

## CHAPTER 17

# Pipe Organs

The pipe organ was known to the Romans and Greeks nearly 2000 years ago and began to develop toward its modern form in the late Middle Ages, the organ in Winchester Cathedral in the tenth century already having 400 pipes and a compass of 40 notes. By the seventeenth and early eighteenth centuries the art of organ building in Europe had reached an artistic and technical peak, particularly in Germany, and some of the greatest music of all time, particularly that of Bach, was strongly influenced by the style and structure of organs of this Baroque period.

With the rise in popularity of the orchestra in the Classical and Romantic periods, the organ suffered an artistic decline because of a desire on the part of its builders to imitate orchestral sounds, though many fine organs continued to be built for cathedrals and halls throughout the world. Fortunately, the workmanship of many early organs was excellent, and some large eighteenth century instruments have survived nearly unaltered to the present day.

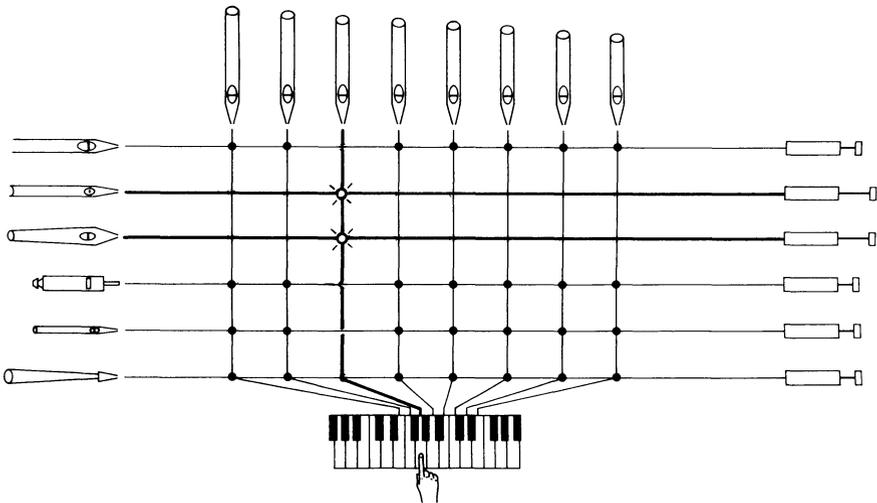
In the past 50 years, there has been a return to the organ as an instrument in its own right, and organs being built today for churches and concert halls have largely returned to the principles that guided the master builders of the eighteenth century. Even the mechanical technology of the organ mechanism has largely returned to its eighteenth century form—for good reason, as we shall see later—though the use of modern materials and electrical aids is rejected only by purists aiming at the reproduction of historical instruments.

In this chapter, we will be concerned almost exclusively with the acoustical aspects of organ building, and the reader is referred to one of the many fine books on the organ (e.g., Bonavia-Hunt, 1950; Andersen, 1969; Sumner, 1973; Lottermoser, 1983) for historical and technical details. Sumner (1973), in particular, gives the specifications of some 144 representative organs from around the world, built between 1497 and the present day, while Andersen (1969) presents 90 specifications illustrated by 80 plates.

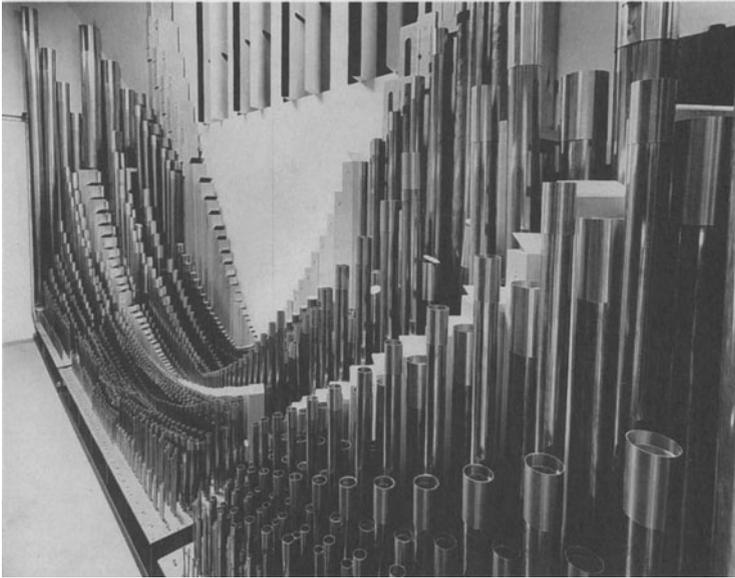
## 17.1. General Design Principles

The pipe organ is essentially a mechanized wind instrument of the panpipe type, in the same way that a harpsichord is a mechanized zither and the piano a mechanized dulcimer. Each pipe is a simple sound generator optimized to produce just one note with a particular loudness and timbre, and the organ mechanism directs air to particular combinations of pipes to produce the desired sound. A set of pipes of uniform tone quality with one pipe for each note over the compass of the organ keyboard is called a rank. A small, portable (portative) organ may have only a single rank, a somewhat larger positive organ designed for chamber music may have three or four ranks, while a large modern concert organ may have as many as 10,000 pipes in more than 200 ranks.

The essence of the mechanical arrangement is shown in Fig. 17.1. The pipes are set out logically, and generally to a large extent physically, in a matrix. The rows of the matrix are the individual ranks, while the columns are the notes of the keyboard. Figure 17.2 shows how this sometimes looks in practice. To give a symmetrical appearance, columns 1, 3, 5, ... of the matrix (C, D, E ...) are set out in order on the left, as viewed from the front of the organ, and columns 2, 4, 6 ... (C#, D#, F ...) in a mirror-symmetric arrangement on the right. Some modern builders, however, prefer the asymmetric soaring appearance of a rank set out in the order 1, 2, 3, 4 ... There is often a further physical



**Fig. 17.1.** The pipes of an organ are laid out as a matrix. Each row of the matrix contains the pipes of a single rank; each column of the matrix contains all the pipes for a single note. Drawstops control the admission of air to the pipes of a rank and keys of a keyboard control the admission of air to the pipes of a note. Pipes on all active intersections produce sound (Fletcher and Thwaites, 1983). (Copyright © Scientific American.)



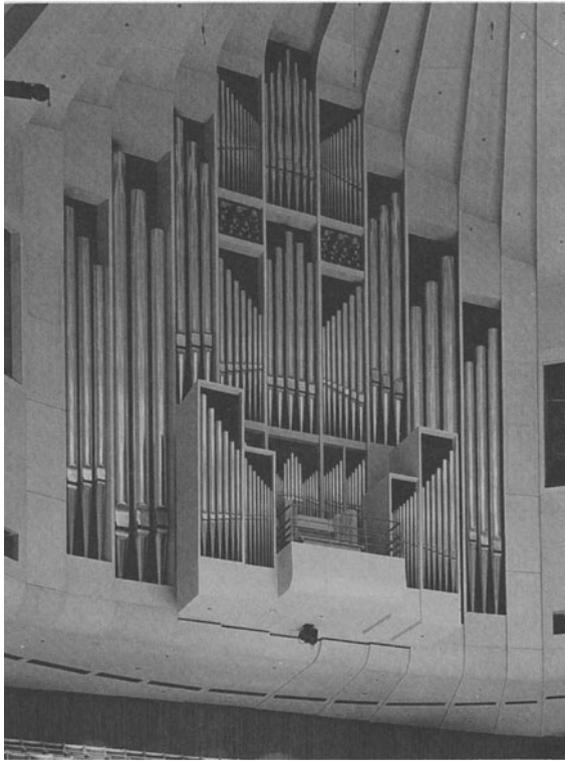
**Fig. 17.2.** Pipe ranks in the Swell division of the organ of the Sydney Opera House. Each rank is split and arranged symmetrically (Fletcher and Thwaites, 1983). (Copyright © Scientific American.)

disturbance to the matrix layout through the displacement of selected pipes from different ranks to the front of the organ case to provide an architecturally appropriate facade, as shown in Fig. 17.3.

While these physical arrangements may add some complication to the mechanism, they do not affect the logic of its design. In medieval organs, the only controls were keys, one for each note, which could be pressed or slid—they were quite large and medieval organs required several organists—to admit air to all the pipes in that matrix column. These pipes were flue pipes, normally tuned in octaves and fifths above the main rank, and constituted what we would now call a mixture, as we see later. This loud rich sound was the only timbre available to the organist. It was wondrously impressive in a large cathedral with a long reverberation time but was of little use for more delicate music.

