# ELECTRONIC MUSICAL INSTRUMENTS

BY S. K. LEWER, B.Sc.

Electronic Engineering

TECHNICAL MONOGRAPHS

3/6 net

Hyde

# ELECTRONIC MUSICAL INSTRUMENTS

By S. K. LEWER, B.Sc.

(*Author of "The Cathode-Ray Tube Handbook"*)

(*First printed* 1948)

*Published at the offices of*
**"ELECTRONIC ENGINEERING"**
28 ESSEX STREET
LONDON, W.C.2

# CONTENTS

## CHAPTER 1

# INTRODUCTION

SOME confusion still exists in various quarters as to what is and what is not an electronic musical instrument. The distinction is quite a simple one. The term Electronic Music is usually reserved for music which is produced initially in the form of electrical oscillations which are under the direct creative control of the performer. An Electronic Musical Instrument is one in which such oscillations are produced, the oscillations being converted into acoustic energy by an electro-acoustic translating device such as a loudspeaker.

It will be clear, therefore, that electric pick-ups and amplifiers for re-playing *recorded* music are not included in this definition. Similarly, the highly publicised electric organ of the cinema, which superseded the earlier pneumatically-operated organ by reason of the increased flexibility of the electro-magnetic action, is also excluded, for it is essentially a pipe organ producing sound by pure acoustic action. Electric amplifier arrangements which merely amplify the sound energy received by microphones from musical sounds already generated are likewise outside the definition.

There are a few instruments (*e.g.*, the Electric Piano and the Electric Guitar) which are both acoustic and electronic, and in a strict analysis of their performance it would be difficult to apply the definition with certainty. No apology is offered for including them amongst the instruments described in the following chapters, for, as electronic instruments, their performance is independent of their acoustic effect.

It is important, too, that a distinction be drawn between electronic music and synthetic sound. Sufficient knowledge has been acquired of the vibrational characteristics of speech and music to form the basis of a new technique in which voices and musical compositions can be synthesised by the direct manufacture of the generative wave-pattern. The technique may, for instance, be applied to photo-electric film methods or to wave-patterns cut in wax, the entire sound track being drawn or moulded by the artist-draughtsman from the known acoustic requirements.[1] As in a Walt Disney film, the process is exceedingly laborious, but its possibilities are great. Words which no man has ever uttered may be made to emanate from a loudspeaker. Speeches may be concocted with particular personal idiosyncracies in the same way that a pictorial artist can represent real people in imaginary postures. Music may be created which no known instrument, acoustic or electronic, could possibly produce. All these are manifestations of synthetic sound. Electronic music, on the other hand, must be originated as a sequence in sounds by the performer, who must always retain the ability to select and combine the acoustic forms according to his art.

### The Production of New Tones

Having postulated the generation of the desired oscillations by electrical means instead of relying on mechanical devices, we find that wide possibilities are opened up for the creation of wave-forms quite different from those which any mechanico-acoustic instrument has been able to produce. A vast range of new tones is made available. This is dangerous ground, for the technical features embodied in these new possibilities are far in advance of artistic performance or aesthetic appreciation. The mere ability to create new sounds has tended to invite adverse criticism from the more conservatively-minded sceptics. This new musical technique has sometimes had the appearance of scientific trickery, and, like the model galleon in the glass bottle, it has been set aside as clever but useless.

A musical instrument is a device for rendering perceptible to the senses an artistic invention in sound which has been conceived by the composer for that particular kind of instrument. The beauty of the composition suffers and may be lost altogether if it is performed on a different kind of instrument. This may be expressed differently by saying that the artistic qualities of an instrument are not fully realised unless it is used to perform music which has been specially written for it, and electronic instruments cannot be excluded from this generalisation.

If this is accepted, there are two possible lines of approach to the broad question as to what we are going to do with electronic musical instruments. Must we make them imitate the conventional acoustic instruments and use them for playing existing musical scores, or may we be allowed to produce entirely new tones and ask the composers to write for these new instruments? There is no need to make a choice between these two possibilities, for both lines of approach can be followed simultaneously. Insofar as new electronic musical instruments can be made to imitate the older acoustic instruments but at less expense or with greater flexibility, their existence is justified, and insofar as composers can develop new forms of musical expression with the extra tone colours made available to them, that also is justified.

### New Composition for New Instruments

Already, several composers, including Hindemith, Honnegger and Milhaud, have written specially for electronic instruments having characteristically new tonal properties. The musical profession has never failed to respond to the attractions offered by technological advances in sound production. Before the pianoforte had been developed as a distinct form of instrument, there were no compositions in existence which were capable of bringing out the full beauty of this instrument. New music had to be written for it. When Tchaikowsky discovered the celeste, he wrote specially for it in his "Nutcracker Suite" with great enthusiasm and in much secrecy lest some other composer should disclose the possibilities of the new instrument to the public before him. The celeste, however, failed to achieve a lasting popularity for reasons which it would serve no purpose to seek. A similar fate may await some of the electronic instruments now being developed. Others may come to be in great demand, and it would be rash to try to frame a specification to which an instrument should conform if it is to qualify for public favour.

### Fundamental Requirements of New Instruments

There are certain requirements which can nevertheless be stated with sufficient certainty in regard to the qualities and characteristics of any new instrument.[2] It must have an interesting range of tone colour or a range of expression. If it has both, so much the better. But if it is devoid of variation of tone colour, and if it is limited to one form of expression, for instance, *glissando* or *staccato*, there is little likelihood of its lasting success. The interest lies in variation, and the greater the variation the greater the interest. An orchestral composition is more satisfying than a piano solo. A quartet is more interesting than a solitary violin.

The basic variations in music are, of course, variations of pitch and time, but these modes of expression are not sufficient to maintain the interest of the modern listener for any prolonged period. As examples of these rudimentary forms, we may mention bagpipes and drums. Such limitations must not exist in any new electronic instrument if it is to rise above the level of a technical novelty and command public interest.

### Electronic Counterparts of Existing Instruments

While the progress of the electronic instrument which produces new tone colours must depend on the creative work of the composers, there is nothing to hinder the advance of those electronic instruments which resemble the existing acoustic instruments in tonal qualities and performance.[3] Perhaps the best example of this kind is the electronic organ. A considerable amount of popularity has been earned by at least one relatively cheap form of electronic organ, mainly because it is something like a pipe organ in effect, yet different from it. The feature which attracts the attention is the *difference*, whereas if there had been no perceptible difference in effect, there would be little or nothing to catch the interest of the public. Yet there are such electronic organs in existence and on the market which so closely resemble the conventional pipe organ that it is difficult to distinguish the one from the other. These are the masterpieces of the electronic musical art, but because the imitation has been so successful the public is ironically still largely unaware of it.

The advantages offered by these successful electronic counterparts of the pipe organ include lower cost, smaller space and weight, freedom from necessity of periodic tuning, and freedom from the harmful effects of humidity. Even if the performance of the electronic organ in some of its forms had to be recognised as inferior to that of the pipe organ, the inferiority would be so slight that in comparison the price to be paid for the allegedly better characteristics of the pipe organ would be unduly high. The smaller and cheaper electronic organs unquestionably fill an important place in the same way as the harmonium, or reed organ, has met the need for a cheaper instrument where the cost and size of a pipe organ would be prohibitive.

Conservatism is very strong in the musical world, and generally speaking there is a reluctance to accept anything which is new, apparently because it lacks the hall-mark of antiquity—or at least of maturity. Most musical listeners dislike the work of contemporary composers, and only a minority find real enjoyment in modern compositions. Beethoven is more popular than Bax. Public taste changes slowly, but it certainly changes.

### Musical Scales

In Western music, the octave is divided into 12 semitones. Oriental music sounds peculiar and sometimes markedly unpleasant to Western ears because it is based on different systems of intervals —*e.g.*, 22 to the octave in India and 14 in Egypt. Possibly, the peoples of Europe and America might be induced, by prolonged educative effort, to appreciate new beauties of musical rendering if the octave were divided into more than the present 12 semitones, although this seems extremely doubtful. A development of this kind would involve a completely new notation for the printed scores. Of all the developments that lie within the bounds of possibility, this may well be the last to take place, and it is safe to assume that the musical scale now in vogue in Europe and America will remain unchanged for many generations to come. The Oriental ear may eventually come to adopt the Western scale, or alternatively the native scales may continue, in which case there may be interesting possibilities for the kind of electronic instrument which is adaptable to the smaller intervals.

### Transients and Envelope Control

A surprising range of expression resides in the control of the time-characteristics of a musical tone. Many of the instruments with which we are familiar are recognisable not only by their tonal colour, or harmonic content, but also by the transient form peculiar to the instrument in question. It has been said that if the tone of a note played on a piano could be maintained at a constant level instead of being allowed to decay as it normally does, the tone would be quite similar to that of a saxophone. Thus, the percussive attack and the exponential decay of the tone produced by a piano in the ordinary way are vitally important in identifying the tone as that of the piano. Similarly, the smaller transients due to the manipulation of the keys are easily detectable in the clarinet and flute. In the string family there is to be found a wide variety of bowing transients, apart from the *pizzicato* effect produced by plucking. The "speech" of organ pipes is a matter of great importance in the same way, and in the *lieblich gedackt* the starting transient is very prominent and involves a strong fifth harmonic. Much of the beauty in music would disappear if these transients were removed.

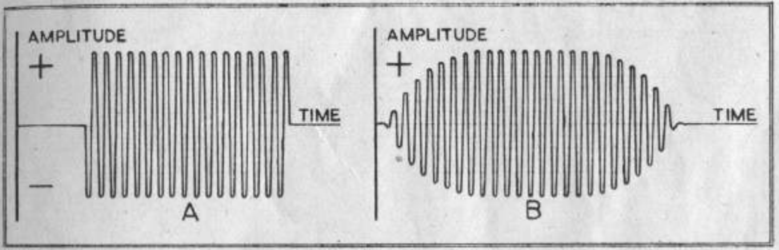


Fig. 1. The wave-form of a sinusoidal tone of short duration—(A) with negligible delay in starting and stopping, giving "hard" attack, (B) with appreciable starting and stopping transients, giving "soft" attack.

If an instrument produced a tone of constant strength immediately after the operating key was actuated, and if the tone vanished instantly when the key was released (see Fig. 1A), the ear would reject it as being positively uninteresting and unpleasant. A gradual starting and stopping of the tone, as indicated in Fig. 1B, giving a rounded form of "envelope," is much more acceptable, but it is important that the rise and fall should not be too slow. If they are, it will be impossible to play a rapid succession of notes without overlapping or undue delay between them. The effect would be either one of confusion or of a heavy, labouring style.

In Fig. 2 a tone is shown which rises rapidly and decays slowly. The simplest example of this form of wave-envelope is the piano, and the effect, at least to Western ears, is accepted as being pleasant. The reverse form, shown in Fig. 3, is not normally obtainable with existing instruments. An interesting experiment to demonstrate this form of envelope may be made by arranging for an ordinary disc record of a piano solo to be rotated in the reverse direction. The effect is strikingly novel but entirely lacking in beauty.

Electronic instruments can generally be provided with some measure of envelope control, and in this respect they are considerably more versatile than existing acoustic instruments where the envelope is determined by mechanical properties such as the natural decay of energy in a struck string. The piano provides a small degree of control over the starting and stopping transients inasmuch as the tone quality varies with the force of the hammer impact and the decay is subjected to strong damper action when required, but after the initial impact energy is constantly leaving the string and the only way to supply more energy is to give it another impact.

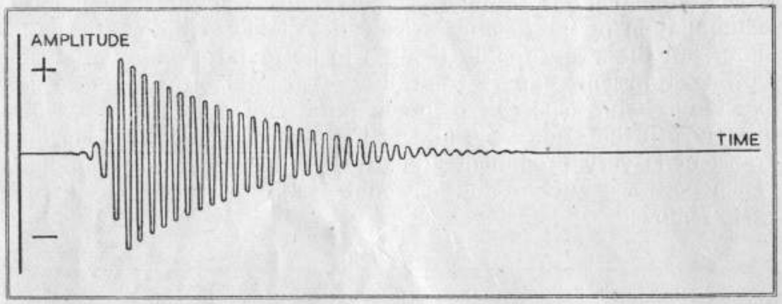


Fig. 2. The wave-form of an oscillation in which the amplitude increases rapidly and decays slowly. Tones having this characteristic are very common in music.

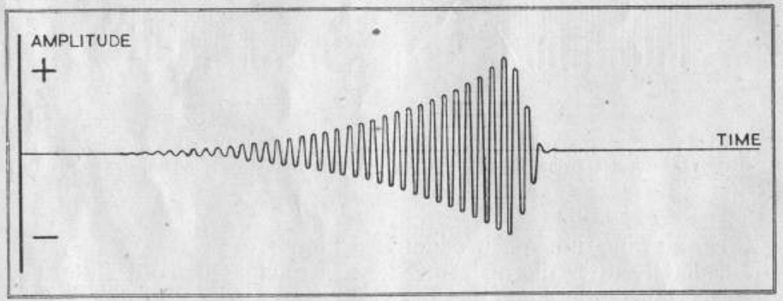


Fig. 3. The wave-form of an oscillation in which the amplitude increases slowly and decays rapidly. Tones of this nature are relatively rare.

### Intensity Control

Another aspect of musical expression is the change of intensity of the sound. The variation of level in orchestral performances is of the order of 1,000,000 to 1 (*i.e.*, 60 db). For the purpose of broadcast transmission this variation has to be compressed into a smaller range, and in order to regain the lost expression amplifier circuit arrangements have been devised for expanding the modulation again. Likewise, much of the beauty of a piano solo resides in the wide range of intensity from *piano* to *forte*. The pipe organ relies partly on the absorbing or shielding effect of heavy wooden shutters for achieving a variation of sound level in the swell organ and partly by varying the number of pipes actuated by each key on the manual.

In electronic instruments the intensity can be controlled over much wider ranges and with the simplest of control mechanisms. The sound output bears no direct relation to the size or design of the instrument, since an amplifier must in any case be used to drive the loudspeaker. The smallest and simplest instrument could be used, if desired, to fill even the largest hall with a deafening volume of music, merely by employing an amplifier system of adequate proportions.

### Stability of Pitch and Tuning

Some existing instruments retain their tuning over very long periods, while others require adjustment at frequent intervals. Almost without exception their pitch varies with the temperature, and most orchestral instruments will exhibit an appreciable variation during a concert performance. These weaknesses have been accepted with a remarkable tolerance, as illustrated by the familiar pause at the beginning of a violin solo while the violinist checks over the tuning of his strings.

It would be an exaggeration to say that no electronic instruments require periodic re-tuning, but in some designs the problem disappears insofar as all the frequencies generated by the instrument are in a fixed relationship with the periodicity of the a.c. supply which energises it. In other electronic instruments the tuning may be dependent on the stability of various circuit components, such as resistors or capacitors, while in at least one instrument (the Novachord) the tuning of the uppermost octave suffices for all the other octaves, since they are derived from the former by direct frequency division.

### Literature

The entire development of electronic musical instruments has taken place during the last thirty years, that is to say, since the advent of the electron tube, or valve, as an amplifier and oscillator. In that period a large number of descriptions have been published in various journals, notably in the U.S.A., Great Britain, Germany and France, of instruments which have been put into commercial production or built experimentally or merely designed on paper.

Most of the published literature is contained in the electrical or electronic technical journals, including the radio press, and only a few superficial accounts have appeared in the music or acoustic publications. This is in accord with the fact that the inventions in the electronic music field have been made predominantly by electronic engineers or electrical physicists, a fact which is not in the least surprising when one remembers that musical knowledge is more common amongst electrical experts than electrical knowledge is amongst musical experts.

It is rare to find a man who is a scientific expert and a musical expert at the same time, and usually some degree of co-operation is desirable, if not essential, for the full realisation of the possibilities of a new type of instrument. Particularly is it important for the designer of an electronic organ to know something about the construction and playing technique of the established forms of pipe organ, otherwise he may be in danger of under-estimating the magnitude of the task and consequently suffer a severe discouragement against continuing his work. If the aim is not to produce an electronic counterpart of an existing instrument, this desirability of a knowledge of music principles and execution is not so great, but obviously some familiarity with the basic requirements will be an advantage.

### History

Many of the early electronic instruments had their origin in Germany, where musical talent and appreciation have for long been widespread, but it is a matter for some surprise that the other famous musical country, Italy, has not so far produced anything noteworthy of this kind. France has contributed some important instruments, notably the Coupleux-Givelet organ. An International Congress was held in Munich in July, 1931, at which European inventors and manufacturers demonstrated their electronic musical instruments, and an orchestra including the Theremin, Trautonium, Hellertion, Vierling and Bechstein electric piano, gave public performances at the Berlin Radio Exhibition in the summer of 1932.

Although a recital by an orchestra of ten Theremins and a keyboard instrument was given at the Carnegie Hall, New York, as early as April, 1930, it was openly recognised in America in 1933 that Europe, and particularly Germany and France, had assumed the leadership in this new musical technique. Yet two years later the sale of electronic musical instruments in the U.S.A. had risen to more than $2,000,000 per annum. Since then, America has greatly outnumbered all other countries in the development of new electronic instruments.

Progress in Great Britain has been steady and thorough, and when further commercial enterprise was halted in 1939 by the outbreak of war, the electronic organ was becoming well established as a competitor of the pipe organ in churches and cinemas. After an intermission of six years, the work was taken up again, and it can be expected that considerable advances will appear when the outcome of pent-up inventiveness begins to take practical form.

## CHAPTER 2

## THE ACOUSTICS OF MUSIC

### Standardisation of Pitch

UNTIL 1939 there was no effective agreement amongst the musical authorities of the world on the subject of musical pitch. Previously the differences in pitch in various countries were surprisingly large. For instance, the familiar "middle C" on the English piano was fixed at 256 c/s (making the next C higher 512 c/s), and other pitches were fixed at 546 (Concert pitch), 528 (Society of Arts), 507 (Tonic Sol-fa), 540 (Old Philharmonic) and 522 (New Philharmonic), while the Diapason Normal set up as a standard by the French Government in 1859 was defined as 522 at 20°C. or 517.24 at 15°C. All these frequencies are arbitrary in character, having no absolute foundation in the science of acoustics, except perhaps the "middle C" of 256, which is said to be an invention of the physicist, being the 10th harmonic of an imaginary sub-acoustic fundamental of exactly one cycle per second. This at least has the virtue of arithmetical simplicity.

The British Standards Institution called an International Conference in London in 1939 at which the five nations that were represented agreed upon a new standard of 440 for A in the treble clef. On this basis C becomes 523.25. The standard A 440 is now available to the music trade and to acoustic engineers in most countries by radio transmission from the National Bureau of Standards station WWV in Washington, D.C. The transmissions are made daily on several carrier frequencies according to the following schedules :—

| Carrier Frequency | Times of Operation | Modulation |
|---|---|---|
| 2.5 Mc/s | 00.00-14.00 G.M.T. | 440 c/s only |
| 5.0 ,, | Continuously Day & Night | 440 & 4000 c/s Daytime<br>440 c/s only : 00.00-12.00 G.M.T. |
| 10.0 ,, | Continuously Day & Night | 440 & 4000 c/s Day & Night |
| 15.0 ,, | Continuously Day & Night | 440 & 4000 c/s Day & Night |

The modulation frequencies (and the carrier frequencies) are accurate to better than one part in ten million. Such accuracy is vastly higher than is required in music, but the service is intended to cater also for scientific measurements where precision of this order is desired. Reliable reception of these signals is generally possible at all times throughout the U.S.A., and on the higher frequencies fair reception is obtained over most parts of the world. Designers of electronic musical systems should therefore have no difficulty in regard to a standard reference frequency.

### Deviation from Standard Pitch

Although a great deal of thought has been given to the question of pitch standardisation, there is a surprising amount of deviation in practice from the adopted standard. Some illuminating measurements were made by the Philips' Laboratories in Eindhoven on the divergencies and the variation in pitch during orchestral concerts.[4] The concerts under observation were received by radio in the ordinary broadcast programmes from England, France, Germany and the Netherlands. By means of a special cathode-ray oscillograph arrangement in conjunction with a standard vibrating string tuned to A 440, it was possible to measure the amount of frequency deviation of the orchestra each time the A was being played. The measurement was, of course, a transient one, but a sufficiently accurate indication could be recorded even if the duration of the note was as short as 0.5 second.

The average of several series of observations made over a period of many months showed that even the best orchestras deviated quite appreciably from the nominal standard of A 440. Thus English performances showed an average of 438.5 c/s, 440.4 for France, 441.2 for Germany and 439.3 for the Netherlands. Not only was the average frequency different from the standard, but there was a considerable variation or spread of frequency during any one performance. The players of the string family and the woodwind often showed a variation of mean pitch according to whether or not they had to play in conjunction with fixed-tone instruments. Fig. 4 represents the amount of frequency spread for the nominal A 440 in a number of English concerts.

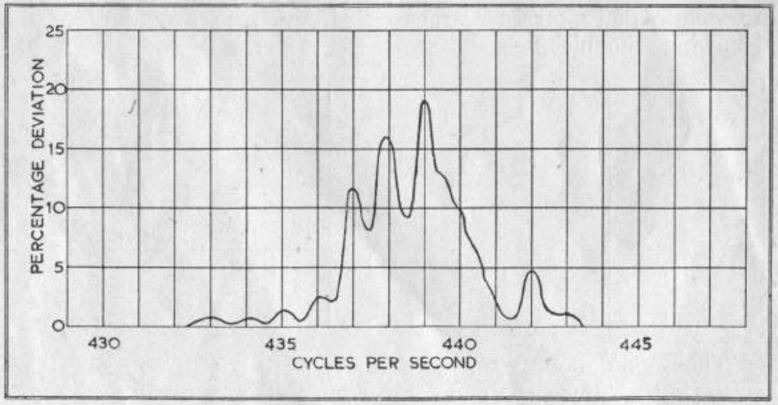


Fig. 4. A record of the deviation of pitch from the nominal value in a number of orchestral concerts. For simplicity, the measurements were confined to the note A (nominally 440 cycles per second).

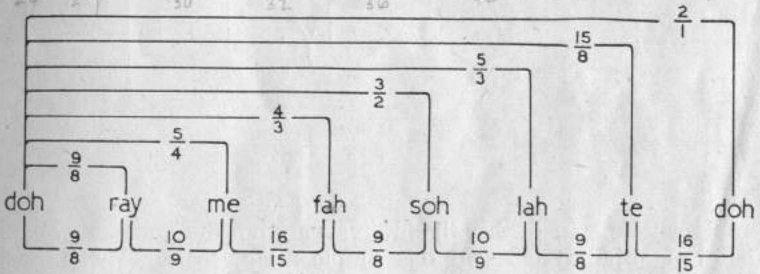
These observations have an important bearing on the design of electronic musical instruments intended for inclusion in orchestras.

### Octaves and Scales

The notes in a musical scale have certain accurately prescribed pitch relationships. The corresponding frequencies are all related to one another in definite arithmetical ratios. If a succession of notes in a major scale is played in rising pitch, it will be found that the eighth note has exactly twice the frequency of the first note. The interval of pitch between them is called an eighth, or an octave. The intermediate intervals are described in a corresponding manner. Thus the interval between the first and the fifth notes in the major scale is called a fifth.

It is not proposed to discuss the origin and structure of musical scales here, and it will be sufficient to state the numerical relationships as they exist in a simple major scale. In an ideal natural scale the ratios are as follows :—

24 27 30 32 36 40 45 48

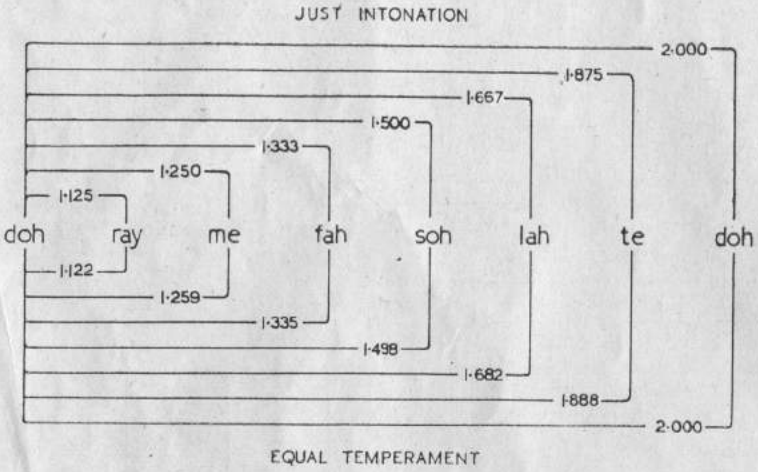


JUST INTONATION OR NATURAL SCALE

A succession of notes having these frequency ratios will be instantly recognised by the ear as a major scale, irrespective of the absolute pitch or key. The relationships extend, of course, above and below the selected octave, the ratios being related to the corresponding octave key notes. If an attempt is made to play a major scale from some other note than the *doh*—for instance, from *ray* to the next *ray* above, the succession of intervals will be entirely different. The first interval will be 10/9 instead of 9/8, a difference of 12.5 per cent. in the frequency ratios, and other discrepancies will be found throughout the scale. Similarly, other adjustments would have to be made in order to play a major scale in any other key.

So many additional notes would be required to permit the scale to be played in any key with this series of intervals that it was decided long ago to modify the ratios. By inserting five extra notes (which can be identified on the conventional keyboard), making 12 intervals in a complete octave, and by equalising the ratios to the value of the twelfth root of 2, a satisfactory scale has been achieved. An approximate value of this ratio is 196/185. Accurately stated, the ratio is 1.05946309.[5]

The idealised scale is known as Just Intonation or Natural Scale. The modified scale with equalised intervals is known as Equal Temperament. The relative ratios are shown below, converted for convenience into decimal form.



It will be evident that the intervals are not the same between all pairs of adjacent notes in this simple major scale. The interval between *me* and *fah* and the interval between *te* and *doh* are half the other intervals. This is represented by the following sequence :—

**doh ray me fah soh lah te doh**
TONE TONE SEMITONE TONE TONE TONE SEMITONE

It is the semitones which correspond to the frequency ratio of $\sqrt[12]{2}$, and the five extra notes are inserted in the whole-tone intervals so that semitones are available everywhere in the sequence when it is required to play in any other key. In the customary nomenclature, each of the extra notes is designated either the "sharp" of the note below it or the "flat" of the note above it. For example, if *doh* is C and *ray* is D, the note in between is C♯ or D♭. The complete octave has now become a succession of 12 semitones :

**D♭ E♭ G♭ A♭ B♭**
**C♯ D♯ F♯ G♯ A♯**
**C D E F G A B C**
TONE TONE SEMITONE TONE TONE TONE SEMITONE

## Table I

### FREQUENCY RATIOS WITHIN AN OCTAVE RELATED TO C

| Just Intonation | | Equal Temperament | |
|---|---|---|---|
| **Frequency Ratio** | **Key** | **Key** | **Frequency Ratio** |
| 1.000 | C | C | 1.00000000 |
| 1.042 | C♯ | C♯ D♭ | 1.05946309 |
| 1.080 | D♭ | | |
| 1.125 | D | D | 1.12246205 |
| 1.171 | D♯ | D♯ E♭ | 1.18920710 |
| 1.200 | E♭ | | |
| 1.250 | E | E | 1.25992105 |
| 1.279 | F♭ | | |
| 1.302 | E♯ | F | 1.33483985 |
| 1.333 | F | | |
| 1.390 | F♯ | F♯ G♭ | 1.41421360 |
| 1.440 | G♭ | | |
| 1.500 | G | G | 1.49830710 |
| 1.562 | G♯ | G♯ A♭ | 1.58740105 |
| 1.600 | A♭ | | |
| 1.667 | A | A | 1.68179280 |
| 1.738 | A♯ | A♯ B♭ | 1.78179740 |
| 1.800 | B♭ | | |
| 1.875 | B | B | 1.88774860 |
| 1.920 | C♭ | | |
| 1.955 | B♯ | C | 2.00000000 |
| 2.000 | C | | |

### Table II
### EQUAL TEMPERAMENT FREQUENCIES RELATED TO THE STANDARD FREQUENCY A = 440.00 c/s

| C♯ | D | D♯ | E | F | F♯ | G | G♯ | A | A♯ | B | C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| [77] 2217·46 | [78] 2349·32 | [79] 2489·01 | [80] 2637·02 | [81] 2793·82 | [82] 2959·95 | [83] 3135·96 | [84] 3322·44 | [85] 3520·00 | [86] 3729·31 | [87] 3951·06 | [88] 4186·01 |
| [65] 1108·73 | [66] 1174·66 | [67] 1244·51 | [68] 1318·51 | [69] 1396·91 | [70] 1479·98 | [71] 1567·98 | [72] 1661·22 | [73] 1760·00 | [74] 1864·65 | [75] 1975·53 | [76] 2093·00 |
| [53] 554·36 | [54] 587·33 | [55] 622·25 | [56] 659·26 | [57] 698·46 | [58] 739·99 | [59] 783·99 | [60] 830·61 | [61] 880·00 | [62] 932·33 | [63] 987·77 | [64] 1046·50 |
| [41] 277·18 | [42] 293·66 | [43] 311·13 | [44] 329·63 | [45] 349·23 | [46] 369·99 | [47] 391·99 | [48] 415·30 | [49] 440·00 | [50] 466·16 | [51] 493·88 | [52] 523·25 |
| [29] 138·59 | [30] 146·82 | [31] 155·56 | [32] 164·81 | [33] 174·61 | [34] 185·00 | [35] 196·00 | [36] 207·65 | [37] 220·00 | [38] 233·08 | [39] 246·94 | [40] 261·62 |
| [17] 69·29 | [18] 73·42 | [19] 77·78 | [20] 82·41 | [21] 87·31 | [22] 92·50 | [23] 98·00 | [24] 103·83 | [25] 110·00 | [26] 116·54 | [27] 123·47 | [28] 130·81 |
| [5] 34·65 | [6] 36·71 | [7] 38·89 | [8] 41·20 | [9] 43·65 | [10] 46·25 | [11] 49·00 | [12] 51·91 | [13] 55·00 | [14] 58·27 | [15] 61·73 | [16] 65·41 |
| 17·32 | 18·35 | 19·44 | 20·60 | 21·83 | 23·12 | 24·50 | 25·95 | [1] 27·50 | [2] 29·13 | [3] 30·87 | [4] 32·70 |

The small index numbers shown against the frequencies correspond to the numbering of the keys on a standard piano keyboard.

