The Physics of Organ Pipes

The majestic sound of a pipe organ is created by the carefully phased interaction of a jet of air blowing across the mouth of each pipe and the column of air resonating inside the pipe

by Neville H. Fletcher and Suszanne Thwaites

No other musical instrument can compare with the pipe organ in power, timbre, dynamic range, complexity of tone and sheer majesty of sound. Like many other musical instruments the organ was brought to a high state of perfection by generations of craftsmen drawing on a slow accumulation of empirical knowledge. By the end of the 17th century the organ had attained essentially its modern form. Two of the 19th century's most illustrious physicists, Hermann von Helmholtz and Lord Rayleigh, reached opposite conclusions about the fundamental mechanism of how organ pipes generate sound but lacked the technical means for resolving the issue. With the advent of oscilloscopes and other modern devices it has become possible to develop a detailed understanding of the mechanism. It turns out that the analyses of Helmholtz and Rayleigh are each valid over certain ranges of the pressure at which air is blown into the organ pipe. The present understanding, which will be described here, is at variance with many of the explanations of organ-pipe mechanisms still found in textbooks.

Pipes cut out of reeds or other hollow-stemmed plants were probably the first musical instruments. They could be made to emit sound by blowing across the end of the pipe, by blowing into the end in such a way that the lips vibrated or by pinching the end in such a way that blowing through it caused the sides of the pipe itself to vibrate. Modern versions of these three primitive wind instruments are flutes, trumpets and clarinets, all of which have been developed so that the performer can play many notes spread over a substantial range of acoustic frequencies.

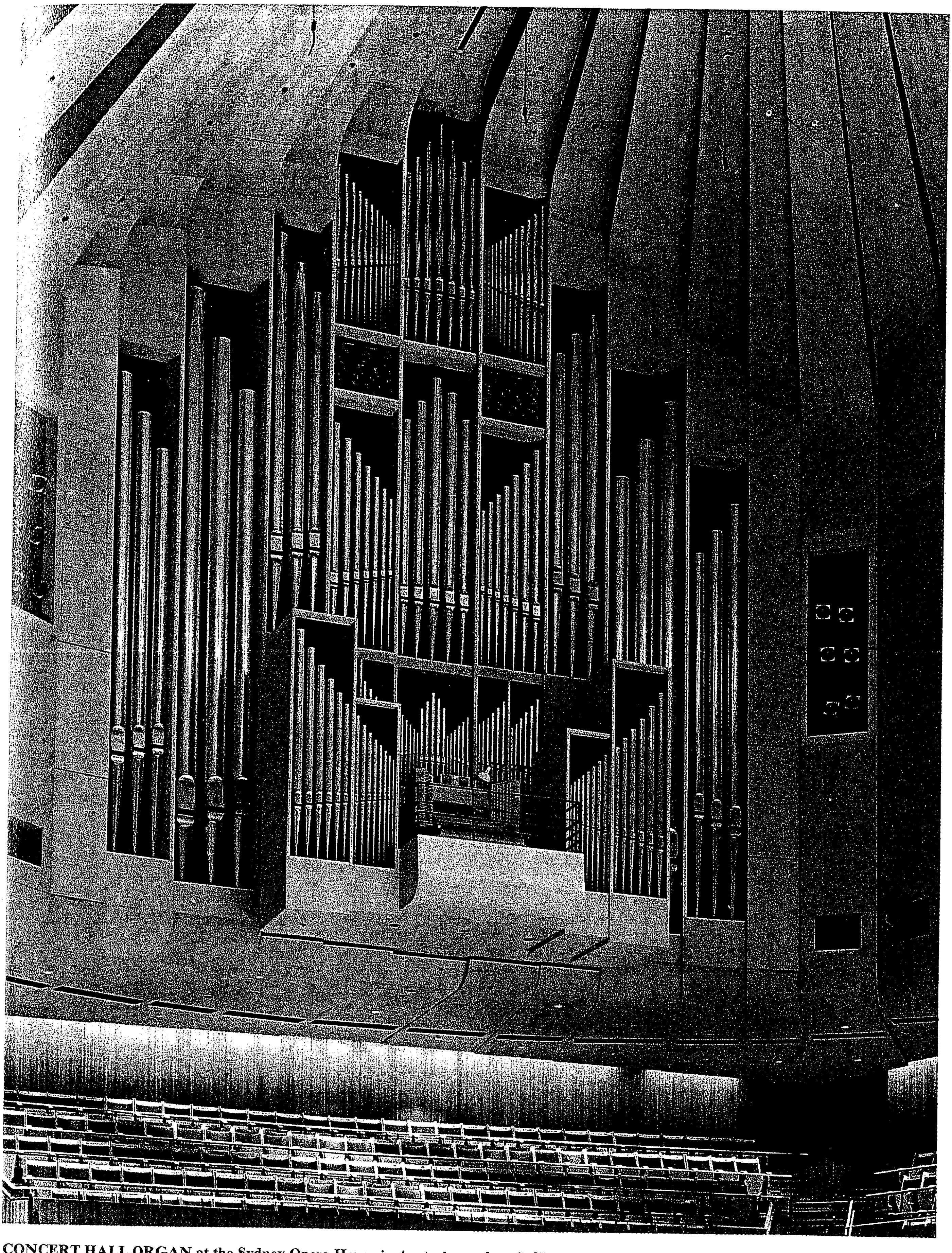
There has been a parallel development in pipe instruments in which a different pipe is dedicated to each note. The simplest such instrument is the panpipe (from "pipes of Pan"), which commonly has about 20 pipes of different lengths, all closed at one end and excited by being blown across the open end. At the other extreme in size and complexity is the pipe organ, an instrument with as many as 10,000 pipes that the player controls through complex mechanical linkages. The pipe organ has a long history. Pottery figures of Alexandrian musicians playing an arrangement of pipes excited by bellows date back to the second century B.C. By the 10th century the organ began to be adopted in Christian churches, and treatises on organ building, written by monks, were in circulation in Europe. The great organ built in the 10th century for Winchester cathedral in England was reputed to have had 400 metal pipes, 26 bellows and two keyboards with a total of 40 keys, each key controlling 10 pipes. In the succeeding centuries there were substantial mechanical and musical advances in organ building, and as early as 1429 an organ with 2,500 pipes was built in Amiens cathedral. By the late 17th century in Germany organs had evolved to their modern form.

The terminology for describing organ pipes reflects their origin in pipes blown by mouth. Organ pipes are open at the top and tapered at the bottom, with a "mouth" (a slot) running across a flattened section above the taper. Inside the pipe is a "languid," or tongue (a horizontal plate), with a "flue" (a narrow slit) between it and the lower "lip" of the mouth. The air that excites the pipe, supplied by a large bellows, reaches the tapered foot of the pipe at a typical pressure of 500 to 1,000 pascals (five to 10 centimeters measured on a water gauge). When the air is admitted to the pipe by the actuation of the appropriate drawstop knob and key, it flows upward and forms a sheetlike jet as it emerges from the flue slit. The jet flows across the mouth and strikes the upper lip, where it interacts both with the upper lip and with the column of air in the body of the pipe to maintain the steady oscillation that generates the pipe's "speech." The problem of how the pipe makes the abrupt transition from silence to steady speech is a difficult one and fascinating in its own right but will not be part of our story. We shall be concerned primarily with the processes that control the steady speech of organ pipes and endow them with their characteristic tone qualities.