The next development was the introduction of stops to turn off the air to particular ranks. This was usually accomplished by means of a wooden lath, known as a slider, with holes in it at positions corresponding to each pipe of the rank. When in register with the pipes, it allowed free access of air to that rank from any key that was pressed. When slightly withdrawn so that solid sections of slider were opposed to each pipe, the air access to that rank was blocked.

At about the time that the slider stop system was introduced, the note action was also stabilized in design. All the pipes sat in holes on top of a windchest, as shown in Fig. 17.4, which represents one column of the matrix.



**Fig. 17.3.** Display pipes of the organ at the Sydney Opera House. Pipes of appropriate size are borrowed from various ranks of the organ and moved to positions at the front of the case. Display pipes are linked to their normal positions by wind trunks and produce sound in the normal way (Fletcher and Thwaites, 1983). (Copyright © Scientific American.)

The windchest itself was divided into separate key channels, one for each matrix column or note, and these operated quite independently except for the influence of each stop slider on all pipes of its rank. The whole windchest can be made, indeed must be made, wider than the keyboard to accommodate the larger pipes. The action can easily be spread laterally by means of rollers, essentially axles fitted with levers at each end, and vertically by extended pull-downs or trackers attached to the lever arms of these rollers. The whole mechanism, known as a slider chest with tracker action, was the basis of organ building up to the mid-nineteenth century and has recently come back into favor for organs of all sizes because of the intimate control of the admission of air to the pipes that it affords to the organist.

We have so far described a single organ controlled by a single keyboard. To allow variety and contrast on larger instruments, it is invariable practice to distribute the ranks on different windchests, each controlled by a different keyboard or pedalboard. Except for small chamber organs, the lower limit is

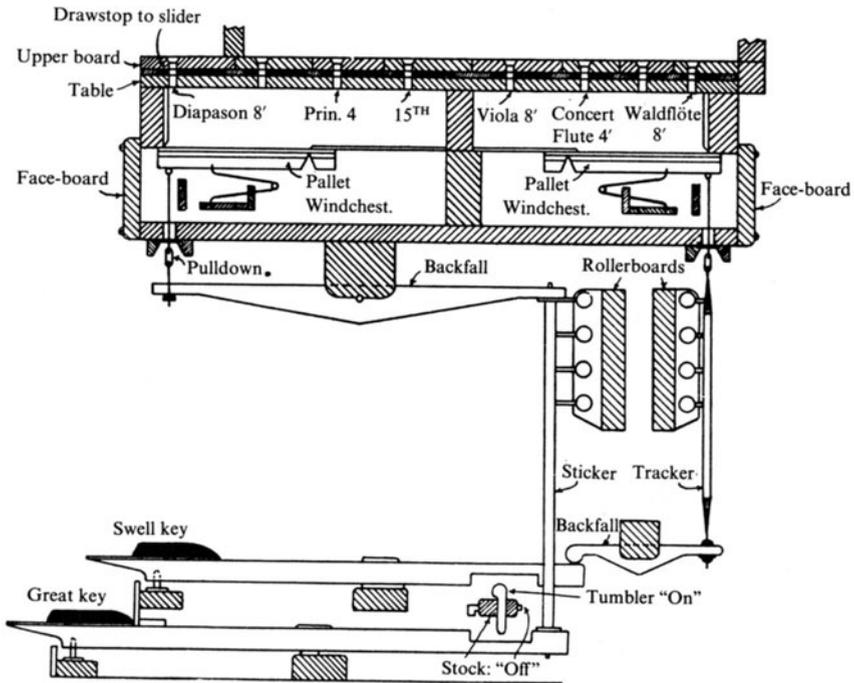
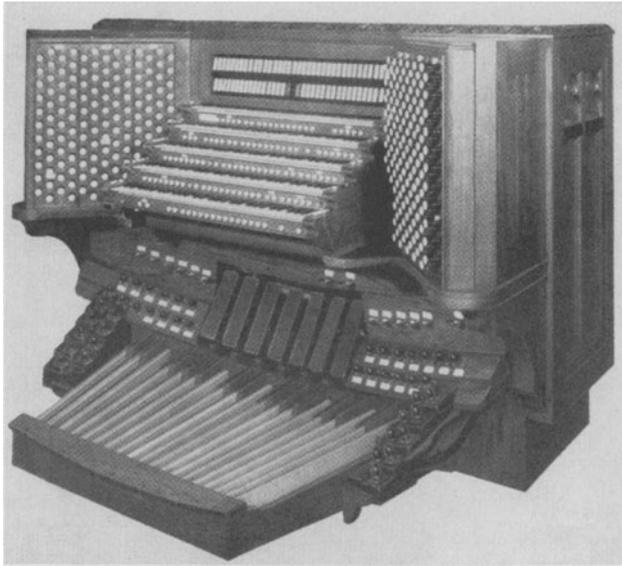


Fig. 17.4. A typical organ tracker action and slider chest. Two independent manuals with slightly different action are shown (Bonavia-Hunt, 1950).

2 manual keyboards of 5 octaves compass and a pedal keyboard of  $2\frac{1}{2}$  octaves. The upper limit for a large concert or cathedral organ is 5 manuals and a pedalboard, the compass of each being 5 octaves for the manuals and  $2\frac{1}{2}$  octaves for the pedals. An example of such a console is shown in Fig. 17.5.

In the German organ-building tradition, all these separate organs, or divisions of the organ, stood open within the organ case and differed from each other in power and timbre. In the British tradition, it became usual in the nineteenth century to enclose one or more of the divisions (and often all but the main great organ) in solid boxes of masonry or timber, fitted with louvres that could be controlled by the organist to produce a swell effect. Modern organs combine the best features of both traditions with several unenclosed and several enclosed divisions.

With the rise of ingenious mechanisms in the nineteenth century, it was natural that these should be applied to the organ. The first were pneumatic levers that enabled the manuals to be coupled to each other and to the pedals without requiring extra playing force on the keys. Pneumatic action was then extended to the primary mechanism as well, so that the only force required on the key was that necessary to open a small valve and allow a pneumatic bellows motor to collapse. With the advent of reliable electrical supplies, key actions using electromagnets were also introduced, either in conjunction



**Fig. 17.5.** The console of a large organ. The drawstops are mounted on the wings, buttons under each keyboard control groups of stops, usually in an adjustable manner, and their functions are duplicated by toe studs. The inclined flat pedals control the opening of the various swell shutters (Aeolian–Skinner).

with a pneumatic action or as a direct valve actuator for each pipe. Along with these innovations came electropneumatic (or now even microprocessor-controlled) stop actions, with combination buttons to select particular sets of stops, and many other devices. Some of these have become standard on modern organs, even those with mechanical tracker action, and some of them have faded into oblivion.

Other aspects of the organ have also benefited from modern technology. The tenth-century Winchester Cathedral organ was reputed to have required the services of 70 men working a total of 26 bellows. This may have been an exaggeration, but certainly several bellows pumpers were required until comparatively recent times. Hydraulically driven bellows were in vogue in the 19th century and served well, but it is now universal practice to use electric blowers and pressure regulators to provide a steady air supply at the different pressures required for the various windchests of the organ.