This equivalence is true only in the Equal Temperament scale. When the frequencies are selected according to Just Intonation, still more notes are required to complete the sequence. While the intervals C-E, E-G♯, G♯-C, etc., are all equally good thirds in the tempered scale, serious discrepancies would occur if this were attempted if the notes were tuned in Just Intonation. In the latter scale, where the intervals have not been equalised in the interests of mechanical convenience, C♯ is not the same as D♭, and neither is D♯ the same as E♭, and so on. Table I (p. 15), which gives the complete series of frequency ratios for the scale in Just Intonation compared with the Equal Temperament scale, shows what compromises have been made.

These considerations of scale intervals are important in regard to the synthesis of complex tones by the addition of harmonics to a sinusoidal fundamental.

**Harmonics**

A harmonic is defined as any single frequency component of a complex tone which falls in a Fourier series of integrally related components. The frequency of a harmonic is therefore related by a simple integer to the fundamental frequency. For instance, an instrument playing a steady complex tone at a frequency of A 440 would be generating a series of harmonics at the multiple frequencies 880, 1320, 1760, 2200, 2640, 3080, and so on. The higher harmonics would in general have smaller amplitudes, and in any event the ear ceases to respond at frequencies above about 18,000 c/s.

### Table III
### HARMONIC COMPONENTS OF A COMPLEX TONE OF FUNDAMENTAL FREQUENCY A = 440 c/s

| Order of Harmonic | Harmonic Frequency | Nearest Tone | Equal Temperament Frequency | Difference in Frequency | Percentage Difference |
|---|---|---|---|---|---|
| 2 | 880 | A | 880.00 | 0 | 0 |
| 3 | 1320 | E | 1318.51 | −1.49 | −0.113% |
| 4 | 1760 | A | 1760.00 | 0 | 0 |
| 5 | 2200 | C♯ | 2217.46 | +17.46 | +0.795% |
| 6 | 2640 | E | 2637.02 | −2.98 | −0.113% |
| 7 | 3080 | G | 3135.96 | +55.96 | +1.81% |
| 8 | 3520 | A | 3520.00 | 0 | 0 |
| 9 | 3960 | B | 3951.06 | −8.94 | −0.225% |
| 10 | 4400 | C♯ | 4434.92 | +34.92 | +0.795% |
| 11 | 4840 | D | 4698.64 | −141.36 | −2.91% |
| 12 | 5280 | E | 5274.04 | −5.96 | −0.113% |

From a list of the Equal Temperament frequencies corresponding to the full chromatic scale (Table II), it will be seen that some of the harmonics of A 440 lie close to some of the fundamental frequencies in the upper register. The second harmonic is, of course, one octave higher, A 880. The third harmonic at 1320 is very near to E 1318.51. The fourth, being two octaves higher, is again an exact multiple at A 1760; the fifth harmonic at 2200 is near to C♯ at 2217.46, and so on.

Each tone colour is characterised by a particular distribution of energy amongst the several harmonics. A trumpet, for instance, generates strong harmonics up to the 20th or even higher, whereas the acoustic energy of a flute is confined to the first three or four harmonics.

Fortunately, if we wish to synthesise a complex tone from its constituents, it is not absolutely necessary to use frequencies which are exactly integral multiples of the fundamental, and we may take frequencies already existing in the Equal Temperament scale, provided that they do not differ too greatly from the integral multiples. Thus, to synthesise a complex tone having a fundamental of A 440, we may take a series of tones as set out in Table III. Apart from the serious discrepancies which occur in the case of the 7th and 11th harmonics, the agreement is fairly good.

Obviously this is extremely convenient in the design of electronic organs of the kind in which each tone colour is produced by harmonic synthesis, for it is then unnecessary to generate a separate series of harmonics for each note, except perhaps for the 7th and 11th harmonics where they are required for a particular tone colour.

### Overtones

In a piano or in any instrument of the string family, the components of the complex tone are not true harmonics inasmuch as their frequencies are not integral multiples of the fundamental. They should be referred to as *partials* or *overtones*. They are slightly lower in frequency than the true harmonic frequencies, the difference decreasing as the cross-section of the string is diminished and as the tension is increased. For a given pitch, a long heavy string under strong tension produces a tone in which the partials more nearly approximate to the harmonic frequencies than in a short string under light tension. This is the reason for the superior tone of the full-size grand piano.

The tone quality of a piano may be fairly well judged by examining the harmonic composition of its base strings. If we hold down the key of $C_{16}$* without having caused the hammer to strike, thus releasing the damper from this string, and then press hard momentarily on the key $C_{28}$, we shall hear a tone coming from the string $C_{16}$. There will be no sound coming from $C_{28}$ because we have allowed the damper to return immediately after the momentary striking, but we have excited the string $C_{16}$ at its second partial. Similarly, still holding the damper off, if we momentarily strike $G_{35}$ we shall excite the third partial in the string $C_{16}$. By striking $C_{40}$ we can excite the fourth partial, and the succeeding partials can be excited by striking, in succession, $E_{44}$, $G_{47}$, $B_{51}$, $C_{52}$, $D_{54}$, and $E_{56}$. The response from the string $C_{16}$ will diminish as the pitch of the exciting note is raised, but if the corresponding tone can be heard coming from the string $C_{16}$ as far as the 10th partial $E_{56}$, the piano can be said to have a satisfactory tone quality.

In the ordinary piano, the strings are necessarily stout in order to supply an adequate amount of energy to the sound-board. A thin string vibrating at the same frequency would dissipate its energy in a much shorter interval of time, although the tone quality of its partial frequencies might be much superior. In electronic string instruments, however, where the acoustic loading of a sound-board is not required, thin strings may well be used with the immediate advantage of producing better tone quality for a given length or for a given tension. Whereas stringed instruments have for centuries suffered from the tonal imperfections resulting from ordinary mechanical requirements, the possibilities which have now arisen from the use of electrical translation are worthy of the most serious attention.

### Tone Quality

Any continuously repeated complex waveform can be reduced by means of Fourier's analysis into a series of purely sinusoidal harmonic frequencies. This is the basis of Helmholtz's theory of musical tone. Numerous experimental studies have been made of the tone quality of orchestral instruments, the results being summarised in the form of acoustic spectra in which the relative amplitudes of the constituent harmonics are shown.[6]

In the same way that a complex tone can be broken down into its harmonic constituents, it is also possible to synthesise a complex tone by sounding together all the required sinusoidal constituent frequencies, each adjusted to its correct relative amplitude. This has been verified experimentally, and so far theory and practice are in perfect agreement.

It is extremely rare, however, in orchestral music, to find a tone which is maintained constant for any appreciable length of time. Either the amplitude or the frequency, or both, of any instrumental tone will be varying slightly but appreciably at any one instant, and, strictly speaking, the application of Fourier's analysis is not justifiable. All percussion instruments and all those in which transients or *vibrato* effects are common, such as the piano, bells, guitar, produce tones which have not only the simple harmonic constituents but also various inharmonic frequencies. The synthesis of such tones from their constituents is extremely difficult and is best regarded as impracticable if not impossible. In electronic instruments, tones of transient character can be generated quite successfully by direct means which, while not always being an exact replica of the acoustic counterpart, are generally accepted as having real musical value.

### Formants

The tone of certain instruments, particularly the string family, is characterised by various resonance effects originating in the body of the instrument and not dependent directly on the pitch of the note which is being played. The primary vibration originating in the string induces vibrations in the resonant body which are not harmonically related to the primary frequency. These induced vibrations are called " formants " (derived from the German word *Hallformanten*). They are present not only in instrumental music, but in vocal music and speech. The formant frequencies are always

---

*The suffix figures refer to the numbering of the keys on the keyboard, beginning with A in the extreme bass high compared with the primary pitch, and do not alter when the pitch is varied. If the pitch rises above the predominant formant, that formant vanishes and generally the tone quality changes and another higher formant becomes predominant.

Electronic instruments have been devised in which the tone is modified by formant-producing elements, such as the Trautonium, but it is not every kind of instrument that lends itself to such elaborations. It is questionable whether the use of formants is of any value in instruments having a wide pitch range or in instruments having relatively simple tone quality. The feature of the Trautonium which renders it so suitable for the inclusion of formants is probably the high harmonic content of its wave-form. Like the violin, the Trautonium has a sharply peaked wave-form, which implies that the tone is extremely rich in harmonics. It is the energy associated with these harmonics which excites the vibrations in the formant-producing system.

### The Tremulant or Vibrato

The human voice in singing has a natural tendency to fluctuate in pitch and strength at a frequency of about 5 c/s. A violinist seems to find it natural to play with a rather slower variation of pitch, induced by the oscillatory motion of the left hand on the finger-board. In the pipe organ the *tremolo* stop is in frequent use to produce the same undulatory tone. In all these instances the rate of pulsation is between 3 and 7 c/s.

The tremulant form of tone modulation is a valuable adjunct to the more expressive means of control, but it must be used with restraint. Too much tremulant is repugnant to the ear. In most electronic instruments it is possible to induce at least an elementary form of tremulant, either as frequency or amplitude modulation. Often a more complex form can be used without excessive elaboration, and the resultant effect is considerably more pleasing.

### The Choir Effect

Where several instruments of the same kind are playing in unison, the effect is not a mere multiplication of the sound intensity. The slightest difference in frequency between two nominally similar tones will result in a changing phase relationship, and while audible beats may not be produced between the fundamental tones, beats are almost certain to arise from the greater difference between their higher harmonics or partials. In the case of several violins playing in unison where the *vibrato* rates are different and possibly the mean frequencies and the partial frequencies are also different, the massed effect is one of peculiar beauty, resembling a choir of voices.

Of all the tonal qualities of orchestral music, the choir effect is the most difficult to achieve in a single electronic instrument.

## CHAPTER 3

# CLASSIFICATION OF INSTRUMENTS

### Basic Distinctions

SINCE the developments in electronic music have come mostly from the electrical rather than from the musical side, it seems logical to make the primary distinctions on an electrical basis. The electrical designer must decide first whether his instrument is to rely on the oscillatory performance of electrical circuits or whether he is willing to use electro-mechanical systems in which the electric oscillations are derived from some kind of mechanical motion. These two main classes may be set down as :—

(A) Electric Circuit Generators
(B) Electro-Mechanical Generators

Where only limited workshop facilities are available, it would be a mistake to concentrate on the electro-mechanical form of generator, for even some of the simplest schemes of this type involve a considerable amount of machining and manual skill. On the other hand, if circuit techniques are well understood, entirely acceptable instruments can be developed without recourse to mechanical ingenuities.

Electric circuit generators can conveniently be divided into two sub-divisions :—

(C) Gas-Discharge Tube Oscillators
(D) Vacuum Tube Oscillators

and each of these can again be divided into

(E) Sinusoidal Oscillators
(F) Complex Wave-Form Oscillators

In the second main class (B), electro-mechanical generators may be either

(G) Rotary, or
(H) Vibratory

and in both of these systems generators of three main types have been used :—

(I) Electromagnetic
(J) Electrostatic
(K) Photoelectric

Other fundamental processes than those listed here could conceivably be applied to electronic musical instruments, such as the thermoelectric generation of acoustic tones, but the purpose of the present survey is to discuss the methods which have so far been found capable of practical development rather than to discuss speculative methods.

Approaching the subject of electronic instruments from the musician's standpoint, we find two main classes :—

(L) Monophonic
(M) Polyphonic

The monophonic instrument is one in which only a single note can be sounded at a time, as in a flute. The polyphonic instruments are capable of playing chords, as in a piano. A further distinction might be made between those instruments which produce tones synthesised from tempered harmonics and those having harmonics in Just Intonation, or between those instruments which are capable of *glissando* playing and those in which only discrete notes can be played, or between instruments which are "touch-sensitive" and those in which the tones are predetermined by the controlling devices. No useful purpose will be served by tabulating all these possible variations, since they are mere classifications of the result rather than the means. The designer is concerned primarily with the means for producing electronic music : the result of his labours will be an instrument the success or failure of which depends on many factors which defy classification.

### Methods of Control

The physical exertion required of a pianist is said to be surprisingly great. Each time a piano key is depressed a certain amount of mechanical work is done, and the aggregate during an ordinary performance can be very high. An organist may expend less energy, since his fingers have only to operate lightly balanced switch mechanisms. The brass, woodwind and strings demand a high physical stamina and impose a serious strain on the muscles. Many of the instruments have to be supported by the hand while they are being played. A violin is gripped between the jaw-bone and the collar-bone. The flute must be held horizontally to the lips by both arms in a raised position. All these physical requirements are the direct outcome of the mechanical characteristics of the respective instruments.

The enormous improvement in the flexibility of control afforded by electric mechanisms has been partly realised in the modern pipe organ, in which the electric action has superseded the earlier pneumatic action. In electronic instruments where the tones are generated in the form of electric oscillations, full advantage can be taken of electrical control in such a manner that the physical demands on the players are reduced to a minimum. Ultimately this must lead to an improvement in playing technique and to wider possibilities in musical composition.

The method of control in electronic instruments is dependent on the basic principle which is adopted, and each system has its own range of capabilities; yet it is reasonable to employ a conventional method of control so that the musician may adapt himself more readily to the new art. This applies especially to the many forms of stringed instruments (*e.g.*, the Vierling violin) and to all those instruments suited to keyboard control. A radically new instrument like the Theremin or Trautonium necessitates the development of a new playing technique, which is apt to discourage the professional musician, and is therefore a disadvantage.

Table IV

| Name of Instrument, Inventor or Manufacturer | Classification | Playing Technique | Nearest Equivalent Acoustic Instrument |
|---|---|---|---|
| Coupleux-Givelet | A-D-F-M | Console | Pipe organ |
| Orgatron | B-F-H-J-M | Console | Pipe organ |
| Hammond* | B-E-G-I-M | Console | Pipe organ |
| Compton Electrone* | B-E-G-J-M | Console | Pipe organ |
| Midgley* | B-E-G-J-M | Console | Pipe organ |
| Neo-Bechstein | B-F-H-I-M | Keyboard | Piano |
| Miessner, Vierling | B-F-H-J-M | Keyboard | Piano |
| Pianotron | B-F-H-J-M | Keyboard | Piano |
| Novachord* | A-D-F-M | Keyboard | — |
| Trautonium | A-C-F-L | Fingerboard | — |
| Martenot | A-D-F-M | Fingerboard | — |
| Theremin | A-D-E-L | Hand in space | — |
| Electric Guitar | B-F-H-I-M | Plucked strings | Guitar |

* These instruments are considered to be of special interest.

**Classification**

| | |
|---|---|
| A | Electric Circuit Generators |
| B | Electromechanical Generators |
| C | Gas-discharge Tube Oscillators |
| D | Vacuum-tube Oscillators |
| E | Sinusoidal Oscillators |
| F | Complex Wave-form Oscillators |
| G | Rotary Generators |
| H | Vibratory Generators |
| I | Electromagnetic Generators |
| J | Electrostatic Generators |
| K | Photoelectric Generators |
| L | Monophonic Instruments |
| M | Polyphonic Instruments |

### General Classification

In Table IV the characteristics of the better-known electronic instruments are listed under the names of the manufacturers or the inventors. A questionnaire recently circulated in England showed that a distinct preference existed for instruments of certain types. These instruments, selected for their musical value and general interest, are marked in the list with an asterisk. It is evident that polyphonic instruments have a greater appeal than the monophonic or melodic type of instrument. Even when a monophonic instrument possesses a wide variation of tone colour, covers a wide compass and can be played *glissando, staccato* or *legato, with* controllable attack and decay, it is likely to have less popular appeal than a polyphonic instrument of inferior versatility.

The same questionnaire indicated an almost unanimous demand for new tone colours, but that if the tone of an electronic instrument resembled that of an existing acoustic instrument it should do so as closely as possible. Poor imitations of a generally accepted tone were regarded as undesirable.

## CHAPTER 4

## ELECTRIC CIRCUIT GENERATORS

IN this chapter we shall review the more important instruments of the circuit generator type, that is to say, those instruments in which there are no rotary or vibratory elements. Circuit generators generally rely on either gas-discharge tubes or vacuum tubes as the source of oscillation. Instruments representative of these two methods will now be discussed.

### The Trautonium

This is the best known example of a gas-discharge tube type of tone generator.[7] It was developed by Dr. Friedrich Trautwein, of the Radio Research section at the Berlin Academy of Music, and was first demonstrated publicly in Berlin in 1930. Subsequently it was put into production by the Telefunken Company.

The generator is a neon-tube oscillator in a simple resistance-capacitance circuit, the frequency being controlled by varying the resistance. Fig. 5 shows the circuit arrangement of a Trautonium in its original form. When the switch S is closed the battery B begins to charge the capacitance C through the resistance R, and the voltage across the capacitance rises until it reaches the value at which the neon-tube N strikes. The charge contained in the capacitance is then dissipated in the neon-tube and the small series resistance $R_1$, and the voltage across the capacitance falls to a very low value at which the discharge ceases and the neon-tube again becomes a non-conductor. At this point the process begins again,

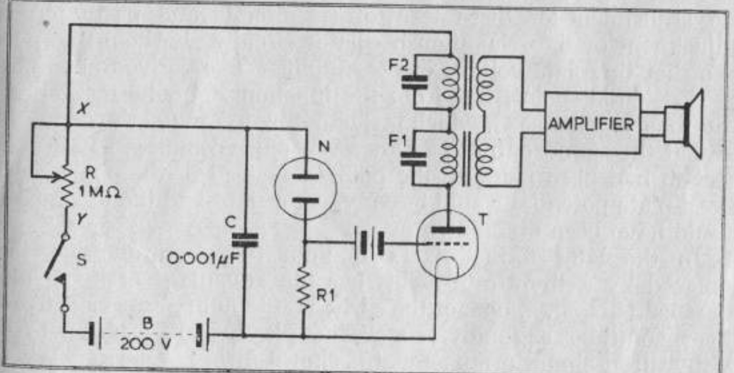


Fig. 5. The circuit connections of a Trautonium in its original form.

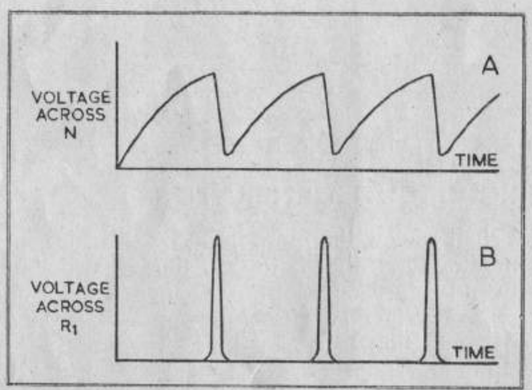


Fig. 6. The voltage/time characteristics of the Trautonium circuit arrangement shown in Fig. 5.

and the cycle is repeated continuously at a rate dependent on the circuit values and the characteristics of the neon-tube. This circuit operates on the familiar principle of the relaxation oscillator, and the wave-form of the voltage across the lamp is the so-called saw-tooth shown in Fig. 6A. The sudden pulses of discharge current which flow through the resistance $R_1$ cause periodic voltage pulses to appear across it, as shown in Fig. 6B, and these voltage pulses are applied to the grid of the triode T.

The plate circuit of this triode contains two or more resonant transformer circuits $F_1$, $F_2$, tuned to different peak frequencies, so that the output voltage wave-form is not simply a magnified replica of the input voltage wave-form applied to the grid. The periodic pulses indicated in Fig. 6B excite damped oscillations in the resonant circuits $F_1$ and $F_2$ (provided that their peak frequencies are higher than the pulse frequency), whereby an extremely complex wave-form is produced. As shown in the diagram (Fig. 5), the output to the main amplifier and loudspeaker is taken from the resonant transformers, and the resultant sound therefore depends partly on the adjustment of these transformer circuits and partly on the adjustment of the relaxation oscillator circuit. It should be noted also that the plate voltage of the amplifier T is derived not from a fixed-potential point, but from the junction X of the resistance R and the capacitance C, which is fluctuating in saw-tooth wave-form, so that the sound output is made even more complex. If the connection had been made to the point Y instead of the point X, the mean plate potential would have been constant and the tone quality would have been different.

In the later forms of Trautonium the neon-tube has been replaced by a thyratron. This has the advantage of being more reliable in action. Some of the early Trautonium performers treated their neon-tubes as fondly as a clarinet player cares for his pet reed. A thyratron circuit arrangement is shown in Fig. 7. Here T is the thyratron, which is normally over-biased for the given plate potential so that it cannot pass any current. The resistor K is stretched over a flat base about two feet long and a wire W mounted parallel to it can be depressed to make contact with the resistor element. When this happens the bias on the thyratron is reduced and the charged capacitance C then discharges through the thyratron until the potential has fallen so low that the thyratron is extinguished.

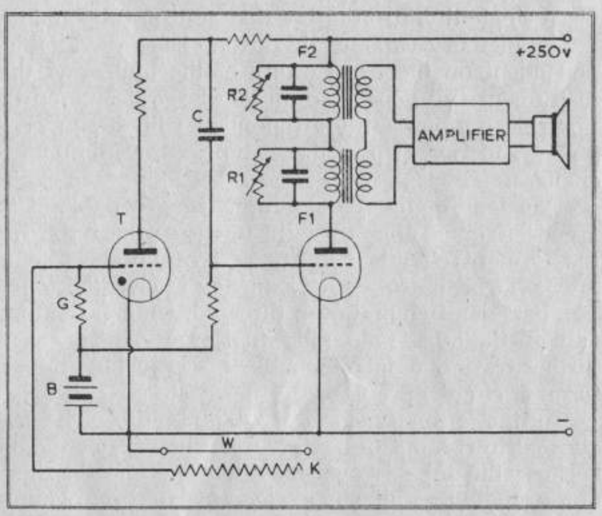


Fig. 7. An improved Trautonium circuit arrangement, using a thyraton T for controlling the pitch. The grid bias on the thyratron is controlled by the finger-board resistor W-K.

The cycle of charging and discharging is automatically repeated as in the case of the neon-tube oscillator, but since the striking voltage of the thyratron is dependent on its grid bias, the frequency of the relaxation oscillation can be varied by suitably changing the grid bias. This can be effected very simply by depressing the wire W to make contact with the resistor K at the desired point.

The finger-board control of the resistor K may also be used in the neon oscillator to constitute the resistor R, but it will then be found that the variation of pitch with change of finger position becomes higher (unless a suitably graded resistance element is used). With the arrangement shown in Fig. 7 the variation of pitch with finger position can be spread more uniformly over the finger-board. The actual spacing of the note positions depends on the relative values of the resistors K and G, the tube characteristics, the grid and plate voltages, and other circuit factors.

The playing is simplified by the provision of rubber keys mounted over the wire at the octaves and fifths. Other intervals of pitch must be estimated by the performer.

This finger-board resistance control may be applied to the grid of a vacuum triode in which the cathode-plate resistance itself comprises the charging resistance R for the neon-tube oscillator of Fig. 5 to secure the improved note spacing, but it is obviously simpler to use a single thyratron rather than a neon-tube and a control tube.

A mercury-vapour thyratron has a variable characteristic dependent on the temperature of the bulb, and the tuning of the instrument will depend to quite a large degree on the temperature. For this reason, a thyratron filled with argon or neon would be much superior, since these types are immune to temperature changes.

The tone of the Trautonium, being capable of variation within a considerable range by adjustment of the resonant frequencies of the formant circuits $F_1$, $F_2$, etc., cannot be said to lack musical interest. If the formant frequency is low, the tone resembles that of a bassoon, rich and deep-throated, while if the formant frequency is high, the tone is more like that of an oboe or even a trumpet. A further variation is obtainable by adjusting the damping of the formant circuits provided by the resistors $R_1$ and $R_2$ (Fig. 7).

In the ordinary form of Trautonium, whenever the wire is allowed to rise out of contact with the resistor the oscillation ceases because the tube is over-biased. The effect is instantaneous and unfortunately results in a *staccato* style of playing. This is the chief drawback of the Trautonium. To a minor extent the volume control, which is an ordinary gain-control potentiometer operated by a pedal mechanism, can be used to overcome the abruptness of the keying, but in anything other than the slowest passages the *staccato* effect remains inescapable.

A *tremolo* can be obtained by the method used in the violin, that is to say, by periodically varying the effective position of the point of contact.

Although the Trautonium is a monophonic instrument, the tone generator system is so simple that it could easily be duplicated so as to provide a large number of generators capable of separate or combined operation. A polyphonic instrument resembling an organ has been designed by W. E. Kock on the basis of neon-tube relaxation oscillators and formant circuits.[8] Fig. 8 shows a simplified diagram of its circuit connections. Only three oscillators appear in the diagram, but obviously the circuit may be extended to include any number. $N_1$, $N_2$, $N_3$ are the neon-tube oscillators which feed into the vacuum triode V and eventually into a common amplifier. Each generator is controlled by a key-operated switch $S_1$. The neon-tube NF is a formant oscillator the functioning of which is controlled by the switches $S_2$. Additional formant circuits may be added to provide extra tone colouration. The instrument suffers from the same drawback as the Trautonium, namely, an invariable and abrupt attack and decay.

### The Theremin (or Aetherophon)

This is another of the pioneer instruments, having been invented by Leon Theremin in 1924. It employs the principle of the heterodyning of two radio-frequency oscillators to produce an audio-

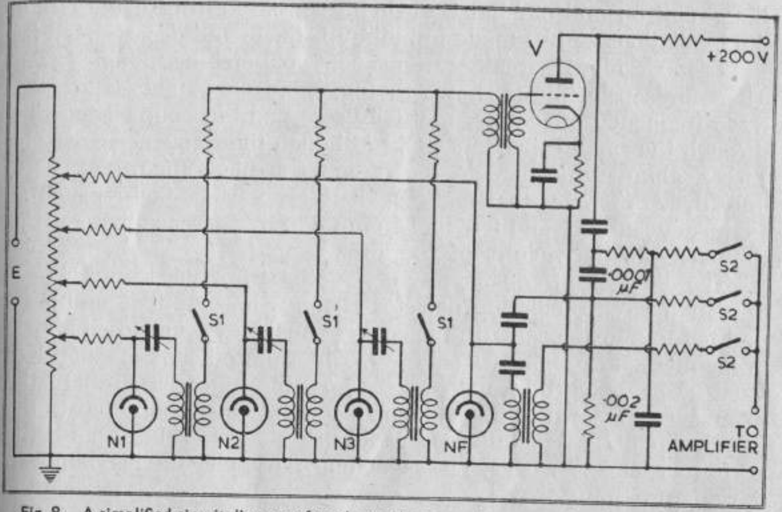


Fig. 8. A simplified circuit diagram of an electronic organ using neon-tube relaxation oscillators and a specially devised formant circuit for modifying the tone quality. The switches S1 are operated by the playing keys and the switches S2 control the formant register.

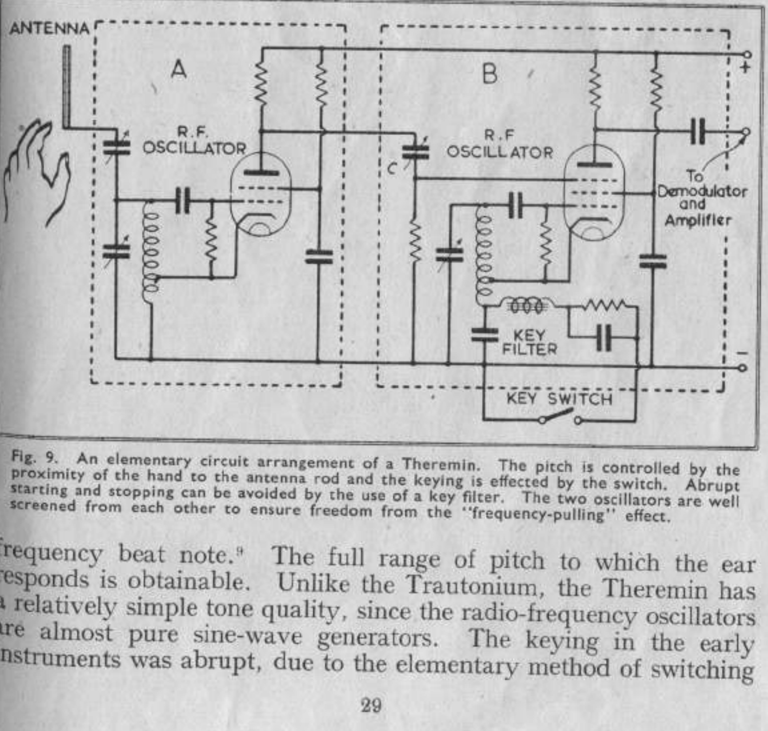


Fig. 9. An elementary circuit arrangement of a Theremin. The pitch is controlled by the proximity of the hand to the antenna rod and the keying is effected by the switch. Abrupt starting and stopping can be avoided by the use of a key filter. The two oscillators are well screened from each other to ensure freedom from the "frequency-pulling" effect.

frequency beat note.[9] The full range of pitch to which the ear responds is obtainable. Unlike the Trautonium, the Theremin has a relatively simple tone quality, since the radio-frequency oscillators are almost pure sine-wave generators. The keying in the early instruments was abrupt, due to the elementary method of switching the circuit on and off, but by using a simple form of delay circuit the oscillations can be made to build up slowly and decay slowly.

