ELECTRONIC MUSICAL INSTRUMENTS AND THE DEVELOPMENT OF THE PIPELESS ORGAN

By G. T. WINCH,* Member, and A. M. MIDGLEY,† Associate Member.

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SUMMARY

Brief reference is first made to the history and development of musical instruments and the scales with which they are associated.

The principles of the design and operation of the pipe organ are referred to in so far as they have a bearing on the problems of the electronic organ, and the possibilities of electronic methods of producing music are indicated. All forms of electronic musical instruments are referred to, and classified according to the systems employed.

The main treatment of the paper concerns the design of electronic instruments which simulate the pipe organ, both in their playing technique and musical effect. The many engineering problems which arise in the construction of instruments of this type are dealt with in some detail. Finally, design and assembly details are given of a complete electronic organ, and reference is made to possible future developments.

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(1) INTRODUCTION

Although the main treatment of this paper deals with the electrical engineering problems which have arisen in the design and development of pipeless organs operating on electronic principles, the success of such instruments is so dependent on a thorough appreciation of the musical aspect of the problem that this paper would be incomplete if reference to the musical traditions and requirements were omitted.

Also, for the sake of completeness, brief descriptions of the development of many types of electronic musical instruments other than those simulating pipe organs have been included.

It is hoped that the short digression into the arts, which the authors have felt to be desirable in introducing the subject, will not entirely lack interest for the engineer, even if he feels, perhaps, that he has little in common with this side of the problem.

In the next Section, therefore, an attempt will be made to trace the history of musical scales and the development of the more traditional forms of musical instruments in so far as this has a bearing on the more recent developments of electronic types of musical instruments.

* The Research Laboratories of the General Electric Co., Ltd., Wembley, England. † Midgley Harmer, Ltd., and Midgley Electrical Instruments, Ltd.

(2) MUSICAL SCALES AND INSTRUMENTS OF TRADITIONAL FORM

(A) Nature of Musical Scales and Harmonies

As far back as the early Chinese, Egyptian, and Greek civilizations, records show that simple forms of musical instruments existed, of the percussion, pipe, and stringed types. In fact, only this year two Egyptian trumpets, about 3 000 years old, were discovered in such a good state of preservation that they were able to be played, and the performance was broadcast by the B.B.C. The musical intervals which could be played on these early forms of wind and stringed instruments were limited to those corresponding to the simpler frequency ratios, and it is interesting to trace the parallel developments of musical scales from the early 5-tone scale used, for example, by the Chinese. Pythagoras is said to have been the first to have established the Greek diatonic scale of 8 complete degrees, i.e. 7 tones and the octave. Records reveal many different subdivisions of the octave; for example, one of the medieval Arabic scales shows a subdivision of 8 tones and the octave. All early music consisted of single-note melodic progressions, and variety was introduced by the use of the various modes of these diatonic scales. It is very interesting to note how many of the characteristic melodic progressions resulting from the use of these old scales persist to this day in Eastern music.

Harmony was a European discovery of only a few centuries ago, and even to-day it has not spread into Eastern countries to any great extent, at least in the form which we understand.

Strictly speaking the musical scale must be flexible if only to make possible the playing or singing of all the concords exactly in tune. It so happens that the positions into which the scale falls in order to produce theoretically correct major triads on the tonic, dominant, and subdominant, correspond to a *tuning* (as shown in Table 1) built up from the harmonics of the tonic, or key note (middle C = 256 c./s.); the frequencies of the resulting notes are also included. It will be seen from col. 2 that the harmonics form the notes of the diatonic scale at pitches one or more octaves higher than that containing the fundamental, or key note. For example, the 10th harmonic of middle C has a frequency of 2 560 c./s., producing a note E three octaves higher than that containing the fundamental.

Stringed instruments of the violin family can be played in the natural scale because the performer controls the effective length of the string with his fingers so as to produce intervals perfectly in tune. Because of the small departures from the natural scale of the pitch of the open strings, indicated in col. 8 of Table 1 for the scale of C, the performer must in certain cases avoid playing the open string if he wishes to play accurately in tune.

The ability of singers and instrumentalists who have developed a very critical ear and accurate technique, to produce music in just intonation is claimed to account for the very perfect harmonies peculiar to part-singing and chamber music.

In the 16th century, and for another 200 years in this country, keyboard instruments were tuned in mean-tone temperament, but some of the intervals were incorrect when the instrument was played in the more remote keys. It was this difficulty which led designers of early keyboard instruments to attempt a compromise in the form of divided "black" keys. Although this reduced the discordant effect, the playing technique was in consequence much more difficult. Actually, 53 subdivisions of the octave would be necessary in order to obtain satisfactory true intonation in all keys. This would necessitate an entirely different form of keyboard; and such a keyboard was devised by Bosanquet.[1]

But the inconvenience of such devices made them impracticable; and for that reason they could not compete with equal temperament, a *tuning* first proposed by Aron in 1529 and Zarliss in 1558. In this tuning the frequencies of successive semi-tones progressed in the ratio of $1 : \sqrt[12]{2}$. This resulted in all intervals being slightly imperfect in all keys, but by amounts which were not objectionable even to the musical ear, and a description of this system was published by Werkmeister in 1691. In 1722 John Sebastian Bach published the first book of his classic work, the 48 Preludes and Fugues for the "Wohltemperierte Klavier," covering all the major and minor keys and thus establishing this system which subsequently was universally adopted in European countries, and marked an important step in the development and design of keyboard instruments.

The absolute pitch of musical instruments has varied considerably in the past, but fortunately there has been a steady tendency towards standardization, and as the result of international co-operation the frequency of 440 c./s. for A has now been adopted in a number of European countries.[2]

(B) Harmonic Analysis and Mechanical Synthesis of Musical Sounds

Although early forms of music consisted of melodic progressions of single notes, even before the advent of harmony, the added artistic effect of producing such melodies on different instruments, each with its characteristic timbre or musical colour, was appreciated. With the introduction of harmony the musician was able to produce a much greater range of artistic effects by the judicious use of instruments of different timbre. These instrumental characteristics arose from the different structural forms of the musical instruments which in turn gave rise to the generation of series of harmonics, each at its own particular intensity level, so colouring the tone of the musical note produced. Helmholtz was the first physicist to investigate these effects, and his classic work,[3] together with that of later investigators, has shown how musical sounds can be analysed into their component frequencies of sinusoidal form, employing Fourier's mathematical methods of analysis. Also, that when components in the form of separately generated notes, produced by sinusoidal air displacement, are sounded simultaneously at the requisite strengths, the characteristic steady note timbre is synthesized in the ear. All these early investigations were carried out with the aid of mechanical resonators such as had been available to craftsmen throughout the centuries and which have been utilized in the development of the various forms of traditional musical instruments.

Table 1

Corresponding note	Scale of "just" intervals			Frequency of equal-temp. scale	Percentage difference, equal temp., from col. 2	Frequency of perfect fifths of stringed instruments	Percentage difference, perfect fifths, from col. 2
	Frequency	Frequency ratio to the tonic	Harmonic number				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
C^1	256	1	1	256	0	256	0
C#				271·222			
D	288	9/8		287·350	− 0·23		
D#				304·437			
E	320	5/4		322·539	+ 0·80		
F	341·333	4/3		341·719	+ 0·11		
F#				362·038			
G	384	3/2		383·566	− 0·11	384	0
G#				406·373			
A	426·667	5/3		430·538	+ 0·91		
A#				456·141			
B	480	15/8		483·263	+ 0·68		
C^2	512	2	2	512	0		
C#				542·445			
D	576			574·700		576	0
D#				608·874			
E				645·079			
F				683·437			
F#				724·077			
G	768/2 = 384	3	3	767·132	− 0·11		
G#				812·749			
A	853·4			861·077		864	+ 1·24
A#				912·282			
B				966·527			
C^3	1 024/3 = 341·333	4	4	1 024	0		
C#				1 084·890			
D				1 149·401			
D#				1 217·748			
E	1 280/3 = 426·667	5	5	1 290·159	+ 0·79	1 296	+ 1·25
F				1 366·875			
F#				1 448·154			
G	1 536/4 = 384	6	6	1 534·264	− 0·11		
G#				1 625·498			
A				1 722·155			
A#	(1 792)*	7	7	1 824·564	+ 1·82		
B				1 933·054			
C^4	2 048	8	8	2 048	0		
C#				2 169·780			
D	2 304/8 = 288	9	9	2 298·802	− 0·23		
D#				2 435·497			
E	2 560/8 = 320	10	10	2 580·318	+ 0·80		
F				2 733·750			
F#	(2 816)	11	11	2 896·309	+ 2·86		
G	3 072/8 = 384	12	12	3 068·540	− 0·11		
G#	(3 328)	13	13	3 250·997	− 2·32		
A				3 444·311			
A#	(3 584)	14	14	3 649·121	+ 1·82		
B	3 840/8 = 480	15	15	3 866·109	+ 0·68		
C^5	4 096	16	16	4 096	0		
C#	(4 352)	17	17	4 339·560	− 0·29		
D	4 608/16 = 288	18	18	4 597·604	− 0·23		
D#	(4 864)	19	19	4 870·995	+ 0·14		
E				5 160·637			
F				5 467·501			
F#				5 792·619			
G				6 137·083			
G#				6 501·994			
A				6 888·623			
A#				7 298·242			
B				7 732·218			

* The values in brackets are the harmonics of C^1, but differ in frequency from justly intoned notes of the chromatic scale shown. These intervals of the chromatic scale are derived from the cycle of diatonic scales built up from each note (col. 2—1st octave) as key note, by the simple frequency relationships in col. 3.

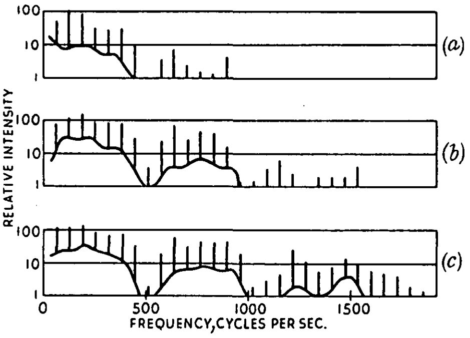


Fig. 1A.—Spectra of grand piano tones at 3 loudness levels (CC = 64 c./s.) (from Meyer and Buchmann[4]).

(*a*) Soft, *p*. (*b*) Mezzoforte, *mf*. (*c*) Loud, *ff*.

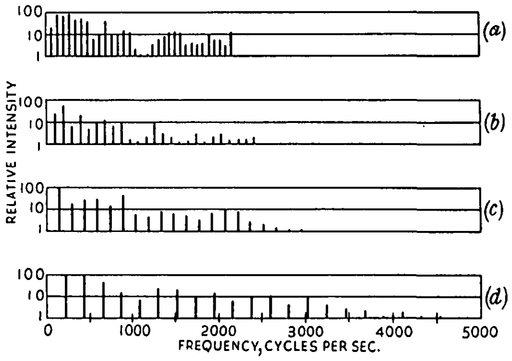


Fig. 1B.—Spectra of cello tones (from Meyer and Buchmann[4])

(*a*) Open C string (64 c./s.). (*c*) Open D string (144 c./s.).
(*b*) Open G string (96 c./s.). (*d*) Open A string (216 c./s.).

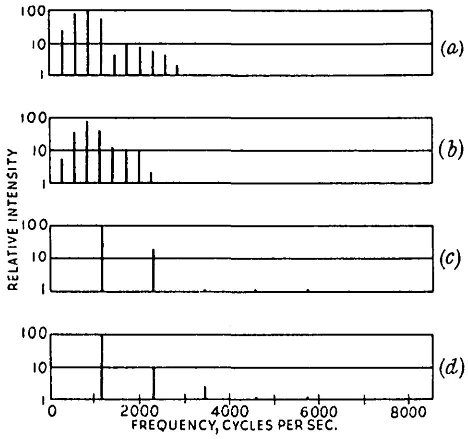


Fig. 1C.—Spectra of flute tones (from Meyer and Buchmann[4]).

(*a*) Metal flute (d^1 = 290 c./s.). (*c*) Metal flute (d^3 = 1 160 c./s.).
(*b*) Wooden flute (d^1 = 285 c./s.). (*d*) Wooden flute (d^3 = 1 140 c./s.).

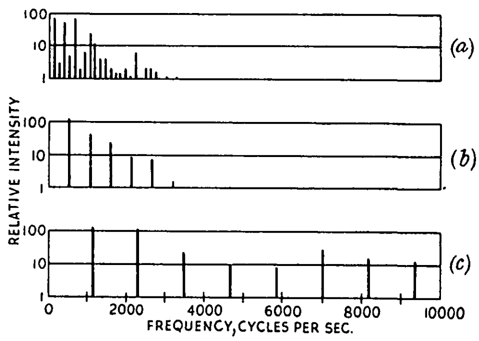


Fig. 1D.—Spectra of clarinet tones (from Meyer and Buchmann[4]).

(*a*) C = 128 c./s. (*b*) c^2 = 512 c./s. (*c*) d^3 = 1 160 c./s.

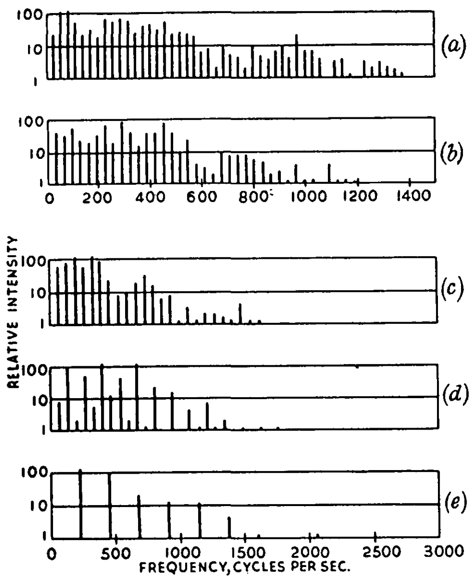


Fig. 1E.—Spectra of bassoon tones (from Meyer and Buchmann[4]).

(*a*) CCC = 32 c./s. (*c*) CC = 64 c./s. (*e*) b^1 = 230 c./s.
(*b*) AAA = 53 c./s. (*d*) C = 128 c./s.

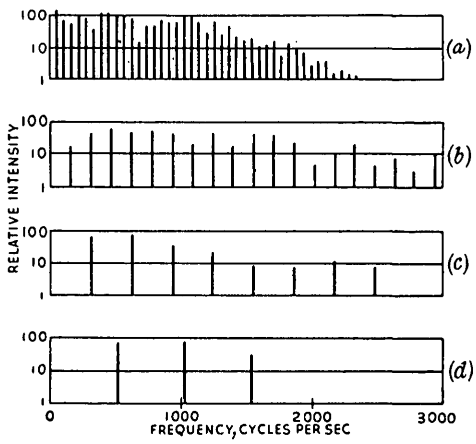


Fig. 1F.—Spectra of trombone tones (from Meyer and Buchmann[4]).

(*a*) BBB = 57 c./s. (*c*) $c\sharp^1$ = 306 c./s.
(*b*) E♯ = 153 c./s. (*d*) c^2 = 512 c./s.

Fig. 1 shows the spectra of some typical steady-tone air compression wave-forms produced by instruments of the orchestra, including a piano played at different

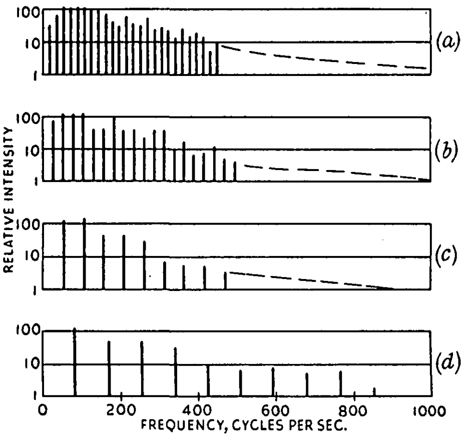


Fig. 1G.—Spectra of trumpet tones (from Meyer and Buchmann[4]).

(a) F♯ = 177 c./s. (b) c^1 = 256 c./s. (c) c^2 = 512 c./s. (d) a^2 = 852 c./s.

loudness levels.[4] Fig. 2 indicates the sound spectra of the steady tones obtained from a number of organ pipes.[5] It may be concluded from these and other similar data that most musical instruments when played softly produce tones less rich in harmonics than those obtained when the instruments are played loudly. Generally speaking, as the loudness increases the number and intensity of the harmonics increases progressively.