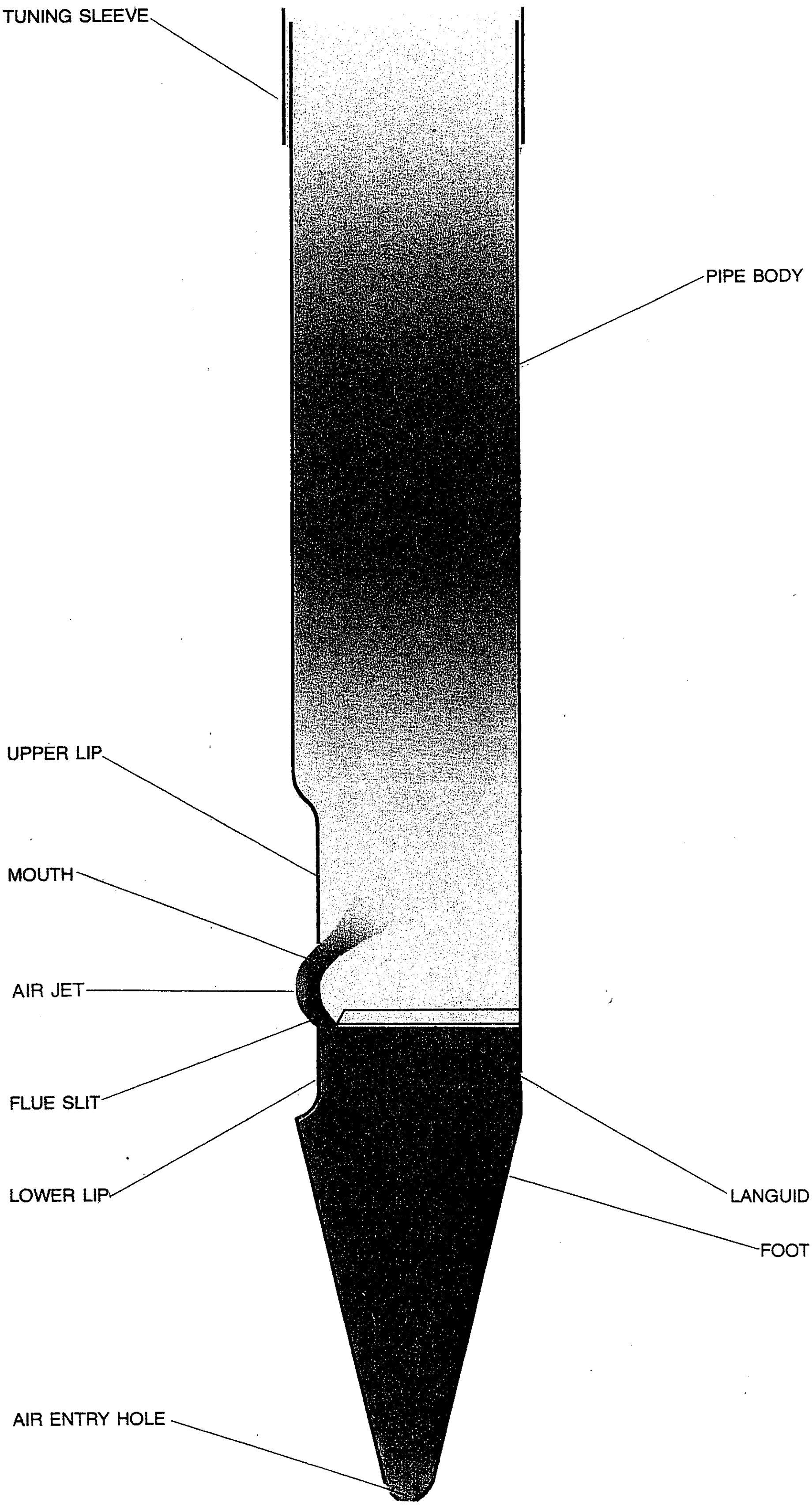
The behavior of the jet that initiates and sustains the organ's speech would seem to present a straightforward problem in fluid flow. It turns out, however, that even a steady jet flowing in a smooth laminar manner is quite difficult to understand theoretically, and the fully turbulent jet that flows in a real organ pipe is impossibly complex. Fortunately the complexity introduced by turbulence actually simplifies the behavior of the jet. If the flow were laminar, the jet would interact with its surroundings through viscosity. In the actual jet viscosity is replaced as the mechanism of interaction by turbulence, and on a scale directly related to the width of the jet. Organ builders go to some lengths to ensure that the jets in their pipes are fully turbulent by cutting fine nicks along the edge of the languid. Paradoxically a turbulent jet is stable and reproducible and a laminar jet is not.

A fully turbulent jet mixes gradually with the surrounding air, thereby broadening and slowing down in a simple manner. When the jet's velocity is plotted against the distance from its central plane, the resulting curve has a bell-like shape, with the maximum velocity in the center. The width of the jet increases linearly with the distance from the flue slit. The momentum of the flow must be conserved, which means that the velocity decreases with the square root of the distance from the slit. This description can be supported theoretically and agrees with experiment (when a small transition region near the flue slit is included).

In an organ pipe that is already excited and emitting sound the jet emerges from the flue slit into the intense sound field in the mouth of the pipe. The air motion associated with the sound is directed into and out of the mouth and therefore at right angles to the plane of the jet. Half a century ago Burniston



CONCERT HALL ORGAN at the Sydney Opera House in Australia, completed in 1979, is one of the largest and most advanced in the world. Designed and built by Ronald Sharp, it has some 10,500 pipes controlled by the mechanical action of five keyboards and a pedal board. The mechanical action, which regulates the flow of air into the pipes, is duplicated by an electric action that is under microprocessor control. The organ can therefore be operated by a magnetic tape on which an original performance has been recorded digitally.



ORGAN PIPE is excited by air blown in from the bottom. The air is formed into a jet by the flue slit between the lower lip and the languid: a plate running across the pipe. When the air blows across the mouth of the pipe, it interacts with the column of air in the pipe at the upper lip, blowing alternately into and out of the pipe. Waves propagating along the turbulent jet maintain a steady oscillation in the air column, causing the pipe to "speak." The standing-wave pattern of pressure in the pipe is represented by the colored shading. The upper end of the pipe is surrounded by an adjustable sleeve, as is shown here, or is closed by an adjustable stopper. Either makes it possible to change the length of the air column slightly for tuning.

Brown of University College London made beautiful photographs of smoke-laden laminar jets emerging into a sound field and found they developed sinuous waves that grew as they traveled along the jet until the jet broke up into a double row of vortex rings rotating in opposite directions. It was the somewhat naive application of these observations and similar ones that led to much of the confused discussion of organ-pipe physics still found in many textbooks.

A more fruitful way to study the behavior of real jets in a sound field is to remove the organ pipe and generate the sound field by means of a loudspeaker. Such studies, conducted by John W. Coltman of the Westinghouse Electric Corporation and by our own group at the University of New England in Australia, have provided much of the current understanding of the physics of organ pipes. Actually Rayleigh had developed a careful and nearly complete mathematical description of the behavior of laminar jets of nonviscous fluids. Because of the fortunate circumstance that turbulence has been found to simplify jet behavior rather than complicate it, Rayleigh's treatment can be carried over with little modification to describe the real jets produced and analyzed experimentally by Coltman and by us.

If one were to forget about the flue slit in the organ pipe, one would expect that the jet, being just a sheet of moving air, would simply be moved back and forth by the acoustic vibrations along with all the other air in the mouth of the pipe. As the jet leaves the flue, however, it is effectively held still by the flue slit itself. This has the same effect as superimposing on the general back-and-forth motion in the sound field an exactly balancing displacement localized at the flue. The localized displacement, which matches the sound field in frequency and amplitude in order to maintain zero displacement at the flue, is carried along with the moving air in the jet and imposes a sinuous wave motion on it.

As Rayleigh showed for a limiting case in his jets, and as we have verified in detail for diverging turbulent jets, the wave motion propagates along the jet at a speed that is a little less than half the speed of the air at the central plane of the jet. In addition, however, the wave grows in amplitude nearly exponentially as it propagates along the jet. In a typical case the amplitude of the wave doubles in traveling about one millimeter along the jet, so that the effects of the wave rapidly dominate the simple back-and-forth lateral motion imposed by the acoustic vibrations.