A modernised circuit arrangement of an instrument using Theremin's principle is shown in Fig. 9. Here A and B are two radio-frequency oscillators, mutually screened but coupled together through the small capacitance C. Although the frequencies may be chosen almost anywhere in the radio-frequency range, since it is only their *difference* that matters, there are various factors such as frequency stability and freedom from radio interference that restrict the choice to the vicinity of 300 kc/s.

The difference-frequency, or beat note, is produced by rectification in the self-oscillating detector B, and the output is amplified and fed to a loudspeaker in the conventional way. One oscillator B is maintained at a fixed frequency, while the other A is caused to vary by changing the capacitance across the tuned circuit. In the arrangement shown in Fig. 9 a small rod antenna, connected to the tuned circuit, is mounted outside the screening box, and the performer effects a varying capacitance by placing his hand in varying proximity to the rod.

In the case of an orthodox stringed instrument, such as the violin, the player knows from experience where to "stop" the strings to obtain the desired pitch, although his finger-board is not calibrated. Similarly, the Theremin player must feel for his pitch and familiarise himself with the pattern in space which corresponds to the chromatic scale.[10] The pattern is manifestly three-dimensional, since the electric field extends in all directions around the rod, whereas the violinist has only one dimension to consider. The Theremin in this form requires a peculiar aptitude on the part of the player, and it cannot be regarded as an easy instrument to play. Rapid passages are virtually impossible, but as a solo instrument played *legato* it can be quite effective. Its beauty is enhanced by its capability of *tremolo* and *glissando*.

The Theremin has also been developed as a keyboard instrument in which the keys control the amount of capacitance connected in the variable-frequency oscillator circuit. It is impossible, of course, to play more than one note at a time, for only one beat note can be derived from the two oscillators, and the keyboard merely provides a fixed scale system in place of the three-dimensional space control.

As an improvement on the direct switching method of starting and stopping the tone, an auxiliary oscillator system has been used with its own antenna to control the amplitude of the tone by means of hand-capacitance variation. In the original arrangement this was achieved by passing the plate current of one of the audio-frequency amplifiers through a small diode, the filament current of which was derived from a coil inductively coupled to the antenna coil, which in turn was coupled to the auxiliary oscillator. The variation of the hand capacitance caused the induced current to vary and thereby the filament temperature and the impedance of the diode were caused to vary. Ultimately the gain of the audio-frequency amplifier was affected by reason of the consequent change of plate voltage. The control of sound intensity by movement of the player's other hand in space involves yet another new playing technique without any intrinsic advantage to justify it. A direct manually-operated control would seem to be preferable.

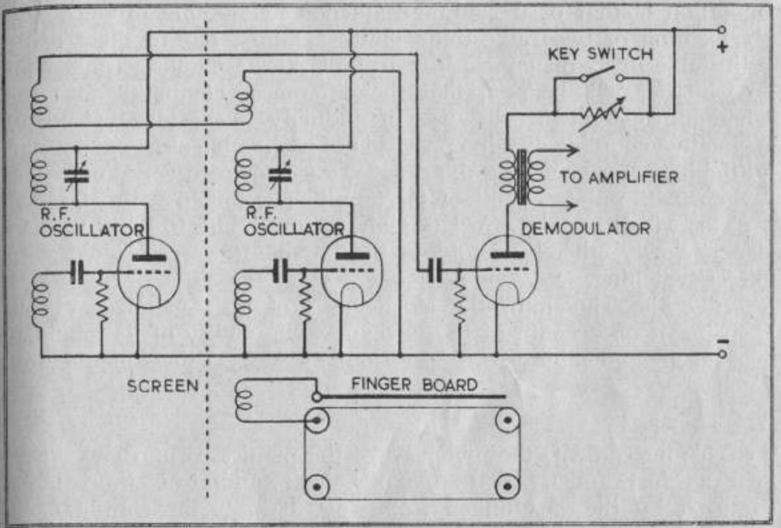


Fig. 10. The Martenot circuit. Frequency variation is achieved by the finger-board control of capacitance in the inductively-coupled circuit. Screening is necessary between the oscillators to avoid "pulling."

Prof. Theremin has also built a finger-board instrument of the 'cello type in which the left hand is used to control the pitch as in an orthodox 'cello, and the right hand operates a volume lever after the manner of the ordinary bow.

An instrument known as the Electronde, which utilised Theremin's heterodyne principle in a rather simple form, was developed in England by Martin Taubman in 1933. The current consumption was sufficiently small to permit the instrument to be operated from self-contained batteries. A single antenna rod was provided for controlling the pitch by movement of the player's right hand in space, while a start-stop switch was held in the left hand, and the volume was controlled by a pedal-potentiometer.[11]

The simple heterodyne principle has very little to recommend it for application to electronic musical instruments, chiefly because it does not permit easy variation of the tone quality. Its only virtue appears to be the readiness with which a note of any required pitch may be produced anywhere within the frequency limits of audibility.

**The Martenot**

This differs very little from the Theremin. The principle of operation is that of the audio-frequency heterodyne produced by the beating of two radio-frequency oscillators, one of them being adjustable in frequency.[12] Fig. 10 illustrates a circuit arrangement in which it will be seen that the differences compared with the Theremin consist in the use of inductive coupling instead of capacitive coupling and the provision of a movable electrode instead of the hand for achieving the necessary capacitance variation. The switch in the plate circuit of the amplifier is linked with a graded resistor which has the effect of allowing the sound to build up and decay slowly, thereby avoiding the harsh attack associated with direct switching.

Like the Theremin, the Martenot is of little value as a solo instrument on account of the unchangeable quality of its tone. It has no great flexibility or expression, but covers the full range of pitch

### The Hellertion

This instrument, the invention of the pianist, Bruno Helberger, of Frankfurt, and Dr. P. Lertes, of Leipzig, and at one time manufactured by the Telefunken Company, permits the simultaneous playing of four notes.[13] Each note is produced by an audio-frequency oscillator of controllable frequency, the variation being effected by depressing a stretched contactor band at suitable points. In order that the four oscillators may be controlled by the fingers of one hand, the four contactor strips are mounted parallel to each other but at different levels.

Musically the instrument is not of great interest, for its tone colour is fixed and its power of expression is limited to *staccato*, *glissando* and *tremolo*.

### The Solovox

The Hammond Clock Company has had on the market for some years a small solo 3-octave keyboard instrument called the Solovox, designed to be placed in front of a piano keyboard, so that the player can use his left hand to provide a piano accompaniment while his right hand operates the Solovox.

A resistance-capacitance type of oscillator functions as a monophonic generator, the frequency being dependent on the resistor and capacitor values switched into the circuit by the depression of the playing keys.[14] An interlocking system prevents the functioning of more than one key at a time. Finger-operated controls are provided for varying the harmonic composition, the attack, and the *vibrato*, and a lever for controlling the volume is fitted below the keyboard so that it can be operated by the player's knee.

### The Coupleux-Givelet Organ

This is an elaborate instrument capable of simulating a pipe organ in a variety of tone colours, and is the best known of French electronic instruments.[15] It was designed by E. E. Coupleux and J. A. M. V. Givelet in 1929. Several models were installed in French churches and one was in use at the Poste Parisien broadcasting station.

Tones of all the desired frequencies are produced by vacuum tube oscillators in association with specially designed filter circuits and coupling transformers. Although in some models attempts were made to reduce the number of tubes by using frequency-doublers, the larger instruments appear to have been made without regard to the number of tubes. For instance, the Poste Parisien instrument, which was provided with 75 stops or tone colour combinations, contained no less than 400 tubes. In another design 700 tubes were required.

The principle employed in the tone generators permitted the use of several different methods of tone-quality control. Each oscillator, which was an ordinary inductively-coupled feedback oscillator, was adjusted to produce an almost pure sinusoidal wave-form, and harmonics were introduced by various alterations to the circuit conditions. For instance, a change in the ratio of inductance to capacitance will distort the pure wave-form and cause harmonics to appear, especially when the inductance is increased. In another method, the grid bias applied to the oscillators may be changed whereby the tubes are caused to operate over different portions of their characteristic curves, again producing wave-form distortion. Filter circuits for regulating the harmonic amplitudes may be used, and by slightly shifting the frequencies of some of the notes, the tone quality will be affected by reason of the altered beats between the harmonics. The possibility of producing synthetic tone qualities by means of harmonic synthesis was also realised.

Although the method of obtaining a *tremolo* effect is crude in that it aims primarily at varying the amplitude of the entire output of the organ, it appears to have the interesting possibility of causing a cyclic variation of tone quality. Fig. 11 illustrates the method, in which it is seen that the rotating element in the magnetic circuit causes a periodic variation in the transfer of energy from the circuit A to the circuit B. The degree of transfer is clearly dependent on the frequency of each component of the generated tone, since the reactances of the windings vary with frequency. The resultant effect, therefore, is to change not only the total amplitude of the complex sound wave but also to change the tone quality. Unfortunately, these two forms

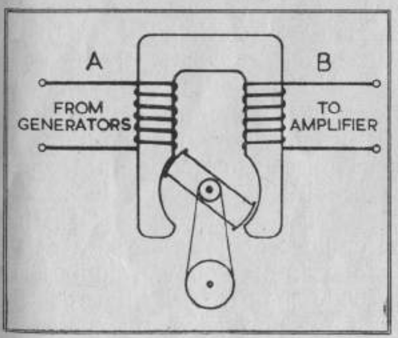


Fig. 11. A tremulant or vibrato generator used in the Coupleux-Givelet organ.

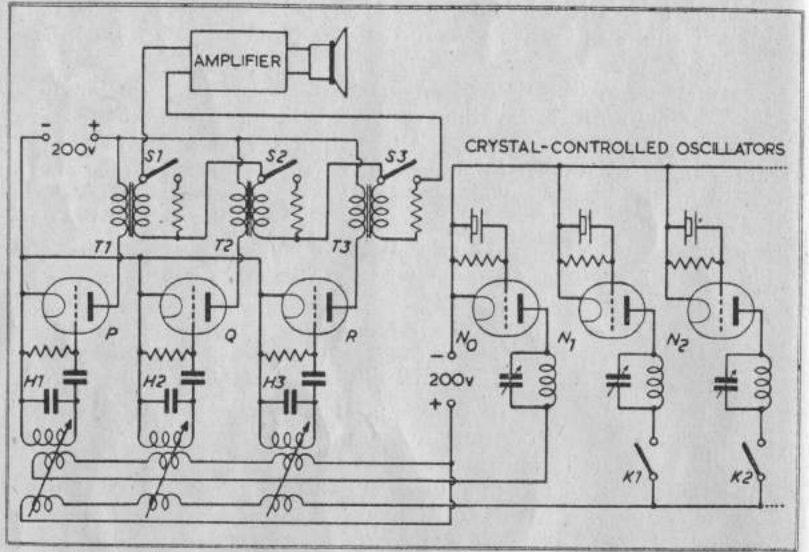


Fig. 12. A section of a circuit arrangement of an electronic organ using the heterodyne principle. Beats are produced between the crystal oscillators and the harmonics are selectively controlled in the auxiliary amplifier.

of variation will always be in phase, and the system lacks the ability to produce the rich choir effect that results from a blending of several different *tremolo* characteristics.

The Coupleux-Givelet organ has now lost some of its importance due to the subsequent development of superior types of organ based on more economical principles.

It was inevitable, perhaps, that the excellent frequency stability of the crystal-controlled oscillator should be recognised as being applicable to the generation of musical frequencies. A good example of a system based on such stabilised oscillators is the organ devised by the French firm, Le Matériel Téléphonique.[16] In this system a radio-frequency crystal-controlled oscillator operates continuously at a frequency f. Similar controlled radio-frequency oscillators adjusted to frequencies differing from f by suitable amounts are set in operation when the corresponding keys are depressed. The frequencies are chosen so as to produce the required tones throughout the musical range by the ordinary heterodyne method. All the oscillators are designed so as to be rich in harmonics, and in consequence the audio beat notes are also rich in harmonics, as appears from the following reasoning. Suppose the frequency of one of the keyed oscillators is $F+f$. By heterodyning the main oscillator operating at a frequency f, the audio beat note $(F+f)-F=F$ is produced. The second harmonic $2(F+f)$ beats with the second harmonic 2f to produce an audio note $2(F+f)-2f$ $=2F$. Similarly, the beat between the third harmonics will be $3(F+f)-3f=3F$, and so on. The richness of the tone, therefore, depends on the harmonics present in the radio-frequency oscillators, and by varying the oscillator current, or by any other method that affects the wave-form of the radio-frequency oscillators, the quality of the beat note can be varied.

In order to achieve a better control over the tone quality, the outputs from the several oscillators are passed through various detector tubes, one for the fundamental frequencies and one for each harmonic required. A simplified section of the complete circuit is shown in Fig. 12. $N_0$ is the continuously running oscillator and $N_1$, $N_2$, $N_3$, etc., are some of the key-operated oscillators which are tuned so as to produce the required beat frequencies with $N_0$. $K_1$, $K_2$, $K_3$, etc., are the switches controlled by the keys. The combined outputs of the oscillators are fed to the several detectors P, Q, R, etc., through the tuned input circuits $H_1$, $H_2$, $H_3$, etc. The outputs from the detectors drive the common amplifier and loudspeaker through the transformers $T_1$, $T_2$, $T_3$, etc., but the contribution from each detector can be switched in or out by the switches $S_1$, $S_2$, $S_3$, etc. Each detector is tuned by its grid circuit H to a multiple of the oscillator frequency generated by $N_0$, so that the fundamental and the harmonics are transmitted to the detector grids, and if the keyed oscillators are functioning, their fundamentals and harmonics will also be transmitted to the detector grids through the respective tuned circuits. The fundamental beat and the harmonic beats will be passed to the output amplifier provided that all the switches S are closed. If any of these switches is opened the corresponding harmonic beat disappears from the composite tone. With the switches closed the amplitude of each harmonic can be controlled by adjusting the shunt resistors across the output windings of the transformers T.

The switches and the shunt resistors can be grouped and arranged selectively under a single control for generating each desired tone quality, and by suitable resistance networks it is possible to provide a variety of tone qualities, each brought into operation by a stop key, and to provide two or more manuals without duplicating the range of oscillators.

Perhaps the most serious disadvantage of this system is the extremely high degree of frequency stability required in the oscillators. Compared with the frequency requirements usually associated with crystal-controlled apparatus, the precision required in musical equipment is very high—in terms of absolute frequency stability. Deviations in the audio tone frequency of the order of 1 c/s are serious in music. To produce a beat note with a stability better than this, the temperature of the crystal elements must be maintained constant within close limits, and other measures are also necessary to prevent any drift of the oscillator frequencies.

As an alternative to piezoelectric crystals, magnetostriction has been suggested for stabilising the oscillators, although if magnetostriction is used, the oscillator frequencies would be considerably lower than those most readily obtainable with crystal control.[17]

### The Novachord

The Novachord was developed by Laurens Hammond and C. N. Williams, of Chicago, and made its appearance in 1939. Since then it has achieved considerable popularity, mostly in broadcast music. It does not aim at imitating any of the usual orchestral instruments, yet besides the tone colours peculiar to itself, it is capable of producing tones similar to those of a piano, organ, the woodwind, brass and plucked and bowed strings. This versatility is due to the combination of a wide range of harmonic content and a flexible envelope control.[18]

In external appearance the Novachord resembles a small harmonium. It has a 6-octave keyboard and a variety of hand and foot controls. Twelve audio-frequency oscillators are provided, each corresponding to the twelve notes of the highest octave, while the notes of the successively lower octaves are obtained by successive frequency division from these fixed oscillators. This feature represents a great simplification in the process of tuning, for once the frequencies of one octave have been adjusted all the other octaves are automatically corrected. The frequency division is effected by a special circuit arrangement incorporating a small pentode or tetrode. Thus the oscillator for the note C is followed by a chain of these frequency-dividers to produce all the C frequencies included in the range of the keyboard, and similarly the C♯ oscillator is followed by a chain of frequency-dividers for all the C♯ frequencies, and similar chains of dividers are provided for D, D♯, etc.

For each of the 72 notes on the keyboard there is, therefore, either an oscillator or a frequency-divider tube. In addition, a control tube is provided for the variation of harmonic composition for each note and for variation of the keying envelope. Including the main amplifier tubes and the power supply, the total number of tubes in the Novachord is 163. The instrument is in consequence rather costly, but when the cost is considered in relation to the performance, the system appears to be reasonably economical. The tubes are operated under very light conditions and may be expected to have a correspondingly longer life. The total power consumption is 450 watts.

Fig. 13 shows part of the Novachord circuit. In this diagram the oscillator section consists of two triodes $V_1$ and $V_2$ (which may conveniently be a twin-triode) connected in a multivibrator or Franklin type of circuit, in which the frequency is determined by the inductance L and the capacitance $C_1$ connected between the grid and cathode of $V_1$. To obtain the highest degree of frequency stability, the coil is constructed so as to have as high a Q-value as possible. Fine adjustment of the frequency is made by altering the position of a single core-lamination inside the coil.

The output from the oscillators, which is made extremely rich in harmonics by biasing the second triode $V_2$ almost to cut-off, drives the first frequency-divider $V_3$ (which is a sharp cut-off pentode such as a 6J7) through a coupling capacitance $C_2$ and the resistance chain $R_1R_2$. The cathode of $V_3$ is biased to cut-off by the resistor $R_3$, which is connected to a bias source of about 100 volts, and from this cathode the tone-frequency voltage is supplied to the associated control tube $VC_3$. A similar frequency-divider stage $V_4$ obtains its drive from the plate circuit of $V_3$, and in turn a further frequency-divider $V_5$ is driven from $V_4$, and so on, until the lowest octave of that particular note is reached.

The action of this kind of frequency-divider circuit cannot easily be described in complete detail. Briefly, it operates by reason of the charging time of $C_3$ and $C_4$ and the varying flow of current through the bias resistor $R_3$, the values being chosen so that every alternate positive pulse on the grid of the divider tube produces a surge of cathode current, whereas the intermediate pulses do not. The various voltages applied to the tube must also be suitably chosen, but it is claimed that the circuit, when correctly adjusted, remains stable and effective over a wide range of input frequency.[19]

Since there are 12 sets of octaves, there are 12 complete circuit arrangements, each of the kind shown in abbreviated and simplified form in Fig. 13, and each having a full complement of 5 frequency-dividers and control tubes. The 12 oscillators range in frequency from $F_{69}$(1397 c/s) to $E_{80}$(2637 c/s). The lowest frequency, obtained after 5 stages of frequency division from $F_{69}$, is $F_9$(43.7 c/s). The highest harmonic frequency generated by the instrument is, of course, much higher than the highest key frequency of 2637 c/s. Provided that the amplifier and the loudspeaker are adequately designed, strong harmonics up to 18,000 or 20,000 c/s may be produced.

Control tubes $VC_2$, $VC_3$, $VC_4$, etc., are associated with the playing keys K. Like the divider tubes, these are sharp cut-off pentodes and are also heavily over-biased. The keying is effected by varying the cathode bias through a system of resistors and capacitors so as to provide an adjustable attack and decay. Normally, with the key up, the capacitance $C_6$ holds a steady charge and the voltage to which it is charged is controllable by the setting of the potentiometer $R_{4\text{-}5}$. If the sliders are set to the "slow" position, the voltage across $C_6$ is very low because the resistor $R_8$ is very much smaller in value than $R_9$ and acts as a low-resistance shunt, and if the potentiometer is set to "fast," the voltage across $C_6$ is high, since $R_9$ then acts as a high-resistance shunt. Until the key has been depressed, the cathode of the control tube receives a steady bias through the resistor $R_6$ from the voltage-divider $R_7$.

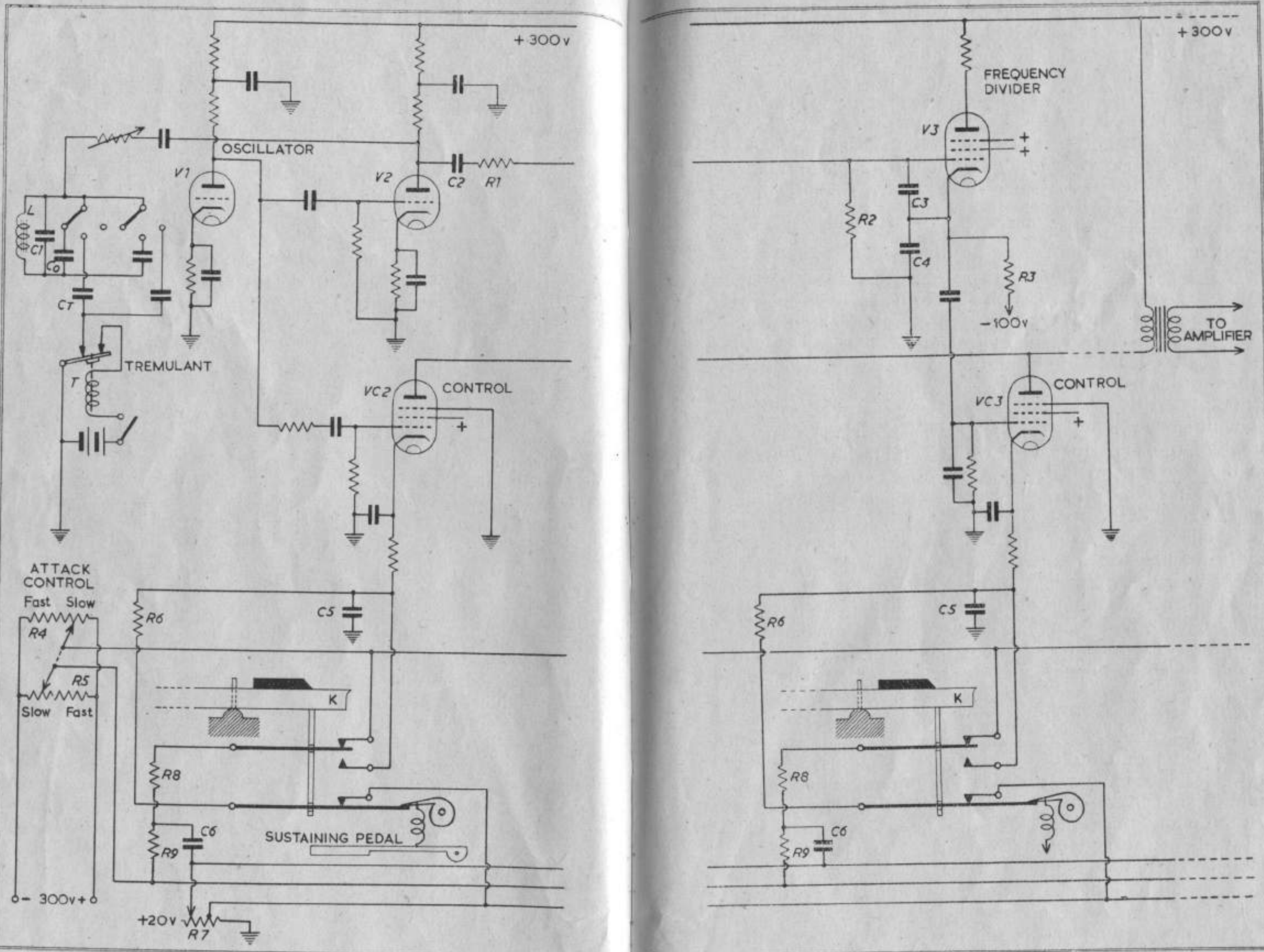


Fig. 13. A section of the Novachord circuit. Twelve pairs of oscillators, V1-V2, and twelve chains of frequency-dividers, V3, provide the full range of tone frequencies. An envelope control cube is associated with each playing key, by which a range of keying characteristics as shown in Fig. 14 is obtainable.

When the key is actuated, $R_8$ is connected to $C_5$ and therefore $C_6$ is allowed to discharge into $C_5$. If $C_6$ has a very small or zero charge, the potentiometer $R_{4-5}$ being set at the "slow" position, there is no immediate effect except that a charging current begins to flow through $R_9$ into $C_6$ and $C_5$, the potential of which slowly rises. The cathode of the control tube therefore rises negatively and the tube begins to pass a current of increasing amplitude. This continues until a maximum is reached. As long as the key remains depressed, the maximum will be maintained, but as soon as the key is released $R_8$ is disconnected from $C_5$ and the cathode lead, and $C_5$ then discharges through $R_6$. A smooth rise and a smooth fall of sound intensity is thereby produced, the tone remaining constant for as long as the key is depressed.

The sustaining pedal, reminiscent of the damper pedal on a piano, actuates the corresponding switches on every key, but the fixed bias values to which the resistors $R_6$ are normally connected through their respective switches are graded over the length of the keyboard to achieve a pleasant acoustic effect. The ear expects tones of lower pitch to have a longer natural decay period than those of high pitch, and this requirement can be met by suitably adjusting the tapping points on the bias voltage-divider $R_7$.

If the potentiometer $R_{4-5}$ is set to "fast," the charge on $C_6$, which is initially large, is partly shared with $C_5$ and partly dissipated in $R_9$ when the key is depressed. The potential across $C_6$ cannot rise appreciably after the discharge because $R_8$ is disconnected from the high-voltage end of the potentiometer and $R_9$ is at the low-voltage end. The cathode bias on the control tube is therefore momentarily raised negatively, and the effect produced is similar to that of a plucked string, irrespective of the length of time for which the key is held down. Actuating the sustaining pedal can have no effect in this case since the charge has already been dissipated.

With intermediate settings of the attack control $R_{4-5}$, the result will be a compromise, so that after the initial surge of sound the amplitude will decay to a smaller value but remain at the lower level as long as the key is depressed. Fig. 14 indicates the various time-characteristics graphically.

To simulate the tone quality of the usual orchestral instruments, it would be necessary to have control over the individual harmonics and to maintain this control over a wide variation of fundamental frequency as the pitch is varied. This is not possible in the Novachord circuit without introducing a complicated and extravagant system of filters. The tone quality can nevertheless be varied over a large range by means of a master control circuit which accentuates or attenuates certain broad bands of frequencies. Fig. 15 shows the connections of the master tone control which is inserted between the common output from all the control tubes and the pre-amplifier. It consists of a series of broadly-tuned circuits resonating approximately at 425, 880 and 2,500 c/s, each being shunted by a variable resistor. Increasing the shunt resistance across any particular tuned circuit causes the tone frequencies lying within that range to be passed more freely to the pre-amplifier. Conversely, decreasing the shunt resistance diminishes the selective effect, and if all the tuned circuits are effectively short-circuited the pre-amplifier receives all the tones at equal amplitude. All these controls are mounted immediately above the keyboard, so that the player can adjust them with the minimum of interruption.

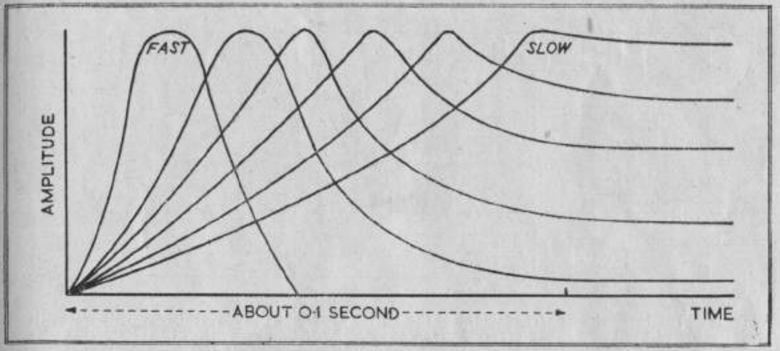


Fig. 14. The amplitude/time characteristics obtainable in the Novachord by varying the resistance-capacitance conditions in the grid bias circuits of the control tubes.

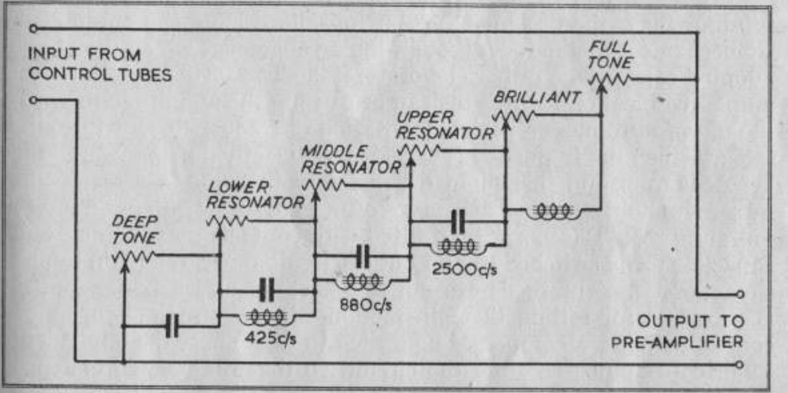


Fig. 15. The common tone-control circuits in the Novachord. By adjusting the shunt resistors, the frequencies lying within predetermined bands can be emphasised. The resonator circuits are broadly tuned, the approximate peak frequencies being indicated in the diagram, and a graduated effect is obtained by the reasonable overlapping of the characteristics.

The Full-Tone control indicated in Fig. 15 acts partly as a gain control, but the main control for the volume is provided by a pedal. This pedal actuates a small variable capacitor connected as a feed-back element between the plate and the grid of the first pre-amplifier stage, an arrangement which is superior to the more usual form of potentiometer control in that it is practically free from mechanical wear and electrical noise.

