by the time the pulse wave forms become equally spaced, there are still 9 or 10 octaves available for tone forming—more than adequate for a very large organ. In passing it might be mentioned that this system, developed by Philips Gloelampenfabrieken requires only 1·6 volts to operate it (Fig. 81).

Oscillations can be produced by the movement of a conductor in a magnetic field, or the reverse. There are two practical ways of attaining this result. Fig. 82 shows a vibrating system in which a free reed of the harmonium type, actuated by wind, moves cyclically in front of one pole of a permanent magnet. The reed may be made of iron or have an iron insert in the vibrating end of the tongue. The permanent magnet is surrounded by a coil of wire, through which a steady flux flows. When the iron armature moves with the reed, the flux is varied in a manner corresponding with the excursion of the armature. The changing lines of force induce a changing voltage in the coil, which may be amplified. The damping effect of the magnet exercises a restraint on the reed tongue, which alters the harmonic development of the reed. The use of the end mode of vibration only almost entirely cuts out the excessive harmonic development of the reed. The net effect of these factors is to cause the induced voltage to have a smoother form. Thus the amplified signal gives predominance to the fundamental tone.

An important feature is that it is no longer necessary to rely on the size or power of the reed to produce acoustic energy. Thus lighter reeds, which will speak more rapidly, can be used. This is particularly noticeable in the bass, where the pitch note of, say, sixteen-foot reeds is never heard at all. The depth of tone obtained electrically is strikingly effective. At the same time there is a certain degree of transmission of physically generated harmonics

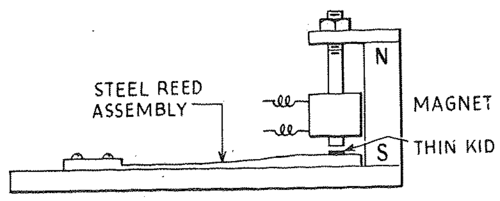

Fig. 83 Magnetic pickup for reed

through the metal of the reed, and although this can be reduced by making the end of the magnet an extremely sharp chisel-shaped point, there is some wave-form distortion for this reason.

It is most difficult to 'voice' steel reeds to produce imitative tones, so that, whilst it is possible to use brass reeds with iron inserts to generate a complex wave, if the whole tongue is made from steel, the use of this form of electromagnetic generator for simple wave forms is precluded by the greater hysteresis (see page 57) introduced by the steel. The electrical output is also very small, because only one pole of the magnet is being used. But by means of suitable electrical filters quite pure waves may be generated, provided that the reeds are in constant vibration.

In Fig. 82, the pickup is shown at the end of the reed. The frequency generated will then be twice that of the reed, since the pole passes the magnet twice in each complete cycle. To generate the natural frequency, a single-sided pickup is required. This is shown in Fig. 83. Note that there is a complete magnetic path in this arrangement, hence the efficiency is four times that of Fig. 82. If the magnet is too powerful, the reed tongue may tend to stick to it; 9 per cent cobalt steel is suitable.

Another form of magnetic generator is shown in Fig. 84, which represents diagrammatically the arrangement employed in the well-known Hammond organ (Chapter 7). It must be emphasized that in this chapter only the principles of operation are summarized, and constructional details are not

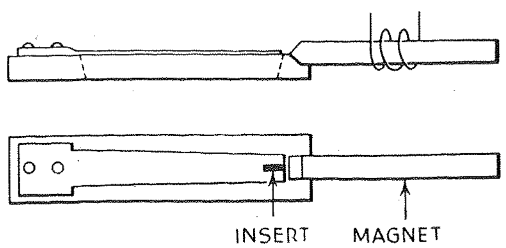

Fig. 82 Electromagnetic reed generator

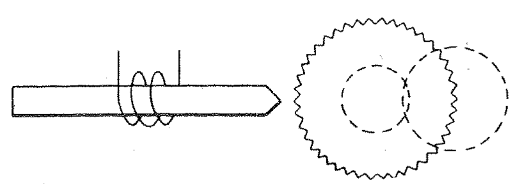

Fig. 84 Arrangement of Hammond tone wheel

given. It might be supposed that after the introduction of the commercial alternating current generator, the idea of producing musical sounds by some form of rotating machine would follow, since the resultant frequency is a function of the number of poles and the speed of rotation. This was indeed so, and the first generator employing a rotating electromagnetic mechanism was devised and made by Professor Thaddeus Cahill in 1897. The patent specifications relating to this instrument show that not only were the fundamental pitch frequencies produced but that Cahill completely anticipated the requirements for harmonic mixing. In those days amplification by means of valves was not possible, since the de Forest patents were not launched until 1907, and further development was abandoned.