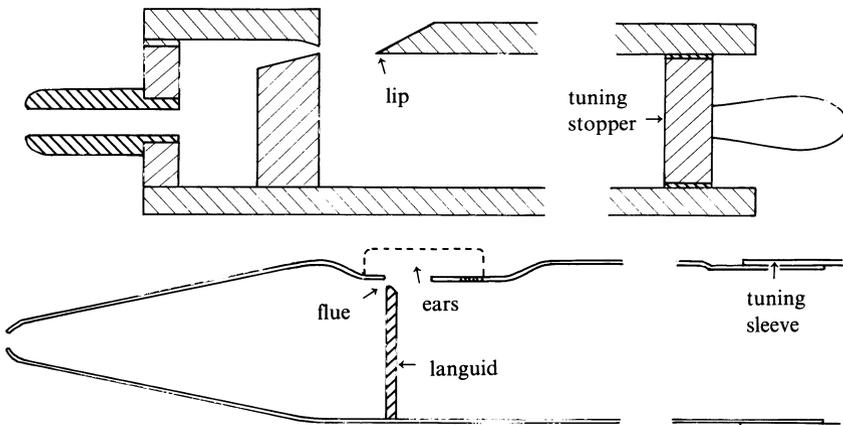
## 17.2. Organ Pipe Ranks

The normal compass of a manual keyboard on a modern organ is from  $C_2$  (65 Hz) to  $C_7$  (2093 Hz). Organs of Bach's time lacked only the seven notes above  $F_6$ . A convenient terminology has developed for specifying organ ranks

because, as we remarked above, they are not all tuned to produce the note nominally being played. For such a nominal or unison rank, the lowest pipe,  $C_2$ , has a sounding length of about 2.6 m which is a little more than 8 feet. Allowance for end corrections makes the physical length very close to 8 ft. Such a unison rank is thus referred to as an 8-ft rank. A rank sounding an octave higher than nominal is a 4-ft rank, a twelfth higher a  $2\frac{2}{3}$ -ft rank, two octaves a 2-ft rank, and so on, these being ranks that reinforce the second, third, and fourth harmonics of the nominal fundamental, respectively.

The pedal keyboard is written in the score as though it had a compass from  $C_2$  to  $G_4$  but the standard pedal stop is a 16-ft rank sounding an octave lower than written. Large organs may also have a 32-ft rank, sounding two octaves lower than written and with a lowest note of about 16 Hz. There has even been one full-length 64-ft rank constructed, with mammoth conical wooden pipes of square cross section and a top opening more than a meter across for the lowest pipe, which has a frequency of 8 Hz. This rank is a reed stop, labeled “contra trombone” on the fine organ built in 1886 for the Town Hall in Sydney, Australia, by William Hill of London. At the time it was built, this organ was the largest in the world—it has recently been lovingly restored to its original condition, pneumatic action and all.

We will consider particular stops later, but for the present we should recognize two basically different types of ranks—flues and reeds. Flue pipes, also called labials because it is the upper lip of the mouth that is important in sound production, belong to the flute-instrument family discussed in Chapter 16. Construction is shown in Fig. 17.6. Open flue pipes are historically the basis of the pipe organ and still provide its foundation sound. We can also have stopped flue pipes, which have the economic advantage that a stopped pipe of 16 ft pitch has a physical length of only 8 ft. In addition, there are



**Fig. 17.6.** Sectional views of a stopped wooden flue pipe and an open metal flue pipe. Details of construction vary from one builder to another.

various partly stopped pipes in which the stopper has a vent or chimney to produce special effects.

Reed pipes, or linguals, have a metal tongue vibrating against a rather clarinetlike structure called a shallot. There are two major classes of reeds, those with full-length conical resonators supporting all harmonics and those with half-length cylindrical resonators supporting primarily the odd harmonics. In addition, we find short reed pipes with cavity resonators rather like trumpet mutes, but they are quite unusual in modern organs.

### 17.3. Flue Pipe Ranks

Flue pipes may be open, stopped, or partly stopped and may be made of wood or metal. The wooden pipes are generally nearly square but some are appreciably rectangular, the main effect of this being to alter the ratio of the mouth width to the circumference of the pipe. Metal pipes are generally cylindrical but may taper to narrower open ends. The mouth opening is cut into a flattened part of the pipe wall and can have any desired ratio to the circumference of the pipe.

One of the first things to be determined by the builder is the length of pipe necessary for a note of a particular frequency. The effective length  $L'$  for an open pipe of frequency  $f$  is half a wavelength, so that

$$L' = \frac{c}{2f}, \quad (17.1)$$

where  $c$  is the velocity of sound in air at the room temperature at which the organ is to be played. This effective length consists of the physical length  $L_0$  together with the end corrections  $\Delta_e$  at the open end and  $\Delta_m$  at the mouth.

$$L' = L_0 + \Delta_e + \Delta_m. \quad (17.2)$$

For a stopped pipe of the same frequency, the effective length  $L''$  is only one quarter of a wavelength and there is no end correction at the stopped end. The required physical length is thus  $L_s$ , where

$$L'' = L_s + \Delta_m. \quad (17.3)$$

If the open pipe is a simple cylinder of radius  $a$ , then, as discussed in Section 8.3, we know (Levine and Schwinger, 1948) that

$$\begin{aligned} \Delta_e &\approx 0.6a & (ka \ll 1), \\ &\approx 0 & (ka > 4), \end{aligned} \quad (17.4)$$

as shown in Fig. 8.8. Calculation of  $\Delta_m$  is not rigorously possible since the mouth is a rectangle cut into the side of the pipe and the acoustic flow geometry is very complex (Dänzer and Kollmann, 1956). Various approximate formulas have been given however (Jones, 1941). Ingerslev and Frobenius

(1947) have derived a result based on approximating the rectangular mouth by an ellipse of the same area and related eccentricity that reduces approximately to

$$\Delta_m \approx \frac{2.3a^2}{(lb)^{1/2}} \quad (17.5)$$

for a mouth of width  $b$  and height  $l$ , with  $l \approx b/4$ , cut in a cylindrical tube of radius  $a$ . Generally,  $\Delta_m \gg \Delta_e$ .

In practice, neither  $\Delta_e$  nor  $\Delta_m$  may be as simple as given by Eqs. 17.4 and 17.5, for the open end may have a tuning slot, tongue, or sleeve and the mouth may have ears or other obstructions. Organ builders have therefore traditionally relied upon rules of thumb or cut-and-try methods, supplemented by centuries of practical experience.

The tone quality of a flue pipe depends on many things, some of them fixed by the dimensions of the pipe body and some influenced by the subtle voicing adjustments made to the pipe mouth when the whole rank is being brought into balance. As we saw in Chapter 16, the flue pipe behaves as an active element in the sound generation process as far as its fundamental is concerned, but largely as a passive resonant filter for the upper harmonics of the sound (Fletcher and Douglas, 1980). It is therefore important to understand the general influence of pipe dimensions on this passive resonance behavior.

Two aspects of this behavior require attention—the frequencies of the resonances relative to the harmonics of the fundamental, and the  $Q$ -factors or damping coefficients associated with each resonance.

The open-end correction  $\Delta_e$  decreases smoothly with increasing frequency (Levine and Schwinger, 1948) and is essentially zero for  $ka > 3.8$  as was shown in Fig. 8.8. The mouth correction  $\Delta_m$  also decreases with increasing frequency and at a rather more extreme rate (Meyer, 1961; Wolf, 1965) as characterized by the parameter  $k\Delta_m^0$ , where  $\Delta_m^0$  is the low-frequency value of  $\Delta_m$ , rather than by  $ka$ . Since from Eq. (17.5), using typical mouth dimensions,  $\Delta_m^0 \approx 3a$ , the sharpening of upper resonances can be quite large and is accentuated by a small mouth area. A useful parameter to quantify this mouth-detuning effect is

$$\frac{\Delta_m^0}{L} \propto \frac{a^2}{(lb)^{1/2}L} \approx \frac{2a^2}{bL} = g, \quad (17.6)$$

where the last form follows from the fact that typically  $l \approx b/4$ . For representative types of flue pipes, the parameter  $g$  ranges from about 0.05 for narrow-scaled soft pipes producing a soft violinlike sound to as much as 3 or even 6 for broad-scaled, narrow-mouthed pipes giving a very dull flutelike sound with little harmonic content.

Since this discussion suggests that the parameter  $g$  should be held constant for all the different sized pipes of a single rank and since the mouth width  $b$  is usually made a constant fraction of the pipe circumference, around one quarter for a pipe of normal diapason or principal tone, it seems that the ratio  $a/L$  should be constant, making all pipes geometrically similar. Such a scaling

rule, however, gives bass pipes that are loud and broad in tone and treble pipes that are thin and weak. The problem of finding a scaling rule that gives tonal coherence and balance across a rank of pipes is of central importance in organ building and one to which the great builders have found satisfactory empirical solutions (Andersen, 1969; Mahrenholz, 1975).

The similarity scaling suggested above would result in a doubling of the pipe radius every octave, “doubling on the 12th pipe” as builders often call it. For a satisfactory scale however, the bass pipes must be made narrower than this and the treble pipes wider. A scaling with doubling at the fifteenth to eighteenth pipe is generally satisfactory for diapason ranks, but in fact the scalings used historically generally depart from such a rule over at least part of their compass.