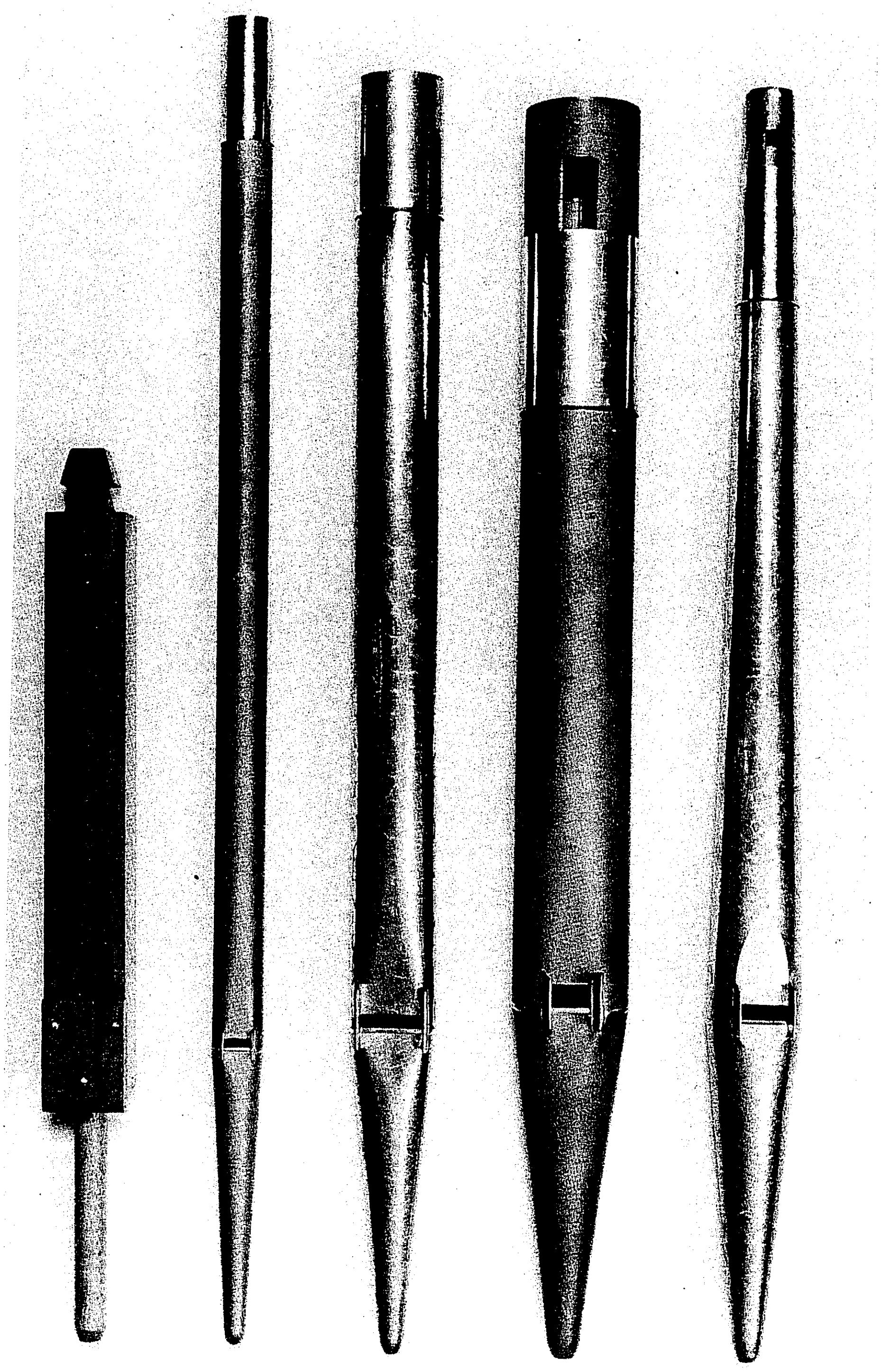
We find that the growth rate of the wave is greatest when its wavelength along the jet is about six times the width of the jet at that point. On the other hand, when the length of the wave is less than the width of the jet, the wave does not grow at all and may even die out. Since the jet slows and broadens as it moves away from the flue slit, only the long waves, that is, those of low frequency, can propagate with large amplitude along long jets. This fact will be an important one when we come to consider the harmonic content of organ-pipe sounds.

Let us now consider the effects of the organ pipe's sound field on the jet. As one can readily imagine, the large acoustic waves associated with the sound field in the pipe mouth will cause the tip of the jet to flick back and forth across the upper lip of the mouth so that the jet will flow alternately into the pipe and outside it. The situation resembles what happens when one pushes a swing that is already swinging. The air column in the pipe is already oscillating, and if the puffs of air enter the pipe in step with the oscillations, the puffs will maintain the oscillations against sundry energy losses, such as the radiation of sound from the pipe and the drag at the pipe walls. If, on the other hand, the puffs are out of step with the oscillations of the air column, the jet will tend to damp the oscillations and the sound will die away.

The relations between the acoustic motions of the air in the pipe mouth and the time the air pulse arrives inside the upper lip are determined simply by the time required for a wave on the jet to travel from the flue slit to the upper lip. The organ builder calls this distance the cut-up. If the cut-up is large or the blowing pressure is low so that the jet velocity is low, the travel time will be long. Conversely, if the cut-up is small or the blowing pressure is high, the travel time will be short.

In order to discover just what the correct phase relation between the oscillation of the air column in the pipe and the arrival of jet pulses inside the upper lip is, it is necessary to know more about how the pulses act on the air column. Helmholtz thought that the dominant factor in the relation was the volume of flow contributed by the jet. Then if the pulses in the jet flow were to impart as much energy as possible to the oscillation of the air column, they should enter the pipe at the times when the acoustic pressure inside the upper lip was at a maximum.

Rayleigh took a different view. He argued that since the mouth is actually not very far from the open end of the pipe, little acoustic pressure can build up just inside the mouth for the jet flow to work against. He considered that the jet flow was essentially stopped as soon as it entered the pipe, thus quickly building up pressure that could act on the flow in the pipe. Therefore according to Rayleigh the maximum amount of energy would be transferred from the jet if the jet flow entered the pipe when the acoustic flow, not pressure, was at a maximum. The difference between these two maximums amounts to a quarter of an oscillation period in the oscillation frequency of the air column in the pipe. In terms of the swing analogy the difference is between giving the swing a push when it is at the top of its arc and has acquired its maximum potential energy (Helmholtz) and giving the swing a push when



FIVE PIPES OF DIFFERENT DESIGN yield a note of the same pitch but different tone qualities. The second pipe from the left is the dulciana, which has a sweet, thin tone resembling that of a stringed instrument. The third pipe is the open diapason, which has the bright, ringing sound most characteristic of an organ. The fourth has the sound of a very dull flute. The fifth is the *waldflöte* (forest flute), which has a soft sound. The wood pipe at the left is closed with a stopper. It has the same fundamental frequency as the other pipes but only odd harmonics: overtones with frequencies that are odd-numbered multiples of the fundamental. The other pipes differ slightly in length because "end corrections" are needed to give them the same pitch.

it is at its lowest point and is moving fastest (Rayleigh).

The problem remained unresolved, and indeed virtually uninvestigated, for nearly 80 years. It has now been fairly satisfactorily decided as a result of work by Lothar Cremer and Hartmut Ising of the Heinrich Hertz Institute for Vibration Research in Berlin, by Samuel A. Elder of the United States Naval Academy, by Coltman and by us. Briefly, both Helmholtz and Rayleigh were partly right. The balance between the two driving mechanisms depends on the blowing pressure and the frequency of the sound, with the Helmholtz mechanism dominating for low blowing pressures and high frequencies and the Rayleigh mechanism dominating for high blowing pressures and low frequencies. For an ordinary organ pipe the Helmholtz mechanism is usually more important.