Fig. 84 shows a toothed wheel of soft iron driven through suitable gearing by a constant-speed motor. In close proximity to the teeth is a permanent magnet with a chisel-shaped point at this end. On the magnet is placed a coil of wire. Rotation of the wheel produces an alternating voltage in the coil of a suitable frequency, which can be amplified. The strength of the signal can be altered by moving the magnet farther from or nearer to the wheel. There is one such wheel for each fundamental frequency, driven by means of a train of gears so proportioned as to increase the pitch of each successive wheel by the required interval of a semitone. The generator wheels have differing numbers of teeth and other distinguishing features, which are detailed in Chapter 7.

Owing largely to the compactness with which a generator of this type can be produced, and its stable mechanical characteristics, as well as its remarkable electrical simplicity and high signal-to-noise ratio, coupled with ease of production and maintenance, this form of generator is widely used.

It is interesting to examine the possible defects which characterize magnetic generators. Since there is a magnetic field of varying intensity acting on the iron armature, owing to the constantly varying position of the latter, the flux must change with the change in magnetic field. The effect of this on iron is shown in Fig. 85. It can be seen that the flux increases rather slowly with the magnetic field, gradually more rapidly, and eventually ceases to produce much effect. At this latter position the iron is said to be saturated.

Thus the change in flux in the iron is not linear

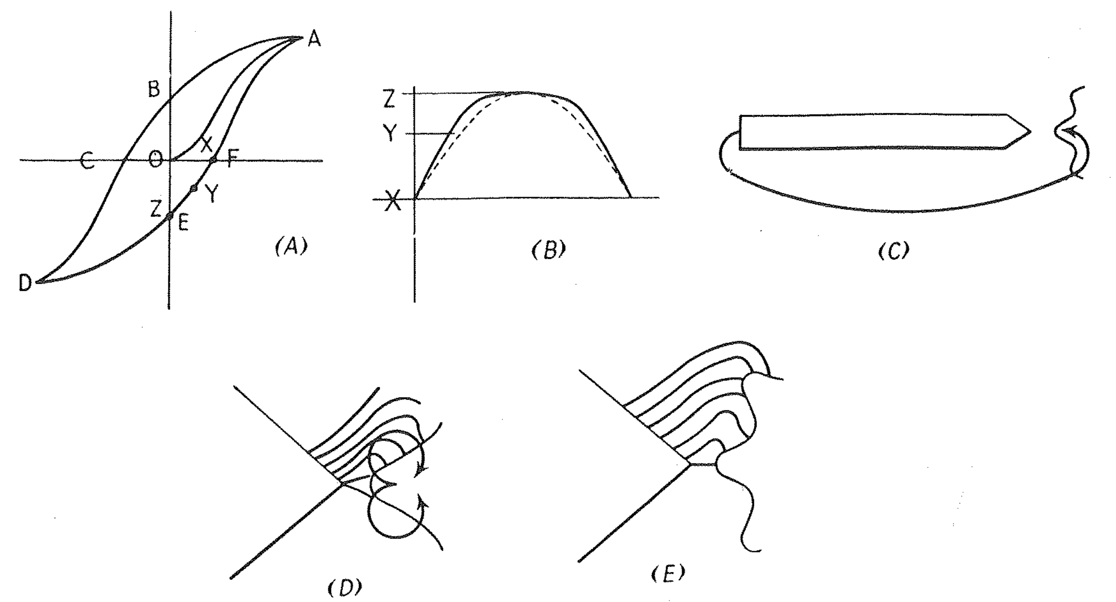

Fig. 85 Change of flux with magnetic field. A = Hysteresis loop; B = Effect on wave form; C = Effect of one end of magnet only; D = Eddy current effect; E = Fringing effect

in relation to the magnetizing force. This gives rise to another effect, known as hysteresis (from the Greek, 'lag behind'). Fig. 85 (*A*) shows a typical hysteresis loop. If the magnetizing force is applied at *O*, the flux will rise to *A* (point of saturation). If now the magnetism decreases, the flux will not return along *AO* but along *AB*. Thus it has not diminished, but is lagging behind. If the magnetizing force is now reversed and simultaneously increased, the curve *BCD* is traced out. Once again, if it is reduced, it gives rise to the curve *DE*; and so on until *A* is reached.