Some theorists of the past have advocated scaling rules of the form

$$a(f_1) = b_0 + \left(\frac{f_0}{f_1}\right) a_0 \quad (17.7)$$

for the radius  $a(f_1)$  at frequency  $f_1$ , relative to the lowest pipe at  $f_0$ . More generally applicable, however, are rules of the form

$$a(f_1) = \left(\frac{f_0}{f_1}\right)^x a_0, \quad (17.8)$$

which correspond to the simple doubling on the  $n$ th pipe rules (where  $n = 12/x$ ). The similarity scaling has  $x = 1$ , while a typical modern scaling has  $x \approx 0.75$ . Numerologically inclined theorists have argued for octave ratios  $2^x$  with particular values such as  $5:3 = 1.667$ ,  $\sqrt[4]{8}:1 = 1.682$ , or the “Golden Ratio” 1.618 of Renaissance art theory. The scaling with  $x = 0.75$  is in fact  $\sqrt[4]{8}:1$ , and the others will be scarcely distinguishable from it, but there is no basis for the numerological arguments. Instead, we must look for physical and psycho-physical reasons behind the scaling (Fletcher, 1977).

Physically, we must consider the quality factors  $Q$  of the pipe resonances as functions of frequency, or preferably as functions of mode number  $n$  for the pipe concerned. There are two sorts of loss mechanisms contributing to the damping: radiation loss from the mouth and open end and losses to the pipe walls through viscosity and thermal conductivity. There may also be losses caused by turbulence at the sharp edges of the mouth, but we shall neglect these as they are mostly associated with the air jet from the flue.

The energy loss rate from the open end of the pipe is proportional to the square of the volume flow  $\pi a^2 v$  multiplied by the frequency squared; the loss to the walls is proportional to the total wall area  $2\pi aL$  and to the product of the acoustic flow velocity  $v$  with the gradient of this velocity across the boundary layer, the thickness of which is proportional to  $f^{-1/2}$ . The total loss rate  $D$  can therefore be written as

$$D = (A'a^4f^2 + B'aL f^{1/2})v^2, \quad (17.9)$$

where  $A'$  and  $B'$  are constants. The total stored energy  $E$  can be similarly written as

$$E = Ca^2Lv^2, \quad (17.10)$$

so that the quality factor  $Q$  at the resonance in question is

$$Q = \frac{2\pi f E}{D} = (A''L^{-1}a^2f + B''a^{-1}f^{-1/2})^{-1}, \quad (17.11)$$

where  $A''$  and  $B''$  are new constants. However, for the  $n$ th resonance of a pipe with fundamental frequency  $f_1$ ,  $f \approx 2ncL^{-1} \approx nf_1$ , so that its  $Q$  value can be written

$$Q_n = (Aa^2nf_1^2 + Ba^{-1}n^{-1/2}f_1^{-1/2})^{-1}. \quad (17.12)$$

Now, if we substitute the scaling law, Eq. (17.8), we find that

$$Q_n = (Af_0^{2x}f_1^{2-2x}a_0^2 + Bf_0^{-x}n^{-1/2}f_1^{x-(1/2)}a_0^{-1})^{-1}. \quad (17.13)$$

If  $x$  has the particular value  $\frac{5}{6} \approx 0.83$ , then this expression is homogeneous in  $f_1$ , and a factor  $f_1^{-1/3}$  can be taken outside the brackets. For such a scaling, which corresponds to an octave scaling ratio  $2^x$  of 1.78, the relative  $Q$  values of all resonances remain the same from one pipe to the next, though the absolute values decline as we ascend the scale. This should give tonal similarity across the whole rank, though the basses may be rather loud compared to the trebles.

A reduction of  $x$  to the usual value near 0.75 should remedy this unbalance in loudness across the rank at the expense of weakening the fundamentals of the lowest pipes. This tendency is further enhanced for any  $x < 1$  by the behavior of the parameter  $g$  in Eq. (17.6). The total effect, therefore, is that a tonally balanced rank has greater harmonic development in the bass than in the treble, a feature that we remarked on in Chapter 11 in relation to the harpsichord and one that accords with the region of greatest human auditory discrimination being between about 500 and 3000 Hz.

## 17.4. Characteristic Flue Pipes

The diapason or principal ranks of a pipe organ produce its major characteristic tone color. They are open pipes, generally made from some form of pipe metal, a tin-rich lead-tin alloy, and have a moderate scaling, around a 4-cm radius at tenor C ( $C_3$ , where the pipe length is 4 ft). Most organs have diapason ranks at 8 ft, 4 ft, and 2 ft pitch on the principal manual (the Great Organ in English terminology or Hauptwerk in German) and may supplement these by ranks at  $2\frac{2}{3}$  ft and 1 ft, in addition to the mixture ranks we will mention later. The mouth width of a diapason pipe is usually about one quarter of the circumference, and the cut-up distance from the flue to the upper lip is about one quarter of the mouth width.

Principal ranks in older organs and in many modern instruments are blown with quite low wind pressure, 0.5 to 0.8 kPa (5 to 8 cm or 2 to 3 in. water gauge). In some cases, the edge of the languid is lightly nicked to produce homogeneous turbulence in the jet and ensure stable speech. During the low point of classical organ building in the earlier years of this century, blowing pressures were raised to 2 kPa (20 cm water gauge) or more, nicking was very heavy, and the cut-up was necessarily greater, giving a loud but dull sound which has now gone out of favor.

Principal ranks also occur in the pedal divisions of larger organs where they may be made either of wood or metal. A 16-ft rank represents the foundation tone, but 8-ft and 4-ft ranks can be provided to reinforce this or for use as solo stops, and pedal mixtures are found on large organs.

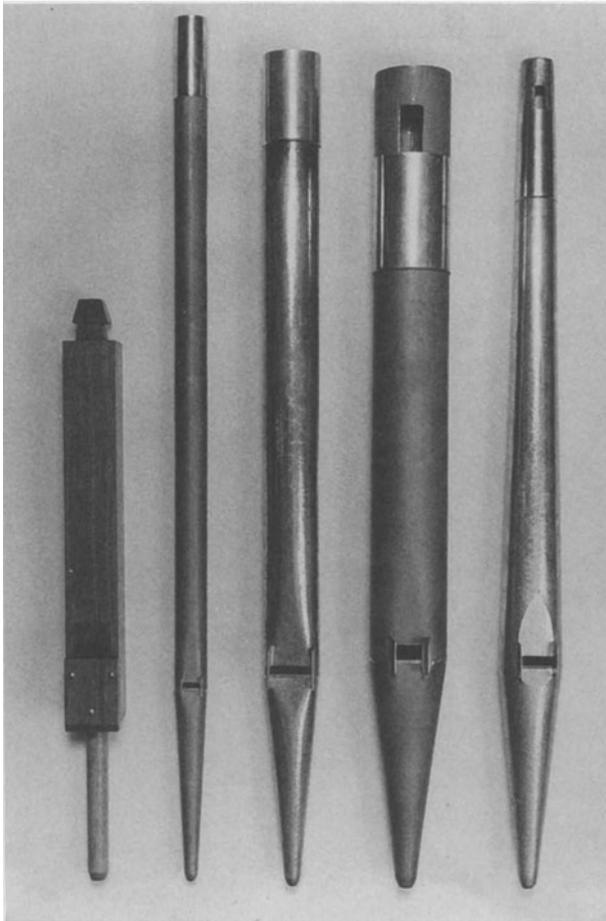
Flute stops of many tone colors are found in most of the organ divisions where they provide a softer and less incisive sound, either as chorus or solo voices. They are typically provided at 8-, 4- and 2-ft pitches and can be supplemented by other ranks, as we shall see later, in the form known as mutation stops. Flute pipes may be of wood or metal, and may be open, tapered or stopped, but are built with generally wider scales, narrower mouths, and softer voicing than diapason ranks. A common stopped flute found on the pedal division of most organs—it is sometimes the only rank on small organs—is the 16-ft bourdon. It is generally an undistinguished rank but, being stopped, it is inexpensive and takes relatively little space. A 16-ft bourdon or other flute is sometimes found as a subharmonic rank on manuals as well. A quiet 32-ft flute is sometimes found in the pedal division of large instruments.