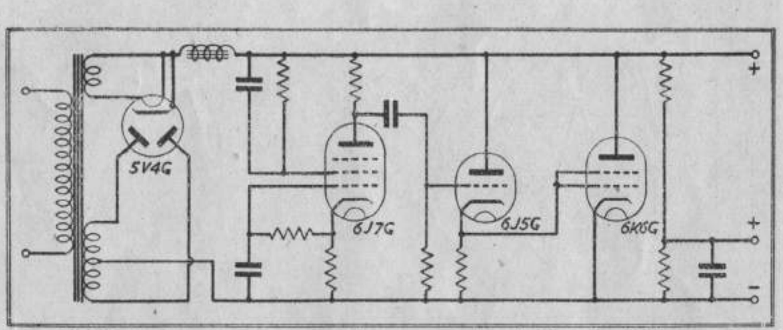


Fig. 16. The basic circuit arrangement of the power supply in the Novachord. This system is preferable to the usual choke-capacitor type of filter circuit on account of the relatively heavy current drain.

From the many possible methods of introducing a *tremolo* or *vibrato* effect, the designers of the Novachord have chosen an electromechanical method. Although the arrangement which they have adopted seems to be rather elaborate, it has two virtues which afford ample justification for it. Instead of causing the amplitude to vary, the *vibrato* produces a periodic variation of frequency. Further, the rate at which the frequency is varied is not exactly the same for all the 12 oscillators, and this slight difference in the *vibrato* rates results in a rich choir effect. Each *vibrato* unit consists of a continuously vibrating reed T (see Fig. 13), fitted with contacts by which a small capacitor $C_T$ is switched in and out of circuit across the main tuning capacitor $C_1$. The reeds are not self-starting, and a panel control is provided for setting them in motion when desired. The same control actuates a compensating switch to disconnect the equivalent small capacitance $C_0$ from the circuit, so that the mean frequency with the *vibrato* in operation is the same as the normal frequency without it. Two different degrees of *vibrato* are available. Since it is only rarely that two adjacent keys will be played together, the number of *vibrato* units is reduced from 12 to 6, each unit serving two consecutive tone generators.

The output from the control tubes is fairly large, and only a moderate amount of gain is required in the amplifier. In the commercial model the amplifier comprises two type-56 tubes followed by four 2A3 tubes in parallel-pushpull. A single power supply is used to feed the entire instrument, and on account of the relatively heavy current load and the need for complete freedom from mains hum, a special stabilised circuit is included to supplement the usual choke-capacitor filter. This circuit is shown in Fig. 16.

## CHAPTER 5

## ELECTROSTATIC TONE GENERATORS

THE fundamental principle employed in all electrostatic instruments involves the law of electrostatic charge which states that the potential V of a charged body is proportional to the charge Q and inversely proportional to its capacitance C. This can equally well be expressed in the form $Q = VC$. If the charge on the body remains constant, it is evident that a change of capacitance must result in a change of potential, and if the potential remains constant, a change of capacitance results in a different charge.

In Fig. 17 a capacitance C is shown connected to a source of potential E through a resistance R. There is no voltage drop across R since no current can flow through it. But if the capacitance C is varied by moving the plate Y nearer to or farther from the plate Z, a current flows through R until the charge on the plate Y reaches the value corresponding to the new capacitance. A momentary voltage appears across R. If the capacitance is caused to vary cyclically in value, a similar cyclic voltage is developed across R. As shown in the diagram, this voltage can be amplified so as to produce a magnified voltage oscillation across the output resistance $R_1$. The arrangement thus constitutes a very convenient form of tone generator when the capacitance C is varied at a musical frequency. It is, of course, a straightforward development of the orthodox condenser microphone.[20]

There are three ways in which a cyclic variation of capacitance can be achieved, namely, by varying either (*a*) the distance between the plates, (*b*) the area of the plates (more strictly the area by which they overlap), or (*c*) the nature of the dielectric. In fact, all three methods have been successfully applied in the construction of electronic musical instruments. The more outstanding examples are described in the following sections.

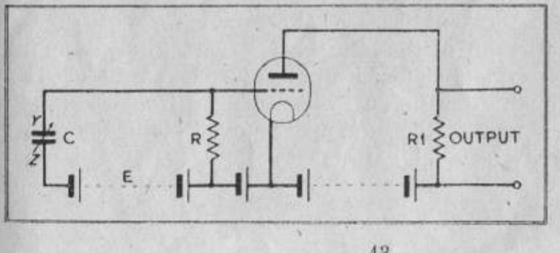


Fig. 17. The fundamental circuit of the electrostatic tone generator. When the capacitance C undulates in value, an oscillation of the same frequency occurs in the output circuit. The reactance of C at the oscillator frequency is usually very high, and accordingly R should be of the order of several megohms.

**The Pianotron**

This is an instrument of standard piano construction, developed by the Everett Company, which can be played either as an ordinary piano or with the electrical output to supplement the direct acoustic tone. As a further alternative, the electrical output may be used to drive a loudspeaker at a point remote from the instrument outside the acoustic range. The fact that the Pianotron produces sound directly does not lessen the interest in it as an electronic instrument.

The vibrating strings of the piano constitute the oscillating electrodes of a number of small capacitances, the co-operating electrodes being a corresponding number of adjustable metal studs mounted in close proximity to the strings.[21] In the simplest arrangement, all the studs are connected together so that they constitute the electrode Y in Fig. 17, while all the strings, which are either already in common contact through the frame of the piano or are specially bonded together, constitute the electrode Z. Fig. 18 shows a practical form of input circuit. The capacitance associated with each string is indicated by Cs. This is in series with the common resistor $R_1$ across the source of polarising voltage. The amplitude of the input signal increases with this voltage and with the value of $R_1$. With the values indicated in Fig. 18, an amplifier of about 100 db gain will be required. The input will also increase as the gap between the stud and the mean position of the string is decreased, but obviously the gap cannot be made less than the maximum amplitude of the string. In the interests of good tone quality, the gap should be made appreciably greater than this. The rate of change of capacitance with the displacement of the string is not linear. The relationship approximates to the hyperbolic, but much depends on the shape of the pick-up electrode. Moreover, the plane in which the string vibrates usually rotates slowly, and a transverse section of the vibration pattern at any point along the string may be elliptical rather than circular. These factors tend to preclude the possibility of designing the pick-up electrodes to meet specific requirements, and it is more satisfactory to rely on experimental trial and error. Usually the optimum gap will be found to range from $\frac{1}{4}$-inch for the bass strings to less than 1/32-inch for the highest octave.[22]

The amplitude of a struck piano string is normally a maximum at its centre, but this is not the best position for placing the pick-up electrodes. Due to the existence of harmonics, the shape of the string at any given moment is a very complex form. Certain positions along the length of the string correspond to nodes of the various harmonics, and if the pick-up is placed at any of these points the corresponding harmonics will be absent from the amplified output. In general, as the pick-up is moved along the string, the amplitudes of the several harmonics will vary, and the best position must be found by experiment. It is preferable to mount the pick-ups near the ends of the strings, more particularly in the bass, in order to achieve the richness of tone associated with high harmonic content. The higher harmonics are just as prominent near the ends of the strings as in the central portions, but the amplitude of the fundamental, and to a lesser extent the lower order harmonics, clearly decreases as the end of the string is approached. Several pick-ups may be used at different positions along each string if desired.

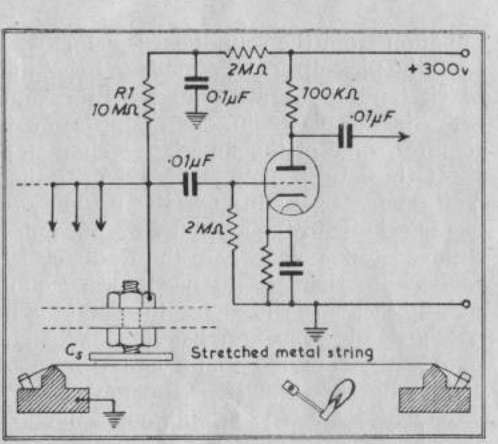


Fig. 18. The essential pick-up circuit of an electrostatic piano. Here the polarising potential is derived from the plate supply of the amplifier, and R1 corresponds to the resistor R of Fig. 17.

In an orthodox piano the tone quality is inseparably related to the amplitude. It is impossible to achieve the same tone quality at different levels of amplitude. The electric pick-up principle, by reason of the associated control of amplitude, permits the independent variation of tone quality and thereby provides a further means of varying the expression.

It is important to provide a rigid mounting for the pick-up studs which will neither resonate with the string vibrations nor respond to the thumps and jarring impulses that inevitably occur in the playing of a piano. The existence of any vibration of the pick-ups will be detected by corresponding noises in the amplified output. Ordinarily the stud corresponding to each note on the keyboard will be broad enough to co-operate with the two or three strings associated with it.

Another consideration which cannot be ignored is the need for thorough electrostatic screening of the pick-up electrodes. Since these electrodes are connected in a high-impedance circuit, the system is markedly sensitive to stray electric fields, and without effective shielding a strong hum due to the a.c. supply mains is almost certain to result.

The manner in which the rows of pick-up electrodes are best mounted depends upon the construction of the piano. In some types it may be found that the pick-ups can be arranged only on the side of the strings opposite to the hammers. While this is satisfactory, it would be preferable to mount them on the same side as the hammers, for in this case there is less likelihood of an objectionable percussive effect.

The decrement of the tones produced by the electrostatic pick-up system appears to be considerably smaller than that of the acoustic radiation from the soundboard. Moreover, the bass notes obtained from the pick-ups can be made to boost the fundamental frequencies which tend to be attenuated by the soundboard. Consequently, with the amplifier in operation, a medium or small-size piano acquires some of the superlative characteristics of a concert grand.

If the loudspeaker is placed near the piano there is a risk of acoustic feedback through the medium of the soundboard. This places a limit to the amplifier output unless the loudspeaker can be removed to a point where the feedback is negligible.

Because there is no need for a soundboard when an electric pick-up system is used for the sound generation, the strings need not be made long and heavy. When they are not required to actuate the soundboard they may be made very thin and correspondingly shorter. It is not even necessary to resort to the extremely high tension, although the tone quality will seriously deteriorate if the tension is reduced too far. These considerations lead to the possibility of designing an electric piano of quite small dimensions and of reasonably light weight, sufficiently so for it to be regarded as a portable instrument. The cost of production would also be greatly reduced, and as a further advantage—an important one in view of the almost universal interest in the piano as a domestic musical instrument—there is the possibility of unrestricted playing practice if the player uses headphones instead of the loudspeaker, for the strings themselves radiate only a minute amount of energy.

Various results may be obtained by the use of specially shaped pick-up elements, so designed and arranged around the strings as to enhance or attenuate the harmonics or to modify the phase relationships or to vary the relation between the string amplitude and the sound amplitude.[23]

It is not essential that the strings should be of metal. Non-conducting strings may be employed by relying on their dielectric constant to cause variations in the capacitance between pairs of fixed electrodes arranged on opposite sides of the strings but off-set from them. The relative positions of the string and the electrodes are suggested in Fig. 19.

### The Electone

An interesting development of the electrostatic pick-up principle as applied to an ordinary piano appeared in the form of the Electone.[24] This instrument, designed by Maurice K. Bretzfelder, is essentially a piano in that it relies on a system of stretched strings excited into vibrations by key-operated hammers. The playing technique, however, is somewhat different from that of the standard piano on account of the greatly modified envelope characteristics.

The tone generators are basically similar to those of the Pianotron as shown in Fig 18, but the essential difference lies in the variation of the polarising potential applied to the individual strings. In the Pianotron all the strings are connected together, and it is convenient to maintain the whole frame at ground potential. In the Electone each string is separately insulated so that the amplitude of the pick-up derived from it is under individual control. As a further elaboration, three pick-up electrodes are provided for each string, located at selected points along the string to permit a choice of harmonic composition. The three complete sets of pick-up electrodes are connected through separate pre-amplifiers and tone-quality controls to a common amplifier.

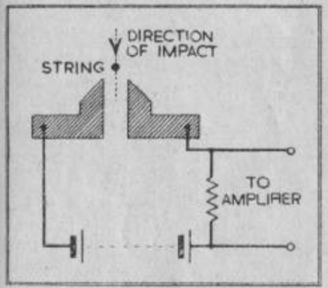


Fig. 19. An electrostatic pick-up arrangement where the string is of non-conducting material. The capacitance change is effected by the dielectric constant of the string.

The circuit arrangement for a single key and the associated common amplifier is shown in Fig. 20. Normally, when the key is up and the string is stationary, no tone signal is passed to the amplifier, although the string may have a polarising voltage applied to it through the key-switch contact $S_1$ from the potentiometer $P_1$. When the key is struck the hammer sets the string N in vibration in the ordinary way, and at the same time the polarising voltage is altered by the change-over from $S_1$ to $S_2$. The voltage derived through $S_2$ from the potentiometer $P_2$ may be greater or less than the previous value given by $P_1$, but in either case the change in the potential of the string N occurs relatively slowly, due to the time-delay in the control network $R_1C_1R_2C_2$. Most of the delay is due to $R_1C_1$, and $R_2C_2$ is designed to have a short time-constant merely in order to absorb the switching surges or " key-clicks."

It is evident that considerable variety of expression can be achieved by selecting the relative voltages supplied by $P_1$ and $P_2$ and the envelope-determining components $R_1C_1$, quite apart from the differences in tone arising from the variation of hammer impact. Since the amplitude of the tone signal fed to the amplifier V is proportional to the polarising voltage on the corresponding string, a sufficiently long time-constant for $R_1C_1$ will prevent the amplifier from receiving the full peak oscillation usually associated with a struck string.

In the Electone there is no soundboard, and the decrement of the strings is therefore very low. While a key is held down the sound output from the amplifier will continue for a considerable time, especially that from the bass strings, giving an organ-like effect. When the key is allowed to rise the amplitude of the string vibration may be reduced to zero rather abruptly by the ordinary damper action, or if the dampers are held off, the decay will be determined by the time-constant of $R_1C_1$.

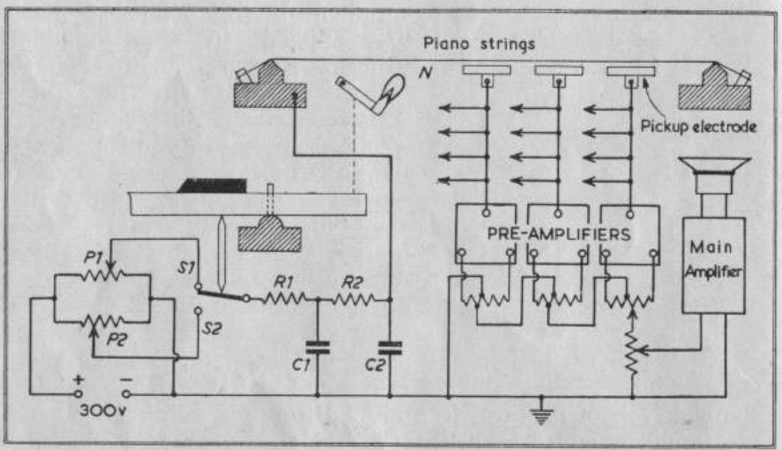


Fig. 20. A section of the circuit arrangement in the Electone, an electrostatic piano-type of instrument in which the tone envelope is controlled by the potentiometers P1-P2 and the delay-network R1-C1 R2-C2. Several pick-up electrodes are used with each string to correspond to the predominant harmonic loops. A separate delay-network is provided for each string but the potentiometers P1-P2 may supply any number of strings.

The effect of $R_1C_1$ on the envelope of the sound output is illustrated in Fig. 21 for the case where the potentiometers are adjusted so that the polarising potential rises gradually after the key is depressed and where the string is still vibrating at appreciable amplitude at the moment when the key is released. The overall result is to produce a tone which begins smoothly and ends smoothly in a manner quite different from that obtained with the ordinary piano action.

Even for a fixed time-constant $R_1C_1$, the resultant envelope can be changed by adjusting the potentiometers $P_1$ and $P_2$. Fig. 22 shows some of the possible variations obtainable with various ratios of the voltages derived from $P_1$ and $P_2$. Where this ratio is unity, that is where the polarising voltage is constant, the tone envelope from the pick-up corresponds entirely with the string vibration—although due to the absence of the soundboard, the envelope will not be the same as that of an ordinary piano.

Other attempts have been made to overcome the abrupt starting characteristic of the normal piano tone by using mechanically coupled vibrating systems. In one form of electric piano devised by O. Vierling, two strings are used for each note, only one of which is struck by the hammer while the adjacent resonating string receives some of the imparted energy through the common mounting.[25] The resonant string thereby comes into oscillation slowly, the rate of build-up depending on the coupling coefficient and other factors. By associating the pick-up element with the resonant string the percussion effect is eliminated. Usually it is difficult to ensure a sufficiently rapid transfer of energy to the coupled string and the result is a heavy, sluggish response.

### Electrostatic Organs

Perhaps the finest electronic organs that have yet been built are those which have employed the principle of electrostatic tone generation. From the preceding descriptions it will be apparent that the electrostatic system has the great advantage—as compared with the electromagnetic system—of permitting flexible control of the tone envelope with relatively simple circuit design and construction. Undoubtedly, this is one of the major factors which have attracted designers to the electrostatic method.

Attention has been divided, however, between the vibratory and the rotary systems. The more elaborate and costly in-

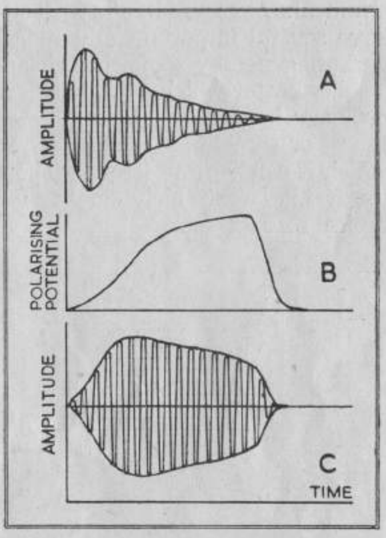


Fig. 21. The oscillation in A represents a typical decay characteristic of a piano string. The curve B is an example of the voltage/time characteristic of the polarising voltage obtainable in the Electone. The composite effect of A and B is shown in C the rising sensitivity of the pick-up tending to compensate for the decaying amplitude of the string vibration.

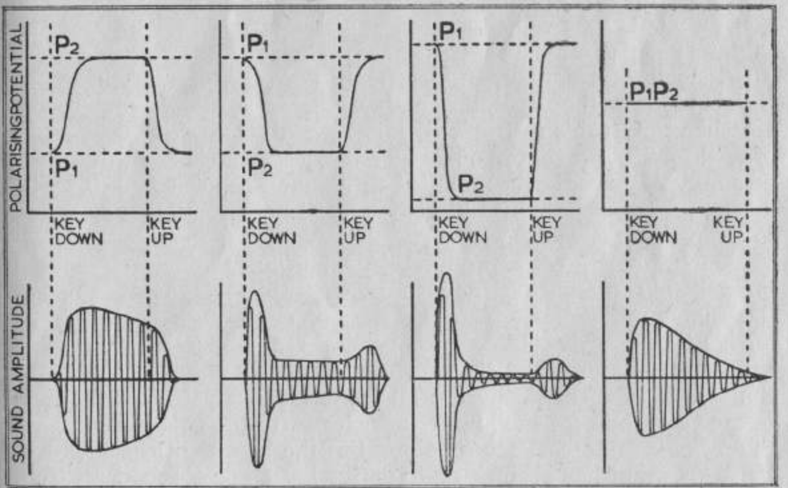


Fig. 22. Examples of tone envelopes obtainable in the Electone by adjusting the relative levels between which the polarising potential varies. The decay of vibration in the string is assumed to be the same in each case.

struments have used rotary elements, but the vibratory generators have several important advantages, chiefly in mechanical respects, and are generally somewhat cheaper.

A vibrator which lends itself readily to the electronic organ is the ordinary harmonium type of reed. This consists of a tongue of brass, or sometimes of steel, firmly fixed at one end to a frame in which it can vibrate freely. The clearance between the tongue and the frame is extremely small. Fig. 23 shows the construction of a typical reed.

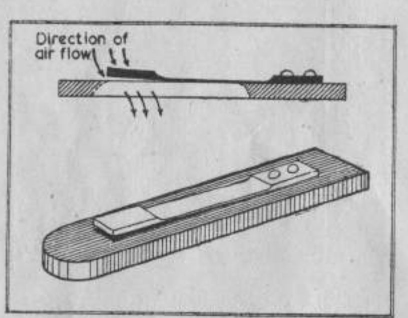


Fig. 23. Air-driven reeds of the type used in the harmonium.

The tongue can be maintained in vibration either by suction or pressure. For the bass reeds a comparatively large air flow is required, but the pressure may be very small, while the treble reeds require higher pressure but very little air flow. The amplitude varies from about ¼-inch to less than 1/1000-inch. Small pick-up screws mounted on insulating strips can be used to constitute a range of varying-gap capacitors with the vibrating tongues. Two of the attractive features of such a system of tone generators are the very low cost and the permanency of tuning.

The basic circuit arrangements of a reed-type generator are essentially similar to those already described in regard to string-type generators. Electrically the reed is analogous to the string as the vibratory capacitative element.[26]

A small electronic organ incorporating reed generators has been developed by the Everett Company from a design by F. A. Hoschke.[27] In this instrument, known as the Orgatron, five ranks of reeds are blown continuously by a bellows arrangement, the entire assembly of reeds being mounted in a sound-proof chamber. The keys operate switches by which the polarising potentials are applied to the pick-up elements.

A tremulant effect is produced by a slowly-running fan mounted immediately in front of a loudspeaker, so that the blades intercept the sound radiation. The effect is, of course, direct amplitude modulation, and because all frequencies are subjected to the same rhythmic variation the "choir" effect is entirely absent. Moreover, the screening effect of the fan blades is much greater for the high frequencies than for the low frequencies, with the consequence that the *tremolo* is much less pronounced in the bass register.

An attempt has been made to derive harmonic components from vibrating reeds by placing pick-up elements at selected positions along the length of the reed (where the reed is long enough to accommodate more than one pick-up) in the same way as harmonics of string vibrations have been obtained. There seems to be no justification for assuming that the reed tongue has such an undulatory shape when vibrating. Admittedly, the acoustic tone quality from a wind-blown reed instrument, such as an accordion or harmonium, is rich in overtones, but these overtones are not due to the peculiarities in the oscillations of the reeds themselves. The rich tone arises from the sharp cut-off characteristic of the air stream produced by the opening and closing of the gap in the frame by the vibrating tongue. Changes in the acoustic quality of a reed as a direct sound generator may be effected by altering the shape of the reed or the frame so as to change the rate of cut-off. The effect on the vibration of the reed will in most cases be negligible.

For this reason it is more satisfactory to rely on harmonic synthesis for the generation of complex tones by reed-type generators. Provided that the gap between the vibrating tongue and the pick-up electrode is fairly large compared with the amplitude of vibration, the electrical output does not differ substantially from a sinusoidal form. Even if small quantities of the lower harmonics are present, they need not interfere with the synthesis of the desired tones, since most of the usual tones are not entirely devoid of harmonics of low order.

A fundamental disadvantage of the ordinary wind-driven reed organ is the slowness of speech in the lower register. Some of the lower frequency reeds may take as much as one or two seconds to reach a steady amplitude. A great improvement is therefore achieved by maintaining the reeds in continuous vibration and using circuit keying of the electrical pick-ups which can be made to yield any desired speed of attack and decay.

One of the experimental organs built by the author utilised reed generators with a reasonable degree of success.[28] Fig. 24 shows the general arrangement of the instrument. An assembly of 40 small brass reeds was mounted in a sound-proof box, all the reeds being driven from a common air supply. Each reed had associated with it a small pick-up electrode consisting of a brass screw, the diameter of the head ranging from ⅛-inch to 5/16-inch according to the width of the reed. The tone frequencies extended over five octaves from 32 c/s to 2,000 c/s.

The output from each reed was controlled by the value of the polarising potential. Therefore, in synthesising a complex waveform of frequency f, the control mechanism was arranged to apply selected voltages to the reeds corresponding to 2f, 3f, 4f and so on. This was achieved by a potential divider system and a multiple array of switch contacts associated with each key. In this arrangement the harmonics were "borrowed" from the fundamentals higher in pitch, in accordance with the example set out in Table III.

If a key corresponding to any of these higher frequencies 2f, 3f, 4f, etc., is depressed at the same time as the key of lower pitch f,

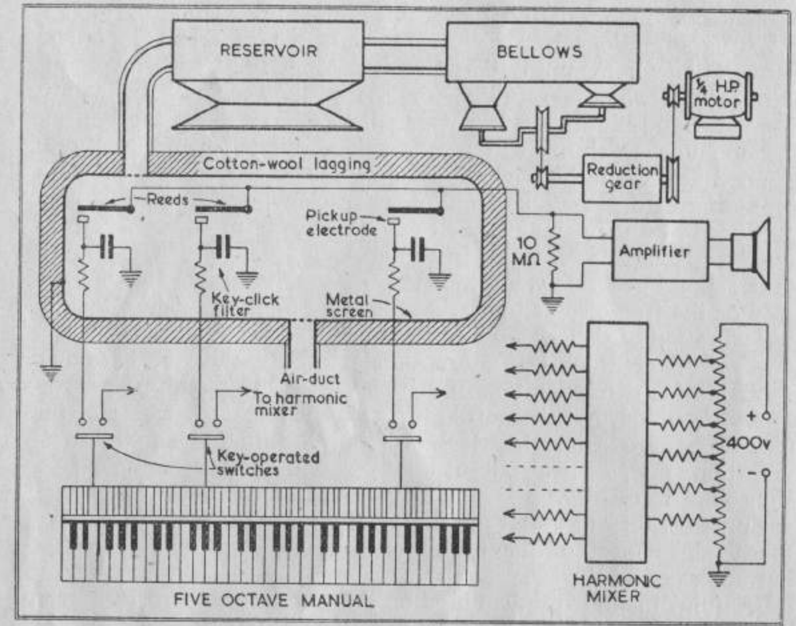


Fig. 24. An electrostatic reed-type organ in which the reed tone-generators are maintained in continuous vibration. Keying is effected by switch control of the polarising potential through harmonic mixing networks and key-click filters. The reeds are mounted on a single rigid frame in an electrostatically-screened soundproof chamber.

the generator for the higher frequency will have to supply the energy not only for the harmonic but also for the fundamental of that frequency. The polarising potentials for the corresponding generator derived through the two key switches must be additive. Borrowing from a third or a fourth key may also have to be allowed for, and some ingenuity is necessary in designing the resistance networks in order to ensure the correct additive characteristics while maintaining independence of the individual generators.

Another system suitable for an organ-type instrument which was investigated experimentally by the author employed a range of continuously vibrating strings.[29] The general arrangement of pick-up electrodes and the polarising potentials was similar to that used in the reed instrument just described. To maintain the strings in continuous vibration, an auxiliary electrostatic pick-up was provided for each string, and the output from this pick-up was amplified and fed back through a coupling transformer to the string so that an oscillatory current having the same frequency was passed through the string. A small magnet was arranged to provide a transverse field for each string with which the oscillatory field due to the current reacted, thereby causing the string to vibrate at its resonant frequency. All the auxiliary pick-ups were connected together and, of course, only one common amplifier was required for driving the complete set of strings. This arrangement is illustrated in Fig. 25. With so many strings connected in parallel, or series-parallel, the impedance of the secondary winding of the maintaining transformer had to be very low. As in the case of ribbon-microphone equipment, such high-ratio transformations are better effected by the use of two transformers in cascade.

The tone pick-ups were entirely separate from the maintaining pick-ups and were connected through the key-switching circuits to a separate tone amplifier. On account of the necessity of driving the strings from a common transformer, it was impracticable to insulate each individual string so as to permit the individual control of the polarising potential. For the same reason it was impracticable to connect the strings to the high-impedance grid circuit of the amplifier. The keying was therefore effected by the mechanical movement of the pick-up electrodes.

In mechanical keying, the pick-up electrodes must be electrostatically screened from the vibrating elements when they are not in service. When they are brought into operation by the depression of the key, the electrodes must move into their specified positions at a suitable rate and without jarring. Unfortunately, where borrowing and additive effects are required, the system tends to become prohibitively complex in mechanical detail.

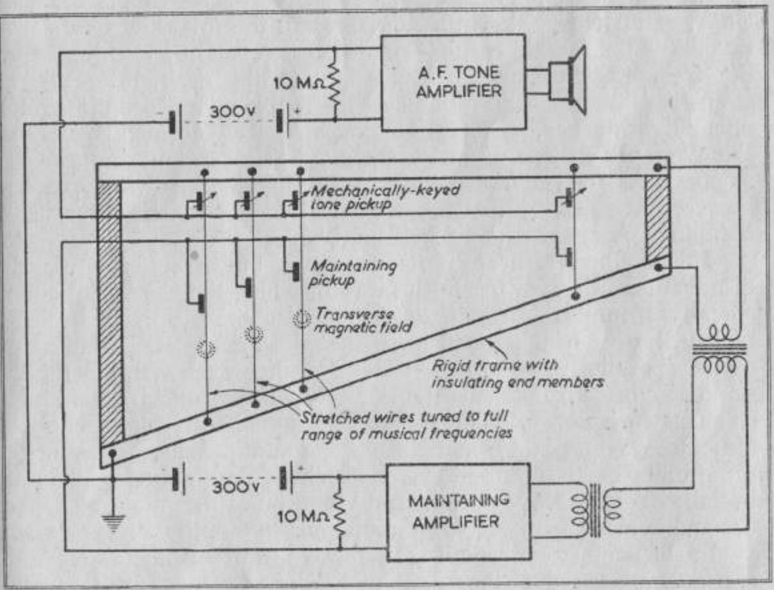


Fig. 25. An experimental electrostatic organ arrangement using strings maintained in continuous vibration. The pick-ups are mechanically linked with the playing keys. Complete screening of the string frame is necessary.