But the tone of different musical instruments is recognized by the characteristic transient conditions at the beginning and end of the note as well as by the steady-state harmonic content. This is particularly the case with percussion instruments, and Trendelenberg and Franz[6] have shown that it is very difficult and often impossible to recognize the characteristic tone of organ pipes and some orchestral instruments if the steady tone only is heard without the characteristic starting and stopping transients. Recent investigations by Jones,[7] using recording methods of harmonic analysis, indicate in a striking manner the different time delays in the starting of the harmonic components produced when an organ pipe of the " lieblich gedackt " type is sounded. The non-harmonic " forerunner " of about 5·5 times the fundamental frequency which occurs during the starting period, in this case contributes to the characteristic quality of the tone, particularly in rapidly played passages.

In parallel with the development of electronic musical instruments, rapid development of electronic methods of harmonic analysis and synthesis[4, 5, 6, 7], have made possible investigations leading to a more complete understanding of tone production. Inventions relating to electronic musical instruments have been very numerous in recent years, and in the following survey it will only be possible to make reference to a few of the more important of these.

(C) Principles, Operation and Control of Pipe Organs

One of the most promising applications of electronic principles has been in the field of instruments which produce steady tones, such as the pipe organ. The advantage of electronic methods in this case is the potentially greater flexibility of control, compactness, and economy, as compared with that of the traditional pipe organ.

Unfortunately, it is only too apparent from a study of the patent literature on electronic organs that comparatively few inventors in this field have an adequate appreciation of the design, operation, playing technique, and musical scope of the modern pipe organ.

For this reason, and in order to avoid any misconception of the magnitude of the problem with which designers of electronic instruments of this form are confronted, a brief description of the principles of operation and control of the pipe organ is given in this Section.

The pipe organ has very aptly been described as the " King of Instruments," as in effect it may be likened to a whole orchestra controlled by one performer, and it has a greater frequency and loudness range than any other single instrument. Although the principle of the pipe organ is familiar to physicists and engineers, the multiplicity of intricate control mechanisms necessary to ensure the present-day high standard of flexibility of control by the performer are probably only fully appreciated by the organ builder and those closely associated with this highly developed craft.

An organ may be likened to an orchestra of wind instruments, some of which simulate in their tone quality

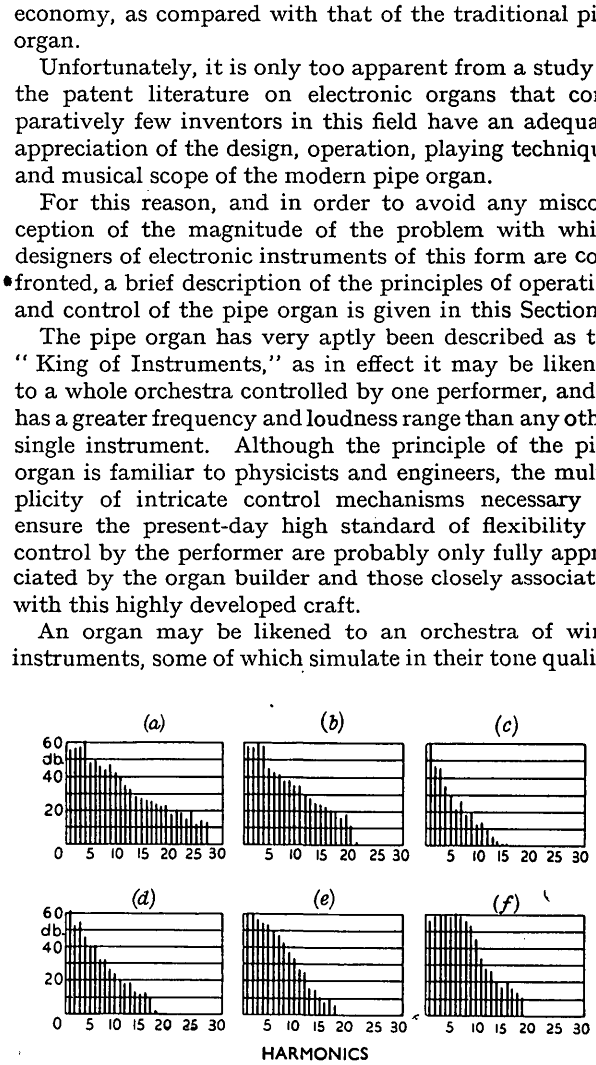


Fig. 2.—Spectra of organ pipes (C′ = 261·6 c./s.) (from Boner[5]).

(a) Viole d'orchestre. (b) Salicional. (c) Open diapason. (d) Geigen diapason. (e) Cornopean. (f) Trumpet.

that of stringed instruments, etc. Theoretically, one pipe per note is needed for each different tone colour, although in practice this is not always the case. For the sake of economy and convenience, by judicious arrangement of pipes and controls it is possible to reduce the number of pipes used. This is termed the " extension " or " unit " principle, details of which will be given later in this Section.

In the orchestra, not only does each different instrument produce a characteristic tone colour or timbre, but each is associated with a particular loudness range, controllable by the player. In the organ, however, each rank of pipes (one pipe per note) has its characteristic timbre and loudness. The only way in which the loudness from ranks of pipes can be controlled is by operating them in a box made of sound-insulating material and provided with adjustable louvres in one side, so arranged that the extent to which they are open or closed is controllable by the performer.

Fig. 3 shows diagrammatically how in early organs each row of pipes of one characteristic tone colour and loudness was mounted on a sound board forming the top

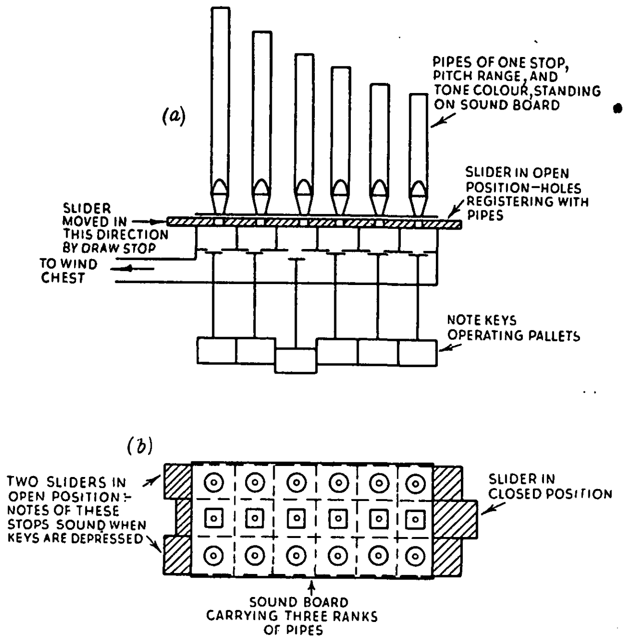


Fig. 3.—Arrangement of pipes, pallets, and draw stop sliders in simple form of organ.
(*a*) Elevation. (*b*) Plan.

of a wind chest. Under each row, or rank of pipes of one tone colour, sliders are arranged which are drilled with a series of holes. When the slider is critically located, these holes coincide with the holes in the sound board on which the pipes are standing, so that when this slide is moved lengthwise all the holes are closed. Below, and at right angles to the ranks of pipes, are arranged pallets which, when opened, allow wind to enter the compartment below all the pipes of the various tone colours which have the same fundamental frequency. If all the sliders are in the closed position, even if a pallet is opened, no note will sound because the wind is *stopped.* This is the origin of the term " stop " applied to the draw knob, stop key, or other means of controlling the position of the sliders. Clearly, if one or more sliders are moved into the " open " position by means of the controlling stops, the respective ranks of pipes will sound as the notes on the keyboard, which open the respective pallets, are depressed. So the performer may play melodies or harmonies on any chosen rank or ranks of pipes and obtain the corresponding timbre and volume associated with the respective pipes. In modern organs the note keys and draw stops operate the pallets and sliders or their equivalents in the appropriate manner by electrical or electro-pneumatic means. This results in much greater flexibility and ease of control.

Because of the limited number of harmonics of flute and diapason pipes, which form the groundwork of organ tone, in order to produce brilliant tone, particularly when many ranks of these pipes are sounding simultaneously, stops are provided which can be used to strengthen the harmonics of the notes being played. Such stops are termed " mutation stops," and are classified according to the pitch at which they sound. Actually, the conventional manner of indicating the pitch of organ stops is by reference to the length of the longest pipe in the rank, assuming it to be an open-flue pipe. In the case of other forms such as stopped pipes and reeds, the stop is still referred to in terms of the length of an open-flue pipe of equivalent pitch. Thus, a stop which sounds middle C at the same pitch as that of the note of this name on the piano will be called an 8-ft. stop, whilst one which sounds an octave lower when the same key is depressed is a 16-ft. stop. Table 2 indicates the pitch of these various nominal pipe lengths, their harmonic relation to one another, and the names by which they are designated on pipe-organ draw stops, or stop keys. In addition, the frequencies of the notes they produce are given, together with the nearest note of the equal-temperament scale (middle C = 256 c./s.). The whole range comprises stops of 32, 16, 8, $5\frac{1}{3}$, 4, $2\frac{2}{3}$, 2, $1\frac{3}{5}$, $1\frac{1}{3}$, $1\frac{1}{7}$ ft. In the case of ranks of pipes, such as the last four referred to, these are often grouped together under the title of " mixture." When a mixture stop is drawn, therefore, several ranks of pipes sound simultaneously. Such stops are not used by themselves but are only drawn when a large number of foundation stops are in action which in themselves are not rich in harmonics. This enhances the natural harmonics, and so gives brilliance to the tone. It will be noted that timbre and loudness are thus inevitably associated. In the organ, as in the orchestra, an increase in loudness brought about by the addition of louder stops, or instruments, results in an increase in the number and loudness of the harmonics.

But it is not sufficient to consider only this simpler form of organ, as such an instrument only allows the performer to play at any one time, melodies or harmonies of any chosen tone colour. By the addition of more keyboards, each one controlling in effect a separate organ, it is possible for the performer to play a solo with one hand at one particular loudness level and tone colour, at the same time accompanying this with the other hand on a second keyboard controlling a rank of pipes of contrasting timbre and loudness. In addition, heavy bass notes of chosen timbre may be played by the feet of the performer if a pedal board controlling yet another organ, is added. It is quite common for organs to be built having three keyboards, and large instruments have up to five, each of five octaves' compass. Actually, one giant instrument in America has seven keyboards, each keyboard of course being associated with what may be considered as a separate organ. These additional keyboards facilitate rapid changes of tone colour and loudness, and enable the performer to be preparing new combinations of stops associated with the keyboards on which he is not actually playing at the moment.

In order to assist the performer in making rapid changes of stops on the several organs under his control, auxiliary mechanisms are provided, usually controlled by push-buttons under the respective keyboards, or manuals. Also, duplicate and additional controls in the form of toe pistons are mounted just above the pedal board, as associated with the top and bottom keyboards are enclosed in boxes and the louvres are controlled, respectively, by the two balanced swell pedals shown in the centre and just above the pedal board. Depression of these swell pedals opens the louvres of the respective swell boxes to any required extent. These balanced swell pedals stay in any desired position when the foot is removed from the pedal, so giving the required crescendo effect to any particular stop or groups of stops in action.

Table 2

Nominal length of pipe	Harmonic series	Tone name	Diatonic interval	Note frequency	
				Scale of "just" intervals	Nearest note on equal-temperament scale
(1)	(2)	(3)	(4)	(5)	(6)
ft. 8	1	Prime	1	64	64 CC
			2	72	71·837 DD
			3	80	80·635 EE
$5\frac{1}{3}$		Quint	5	96	95·891 GG
			7	112	114·035 AA♯
4	2	Octave	8	128	128 C
			9	144	143·675 D
			10	160	161·269 E
$2\frac{2}{3}$	3	Twelfth	12	192	191·783 G
			14	224	228·070 A♯
2	4	Fifteenth	15	256	256 c^1
			16	288	287·350 d
$1\frac{3}{5}$	5	Tierce	17	320	322·539 e
$1\frac{1}{3}$	6	Larigot	19	384	383·566 g
$1\frac{1}{7}$	7	Septième	21	448	456·141 a♯
1	8		22	512	512 c^2
	9		23	576	574·700 d
$\frac{4}{5}$	10		24	640	645·079 e
$\frac{2}{3}$	12		26	768	767·132 g
	14		28	896	912·282 a♯
$\frac{1}{2}$	16		29	1 024	1 024 c^3
	18		30	1 152	1 149·401 d
	20		31	1 280	1 290·159 e
$\frac{1}{3}$	24		33	1 536	1 534·264 g
	28		35	1 792	1 824·564 a♯
$\frac{1}{4}$	32		36	2 048	2 048 c^4
	36		37	2 304	2 298·802 d
	40		38	2 560	2 580·318 e

shown in Fig. 26 (see Plate 5), which is actually a photograph of the console of an electronic organ in which the controls and layout are similar to that of a two-manual pipe organ. As was mentioned in the case of the simple form of pipe organ, in addition to the means of expression which the organist has at his command in the form of different tone colours and loudness resulting from various combinations of stops played from different manuals, the enclosing of one or more of the independent organs in a box with louvred shutters enables a " swell " effect to be obtained. In a pipe organ controlled from a console such as that in Fig. 26, the groups of pipes

It is interesting to note that, even with this method of loudness control, the resultant effect is to suppress the higher harmonics when the box is closed, so that, as with adding stops, a crescendo increases not only the loudness but also the proportionate strength and number of upper harmonics.

Although in the foregoing paragraphs brief mention has been made of the various methods of operation and control of a modern pipe organ, it will be obvious that a tremendous amount of detail is involved in the auxiliaries necessary to bring about this very flexible form of control, which cannot be dealt with here.[8] Actually, most of the complicated controls of modern organs are operated by electrical or electro-pneumatic devices; in fact electrical methods of control have in recent years revolutionized the design of pipe organs.[9] One outstanding result of electric action and control has been the development of the "extension" or "unit" system, referred to earlier, which is widely used in the theatre organ and small pipe organ. This system enables very much greater flexibility to be obtained with a limited number of pipes, these being arranged in units of, say, 96 pipes of each tone colour, one pipe for each semitone of 8 octaves. From such a unit, by electrically controlled selecting systems resulting in overlapping as shown in Table 5, the approximate equivalent of stops of 16, 8, 4, and 2 ft., each of 5 octaves' compass, are obtained. Of course this method has its limitations and must be used with discretion.

Perhaps the authors may be forgiven for digressing to this extent from the main subject, as it will be apparent that the full significance of the advanced state of development of pipe organs must be appreciated when considering the application of electronic methods of producing instruments of the organ type if they are ever to be serious competitors of the present-day pipe organs.

(3) IDEAL REQUIREMENTS FOR MUSICAL EXPRESSION

(A) Scope and Limitations of Traditional Musical Instruments

Before considering electronic forms of musical instruments, it may be instructive to review the limitations of the older forms of instruments. As has already been mentioned, great skill and ingenuity have contributed to the present standard of perfection of the traditional forms of musical instruments, and, with these, musicians have produced musical masterpieces. However, it must not be overlooked that such instruments are dependent on the limitations of mechanical resonators, and this automatically determines their size, loudness, cost, degree of flexibility of control, and the tone colours which they can produce.

(B) Possibilities of Electronic Methods

The attraction of electronic methods of producing (as apart from reproducing) music is that, at least theoretically, it should be possible to generate electric current of any desired fundamental frequency and harmonic content. Such currents when amplified and converted to sound-pressure waves by means of loud-speakers should enable sound waves to be generated of any frequency and harmonic form, over an almost infinite loudness range. The flexibility of control of such methods of sound production should exceed that of any of the traditional forms of musical instrument, and there seems every reason to expect that the bulk and cost should be only a fraction of that of large and elaborate instruments such as pipe organs.

The following Sections will indicate to what extent these theoretical possibilities have been realized, and what may be expected of future developments.

(4) EVOLUTION OF MUSICAL INSTRUMENTS OF THE ELECTRONIC TYPE

So very many systems have been proposed for producing musical tones of different timbre by electronic methods, that it will only be possible to make brief reference to many of them. They will nevertheless be included for the sake of completeness and also in order to show what part they may have played in influencing later investigators. Also, reference will be made to some of the more important patent specifications as in many cases details of the systems have not been published elsewhere.

Table 3 indicates the various branches of electronic musical instrument development. It will be noted that these developments may be considered in three main groups, namely melodic or single-note instruments, harmonic or multi-note instruments of the percussion type essentially developed from the piano, and harmonic instruments simulating the pipe organ both in playing technique and musical effect. The developments will therefore be dealt with in this order, and only the last group of these will be considered in detail.