Chimney flutes, in which the stopper is pierced by a narrow pipe, produce interesting and characteristic solo sounds. The length of the chimney can be set so that the whole pipe has a sharp resonance, usually at the fifth harmonic, giving a very pleasant sound. Such a rank is sometimes called a gedackt on German or English organs. In other solo flutes, various types of resonant caps or other devices can be used to produce interesting new voices.

Another common rank is the harmonic flute, a double-length pipe with a small hole near its center so that it always overblows to its second mode, though with a suggestion of the suboctave mode and its odd harmonics to enrich the tone.

Finally, we should mention the so-called string ranks with names such as violone, gamba, or salicional. These are all soft-toned ranks of very narrow scaling, voiced to give a weak fundamental and a large range of well-developed harmonics. These ranks are not found on baroque organs but have their origin in the earlier years of the orchestral imitative period. However, they do represent a useful and distinctive quiet chorus effect and are present on most modern organs of medium to large size.

The wealth of variety among these ranks is so large that it is impossible to document their structure or sound in detail. Some examples are shown in Fig. 17.7. An extensive glossary is given by Sumner (1973), while some measurements have been presented by Boner (1938), Tanner (1958), and Fletcher et al. (1963).



**Fig. 17.7.** Varieties of flue pipes. From left to right: a stopped wooden flute; a string-toned dulciana; a principal or diapason (note the tin-rich spotted metal pipe alloy); a dull-toned flute; and a soft waldflöte. All pipes sound the same note  $C_4$ ; the length differences are due to differing end corrections (Fletcher and Thwaites, 1983). (Copyright © Scientific American.)

## 17.5. Mixtures and Mutations

In the earliest organs, as we have already remarked, ranks of pipes were tuned in octaves and fifths above the fundamental for each note, and all sounded together. This synthesis principle is the basis of the mixture and mutation stops of baroque and modern organs.

In virtually all natural sounds, increasing loudness is associated not simply with a uniform increase in sound pressure level at all frequencies, but rather

with a change in the slope of the frequency spectrum to give more weight to components of higher frequencies. This is a natural consequence of the nonlinearities associated with the production of such sounds. Because of masking in the human auditory system and other well-established psychophysical phenomena (Stevens and Davis, 1938; Plomp, 1976), the ear also perceives sounds of wide bandwidth as being louder than sounds with only a few strong components. An organ mixture stop achieves this end not by simply adding more and louder unison ranks with reasonable harmonic development, but by adding higher pitched ranks to selectively reinforce the upper harmonics (Pollard, 1978a, 1978b).

Mixtures are generally ranks of diapason-scaled pipes designed to augment the normal 8-ft + 4-ft + 2-ft diapason chorus. They generally have from 3 to as many as 10 ranks all properly balanced and coupled together. In normal mixtures, only octaves and fifths are used, but the selection of pitches breaks back at various parts of the compass to concentrate most of the sound energy over a broad band between about 500 Hz and 6 kHz. For example, for a 4-rank mixture, we might have

Harmonic	3	4	6	8	12	16	24
C <sub>2</sub> -B <sub>2</sub>				1 ft	$\frac{2}{3}$ ft	$\frac{1}{2}$ ft	$\frac{1}{3}$ ft
C <sub>3</sub> -B <sub>3</sub>			$1\frac{1}{3}$ ft	1 ft	$\frac{2}{3}$ ft	$\frac{1}{2}$ ft	
C <sub>4</sub> -B <sub>4</sub>		2 ft	$1\frac{1}{3}$ ft	1 ft	$\frac{2}{3}$ ft		
C <sub>5</sub> -C <sub>6</sub>	$2\frac{2}{3}$ ft	2 ft	$1\frac{1}{3}$ ft	1 ft			

The same sort of arrangement applies to mixtures with more or fewer ranks; the difference between various mixture types derives from the number of ranks and their general center of pitch.

Another type of mixture, which is of German origin, also exists, in which a rank sounding a 5th or 10th harmonic ( $1\frac{2}{5}$  ft or  $\frac{4}{5}$  ft) is added. The names Zimbel or Sesquialtera are usually used for such a mixture, while a mixture composed entirely of octave pipes is usually called a Piffero or Schreipfeife. When used in combination with a full diapason chorus, or with reed stops, a full mixture in a reverberant building produces a thrilling blaze of acoustic color.

Rather different are the mutation stops, although they too are designed to reinforce particular harmonics of the fundamental. They are used, however, as solo voices with component ranks of flute character and do not have the breaks characteristic of mixtures. Generally, the third, fourth, and fifth harmonics of the fundamental ( $2\frac{2}{3}$  ft, 2 ft,  $1\frac{3}{5}$  ft) will be available as separate ranks to be added in any combination to the 8-ft flute rank to produce a reedlike solo voice called a Kornett, much used for playing decorated melodies in baroque music. Larger Kornetts with more ranks also exist. It is interesting that such synthetic stops, anticipating the principles of modern electronic music, go back in history to the Middle Ages!

## 17.6. Tuning and Temperament

Mixture ranks bring into sharp focus the insoluble problems of tuning and temperament for keyboard instruments, and it is worthwhile to examine these briefly. Unlike a piano string, the overtone components of an organ pipe sound are strictly harmonic and phase locked to the fundamental. Beats and other interference effects are therefore very obvious. There is no problem in tuning octaves on the keyboard or between octave ranks, because the overtones of all organ pipes are exact harmonics, and the organ has exact octaves throughout its entire compass, unlike the stretched octaves characteristic of the piano.

When the tuner lays out the other notes of the scale, however, he or she meets the classic problem of tuning and temperament (see Chap. 9 in Rossing, 1982). For perfect concord and no beats, we require simple integer frequency ratios for all important musical intervals: 2 : 1 for the octave, 3 : 2 for the perfect fifth, 5 : 4 for the major third, etc. A cycle of fifths,  $F \rightarrow C \rightarrow G \rightarrow D \rightarrow A \rightarrow E \rightarrow B \rightarrow F\# \rightarrow C\# \rightarrow G\# \rightarrow D\# \rightarrow A\# \rightarrow E\#$ , should ideally bring us back to an  $E\#$ , which is the enharmonic equivalent of the  $F$  from which we started. However, the prime number theorem shows that the frequency ratio  $(\frac{3}{2})^{12}$  reached by this progression cannot be an exact number of octaves  $2^N$ , with  $N = 5$  (since it is not possible for  $3^{12}$  to precisely equal  $2^{17}$ ). The error, which is called the Pythagorean comma, is about 1.3% or nearly a quarter of a semitone. The system of equal temperament used universally today distributes this error equally over all 12 of the fifths by tuning each one flat (tempering it) by about 0.1%. This gives a slow beat that is detectable but not really objectionable since the audible beat rate (between the third harmonic of the lower note and the second harmonic of the upper) is about one per second in the midrange of the keyboard.

The situation with major thirds is, however, very much worse. Three equal-tempered major thirds ( $C \rightarrow E \rightarrow G\# \rightarrow C$ ) make up an octave, so the frequency ratio of each is  $2^{1/3} = 1.260 \dots$ , which is nearly 1% greater than the just major third,  $\frac{5}{4} = 1.25$ . There is thus a rather fast beat between the upper components of two notes a major third apart, giving a sense of roughness to the interval. The situation is much worse when a mixture such as the sesquialtera, which contains a fifth-harmonic rank tuned a just major third above one of the octaves of the fundamental, is added to the sound, for there is then a direct beat between this rank and one of the octave ranks from the higher note. The components of one note of the mixture cannot be tuned to tempered intonation for they would then beat together, producing just as bad an effect.

Organists in the Baroque and Classical periods generally minimized this problem by tuning their organs to some form of meantone tuning (Barbour, 1953; Backus, 1977; Rossing, 1982). In this system, the important fifths are tuned slightly flatter than in equal temperament so that the important major and minor thirds are exact, with frequency ratios of  $\frac{5}{4}$  and  $\frac{6}{5}$ . This system

concentrates most of the mistunings into rarely used intervals and, of course, cannot close the cycle of fifths. Some organs even had a split  $A\flat/G\sharp$  key to accommodate the worst of this problem. Though meantone tuning gave sweet-sounding mixtures and major triads, its limitations eventually made it obsolete, and modern ears have come to tolerate the clash of sounds inevitable in equally tempered full chords. A few new organs are, however, now being tuned to the best of these older systems.