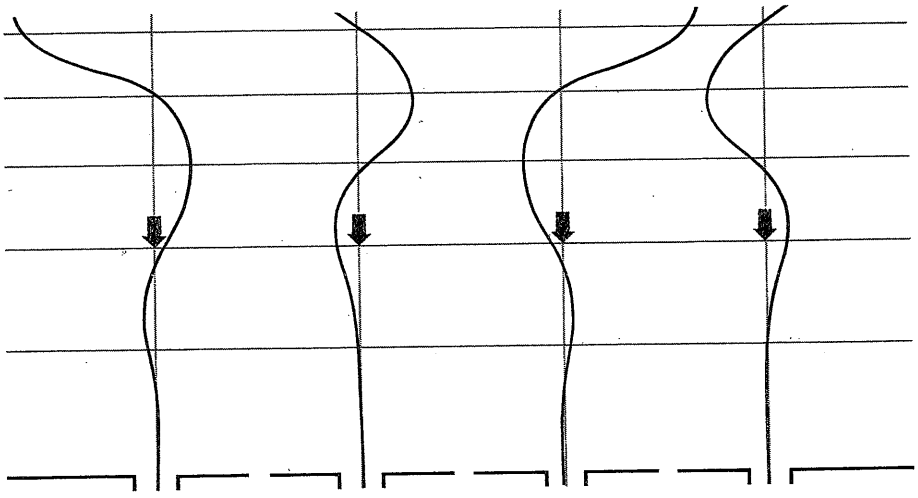
A simple and effective method for studying the properties of the jet was devised by Coltman and has been modified and extended in our laboratory. Essentially one examines the behavior of a jet at the mouth of an organ pipe that has been fitted with wedges of absorbent felt or foam at the far end so that the pipe is prevented from speaking. A sound wave is then directed down the pipe from a loudspeaker outside the far end. The wave is reflected from the mouth end, with and without the jet blowing. In both cases the incident and reflected sound waves interact inside the pipe to create a pattern of standing waves. By measuring with a small probe microphone the changes in the pattern when the jet is turned on, we can determine whether the jet adds energy to the reflected wave or subtracts it.

What our experiments actually determine is the acoustic "admittance" of the jet, which is defined as the ratio of the acoustic flow out of the mouth, produced by the presence of the jet, to the acoustic pressure just inside the mouth. The acoustic admittance has both a magnitude and a phase angle, which can be plotted as a function of frequency or of blowing pressure. When either the frequency or the blowing pressure is varied separately and the admittance is appropriately plotted, it takes the form of a spiral [*see top illustration on opposite page*]. The distance from the origin of the spiral represents the magnitude of the admittance and the angular position along the spiral represents the delay in the phase of the sinuous wave that is imposed on the jet by the acoustic oscillations in the pipe. A delay of one wavelength corresponds to 360 degrees around the spiral. Because of the special properties of turbulent jets it turns out that if the admittance is multiplied by the square root of the blowing pressure, all the measurements for a particular organ pipe fall in the same spiral.

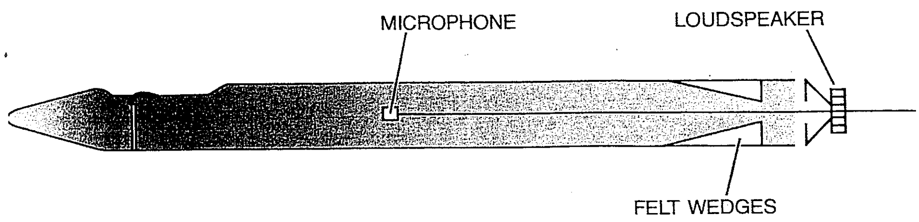
If we keep the blowing pressure constant and increase the frequency of the input sound wave, the point representing the admittance spirals inward toward the center in a clockwise direction. If we hold the frequency constant and increase the blowing pressure, the point spirals outward in the opposite direction.

When the point representing the admittance lies in the right half of the spiral, the jet is taking energy from the pipe flow and energy is therefore being dissipated. When the point lies in the left half, the jet is imparting energy to the pipe flow, which means that the jet is acting as an acoustic generator. When the point is in the upper half of the spiral, the jet lowers the natural resonance frequency of the pipe; when the point is in the lower half, the jet raises the natural resonance frequency. The reference angle from which the phase delay is measured depends on whether the Helmholtz or the Rayleigh excitation mechanism is dominant, and this, as we have remarked, depends on the blowing pressure and the frequency. It is never far, however, from the zero, or three-o'clock, position on the right arm of the horizontal axis.

Since 360 degrees around the spiral represents a phase delay of one wavelength in the sinuous wave propagated along the jet, it follows that for phase delays from rather less than a quarter of a wavelength to nearly three-quarters of a wavelength a representative point on the spiral will lie to the left of the center line, or in the region where the jet acts as an acoustic generator. We have



SHAPE OF THE AIR JET is shown in consecutive "snapshots" as it emerges from the flue slit into the acoustic velocity field generated in the mouth of the pipe by the resonating air column inside the pipe. The periodic displacement of the air in the mouth creates a sinuous wave that propagates with a speed equal to half of the speed of the air at the central plane of the jet and grows exponentially until its amplitude exceeds the width of the jet. The horizontal divisions show distances traveled by the jet wave in successive quarter periods of the oscillation period T. The lines get closer together as the jet loses speed. In an organ pipe the upper lip is positioned at about the location of the arrow, so that the air jet blows alternately into and out of the pipe.



ACOUSTIC GENERATING PROPERTIES OF THE JET can be measured by inserting felt or foam wedges in the open end of the pipe to keep it from sounding and introducing a sound wave of small amplitude from a loudspeaker. The sound wave is reflected from the opposite end of the pipe and interacts at the mouth with the air jet. The interaction of the jet with the standing-wave pattern in the pipe is examined with a movable microphone. In this way one can establish whether the jet is adding energy to or subtracting energy from the wave reflected at the base of the pipe. In order for the pipe to sound, the jet must add energy. The measurements are in terms of the acoustic "admittance": the ratio of the acoustic flow out of the mouth to the acoustic pressure just inside the mouth. A plot of the admittance for various combinations of blowing pressure and frequency yields the spiral curve at the top of the opposite page.

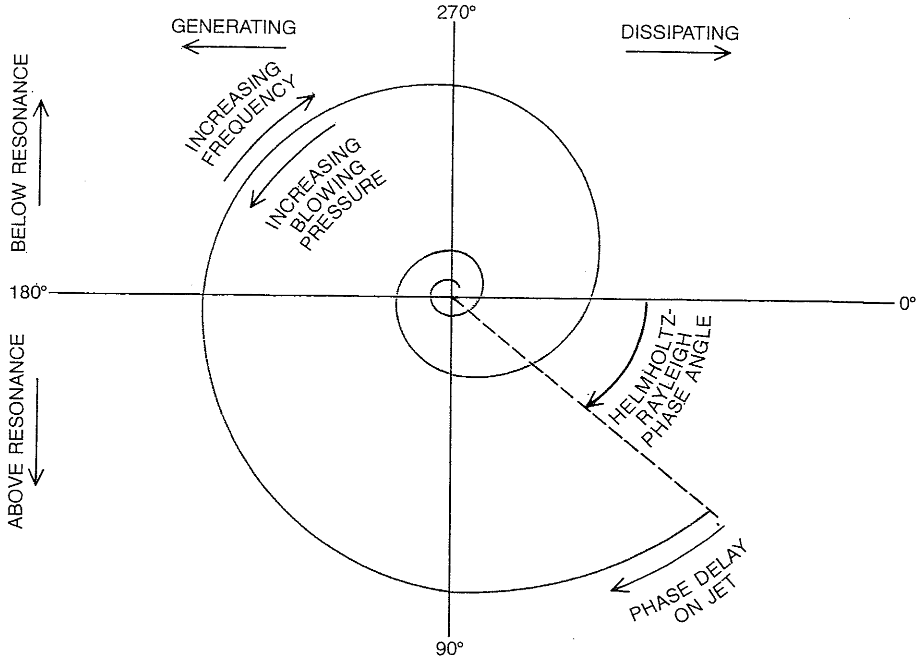
also seen that at a constant frequency the phase delay is a function of blowing pressure, which controls both the speed of the jet and the speed with which the sinuous wave propagates on the jet. Since the wave speed is half the jet speed and the jet speed is proportional to the square root of the blowing pressure, the blowing pressure has to change considerably to alter the phase of the jet wave by as much as half a wavelength. Actually there is about a ninefold range of pressure over which the pipe can emit its fundamental sound if other conditions are right. In practice, however, the pipe will overblow to a mode of higher frequency before the upper end of this pressure range is reached.

We should point out that the spiral can have more than one loop extending far enough into the left side to overcome dissipative losses in the pipe and generate a stable sound. The second such loop, which is generally the only other one that can cause the pipe to sound, corresponds to about three half wavelengths on the jet. Because the jet has only a small admittance at this point the sound generated is weak compared with the sound for a point in the outer loop of the spiral.