(A) Melodic or Single-Note Instruments

The Duddell singing arc[10] was probably the first melodic electronic musical instrument, although obviously its form and potentialities were not such as to attract interest in it as a serious musical instrument. In fact, only one serious attempt was made to construct an electronic form of musical instrument prior to the advent of the thermionic valve, namely that by Cahill[11] in 1897, and this will be dealt with when considering Group (C) (*f*) (ii) in Table 3.

In 1915 Lee de Forest[12] lodged the first patent application for a musical instrument utilizing thermionic valves for producing musical tones. His instrument consisted of a valve oscillator, the frequency of which was controlled by adjustable capacitance. The amplified audio frequency was then fed to a loud-speaker which produced the musical notes.

This was followed at a later date by a number of inventions in which various forms of oscillatory circuits were proposed, with the object of facilitating playing technique, and to some extent controlling the harmonic content or timbre of the notes produced by the superposition of formant frequencies. This method of timbre control attempts to simulate the effects which are observed in the case of vowel sounds in speech and in the notes produced by a few instruments of the orchestra such as the violin and bassoon. In these cases the tone is influenced by bands of resonant frequencies, or formants, common to a considerable pitch range. By separately generating these formant frequencies and superposing them on the note frequencies, the electronic instrument is made to produce a limited range of tone colours. In another variation of the circuit for producing these effects, neon lamps are incorporated in conjunction with condensers and discharging resistances to produce audio-frequency oscillations.[13] One example of the form of circuit used in this type of instrument is shown diagrammatically in Fig. 4.

Two instruments of this melodic type have attracted

Table 3

CLASSIFICATION OF ELECTRONIC MUSICAL INSTRUMENTS

Group	Sub-group	Division
(1)	(2)	(3)
(A) Single-note form	(*a*) Electric arc	—
	(*b*) Oscillating valve circuits	—
	(*c*) Oscillating neon-lamp circuits	—
(B) Multi-note keyboard percussion form	(*a*) Struck string or tuned rod as generator	(i) Electromagnetic pick-up (ii) Electrostatic pick-up
(C) Multi-note keyboard organ form	(*a*) Maintained tuning fork or vibrator as generator	—
	(*b*) Maintained strings as generators	(i) Electromagnetic pick-up (ii) Electrostatic pick-up
	(*c*) Cathode-ray generator	—
	(*d*) Multiple oscillator circuits utilizing valves and neon lamps	(i) Thermionic-valve osc. circuits (ii) Neon-tube osc. circuits
	(*e*) Wind-maintained reeds as generators	(i) Electrostatic pick-up (ii) Electromagnetic pick-up
	(*f*) Rotary forms of generator	(i) Photo-electric (ii) Electromagnetic (iii) Electrostatic

Note:—There are two distinct methods which may be adopted with any of the above forms of instruments:—
(*a*) To generate directly complex wave forms of the required shape to produce the various tone colours.
(*b*) To generate series of sinusoidal wave forms of the required fundamental and harmonic frequencies, and by mixing circuits combine these to form the required complex wave forms and tone colours by synthesis.

considerable attention as solo instruments and may be quoted as examples. In the instrument invented by Theremin[14] and known as the Aetherophon, two supersonic valve oscillators produce beat frequencies in the audio range, the desired frequency or pitch of the note being controlled by the hand capacitance of the player. This is accomplished by moving the hand to different positions in space with respect to an electrode in the form of a vertical rod projecting from the oscillator cabinet. Starting and stopping of the notes is accomplished by means of a switch held in the other hand of the performer, but this latter development is due to Martin Taubman, and is incorporated in his instrument known as the Electronde. In the hands of an accomplished musician this instrument can be very effective for solo work of slow tempo.

The Trautonium, invented by Trautwein,[15] has a measure of timbre control which is realized by superposing formant frequencies on those generated by means of neon tubes. The pitch of the notes is in this case controlled by means of a variable resistance in the form of a spun-wire cord stretched over a steel band, the wire being pressed on to the band at the desired point by the performer. To ensure the correct positioning of the finger for any particular note, a dummy keyboard is arranged adjacent to the wire, thus indicating the contact positions for any given note within the compass of the instrument.

Instruments of this class do not lend themselves to development as multi-note instruments, for fairly obvious reasons, and consequently their scope has been strictly limited.

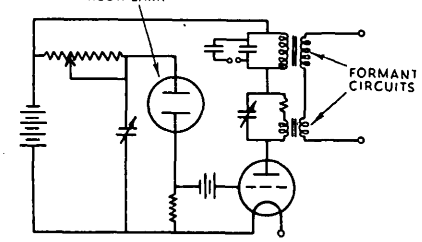


Fig. 4.—Neon-lamp oscillator circuit.

(B) Percussion Type, Keyboard-Controlled Multi-note Instruments of the Piano form

A type of instrument which has been developed mainly by Vierling and Miessner,[16] consists essentially of piano-type action and strings mounted on a frame in the conventional manner, but with no soundboard. The general form of arrangement adopted in such instruments is shown diagrammatically in Fig. 5, from which it is clear that if different excitation voltages are applied to the respective pick-up bars and the strings connected to the grid circuit of an amplifier, when the strings are vibrated by the hammer blow the resulting variations in capacitance at the respective audio frequencies can be used to produce musical notes. The harmonic content of the notes will depend on the proportionate excitation of the various pick-up bars and their positions along the strings. The strings are usually struck by a hammer operated from the keyboard, as in a normal piano, although Palmgren[17] has suggested an electrostatic method of starting the vibration of the string. Various methods have been proposed for controlling the extent to which the starting transients are included in the component fed to the amplifiers for production by loud-speakers, and for controlling the harmonic content of the steady tone produced. Such instruments have a much greater dynamic range than normal pianos, this being made possible, of course, by the valve amplification and loud-speakers used. Also, greater variations in tone colour and wave-form envelope shape are at the command of the performer, although the playing technique is only a modification of that required for playing a normal piano.

Simple forms of such instruments have recently appeared on the market, in which, by means of electro-

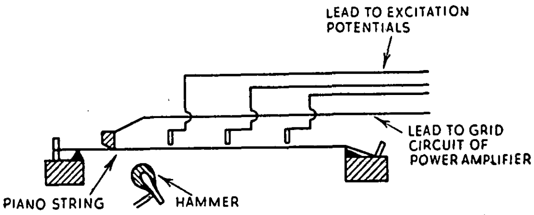


Fig. 5.—Struck string as generator, with electrostatic pick-up.

static pick-up and amplifier arrangements, quite a small instrument is made to produce tone more nearly approaching that of a grand piano. The volume can be set to suit the particular requirements, and in some examples, while playing, the performer has limited control over tone or volume in addition to that normally available to the pianist by keyboard technique.

(C) Electronic Instruments Simulating Pipe Organs

Reference to Table 3 shows that many different systems have been proposed, but unfortunately it is impossible in this brief survey to detail all the many ingenious variations. Only general descriptions of many of the systems will therefore be given.

Of the six sub-groups of group (C) in Table 3, only systems (C) (*d*) (i) using thermionic valves as generators, (C) (*e*) (i) using wind-maintained reeds with electrostatic pick-up arrangements, and (C) (*f*) (ii) and (iii) utilizing rotary generators of the electromagnetic and electrostatic forms, have reached the stage of development where full-compass organs are actually being built for the market. These systems will be dealt with under the respective headings in the next Section.

(5) THE PROBLEMS OF THE PIPELESS ORGAN

(A) The General Problem

From the foregoing Sections, and in particular Section (2) (C), it will be clear that the requirements are very exacting if an electronic instrument is to be built which will be competitive with modern pipe organs. It would appear that with electronic methods it should be possible to construct an instrument comparable with a pipe organ at a greatly reduced cost and of considerably smaller dimensions. This, it must be admitted, is one of the prime considerations behind the development of all commercially available instruments, and it is the attempt to simulate the tones of a pipe organ accurately, having in mind these commercial considerations, which calls for a high degree of skill and ingenuity on the part of the inventor and designer.

Considering the requirements for the imitation of the pipe organ, these may be divided into eight main problems, as follow:—

(a) Pitch Range.

The range of pitch of the fundamentals of all the notes of a pipe organ is from the lowest note of the 32-ft. pedal stops with a frequency of approximately 16 c./s., to at least the top note of the 2-ft. manual stops with a

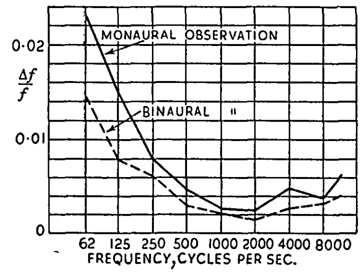


Fig. 6.—Relation between pitch discrimination and frequency of pure note at sensation level 40 db. above threshold (Shower and Biddulph[18]).

frequency of the order of 8 000 c./s. Actually, in larger instruments some of the mutation stops may extend to higher fundamental frequencies. Also, the harmonics of notes of some of the tone colours it is desired to produce may extend to the limit of the audio-frequency range.

(b) Accuracy of Pitch.

As far as accuracy of pitch is concerned, it is important that all the octaves be perfect because when sustained notes are sounded in octaves, beats are immediately apparent if there is the slightest error in tuning. With regard to the intervals within the octave, a small departure from the theoretical equal temperament intervals is allowable, such for example as the differences which actually occur between individual pianos and organs due to the small differences in the technique of the tuners.

From the point of view of the design of an electronic organ it is important to know in terms of frequency what errors are tolerable in the case of these intervals within the octave.

Observations of the least perceptible difference in pitch of notes played successively have shown that the ear is most sensitive between 1 000 and 2 000 c./s. Shower and Biddulph[18] investigated this effect by means of a heterodyne oscillator which could be adjusted to produce notes of pure sinusoidal form at any desired frequency throughout the audio range. These results are summarized in Fig. 6, from which it will be seen that monaural hearing is less critical than binaural hearing, the latter being susceptible to changes of 0·1 % in frequency in the most sensitive range.

In connection with the design of an experimental photoelectric organ in 1933, independent experiments were made by one of the authors[34] in collaboration with Messrs. Rushworth and Dreaper, organ builders, to determine the tolerable departures from the equal-temperament scale. Of three alternative designs involving departures of varying degrees, that shown in Table 4, when set up on a rank of pipes, was considered to be quite satisfactory. It will be seen that this confirms the results of Shower and Biddulph, namely that an error of the order of 0·1 % is tolerable. Of course, if sustained notes were played on an instrument having

Table 4

Differences of Frequency from Equal-Temperament Scale in Experimental Photo-Electric Organ

Note	Percentage error in frequency
C	+ 0·040
C#	− 0·105
D	− 0·112
D#	− 0·024
E	+ 0·115
F	− 0·070
F#	+ 0·126
G	− 0·010
G#	− 0·140
A	0
A#	+ 0·080
B	+ 0·100
C	+ 0·040

these inaccuracies of tuning, in unison with another instrument tuned exactly to the equal-temperament scale, noticeable beats would result. For this reason it would appear desirable to design instruments which will show the smallest possible departures from equal-temperament tuning. However, it should not be overlooked in this connection that it is the small tolerable errors of tuning of individual ranks of pipes in the case of the organ, or of the many instruments of the orchestra, resulting in a random distribution of frequency errors for each note played by the many pipes or individual instruments, which produce the chorus effect. This is not to be undervalued from the aesthetic point of view.

In the case of electronic instruments, with the exception of those utilizing synchronously-driven rotary forms of generator, the tuning adjustments will require to be made somewhat after the manner adopted with traditional forms of musical instruments. Such instruments are in consequence liable to go out of tune, and the frequency with which retuning will be necessary will, of course, depend on the particular design of the instrument.

With regard to instruments in group (C) (*f*), Table 3, the tuning is dependent on the following characteristics of the rotary generators:—

(i) The constancy of speed of the synchronously driven generator, including hunting effects introduced by the gears or other forms of drive.
(ii) The accuracy of the gear ratios employed to drive the shafts carrying rotors or groups of rotors.
(iii) The number of wave-forms, scanning lines, or equivalent, on the rotor and/or stator, and the accuracy with which the dividing is carried out.

These points will be dealt with more fully later in the paper.

It will be clear that once an instrument of any of the forms employing synchronously-driven generators has been designed and built, the tuning is fixed by the mechanical constants of the components. If, therefore, it is designed and constructed correctly it will always remain perfectly in tune; conversely a poor design and bad workmanship will result in an instrument which can never be in perfect tune.

(c) Intensity Range.

The loudness level from all pipes of the same timbre in a correctly voiced organ is generally adjusted to be sensibly equal throughout the whole pitch range, at least so far as the ear of the voicer is able to judge. Actually, in some cases a progressive increase in loudness is intentionally produced towards the higher notes in order that when chords are played the treble notes shall be prominent.

No figures are available for the actual (as apart from the relative) intensities of the various pipe tones in an organ, and therefore the initial setting in the case of electronic instruments is best carried out by aural methods. The values chosen are dependent to some extent upon the differences in sound intensity level which it is desired to obtain.

The range of intensity available in pipe organs varies considerably, depending on the size of the instrument. However, this will be in the region of 40 decibels for small instruments, extending to something approaching double this value for the one or two giant instruments which have been built.

The actual intensity of the full organ is a factor which can only be considered in relation to the acoustical properties of the building in which it is to be housed. The building also has an appreciable effect upon the actual quality of the various stops, but as this subject is a very extensive one it is not possible to treat it in detail here, and reference should be made to the various available publications.[19]

(d) Timbre Range and Starting Transients, etc.

The combined intensity and timbre range of pipe organs is greater than that of any other single instrument, and although the most characteristic tone colour is that of the diapason stops, many other tone colours are available, which may be used in combination with the foundation diapason tones, or for solo purposes and to produce special effects. These comprise imitations of string tones and most orchestral wind instruments, together with tones peculiar to the pipe organ.[20] Also, in the case of the theatre organ, bells and percussion effects, etc., are included.

In order to imitate these many tone colours by electronic means, a knowledge of their respective sound-pressure wave-forms or the harmonic composition of the tones produced is necessary.

Meyer and Buchmann[21] and Boner[22] have analysed the tone of many instruments of the orchestra, and also that from organ pipes of various types. These and other similar data may usefully be used in designing the wave-form records or synthesizing arrangements for producing, by electronic means, the steady tone colour of these various instruments.

The problem of the starting and stopping characteristics is, however, a much more difficult one, and although very considerable inventive genius has been shown in the many proposals which have been made for accomplishing this, usually a compromise has to be adopted. Even if the exact harmonic content and time delays of the starting and stopping transients are not imitated, in some cases a measure of the effect is produced when the envelope of the sound wave-form is suitably controlled.

In the design of an electronic organ provision should be made, if possible, for the easy control by the performer of the harmonic content of the steady tone of at least one stop in addition to the means of tone control provided by stops imitating existing instrumental tone colours. This should prove of value to the musician in enabling him to use new tone colours, and also in investigations in harmonic synthesis which the electronic organ makes possible. Some provision must also be made for the control of the envelope of the complex sound-pressure wave-forms produced, if it is not possible to imitate exactly the required starting and stopping transient conditions.

In pipe organs the tremulant has come to be considered essential for producing vibrato effects when required; the electronic organ must therefore also be provided with suitable means for simulating this low-frequency fluctuation in pitch and/or volume.

(e) Harmonics—Tempered versus Untempered, etc.

Table 5 shows the fundamental frequencies in cycles per second of all notes of the tempered scale for a compass of 9 octaves, the pitch of the notes being based upon A (= 440 c./s.). When considering the design of electronic instruments of the form in which the different tone colours are obtained by synthesis, the question naturally arises from a consideration of Tables 1, 2, and 5, as to the possibility of using the notes of the tempered scale nearest to the corresponding harmonics required, instead of generating further exact harmonic frequencies. It will be seen that it is unnecessary to produce additional frequencies for use as harmonics which are already present as octaves, also that in many cases the frequencies of the notes of the chromatic scale nearest to the required harmonics are so little different that it would appear possible to use them as such. The possibility of using " tempered harmonics " is very attractive from the commercial point of view, when considering the size, weight, and cost of the generators.

The exact tones which it is desired to imitate must of course be known when this question is being considered, and if necessary, a compromise adopted.