### 17.7. Sound Radiation from Flue Pipes

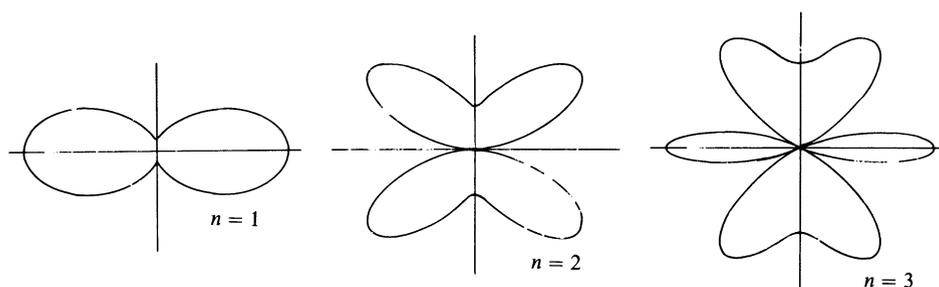
The radiation of sound from stopped pipes is a relatively simple matter, since there is only a single radiating source at the pipe mouth. Because the mouth is very small compared with the pipe length, and therefore with the wavelength of the fundamental, the radiation pattern of the lower harmonics of the sound is nearly isotropic. For higher harmonics, when the wavelength becomes less than a few times the width of the mouth, the radiation pattern becomes concentrated to the front of the pipe, with a large angular spread in the vertical plane and a smaller spread in the horizontal plane.

Much more significant is the radiation pattern for an open pipe, for then we have two coherent sources, at the mouth and open end respectively, which are acoustically in phase for odd harmonics and out of phase for even harmonics. It is not immediately clear that the strength of these two sources is the same, for the area of the mouth is typically less than one fifth of the area of the open end, and the flow of the jet must also be considered. The discussion of Section 16.3, however, showed us that the acoustic flow in the pipe, and thus at the open end, is exactly equal to the sum of the jet flow and the mouth flow, and, since the power radiated depends only on the total acoustic flow and not on the aperture size, we expect the strengths of the two sources to be exactly equal. This point has been confirmed experimentally by Coltman (1969).

The consequences of this balance are quite significant. If we consider the  $n$ th harmonic of the pipe, then the phase relation between the two sources is  $(-1)^{n+1}$ . If  $L$  is the physical length of the pipe, slightly less than an integral number of half-wavelengths, then the radiation pattern is symmetrical about a plane through the midpoint of the pipe and perpendicular to its length, and the intensity radiated in a direction making an angle  $\theta$  to this plane is proportional to

$$\begin{aligned} I(\theta) &= [\cos(kL \sin \theta) + (-1)^{n+1}]^2 + \sin^2(kL \sin \theta) \\ &= 2[1 - (-1)^n \cos(kL \sin \theta)], \end{aligned} \quad (17.14)$$

where  $k = 2\pi n f_1 / c$  and  $f_1$  is the sounding frequency of the pipe. Calculated polar diagrams for several harmonics of a typical pipe are shown in Fig. 17.8, and these are confirmed by measurement, the near cancellation at certain



**Fig. 17.8.** Typical radiation patterns for three harmonics of an open flue pipe, standing vertically. The total end correction is assumed to be 20% of the pipe length.

angles being very pronounced for the first few harmonics in an anechoic environment.

Fortunately, most organs are heard in relatively live environments and at a considerable distance from the instrument, so that it is the total radiated power that is important rather than the intensity radiated in a given direction. Indeed, standing waves in the hall are likely to be of more audible importance than these directional effects. The phenomenon is, however, of importance if we are recording an organ using microphones close to the pipes or, even more, if we are examining the tonal spectra of organ pipes on the basis of such measurements.

## 17.8. Transients in Flue Pipes

In Chapter 16, we discussed briefly the starting transients of jet-blown instruments, organ pipes being those best understood because of the reliably reproducible nature of the air supply mechanism. Experimental studies have been reported by Trendelenberg et al. (1936, 1938), Nolle and Boner (1941), Caddy and Pollard (1957), Franz et al. (1969–1970), Keeler (1972), Pollard and Jansson (1982a, 1982b), and Nolle (1983). Fletcher (1976) has provided a theoretical basis.

All these studies show that the initial transient stage lasts for 20 to 40 periods of the fundamental of the pipe, during which time the components of the sound build to their steady levels, but the behavior of these components during the transient depends on the voicing of the pipe and the nature of the blowing pressure transient in the pipe foot. For a pipe voiced and blown near the middle of its stable regime of normal speech and for a relatively slow rise in blowing pressure, the fundamental and overtones rise in level together and rapidly achieve locking into harmonic relationship. If the pipe is voiced so that it is close to overblowing to its next mode however, and particularly if the blowing pressure is applied rather abruptly, there may be an initial

burst of sound at the second mode frequency—either the octave or twelfth depending on whether the pipe is open or stopped—before the steady sound develops. This premonitory sound is not locked in frequency to the fundamental and may differ significantly from exact harmonic relationship to it.

Baroque builders enjoyed the presence of these transitory sounds and purposely voiced some of their flute ranks, usually stopped, to give a clear chuff. This sound has returned to vogue for particular ranks of the modern organ, but for many years considerable pains were taken during pipe voicing to eliminate it.

For most ranks of the organ, the attack transient simply represents a characteristic component of the timbre, but for low-pitched pedal ranks, the delay time, approaching a second, before the pipe settles to steady speech can present musical difficulties. There is little that can be done about this for a single pipe, for the jet must feed acoustic energy to the air column and this takes time. However, when the fundamental pipe has its sound augmented by octaves and mixtures at much higher pitches, these pipes speak relatively quickly with their own typical initial transients, and the attack is prompt. The ability of the human auditory system to imply a fundamental when an adequate range of its upper harmonics is present gives tonal coherence and a consistent low pitch to the perceived sound.

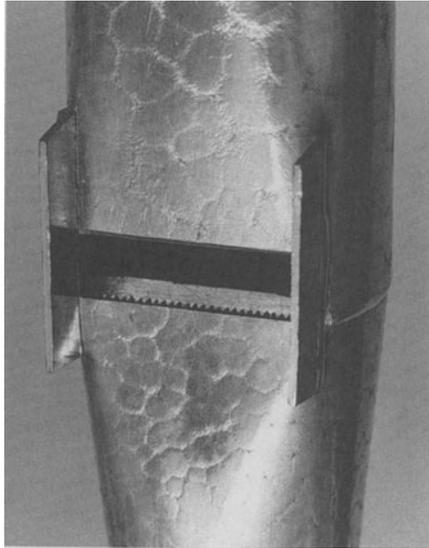
### 17.9. Flue Pipe Voicing

One of the great advantages of lead–tin alloys for pipe making is their relative softness, which means that pipes can be readily finished and adjusted by hand using simply a small, sharp knife. Parameters available to the voicer for adjustment, though some of them only on a one-time basis, are

- the opening in the foot of the pipe, effectively controlling the blowing pressure at the flue slit;
- the width of the flue slit, and whether or not there is nicking at the edge of the languid;
- the cut-up and shape of the upper lip, effectively controlling the jet length;
- the height of the languid, effectively controlling the direction of the jet relative to the upper lip; and
- the upper cap, tongue, or sleeve, effectively controlling the pitch for tuning.

In all these adjustments, the voicer must have regard to the steady sound of the pipe, to its promptness of speech, and to the presence or absence of any desired starting transient or chuff. The mouth of a diapason pipe after voicing, in this case with particularly heavy nicking, is shown in Fig. 17.9.

Obviously, these are all matters at the very heart of the organ builder's art, but the physical effect of many of the adjustments can be easily understood in terms of our discussion in Chapter 16 (Bonavia-Hunt, 1950; Mercer, 1951, 1954; Fletcher, 1974; Nolle, 1979, 1983).



**Fig. 17.9.** The mouth of a metal open diapason pipe after voicing with unusually heavy nicking of the languid. Note the ears to either side of the mouth and the characteristic surface pattern of the tin-rich spotted metal pipe alloy (Fletcher and Thwaites, 1983). (Copyright © Scientific American.)