Successive changes reproduce the curve *ABCDEFA*, but *OA* is not traced out again.

The width of the loop at *BE* is dependent on the nature of the material, and is lowest for soft iron, this being the main reason for the use of this material in generators of the type used for music. The effect of the hysteresis loop on the wave form can be seen from (*B*). If we have a rotating device which mechanically traces out the profile of a sinusoidal wave, and it is associated with means for varying the strength of a magnetic field, we can assume the device to have a point which describes the wave form (curve *A*). If three points, *X*, *Y* and *Z* are taken on the hysteresis loop of the magnetic circuit, then at the appropriate moments when the tracing point passes through that portion of the loop the current in the device with the point must be modified by the non-linear rate of change in flux so as to displace the wave which would be generated by a linear rate of flux change (curve *A*) to the position of curve *B*.

The effect of this is to somewhat flatten the top of a wave resulting from the combination of *A* and *B* (which are shown exaggerated) and, as we know, the flat top must contain harmonics. There must therefore be some distortion. If we consider (*C*) it will be seen that if only one end of the magnet is used, the flux lines due to the other pole will be absorbed to some extent by the armature or screening box. This will somewhat affect the wave form. (*D*) shows the effects of eddy currents in the armature, which produce a field at right angles to the main magnetic field and modify it. The eddy current loss is proportional to the square of the frequency; it is also known that the eddy current loss is related to the grain or particle size of the iron, becoming less as the grain is reduced in size; heat treatment of the discs can also be used to modify the magnetic properties greatly. (*E*) illustrates the effect of fringing due to adjacent teeth, causing a fresh distribution of flux.

All the foregoing effects are interlinked and greatly complicated by the fact that the relative positions of the armature and magnet are constantly changing. But the total amount of distortion is small and can be much reduced, though not entirely eliminated, by suitable electrical means.

In any generator loaded by a permanently energized magnetic system, there is a force acting to cause any wheel, when at rest, to assume a position so that a tooth is opposite the end of the magnet. This reacts on the gears when the system is rotating, and acting upon that force again is one due to the rate of change of the force from the driving motor acting upon the teeth of the gear wheels. That is because there is, or may develop, some back-lash in the teeth of the gear wheels. Ingenious methods have been devised to overcome this effect.

Another approach to the rotating magnetic generator is shown in Fig. 86. The Hammond arrangement is designed to produce sinusoidal wave shapes for additive mixing. At the same time, the gears driving this generator must conform to the intervals of the equally tempered scale (or very nearly so). A glance at the frequency table (Appendix I) shows how limited are the powers of synthesis from E.T. tone sources; only the even harmonics are really usable, all odd harmonics beyond the fifth producing considerable distortion. Clearly the

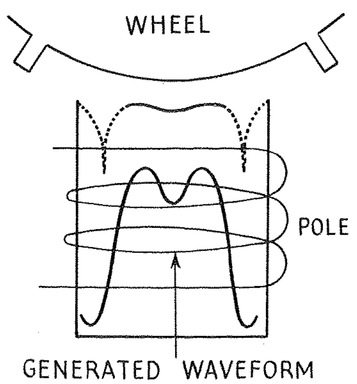

Fig. 86 Complex-wave-form rotary magnetic generator

synthesizing powers of such an instrument are very limited.

The generator of Fig. 86 used the wheels as pitch sources only, the wave form of the oscillations being obtained by shaping the pole piece in the desired manner. A generated wave consisting of fundamental and third harmonic is drawn on the pole piece required to produce this wave. Owing to fringing effects, it is no use deepening the clefts (*shown dotted*). An advantage of such a generator is that several different pole shapes can be radially disposed around any one wheel, thus enabling pre-formed tones to be extracted even if the pitch wheels are in equal-temperament relationship; for the harmonics from each wheel will then be in the correct ratio to the fundamental, so the biggest drawback to the additive instrument is removed.