The diagrams in Fig. 2 indicate the numbers and proportions of harmonics produced by various instruments. From these data it would appear that for the successful imitation of the steady tones of all the instruments cited, up to 50 harmonics are required. As the audible limit is in the region of 10 000 to 20 000 c./s., it follows that in the case of notes having fundamentals of frequencies approaching the top of the audible range the higher harmonics, even if present, will not be heard. However, these latter harmonics, by reason of the production of beats at lower frequencies within the audible range, may in some cases influence the resultant tone colour.[23]

It will also have been noted from Figs. 1 and 2 that in many cases the harmonics shown by analysis are very weak. Experiments carried out by one of the authors have confirmed that the presence of these weak harmonics, although often inaudible when radiated alone at the strength indicated by the harmonic analysis, when sounded in combination with the fundamental and other harmonics, markedly influence the tone colour of the resulting note of complex wave form. This was readily demonstrated by generating a tone of complex wave form, using electronic methods, in which one of the higher harmonics had a value approximately 40 db. below the intensity of the fundamental. Sounded by itself this harmonic was inaudible, and yet by changing its intensity level from 40 to 38 db., or from 40 to 42 db., the change in the tone quality of the resultant note was immediately apparent. This effect is most pronounced when the harmonic is in the region where the ear is most sensitive.

This latter point has a very important bearing on the range of intensity adjustment which must be available in an electronic instrument, and also the allowable tolerance in the relative intensity settings of the various harmonics of complex tones.

(f) Sinusoidal Wave-form Generators.

In electronic instruments of the form in which the tones of complex wave forms are synthesized by the combination of predetermined proportions of the various harmonic components of sinusoidal form, an important consideration is the relation between radiation intensities of sound pressure waves of sinusoidal form and the relative loudness as appreciated by the average ear throughout the audible frequency range. The curves published by Fletcher[24] showing these relationships at different intensity levels are given in Fig. 7. These data enable the radiation intensity of each harmonic of a synthesized tone to be determined in relation to the relative loudness required in the composite tone. For example, it is interesting to note the experience of one of the authors in adjusting the level of a 96-note sinusoidal wave-form generator so that the loudness of the individual notes of the equal-temperament scale throughout the compass of the instrument should be uniform. This was first carried out with the co-operation of a skilled organ voicer, and the levels so set up appeared to be uniform in loudness when notes of sinusoidal form only were played. However, when various tone colours were synthesized the notes of the resulting tone colours were non-uniform in loudness to a degree which was quite intolerable. The reason

Table 5

EQUAL-TEMPERAMENT FREQUENCIES
(A = 440 c./s.)

←——1 ft. Pitch——→ (C³ to C⁶)
←——2 ft. Pitch——→ (C² to C⁵)
←——4 ft. Pitch——→ (C¹ to C⁴)
←——8 ft. Pitch——→ (C to C³)
←——16 ft. Pitch——→ (CC to C²)

	CCC	CC	C	C¹	C²	C³	C⁴	C⁵	C⁶
C	32·703	65·406	130·812	261·625	523·251	1 046·502	2 093·004	4 186·008	8 372·016
C♯	34·647	69·295	138·591	277·182	554·365	1 108·730	2 217·460	4 434·920	8 869·840
D	36·708	73·416	146·832	293·664	587·329	1 174·659	2 349·318	4 698·636	9 397·272
D♯	38·890	77·781	155·563	311·126	622·253	1 244·507	2 489·014	4 978·028	9 956·056
E	41·203	82·406	164·813	329·627	659·255	1 318·510	2 637·020	5 274·040	10 548·080
F	43·653	87·307	174·614	349·228	698·456	1 396·912	2 793·824	5 587·648	11 175·296
F♯	46·249	92·498	184·997	369·994	739·988	1 479·976	2 959·952	5 919·904	11 839·808
G	48·999	97·998	195·997	391·995	783·991	1 567·982	3 135·964	6 270·928	12 541·856
G♯	51·913	103·826	207·652	415·304	830·609	1 661·218	3 322·436	6 644·872	13 288·744
A	55·000	110·000	220·000	440·000	880·000	1 760·000	3 520·000	7 040·000	14 080·000
A♯	58·270	116·540	233·081	466·163	932·327	1 864·654	3 729·308	7 558·616	15 117·232
B	61·735	123·470	246·941	493·883	987·766	1 975·532	3 951·064	7 902·128	15 804·256

for this was obvious after measurements of the generator outputs had been made by means of a valve voltmeter, which indicated that the intensity levels were such that the condition for uniform loudness was not accurately satisfied. These inaccuracies introduced as the result of one single observer's judgment, together with those resulting from the effect of standing waves at the time the observation was made, appear in exaggerated form when several frequencies are combined, and subsequent adjustment of the generator output in accordance with the curves in Fig. 7 resulted in uniformity in loudness not only of the notes of sinusoidal form but also in the case of notes in all the synthesized tone colours.

Another important point which must not be overlooked in generators of this type is that accuracy of imitation of the steady tone colours depends on the purity of the wave forms of the individual harmonic components.

(g) Complex Wave-form Generators.

In these systems, in one of many ways, the sound-pressure wave-form of the various steady tone colours is recorded. These records, or others derived from them, are used in various forms of generators to produce the notes of complex wave form. Alternatively the desired wave forms may be derived from harmonic analyses and then transferred to the particular form required in the generator. Bearing in mind the number and relative

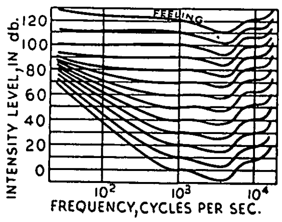


Fig. 7.—Contour lines of equal loudness for normal ear (Fletcher and Munsen[34]).
0 db. = 10^{-16} watt per cm² = 0·0002 dyne per cm²

intensity of the various harmonics which are deemed necessary, it will be seen that very accurate recording is called for and many proposals have been made in connection with this very difficult technique.

From the reasoning given in the previous Section regarding the intensity levels of fundamentals and harmonics, it follows that care must also be exercised in arranging the relative intensity levels of the various notes of different quality. In many such systems the construction proposed allows of some measure of compensation, either in a general way by suitably designing the characteristic of the amplifier, or in a more detailed manner by adjusting the intensity of each individual note in the various tone colours. However, this does not allow of the fine adjustment of the relative intensity of the individual harmonics to compensate for the acoustical properties of the particular building in which the instrument is housed, nor for the non-linear frequency characteristics of the amplifiers, loud-speakers, etc.

(h) Arrangement of Controls on Console.

The modern pipe organ console has been evolved as the result of years of development, and provides the means whereby the rapid changes of stops or groups of stops and the operation of expression controls can be brought about with a minimum of effort on the part of the performer. Whether in the development of the new electronic types of instrument it is wise to adhere strictly to the pipe organ console design is, of course, a somewhat controversial point. The argument in favour of the retention of the normal form of console is that the normal organ-playing technique, which can only be acquired after years of study, may still be used. It is clearly undesirable suddenly to introduce new methods of control which would seriously embarrass contemporary organists. However, there would appear to be no objection to providing alternative or additional means of expression.

(B) Frequency Generators—Electrical Considerations

The electrical problems involved in the various generator systems which have been proposed and used in the construction of full-compass organs will now be dealt with in the order in which they are classified in the sub-groups of group (C) in Table 3. As has been previously pointed out, sub-groups (C) (*a*), (*b*), and (*c*) have not been developed past the experimental stage and will therefore not be dealt with here.[25]

Of the three remaining systems, valve and neon-lamp generators are the ones in which no moving parts are required. In the case of reed generators, compressed air is needed to vibrate the reed, whereas the rotary-generator systems require synchronous electric motor drive.

(a) Multiple Oscillator Circuits.

The choice of oscillatory circuits for use in electronic musical instruments depends on many factors, the foremost of these being the stability of the frequency, as upon this depends the constancy of tuning of the instrument, the importance of which has already been stressed.

Many circuit arrangements have been suggested, each of which has its own peculiar limitations and advantages. For example, the use of one valve for each fundamental[26] and each harmonic naturally involves a large number of valves with their appropriate resonant circuits, cathode heater, and anode supplies, and the arguments in favour of the use of tempered harmonics would in this case materially assist in reducing the number of valves required. In order to reduce the number of cathode heater circuits, proposals have been made to use special valves in which one cathode functions for a number of independent oscillatory circuits.[27]

In 1930, Coupleux[28] demonstrated in France an organ having two manuals of three octaves' compass and pedals of normal compass, in which valve oscillatory circuits were used to generate complex wave-forms and filter circuits arranged to select the particular frequencies as required. Six months later he built a full-compass instrument, and in 1931 a two-manual and pedal organ having 22 stops and utilizing 250 valves was installed in a French church. Subsequently he built a three-manual and pedal organ of 76 stops incorporating 400 valves, which was installed in the studio of the Poste Parisien broadcasting station. In these instruments each note-frequency oscillator circuit was provided with means for adjusting the frequency so that the tuning could be carried out after the manner employed in tuning a piano or pipe organ, the constancy of pitch depending on the constancy of the valve characteristics and associated circuit components. The stop keys brought into action banks of filters for modifying the generated waveforms to produce the necessarily limited and somewhat arbitrary range of tone colours.

An experimental two-manual and pedal organ was built by Kock,[29] employing as generators neon lamps in oscillatory circuits; this was claimed to be very stable. Here again special filter circuits brought into action by the stop-key mechanism provided a limited range of tone colours.

Neither of these two forms of instrument has appeared in this country, nor apparently has been developed further, presumably due to difficulties in maintaining tuning sufficiently constant, limited tone colour range, and cost and bulk of the oscillatory and filter circuits.

Quite recently, an instrument of American origin,[30] developed by Williams and Hammond, made its appearance in this country. This can hardly be classed as an organ, although it can be used to produce sustained tones in addition to the many percussion and specialized effects. Like a piano, it has only one 6 to 7-octave keyboard and no pedals other than for controlling expression. In this instrument frequencies of the 12 notes of the top octave are generated by beat-frequency oscillators, many of the components of which are of special construction to ensure accuracy and constancy so that the generated frequencies shall be maintained to the necessary accuracy. The output from these 12 oscillators is connected respectively to frequency-halving circuits of special design which thus provide the note frequencies for the next lower octave of 12 semitones. This process is repeated for each octave down to the lowest note on the keyboard. The output from these divider circuits is then taken through control valves operated by the note keys to the amplifier, filter, and loud-speaker circuits. Three filter circuits controlling the top, middle, and bottom registers, give a measure of tone control, whilst special filter networks enable the envelope of the wave form of the note to be modified. Volume and tremolo effects are also provided. In all, about 160 valves are used in this instrument, which is able to produce a very large number of effects, including imitations of the harpsichord, guitar, and piano.

(b) Wind-Maintained Reeds as Generators.

This form of generator is seldom used for generating sinusoidal wave forms for synthesizing tone colours, as the complex nature of the vibrations of free reeds makes this extremely difficult.

The reed-type generator,[31] such as is incorporated in a two-manual and pedal instrument due to Hoschke, depends for its action upon the change in electrostatic capacitance between the metal tongue and small insulated electrodes placed above it. The reeds used for this purpose are similar to those employed in harmoniums, etc., and are vibrated by low-pressure wind.

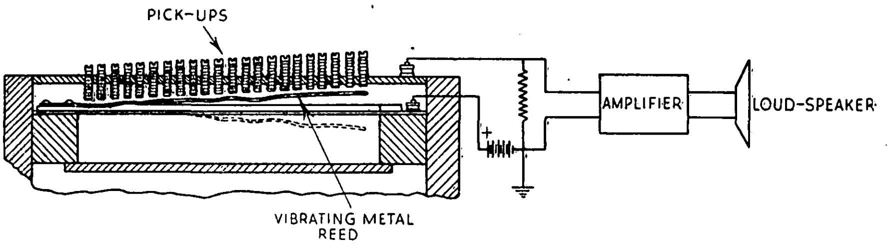


Fig. 8.—Wind-maintained reed generator.

By arranging a number of small screws immediately above the vibrating reed to act as pick-up electrodes, and connecting them in a circuit of the form shown in Fig. 8, a musical note of fundamental frequency of that of the reed will be obtained. The tone of this note will, of course, depend on the relative positions of the pick-up electrodes and the characteristics of the vibrating tongue.

There are, of course, other ways of controlling the tone produced by reed generators; some depend upon electrical considerations,[32] but most of these are based on practice common to reed-organ builders, such as shaping of the ends of the reeds in the manner shown in Fig. 9. If such reeds are used in conjunction with pick-up electrodes shaped as in Fig. 10, tones containing fewer harmonics will be generated. Reeds of the form shown in Fig. 11 make use of a variation in area to produce capacitance variations. The electrical output from this type of generator is very low, being in the region of -70 to -80 db. (zero level $= 0\cdot006$ watt) and consequently high-gain amplifiers, of the order of 100 db. gain, are required.

The stopping and starting characteristics of the resultant generated wave forms from this type of generator follow closely those of the actual reed. They may be modified to some extent by suitable resistance-capacitance networks connected between the reeds and the amplifying valves. In this way smoother tones may be produced.

(c) Rotary Forms of Generator.

(i) *Photo-electric Scanning.*

Mercadier, in 1890, made use of photoelectric scanning methods, but his proposals were in connection with the generation of a number of audio frequencies for use in multi-channel telegraphy.

Photo-electric methods of scanning used in electronic musical instruments may be divided into two main groups, namely those in which the light from an illuminated stationary slit is modulated by the passage in front of the slit of a variable-density or variable-area form of mask[33] after the manner of the sound track of a talking film, and those in which the illuminated mask of the wave form is stationary and is traversed by a series of slits one fundamental wavelength apart,[34] in the manner shown in Fig. 12. In both these forms the resultant modulated beam or beams of light are concentrated on to one or a small group of photo-electric cells, the output from which is fed to a power amplifier and loud-speakers.

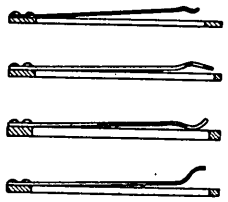


Fig. 9.—Examples of shaped reeds.

Many ingenious variations on these two forms have been proposed,[35] but only two complete full-compass organs have been constructed, one in France by Toulon and the other in Germany by Welte. Photo-electric organs of one and two manuals but no pedals have been constructed in America.[36]

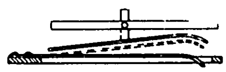


Fig. 10.—Example of shaped reed with special pick-up.

Toulon[37] was probably the first to construct a full-compass photo-electric organ, and his instrument utilizes stationary wave forms arranged radially, one row per tone colour, immediately in front of a rotating disc carrying slits in concentric rows at diameters corresponding to those at which the wave forms are placed, as shown in Fig. 12. The slits are spaced one fundamental

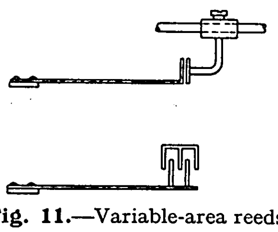


Fig. 11.—Variable-area reeds.

wavelength apart so that the wave masks are scanned at the appropriate speeds. The rows of slits are arranged at the different diameters so that the numbers of slits in each successive concentric ring are approximately proportional to the frequencies of the tempered scale. The tuning inaccuracies are, however, greater than 0·1 % in frequency, the normally acceptable limit [see Section 5(A)(*b*)]. In this particular arrangement one rotating disc carrying slits, together with its associated wave forms, is required for each octave. The optical arrangements utilized in this instrument are very compact and are indicated diagrammatically in Fig. 13. It will be seen that all the modulated light beams from all the notes of different tone colours of one octave are concentrated by the condenser lens on to one photocell, and the shuttering of the modulated beams of light associated with the individual notes is achieved by small electromagnetically operated shutters which operate at the focal point of the individual beams, so that

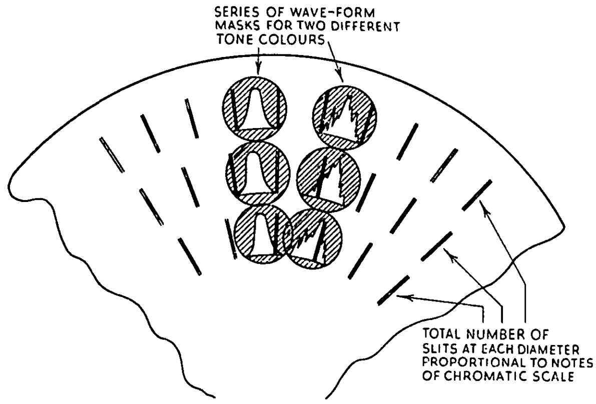


Fig. 12.—Sketch showing arrangement of stationary wave-form masks and slits on portion of rotating scanning disc of photo-electric organ.

the amount of movement required is extremely small. Eight such units are employed, one for each octave, so that eight photocells are required. The number of light sources used in this case is only four, because of the symmetrical disposition of the units on either side of the tungsten-filament lamps. The control of the many shutters from the console is carried out in a manner similar to that used in operating the pallets in pipe organs of the " unit " type.