## 17.10. Effect of Pipe Material

There is a long organ-building tradition that holds that the best material for bright-toned organ pipes is a tin-rich lead-tin alloy and that too much lead gives a dull-toned pipe, as may be required for a flute rank. Such an alloy is, however, quite expensive and not very strong, so that zinc has often been used for the larger pipes. Some pipe ranks are, of course, made from wood but there does not appear to have been much discussion about the merits of various different timbers, provided only that they are reasonably thick and smooth.

Scientific discussion has persisted on the subject for more than a century with many ingenious explanations being advanced to explain the superiority of one material over another. Miller (1909), in particular, devised a demonstration with a double-walled metal pipe and showed that the tone quality varied greatly as the space between the walls was progressively filled with water.

Most of the uncertainty has now effectively been laid to rest by the work of Boner and Newman (1940), which showed little effect even for pipes made of paper, and by the more thorough analysis of Backus and Hundley (1965), which confirmed this result and provided at the same time an explanation of the effects observed by Miller and others.

Briefly, the pipe walls can affect the radiated sound only if they are set into

vibration of reasonably large amplitude by the pressure variations in the air column. Whether or not this is possible depends essentially on the geometry of the pipe walls. An exactly circular pipe with walls of reasonable thickness will be sufficiently stiff against radial vibrations that almost no motion can occur, and so there can be no audible effect of wall material properties. Conversely, the walls of a pipe of square cross section made from thin metal, such as was the case in Miller's pipe, can vibrate to quite large amplitude and greatly affect the sound. No organ builder would contemplate making square pipes of thin metal for just this reason, since the effects are unreliable and unpleasant. In the middle ground, nominally round pipes that have been distorted to elliptical shape can vibrate to a small extent, but the measured levels are so low that there is a negligible audible result for normal pipes. Even if these low-level effects were regarded as significant, it is much easier to modify them by changing wall thickness than by changing pipe material. In wooden pipes, which have the possibly susceptible rectangular form, problems are avoided by using timber or plywood that is sufficiently thick and stiff to have a negligible vibration amplitude. No organ builder has been persuaded to use thin plywood for his bass pipes!

When it comes to transients, there is perhaps a little more possibility of effect since the geometry of the mouth allows mechanical vibrations of the tube wall to be excited at the upper lip by the initial pulse of air. Again, however, the resonance frequencies of these vibrations and the response of the pipe wall at the sounding frequency of the pipe are dominated much more by wall thickness than by the properties of the wall material. All that can be said is that preferred materials, such as pipe metal, have high internal damping so that any wall transient will die out rapidly, while other materials, such as steel or bronze, have smaller damping and may give more audible transients. However, alloys rich in lead should be better than their tin-rich relatives from this viewpoint.

Perhaps more important than any of the virtually negligible acoustic differences are the properties of the pipe material in relation to pipe construction, voicing ease, and appearance. The tin-lead alloys, common as pewter in drinking vessels back to Roman times, are ideal from this point of view, being hard enough to stand unsupported as pipes of reasonable size and soft enough to be cut with ease by the voicer's knife. Of these alloys, those with a high tin content can be burnished to a bright finish, which is durable in time, while those rich in lead are dull and tend to grow oxide films. Typical compositions range from 30 to 90% tin, with the higher tin fractions generally being used for diapasons and the lower fractions for flutes.

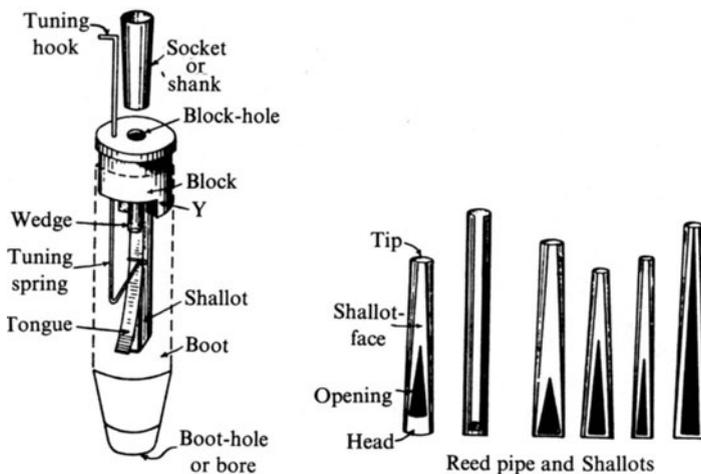
These virtues still commend tin-rich tin-lead alloys to modern organ builders, but improved manufacturing methods allow the use of zinc for large pipes, copper for particular display pipes, and even spun brass for show pipes of the trumpet family mounted in heraldic fashion on the front of the organ case. The art of the pipe voicer is completely dominant in determining the sound quality.

## 17.11. Reed Pipe Ranks

Although it is possible to build a very satisfactory small organ using flue pipes only, reed-driven pipes, which were introduced into organ building about the fourteenth or fifteenth century, provide an exciting variant in timbre and are an essential part of any large modern organ.

The reed-driven acoustic generator of the pipe has the structure shown in Fig. 17.10. The reed is a curved tongue of brass closing against a matching cavity called a shallot. The vibrating length of the reed is determined by a stiff wire pressing it against the shallot. The whole arrangement is superficially similar to a clarinet mouthpiece, except that the face of the shallot is quite flat and the reed curved, while in a clarinet the reed is flat and the mouthpiece has a curved lay. From an acoustic point of view, however, this resemblance is only superficial. In a clarinet, the reed resonance is at a frequency much higher than the note to be played, the reed is highly damped, and the playing frequency is controlled mostly by the acoustic impedance maxima of the pipe. In an organ reed, on the other hand, the reed is very lightly damped and is tuned to the frequency of the note to be sounded. The pipe is also tuned to this note, but its function is largely that of a passive acoustic resonator determining the loudness and tone quality of the sound produced by the reed. Both these possibilities are treated quite explicitly in our discussion of reed generators in Section 13.2; the difference between the two situations is only a matter of differences in the values of various parameters describing the reed.

We do not need to repeat our discussion of reed generators here, but only to emphasize some particular points. The reed itself, since it operates at very



**Fig. 17.10.** The reed assembly in a typical oboe or trumpet stop, with shallots for ranks producing other different tone qualities (Bonavia-Hunt, 1950).

nearly its resonance frequency, moves in a nearly sinusoidal manner, though there is some distortion because of the way in which the curve of the reed unrolls against the face of the shallot. This curve, the shape of which is crucial to the operation of the pipe, is imparted to the tongue by burnishing it against a flat plate during the voicing operation. A well-voiced reed does not usually quite close the opening in the shallot at the extreme of its motion.

In very large bass pipes, the reed tongue may be weighted to lower its frequency in a convenient way. Some weighted tongues, such as the 64-ft reed on the Sydney Town Hall organ with its fundamental of 8 Hz, have a small pneumatic actuator to set the reed into initial motion and ensure prompt speech, but this is not normally necessary.

The flow of air through the reed into the pipe is controlled by the motion of the reed in conjunction with the shape of the opening in the shallot. This opening is basically triangular but, as shown in Fig. 17.10, it may be short or long. Different shapes clearly impart different waveform characteristics to the acoustic flow.

The pipe part of the reed pipe is, as remarked previously, largely a passive resonator since the  $Q$ -value of the reed is quite high and its frequency is little affected by the tuning of the pipe. Since the reed works near an acoustic impedance maximum for the pipe in order to achieve maximum energy transfer, a normal conical resonator is half a wavelength long, as in an oboe, and the physical pipe length is the same as an open flue pipe of the same pitch. A cylindrical resonator, on the other hand, need only be one quarter of a wavelength long and will couple essentially to only the odd harmonics of the reed generator, as in a clarinet. Such half-length reed pipes, like the clarinet, were a rather recent development and are generally used for characteristic solo voices with names such as *schalmei* and *clarinet*. The sound in the lower part of the compass is often quite like that of a clarinet because of the characteristic weak second harmonic. These ranks generally occur at 8-ft pitch only.

More central to organ reed color are those ranks with conical resonators of full length which support all harmonics generated by the reed. Generically, they are called reeds, but the stop names are more often those of brass instruments: trumpets, tubas etc. These ranks occur at 16-ft, 8-ft, and 4-ft pitches on large organs and together make a chorus of great power and impact that can be used either alone, with mixtures, or with a full diapason chorus. Some very large organs have 32-ft or even 64-ft reed ranks.