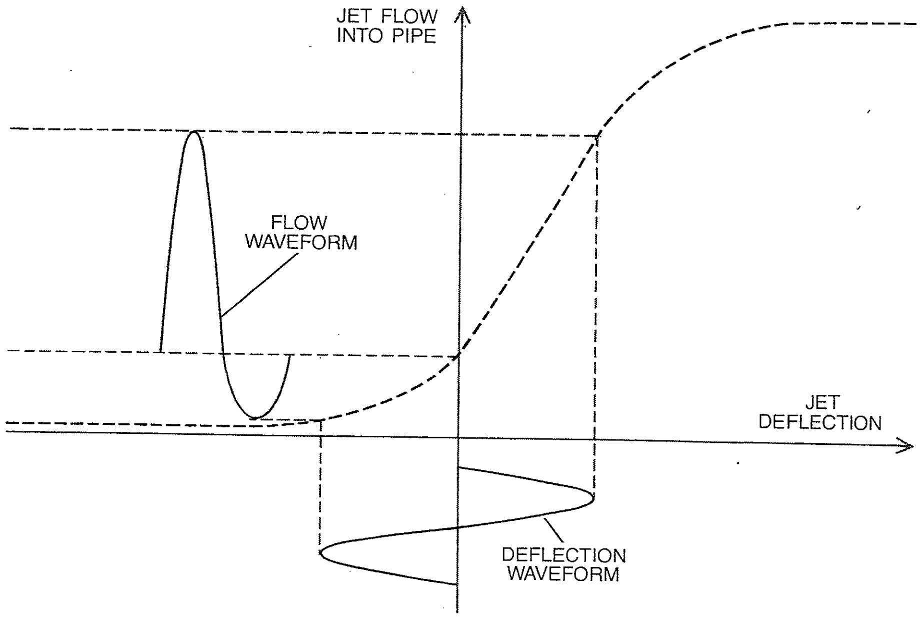
The admittance spiral we have been discussing has an additional complication if the deflection of the jet at the upper lip becomes greater than the width of the jet. The jet then blows nearly completely into and out of the pipe mouth in each cycle and the impulse it gives to the reflected wave in the pipe becomes independent of further increases in amplitude. The efficiency of the jet as a generator decreases accordingly. The admittance spiral simply shrinks in size as the amplitude of the jet deflection increases.

The loss of jet efficiency with increasing deflection amplitude is accompanied by increasing energy losses in the organ pipe. The pipe oscillation rapidly settles down at an amplitude for which the energy supplied by the jet exactly balances the energy lost by the pipe. Rather surprisingly it turns out that in most instances the energy losses through turbulence and viscosity are much larger than the losses through sound radiation from the mouth and the open end of the pipe.

The sound of a real organ pipe is not, of course, limited to a single frequency; it has many components of higher frequency. One can demonstrate that these components are all exact harmonics of the fundamental frequency: integer multiples of that frequency. Under steady blowing conditions the shape of the sound wave seen on an oscilloscope remains exactly the same. Even the smallest deviation from exact integer multiples for the frequencies of the components would lead to a slow



ACOUSTIC ADMITTANCE OF THE JET as a function of frequency or of blowing pressure takes the form of a spiral in which the distance from the origin represents the magnitude of the admittance and the angular position represents the phase relation between the acoustic flow out of the mouth of the pipe and the pressure just inside the mouth. When the outflow is in phase with the pressure, the admittance lies in the right half of the spiral and the energy of the jet is being dissipated. For the jet to act as an acoustic generator the admittance must lie in the left half of the spiral, which requires that the back-and-forth displacement of the jet be offset, or delayed, in phase with respect to the pressure inside the mouth of the pipe. The wave reflected from the jet is then larger than the incident wave. The reference angle from which the phase delay is measured depends on which of two excitation mechanisms discussed in the text is dominant, the one proposed in the last century by Hermann von Helmholtz or the one proposed by Lord Rayleigh. When the admittance falls in the upper half of the spiral, the jet lowers the natural resonance frequency of the pipe; when it falls in the lower half of the spiral, the jet raises the resonance frequency. The outer parts of the spiral have been reduced in size for clarity.

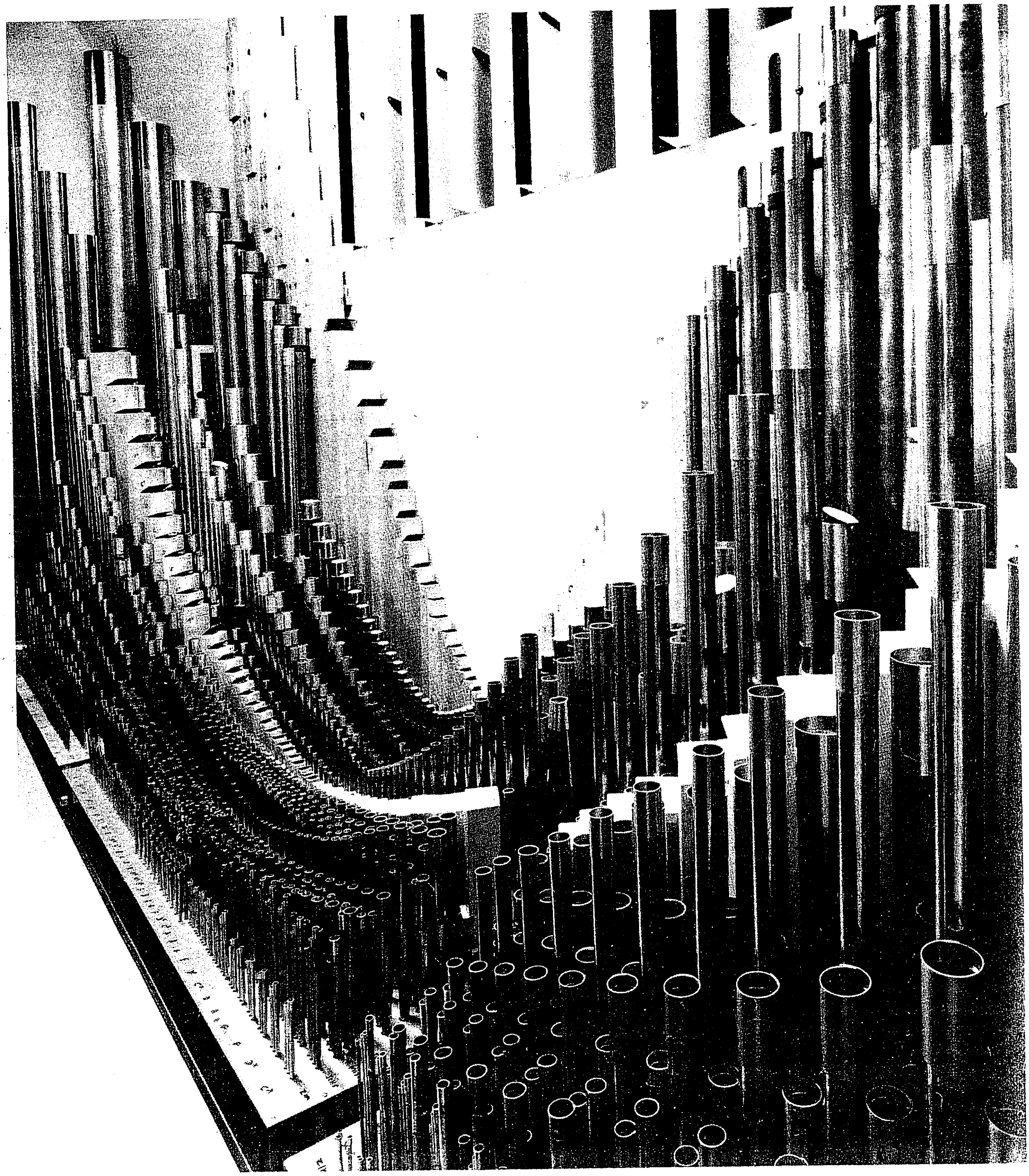


CURVE GIVING THE JET FLOW INTO A PIPE (*broken curve*) for a given deflection is asymmetric around zero deflection because the lip of the pipe has been adjusted to cut the jet slightly away from its central plane. When the jet is deflected in a simple sinusoidal way with a large amplitude (*solid black curve*), the jet flow into the pipe (*colored curve*) "saturates" first at one end of its range, where the jet is blowing completely outside the pipe lip. For a still larger amplitude the jet flow will also saturate at the other end of its range, where the jet is blowing completely into the pipe. The offset of the lip gives the flow waveform an asymmetric shape that has frequency components at all integer multiples of the deflection frequency. It is these harmonic components that are responsible for the rich sound of a well-adjusted organ pipe.

but clearly discernible change in the waveform.