The photo-electric organ constructed by Welte[38] employs a series of variable-area sound tracks arrranged concentrically on discs rotated synchronously at appropriate speeds. Small lamps illuminate the stationary scanning slits, and the resultant modulated light is concentrated on the photo-electric cells. The form of one scanning unit used in this instrument is shown in Fig. 14 (see Plate 1, facing page 532).

(ii) *Electromagnetic Generators.*

The electromagnetic system of generation was used by Cahill[39] in 1897, and it appears from his very complete and practical patent specification that he appreciated fully all the requirements for producing by synthesis musical notes of various tone colours. At that time the thermionic valve was not invented and he used large generators in order to obtain the requisite power. Contactors controlled from the console were used for mixing in appropriate proportions the alternating currents of sinusoidal wave form and various audio frequencies. He actually had this instrument constructed, and proposed to distribute the music over a telephone network, despite the limitations of such a means of translating the

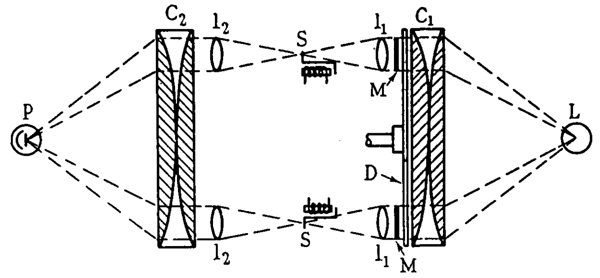


Fig. 13A.—Toulon's scanning unit.

L = light source.
C_1 = condenser lens producing approximately parallel light.
M = wave-form masks.
l_1 = small lenses for producing images of masks at l_2.
S = electromagnetically controlled shutters at focal points.
C_2 = condenser lens concentrating all beams on photocell P.

generated currents into musical sounds. The plant and control mechanisms occupied a very large room, and eventually the project failed for financial reasons.

It was not until after the invention of the thermionic valve and the development of amplifiers and loud-speakers that further proposals were made for developing this principle.[40] By means of valve amplification the use of very small generators was made practi-

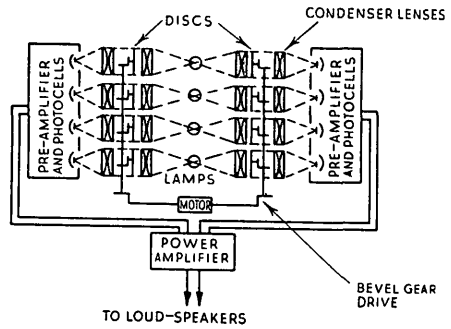


Fig. 13B.—Toulon's assembly of scanning units; one unit per octave.

cable, the simplest form consisting of a small iron disc with suitably shaped periphery mounted on a shaft and arranged to rotate in front of an electromagnetic pick-up. In early forms the pick-up was polarized electromagnetically, but in later designs the core is a permanent magnet. A unit of such a generator incorporated in a contemporary electronic organ developed by Hammond[41] is shown in Fig. 15. Rotation of the wheel produces an alternating current in the pick-up coil, corresponding approximately in wave form to the shape of the indentations on the wheel, and in frequency to the number of wave forms and speed of rotation. It will thus be seen that if a series of such generators are

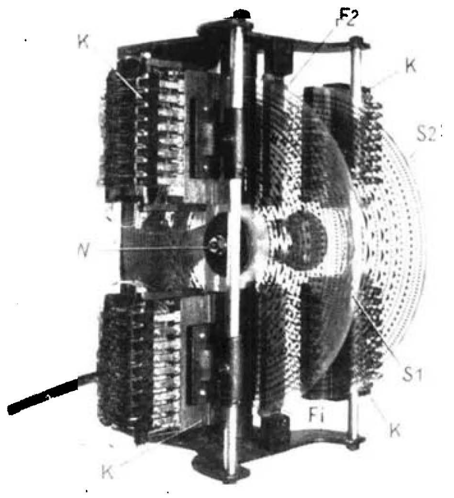


Fig. 14.—Welte photo-electric organ scanning unit.

W.—Spindle.
K.—Mechanism containing exciter lamps and shutters.
Fi and F2.—Photocells.
S1 and S2.—Discs carrying sound tracks.

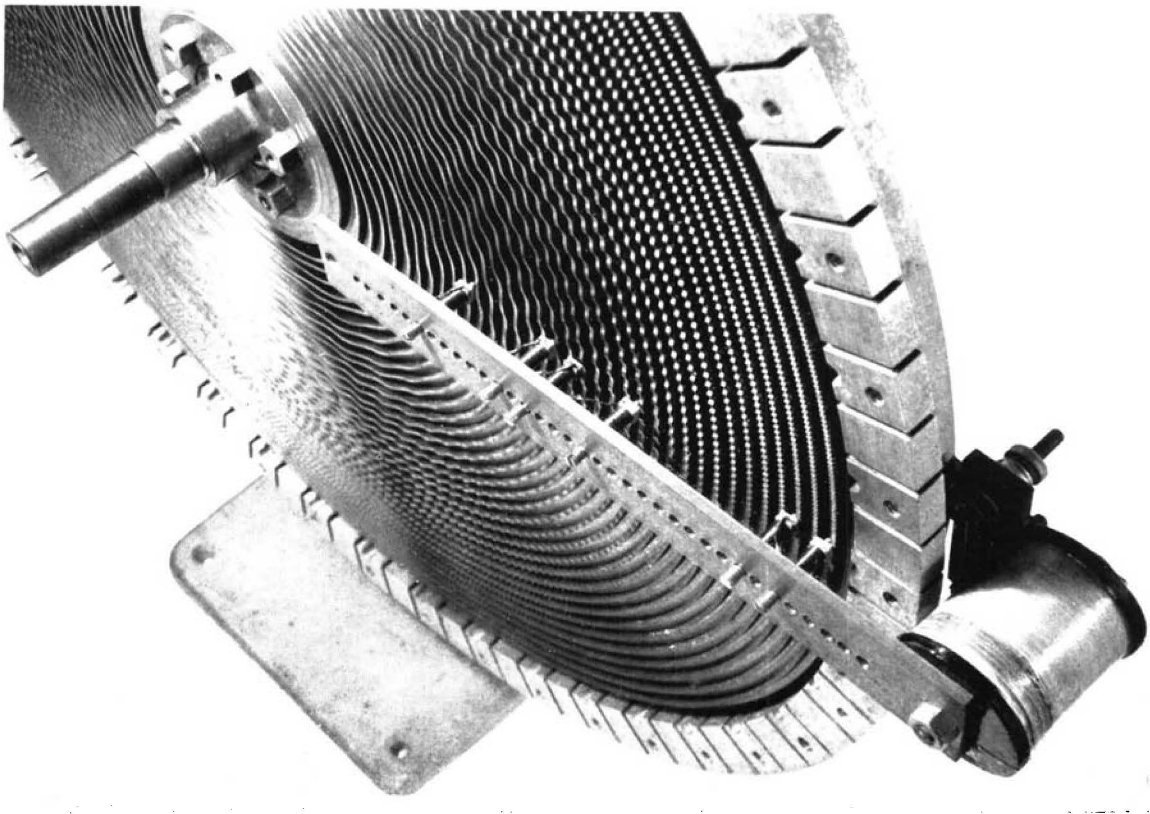


Fig. 16.—Partly assembled multi-frequency electromagnetic generator, showing portion of disc, and pick-ups on one radial arm.

(Facing page 532.)

Plate 2

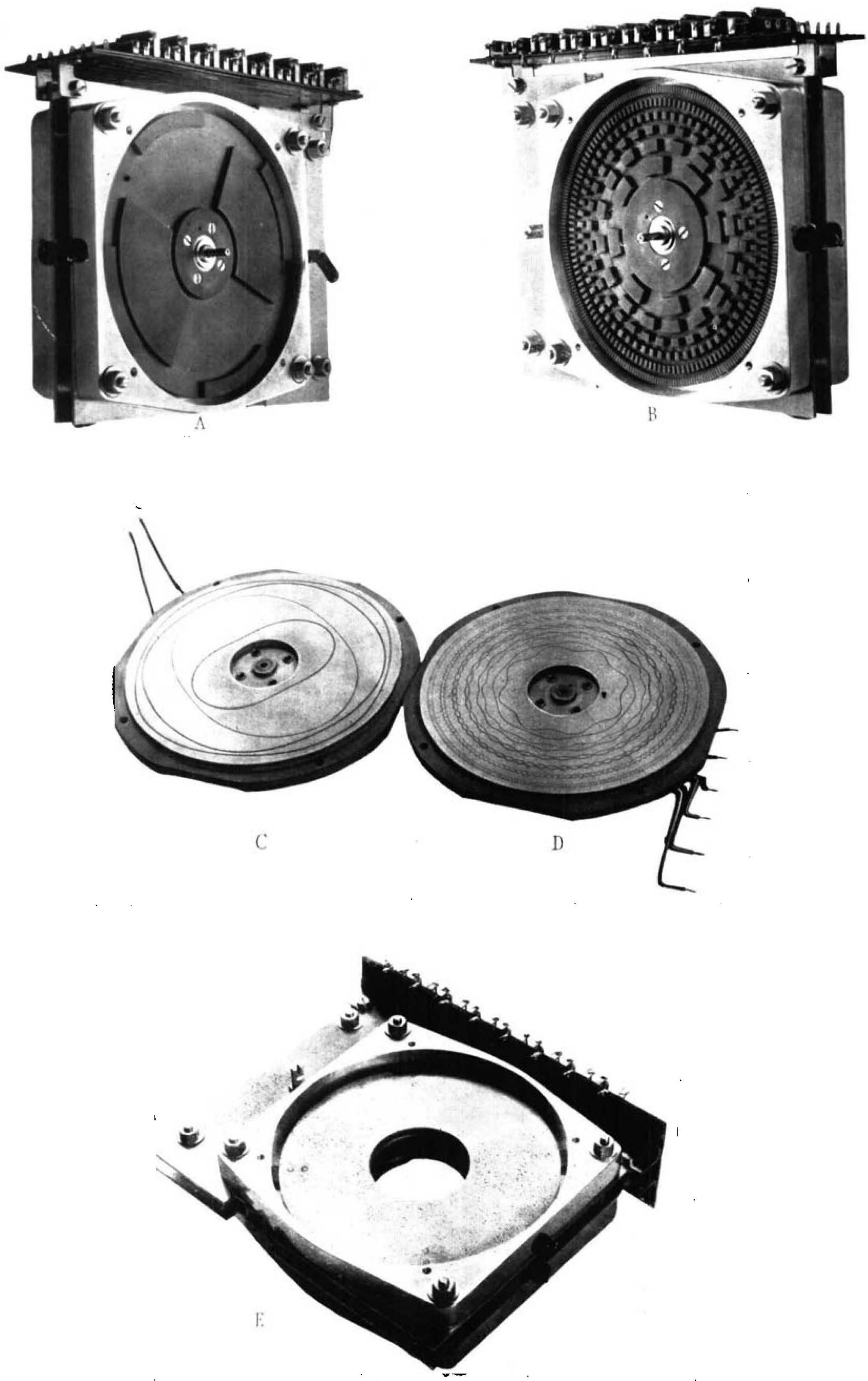
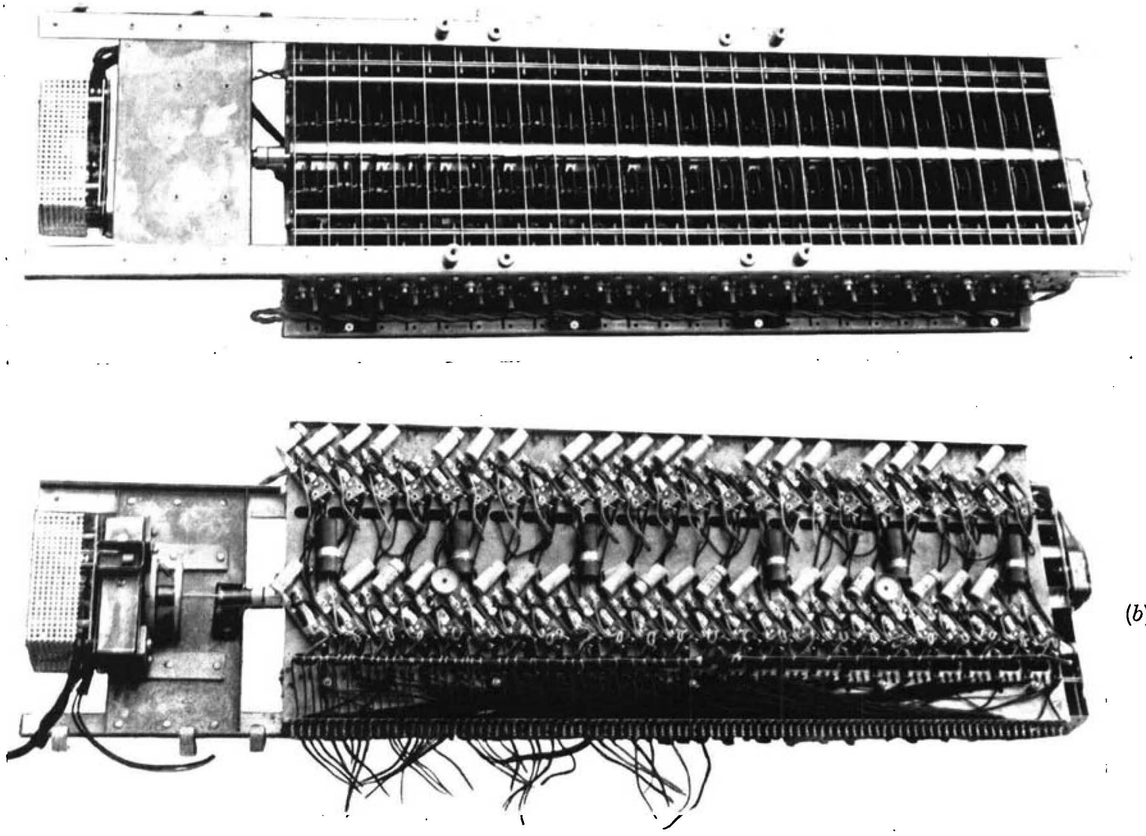


Fig. 21.—Electrostatic generator—partially assembled components.

A and B.—Bakelite rotors exposed. C and D.—Stators with sinusoidal contours. E.—Disc stator.



ı)

(*b*)

Fig. 22.—Assembly of 96-note electromagnetic generator.

(*a*) Alternator discs exposed.
(*b*) Mechanically damped synchronous drive (on left). Components of filter circuits (on right).

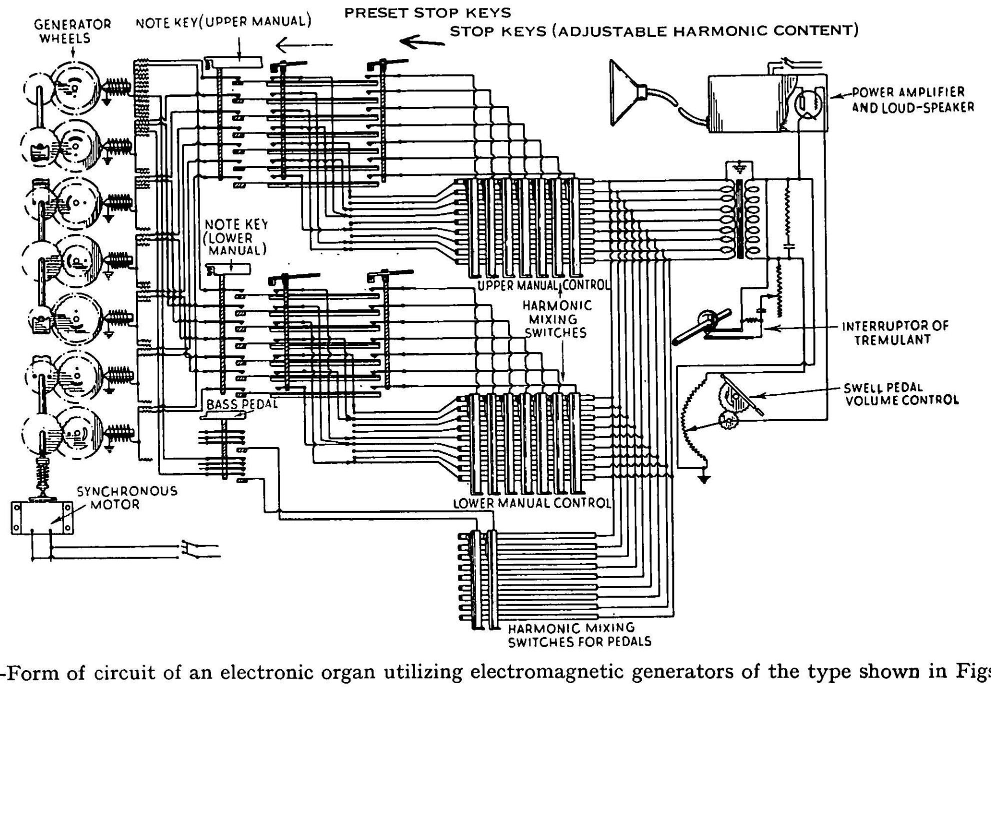


Fig. 23.—Form of circuit of an electronic organ utilizing electromagnetic generators of the type shown in Figs. 15 and 22.