### Rotary Systems

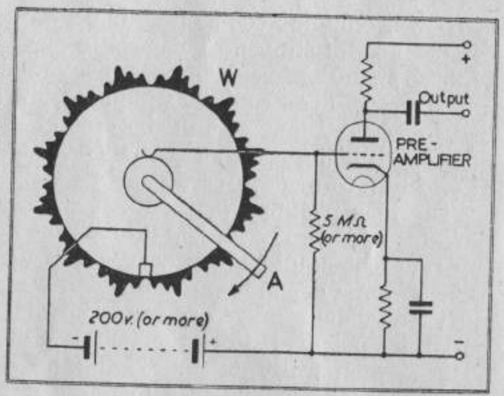


Fig. 26. The elements of a rotary electrostatic generator for producing a complex tone. The pick-up arm rotates at constant speed and at a constant distance from the wave-pattern.

Much effort has been devoted to the perfection of rotary electrostatic tone generators with the intention of producing an instrument that would compete seriously with the orthodox pipe organ.[30] This type of electronic organ appeared first about 1930, and since then its progress has been astonishing. It is debatable whether the rotary system represents the best solution to the problem, for it has certain limitations and defects, and other methods may yet remain capable of even higher development.

An attractive method of generating complex tones by a rotary system is the scanning by a radial arm of a conductive wave-pattern repeated continuously around the circumference of a circle. This principle is illustrated in Fig. 26. The circuit is essentially the same as the arrangement shown in Fig. 17. In the rotary system shown here, A is the radial arm that rotates at a constant speed, and W is the fixed wave-pattern corresponding to the desired tone. The circular pattern consists of several complete wavelengths in an unending sequence. The variable capacitance is formed by varying the overlap between A and W, the gap being constant and as small as possible. Instead of using a radial arm and a fixed wave-pattern, the converse arrangement of a rotary wave-pattern and a fixed scanning bar could equally well be used.

This method is neat in its principle, but it suffers from the disadvantage that, owing to the way in which the electrostatic field spreads around the conductive elements, the scanning becomes blurred by a "fringing" effect so that the finely detailed structure of the complex wave-form is lost. In other words, the method is unsatisfactory for the generation of wave-forms which contain high-frequency overtones. The power of resolving the high-frequency structure of the pattern increases as the gap is reduced, but at the same time inevitable imperfections such as the minor irregularities in flatness of the wave-pattern and vibration of the rotating element become evident as disturbing undulations in amplitude.

In such rotary systems it is preferable to use a moderately wide gap and to overcome the resultant loss of sensitivity by designing the scanning elements so that the effective area is greater. An obvious improvement in this direction is to multiply the number of scanning bars. The limit is reached when there is one bar for each wavelength. If several different pitches are to be produced by several different wave-patterns mounted on the same disc, each pattern must have its own set of radial pick-up elements, one for each ring of wave-patterns.

Two alternative grouping arrangements are possible where the rotary system is used. A disc or cylinder may be provided with one set of wave-patterns for each of the 12 semitones that comprise an octave, all of the sets being arranged in concentric rings. Any note within this octave can be played by suitably polarising the corresponding pick-up electrode. If the disc or cylinder is rotated at double-speed, the pitches of all the notes will be one octave higher. If the speed is again doubled, the notes will appear in the next higher octave. A succession of identical discs, each running at twice the speed of its predecessor, will therefore cover the entire pitch range of the instrument, extending over as many octaves as there are discs.

The other alternative is to provide one disc for each of the 12 semitones of the octave and design its wave-patterns, again arranged in concentric rings, to produce the fundamental and as many harmonics of the fundamental as may be desired. One disc will then generate all the A frequencies, another all the A♯ frequencies, and so on. Since all the pitches will conform to the Equal Temperament scale, the speeds of the successive discs must be graded so that each rotates $\sqrt[12]{2}$ (*i.e.*, 1.05946) times as fast as the disc for the semitone below.

In the first alternative, where all the semitones of an octave are grouped in 12 rings on one disc, the speed of the disc must be relatively low, because the number of wave-patterns in each ring will then have to be correspondingly large, and it is only by using a large number of wave-patterns that it becomes possible to achieve sufficiently accurate pitch for all the notes. The correct frequencies of the semitones within an octave, stated in cycles per second, have no common factor, and perfect tuning could be attained only by having several hundreds of wave-patterns in each ring and rotating the ring at a very low speed, perhaps less than 1/10 revolution per second. For instance, $A\sharp_{38}$ could be generated by a ring of 2,331 wave-patterns rotating at exactly 1/10 revolution per second. Fortunately, however, such precision is hardly necessary, and it is quite practicable to use a smaller number of wave-patterns and a higher shaft speed, such as 233 elements at a speed of exactly one revolution per second, without incurring unacceptable errors in tuning. The problem is to choose a speed which gives negligible error for all the different frequency-rings carried by the disc.

It is generally found preferable to adopt the second alternative where all the frequencies generated by one disc are harmonically related and where the disc speeds are progressively increased in the necessary ratio of $\sqrt[12]{2}$. In this case the accuracy of pitch depends on the accuracy of the gear ratios or pulley diameters. If gears are used, the wheels must have a sufficiently large number of teeth in order to approximate as closely as possible to the correct value of 1.05946. A pair of wheels having 196 and 185 teeth will be found satisfactory for this purpose.

The design and construction of the gearing or pulley system must fulfil certain stringent requirements. Apart from the necessity of choosing the ratios accurately, the speed must be constant within very fine limits. Also, any vibration of the shafts or irregularities in the bearings will cause unpleasant frequency modulation or a noisy background and must be reduced as far as possible. Mechanical noise from the motor and the gearing must be negligible. If pulleys are used, there must be no slipping of the belts.

These design problems have been satisfactorily overcome in various commercial instruments, but not without lengthy experimentation. Besides the careful selection of bearing materials and dimensions, it has been necessary in some cases to include mechanical torque filters incorporating spring drives and flywheels. A synchronous motor operating from a frequency-stabilised a.c. supply is usually necessary.

When the gap between the rotary and the stationary elements is small, as it usually must be in order to achieve a reasonably high sensitivity, a correspondingly high degree of precision in mounting is required both in regard to perpendicularity and freedom from eccentricity. Although the present discussion relates to electrostatic methods of tone generation, precision of the same order is necessary in the electromagnetic and photoelectric rotary systems.

A very successful organ using rotary sinusoidal electrostatic generators has been marketed by the John Compton Organ Company under the name Electrone.[31] The first instruments built to the design of L. E. A. Bourn were first demonstrated in 1935. Each note of the lowest octave and the harmonics belonging to it are generated by one set of rings arranged on the face of a disc. There are thus 12 such discs. The rotary elements associated with the stator discs are geared to rotate at speeds which progressively increase from one to the next in the ratio of $\sqrt[12]{2} : 1$. The sinusoidal patterns are arranged on the stators, and the scanning forms are carried by the rotors. To increase the efficiency, a rectangular scanning form is used in preference to a thin bar element.

Fig. 27 shows two wave-patterns and the associated scanning forms as they would appear if the motion were linear instead of rotational. When these patterns are arranged to lie on the circumference of a circle, the shapes are necessarily modified so as to produce the same sinusoidal variation of the capacitance.

The stators are made by coating a disc of insulating material with a conducting surface and then removing the unwanted areas between the wave-patterns. The rotor construction is similar in that the scanning forms appear as islands surrounded by recessed areas.

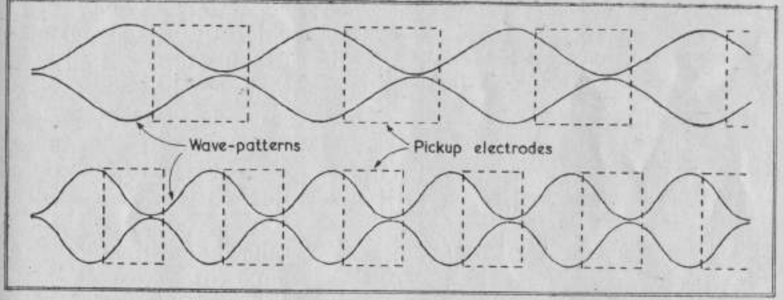


Fig. 27. Sections of the wave-patterns of a rotary electrostatic tone-generator designed to give a pure sinusoidal tone. For simplicity, the patterns are shown converted to linear form. Multiple pick-up electrodes of large area yield a greater output than a single bar-type pick-up.

All the 12 sets of generators—that is to say, all the 12 pairs of stators and rotors—are identical. This is obviously an important advantage in manufacture.

The clearance between stators and rotors is about 1/32-inch, and the polarising potential applied to the generators is of the order of 200 volts. A two-stage pre-amplifier is found to be desirable on account of the high degree of overall amplification required, even with the improved capacitor system indicated in Fig. 27. The polarising potentials are derived through the key-click filters and decoupling resistors from resistance networks associated with a bus-bar system operated by the ordinary stop controls. So much voltage-drop occurs in the resistance networks that the main supply voltage for the polarising circuits is as high as 600 volts. It is clear, therefore, that the polarising voltages could not be appreciably increased without introducing serious switching problems.

Complex tones are synthesised by the superposition of the required harmonics with the appropriate amplitudes by applying suitable voltages to the corresponding rings through selector switches connected to the system of bus-bars. Where the required harmonics differ by an unacceptable amount from the notes in the Equal Temperament scale, they are obtained from separate discs running at specially selected speeds.

Ample output is obtained from the bass generators, and this allows the use of a falling bass characteristic in the amplifier in order to reduce the hum pick-up.

Another organ of a rather similar character has been developed by A. H. Midgley and A. M. Midgley.[32] The major difference between this and the Compton instrument lies in the use of a rotating solid dielectric between the conducting stators. The two elements of each tone-generating capacitance are stationary, one being of sinusoidal form arranged round the circumference of a circle, and the other being a plain disc, while the rotor carries a set of "rectangular" segments of Bakelite, each segment being half a wavelength long. Fig. 28 illustrates the principle of the Midgley

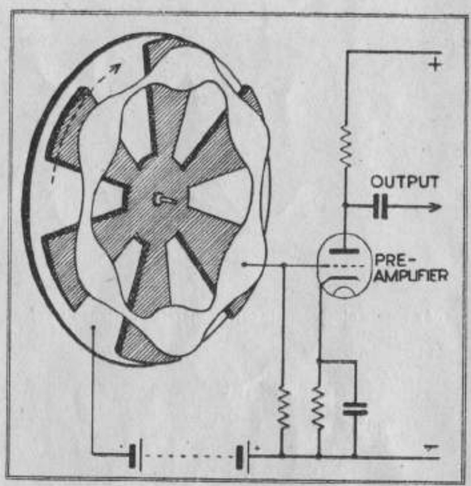


Fig. 28. A rotary electrostatic tone-generator in which both electrodes are fixed and the sectional dielectric rotates between them.

generators. One of the chief advantages claimed for this type of construction is the absence of any necessity to make contact with the rotary element and the consequent risk of electrical contact noise. On the other hand, there are two gaps in series between the capacitor electrodes with the solid dielectric spaced midway between them, and the change of capacitance can therefore only be a fraction of the change that would result from a complete substitution of air by the solid dielectric. Some uncertainty exists regarding the effect of electrostatic charges on the surface of the rotor, and it would probably be equally satisfactory if the rotor were made of metal instead of a non-conductor.

As in the Compton organ, each set of harmonics is generated by a set of concentric rings arranged in one generator disc assembly, and the generator speeds are related successively in the ratio $^{12}\sqrt{2} : 1$. It is impracticable to produce a complete set of harmonics on one disc, for the outside diameter would have to be quite large to accommodate all the required rings. Two or three identical discs, each having perhaps six or seven rings, running at multiple speeds, provide the same harmonic range without incurring the mechanical difficulties associated with large diameters.

In such rotary electrostatic organs, a *tremolo* effect is best obtained by rocking the stators about the axis of the rotors at the desired speed. The modulation produced in this way is purely frequency variation, but in addition, or alternatively, amplitude modulation can be introduced by suitably varying the polarising potentials applied to the tone elements. The number of tone-generating discs is sufficiently large to give a "choir" effect when the rocking speeds of the respective stators are staggered.

An interesting mechanism for producing *glissando* with the same type of generator has been described by L. E. A. Bourn.[33] The tone generator G (Fig. 29) is driven by a variable-ratio system $P_1P_2$ from the motor M. Normally the spring T keeps the pulley-belt in the position giving the highest speed. The contacts of the relay R are normally closed, so that when the switch Q is closed the solenoid S draws the belt towards the lower speed ratio. If any one of the keys K is now depressed, the corresponding tone ring is energised through the ordinary resistance network (not shown in the diagram), and at the same time the contacts of the relay R open and allow the spring T to draw the pulley-belt towards the higher speed ratio. As long as any one of the keys K remains depressed, other keys included in the same arrangement may be played and will yield a steady tone at the corresponding maximum frequencies. If all the keys are momentarily allowed to rise, the speed of the generator will instantly fall again and any key subsequently pressed will yield a gliding tone as the speed once more rises.

Perhaps the most difficult problem in the design of rotary electrostatic organs is the arrangement of the resistance networks by which the correct potentials are applied to the tone rings. Considerable ingenuity has been shown in the attempts to simplify the design of the networks and to reduce the wiring to practicable proportions. A two-manual organ with pedal clavier, having a reasonably complete selection of stops, contains some hundreds of thousands of electrical connections, mainly between resistors and switch contacts. The switches themselves are so numerous that their design must be of the simplest possible form if the cost of construction is to be kept reasonably low.

A simplified circuit diagram of the bus-bar connections corresponding to one manual in such an organ is shown in Fig. 30. A full explanation of the procedure used in evaluating the resistance in the stop-selecting network cannot be given in the limited space available here. It must suffice to say that circuit arrangements of this kind are necessary because the harmonics of various notes are borrowed from the tone generators, which are primarily intended for the fundamentals of other notes higher in the scale, and because the generators have an extremely high internal impedance. The voltage-regulation of each generator is very poor, and

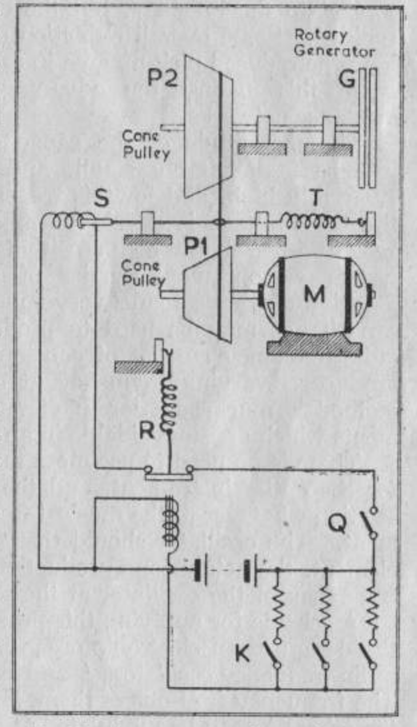


Fig. 29. An arrangement for producing a gliding tone by varying the speed of a rotary electrostatic generator.

"robbing" is likely to occur. The problem is therefore to arrange for several different loads to be connected selectively to the generators without disturbing the voltage conditions in the several circuits.[34]

As long as each generator contains a complete set of pick-up elements spaced round the ring and connected together as if they were one pick-up, there seems to be no easy alternative to this complicated resistance network; but if several separately insulated pick-ups can be mounted on the same ring, all corresponding to the same generator, each of these pick-ups may be used to provide one harmonic component of some lower note. Thus the generator for $A_{61}$(880 c/s) may be provided with perhaps ten or more separate pick-ups, one for the fundamental and each one of the others supplying the harmonics of $A_{49}$(440), $A_{37}$(220), $A_{25}$(110), $A_{13}$(55.0), $A_1$(27.5), $D_{42}$(293.7), $F_{33}$(174.6), $D_{30}$(146.8), and so on. Outputs of many different voltage levels but all at the same frequency could be obtained in this way without interfering with the level of the output from any one pick-up. The simultaneous playing of more than one tone colour merely requires the raising of the potentials applied to the bus-bars, but the danger of "robbing" would be avoided. Some overall reduction of generator output would result from the reduced pick-up area in each circuit, and the designer must weigh this against the advantage of simplified design of the resistance networks.

The magnitude of the capacitances involved in these rotary systems is inevitably small, and the equivalent reactances are invariably high, and for this reason the main resistor across which the tone voltage is developed must be of a high order so as to achieve a reasonably high sensitivity. If instead of a d.c. polarising system a continuous carrier of radio frequency be used, the sensitivity can be made very much higher.[35] The variation of capacitance may be used to produce a varying impedance for a radio-frequency current of constant frequency, or alternatively to produce a varying frequency at constant amplitude. The latter method is much superior in view of the complex wiring arrangements which are unavoidable in an organ console.

There is no need to use more than one radio-frequency oscillator for the entire instrument, and the frequency of oscillation has no relation whatever to the musical frequencies produced by the instrument. The oscillator should therefore be regarded as an auxiliary element, the actual tone production being the result of varying the frequency of the oscillator at the required tone frequencies.

A scheme for applying this principle of frequency modulation to the design of an electronic organ is shown in Fig. 31. Two stable radio-frequency oscillators A and B are allowed to run continuously. The frequency $f_1$ of one of them, B, is fixed, and the frequency $f_2$ of the other, A, can be modulated at audio-tone frequencies, the mean value being chosen so that the difference $f_1 - f_2 = f_0$ is of some suitable value, such as 100 kc/s or 450 kc/s. The outputs from the

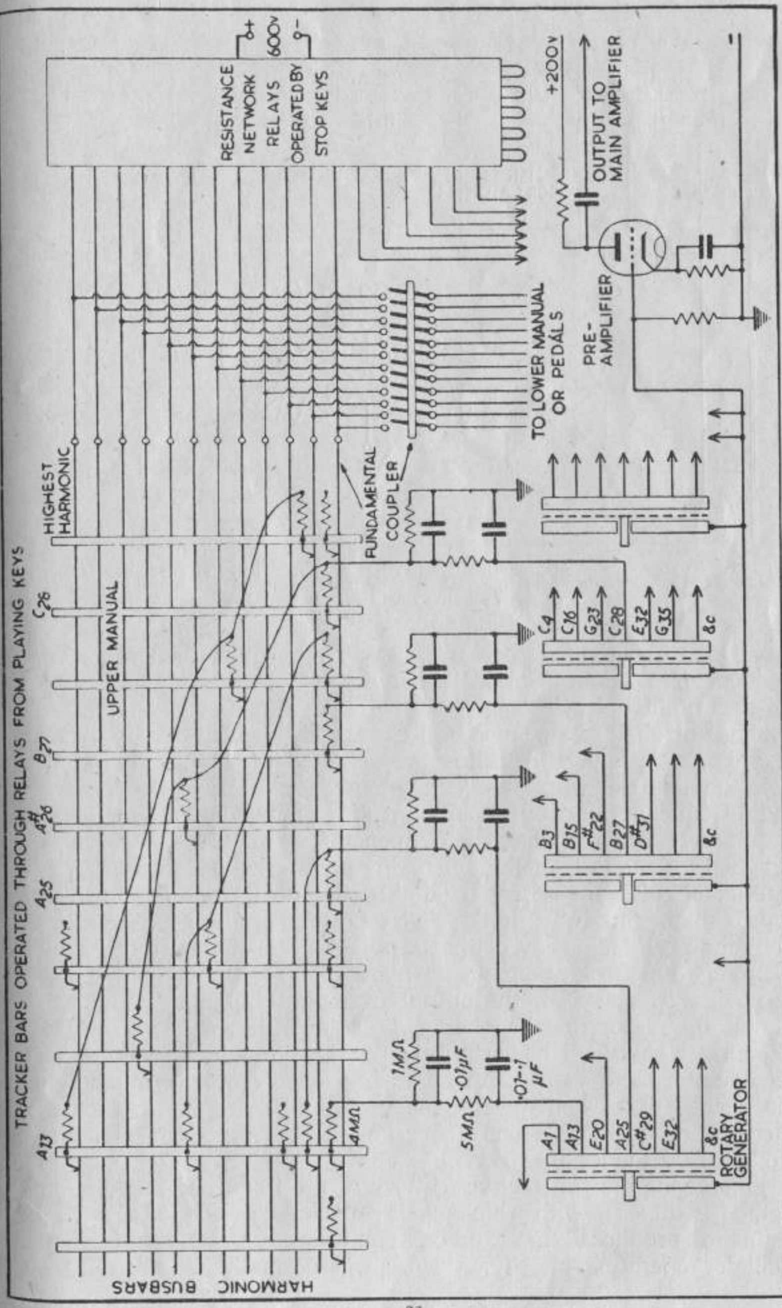


Fig. 30. A simplified diagram of the bus-bar connections in an electrostatic organ. Complex tones are obtained by harmonic synthesis, each bus-bar contact being used to apply the requisite excitation potential for the respective harmonics.

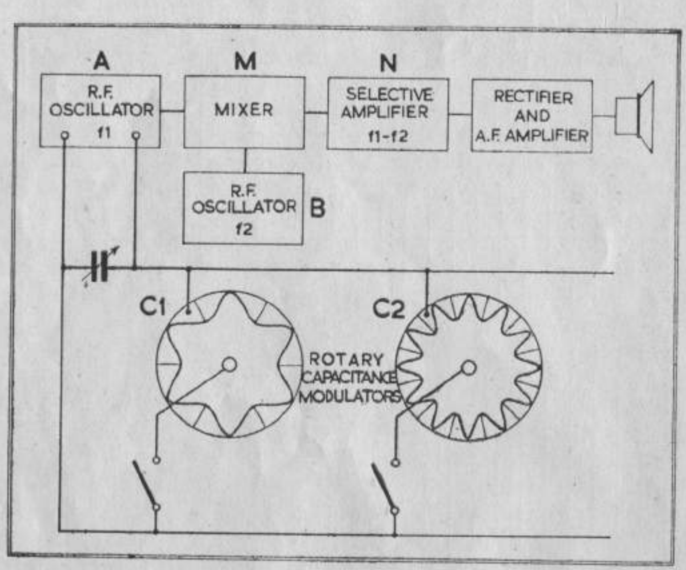


Fig. 31. An arrangement for producing tones by frequency modulation of a radio-frequency oscillator. The modulated beat frequency is converted to amplitude modulation in the selective amplifier.

two oscillators are fed to a mixer M, from which the difference-frequency $f_0$ is taken to a selective amplifier N.

The tuning circuit of the oscillator A contains a number of switch-controlled capacitances $C_1$, $C_2$, $C_3$, etc., which can be varied at audio-frequency. When these are switched into circuit the output from the oscillator will be frequency-modulated at the corresponding audio-frequency, say by an amount $\delta f$. The signal passed to the amplifier N will then have a frequency $f_0 \pm \delta f$. The amplifier is designed to have a gain characteristic of the form shown in Fig. 32, and its circuits are adjusted so that the point of operation lies approximately midway in the linear portion of the characteristic. Thus the peak frequency of the amplifier is off-set from the normal incoming difference-frequency $f_0$ by a fixed amount F. If the frequency $f_0$ is altered, the output from the amplifier is similarly altered by reason of the change of gain with frequency of the incoming signal. The output is passed through a rectifier, or demodulator, and then to an audio-frequency amplifier and loudspeaker, so that when the frequency of the carrier $f_0$ is caused to fluctuate at an audio-tone frequency, a corresponding tone is produced by the loudspeaker.

One of the most attractive features of the frequency-modulation method is the ease with which small capacitance variations may be made to produce large audio amplitudes. A radio-frequency oscillator operating at, say, 5 Mc/s will normally require only a small capacitance in its tuning circuit, perhaps 100 $\mu\mu$F. To shift the frequency by 1 kc/s the capacitance must be changed by 0.04 $\mu\mu$F, which is an exceedingly small variation. A frequency change of 1 kc/s in 5 Mc/s is admittedly small, but by using the superheterodyne principle and converting the carrier frequency to a much lower frequency, such as 450 kc/s, the proportional variation can be made much larger. The change of rectified current resulting from a 1 kc/s variation in the 450 kc/s selective amplifier can be made quite large. In other words, a much stronger audio tone will be generated by this method than by using the same capacitance variation to produce a voltage variation across a fixed resistance with the same amount of amplification.

In the frequency-modulation system it is essential to maintain the mean capacitance at the value which sets the carrier frequency $f_0$ at the midway position on the gain characteristic. This is important, for if the capacitance modulation extends beyond the linear part of this characteristic, amplitude distortion will occur. Any number of tone-generating capacitances may be connected to the tuning circuit and operated simultaneously, provided that the mean capacitance is not appreciably altered.

Unfortunately, the advantage of being able to control the keying envelope by resistance-capacitance networks is lost in resorting to oscillatory voltages in place of d.c. polarisation. The simplest form of keying in such a system is that of capacitance keying. To avoid undue mechanical complications it is preferable to effect the keying in a series-connected differential capacitor. A suitable arrangement is suggested in Fig. 33. The pick-up arm P and the tone ring R provide the continuously available capacitance variation at tone frequency. Between this and the oscillator tuning circuit, a differential capacitor XYZ is connected in such a way that the mean capacitance remains unaltered. The rotor X is mechanically linked with the playing key, so that when the key is depressed the rotor X

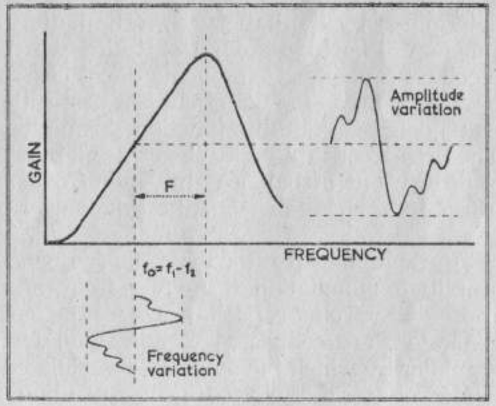


Fig. 32. The gain/frequency characteristic of the selective amplifier N shown in Fig. 31. The mean beat frequency $f_0$ is offset from the peak frequency by an amount F such that the system operates over the widest linear part of the characteristic.

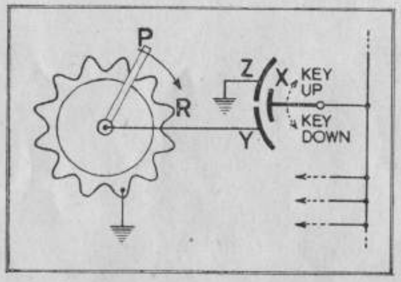


Fig. 33. A differential-capacitor arrangement suitable for mechanical keying in a frequency-modulation type of electrostatic tone generator.

moves from its normal position opposite the grounded element Z to the live eleelement Y. In order to avoid unpleasant transients, a mechanical delay device can be carried over a wide range, and a reciprocating motion will afford an amplitude *vibrato*.

An ingenious electrical method of achieving a variable time delay in circuits where the current to be modulated is already oscillatory has been described by E. Scott.[36] The method depends essentially on the steep negative resistance-voltage characteristic of the material known as *Thyrite* or of tungsten filament lamps. With such resistors, an increase in voltage across them causes a much greater increase in current, which means that the resistance varies inversely with the voltage and at a higher rate.

The basic arrangement of the circuit is shown in Fig. 34. A constant radio-frequency voltage from the centre-tapped output of the oscillator-amplifier OA is fed to a succession of shunt circuits $C_1R_1R_2$, and since the impedance of the capacitance $C_1$ is negligible at this frequency, the junction of $R_1$ and $R_2$ shown at T is at zero potential with respect to the radio-frequency voltage. $R_1$ and $R_2$ are matched resistors having a suitably steep negative characteristic.

Each playing key, denoted by K, connects the battery B to the junction T through the time-delay circuit RC. The choke L serves merely to prevent the radio-frequency current from entering the battery circuit. When key K is depressed, the voltage of the junction T rises at a suitably chosen rate and reaches a steady value determined by the battery B. The battery current flows from the junction T back to ground only through the resistor $R_2$, since the blocking capacitor $C_1$ prevents direct current from flowing through $R_1$. As soon as the direct current passes through $R_2$, the resistance value decreases and the junction T is no longer at ground potential. The bridge constituted by the centre-tapped inductance and $C_1R_1R_2$ is thrown out of balance and radio-frequency voltage is applied—after a time-delay dependent on the values of R and C—to the tone generator N.

In the tone generator the radio-frequency current is subjected to amplitude modulation at the tone frequency by reason of the series-connected varying capacitance. All the output elements of the tone generators are connected together and fed to a demodulator and amplifier by which the amplitude modulated radio-frequency carrier is made to yield audio tones corresponding to the actuated keys.

