

PHYSICISTS and FIPPLE FLUTES at APL

Amateur chamber music groups are springing up throughout the land as a result of the twentieth century revival of the recorder, or English fipple flute. This wooden end-blown

instrument, used in the time of Johann Sebastian Bach and George Frederick Handel, has in its literature some of the greatest music of the ages. It is, at the same time, one of the

easiest instruments to learn to play, which perhaps accounts in part for its growing popularity.

Pictured in the accompanying illustration (Fig. 1) are members of the occasional-Friday-lunchtime chamber music group of the Applied Physics Laboratory. The APL Altkammermusikgesellschaft (the old chamber music society), or AKMG as it is familiarly known, has been functioning for about four years under the able and imaginative leadership of Martin Davidson.* There have been other recorder players at APL even before the formation of AKMG; for example, Dr. R. Herman, who published an article on recorders in the *American Journal of Physics*.¹ Only within the last four years, however, has recorder playing become an organized activity at the Laboratory. The recorder group that meets in Parsons Auditorium has been augmented from time to time by other musicians,

Dr. Samuel A. Elder, a physicist on the Rocket Tunnel Project staff of the Fluid Mechanics Group, is responsible for development of a new recording pyrometer, discussed in "Transistorized Pyrometer With and Without Feedback," *APL Technical Digest*, 2, May-June 1963, 17-18.

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¹ R. Herman, "Observations on the Acoustical Characteristics of the English Flute," *Am. J. Phys.*, 27, 1959, 22-29.



Fig. 1.—Members of the Altkammermusikgesellschaft enjoy a 17th century quartet by Frescobaldi in Parsons Auditorium. Left to right, they are: R. P. Rich, soprano recorder; A. H. Dell, bass recorder; the author, alto recorder; and M. Davidson, tenor recorder.



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including a summer bassoonist, a Baroque vocalist, and a chemist accompanist.† The latter has so far confined his art to the piano since the auditorium is not equipped with a harpsichord.

Actually, the brief Friday noon get-togethers represent only a small fraction of the musical activities of the AKMG members. Martin Davidson has been heavily involved in the work of the Washington Chapter of the American Recorder Society (ARS). Last year he undertook the task of publishing a complete directory of the approximately 200 players in the Washington area. He also teaches the recorder. A number of Washington ARS members are his former pupils.

Al Dell's home-workshop hobby, at the moment, is making recorders and wooden cross flutes (Fig. 2). His one-key flutes, made after the style of those used in Mozart's day, have been played by experts and declared to be of high quality. The one-key flute was historically the immediate successor to the Baroque recorder as a concert instrument. Composers of the Classical period that followed the age of Bach favored the cross flute over the recorder because of the



Fig. 2—A. H. Dell poses with reproductions of an 18th century cross flute and several 17th century recorders. Other "one-key" flutes made by Mr. Dell are on loan to area musicians.

† Respectively, D. Klausner, a summer assistant in the Research Center in 1961, Miss Kathryn Froelich, associate engineer, and Dr. E. J. Blau, senior chemist.

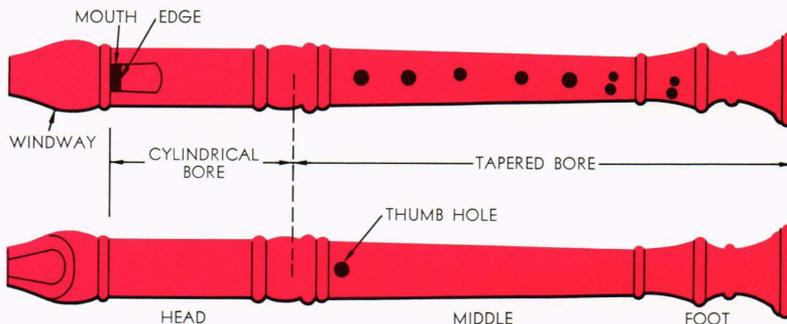


Fig. 3—Recorders are usually made in three parts, the upper, or head, portion being cylindrical in bore, and the mid and foot sections being tapered. Early recorders of the Renaissance period had straight cylindrical bores.

greater loudness and dynamic range of the former. This was the period in which the piano replaced the clavichord,² the violin family won out over the soft-toned viols,³ and the modern orchestra was born.

Dr. Robert Rich, director of the University Computing Center of The Johns Hopkins University and supervisor of APL's Computing Center, is another member of AKMG who has instrument-making as a hobby. He has invented a new chamber music instrument that he calls the *trecorda*. This is essentially a keyed version of the guitar, with a soft tone that blends well with recorders. In outward appearance it is easily mistaken for some obscure court instrument of the Renaissance period. As a matter of fact, the *trecorda* could have been invented in Shakespeare's time!