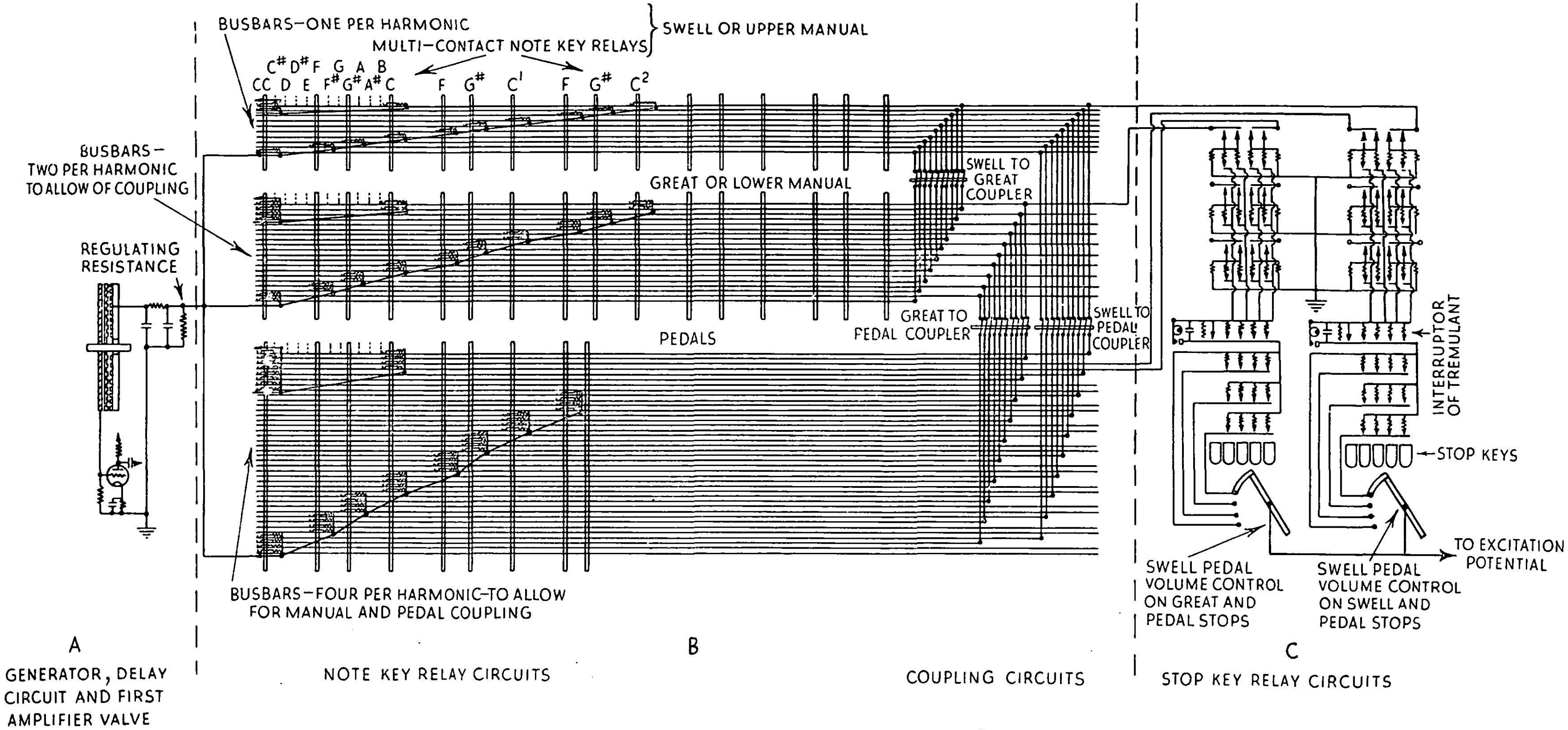
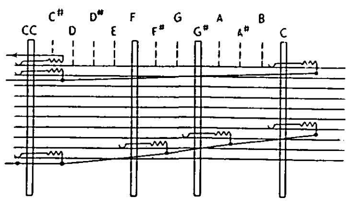


Fig. 24.—Form of circuit of an electronic organ utilizing electrostatic generators of the type shown in Fig. 21 (see Plate 2).



Enlarged view of note key relay shown in left-hand top corner of Fig. 24.

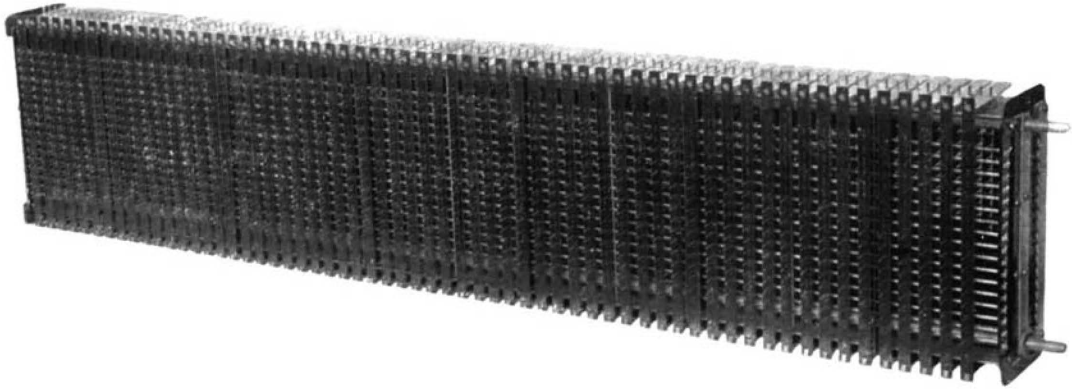


Fig. 25.—Assembly of 61-note key relays having 16 busbars—one per harmonic.

Fig. 26.—Complete electronic organ, incorporating electrostatic generators and circuits as in Figs. 21 and 24.

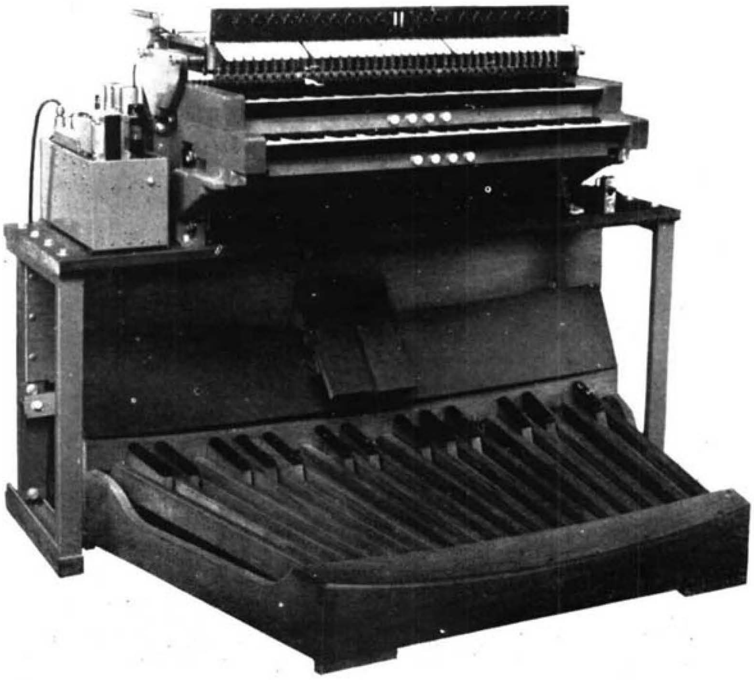


Fig. 27.—Electronic organ of Fig. 26, without case, and toe pistons.

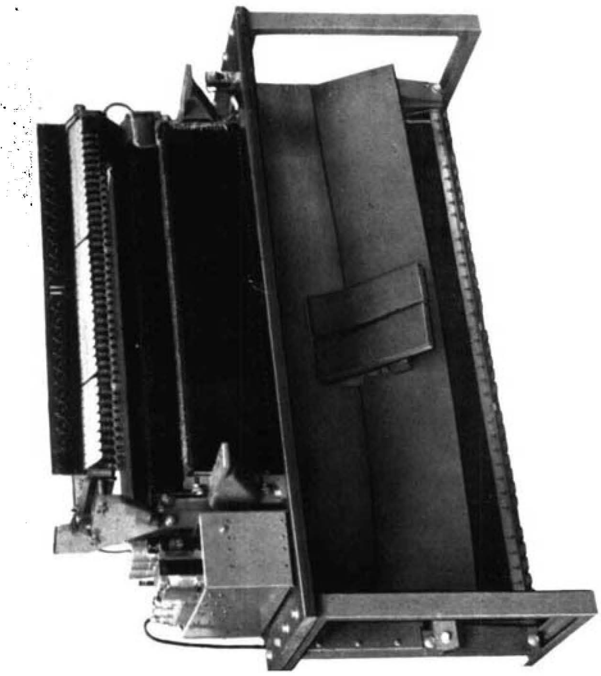


Fig. 28.—Electronic organ; as Fig. 27, but without keyboard and pedals, showing note key relays.

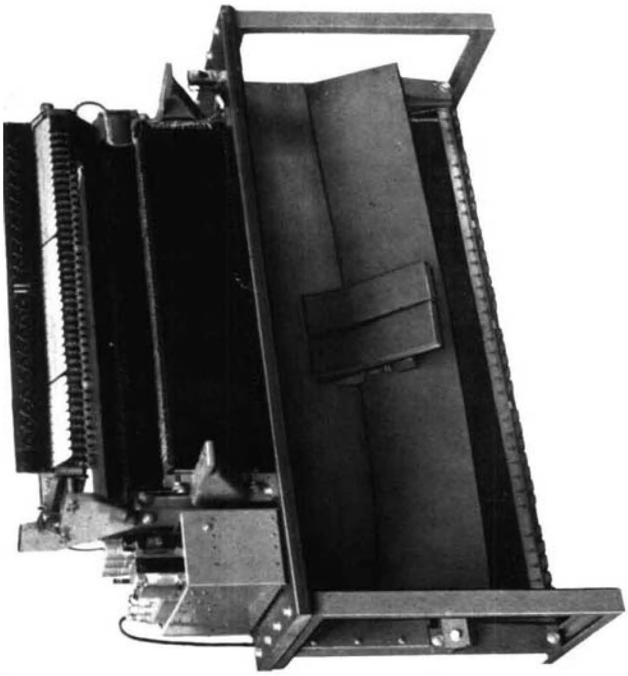


Fig. 29.—As Fig. 28, but with stop key relays raised and note key relays hinged forward.

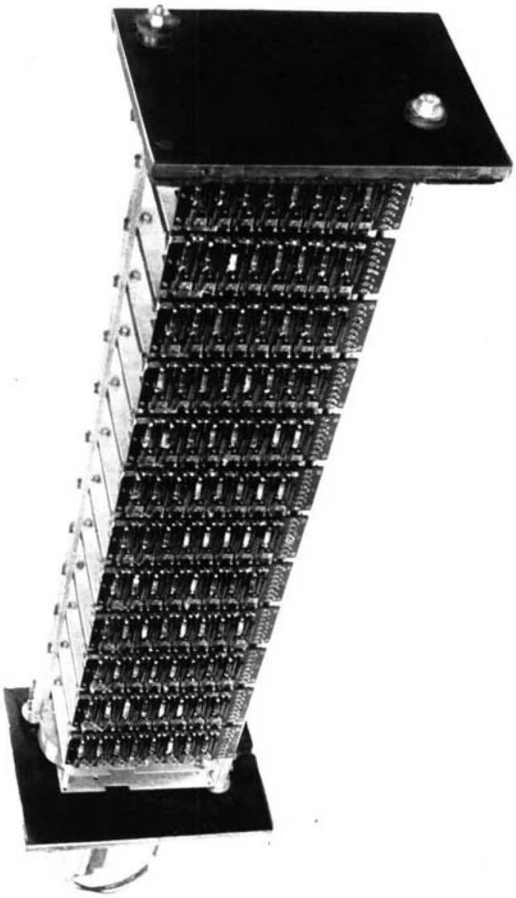


Fig. 30.—Electrostatic generators of organ in Fig. 26, showing unit assembly.

used, producing the fundamental and harmonic frequencies required, it should be possible to combine these currents of various frequencies in any desired proportions to produce various complex wave-forms. This form of generator is not only the simplest, but in practice it has proved the most economical, to construct. The electrical output from it is high as compared with that from electro-

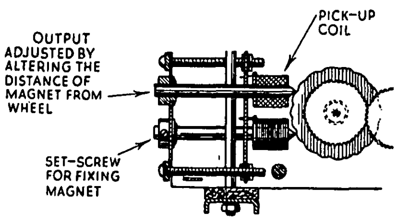


Fig. 15.—Electromagnetic generator; one disc per note; simple wave-form type.

static and photo-electric generators, and in consequence less amplification is required. In addition, the background noise level is low, and this, combined with the high output, enables a very quiet generator to be produced. A difficulty associated with this, and in fact all electromagnetic systems, is the elimination of fringing effects. This is of particular importance if sinusoidal wave forms are being generated, as spurious frequencies are introduced [see Section (5)(A)(*g*)]. This effect can be reduced to some extent by suitably shaping the pole-pieces or by the introduction of filter circuits to control the generated wave form.

In another form of generator which has been constructed experimentally,[42] a number of concentric ridges are cut on one face of a rotatable iron disc. On the face of each ridge, at right angles to the plane of the disc, sinusoidal wave forms are cut. The size and number of wave forms is so arranged that, progressing from the inner

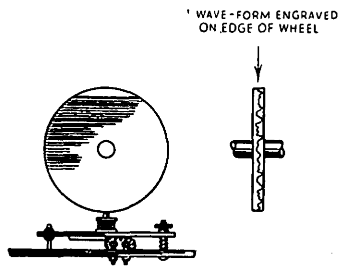


Fig. 17.—Electromagnetic generator. One disc per note—complex wave-form type.

ring, each successively larger ring has twice the number of wave forms of the inner adjacent ring. Series of magnetic pick-ups consisting of radially arranged iron strips with pole-pieces in the form of grub screws opposite each of the concentric rings, are set radially facing the side of the disc on which the wave forms are engraved, as shown in Fig. 16 (see Plate 1). It will be seen that by altering the relative distance of the screws in the pick-ups, chosen proportions of the frequencies generated when the disc is rotated may be obtained. Also, the magnitude of the current of complex wave form so generated may be controlled in each radial pick-up bar by varying the electromagnetic excitation. In an alternative arrangement the numbers of wave forms on successive generator rings may be proportional, within the allowable inaccuracies in tuning, to the semitone intervals of the equal-temperament scale.

Whilst this construction considerably reduces the number of moving parts, as compared with the single-note disc generators, it is more costly, and fringing effects are also present.

A further example of an electromagnetic generator developed by Robb[43] is indicated in Fig. 17. Here complex wave forms are engraved on the edge of the discs, the idea being to use one disc per note per tone colour, each disc generating, in its associated pick-up, current of the

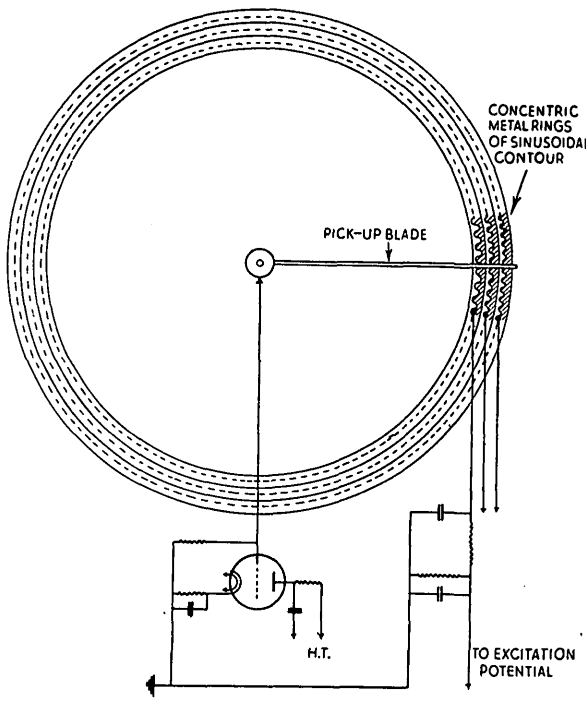


Fig. 18.—Electrostatic simple wave-form generator.

appropriate complex form. This system also suffers from fringing effects, and the construction has proved very costly.