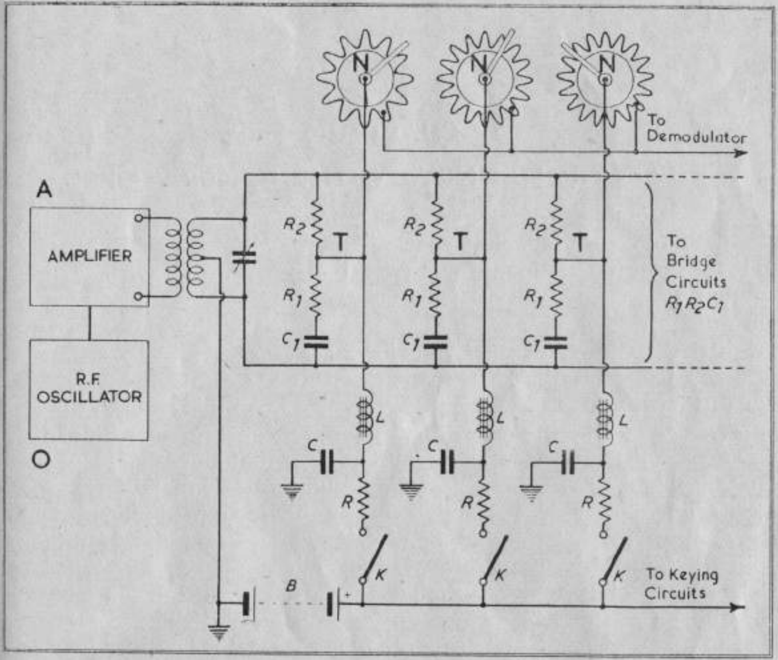


Fig. 34. A keying system for electrostatic tone generators operating on the modulated-carrier principle. Each resistor R2 is made of *Thyrite* or other suitable material which changes in resistance value when current from the key switches passes through it, thereby disturbing the R.F. balance of the bridge and allowing the corresponding generator to modulate the R.F. current fed to the demodulator.

This system of keying is not so well suited to the frequency-modulation method of tone generation on account of the large number of resistive shunt circuits which would have to be connected across the frequency-determining circuit of the oscillator.

## CHAPTER 6

# ELECTROMAGNETIC TONE GENERATORS

THE chief advantage of electromagnetic systems over their electrostatic counterparts is the much greater output which can be obtained direct from the generators. Further, there is no need to use high polarising voltages, and no special precautions are necessary with regard to insulation, since all the impedance and resistance values are relatively low.

On the other hand, effective screening of magnetic systems against stray a.c. fields must be provided, and this adds to the size and weight of the instrument. Fringing effects are more difficult to overcome than in electrostatic systems, so that there is a tendency for the higher frequencies to become unduly attenuated.

Several successful instruments using the electromagnetic principle have been marketed, notably electric guitars and the Hammond organ. The earliest instrument, the Telharmonium, developed by Thaddeus Cahill in 1897, produced a variety of tone colours by the synthesis of sinusoidal wave-forms, each generated by a separate electromagnetic dynamo capable of giving the required power output directly, since no amplifiers were available at that time.[37]

Fundamentally, the electromagnetic tone generator must be based on the movement of either a conductor carrying a current or a magnetic armature in a magnetic field. For reasons of simplicity, the preferred construction is that of the moving-iron type. The armature may be a steel wire or reed or a wave-shaped disc or drum. A system which seems to be capable of interesting development but which does not yet appear to have been used is the production of tones by magnetic ribbon or tape in which the musical wave-forms have been recorded as variations in the magnetic intensity. The acoustic quality of the musical output from such an instrument should be at least as good as the quality of recording as made by the established techniques. The method of using continuously running recorded wave-forms to be selected as required by a suitable selector and mixer system has been successfully applied to photo-electric generators, and there seems to be no reason why it should not also be applied to the magnetic tape generator.

The guitar is perhaps the simplest example of an electro-magnetic instrument, for all that it requires is a magnet with properly shaped pole-pieces provided with a high-impedance coil for connection to the amplifier. Fig. 35A shows a side-view of a simple form of pick-up, and Fig. 35B shows how the pole-pieces are placed in relation to the strings. The magnetic field may conveniently be produced by a number of small bar magnets side by side, as shown in Fig. 35C.

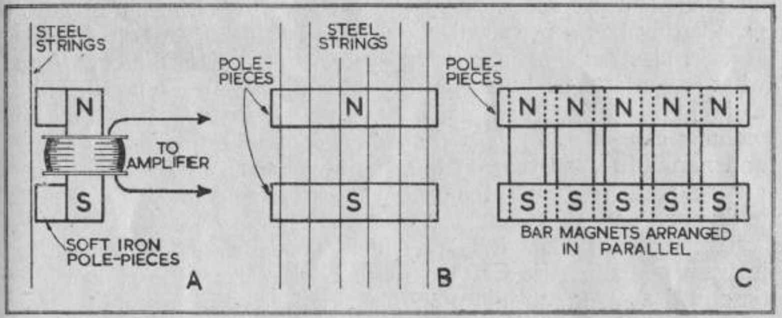


Fig. 35. An electromagnetic pick-up arrangement for a steel-stringed guitar.

Another suitable construction is suggested in Fig. 36. Two flat bar magnets are mounted close to the strings with their fields arranged so as to assist each other. A flat coil is wound round the edges of each magnet and the two coils are connected in series in the manner shown in the diagram.

In both arrangements the pick-up coils should have a high impedance if they are to be connected directly to the amplifier. Several thousand turns of fine-gauge enamelled copper wire (about No. 40 s.w.g.) would be suitable. Alternatively a lower impedance winding may be used in conjunction with a suitable matching transformer.

The piano also lends itself admirably to an electro-magnetic pick-up system, all the strings being made of steel. Obviously, it is impracticable to include all the strings in one single magnetic system. In the Nernst-Siemens-Bechstein piano, developed by the Bechstein and Siemens companies in Berlin from the designs of O. Vierling and Dr. Walter Nernst, the strings are divided into groups of five, and a small electromagnet is provided for each group. Unless it is desired to exercise some form of differential control over the several sections, all the pick-up coils may be connected together, preferably in series-parallel, and taken to the amplifier. The Bechstein instrument has no soundboard, and to take advantage of the greatly reduced decrement, two degrees of mechanical damping are provided, thereby adding to the range of expression.

Another instrument, using the same principle, called the Electrachord,[38] has been developed by the piano manufacturer, August Förster, in conjunction with the Lorentz Company, from the designs of O. Vierling, B. F. Miessner and E. T. Jacobs. Several other electromagnetic pianos have been described, but all of them are basically the same and may be regarded as elaborations of the electric guitar.

Much of the tonal quality of the violin family is due to the characteristic properties of the gut used for the strings. However, O. Vierling has constructed a violin and a 'cello with steel strings and an electromagnetic pick-up system,[39] but it is difficult to see what advantages such instruments offer other than the possibility of a diminished decrement. Even this may be a drawback, for the violinist cannot easily hasten the decay of vibration of his strings and normally must rely on their natural decrement. If the decrement is made too small, the effect is likely to be confusing and tiring to the ear.

Instead of strings it is possible to use magnetic reeds. An instrument called the Clavier, designed by Lloyd Loar, has been described as an electronic piano, although it obtains its tones from reed generators.[40] The essential elements of its construction are shown in Fig. 37A. A thin strip or reed of steel R vibrates when plucked and alters the magnetic flux in the iron circuit PM, part of which must be permanently magnetised. The reed is tuned by adjusting its effective length. The current induced in the high-impedance winding C is fed into the amplifier circuit in common with the output from similar coils associated with other reeds for other pitches. Since no soundboard is used, the decrement is low and controlled artificial damping is desirable.

In the arrangement shown, the frequency of the induced current is the same as that of the vibration, but if the construction is modified in the manner shown in Fig. 37B, the frequency of the induced current is doubled, for the magnetic flux is diminished at each deflection of the reed from its central position, up and down. The starting transients have a marked percussive quality which is unavoidably associated with any form of plucking or striking, but by using a double-length reed clamped only at its centre and placing the pick-up on the side of the clamp opposite from the plucked end a very gradual rise of amplitude is obtained. The wave-envelope is, of course, not adjustable, and the time-constant of the transfer of energy from one section of the reed to the other is rather too long to be musically pleasing. Another disadvantage of the centre-clamped reed is that tuning cannot be effected by adjusting the length. Instead, the technique of adjusting tuning forks by removing material near the tip to raise the frequency and removing material near the clamp to lower the frequency must be used.

Numerous attempts have been made to design an organ on the basis of electromagnetic tone generators. It is easy enough to produce an oscillatory current by rotating a toothed wheel near the pole-piece of an electromagnet, but there is some difficulty in producing a pure sinusoidal wave-form. Further, it may be said that difficulty in obtaining pure wave-forms also implies difficulty in obtaining complex wave-forms, for the deleterious fringing effects, which are not easily allowed for in the design, are present in both cases.

In one arrangement described by L. E. A. Bourn it was proposed to use a tuned filter circuit for producing a sinusoidal waveform from each generator, the desired complex tones being obtained by synthesis of selected pure tones.[41] The elements of the circuits are shown in Fig. 38. The tone wheel W rotates at constant speed, the number and shape of the undulations being chosen to give a tone of the required pitch and of a waveform as nearly pure as possible.

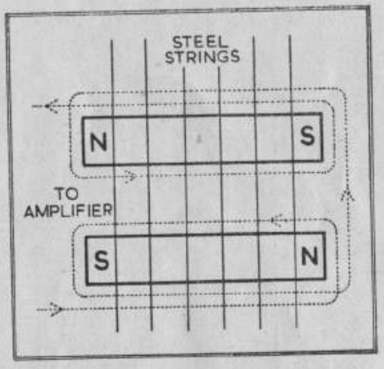


Fig. 36 (above). An alternative pick-up for a guitar.

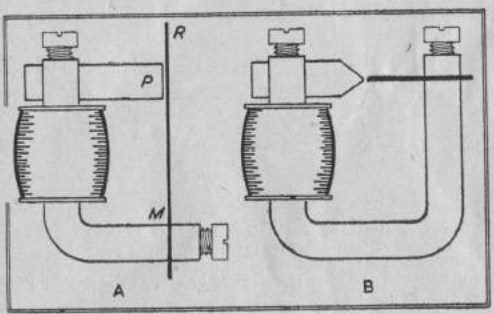


Fig. 37 (left). Two forms of vibration reed-type electromagnetic generators. In A the generated frequency is the same as the vibration frequency, but in B the generated frequency is twice that of the reed.

Normally no current is induced in the coil $L_1$ because there is no magnetisation of the soft-iron core I. When the key K is depressed the winding $L_2$ is energised and a tone-frequency current is generated in $L_1$, its amplitude depending on the adjustment of the resistance R in the energising circuit. The output from the coil $L_1$ is passed through the switch S into the tuned transformer T, which serves to attenuate all frequencies other than the desired fundamental tone frequency. The transformer is made sharply resonant by using very loose coupling between the windings, but even so it has been found practicable to rely on the same tuned circuit to filter unwanted frequencies from other tones which are only slightly different from the primary tone. Such other tones will naturally occur as harmonics of certain notes of lower pitch. This is not essential to the design, but is a convenient means of economising in the otherwise large number of transformers. The switch S associated with each tone wheel is controlled by the stop mechanism which selects the harmonic tones for synthesising the complex wave-forms.

Although no simple method of introducing a time-delay in the keying characteristic has been suggested, the use of a resonant transformer is said to overcome the unpleasant key-clicks which usually arise in inductive circuits.

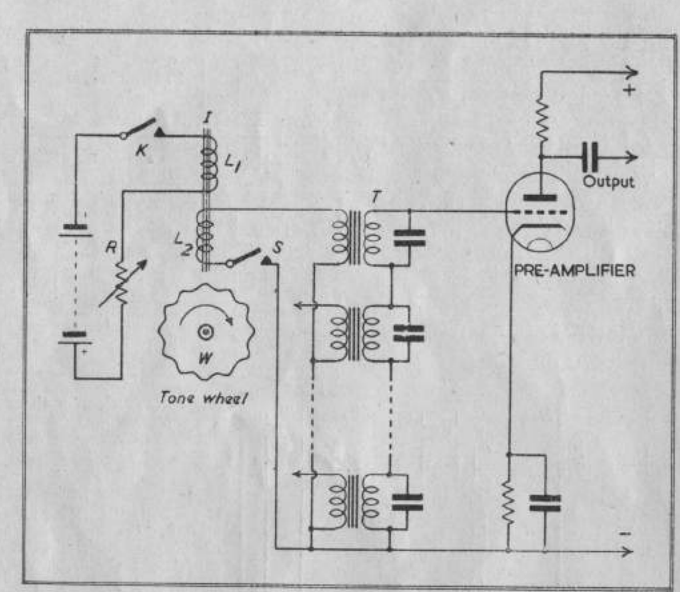


Fig. 38. An improved form of rotary electromagnetic sinusoidal tone generator using a resonant transformer T to attenuate all other frequencies than the desired fundamental. Several such transformers feed into a common amplifier. No tone voltage is induced in L1 until the auxiliary winding is energised by closing the key switch K.

Even when the key K is open, the core I will retain a small degree of magnetism due to the hysteresis in the iron, and if the switch S is allowed to remain closed a note of perceptible intensity will be produced. A system of mechanical interlocking is therefore provided which ensures that the switch S cannot be closed unless one or other of the keys K in the associated circuits is depressed. This avoids the possibility of background noise when the instrument should otherwise be silent.

Another rotary electromagnetic generator system for an organ has been described by A. H. Midgley.[42] In this design each component frequency is of sinusoidal form and is generated in a pick-up coil by the varying magnetic flux produced by the movement of an undulating surface past a stationary pole-piece. The undulations are cut in the edge of a thin circular ridge which stands out from the face of a continuously rotating iron disc, as indicated in Fig. 39. The magnetic circuit comprises the disc D, the hub H, the yoke M, the pick-up screws S and the undulating ring R. Current of the corresponding tone frequency is generated in the coil C when the magnetising coil L is energised.

Each disc carries a number of concentric rings similar to R but having suitable diameters to provide a complete set of harmonic frequencies of the fundamental note. For other notes in the Equal Tempered scale, there are 11 other discs also running continuously, with speeds increasing progressively in the ratio $\sqrt[12]{2} : 1$.

To derive harmonic frequencies from the various rings for each tone colour, a set of pick-up screws similar to S is provided, all carried by the same yoke M, the gaps being adjusted to give the required amplitude. In the design of the undulating surface of the ring R, it is necessary to assume a fixed mean gap between the ring and the pick-up screw, and if the screw is adjusted so that the gap is appreciably different from that value, the wave-form will no longer be sinusoidal owing to the fringing of the magnetic field.

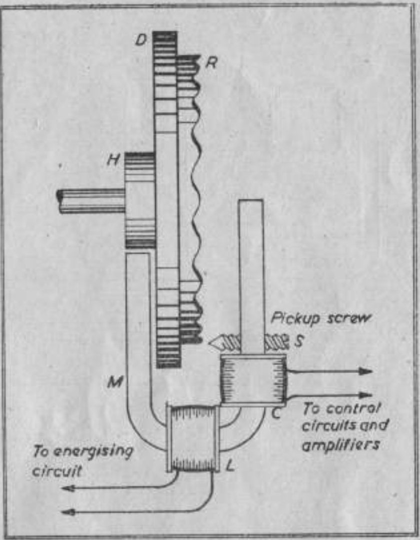


Fig. 39. A rotary electromagnetic tone generator having an edgewise undulation cut in a rotating iron ring. An auxiliary keying winding is provided for sensitising the pick-up.

A proposal to use magnetic discs having a complex surface waveform for the direct production of complex tones has been made by F. M. Robb.[43] In other respects the general arrangement resembles that of the other electromagnetic organs already described. The complex tone wheels can be made with either hill-and-dale or lateral cut, the pole-pieces of the pick-ups being designed accordingly. The method suffers from the general limitation due to fringing effects, and, of course, the abruptness of the keying associated with switched magnetic generator circuits.

Another early design of an electromagnetic organ is due to R. H. Ranger,[44] but in this arrangement the chief features of interest appear to be a relay circuit system for connecting a limited number of separate amplifiers to the keyboard so that each note temporarily has its own amplifier and an air-driven turbine for rotating the tone generators at a closely-regulated speed.

Perhaps the best-known instrument in this class is the organ designed by Laurens Hammond.[45] This has been marketed for several years and has achieved a widespread popularity in spite of certain rather prominent limitations. As a post-war development, the Hammond organ is being manufactured in England, whereas previously it was being produced only in America. No doubt it owes much of its popularity to the determined efforts on the part of its designer to devise an instrument which could be produced in a robust and reliable form at a reasonably low cost.

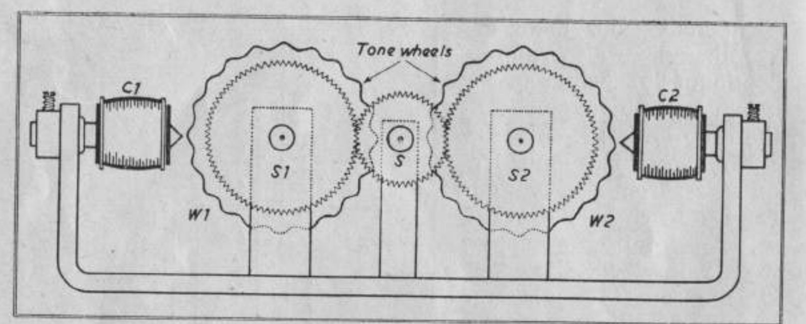


Fig. 40. A section of the Hammond organ generator assembly, showing the gear drive, the tone wheels and the pick-up electromagnetics

The Hammond organ is similar in principle to several of its forerunners. It uses a system of rotary electromagnetic disc generators to produce sinusoidal wave-forms which can be synthesised into complex tones as required, the control being effected from two 5-octave manuals and a pedal clavier of conventional design.

To provide all the required fundamental tones and their harmonics, 91 generators are used, each consisting of a suitably shaped disc about 1½ inches in diameter, rotating at a constant speed so that its periphery passes close to the tip of a fixed electromagnet. These discs are mounted on a number of shafts all geared together through accurately determined ratios, and the entire mechanism is driven from a synchronous motor. Great care has been taken to eliminate the last traces of speed variation of the tone-generator shafts by means of flywheels and resilient couplings and anti-vibration mountings. The characteristics of the torsional filters are such that the period of any hunting that may occur will only result in a frequency variation at a rate comparable with the usual rate of *vibrato*, so that any such fluctuations may enhance the tonal quality rather than detract from it.

The entire generator system is contained within a shallow trough-like frame in which are mounted two parallel rows of tone wheels. The magnetised pick-ups are arranged horizontally and are fixed to the side walls of the trough. Fig. 40 shows in section the elements of this assembly. A central shaft S, driven from the motor, rotates the shafts $S_1$ and $S_2$ through gear wheels of various ratios. These shafts do not extend throughout the length of the assembly, for the speeds range progressively between the minimum and the maximum through a succession of countershafts in accordance with the frequency requirements. The tone wheels $W_1$ and $W_2$ have their perimeters shaped so as to generate a sinusoidal current in the associated coils $C_1$ and $C_2$. A high degree of precision is necessary in the shaping and mounting of the tone wheels so that there is no unwanted modulation of the tone amplitude. Harmonic-suppression filters are inserted in each generator circuit except in the highest octave, where the harmonics have frequencies outside the range of any generator fundamental.

The slowest tone wheels have two high-points on the perimeter, and the number of high-points increases in arithmetical powers of two as far as 128 for the fastest tone wheels, the rotational speeds varying from approximately 960 to over 2,500 revolutions per minute. The range of frequencies extends from 32.7 to about 6,000 c/s.

Whereas the electrostatic type of generator presents difficult design problems when it is necessary to use the output of the same generator to supply energy for the harmonic components of other pitches owing to the very high impedance of the generator, the electromagnetic system is free from such difficulties, for the power available from each electromagnetic generator is far more than sufficient to supply all the required components. The impedance of the coil winding is made quite low, so that very many circuits may be connected to the same coil without affecting the output voltage, the circuits being of relatively very high impedance. In other words, the voltage regulation of the system is extremely good—or again, the system is free from the "robbing" effect.

On account of this feature, the circuit arrangements for producing a variety of tone colours from a common set of frequency sources are simple compared with the corresponding circuits which are found necessary in the electrostatic organ. A typical section of the complete circuit is shown in Fig. 41. It will be seen that the same generators supply both manuals and also the pedal clavier, as far as their pitch ranges overlap, and that the outputs from all the tone selector switches are fed into a common transformer.

A simple form of *tremolo* is achieved by varying the attenuation of the composite signal before it is fed into the main amplifier. The attenuator consists of a periodically varying shunt resistance connected across the transformer T through the cam-operated switch S. By reason of the series capacitance C, the *tremolo* is more pronounced at the higher frequencies. The potentiometer P, which is linked with the swell pedal F, controls the gain for all frequencies equally. In the larger types of Hammond Organ, a separate swell pedal is provided for independently controlling the amplitudes from the two manuals, and in these instruments the control for the lower manual also controls the pedal clavier.

The number of harmonics and sub-harmonics available for combining with the fundamental is limited for practical reasons to eight, and on account of the wide divergence between the seventh harmonics and the frequencies of the Equal Tempered scale, this harmonic is not included in any of the combinations. The maximum frequency which is incorporated in any tone is therefore ten times the frequency of the lowest. A set of draw-bars permits the player to select the amplitudes of the respective harmonics so as to build up any desired tone quality.

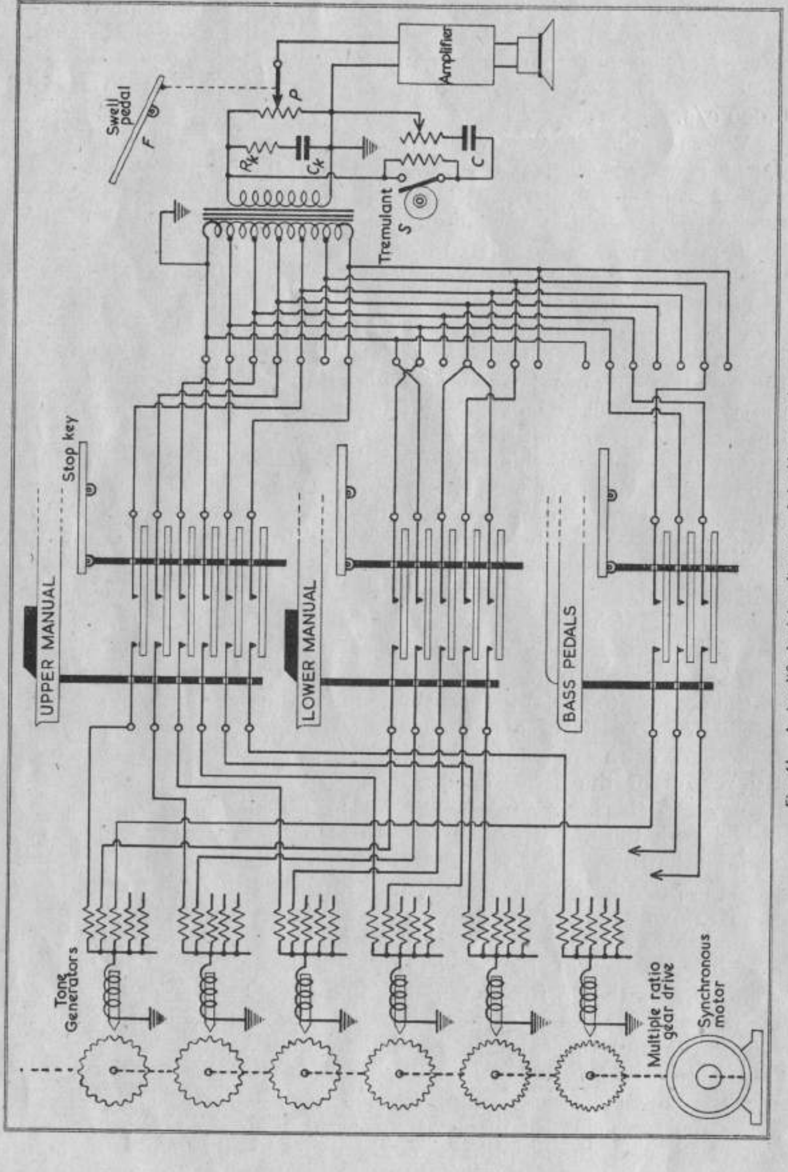


Fig. 41. A simplified wiring diagram of the Hammond organ.

A "choir," or "chorus" effect is introduced when required by switching in a separate set of rotary generators which have a very low output and are geared to run at speeds which are slightly less and slightly greater than the nominal pitch frequencies. When the playing keys are actuated, rich beating effects are produced by interference between the adjacent frequencies.

In a design where electromagnetic tone generators are switched into the amplifying circuit through key switches, the attack is inevitably abrupt. For some styles of playing, this is undoubtedly an advantage, but at the same time it limits the range of expression. The brisk quality of its attack is perhaps the most prominent characteristic of the Hammond Organ. The inductive surges, or key clicks, have been eliminated by the use of the capacitance CK and the resistance RK, connected in series across the transformer T (see Fig. 41), and in order to overcome the consequent loss of sensitivity at the higher frequencies the pick-up coils for these frequencies are designed to have a somewhat higher impedance, so that the output voltages are correspondingly greater. While the elimination of key clicks may make the apparent suddenness of the attack less prominent, there can be no effect on the rate of build-up of the tone frequency.

One method of introducing the desirable time-delay would be to insert small variable-coupling transformers in each circuit between the tone generators and the main amplifier transformer and to use some form of mechanical delay device such as a piston-type solenoid to effect the keying, instead of merely switching the generators in and out of circuit. Where the complex tones are synthesised from sinusoidal wave-forms, it would be necessary to incorporate a delay mechanism for each harmonic of every note, and it becomes debatable whether the additional complication and expense can be justified by the improvement in musical expression.

## CHAPTER 7

# PHOTOELECTRIC TONE GENERATORS

THE feature of the photoelectric principle which makes it so attractive is the possibility of scanning a recorded complex wave-form as already used in the highly-developed technique of talking-films. Fringing effects, although not entirely absent, are very much smaller than in either electrostatic or electromagnetic instruments using rotary generators. One of the primary requirements of all such photoelectric systems is that the light source shall be free from unwanted modulation. Caution is therefore necessary where it is proposed to use a.c. supplies for energising the lamps, whether they be of the filament or of the electron-discharge type.

The use of a photocell in electronic musical instruments is not confined to the scanning of pictorial wave-patterns. For instance, a system has been proposed by J. Halmágyi and N. Langer in which a glow-discharge tube is used as a relaxation oscillator (see Chapter 4), and light emitted from this tube is caused to activate a photocell connected to the input of the main tone amplifier.[46] The purpose of this arrangement is to prevent reaction from the amplifier on the oscillator circuits and thereby to improve the frequency stability. With modern amplifier technique, however, adequate isolation can easily be obtained and the optical link is no longer necessary.

Another of the early photoelectric instruments was that described by E. Spielman.[47] It was intended to simulate a piano in regard to expression although a variety of tone colours could be obtained. Each tone was generated by the cyclic variation of the light intensity reaching a photocell from a lamp through a moving succession of apertures. The apertures were arranged in a ring on a disc, each ring corresponding to one pitch. As in the rotary electrostatic systems, there were several concentric rings on each disc, harmonically related, and there were 12 discs, one for each note of the octave. Separate lamps were used, each being controlled through a rheostat operated by a touch-sensitive key.

The drawing in Fig. 42 indicates the constructional arrangement in the Spielman piano for controlling the light intensity. When the key K is depressed, a lever L is rotated about its pivot P and the flexible metal strip is brought into contact with the exposed resistance element R. A deeper depression of the key causes the flexible strip to make progressive contact with the resistance, so that the lamp becomes brighter. Similarly, the lamp is dimmed as the key is allowed to rise. An armature A is fixed on the lever L so that when the electromagnet M is energised the lamp is maintained at its maximum brilliancy until the magnet circuit is opened.

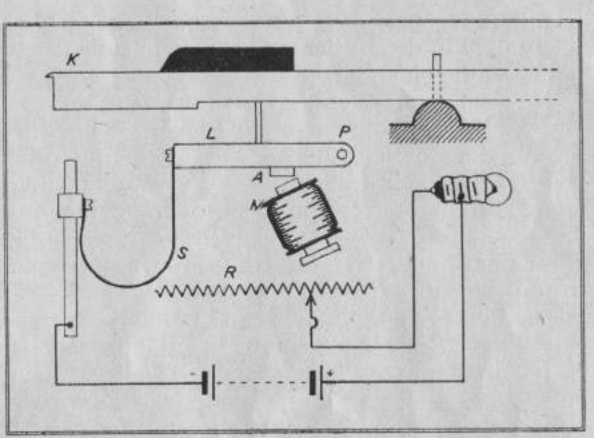


Fig. 42. A keying system for a photoelectric piano. The flexible metal strip S is pressed into varying contact with the resistor R.

The instrument was provided with two pedals, one to reduce the general volume by means of an attenuator, and the other to sustain the activated notes by means of the electromagnets, after the manner of the pedal controls in an orthodox piano.[48]

Several organs have been designed on the basis of optically scanned wave-forms in conjunction with a photocell-amplifier, and the first instrument employing this principle to be marketed in England is being produced by The Miller Organ Company. Almost all these instruments incorporate a rotary mechanism with accurately determined speeds as in the corresponding electrostatic and electromagnetic organs.

The scanning arrangements may be divided into two classes: (*a*) those in which a stationary wave-pattern is scanned by a succession of slits, and (*b*) those in which a succession of wave-patterns moves past a stationary slit. The wave-pattern may be of either the variable-density type or the variable-area type, but in both cases the maximum frequency which the system can generate is limited by the diffraction effects arising from the passage of light through the narrow slits. On this account blue light is preferable to red light, as it has a shorter wavelength.

Tone-envelope control may be achieved by varying the rate at which the lamp brilliancy is varied or by the mechanical displacement of graded masks in the optical path. A *tremolo* effect is obtainable in a similar way if plain amplitude modulation is sufficient, or by reciprocating the stators if frequency modulation is desired.

Generally the output of a photocell is small, and a high-gain amplifier affording a magnification of about 100 db is necessary. Apart from the inevitable amplifier noise, the photoelectric system has the advantage of a very low background level, since it is relatively easy to design the optical system so that unwanted light does not enter the photocell.