This behavior is interesting because the resonances of the air column in an organ pipe, or indeed in any open pipe, have frequencies that differ slightly from exact harmonic multiples. The reason is that the effective length of the pipe decreases slightly with increasing frequency because of changing acoustic flow at the open ends. As we shall see, the harmonics in the sound of an organ pipe are generated by the interactions of the jet and the pipe lip, so that the pipe acts largely as a passive resonator as far as the upper harmonics are concerned.

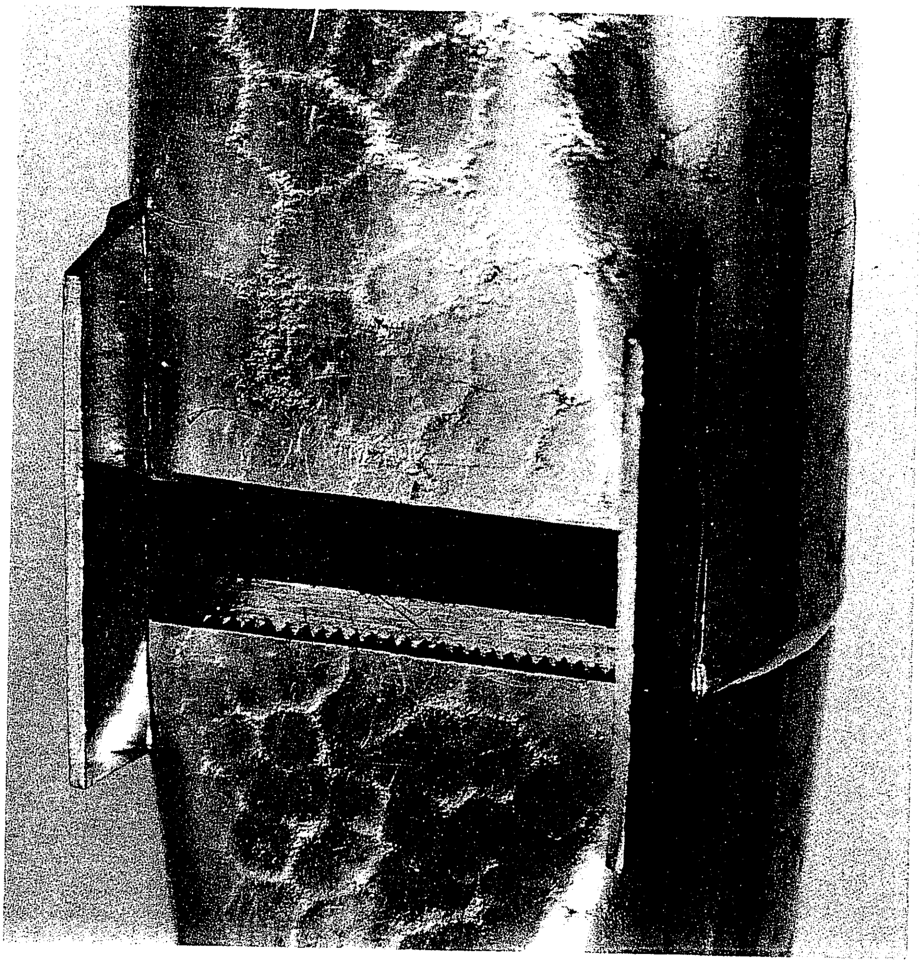
The resonances of a pipe develop when there is maximum movement of the air at the open ends of the pipe, which is the same as saying that the admittance of an organ pipe should be at a



INTERIOR VIEW OF ORGAN at the Sydney Opera House shows some of its 26 ranks of pipes, most of which are of metal but some of which are of wood. The length of the speaking part of each pipe doubles at every 12th pipe; the pipe diameter doubles at about every 16th pipe. Through long experience master organ builders arrived at the proportions necessary for achieving balanced tone quality.

maximum at the mouth. This leads to the conclusion that the resonances of a pipe open at its far end occur at frequencies for which the pipe length is an integral number of half wavelengths for sound in air. If the fundamental frequency is f_1, the upper resonances are $2f_1$, $3f_1$ and so on. (Actually all the upper resonance frequencies are stretched a little beyond these ideal values, as we noted above.)

For a pipe that is stopped, or closed, at its far end, resonances occur when the pipe length is an odd number of quarter wavelengths. Therefore a stopped pipe need be only half as long as an open pipe to produce the same note; its resonances are at f_1, $3f_1$, $5f_1$ and so on.



MOUTH OF AN ORGAN PIPE OF THE DIAPASON FAMILY **reveals how the languid of the pipe has been "nicked" in order to achieve homogeneous turbulence in the air jet. The pipe is made out of "spotted metal," a tin-rich alloy of lead and tin that solidifies to the surface pattern seen here when it is cast in a metal sheet. The sheet is then formed into a pipe.**

Returning to the organ-pipe jet, we have seen that high-frequency disturbances tend to die out along the jet as the width of the jet increases, so that, almost independently of the higher-frequency components in the acoustic field at the pipe mouth, the tip of the jet at the upper lip moves back and forth almost sinusoidally at the frequency of the fundamental component of the pipe sound. A sinusoidal flow of the jet, however, does not lead to a sinusoidal jet flow into the pipe, because the flow "saturates" by flowing completely inside or outside the upper lip at each end of the jet's deflection range. More than that, the lip is usually offset so that it does not cut the jet exactly along its central plane, thus making the saturation asymmetric. The waveform of the jet flow into the pipe therefore has all the harmonics of the fundamental frequency, locked into precise frequency and phase relation, and the relative amplitudes of the high-frequency harmonics increase rapidly as the amplitude of the jet deflection increases.

In a typical organ pipe the distance the jet is deflected in the mouth is on the same order as the width of the jet at the upper lip. As a result there is a wide spectrum of harmonics in the jet flow. If the jet were to strike the lip exactly symmetrically, the even-numbered harmonics would be absent from the excitation. The jet is usually given a small offset so that all the harmonics are present.

As one might expect, the quality of sound delivered by an open pipe is rather different from that delivered by a stopped pipe. The frequencies of the harmonics in the driving force produced by the jet are exact integer multiples of the fundamental frequency of the wave in the jet. The air column in the pipe will respond strongly to a particular harmonic only if the pipe's acoustic admittance is large, which corresponds to a sharp resonance peak close to the frequency of the harmonic. A stopped pipe, which has only odd-numbered resonance peaks, therefore suppresses all the even-numbered harmonics of its fundamental. The result is a characteristic "hollow" sound in which the even-numbered harmonics are weak, although they are not totally absent. An open pipe, on the other hand, achieves a "brighter" sound because it responds to all the harmonics of its fundamental frequency.

The resonance characteristics of a pipe are determined largely by its energy losses. These losses are of two types: (1) viscous and heat-conduction losses to the pipe walls, and (2) radiation losses from the mouth and the open end. The viscous and heat-conduction losses are more important for narrow pipes than they are for wide pipes and turn out to be more important at low frequencies than they are at high frequencies. The reverse is true for radiation losses.