(iii) *Electrostatic Generators.*

One early form of electrostatic generator, due to Bourn,[44] is shown diagrammatically in Fig. 18. This comprises a stationary disc of insulating material on which are arranged concentrically a series of metallic rings, one edge of which is of sinusoidal form. A flat metal arm mounted at right angles to the plane of the disc, with one edge about $\frac{1}{64}$ in. away from it, rotates over the disc about its own centre. The rotating arm and the sinusoidally shaped rings form a capacitance varying cyclically in a manner depending on the speed of rotation and the number and shape of the wave-forms on the metal rings. By connecting these elements in the circuit shown in the Figure, small voltages of sinusoidal wave form are generated when any one ring is keyed into the excitation circuit. If more than one ring is keyed into circuit at the same time, a voltage will be generated, having two or more component frequencies superposed in proportions depending on the values of the excitation potentials. By suitable choice of these excitation potentials, a chosen complex voltage wave-form may be generated.

The output of such a generator is very small and is liable to be uneven due to mechanical difficulties in maintaining accurately the distance between the rotating metal arm and the stator. Very small mechanical errors may in consequence introduce very objectionable cyclic modulation of the output. Also, fringing troubles will arise from this form of construction, and the generation of sinusoidal wave forms will only be approximated.

These difficulties are overcome by making the rotor of the web form shown in Fig. 19, and the stator as in Fig. 21(*d*) (see Plate 2). Here, the number of radial lines or scanning elements has been increased[45] so that they are spaced $\frac{1}{2}$ wavelength from one another. This results in an appropriate increase in output and also provides a compensation effect, should the scanning disc run out of truth owing to small mechanical inaccuracies of mounting. By forming the rings from metal, sputtered on to an insulating base, and afterwards engraving the concentric sinusoidal contours, an island is left between each ring. If this island is connected to earth, fringing is prevented by reason of the resulting focusing effect of the lines of force. The circuit arrangements in Fig. 18 entail the use of a brush-type contact between the rotating collecting arm or multiple scanning elements and the grid circuit of the first amplifying valve.

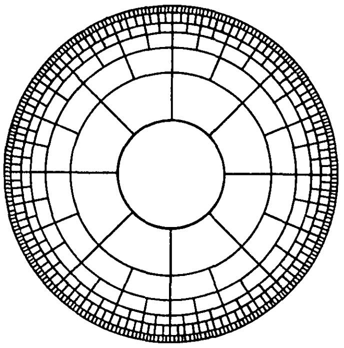


Fig. 19.—Web form of rotor with multiple scanning elements.

In the circuit arrangement[46] in Fig. 20, the brush connection is in the earthed side to overcome the possibility of noise being generated owing to this moving contact.

A method of still further increasing the output consists in making the scanning elements in the form of segmented areas covering half the corresponding wavelength.[47]

In systems where the rotor and stator are placed close together, stray leakage currents, giving rise to noise, may be generated as the result of the presence of small particles of dust or moisture.

The above effects are minimized in a later form of generator construction[48] shown in Fig. 21 (Plate 2). This avoids the need for moving contacts, and allows of the use of larger spacing between the electrodes, thus reducing the mechanical and electrical difficulties.

In this arrangement the bakelite rotors are of the form shown at A and B in the photograph of the partly assembled generator. The corresponding stators for this generator are shown at C and D, respectively, whilst the plane disc form of stator E fits on the opposite side of the rotors in both generators. In this construction the bakelite rotors produce sinusoidal variations in the dielectric between the corresponding concentric conducting rings of sinusoidal contour on the stators, and the stator discs. For example, a complete generator for providing two low frequencies consists of a rotor such as A, revolving between a stator C and a disc E. By connecting the conducting rings on one stator C to the appropriate excitation potentials through suitable resistances and switching circuits, and the other stator disc E to the grid circuit of the amplifier, voltages of sinusoidal wave form may be generated.

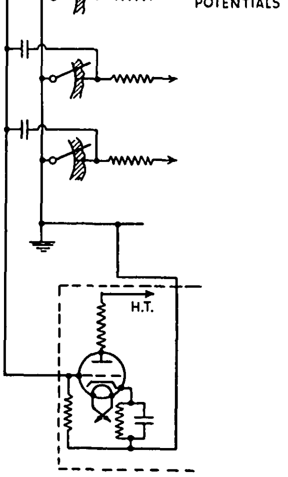


Fig. 20.—Circuit arrangement for electrostatic generator with brush connection in earthed lead.

Systems have also been proposed by Curtis, Estell Scott and Biggs involving the use of electrostatic generators to modulate the high-frequency currents produced by valve oscillators.[49] Subsequently, the modulated high frequency is passed through a detector stage, and the audio-frequency component amplified. The advantages claimed for this system are that the construction of the rotary generator is extremely simple, the signal/noise ratio practically infinite, and amplification problems simplified. As keying and mixing of high frequencies can be accomplished through small condensers, it is proposed to use such methods to avoid key contacts and mixing circuits. By using different high-frequency carriers, the frequencies for several manuals could be supplied from the one rotary generator, via suitable filter circuits. The possible disadvantage of this arrangement is the danger of mutual and radio interference, and although it is claimed that this could be rendered innocuous by adequate shielding, the authors are not aware of any full-compass organ which has been constructed on this principle. It is believed that this system has not passed the very early experimental stage.

(C) Frequency Generators—Mechanical Considerations

(a) Generators other than Rotary Forms.

The non-rotary forms of generator classified under sub-groups (C) (*a*), (*b*), (*c*), (*d*), and (*e*) of Table 3 involve no particular mechanical problems, and in all cases key-boards, consoles, and methods of control, follow normal pipe-organ practice.

(b) Rotary Generators.

In the case of rotary forms of generator there are many mechanical problems to be surmounted, foremost among these being that of providing the accurately constant-speed drive to the various rotors.

In all rotary systems, whether photo-electric, electro-magnetic, or electrostatic, the accuracy of pitch depends on the accuracy of rotation of the generator rotor. According to the particular system employed, one of two general forms of drive will be necessary.

Where all the 12 semitones within the octave are derived from one disc, cylinder, or group of generator rotors on one shaft, each successive shaft will need to be driven at twice the speed of that providing the frequencies for the octave below, so that the gear ratios in this case are simple ones. The accuracy of the musical pitch will obviously depend on the number of scanning elements or generator poles provided for generating each semitone, and on the constancy and actual speed of the rotational drive. For example, to take the case of a photo-electric scanning disc provided with slits radially engraved one fundamental wavelength apart in concentric rings, clearly if the intervals are to be those of the tempered scale to within $0 \cdot 1\ \%$ [see Section 5(A)(*b*)] it will not be possible to use less than a predetermined number of slits in each ring. This will automatically determine the actual speed of rotation of the disc for a given musical pitch.

In the alternative form, the fundamental frequency and all its harmonics are derived from one disc, cylinder, or group of separate note generators all carried on one shaft. The semitones are provided by driving 12 such generators, or sets of generators, at speeds progressively increasing in the ratio $1 : \sqrt[12]{2}$. The accuracy of the pitch of the semitone intervals will therefore be governed by the gear ratios employed.

Even if precision-made clock gears are used in the drive from the synchronous motor, irregularities in speed will occur, resulting in frequency variations in the notes produced which will be intolerable to the ear. However, it has been found that by the use of carefully designed mechanical filters these speed variations can be damped out.

One example of a 96-note electromagnetic generator[50] is shown in Fig. 22 (see Plate 3). The upper picture shows the many generator wheels and their associated magnets, whilst in the lower view the synchronous-motor drive with its mechanical filters can be seen on the left. On the top of the generator housing are the components of the electrical filter circuits, previously referred to, which are necessary in order to eliminate the unwanted harmonics in the generated currents, the wave form of which is only approximately sinusoidal. The mechanical filter in the drive will be seen adjacent to the synchronous motor. This comprises a spring-driven flywheel to reduce hunting, followed by a spring drive to the first counter shaft on which is mounted the driving gears for the first set of rotors. The drive to the rotors is then taken via a small hair-spring so that any non-uniformity due to back-lash or imperfections in the gears is damped. In this manner the necessary constancy of speed is maintained. It is interesting to note that the hair-spring drive to the rotors also considerably reduces the generation of impulse voltages due to the backlash in the teeth of the gear wheels, this being possible by reason of the following facts: the voltage generated is proportional to the rate of change of motion of the rotors, which in turn is proportional to the rate of change of the force acting upon the teeth of the gear wheels. This force is, of course, a product of the backlash in the teeth.

As these generators are usually housed in the organ console, the small self-starting synchronous motors used must be practically silent. In fact all vibration of the generator mechanism must be reduced to a minimum as it gives rise to background noise in the amplifier and loud-speaker system.

In electrostatic generators microphonic noise can arise from extremely small relative movements of the generator components. In consequence, those parts liable to vibrate need to be damped, or preferably a form of construction adopted in which this trouble is eliminated. This can be achieved by moulding the components. The choice of gearing and shaft diameters is also of importance and it has been found in practice that the use of small diameters assists in reducing noise. Actually, this results in a cheaper form of construction since the shafts can be made from the ground steel rod available in small diameters in the trade.

(D) Mixing Circuits

In the various generating systems, methods must be devised for combining the many frequencies generated, and in this connection, as stressed in Section 5(A)(*g*), it is necessary to take into account the relation between the sensation of loudness at different frequencies and the radiation intensity.

In considering the circuit arrangements for producing equal steps in loudness of the tones produced, the energy steps must be in geometrical ratio in accordance with Weber's law which states that "Equal increments in intensity of sound as interpreted by the ear are increments which bear a definite relationship to the intensity of sound before the increment."

In addition it may be well to bear in mind that when considering the circuit arrangements for producing a given summation of energies, the voltages or currents involved must be proportional to the summation of the square root of the energies. The importance of this is to ensure that:—

(i) When more than one note of the same tone colour is played at a time the loudness of the individual notes is not different from that when notes are played singly.

(ii) When several individual tone colours are played simultaneously by the addition of stops, the resultant combination tone shall truly represent the addition of the tone colours and loudness, as when stops are added in a pipe organ.

The methods of mixing fall into three general groups as follow:—

(a) Addition of Modulated Light by Photocell.

In the light scanning methods used in photo-electric types of organ, the problem of mixing is an optical one. The components of the many individual scanning elements must be so arranged that the modulated light beams are all collected on to one photocell or a small group of photocells. Many methods have been proposed, and Fig. 13, which has already been referred to, is an arrangement used by Toulon,[51] requiring one photocell per octave, i.e. 8 photocells in all. These photocells are connected in a parallel network and thence to the input circuit of a power amplifier and loud-speakers. In another example, used by one of the authors[52] in an experimental instrument, again all the scanning slits for the 12 semitones within the octave were carried on one disc. The parallel light, either from groups of single-note projectors or a small number of multiple-note projectors, was in this case passed through the wave masks and scanning discs to one or more large parabolic mirrors, which focused the modulated light beams on to one or more photocells.

(b) Addition of Audio-Frequency Components.

In general, in the generator systems classified under (C) (*a*), (*b*), (*d*), (*e*), and (*f*)(ii) in Table 3, in which either complex or sinusoidal wave-form audio frequencies are generated and subsequently combined, some form of mixing circuit must be provided.

In complex wave-form systems this is accomplished by arranging for the outputs of the various generators to be fed to multi-ratio transformers, the feeds from the generators for each particular tone colour being provided with limiting impedances in order to keep the primary loading on the transformer as constant as possible. If this is not done, frequency distortion will occur according to the number of notes being played. A similar circuit arrangement is required for combining the various note frequencies associated with their respective stops as they are brought into action. In these systems this is very difficult to achieve. Approximations to the ideal additive requirements are usually employed in attempts to simulate the progressive increase in loudness which occurs in pipe organs when many notes and stops are played simultaneously.

As one example of a *simple* wave-form generator, Fig. 23 (Plate 3) indicates the complete circuit of an organ incorporating the 96-note, simple wave-form tempered-harmonic generator of the single-note-per-disc, magnetic type. By means of the multi-contact key switches the current from the note-frequency generators is fed via a limiting resistance to the stop switches, which are adjustable over the busbars connected to the 8 tappings on the primary of the output transformer, which feeds the power amplifier. The tappings of the transformer primary are such that the successive tappings provide voltages in geometrical progression. This is in order that adjustment of the harmonic mixing switches which make contact on these busbars shall provide successive equal increments in loudness, in accordance with Weber's law. Each of the harmonics of one note is obtained via a limiting resistance from the appropriate generator through one of the contacts of the key switch to the appropriate harmonic mixing switches. The resistances in each circuit are high in value compared with that of the generators in order to avoid appreciable voltage-drop when the many circuits are paralleled.

It will be clear that the depression of a key switch will connect to the transformer the generators supplying frequencies which have been selected by the harmonic mixing switches, the intensity of the particular harmonics being regulated by the extent to which the mixing switch is drawn and the particular busbar which has been connected in this manner.

Additional multi-contact stop switches are provided so that any harmonic content which, by experiment with the harmonic mixing switches, has been found pleasing, can be connected to the appropriate tappings of the output transformer. Depression of one of these stop keys can then be made to produce the same result as setting up a particular harmonic combination on the mixing switches. For convenience in playing the instrument, several such switches are provided for each manual, and so arranged that depression of one releases any other which may previously have been in operation. It is not possible in this arrangement to add the tone colours of the individual stops as in a pipe organ.

A very simple means of adjustment is provided for ensuring that the output of all note-frequency generators throughout the compass of the instrument can be set so that the loudness of the resultant notes is uniform. This is accomplished by adjusting the distance from the tone wheel of the magnet carrying the pick-up coil. The means provided for accomplishing this adjustment are indicated in Fig. 15. Of course, a progressive increase or decrease in loudness throughout the frequency range can be made with equal facility, if required, and in all cases it is easy to avoid the non-uniformity in loudness of successive notes which might otherwise arise due to the circuit, and in particular the loud-speaker frequency characteristic.

In order to reduce "key clicks" and the influence of spurious high harmonics arising from magnetic fringing effects in the generators, a resistance-capacitance network is placed across the output of the transformer.

This system does not provide means for regulating the envelope of sound waves produced, other than in a general manner by the skilled manipulation of the adjustable potentiometer in the secondary side of the output transformer, which is operated by a swell pedal as in normal pipe-organ practice. A tremolo, adjustable for frequency, is produced by a motor-driven interrupter system associated with a resistance-capacitance network, also across the secondary of the transformer.

(c) Addition by Control of Excitation Potentials in Electrostatic Generators.

The mixing circuits which will now be described are used in conjunction with electrostatic rotary generators, and in modified forms in other types of electrostatic generator. In such generators the a.c. output, and therefore, the voltage impressed on the grid of the first amplifier valve, will be proportional to the d.c. excitation voltage applied to the generator electrodes. The generation of sinusoidal or complex voltage wave-forms of the required magnitudes is therefore most readily performed by applying the appropriate d.c. voltages to the generators.

A circuit diagram indicating the method of operation and control of the generator excitation in one example of an electronic organ operating on this principle is shown in Fig. 24 (Plate 4). This figure is divided into three sections. A is the generator and circuit for controlling the starting and stopping time or envelope shape of the notes produced. This enables the comparatively slow speech associated with organ tones, or alternatively percussive and other special effects including bell and xylophone tones,[53] to be imitated. By the same means the undesirable transients, which occur on the closing of the many circuits operated by the note keys, can be eliminated, thereby avoiding " key clicks."

The note key relay circuits shown at B in the Figure enable the required excitation potentials to be applied to the generator. One set of note key relays is shown in Fig. 25 (Plate 4). The application of the required excitation potentials to the appropriate generator rings is accomplished by providing one limiting resistance in series with each note key switch contact. For any one note of the scale, the depression of the note key moves one of the vertical tracer bars which operate the multi-contact note key switches, and connects them with the appropriate busbars. The number of busbars required depends on the number of harmonics which will be utilized in synthesizing the tone. In the circuit diagram, Fig. 24, it will be noted that only 10 busbars and multiples of 10 are shown. This is only to simplify the drawing, but in the actual instrument, as will be seen from the photograph of the unit in Fig. 25, 16 busbars are used for the 16 harmonics. It should be observed that, as the harmonics are derived from the 96 notes of the tempered scale, the number available for the higher notes becomes progressively less. It will be clear from the circuit diagram that each frequency generator ring is connected through the appropriate resistances to a number of note switch contacts. For example, the generator ring producing the frequency of the note C^2 is connected to a switch contact operated by tracer bar C^2, which is moved by the note key of that name.

