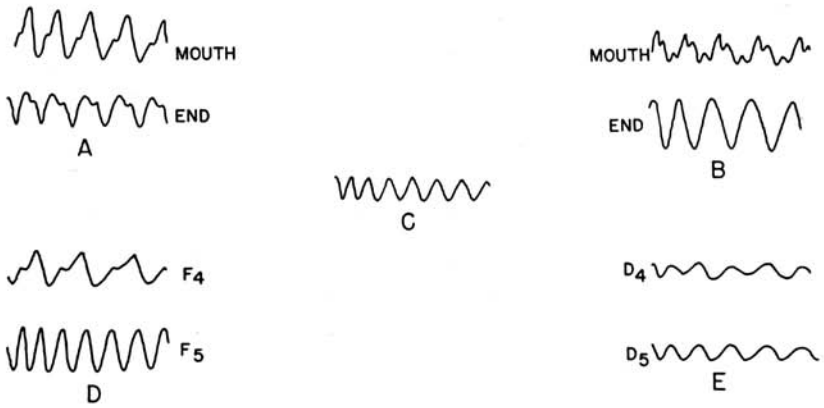

FIG. 3.—Oscillographic wave-forms: *A*, organ pipe, mouth and open end; *B*, recorder, mouth and open end; *C*, "English flute" of Figure 1, fundamental tone; *D*, Boehm flute, sounding F_4 and F_5; and *E*, Boehm flute, sounding D_4 and D_5.

far as the listener is concerned. The two sources of sound are separated from each other by a distance comparable to the half wave-length of many of the vibrational components present; thus, if the angle between flute and listener should be such as to make two of these components interfere destructively, a distorted tone would be heard. In fact this seldom happens, because the harmonic content of the upper register, where such interferences might most easily occur, is usually low. This behavior is illustrated by the case of the flue-type organ pipe, which emits quite different wave-forms at mouth and at open end (Fig. 3 A). When the pipe is set vertically, at a reasonable distance, these combine to produce a respectable sine-wave. In the recorder, the ancestor of the flute with a whistle mouthpiece, the composition of the two wave-forms is such that, even when combined, many harmonics are present. (Fig. 3 B).

No doubt since the first metal flute was made, there have been disputes as to which is better, metal or wood. It seems proper to say that they are different, but equally good; they will give equivalent performances in competent hands. As to tone, the Boehm flute excels, if its whole range is concerned; yet the older instruments, properly played, were often extremely good. In Figure 3 C is shown the wave-form of a note from the "English flute" of Figure 1, which may be compared to Figure 3 D, representing the F_4 and the F_5 of the Boehm flute of Figure 1. The lower note has a rather high harmonic content, predominantly first and second harmonics; the higher note has a much lower harmonic content. These wave-forms may be compared to the frequency spectra presented by Olson (1952) for the corresponding G.

Of the many other available illustrations of characteristic acoustic behavior of the flute, only one, of particular interest, will be given (Fig. 3 E). Two notes, the low D_4 and the D_5 an octave above it, were sounded; the difference in fingering is only

that the first hole is opened, prohibiting the existence of an antinode in the center of the tube. The two wave-forms look surprisingly alike, yet the tones sound entirely different. The explanation is that in the lower note there is a large component of second, third, and even fourth harmonics, producing difference frequencies between each other and between each component and the fundamental. Thus, a large part of the sound heard by the ear is actually beat tones having the same frequency as the fundamental. The magnitudes and phase relations for a satisfactory combination are somewhat critical, so that it is not surprising that good performance in the lower register of the flute demands both a good instrument and good playing.

As an illustration of what can happen when such a beat tone is produced, the organ pipe previously described can be made to sound its fundamental (with the end closed) and a note approximately an octave higher, but not harmonically related. Under the proper pressure, both notes are clearly heard simultaneously, and with them a strong beat at six or eight cycles per second. The condition is unstable, but definite. As with most beat-notes, the principal effect is subjective, but it can be shown on an oscillograph record.

Conditions for best performance of a flute are rather critical. Roughness in the bore or the holes, soft or leaky pads, or even a thick layer of dust, can produce an observable effect. The external acoustic pattern is readily distorted by surrounding objects, and internal disturbances are even more easily produced. Excepting for the lowest C♯ and C natural, for every note produced by the Boehm flute venting holes are open at all times, yet even minor obstructions in the open end impair the tone to some extent. The concept of acoustical impedance, widely used in the mathematical analysis of acoustic systems, often leads only to confusion when applied to certain instruments of the flute type.

Most of the design principles of flutes are empirical and, while they can usually be rationalized, they are not easily anticipated. Bulbous flutes, such as the aulos and the ocarina, tend to give purest tones, since they act like spherical volume resonators; flutes with a large length diameter ratio tend toward complex tones; flutes which depend entirely upon venting holes instead of an open lower end usually emphasize this tendency. Some flutes manage to break all the rules, as in the ancient Chinese and certain primitive flutes which employ a cylindrical bore and equally spaced holes of uniform size to produce accurate diatonic scales.

Summary

The paper has given a brief introduction to the historical background of the flute, described the generally accepted theory of vibrating air columns, and presented some data tending to correct some incomplete descriptive theory. Some acoustic data representative of modern instruments are presented. In addition to its general interest to the student of physics, the discussion may be of value to the student of music.

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