The loudness and harmonic development of a reed rank is governed by the same sort of scaling rules as apply to flue ranks, with variation in the reed and shallot replacing variations in mouth configuration. Wide-scaled pipes are broad and loud in tone, while narrow-scaled ranks are keen and softer. These softer ranks are often given woodwind names, such as oboe or bassoon.

As well as the chorus reeds, we also find solo reeds of various types, from the great tuba stops of English cathedral organs to the horizontally mounted fanfare trumpets of French and Spanish organs. As with flue pipes, the variety is too large for us to survey here, and organ builders strive to achieve their own individual balances of tone colors.

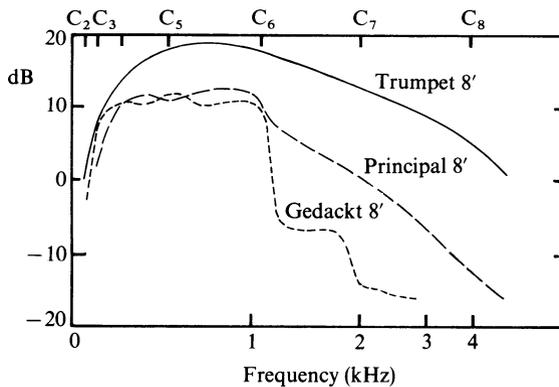
The blowing pressure requirements for reed pipes are similar to those for flues, though there is a general tendency to use rather higher pressures—the organ built in 1929 for the Atlantic City Convention Hall had a battery of reed stops operating at immense power on 25 kPa or 2.5 meters water gauge!

## 17.12. Analysis of Timbre

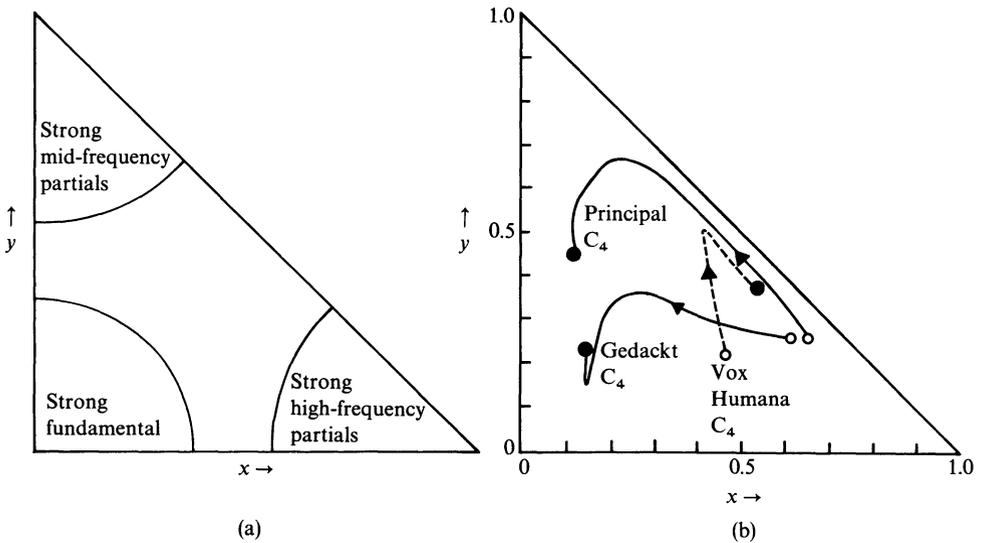
Several proposals have been investigated for the more or less objective evaluation of the timbre of organ pipes, either individually or when played as complete ranks, that rely upon fewer parameters than those needed to specify the complete spectrum and its timbre evolution. We mention just three of these here.

Sundberg and Jansson (1976) evaluated the long-time average spectra (LTAS) of complete ranks for different stops on a particular organ and found characteristic spectral shapes for each stop. The LTAS was evaluated by playing a full-compass scale on the rank, recording it at 10 different microphone positions, and then averaging the spectra through a bank of filters set at one-third-octave spacings. Such an analysis shows up characteristic timbre differences, as is illustrated in Fig. 17.11.

Pollard and Jansson (1982a,b) used a different method to assign a particular point in a 2-dimensional tristimulus diagram to the sound of an individual pipe, as shown in Fig. 17.12(a). The three vertices of the diagram represent a strong fundamental, strong midfrequency partials (actually harmonics 2, 3, and 4) and strong upper partials (harmonics 5 and above), respectively, and the position of the representative point on this diagram is constrained by the requirement that total loudness should be normalized. This diagram has the advantage that the path of the representative point during the initial transient can also be plotted, as shown for several representative pipes in Fig. 17.12(b). The loudness of the sound is, of course, not represented on the diagram.



**Fig. 17.11.** LTAS analysis of the tone of three typical organ pipe ranks (after Sundberg and Jansson, 1976).



**Fig. 17.12.** (a) Tristimulus diagram for the representation of musical timbre. (b) The initial transient and steady-state representation of principal, flute (gedackt) and imitative reed (vox humana) organ tones on the diagram together with a trumpet, clarinet and viola (after Pollard and Jansson, 1982a).

Finally, Padgham (1986) has adopted a two-dimensional subjective scale with tone  $\Theta$  ranging from 0 to 24 through flute  $\rightarrow$  diapason  $\rightarrow$  string  $\rightarrow$  trumpet and complexity  $C$  given a value between 0 and 100. (In his diagrams,  $\Theta$  is plotted as an angle on a 24-segment circle and  $C$  as a radius, but this is rather misleading since the tone scale is not closed—24 is at the opposite extreme to 0 rather than being identical to it.) The significant thing for our present discussion is that Padgham finds the subjective tone coordinate is well correlated linearly with the sound pressure level of the second harmonic relative to the fundamental for  $0 < \Theta < 12$  (flute  $\rightarrow$  string) and with the relative level of the third harmonic for  $12 < \Theta < 24$  (string  $\rightarrow$  trumpet). The subjective complexity  $C$  is similarly correlated with the arithmetic sum of the sound pressure levels in third-octave bands from 9 to  $\infty$ .

### 17.13. Tonal Architecture

An organ is so much a part of the building in which it is played that it is impossible to separate tonal design from architecture. An organ for a large cathedral with a reverberation time approaching 12 s will need to be entirely different from an organ in a concert hall with a reverberation time of 3 s or from a small organ for chamber music. Much has been written

about this subject, about different national traditions in organ building, and about individual organ specifications (Bonavia-Hunt, 1950; Andersen, 1969; Sumner, 1973). We have space here for only a few remarks.

The organ is an instrument in its own right; it is not a substitute for an orchestra. A satisfying organ must therefore have, as a first requirement, a satisfying main chorus built from properly scaled diapason ranks, if possible including a mixture. Attempts to take short cuts, for example by using electric action to borrow higher pipes from an extended rank to produce nominal 4-ft, 2-ft, and even mixture pitches produces a characteristic theater organ sound.

For most music, a balancing smaller chorus of softer diapasons or even flutes is required, and this is best located on a second manual to give flexibility. Contrapuntal music requires an equally independent pedal division with its own chorus of voices, a requirement met for centuries on German organs but typically given scant attention in small English-style organs until comparatively recently.

With an increase in organ size, chorus reed ranks are added, then solo ranks of various types and contrasting choruses on different keyboards are added. It is here that national traditions enter, with German organs concentrating on bright flue pipes, mixtures, and mutations, Spanish organs providing ceremonial trumpet stops, and English organs concentrating on full, rich choruses with an emphasis on enclosed divisions.

Modern large organs attempt to combine the best of many of these traditions so that they are effectively several instruments in one, the player being able to select just that range and distribution of ranks required for the performance of each particular piece of music. A good example is the organ in the Sydney Opera House, completed in 1979, the design of which has been described by its builder (Sharp, 1973). It has some 10,000 pipes in 205 ranks grouped into 127 stops that are distributed over 5 manual keyboards and a pedalboard. The action is entirely mechanical, but there is a microprocessor-controlled stop action and a duplicate electrical action used to couple the manuals or even for remote playing. Organs of this type attempt to blend tradition with the best of modern scholarship, insight, and technology to perpetuate a noble instrument.

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