My own interest in the recorder is both musical and scientific. Two summers ago I played with a trio of strolling musicians at the Sylvan Theater production of "The Taming of the Shrew." In spite of my costume, I was recognized by a few of the APL personnel who were among some 70 thousand visitors taking advantage of the free Shakespeare performances.

During last year's vacation I visited the New England workshop of Friedrich von Huene, who is one of the foremost of modern recorder makers. When he learned that I am a physicist, Mr. von Huene said: "Good, I have a problem for you. Tell me what scaling laws one

should use in designing larger instruments." At the time, he was just beginning work on a Great Bass in F, the largest of the recorder family. This six-foot giant cannot be designed according to the same rules as can normal-sized recorders and still be playable by normal-sized people. The large, widely spread finger holes require an elaborate system of keys and pads to extend the capabilities of the human hand.

An even greater problem is the breath volume required. Human vital capacity, or total exhalable air volume, is about 4500 cc. A Great Bass designed according to the scaling laws of small instruments would demand some 500 cc/sec on its lowest note and as much as 1300 cc/sec in its upper range. Apart from the production of occasional *oom-pahs*, it would be relatively useless as a musical instrument. What Mr. von Huene wanted to know was how to make it loud and still playable. Although I did a little thinking about the problem through the winter, the real impetus to research came last spring. At that time Dr. Paul E. Clark, managing editor of the *Digest*, asked me to write an article on "recorder playing as a physicist's hobby;" I immediately began a survey of books and scientific papers related to the subject. Before long, I began to realize that the time was ripe for the first fundamental treatment of recorder acoustics. Only within the last decade has the basic knowledge become available to make such a task possible.

There is still much to be done, but since the beginning of the summer I have made enough progress to be able to present a technical paper at the

² C. Welch, *Six Lectures on the Recorder*, Oxford University Press, London, 1911, 128.

³ Carleen M. Hutchins, "The Physics of Violins," *Sci. American*, 207, Nov. 1962, 79-93.

November meeting of the Acoustical Society of America, in Ann Arbor, on the subject of recorder voicing. My wife Sylvia, an equally enthusiastic advocate of recorder playing and a former technical illustrator, did the ink drawings for my slides.

"Voicing" is the name given to the fine adjustments of mouth geometry and bore profile that make the difference between a good recorder and a bad one. It is, as the Englishman Carl Dolmetsch told me, "a subtle art." Mr. Dolmetsch, whom I met after one of his concerts in the U.S., is noted both as a virtuoso and as a maker of some of the finest available recorders. His father, Arnold Dolmetsch, is generally considered to be responsible for the renaissance of the recorder.

Figure 3 shows the profile of the alto recorder, an instrument about 42 cm long. Very-low-pressure air is blown through the narrow windway at the left, at a rate of about 100 to 200 cc/sec. This excites the hollow pipe at a resonant frequency determined by the pattern of open and closed finger holes in the mid-section. Recorders are usually made in three sections, of which the upper, head portion is cylindrical in bore, while the mid and foot sections are tapered. The acoustic function of the taper seems to be to match the large upper bore, required for good sound volume, to the narrow foot bore required for wide-scale range. Early recorders of the Renaissance period had straight cylindrical bores and thus could not encompass as wide a scale as the Baroque model shown here.

The family of Baroque recorders is shown in Fig. 4. The instruments pictured here are part of a large and excellent collection belonging to Dr. Wesley M. Oler, an internal medicine specialist of Washington, who is shown holding a small gamba. Dr. Oler, who is also an expert recorder player, has worked closely with me in making the acoustic measurements.

The recorder family comprises six (or seven) sizes of instruments, ranging from great basses, such as that shown on the extreme left in Fig. 4, to the diminutive sopranino shown at the extreme right. The seventh size is the extremely rare Great Bass in F of the size now being made by



Fig. 4—Dr. W. M. Oler, internal medicine specialist and owner of nearly 100 recorders, helped take the data on which this article is based. Shown here are some Baroque recorders from his collection.

Friedrich von Huene. I was surprised to discover that all well-voiced recorders produce nearly the same sound power, except for the extremely large types, which are slightly weaker. On its lowest note, a recorder puts out, according to my measurements, approximately 30 microwatts of acoustic power. Near the middle of its scale where it has maximum strength,⁴ the output is about 2.5 milliwatts. These figures are, to a fair approximation, independent of not only the instrument size, but also the manufacturer and the player. This uniformity may be the result of a fundamental gain-bandwidth-product limitation, analogous to that of an electronic amplifier.