In order to tune such generators exactly, each train of wheels for seven octaves is mounted on a non-magnetic spindle and rotated by a coned friction disc, as shown in Fig. 87. For seven octaves, the wheels would have 1, 2, 4, 8, 16, 32 and 64 teeth respectively.

The use of such a generator also simplifies the keying arrangements and allows stops to be added to a reasonable extent, which is not possible with the Hammond method (Fig. 84).

It seems such an obvious thing to use magnetic tapes pre-recorded with suitable wave forms as an organ generator, that it is, on the face of it, surprising that no such instrument is on the market. However, there is a special kind of magnetic tape musical instrument on which a very large number

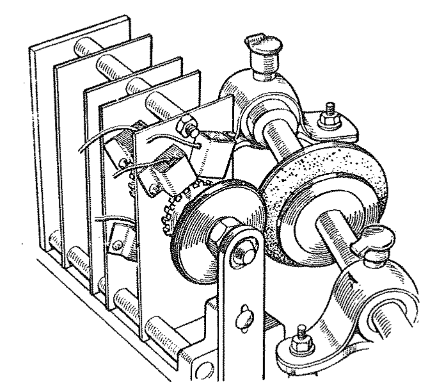

Fig. 87 Cone friction drive for magnetic generator

of effects is obtainable, including organ tone qualities. This is the Mellotron, and because of its complexity, the description of the device will be found under commercial organs in Chapter 7. Broadly speaking, the problems of wear, dust altering the head gaps, partial magnetization in time, noise, and the enormous mechanical difficulties all combine to make a true organ of conventional tonality almost prohibitive. Precision mechanical engineering is always costly and such an instrument could not compete with the transistor generator.

Electrostatic generators

Oscillation generators of this type fall into three groups—

1. Those using vibrating wires as the source, actuated by hammers.
2. Those using vibrating reeds, actuated by wind.
3. Those using rotating capacitors of variable capacitance, driven by a constant-speed motor.

The principle upon which these groups function is common to them all. It is a function of the capacitance change induced by relative movement of the parts.

Fig. 88 shows a circuit comprising a variable capacitance *C*, a resistor *R* between one element of the capacitance and a source of high voltage, and a grid resistor *Rg* associated with an amplifying valve. If the relative separation of the capacitor plates is varied, the capacitance changes and a corresponding voltage drop occurs in the high resistance *R*. The voltage variations are transmitted through *Cg* (which has a capacitance many times that of *C*) and so effect corresponding variations in the grid potential across *Rg*.

The resulting potential variations due to the change in *C* are proportional to the change in

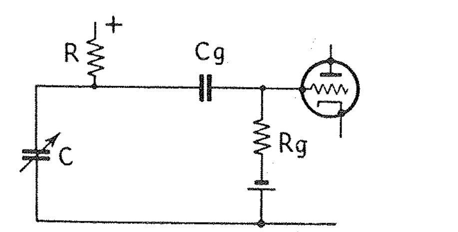

Fig. 88 Capacitance principle

capacitance of *C* divided by the total capacitance, provided the values of the resistances of *R* and *Rg* are sufficiently great to prevent any appreciable current from appearing in *C*. If current flows, the voltage variations will reduce in proportion, and the response will not be linear.

Since the capacitances involved are usually extremely small, the device is essentially a high-impedance one, and the grid lead should be kept short to avoid stray fields. The capacitance of the leads should also be small. This capacitance must be included in the total capacitance mentioned above, so that if the leads exercise much shunting the output will be reduced.

1. *Stretched wire generators*. At least two forms of electric piano have been developed employing such generators. The wires are polarized by means of a high-voltage source through a resistance. When the string is vibrated by means of the hammer action, changes in capacitance between the wires and small metal studs mounted above them are induced as explained, for one end of the studs is connected to the valve grid. These changes in capacitance follow the movement of the wire exactly, and in consequence the amplified voltage changes are a replica of the vibrating condition of the wire at that point. Further details of the exact construction are to be found in Chapter 7.

2. *Vibrating reed generators*. These function in exactly the same way and are connected in similar circuits, metal studs above the reed being coupled to the valve grid and the reed tongue and base suitably polarized (Chapters 7 and 8).