In a simple form of photoelectric organ, due to C. R. MacCullum and A. MacCullum,[49] a rotating hollow cylinder is perforated with several rings of longitudinal slits, each ring corresponding to one note on the keyboard, and stationary wave-patterns are placed as desired in the correct positions opposite the rings. The wave-patterns are of the variable-density type consisting of parallel graduations, and are recorded in rows on a pliable film. Each row corresponds to a particular tone colour and can be brought into position by rotating the rollers on which the film is wound. Keying is performed by moving shutters of graduated transparency in front of the lenses associated with each light-path through the wave-patterns and the rings in the slotted cylinder. The elements of the system are shown in Fig. 43.

An organ similar in principle to the one just described but using a continuously-running film instead of a cylinder has been designed by I. Eremeeff for direct connection to a broadcast transmitter.[50] The instrument was provided with two manuals extending over $7\frac{1}{2}$ octaves, but had no pedal clavier.

An arrangement using discs instead of cylinders has been described by S. Prisner.[51] The sounds generated by the instruments which it is proposed to simulate are recorded on circular tracks on a transparent disc. The disc rotates at constant speed, all the tracks being illuminated by a cylindrical lens which concentrates the light from a tubular lamp in a thin line coincident with a radius of the disc. Keying is effected by shutters and the transmitted light is passed into one or several photocells. Another design using cylinders or discs has been described by A. H. Brackensey.[52]

A conical drum carrying series of slits in its surface as an alternative to the cylinder has been suggested by G. T. Winch, who also contemplated a disc construction.[53] In the disc system it was proposed to use individual lamps for each note and for each tone colour, and to switch the lamps into circuit as required by ganged stop-switches and multiple key contacts. The disc D in Fig. 44 is made of opaque material or of glass with a blackened surface, and with several sets of equi-spaced radial slits arranged in concentric circles N, corresponding to various pitch frequencies. The proportioning of such a disc is determined by the same considerations as apply to the electrostatic and electromagnetic rotary generators. Parallel with this disc are several sets of wave-patterns (either variable-area or variable-density), two of which are shown at $P_1$, $P_2$. A miniature filament-type lamp S is provided for each ring of slits N, and the light from it is focused on the slits by the lens S. When one of the keys K is depressed, the filament lights up at a rate which depends on the lamp characteristics and the circuit adjustment, and the light passing through the slits is modulated with the complex wave-form

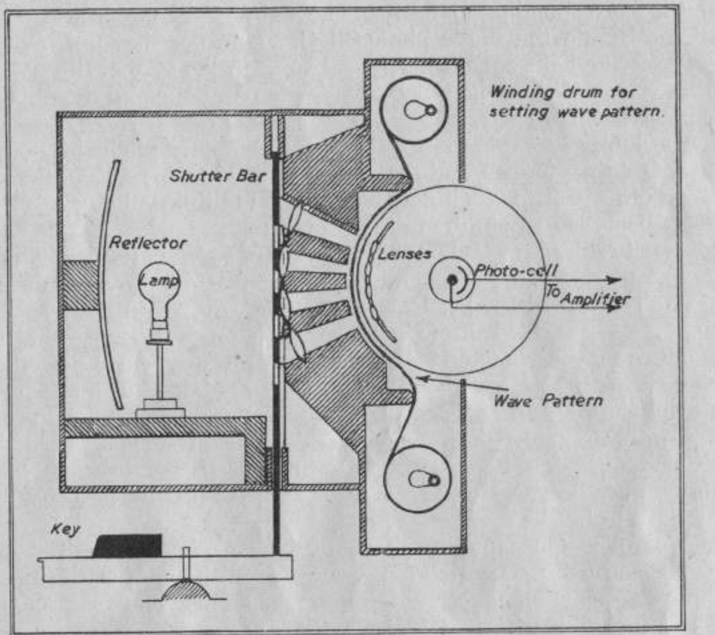


Fig. 43. A section of a cylinder-type of rotary photo-electric organ. The cylinder is provided with peripheral rows of slits corresponding to the various tone frequencies. Wave-patterns are carried on a stationary film held close to the rotating cylinder and set to various positions by the winding handles.

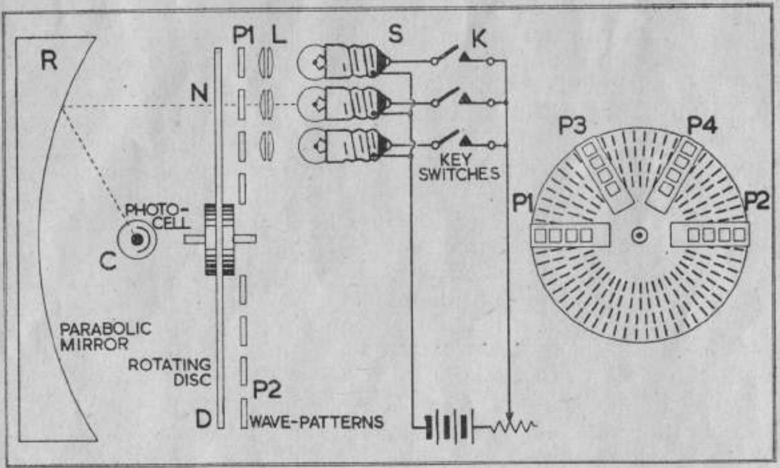


Fig. 44. A disc-type of rotary photo-electric organ. The arrangement of the slits on the disc is shown in the sketch at the right. Each radial strip carries a different set of wave-patterns and a corresponding lamp and lens system.

of the corresponding pattern. The light is then reflected by the mirror R into the single photocell C. In order that the photocell may receive light equally from any lamp in the system through any of the rings of slits, the reflector is made parabolic and the photocell is placed at its focus.

It is impracticable to include all the necessary pitch-rings on one disc, and therefore several discs must be used. Preferably there will be 12 discs, one for each note with all its multiples, the speeds being related successively in the ratio of $\sqrt[12]{2} : 1$.

Each radial arm P should carry a set of wave-patterns giving the same tone quality, but several such arms may be provided for each disc, as shown at $P_1$, $P_2$, $P_3$, $P_4$. In this way, when the associated lamps are connected through the ganged stop-switches, several tone qualities may be obtained simultaneously for any single note that is played. All the circuit combinations are contained in the filament-heating supply, and on account of the importance of avoiding hum from a.c. supplies, the lamps should be fed from a battery. By fitting lamps of different current-rating for the same wattage, the attack may be varied, and a master rheostat provides a convenient swell control.

Complex tone quality may, of course, be synthesised from photoelectrically generated sine waves as in the case of the electrostatic and electromagnetic systems. An arrangement for producing tones in this way for a pedal clavier has been described by P. T. Hobson.[54] It is in many respects the photo-electric counterpart of the electrostatic organ devised by L. E. A. Bourn,[31] except that each disc provides all the 12 tones of one octave and that, in consequence, the disc speeds increase progressively in the octave ratio of 2 : 1. Several radial rows of exciter lamps are mounted adjacent to the discs, after the manner of Fig. 44, so that more than one lamp is associated with each pitch-ring. Where only the fundamental tones are required, the keys operate directly to switch in the corresponding lamps, but when complex tone colours are desired the stop switches are operated, whereby the additional lamps are brought into circuit through separate resistors, of suitably chosen value, so that the light intensity is in agreement with the amplitude of the respective harmonics. The principle used here is analogous to that of the harmonic mixing circuits of the Hammond Organ.[45]

An interesting suggestion, made by H. G. Matthews,[55] for directing the beams of light into the required positions is the use of light conductors. Provided that the curvature of a glass rod is not too abrupt, light which enters at one end is projected from the other end with only a small loss of intensity due to the imperfect transparency of the material. There is negligible loss of light energy through the walls of the rod, since the internal reflection is almost perfect. This technique, which is commonly used in surgery and in other work where it is necessary to direct light into awkward crevices and cavities, might well be applied to the construction of photo-

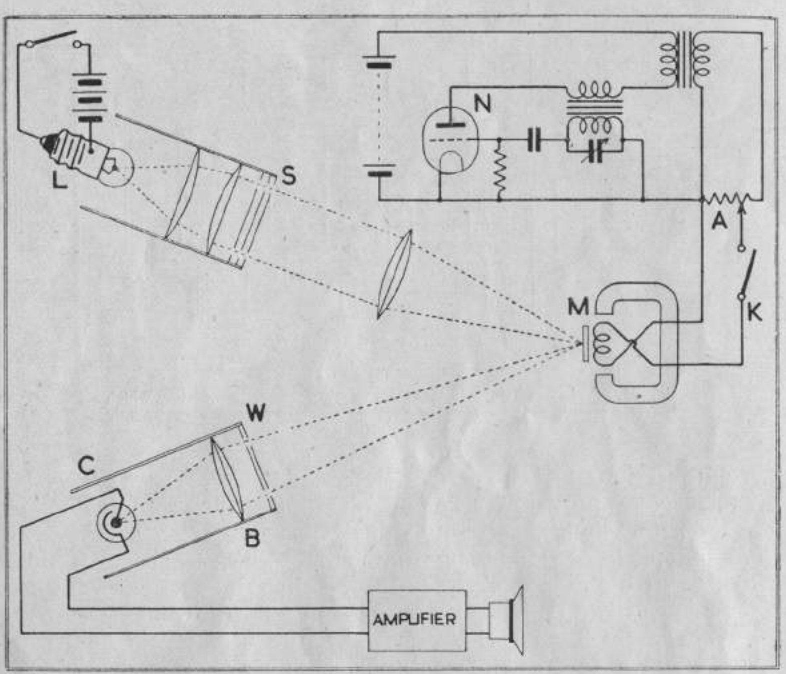


Fig. 45. A vibratory photoelectric tone generator using an oscillating mirror. Keying shutters and selected wave-patterns are interposed in the light path.

electric musical instruments, either for the distribution or for the collection of the various beams of light.

A reflecting mirror-type oscillograph in conjunction with a number of fixed frequency-generators provides a convenient alternative to a rotary mechanism. The basic features of such an arrangement are shown in Fig. 45. Alternating current of a suitable tone-frequency is generated by the oscillator N and is fed into the mirror-oscillograph M at a suitable amplitude through the attenuator A and the key K. Light from the lamp L passes through a condenser-lens system and a slit S, after which it is focused on to the oscillograph mirror. The reflected beam is then passed through the wave-pattern W, which acts as a mask to produce an oscillatory variation in the intensity of the light entering the photocell through the lens B. Various tone qualities may be achieved by substituting different patterns at W. It is important to maintain the amplitude of the mirror accurately constant at the value which causes the light beam to swing over the full width of the pattern. Distortion will be introduced if the amplitude is too great or too small.

Such an arrangement has been proposed by P. T. Hobson as a means of supplying the pedal tones of an organ.[56] If only one note is required at a time, as is often sufficient in the pedal clavier, the

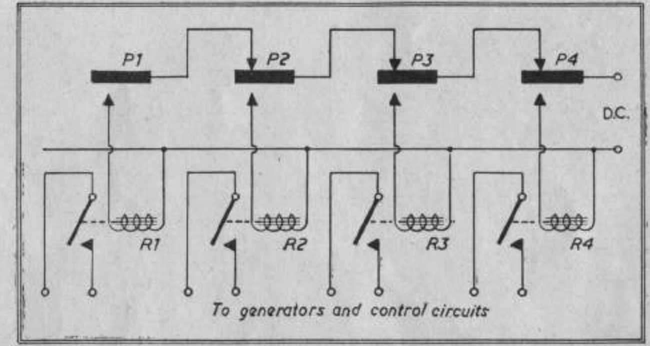


Fig. 46. A key-switching system for a single tone generator which provides that when two or more keys are depressed simultaneously only the key farthest to the right is effective.

system just described can easily be adapted to cover a wide range of frequencies by providing a key-operated set of tuning capacitors in the oscillator circuit, each individual capacitor being adjusted to give the pitch corresponding to the key which connects it into circuit. In order to prevent false operation by the simultaneous depression of two or more keys, the "melodic" switching system may be used. The principle on which this is based is shown in Fig. 46. Here $P_1$—$P_4$ represent four of the pedals and $R_1$—$R_4$ are the associated relays that are used to actuate the frequency-determining circuits. If the pedal $P_1$ is depressed, the corresponding relay $R_1$ is energised. Alternatively, if any other single pedal is depressed, the corresponding relay is energised, provided that all the pedals to the right of it are in the raised position. Suppose $P_2$ is being played, and suppose $P_3$ is depressed while $P_2$ is still held down. The relay $R_3$ will be energised, but the supply to $R_2$ will be cut off. In general terms, any pedal to the *right* will take control over the key that is being played.

Although the pedal clavier is often required to produce only one note at a time, provision must be made for two simultaneous notes. The generator system will then have to be duplicated and the "melodic" circuit elaborated as indicated in Fig. 47 to permit the two generators to work independently and yet to prevent false operation of either generator.

It is not essential that the generators shall be of the feedback-amplifier type shown in Fig. 45. Any other source of tone-frequency current may be used, such as a self-maintained tuning fork, and if a generator can be provided for each note within the entire compass of the instrument, the "melodic" switching will be unnecessary.

Many other photoelectric instruments of the organ class have been devised, mostly employing the principles already mentioned, but particular attention may be drawn to an ingenious method, due

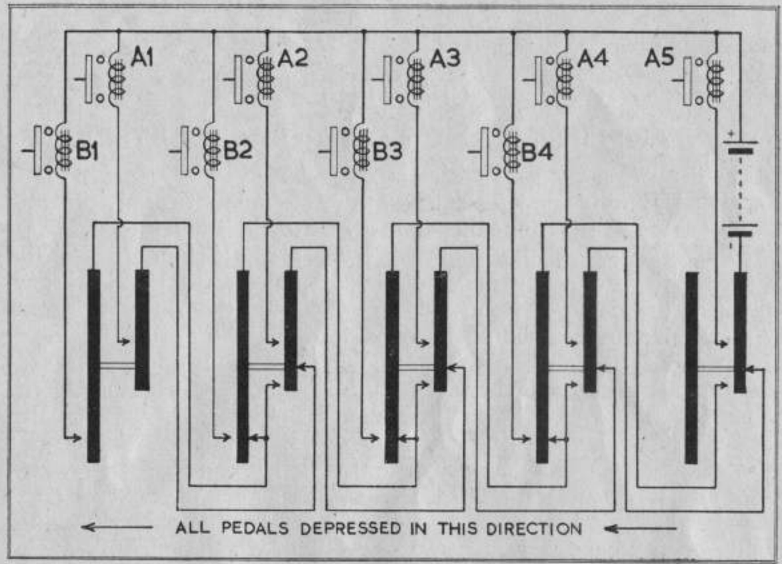


Fig. 47. An elaboration of the key-switching system shown in Fig. 46 adapted for two tone generators. Here two keys are effective when more than two are depressed, the effective keys being the two farthest to the right. All the relays A are connected to one generator, and all the relays B are connected to the other generator.

to R. W. Bumstead,[57] in which the required tones are produced by circularly scanning a silhouetted wave-pattern projected on to the sensitive screen of an iconoscope. The system is dependent on the correct adjustment of a number of inter-related supersonic oscillator and frequency-modulation circuits, requiring highly skilled supervision, and the iconoscope must be specially constructed to suit the circuit conditions. It may be said, therefore, that the interest of the method lies more in its ingenuity than in its practicability.

## CHAPTER 8

# AMPLIFIERS AND CONTROL CIRCUITS

### Amplifiers

THE amplifiers associated with electronic musical instruments for converting the tone-generator output into acoustic energy at the required level are of standard design. Clearly, the frequency range of the amplifier must be at least as great as the range of frequencies produced by the tone generators. An organ amplifier should be capable of handling all frequencies from 30 c/s to about 18,000 or 20,000 c/s without appreciable loss at the extremities, but here it may be noted that a uniform gain-characteristic over the entire range is not necessary, for any deficiencies can be compensated by adjusting the output levels of the generators over the appropriate frequency bands. The generators and the amplifier should be designed as complementary components of a single system, as in the case of a gramophone amplifier with a rising bass characteristic for use with lateral-cut disc records.

The power rating of the amplifier system will depend on the size of the room or the hall where the instrument is to be heard, and may range from 3-watts for a small monophonic type of instrument to 10-watts for an electric piano to be played in a room of average size, and up to 50 or 100-watts for organs in large halls and churches.

The amount of gain required varies according to the manner in which the tone voltages are generated. Low-level generators, such as the electrostatic and photoelectric types, may require a gain of 100 db, but again much depends on the constructional principles employed and the magnitude of the exciting potentials or the intensity of illumination. It is therefore not feasible in this limited space to give specific designs for amplifiers suitable for all the various instruments which have been described. As a guide, however, circuit layouts are shown in Figs. 48 and 49 of two amplifiers which are representative of the requirements of a small solo instrument and of an organ respectively.

### Power Supplies

In general, it is better to use separate power supplies for the amplifier and the tone-generator system. Unwanted feedback effects may occur if a common supply is used or perhaps a certain elusive hum, especially in the electrostatic type of instrument.

The total power consumption, even in the biggest electronic organs, is usually less than 500 watts, so that the running costs are trivial. An a.c. supply is not always essential. Some tone-generator methods do not require a.c., and satisfactory amplifiers can be built to operate on d.c., but where a rotary generator system is used, it is clearly an advantage to rely on an a.c. supply of controlled frequency for stabilising the speed of the rotors, and therefore the pitch of the instrument.

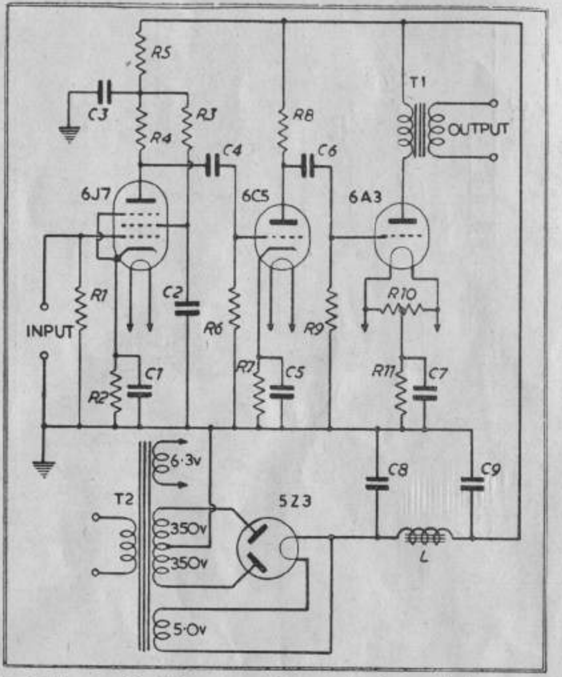


Fig. 48. Circuit diagram of a 3.5 watt amplifier suitable for small electronic instruments.

| | | | |
|---|---|---|---|
| C1 | 25$\mu$F. electrolytic (25v.) | R1 | 2M$\Omega$ (½ watt) |
| C2 | 0.05$\mu$F. paper (600v.) | R2 | 2,600$\Omega$ (1 watt) |
| C3 | 8$\mu$F. electrolytic (450v.) | R3 | 1.2M$\Omega$ (1 watt) |
| C4 | 0.01$\mu$F. paper (600v.) | R4 | 0.5M$\Omega$ (1 watt) |
| C5 | 25$\mu$F. electrolytic (25v.) | R5 | 50,000$\Omega$ (1 watt) |
| C6 | 0.01$\mu$F. paper (600v.) | R6 | 0.5M$\Omega$ (½ watt) |
| C7 | 50$\mu$F. electrolytic (50v.) | R7 | 6,000$\Omega$ (1 watt) |
| C8 | 4$\mu$F. paper (600v.) | R8 | 0.5M$\Omega$ (1 watt) |
| C9 | 8$\mu$F. electrolytic (450v.) | R9 | 0.5M$\Omega$ (½ watt) |
| | | R10 | 50$\Omega$ centre-tapped |
| | | R11 | 800$\Omega$ (10 watt) |
| T1 | Output transformer (primary impedance 2,500$\Omega$) | | |
| T2 | Power Transformer, 350+350v., 90mA., 6.3v. 2A., 5v. 3A. | | |
| L | Choke, 30H (90mA.) | | |

If the supply is a.c. of uncertain frequency, or if it is d.c., a rotary system can still be used. An electrically-maintained tuning fork provides a convenient source of interrupted d.c. for running the synchronous motor, a rectifier or converter being required if the supply is uncontrolled a.c.

### Control Circuits

It is one thing to generate musical tones and another thing to

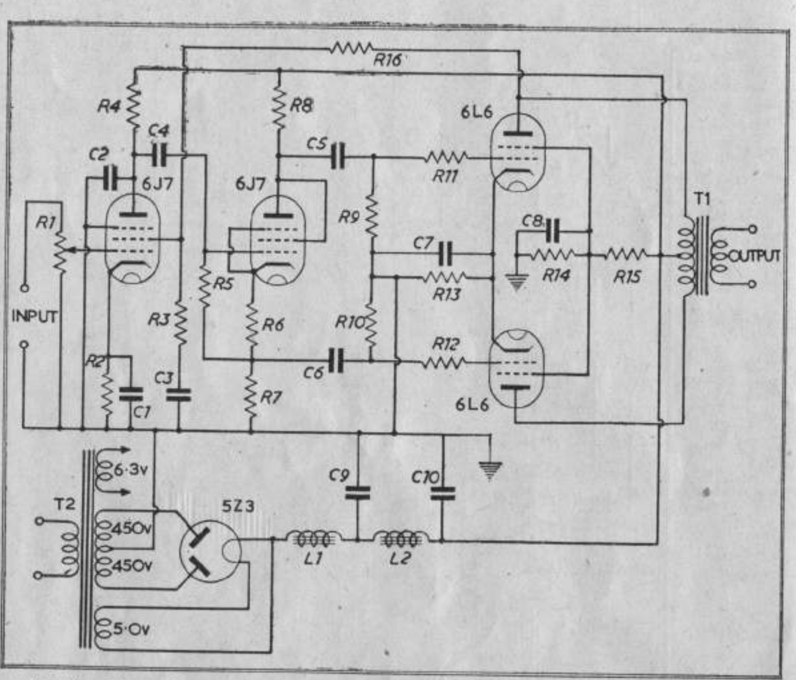


Fig. 49. Circuit diagram of a 25 watt amplifier suitable for electronic organs and other large instruments. In this amplifier improved performance is obtained by the inclusion of negative-feedback through the resistor R16 from the output transformer to the screen of the first stage.

| | |
|---|---|
| C1 | 25μF. electrolytic (25v.) |
| C2 | 0.0001μF. mica (600v.) |
| C3 | 0.5μF. paper (600v.) |
| C4 | 0.02μF. paper (600v.) |
| C5 | 0.1μF. paper (600v.) |
| C6 | 0.1μF. paper (600v.) |
| C7 | 50μF. electrolytic (50v.) |
| C8 | 8μF. electrolytic (550v.) |
| C9 | 4μF. paper (800v.) |
| C10 | 8μF. electrolytic (550v.) |
| L1 | Swinging choke 5/25H. (250mA.) |
| L2 | Choke 20H. (250mA.) |
| R1 | 1MΩ potentiometer |
| R2 | 2,000Ω (1 watt) |
| R3 | 30,000Ω (1 watt) |
| R4 | 250,000Ω (1 watt) |
| R5 | 1MΩ (½ watt) |
| R6 | 5,000Ω (1 watt) |
| R7 | 100,000Ω (1 watt) |
| R8 | 100,000Ω (1 watt) |
| R9 | 250,000Ω (1 watt) |
| R10 | 250,000Ω (1 watt) |
| R11 | 10,000Ω (½ watt) |
| R12 | 10,000Ω (½ watt) |
| R13 | 200Ω (10 watt) |
| R14 | 5,000Ω (20 watt) |
| R15 | 1,400Ω (15 watt) |
| R16 | 1.5MΩ (1 watt) |
| T1 | Push-pull output transformer (primary impedance 6,000+6,000Ω) |
| T2 | Power transformer, 450+450v., 250mA., 6.3v. 3A., 5v. 3A. |

control them. From the descriptions in the foregoing chapters it will be evident that often as much ingenuity is required to devise satisfactory methods for controlling the tones as for generating them. The word *control* is used here, of course, in the narrow sense of acoustic regulation rather than in the broad sense of the execution or rendering of musical compositions.

The elementary forms of control, such as keying, are usually peculiar to each particular method of tone generation, and these have been described in conjunction with the associated type of instrument. There are, however, other control features which may be found in the amplifier belonging to any instrument, such as general volume control, *vibrato*, and synthetic reverberation, and these are discussed in the following pages.

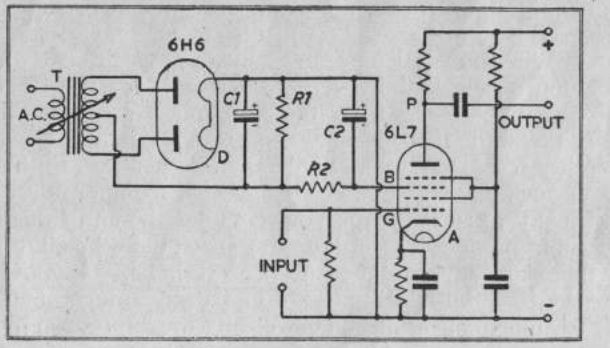
### Volume Control

In ordinary amplifier technique, the gain can be very conveniently adjusted by means of a potentiometer consisting of a high-resistance wire element over which a slider can move so as to provide a variable tapping point. With the amount of use that such a potentiometer would have as a loudness control in a musical instrument, the effect of wear and dirt would very soon result in scratching noises whenever the slider was moved to a different position. For reliable operation over a long period of time it is desirable to avoid sliding contacts, especially in the early stages of high-gain amplifiers, and the gain must be varied by some other method.

An interesting system which has the virtue of being entirely noiseless and which also has the advantage of permitting remote control, has been described by H. S. Polk.[58] The circuit arrangement is shown in Fig. 50. It is a variable-bias system for varying the gain-factor of the heptode A, which may be the first stage of the main amplifier. The tone-frequency voltage is fed to the first control grid G, and the output is taken from the plate in the usual way. An adjustable bias for the second control grid B is provided by the variable transformer T and the double-diode rectifier D and a filter circuit $R_1R_2C_1C_2$. Either the core or the coils of the transformer may be movable, and the transformer itself may be quite small, since its only function is to supply a bias voltage across the high resistance $R_1$. Obviously the grading of the control depends on the construction of the transformer and the manner in which the movable part is linked with the control pedal or lever, but the design should permit sufficient bias to be applied to the heptode for reducing the sound level to an effective zero.

If a radio-frequency amplifier is used as part of the amplifying

Fig. 50. A variable gain control system in which all moving contacts are avoided. The transformer T is specially constructed having a movable core or movable windings for supplying a variable bias to the amplifier.



system, such as in the frequency-modulated and amplitude-modulated carrier methods, the gain can be varied by means of a variable capacitor of conventional size. Provided that the capacitor is well constructed, the arrangement is completely noiseless.

In photoelectric systems the general volume level can be controlled by obscuring the light sources with suitably graded masks or by adjusting the current in the lamps. Usually a tungsten filament lamp will be used and the thermal inertia of the filament can be relied upon to absorb any momentary small irregularities in the controlling resistor.

### Vibrato System

It is impossible to add a frequency-modulation type of *vibrato* to the composite tone voltage in the main amplifier. All that can be done outside the generator is to modulate the amplitude, but by discriminating between various bands of frequencies in the audio range with the aid of tuned filters, it would be possible to superpose amplitude modulation at different rates for each band of the audio range. Thus a brighter effect would be obtained than with a single *vibrato* for the entire output.

Musicians do not seem to agree on the question of amplitude versus frequency variation for *vibrato* effects, and it is perhaps safest to say that no general ruling can be expected. A combination of both forms of variation is probably the best solution in any case, and the predominance of one or other form in the combination may depend on the tone colour and on the pitch. On this basis it is evident that *vibrato* should be incorporated in the generator system wherever possible.

### Synthetic Reverberation

Since the ear has come to appreciate the beauty of musical tones when the instruments have been played in large halls with reflecting surfaces, some degree of reverberation is almost essential to any musical performance. Orchestras, organs, pianos and other instruments of the *conservatoire* seem to lack body when played in the open air. Exceptions to this generalisation are military bands and bagpipes, which are usually heard only in the open air, where the reverberation factor is zero.

When musical tones are generated electrically and produced by a loudspeaker, the reverberation of which the listener is aware is only that arising from the reflecting surfaces in the room which contains the loudspeaker. Sometimes this may be sufficient, but in other cases additional reverberation may be highly desirable. Various devices have been suggested for adding reverberation electrically to sound-amplifying circuits. Some of them are in regular use in broadcast technique to replace the echo studio and to modify the acoustic properties of concert halls. Synthetic or artificial reverberation may be used to great advantage in electronic musical instruments as a means of varying the expression in a way which is both striking and novel. Reverberation is defined as the time required for the intensity of the sound to decay to one millionth of the original value—a reduction of 60 db.

A method developed by the Columbia Broadcasting System uses the decay of fluorescence to simulate the decay of sound level in a reverberant room.[59] The fluorescent material, which must have a suitable afterglow characteristic, is applied as a coating on the rim of a disc rotating at 400 revolutions per minute. The diameter of the disc is 20 inches, giving a peripheral speed of more than 30 feet per second. Ultra-violet light from a special quartz mercury-vapour lamp is focused through a quartz lens on to the fluorescent coating, and by modulating the light intensity with the sound voltage, a corresponding variation in the intensity of fluorescence is produced. This intensity diminishes fairly rapidly, but persists long enough to produce a succession of pulses in a series of photocells placed at selected positions around the edge of the disc. The outputs from these photocells are fed into a common amplifier at suitably graded amplitudes, and combine to produce an acoustic effect resembling the multiple repeated reflection from the various surfaces of a room. According to the designers, it is not necessary to stabilise the speed of the disc to a very high degree, since both the recording and the pick-up occur on the same disc and any variations in speed are automatically neutralised.