The recorder belongs to a class of musical instruments in which the sound is generated by the action of a sloshing air jet, without the help of any moving solid surfaces such as are found in the clarinet and oboe. Physicists classify the recorder, along with the flue organ pipe and transverse flute, as a jet-edge resonator. In the recorder the jet-edge driver is located in the "head" portion of the instrument at the top of the bore. Figure 5 is a schematic representation of the mouth of the recorder, showing the oscillation of the jet about the fixed edge. Switching of the jet from one side of the edge to another is caused by the growth of a transverse undulation, triggered at

the orifice, that eventually becomes large enough to shift the entire jet across the edge. The modulated flow of air in the mouth of the pipe is equivalent to a spherical radiator of sound, since the wavelength is much larger than any mouth dimension.

This type of sound generator will work with or without the presence of a resonator pipe, and is called an "edgetone." In 1961 Dr. Alan Powell,⁵ a former British scientist who is now an American citizen, showed that the edgetone oscillator is similar to an electronic-feedback-amplifier circuit. In his model of the edgetone, amplifier gain corresponds to the growth of the jet disturbance resulting from hydrodynamic instability. Even when there is no resonator present, the resultant "dipole" source caused by the sloshing of the jet triggers a new disturbance back at the orifice and thus provides positive feedback to make the oscillations regenerative. Frequency of a free edgetone is determined by the speed at which the growing undulation moves from orifice to edge. Dr. Powell had long been convinced that the "gain" of the edgetone system must come from the tendency of high-Reynolds-number jets to break up into turbulence. He and one of his graduate students⁶ were able finally to prove this by studying the

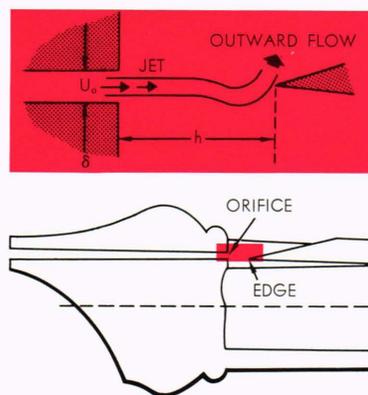


Fig. 5—Physicists classify the recorder along with the flue organ pipe and transverse (or Boehm) flute, as a jet-edge resonator type of instrument. This schematic shows the basic driving mechanism, which contains no moving parts.

⁵ A. Powell, "On the Edgetone," *J. Acoust. Soc. Am.*, **33**, 1961, 395-409.

⁶ R. C. Chanaud and A. Powell, "Experiments Concerning the Sound-Sensitive Jet," *J. Acoust. Soc. Am.*, **34**, 1962, 907-915.

⁴ A. von Lüpke, "Untersuchungen an Blockflöten," *Akustische Zeitschrift (Zürich)*, **V**, 1940, 39-46.

conditions under which free jets become unstable and by plotting their data in special nondimensional coordinates—Strouhal number (S) as the ordinate and Reynolds number (Re) as the abscissa. When the stable regions of edgetone oscillators were plotted in the same coordinates, they fell neatly within the unstable region of the free jet as predicted.

It has long been known that the empirical frequency formula⁷ for free edgetones does not work when applied to pipes. The pipe resonance modes are dominant over the natural edgetone modes just as a quartz crystal can be made to control an electronic oscillator. Dr. Powell suggested that this is because the sound field in the pipe provides a stronger feedback from edge to orifice.⁵

Figure 6 shows a Strouhal-Reynolds plot similar to that used by Dr. Powell. I have employed slightly different definitions of the coordinates, using the edge-orifice distance h where Powell used the jet thickness δ . In this representation Powell's stable edgetone regimes appear as horizontal and parallel line segments, arranged in order of their mode number. The lowest mode, M^I , corresponds to the simple to-and-fro motion pictured in Fig. 5. Higher modes correspond to more complicated undulations of the jet. Strouhal number in this plot is defined as the frequency times the orifice-edge separation, divided by the mean orifice velocity U_o . It is thus a nondimensional measure of oscillation frequency, though for a fixed frequency the Strouhal number decreases with increasing U_o . The utility of this type of representation is due to the fact that edgetone modes are lines of constant Strouhal number. Reynolds number—the product $U_o h$ divided by the kinematic viscosity—corresponds in a rough way to blowing pressure. Both scales are logarithmic. The broken line shows the actual path by which the state of an edgetone-resonator is changed as the blowing pressure is continually increased from zero. A number of transient sounds occur as the Rey-

nolds number approaches the edgetone threshold, corresponding to the excitation of both free edgetones (horizontal lines) and pipe resonances (diagonal lines). This effect is known as "chiff" in an organ pipe and lends a certain charm to the tone quality of old organs.