3. *Rotating variable capacitors*. The only real difference here from 1 and 2 above lies in the construction and drive. In consequence no detailed explanation will be given at the moment. One important feature is that since at least part of the generator is rotating, there must be a means of making constant contact with it. In some cases this is done with a brush, like a d.c. electric motor, in other cases the capacitance change is transferred through an associated capacitance, the relative spacings of which do not alter. A capacitor may rotate and still fulfil this condition which is the principle of the long-established Compton organs. Since it is difficult to explain the basic circuits without expanding them into a complete organ system, the reader will find the rotating generator and charging system described in Chapter 7 under Compton.

The signal level from most types of electrostatic generator is very low and owing to the high potential difference between the electrodes, noise may be introduced if the insulation is not quite perfect. Very careful attention to the screening is necessary and it is most important to exclude damp. Physical or mechanical vibration has an adverse effect on capacitative generators, since if any of the elements can vibrate owing to an external force they may function as a microphone and introduce spurious signals. Mechanical rigidity in the assembly is probably more important in this group of oscillation generators than in any other type.

Photo-electric generators

Several instruments have been made using the principle of the varying conductivity of certain materials under the incidence of light. The variation in conductivity is caused by the emission of a more or less dense stream of electrons from the material and was, of course, the means by which sound films were reproduced until recently.

A structure with these properties is known as a photo-electric cell. One form consists, for our purpose, of an evacuated glass bulb in which are mounted two electrodes. One is a plate of metal on the surface of which is deposited some substance rich in photo-emissive properties, and the other is a wire structure to which the electrons are attracted. This is generally small in cross-section so as to allow as much light as possible to reach the plate.

Fig. 89 shows an elementary circuit in which the wire is the anode and the plate the cathode. If the cell is connected as shown, on applying a positive

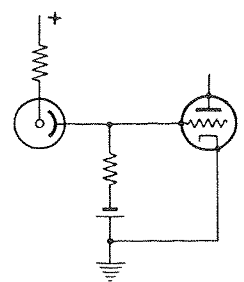

Fig. 89 Photo-electric principle

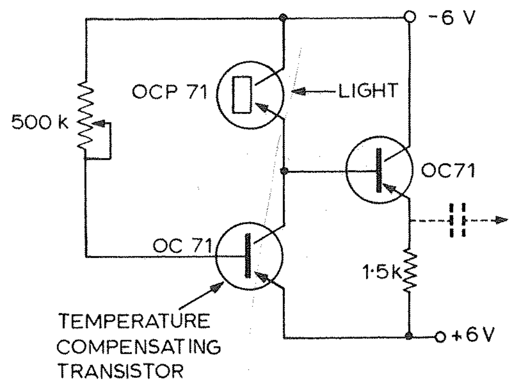

Fig. 90 Circuit for a photo-sensitive transistor generator

potential to the anode a stream of electrons will leave the cathode and travel over to the anode if light is allowed to fall on the cathode. The current will be proportional to the amount of light if the circuit constants are properly calculated for the type of cell in use. Increased sensitivity can be obtained if inert gas is introduced into the cell. With the introduction of photo-sensitive transistors, most of the difficulties encountered with conventional photo-cells have disappeared. Because of their small size, one can be used for each signal, and very small light intensities and operating voltages are required. A circuit for such a transistor is given in Fig. 90.

As a matter of fact, all transistors are to some extent photo-sensitive and light has therefore to be excluded by an opaque casing or coating. A portion of this is removed to make the cell light-sensitive. Other materials can be used to make cells responsive to light, notably cadmium sulphide or cadmium selenide. This kind of photo-cell exhibits a slight time lag which makes it unsuitable for photo-electric organs, but it is used to a considerable extent for volume, stop and keying controls as we shall see later on. By correct proportioning, the resistance change under the influence of light can be made to cover from several megohms to only a few ohms.

At the present time, all types of semiconductive cells suffer from a limited upper frequency response, which in the best case does not extend much beyond 5 kHz. The vacuum cell just described must therefore be used for frequencies above this.