This allows the generation of a voltage of sinusoidal form when the key is depressed, so that a pure note of correct pitch will be sounded, providing the busbar has been connected to an exciting potential by the operation of a stop key switch. But it will also be seen that the same generator ring is connected to contacts operated by the tracer bars of all note keys having a fundamental pitch such that the frequency C^2 is one of the first 16 harmonics. Each frequency generator ring is connected in a similar manner to note key switch contacts corresponding to the note of the generated frequency and also the other notes of which the generated frequency is one of their harmonics. When, therefore, an excitation potential is applied to one busbar by a stop key relay, shown at C in Fig. 24, and a note key depressed, an excitation potential will be applied to one generator ring. Should the stop key relay only excite the busbar which makes contact with the generator rings providing frequencies corresponding to the fundamentals of the note keys, then when note keys are depressed only fundamental tone will be generated. Different stop keys can be arranged to excite different busbars or combinations of busbars in any desired manner so that depression of a note key will then result in the generation of a note, not only of fundamental pitch but having any required number and proportion of the available harmonics. The correct proportioning of the limiting resistances in series with each note key and stop key contact ensures that the simultaneous depression of more than one note and/or stop key will produce the correct additive effect in the resultant musical notes.

It will be seen that if the note key resistances were of a very low value, the busbars would virtually be short-circuited. Alternatively, if they were all of very high value, the potential across the regulating resistance, shown in section A of the circuit diagram, would be very small and not in proportion to the energies necessary to produce, in accordance with Weber's law, the correct loudness increments. It has been found in practice that, provided the regulating resistance is between one-third to one-fifth of that of the key resistances, then the correct additive effect will be obtained within the limits tolerable to the ear.

The charging or excitation potentials applied by the stop keys must be proportional to the summation of the square root of the energy levels at which the several frequencies are required either as fundamentals or harmonics, to produce the required tone colours. The correct proportioning of the stop key resistances connected to the negative side of the d.c. excitation supply determines the actual potentials applied, and the accuracy with which the tone colours, singly or in combination, are produced.

Space will not permit of the treatment of methods of calculating the values of these resistances and those regulating the loudness, as controlled by the swell pedal which operates by varying the busbar excitation potentials. For further details, therefore, reference should be made to the appropriate patent specifications.[54] This method of regulating the loudness is used in preference to gain controls on the power amplifier, as it avoids the increase in background noise with increasing loudness, and enables the groups of stops on the individual keyboards and pedal board to be separately controlled for loudness, by means of separate swell pedals, varying independently the potentials applied to the busbars of the respective keyboards and pedal board. Also, by suitable proportioning of the stop-key volume-control resistance values, it can be arranged that, in all or some stops, the higher harmonics increase in loudness progressively as loudness is increased by operation of the swell pedal. This simulates the effect produced by the swell box in a pipe organ (see Sections 2B and 2C).

The double set of busbars and note key contacts associated with the lower or " great " manual are necessary in order that when the " swell to great " multiple contact switch, shown in the diagram, is closed, notes played on the " great " will be coupled to notes of the same name on the " swell." Similarly, the four sets of busbars associated with the pedal board are required to produce the " great to pedal " and " swell to pedal " coupling effects, which, together with the "swell to great" coupling, are required in pipe-organ playing technique. These three couplers are operated by the three multiple-contact switches, which can be brought into action by the appropriately marked stop key switches on the console. The tremulant effect is produced by the cam-driven interrupter shown in section C of the circuit diagram, and is also brought into operation by a stop key switch.

Thus it will be seen that in this system the mixing circuits are so designed that a sensibly true additive effect, both of notes and stops, is obtained as in a pipe organ, together with manual and pedal coupling facilities and independent control of loudness of manuals and pedals by separate swell pedals.

(E) Sound-Producing Equipment

Considerable progress has been made in the design of amplifiers and loud-speakers in recent years, particularly in connection with sound-film developments. The quality of reproduction has made steady advances, and very great acoustical outputs can now be obtained as the result of new and more efficient designs of amplifier and loud-speaker. Therefore, it is not proposed to deal at length with this subject.

It is interesting to note, however, that although the requirements for sound-producing equipment to be used in electronic organs involve problems peculiar to this particular application, the design of special sound-producing systems for this purpose has received comparatively little attention.

As has been stressed earlier, in a number of the systems used in electronic organs, irregularities in the frequency-response curve of the amplifier and loud-speaker system can be compensated in some measure by adjustment of the output of the individual frequency generators. In such systems, therefore, very uniform frequency-response characteristics are not essential, although obviously in types of generator where the output of the individual note frequencies is not adjustable, a uniform frequency-response will be necessary.

The main difficulties arise in the extension of the frequency range down to the limit of approximately 16 c./s., and the uniform radiation of the sound, as high directional intensities are very undesirable, except perhaps in exceptional circumstances. The problem of amplification and the production of notes at the very low frequencies and high loudness levels normally associated with the pedal stops of pipe organs, is a very real one.

It is now common practice in the design of high-power sound-producing equipment to divide the frequency range into two sections, using separate loud-speakers for the high- and low-frequency ranges, respectively. This has led to the development of multi-cellular speakers for the high frequencies, which have in some measure overcome the difficulties arising from undesirable directional radiation in this range of frequencies. Such loud-speaker systems are at the moment costly and very bulky.

A loud-speaker system which has been specially developed for use in conjunction with electronic organs incorporates an amplifier having a suitably extended frequency response, and high- and low-frequency range loud-speakers of special design.[55] These speakers have stretched aluminium foil diaphragms mounted on circular rings. The diaphragm has a moving-coil drive and at low frequencies operates approximately as a piston in the surrounding baffle. The polar distribution of the sound radiated from this form of loud-speaker is extremely uniform so that there are no undesirable focusing effects. Sound-producing systems of this form are actually incorporated in electronic organs of the design depicted in the next Section.

One problem in connection with sound-production systems which has received considerable thought in the sound-recording and broadcasting fields is that of artificial reverberation.[56] This is of particular interest in relation to electronic organs, as some suitable means of introducing artificial reverberation into the system would help to solve the difficulty of the "dead building"—a problem with which the organ builder is continually faced. Many systems have been proposed for broadcasting and other uses, and have been applied with some measure of success, but as far as the authors are aware none has been evolved which may successfully be incorporated in an electronic organ.

(6) GENERAL ASSEMBLY OF A COMPLETE ELECTRONIC ORGAN

In order to indicate the general form of the component assemblies, and the compactness of a complete electronic organ, photographs of one example incorporating rotary electrostatic generators are given in the following figures. The circuit arrangements, etc., of this instrument have already been described earlier in this paper.

Fig. 26 (see Plate 5) is a view of the complete console the overall dimensions of which, without the pedal board, are 49 in. high, 62 in. wide, and 29 in. deep. The pedal board is detachable for convenience in transport and the loud-speaker cabinets, which also house the power amplifier, the size and number of which will depend on the building in which the organ is to be installed, are separate components. In the photograph the stool has been removed so that the pedal board, toe pistons and swell pedals may be more readily seen.

The layout of the keyboards and controls is in accordance with the standards of the Royal College of Organists, and just above the two manuals of 5-octave compass will be seen the three groups of stop keys associated respectively with the pedal organ, on the extreme left, the great organ, and the swell organ on the right. The tone colours imitated when the various stops in their respective departments are operated, are indicated in the specification for this particular instrument (Table 6). It will be appreciated by reference to Section (5) (D) (*c*) that tone colours of stops of individual instruments can be set to suit the particular requirements by appropriate arrangement of the excitation voltages applied to the busbars by each stop key. Thus, for example, the tone colours of the stops in the instrument shown could be altered to be suited to theatre requirements, instead of as at present the tone colours being imitations of tones mostly associated with those available on church organs. The stops in the specification marked "Mutation" are associated with the two groups of 9 rotary switches which will be seen on the console just below the bottom of the music rest. When the 8-ft. mutation stop is operated on the great organ, for example, adjustment of the left-hand group of rotary switches enables a tone to be set up at 8-ft. (normal) pitch, having any desired combination of harmonic content available. Each rotary switch has 10 positions, and clockwise movement of the switch adds the particular harmonic which it controls, in steps giving equal loudness increments. The action of the 16-ft. mutation stop is similar, except that the tone in this case will be at 16-ft. pitch, or an octave lower. The two mutation stops operating on the swell manual can be used in a similar manner. Also, any one or all of these mutation stops may be used separately or in combination with other stops of fixed tone colour, and the result will be similar to that obtained when additional stops are drawn on a pipe organ. The thumb pistons (which will be seen under each manual) and the toe pistons (on the sloping panel just above and in front of the pedals) control the appropriate groups of stops. The same principles of design are applied in these accessory controls as are employed in electrically-controlled pipe organs. Actually, in this instrument, the relays operating the stops from these pistons are accessible from the back of the console, and the particular groups of stops which they severally bring into action can be pre-set by the organist to any desired combination in a matter of a few seconds. The balanced swell pedals, controlling the loudness of the stops drawn in the respective departments, are between the two groups of toe pistons.

Fig. 27 (Plate 5) shows the same console with the case removed; the voltage amplifier will be seen on the left-hand side. In Fig. 28 (Plate 6) the keyboards and pedal board have been removed, revealing the note key relays, etc. Fig. 29 (Plate 6) shows the manner in which the stop key relays and the note key relays may be raised in order to give access to the various resistances, for initial adjustment. Fig. 30 (Plate 6) shows the motor and generator assembly, which is normally housed at the back of the note key relays, the motor of which can just be seen on the right-hand side of Figs. 28 and 29.

Although, as will have been gathered from the details given earlier, the circuits are fairly involved, the form of wiring adopted has so simplified the technique that no skilled labour is required to wire the instrument. This also applies to the mechanical assembly, as every component is mass-produced, the majority of the small components being of pressed construction. The wiring technique adopted[57] involves soldering cross-connecting bare wires to appropriate tags on opposite edges of strips of bakelite, these subsequently being fitted into their appropriate positions in frame assemblies in a manner which renders the completing of the circuits a very simple operation.

(7) FUTURE DEVELOPMENTS

Having considered the development of electronic instruments to date, particularly that of electronic organs, it may be interesting to speculate as to future developments. No one will deny, of course, that electronic organs are still in their infancy, as compared with traditional forms of musical instruments. Nevertheless, a stage has now been reached when the designers of electronic organs may be proud of their achievements during the last decade, having in mind the hundreds of years of development which have contributed to the present high standard of excellence of the modern pipe

Table 6

SPECIFICATION OF ELECTRONIC ORGAN INCORPORATING ROTARY ELECTROSTATIC GENERATORS

Compass of manuals—CC to C—61 notes
Compass of pedals—CCC to G—32 notes

Stops of lower manual; or great organ.			*Stops of upper manual; or swell organ.*		
1.	Contra salicional	16 ft.	1.	Quintaten ..	16 ft.
2.	Diapason ..	8	2.	Geigen ..	8
3.	Gemshorn ..	8	3.	Viola da gamba	8
4.	Wald flute ..	8	4.	Gedackt flute	8
5.	Dolce	8	5.	Salicet ..	4
6.	Principal ..	4	6.	Cor de nuit ..	4
7.	Gemshorn ..	4	7.	Nazard ..	$2\frac{2}{3}$
8.	Open flute ..	4	8.	Flautino ..	2
9.	Twelfth ..	$2\frac{2}{3}$	9.	Contra fagotto	16
10.	Fifteenth ..	2	10.	Cornopean ..	8
11.	Tromba ..	8	11.	Oboe	8
12.	Clarinet ..	8	12.	Clarion ..	4
13.	MUTATION ..	16	13.	MUTATION ..	16
14.	MUTATION ..	8	14.	MUTATION ..	8

(i) Swell to great
(ii) Tremulant
(iii) Tremulant

Pedal organ

1.	Contra violone	32 ft.
2.	Major bass (G)	16
3.	Violone (S)	16
4.	Sub bass	16
5.	Octave (G)	8
6.	Bass flute (S)	8
7.	Trombone (G)	16

(iv) Great to pedal
(v) Swell to pedal

Accessories.

Five double-touch thumb pistons to great and pedal
Five double-touch thumb pistons to swell and pedal
Three toe pistons to pedal
Five toe pistons to swell (duplicating)
One reversible thumb piston for swell to great
Balanced swell pedal operating on great organ
Balanced swell pedal operating on swell organ

Note:—

Pedal stops under control of balanced great and swell pedals are marked (G) and (S), respectively.
The first touch of the thumb pistons operates manual stops only; the second touch operates pedal stops.

organ. Obviously, immediate attention will be directed towards the perfection of details of design of instruments operating on the principles already referred to in some detail, and it is certain that surprising improvements will follow from the increased range of tone colours and effects which will become possible.

Other principles may be anticipated; for example, the use of a cathode-ray method of wave-form generation has been proposed.[58] The attraction of such a method would seem to be the absence of moving parts, although it is difficult to say at this stage whether or not this advantage would be outweighed by the more elaborate nature of the components.

One of the most promising possibilities is the increased scope which will be offered to musicians in modes of expression. Present-day composers are striving to express new ideas, but with traditional musical instruments they are limited to the chromatic scale and the tone colours which are available and which have remained sensibly the same for many years. The electronic organ offers the possibility of new tone colours and effects, and because the tuning is only a matter of mechanical design there should be no difficulty in producing an instrument to play in just intonation, making use of a keyboard of the form suggested by Bosanquet, which was referred to earlier, or the simpler approximation recently proposed by Williamson.[59] In this latter arrangement, notes are selected from two tempered scales having frequencies in the ratio of 119 : 118, and it is proposed to use a normal keyboard provided with selector mechanisms to enable the performer to play at will in equal temperament or in any chosen natural scale. Similarly, the quarter-tone scale presents no particular technical difficulties such as are present in traditional forms of instrument. Theoretically, the scope of the electronic organ is very extensive, but, as has been shown, the practical possibilities are limited at the moment by the engineering problems involved.

From the point of view of compactness, portability, flexibility of control, constancy of tuning, and economy, obviously these instruments have a promising future.

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After the advance copies of the paper had been distributed Mr. Ll. S. Lloyd kindly suggested improved wording for the references on page 518 to musical scales, etc. The modifications have been incorporated for the *Journal*.

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(54) A. H. and A. M. MIDGLEY: British Patents 482284—23/9/36, 498128—30/3/37, 493320—29/4/37, 498130—28/4/37, and 499771—28/7/37.
(55) A. H. MIDGLEY: British Patent 332272—15/4/29, and 416998—18/5/33.
(56) K. A. MACFADYEN: British Patent 489170—25/7/37.
(57) A. H. and A. M. MIDGLEY: British Patent 491267—28/7/37.
(58) DAVIES [see (25) above].
(59) C. WILLIAMSON: *Journal of the Acoustical Society of America*, 1939, **11**, 216.

WRITTEN CONTRIBUTIONS TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. L. E. A. Bourn: It is a pity that the authors do not give more details with regard to the working of the new generator. The circuit given in Fig. 20 and alleged to be " noiseless " is in my opinion no better in this respect than the arrangement shown in Fig. 18, as it is just as essential that good contact be established in either case. Furthermore, this circuit is subject to the disadvantage that two extra components per frequency are required associated with the grid lead.

The latest type of generator invented by one of the authors is stated to show marked superiority over my earlier type; but from the descriptions available I cannot see that this is the case. In my original and later types a single air-gap only is needed, and exposed dielectric is carefully avoided. In this new type, however, not only must there be two air-gaps plus the thickness of the rotor, but the dielectric, however perfect, would most probably give trouble. If the minimum safe gap is, say, 1/64 in. and the rotor 3/16 in., the effective capacitance is reduced to approximately one-sixth with a proportional reduction of signal/noise ratio: also the rotor will acquire charges owing to absorption effects which cannot leak off immediately and would cause greatly increased background noise.

It is probable, however, that the rotor does not behave as a dielectric at all but as a conductor, by virtue of the fact that there is no appreciable current flow. If this be the case, or the mere dusting of graphite or other conductive material would make it so, it would not only result in an increase in efficiency from 1/6 to 1/2 but