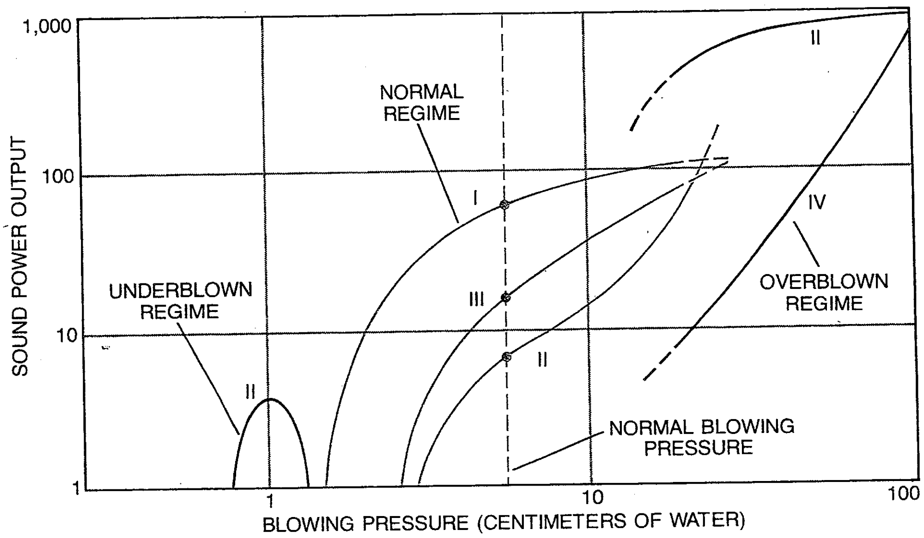
The upshot is that, for a given pipe length and hence for a given fundamental frequency, wide pipes are efficient and well-tuned resonators for only the fundamental and its first few harmonics, which results in a dull, "fluty" sound. Narrow pipes are good resonators for a large range of harmonics, and because higher frequencies are radiated more efficiently than lower ones the tone is thin and "stringy." Between these two extremes are pipes with the bright, ringing sound characteristic of a good organ. These are the pipes called principals or diapasons.

A large organ may in addition have ranks of pipes with a conical body, a perforated stopper or other geometric variations. These features are designed to modify the resonance frequencies of the pipe and in some instances to enhance a narrow range of the higher harmonics to produce a particular tone color. The material from which the pipe is made is of only minor importance.

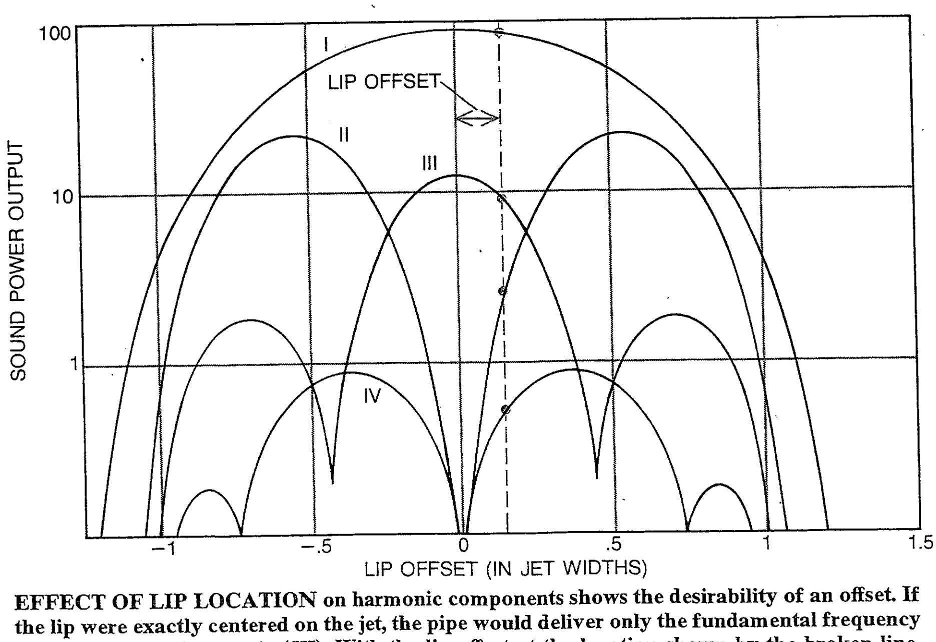
The fact that the air in a pipe can vibrate in any one of an entire set of possible modes introduces additional complications in the acoustic behavior of pipes. For example, if the blowing pressure in an open pipe is increased so that there is just a quarter of a wavelength of the first mode, f_1, on the jet, the point in the admittance spiral for this first mode will move into the right half and the jet will cease to maintain the mode. At the same time the second mode frequency, $2f_1$, is such that it corresponds to half a wavelength along the jet, so that it can be strongly driven. The sound of the pipe will therefore jump to this second mode, almost an octave above the first, the exact frequency depending on the resonance frequency of the pipe and on the blowing pressure.

A further increase in the blowing pressure can excite the next mode, at $3f_1$, if the cut-up of the pipe lip is not too great. Conversely, it often happens that a low blowing pressure inadequate to drive the fundamental will softly drive one of the higher modes in the second loop of the admittance spiral. These overblown or underblown pipe sounds, although they are interesting in the laboratory, are not exploited in pipe organs except for special effects.

The main problem facing the organ builder who has created a single pipe of the appropriate sound quality is to design a rank of pipes covering the musical compass of the keyboard and matching one another in loudness and harmonic content. A set of geometrically similar pipes, simply scaled up or down in size, does not meet this requirement: the pipes differ in how wall and radiation losses affect different frequencies. In order to achieve constant behavior across the acoustic spectrum one must apply a scaling rule. The diameter of the pipe is varied with the length of the pipe raised to a suitable power, k, whose value is less than 1. The result is that the long bass pipes are made somewhat narrow. The theoretically determined value of k is $5/6$, or .83, but when the psychophysics of human hearing is taken into account, a value of .75 proves to be more satisfactory. That value turns out to be close to the empirical rule developed by the great organ builders of the 17th and 18th centuries.



EFFECT OF CHANGING BLOWING PRESSURE on sound output is depicted for a typical organ pipe. The Roman numerals represent the first few harmonics. The central regime (*color*) covers the range of normal speech, with a good balance at normal blowing pressure. At higher pressures the pipe overblows to its second mode; at low pressures there is a weak second mode.