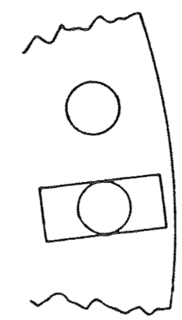

Fig. 91 Disc with round hole and square aperture

This property of photo-emission may be used to generate either simple or complex waves by variations in construction. If we project a beam of light on to a photo-cell through holes cut in an opaque revolving disc, then if the holes are circular and spaced two diameters apart, running past a fixed rectangular hole one diameter wide, the variation of light on the cell will be approximately sinusoidal (Fig. 91). It is obvious that by properly choosing the number of holes and speed of rotation, a note of any pitch can be produced.

A further extension of this method is to use narrow slits instead of circular holes and to cause them to scan a mask of length equal to the spacing between the slits. If the mask has the wave form of some characteristic instrument engraved on it, a sound of that wave form will be heard on amplifying the output from the photo-cell (Fig. 92). A number of concentric rings of slits may appear on one disc of large diameter, the combined images of which can be focused on a common photo-cell by lenses or a parabolic mirror. If each mask has its own exciter lamp, these lamps may be controlled

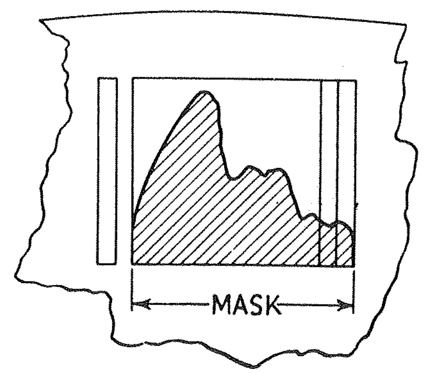

Fig. 92 Disc with rectangular slits and mask

by playing keys and the volume of the sound regulated by altering the brightness of the lamps. The apparatus for this very convenient method is, however, extremely difficult to construct, and in the form described it has not been found possible to reduce the frequency errors as between one row of slots and another to even the maximum departure of ± 0·05 per cent.

Another method is to record photographically a fundamental together with the appropriate harmonic series of wave forms, as in Fig. 93. Then, if a sufficiency of exciter lamps is provided, it becomes possible to use such a generator for additive synthesis, with little or no limit to the number of combinations usable at any one moment. An organ with four manuals, using this method, has actually been built.

In yet another arrangement, rotating glass discs carry photographically-reproduced wave forms which may be either simple or complex tones. In one instrument of this type the discs could actually be changed, so that it was possible to keep a number of different 'stops', as if they were gramophone records. The qualities of photographic emulsions are not particularly stable, especially under the influence of concentrated light, and some shrinkage of the emulsion has been noted, giving rise in time to distortion.

Recently some interest has been shown in a method by which pre-formed tone qualities are photographed on to a metal disc, which is subsequently etched away so that light can pass through the 'sound tracks'. Previously the thin

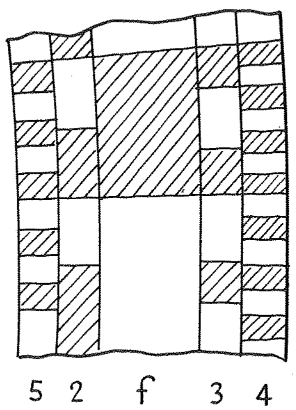

Fig. 93 Section of photo-electric disc for additive synthesis

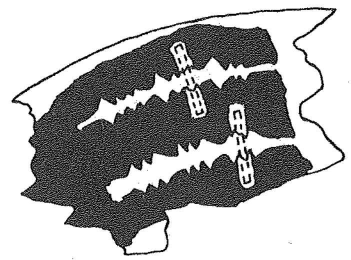

Fig. 94 Noise reduction system

metal foil has been bonded to a glass disc to hold it rigid. The standard arrangement of exciter lamp and photo-cell used for motion picture projectors is satisfactory, but to make the assembly of the 12 sets of discs, etc., more compact, the images from the slits are collected by a concave mirror and focused on a single central photo-cell.

An interesting point is that in any other photo-electric system, the light can pass through any aperture exposed, regardless of whether this contributes to the sound or not. This problem arose in the early days of sound film and gave rise to background noise, due to abrasions and imperfections of the film base. By electrical means, the light was later practically removed except at moments of modulation, thus ensuring a silent background. As an organ is a sustained-tone instrument, any ground noise can be very irritating. The reduction system is seen in Fig. 94. A double-sided track is recorded, and at times of no sound, only a minute slit appears. The herring-bone track is scanned by a horizontal slit, shown dotted.