The diagonal lines are fixed frequencies corresponding to the first few resonant modes of the pipe, due to standing waves of sound. The dominance of the pipe feedback is shown by the way in which the state of the system tends to approach the pipe resonant frequency as the Reynolds number is increased. The crossing point "O" in Fig. 6 is the place at which the pipe is normally driven in sounding its lowest note. At a slightly greater Reynolds number, "overblowing" occurs and a sudden jump brings the system to the second pipe mode (or octave). Still harder wind pressure causes a succession of overblows to higher modes.

I have called this plot a *universal mode diagram* because it represents the coupling of edgetone and pipe modes in a scale-invariant way. Experimental data for recorders indicate that the fundamental pipe mode line always crosses the first edgetone mode line near its beginning. Physically, this is due to the practical necessity of fitting all the desirable pipe modes within the stable regime of the first edgetone mode. This fact leads to a simple scaling law, relating the edge-

orifice separation to the fundamental pipe frequency, $h \doteq \sqrt{72/f_o}$ cm. We have plotted on the universal mode diagram in Fig. 7 the entire two-octave scale of an alto recorder. Each note was blown in tune at its optimum point. Notice that four pipe modes are required to cover the scale range. By overblowing to modes in the upper octave, it is possible to encompass more notes with fewer finger holes.

All scale notes of the recorder are driven by the first edgetone mode. Higher modes seem to be important only during the starting transient of a note.

The degree of fluctuation of the driving point from one note to another is a measure of the accuracy of the instrument's intonation. The alto recorder used for these measurements is an unusually fine one made by my friend, Friedrich von Huene, and it can be blown in tune on every note very easily. In taking the data for this plot, the velocity U_o was measured by means of a home-made pitot probe and water manometer.

Another type of measurement we have made utilized a $1/8$ -inch diameter probe tube mounted on a calibrated condenser microphone borrowed from the Laboratory. With this equipment Dr. Oler and I plotted the axial sound pressure fields for each note on a number of recorders. Data of this type have led to an understanding of the radiating source

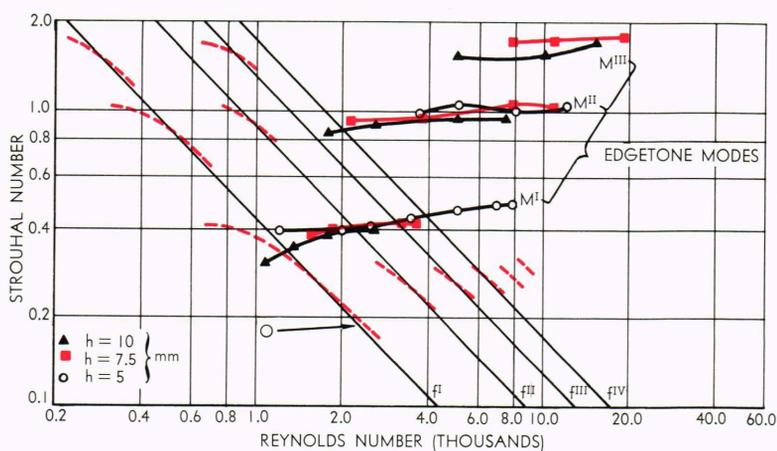


Fig. 6—When pipe resonance modes and edgetone modes are plotted simultaneously on an S - Re graph, the universal mode diagram that results helps to explain many of the mysteries of recorder acoustics. Strouhal number is here defined as sound frequency times orifice-edge separation, divided by the mean jet velocity at the orifice. Reynolds number is the product $U_o h$ divided by the kinematic viscosity of air (≈ 0.15 cgs). (Edgetone data are from: A. Powell, *op. cit.*)

⁷ G. B. Brown gives the following empirical formula for edgetone frequencies: $f \doteq 0.466j (U_o = 40) (1/h - 0.07)$ where $j \doteq 1, 2, 3, 3.8,$ and 5.4 ; from "The Vortex Motion Causing Edge Tones," *Proc. Phys. Soc. (London)*, 49, 1937, 493.