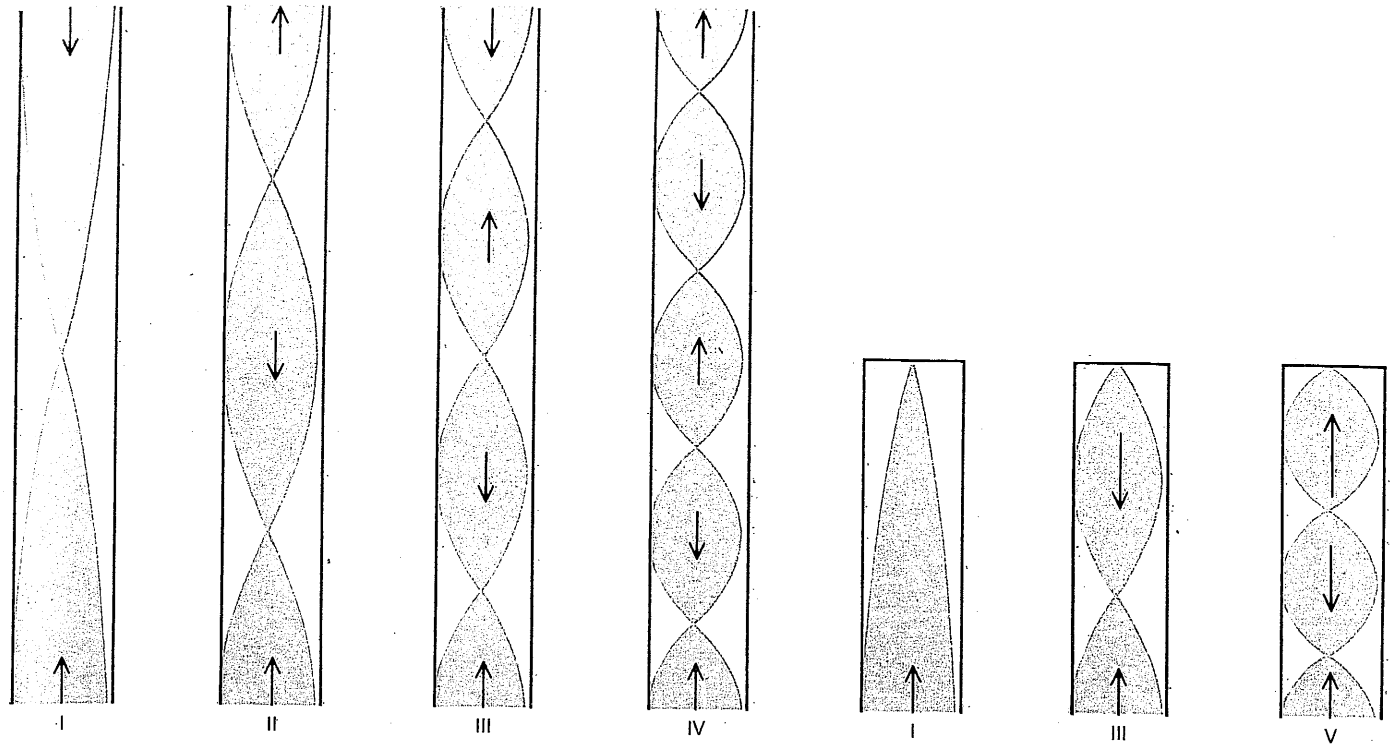


EFFECT OF LIP LOCATION on harmonic components shows the desirability of an offset. If the lip were exactly centered on the jet, the pipe would deliver only the fundamental frequency (*I*) and the third harmonic (*III*). With the lip offset at the location shown by the broken line, the second and fourth harmonics are introduced, greatly enriching the quality of the sound.

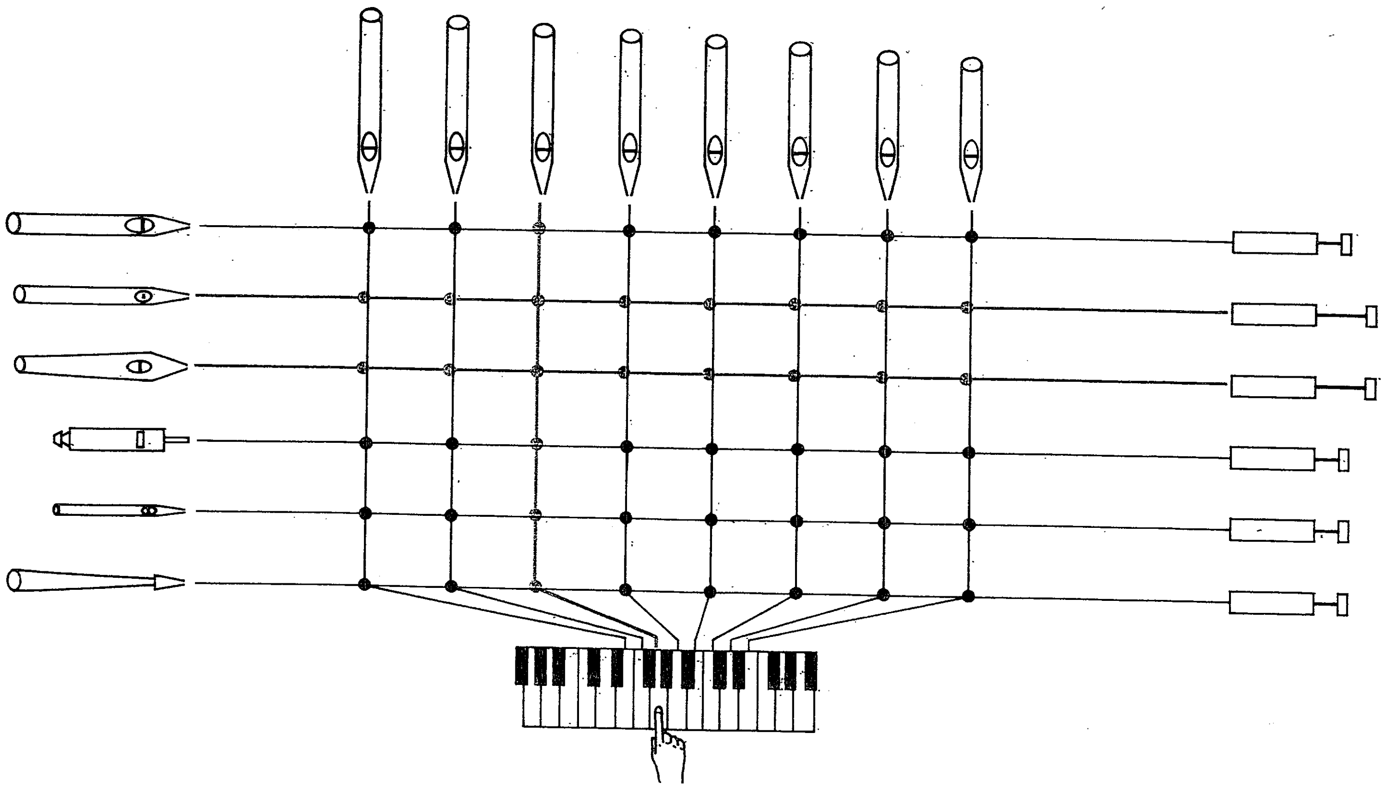
Finally, and of course important from the viewpoint of the player, comes the mechanism by which the speech of the multitude of pipes in a large organ is controlled. The basic design is delightfully simple and resembles the rows and columns of a matrix. The pipes are laid out in ranks, corresponding to the rows of the matrix. All the pipes in each rank have one tone quality, with one pipe for each note of the keyboard or pedal board. The air supply to each rank is controlled by a drawstop knob with the name of the rank written on it. The air supply to the pipes associated with each note, or column of the matrix, is controlled by the keyboard key for that note. A given pipe will sound if and only if it is in a rank for which the drawstop is pulled and on a key channel for which the key is depressed.

In these days one can imagine a host of ways of implementing such a scheme based on digital logic and electrically operated valves under each pipe. Early organs had simple mechanical levers and pallet valves to let air into the key channels, and perforated mechanical sliders to control the entry of air into an entire rank of pipes. Apart from having the virtues of simplicity and durability, this mechanical system gave the player precise control over the rate of opening of the key-channel valve and a feeling of closeness to the operation of an otherwise rather mechanical instrument.

In the 19th century and the early 20th large organs were built with all manner of electromechanical and electropneumatic mechanisms, but recently the emphasis has shifted back to mechanical action for the keys and the pedals, with sophisticated electronic controls for setting stop combinations as the instrument is being played. The organ in the concert hall of the Sydney Opera House, for example, is the largest organ in the world to have a mechanical action. Completed in 1979, it has 10,500 pipes in 205 ranks distributed across five keyboards and a pedal board. The key action is mechanical but is duplicated by an electrical action so that electric couplers can be used. Thus a live performance can be recorded digitally and the tape can be subsequently used to operate the organ, thereby re-creating the original performance. The stops and combination pistons are all electric or electropneumatic and are under the control of microprocessors having versatile stored-program capabilities. In such ways the best resources of modern technology, combined with traditional design and the skills of individual craftsmen following principles known for centuries, create the flexible and glorious sound of a large organ.



STANDING-WAVE RESONANCE PATTERNS are represented schematically for pipes open or closed at their upper end. The width of each colored pattern corresponds to the acoustic vibration amplitude in various parts of the pipe. The actual air motion is parallel to the axis of the pipe. Arrows show the direction of air motion during one half of the vibration cycle; during the other half the direction is reversed. The Roman numerals are the harmonic numbers and are proportional to the vibration frequencies. An open pipe has resonances for all the harmonics of its fundamental. A stopped pipe need be only half as long to produce the same note but has resonances for only the odd harmonics. Vibration patterns actually extend slightly beyond the ends of the pipe (calling for the end correction), and the complex geometry of the pipe mouth distorts the patterns somewhat at the lower end of the pipe without altering their "basic" nature.



PIPES OF AN ORGAN are arranged like the rows and columns of a matrix. In this simplified diagram each row, which is called a rank, consists of pipes of the same type with one pipe for each note (*top*). Each column, which is associated with one note on the keyboard (*bottom*), provides access to all the pipes of different kinds (*left*). The drawstops of the organ console (*right*) admit air to all the pipes of a rank; the keys of the keyboards admit air to all the pipes in the key channel for that note. The mechanism is arranged so that air reaches a pipe only if both its row and its column are activated. In the situation that is depicted in the diagram just two pipes will sound.