One of the difficulties with any generating system is to obtain enough tone sources, in a comparatively simple device, to synthesize a large instrument. For example, one set of 8-ft pitch oscillators cannot be used over and over again for different tone qualities without some (if not all) of them becoming degraded. Of course, this is often done in the less expensive organs, with disastrous effects on large combinations of stops. All the individual tonal qualities disappear, and only a 'sound' is left.

A new form of generator overcomes those difficulties in a novel and convenient way. Fig. 95 shows a transparent cylinder, arranged for mounting on a driving spindle. The tube, made from

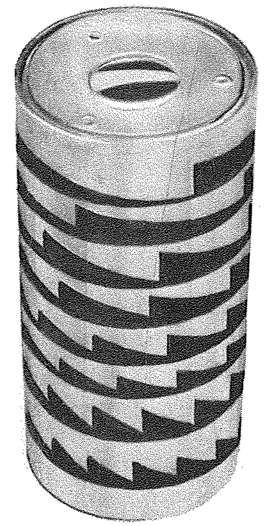

Fig. 95 Diakon cylinder for mounting on driving spindle

Diakon, is sprayed with an opaque plastic layer, which will attach itself to the Diakon but will not cement itself thereto. The black layer is then engraved on a special machine with eight sawtooth tracks, as illustrated. The engraved strip is pulled off, leaving the sawtooth wave forms transparent and the rest opaque.

Eight non-metallic rings encircle the cylinder, each of which contains pairs of photo-transistors with short focus lenses, situated 180° apart. By this means, small errors in engraving or concentricity are cancelled out and the signal strength is increased. Even illumination of all the tracks is ensured by a conical plastic lens, as in Fig. 96.

Since each track has twice the number of waves of the previous one, eight octaves are available on any one tube. Each cylinder is driven, through pulleys, at the correct speeds to produce the intervals of the equally tempered scale. Thus twelve cylinders form the complete generator.

The advantages are—

1. By having enough photo-cells, one can have as many *quite independent* stops as desired.

2. Through the use of sawtooth-shaped waves, all the harmonics required to form any tone are contained in *each wave*, so that there is no robbing or degradation due to borrowing or addition.

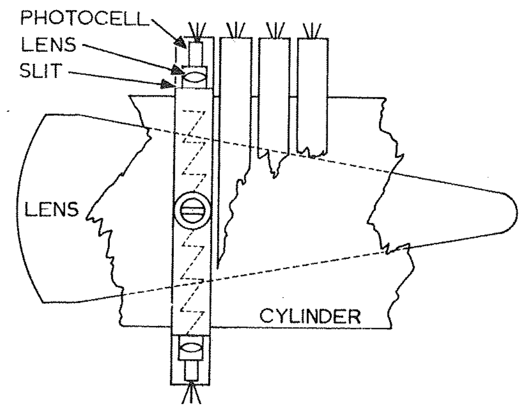

Fig. 96 Conical lens for even illumination of the tracks

Such a generator is not cheap to make, but is far less expensive than a comparable valve organ. As described, it is possible to have six 16 ft, twelve 8 ft, ten 4 ft and eight 2 ft separate sources and, of course, mutations as well. A very novel feature is that if the rings are mounted so that they can be rotated to and fro around the cylinders, a large number of different rates of vibrato can be obtained. Rings may be coupled by connecting rods so that groups can be simultaneously oscillated.*

The following general notes apply to all rotating photo-electric generators—

1. The aperture must be quite evenly illuminated.

2. The focused image must be sharp.

3. No shadow should appear on the photo-cell as the wheel passes the mask.

4. The photo-cell itself should be evenly illuminated over its whole surface; this is now easy if photo-transistors are used, or the ORP12 types.

It should be remembered that the rate at which the filament of an electric lamp heats up is usually of the order of thirty to seventy milliseconds; therefore direct keying of lamps is not a possibility if percussive or even very rapid attacks are called for in a photo-electric musical instrument. The same characteristic is of course an advantage in organ simulation, since the build-up times correspond quite closely to those of pipes.

* Patent applied for.