Another system, originated by A. N. Goldsmith,[60] uses an endless steel tape running continuously over a pair of pulleys. The elements of the arrangement are shown in Fig. 51, from which it will be recognised as a magnetic recorder system. Sound voltages from the main amplifier M are supplied to the recording head A and are also passed through to the output terminals of the unit. The moving tape with the induced variations in magnetic intensity passes

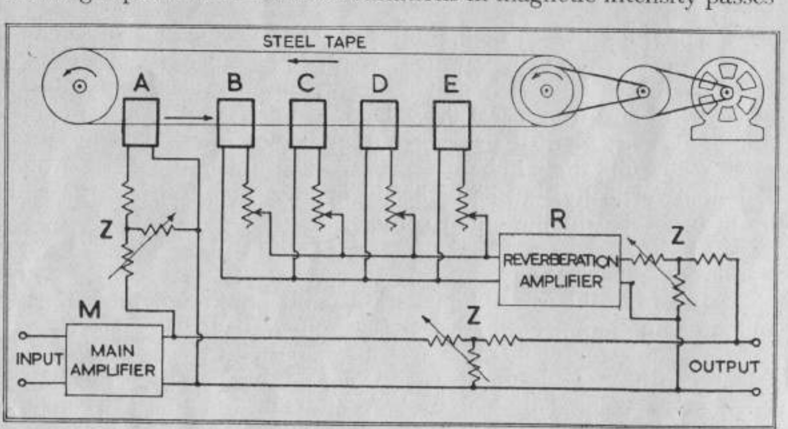


Fig. 51. An arrangement for producing synthetic reverberation. The recording head A induces a magnetic pattern in the moving steel tape and the reproducers B, C, D, E, respond after progressive time intervals. The head A also contains an erasing device.

in succession through the pick-ups B, C. D., etc., the outputs from which are adjusted to the desired amplitude and are then fed into the reverberation amplifier R. The output from this is added to the output from the main amplifier M. By choosing a suitable speed for the tape and suitable spacings for the pick-ups, the reverberation characteristics may be varied over a wide range. A delay of as much as 3 seconds for the final pick-up is easily obtainable, if required, without making the loop of tape inconveniently long. An obliterating magnet is included in the recording head to remove the induced magnetism before the tape re-enters the field of the recording magnet.

The degree of reverberation varies with the pitch in most concert halls, and to simulate this condition the outputs from the succession of pick-ups B, C, D, etc., are passed through frequency filters in the reverberation amplifier so that the delayed voltages added to the output by the pick-ups are graded according to their frequencies.

A reverberation unit relying on pure vibrational reflection effects has been designed by L. Hammond expressly for use in electronic organs.[61] As in the steel tape unit just described, part of the output from the tone generators goes direct to the main sound amplifier and from there to the loudspeaker, and another part is fed into the reverberation unit. Here the tone voltages actuate a moving-coil driving unit to which are coupled five long coiled springs. The vibrations imparted to the springs travel along to the remote ends which are attached to a corresponding set of Rochelle-salt piezoelectric elements. The voltages developed by these pick-ups are fed into an auxiliary amplifier connected to the loudspeaker. On account of the relatively low velocity of sound in the springs—between 40 and 50 feet per second—an appreciable delay occurs, so that each piezoelectric element contributes an echo of the original tone.

To produce the effect of multiple echoes, which together constitute reverberation, the springs are made of different lengths and their mountings are such that some of the energy of vibration is reflected to and fro several times before it dies away to a negligible amplitude. Some of the springs are immersed in oil-filled tubes to modify the vibrational characteristics. The unit must therefore be mounted vertically, but as its height is only three feet it can easily be incorporated in the organ console.

**Background Suppression**

Apart from the microphonic effects which are sometimes present in high-gain amplifiers, there are other sources of unwanted electrical noise in some tone generator systems, especially electronic organs, which can become very obtrusive when the playing ceases in those momentary silences that occur here and there in musical compositions. These noises may originate in unintentional polarising voltages due to contact potential-difference in the electrostatic generators, in stray magnetic fields in electromagnetic generators, in imperfect optical shielding in photoelectric generators, and so on. If the effect exists at all, it generally appears as a confused noise or muffled roaring sound. This is the composite output of all the individual frequency generators acting continuously even when all the playing keys or other controls are idle.

One of the simplest cures for background noise in a keyboard electronic instrument is the provision of a further pair of contacts on each playing key which can be connected in a muting circuit so that the amplifier gain is diminished when all the keys are idle. In order to avoid unpleasant transients, it is important to ensure that the starting and stopping of the notes are effected only by the playing keys and not by the muting arrangements: The muting must come into action only after all the notes have ceased, and must be removed before the next note is played.

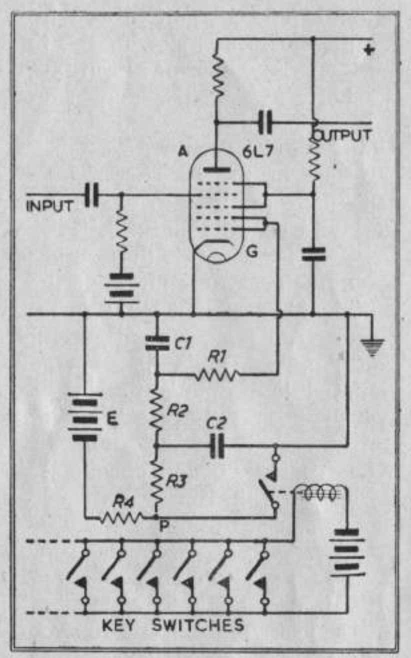


Fig. 52. A circuit arrangement for eliminating background noise. When no playing keys are actuated, the gain of the amplier is greatly reduced. It rises to normal when any key is depressed. Delay circuits are included to avoid switching transients.

An improvement on the simple method of direct switching uses a bias-controlling circuit in one of the amplifier stages.[62] The elements of the circuit are shown in Fig. 52. The amplifier tube A is a heptode in which the first two grids G are connected together and used for controlling the gain between the input and output terminals by means of its variable bias. Normally the bias E is sufficient to reduce the gain to zero. When any key is depressed the relay R is energised and the closing of its contacts causes the potential of the point P to fall instantly to cathode potential. The change of bias on G, however, is delayed by the time-constants of the network $R_1R_2R_3C_1C_2$. The capacitor $C_1$ discharges through the resistors $R_2$ and $R_3$, while $C_2$ discharges through $R_3$. The resistors have relatively low values so that the bias falls reasonably quickly and the note begins to sound almost as soon as the key is depressed. When all the keys have been allowed to rise, the relay contacts open and the bias, which is the voltage across $C_1$, rises slowly, due to the relatively high resistance of $R_4$ in series with $R_2$ and $R_3$, and to the time taken to charge $C_2$ through $R_3$ and $R_4$. The gain of the amplifier therefore falls slowly, the time-constants being chosen so that the last note which has been played decays naturally without being cut short.

### Auditorium Acoustics

Much of the success of an electronic musical instrument will depend on the way in which it is presented to its critical listeners. It should sound "natural." That is to say, the intensity and the direction from which the sound is received by the audience should not differ greatly from what the audience would expect of a conventional instrument having similar tonal quality. For instance, if the electronic instrument resembles a violin or guitar in tone, it would be a mistake to propagate the sound from a loudspeaker mounted high above the heads of the audience. Again, if the instrument is of the solo "melodic" type, the listener will be puzzled and unreceptive if the sound arrives in several different directions from a battery of loudspeakers.

The ear, having grown accustomed to pipe organs of large dimensions, will immediately detect an unnatural quality if the sound of even a perfect electronic equivalent of a pipe organ comes from a small and compact source. A loudspeaker which is provided with an inadequate baffle area will produce what has been described as "acoustic glare," and to avoid this effect the loudspeaker system of an electronic organ should be sufficiently extensive to simulate the dispersed radiation inevitably associated with hundreds of pipes.

It is preferable to use a baffle type of loudspeaker, but for instruments which are intended to simulate the smaller acoustic instruments such as the violin, a large baffle is superfluous, and for such purposes a small cabinet type of speaker may be more satisfactory.

The sound propagation from an orthodox grand piano is generally considered more pleasing (apart from the differences in the mechanical action) than that from an upright piano. This is a consequence of the fact that its soundboard is horizontal. In the case of an electronic piano, the loudspeaker baffle might well be mounted horizontally so as to obtain a similar propagation characteristic.

Most cone-type loudspeakers exhibit a marked focusing of the higher frequencies, the sound intensity being appreciably greater near the axis of the cone. When the listener moves to a different position the quality of the sound appears to change. If the quality is satisfactory away from the region of the axis, it is almost certain to be too harsh or strident when the listener is in the axial zone. In at least one electronic instrument, the loudspeakers are directed at a slanting angle towards the floor, so that only the diffused reflected radiation of the higher frequencies can reach the audience.

# LITERATURE

## REFERENCES

[1] "Synthetic Sound," H. Rosen, *Wireless World*, 3rd February, 1933, p. 101.

[2] "Design Considerations for a simple and versatile Electronic Musical Instrument," B. F. Miessner. *J. Acous. Soc. Am.*, January, 1935, p. 181.

[3] "The Future of Electronic Music," S. K. Lewer. *Electronic Engineering*, June 1944, p. 32. See also Discussion, August, 1944, p. 124.

[4] "Orchestral Pitch," B. van der Pol and C. C. J. Addink. *Wireless World*, 11th May, 1939, p. 441.

[5] "The Principles underlying the Tuning of Keyboard Instruments to Equal Temperament," G. F. Herrenden Harker. *J. Acous. Soc. Am.*, April, 1937, p. 243.

[6] "Absolute Measurements and Spectra of Certain Musical Instruments and Orchestras," L. J. Sivian, H. K. Dunn and S. D. White. *J. Acous. Soc. Am.*, January, 1931, p. 330.

[7] F. Trautwein. British Patents 380470, 403365.

[8] "Der induktive Glimmentladungsoszillator und seine Anwendungsmöglichkeiten," W. E. Kock. *Zeitschrift für Technische Physik*, No. 15, 1934, p. 377.

[9] L. Theremin. British Patent 244133, U.S. Patent 1661058.

[10] "Pitch Control for an Electronic Musical Instrument," T. R. Bunting. *Electronics*, September, 1932, p. 287.

[11] "The Electronde." *Electrician*, 5th January, 1934, p.18.

[12] "The Martenot Instrument," R. Raven-Hart. *Wireless World*, 16th July, 1930, p. 58.

[13] P. Lertes and B. Helberger. British Patents 347082, 369837, U.S. Patent 1847119.

[14] "Audio Frequency Generator," S. K. Lewer. *Wireless World*, January, 1944, p. 2.

[15] E. E. Coupleux and J. A. Givelet. British Patent 359967.

[16] "Le Matériel Téléphonique, S.A." British Patent 455324.

[17] "Magnetostriction Oscillators," G. W. Pierce. *Proc. Acad. Arts and Science*, April, 1928.

[18] "The Novachord," F. D. Merrill. *Electronics*, November, 1939, p. 16.

[19] L. Hammond. U.S. Patent 2126682.

[20] "The Electrostatic Transmitter," E. C. Wente. *Physical Review*, 10, 1917, p. 41.

[21] B. Davis. British Patent 501685.

[22] "Practical Design for an Electronic Piano," F. D. Merrill. *Electronics*, May, 1939, p. 30.

[23] O. Vierling. British Patent 405278.

[24] "The Electone—an Electronic Piano," G. S. Taylor. *Electronics*, January, 1939, p. 26.

[25] O. Vierling. British Patent 414352.

[26] A. H. Midgley. British Patent 434421.

[27] F. A. Hoschke. British Patent 451798, U.S. Patent 2015014.

[28] "Problems in Electronic Organ Design," S. K. Lewer. *Electronic Engineering*, September, 1944, p. 149.

[29] S. K. Lewer. British Patent 442379.

[30] "Electronic Musical Instruments and the Development of the Pipeless Organ," G. T. Winch and A. M. Midgley. *J.I.E.E.*, June, 1940, p. 517.

[31] L. E. A. Bourn. British Patent 403444.

[32] A. H. and A. M. Midgley. British Patent 454720.

[33] L. E. A. Bourn. British Patent 446352.

[34] A. H. and A. M. Midgley. British Patent 499771.

[35] See [28].

[36] E. Scott. British Patent 495271.

[37] T. Cahill. U.S. Patents 580035, 1107261, 1213803, 1213804, 1295691.

[38] "The Förster Electrachord," O. Vierling. *Zeitschr. d. Verein. deutsches Ingen.*, No. 35, 1936, p. 1069.

[39] "Electronic Music," N. I. Daniel. *Communications*. July, 1940, p. 26.

[40] "Electronic Music from Vibrating Reeds," R. G. Silbar. *Electronics*, July, 1934, p. 226.

[41] L. E. A. Bourn. British Patent 388036.

[42] A. H. Midgley. British Patent 380781.

[43] F. M. Robb. British Patent 409751.

[44] R. H. Ranger. British Patent 370475.

[45] L. Hammond. British Patent 454502, U.S. Patent 1956350.

[46] J. Halmágyi and N. Langer. British Patent 403204.

[47] E. Spielman. British Patent 315286.

[48] "Le piano photoélectrique Spielman," E. Weiss. *La Nature*, 1st July, 1930.

[49] C. R. and A. MacCullum. British Patent 381210.

[50] "WCAU's Photocell Organ." *Electronics*, May, 1934, p. 157.

[51] S. Prisner. British Patent 388733.

[52] A. H. Brackensey. British Patent 286768.

[53] G. T. Winch. British Patent 387376.

[54] P. T. Hobson. British Patent 421662.

[55] H. G. Matthews. British Patent 254437.

[56] P. T. Hobson. British Patent 432960.

[57] R. W. Bumstead. U.S. Patent 2241027.

[58] "A Contactless Volume Control," H. S. Polk. *Electronics*, September, 1939, p. 40.

[59] "Synthetic Reverberation," P. C. Goldmark and P. S. Hendrick. *Proc. I.R.E.*, December, 1939, p. 747.

[60] "Artificially Controlled Reverberation," S. K. Wolf. *J. Soc. Motion Picture Engrs.*, April, 1930, p. 390.

[61] "Artificial Reverberation for Electronic Organ Music," *Electronics*, March, 1940, p. 42.

[62] J. I. Taylor. British Patent 505763.

## ADDITIONAL BIBLIOGRAPHY

### General Instruments

"Electronic Musical Instruments and the Progress of the Pipeless Organ," L. Vellard. *Rev. Gén. de l'Elec.*, April, 1941, p. 214.

"Types and Characteristics of Electronic Musical Instruments," J. H. Jupe. *Electronics, Television and S.W. World*, January, 1941, p. 7.

"Electronic Music," L. E. C. Hughes. *Nature*, 3rd February, 1940, p. 170.

"A New Electrical Musical Instrument—the Storytone." *Scientific American*, November, 1939.

"The Electrical Production of Musical Tones," S. T. Fisher. *J. Soc. Motion Picture Engs.*, March, 1939, p. 289.

"Electrical Music," Sir James Jeans. *Electrician*, 3rd March, 1939, p. 283.

"New Paths in Electrical Music." *Funktechnische Monatshefte*, December, 1937, p. 372.

"Electro-acoustic Musical Instruments," W. Aschoff. *Naturwissenschaften*, 10th September, 1937, p. 598.

"Electronic Music and Instruments—a Survey," B. F. Miessner. *Proc. I.R.E.*, November, 1936, p. 1427.

"The Polytone," F. M. Sammis. *Radio-Craft*, May, 1934.

"Electrical Musical Instruments," R. W. P. Leonhardt. *Electrical Review*, 9th March, 1934, p. 339.

"Electricity and Music." *World Radio*, 9th February, 1934, p. 195.

"Application of Electronics to the Piano," B. F. Miessner. *Proc. Radio Club of America*, January, 1934.

"Elektrische Musik Instrumente, ihre Wirkungsweise und Aufgaben," W. Janovsky. *E.T.Z.*, 13th July, 1933, p. 675, and 27th July, 1933.

"Electronic Musical Instruments of Europe and U.S." *Electronics*, March, 1933, p. 65.

"Electrical Musical Instruments at the Berlin Radio Exhibition." *Radio Ber. für Alle*, September, 1932, p. 387.

"Elektrische Musik," O. Vierling. *E.T.Z.*, 18th February, 1932.

"Recent European Developments in Electrical Musical Instruments," R. Raven-Hart. *Electronics*, July, 1931, p. 18.

"The Electrical Future of Music," E. E. Free. *Radio News*, July, 1931.

"The Music of the Electron," Dr. A. N. Goldsmith. *Electronics*, September, 1930, p. 270.

"Un Appareil de Musique Radioéléctrique," E. Weiss. *La Nature*, 15th July, 1930.

"Nouveaux Instruments de Musique Radioéléctrique," E. Weiss. *La Nature*, 15th September, 1930.

"Electrical Music," Schultze. *Funk*, 27th June, 1930.

"Radio-electric Musical Instruments," J. Reyval. *Rev. Gen. de l'Elec.*, 14th June, 1930, p. 945.

"Electro-musical Instruments," F. Trautwein. *Funk*, 13th June, 1930.

"Les Instruments Musiquaux Electriques," C. T. Hourst. *L'Ingénieur Constructeur*, September and October, 1929.

"Radio-clavier," Th. V. Müller. *Radio Welt*, 10th May, 1929.

"Les Instruments de Musique à Oscillations Electriques," A. Givelet. *Le Génie Civil*, 22nd September, 1928.

"Building the Tromborad," G. B. Ashton. *Radio News*, April, 1927.

"The Piano-Rad," C. J. Fitch. *Radio News*, November, 1926.

### Electric Circuit Generators

"A Novel Solo Auxiliary—the Hammond Solovox." *The Ideal Kinema*, 5th December, 1946, p. x.

"The Solovox," L. Hammond. *Science*, 4th October, 1940, suppl. p. 12.

"The Novachord," L. Hammond. *Science*, 10th February, 1939, suppl. p. 6.

"Generating Sine Waves with a Gas-discharge Tube," W. E. Kock. *Electronics*, March, 1935, p. 92.

"The Electronic Organ at 'Poste Parisien'," R. Raven-Hart. *Wireless World*, 22nd December, 1933, p. 475.

"The Trautonium," *Telefunken Zeitung*. August, 1933, p. 46.

"Das Hellertion, eines neues elektrisches Musikinstrument." *Funkblaster*, 3rd July, 1931.

"Neon Musical Oscillator," R. Raven-Hart. *Wireless World*, 10th December, 1930, p. 648.

"A New Electronic Instrument," W. Saraga. *Funktechnische Monatshefte*, October, 1930.

### Electrostatic Tone Generators

"Design for an Electronic Reed Organ," F. D. Merrill. *Electronics*, April, 1940, p. 42.

"A New Electronic Musical Instrument," E. E. Kent. *J. Acous. Soc. Am.*, January, 1940, p. 352.

"An Experimental Electronic Violin," L. H. Stauffer. *J. Applied Physics*, February, 1939, p. 96.

"An Electrostatic Audio Generator," E. B. Kurtz and M. J. Larsen. *Electrical Engineering*, September, 1935, p. 950.

"The Orgatron." *Music Trades Review*, August, 1935.

"Electrical Organ Tones." *Wireless World*, 24th May, 1935, p. 514.

### Electromagnetic Tone Generators

"A Hundred-Element Tone Synthesiser," E. C. Wente, C. A. Lovell and J. F. Muller. *J. Acous. Soc. Am.*, July, 1946, p. 253.

"The Hammond Organ." *Nature*, 1937, p. 1043.

"Keyboard and Loud-Speaker," R. Raven-Hart. *Wireless World*, 27th January, 1933, p. 67.

"The Cahill Telharmonium." *Electrical World*, 1906.

### Photoelectric Tone Generators

"Photoelectric Tone Generator," L. E. Greenlee. *Electronics*, September, 1946, p. 93.

"Photoelectric Organ," R. E. Campbell and L. E. Greenlee. *Radio News*, June, 1946, p. 25, and July, 1946, p. 36.

"WCAU's Photona Organ." *Electronics*, 1935, p. 123.

### Theory of Music

"Argument for Electronic Music," S. T. Fisher. *Electronics* May, 1944, p. 214.

"A Design for a Keyboard Instrument in Just Intonation," C. Williamson. *J. Acous. Soc. Am.*, October, 1939, p. 216.

"Approximate Calculations of Tempered Scales—and their Application to Rotating-Generator Electric Organs," F. Trautwein. *Akustische Zeitschr.*, July, 1939, p. 261.

"The Frequency Ratios of the Tempered Scale," C. Williamson. *J. Acous. Soc. Am.*, October, 1938, p. 135.

### Miscellaneous

"What is Synthetic Sound ?" *Wireless World*, March, 1944, p. 91.

"Synthetic Reverberation," D. W. Aldous. *Electronic Engineering*, August, 1943, p. 117.

"Known and Novel Sounds from Electrical Musical Instruments," H. Bode. *Bull. Assoc. Suisse des Elect.*, 26th August, 1942, p. 479.

"Electronic Vibrato Control for Amplifiers," B. Ephraim. *Electronics*, Feb., 1941, p. 52.

"Electronic Church Chimes," F. Dostal. *Electronics*, August, 1939, p. 18.

"Analysis of Musical Sounds," A. Dammann. *Comptes Rendus*, 24th April, 1939, p. 1283.

"Synthetic Reverberation," S. Begun and S. K. Wolf. *Communications*, August, 1938, p. 8.

"Acoustic Spectra of Organ Pipes," C. P. Boner. *J. Acous. Soc. Am.*, July, 1938, p. 33.

"Synthetic Reverberation," J. K. Hilliard. *Communications*, August, 1934, p. 62.

## BRITISH PATENTS

### Electric Circuit Generators

| | |
|---|---|
| 244133 | Theremin |
| 342952 | Coupleux and Givelet |
| 347082 | Lertes and Helberger |
| 353918 | Langer and Halmágyi |
| 359967 | Coupleux and Givelet |
| 365309 | Hitchcock |
| 365883 | Coupleux and Givelet |
| 369837 | Lertes and Helberger |
| 369838 | Lertes and Helberger |
| 371641 | Carlson |
| 371642 | Young |
| 378068 | Coupleux and Givelet |
| 378069 | Coupleux and Givelet |
| 378070 | Coupleux and Givelet |
| 380470 | Trautwein |
| 390678 | Halmágyi and Langer |
| 391029 | Coupleux and Givelet |
| 393821 | Coupleux and Givelet |
| 393822 | Coupleux and Givelet |
| 403204 | Halmágyi and Langer |
| 403365 | Trautwein |
| 404524 | Leithäuser *et al* |
| 408645 | A.E.G. |
| 409647 | *Puget |
| 410238 | Coupleux |
| 410451 | Coupleux |
| 410910 | A.E.G. |
| 430874 | Coupleux and Givelet |
| 432960 | Hobson |
| 449302 | Hobson |
| 455324 | L.M.T. |
| 474838 | Potencier |
| 477653 | Kock |

### Electrostatic Tone Generators

| | |
|---|---|
| 401537 | Palmgren |
| 403444 | Bourn |
| 405278 | Vierling |
| 408998 | Vierling |
| 409684 | Vierling |
| 412279 | Vierling |
| 414352 | Vierling |
| 418898 | Jacobs |
| 433050 | Bourn |
| 433380 | Bourn |
| 434421 | Bourn |
| 442379 | Lewer |
| 446352 | Bourn |
| 447627 | Bourn |
| 448193 | Bourn |
| 451798 | Hoschke |
| 453846 | Bourn |
| 454720 | Midgley |
| 454783 | Midgley |
| 459439 | Bourn |
| 464863 | Midgley |
| 482284 | Midgley |
| 487220 | Midgley |
| 489695 | Midgley |
| 491267 | Midgley |
| 493320 | Midgley |
| 494758 | Bourn |
| 494759 | Bourn |
| 498128 | Midgley |
| 498130 | Midgley |
| 499330 | Midgley |
| 499771 | Midgley |
| 501339 | Bourn |
| 501397 | Bourn |
| 501520 | Midgley |
| 501685 | Davis |
| 501733 | Bourn |
| 520137 | Midgley |

### Electromagnetic Tone Generators

| | |
|---|---|
| 379151 | Rouzet |
| 380781 | Midgley |
| 388036 | Bourn |
| 405278 | Vierling |
| 409684 | Vierling |
| 409751 | Robb |
| 414352 | Vierling |
| 418898 | Jacobs |
| 422735 | Nernst |
| 454502 | Hammond |
| 507478 | Frohman and Taylor |

### Photoelectric Tone Generators

| | |
|---|---|
| 254437 | Matthews |
| 286768 | Brackensey |
| 315286 | Spielman |
| 359125 | Matthews |
| 374013 | Driescher |
| 381210 | MacCullum |
| 387376 | Winch |
| 388733 | Prisner |
| 390623 | Hardy |
| 403204 | Halmágyi and Langer |
| 421662 | Hobson |
| 432960 | Hobson |
| 435529 | Bechstein |
| 438681 | Winch |
| 503598 | Ropohl |

### Electric Pianos

364415 Driescher
401537 Palmgren
422735 Nernst
436207 Hourst
501685 Davis

### Modulated Current Systems

495271 Scott
512943 Biggs

### Miscellaneous

370475 Ranger
381676 Könemann
390574 Luedtke
401241 Compton
440199 Macfadyen
478142 Werndl
489179 Macfadyen
494165 Hammond
499370 Hammond
505763 Taylor

## UNITED STATES PATENTS

### Electric Circuit Generators

1661058 Theremin
1832402 Langer
1847119 Lertes and Helberger
1911309 Coupleux and Givelet
1933299 Vierling
1937389 Langer
1980911 Coupleux and Givelet
1980912 Coupleux and Givelet
1993890 Langer
2017542 Langer
2035238 Langer
2126464 Hammond
2126682 Hammond
2203432 George
2233948 Kock
2266030 Hammond
2292757 Hathaway
2293499 Fisher
2301869 Hammond
2301871 Hanert
2323231 Merrill
2323282 Kock
2340001 McKellip
2340002 McKellip and Ford
2342338 Hanert
2357191 Hanert
2365566 Langer
2365567 Langer
Re 20831 Smiley

### Electrostatic Tone Generators

1912293 Miessner
1929029 Miessner
1933294 Jacobs
1933295 Miessner
1933296 Jacobs
1933297 Miessner
1933298 Miessner
1953753 Firestone
2001708 Curtis
2015014 Hoschke
2018924 Ranger
2027074 Miessner
2219539 Riechers
2243728 Zuck
2250258 Firestone
2300609 Zuck
2302457 Midgley
2318935 Fisher
2318936 Fisher
Re 20416 Culver
Re 21137 Firestone
Re 22321 Fisher

### Electromagnetic Tone Generators

580035 Cahill
1107261 Cahill
1213803 Cahill
1213804 Cahill
1295691 Cahill
1893250 Severy
1899884 Severy
1914173 Severy
1933295 Miessner
1935215 Severy
1941870 Severy
1956350 Hammond
1992316 Loar
1995317 Loar
2020557 Loar
2159505 Hammond
2216513 Firestone
2224729 Hammond
2225299 Demuth
2234490 Gilbert
2258241 Demuth
2258990 Lundie
2262179 Hammond
2262494 Hammond
2285132 Weathers *et al*
2294861 Fuller
2301870 Hancock
2318936 Fisher
2319087 Rienstra
2323232 Miessner
2383553 Johnston

### Photoelectric Tone Generators

1991522 Ranger
2039659 Ranger
2221097 Koehl
2318144 Darke
2376493 Land and Graban

### Electric Pianos

1933295 Miessner
2250065 Koehl
2252708 Douden
2305575 Koehl

### Modulated Current Systems

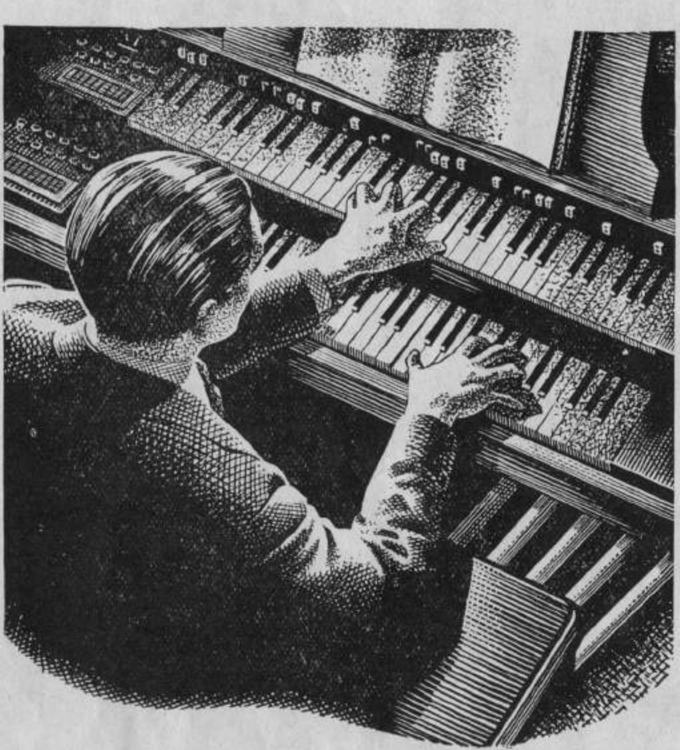
2001708 Curtis
2241027 Bumstead
2314496 Hammond

### Miscellaneous

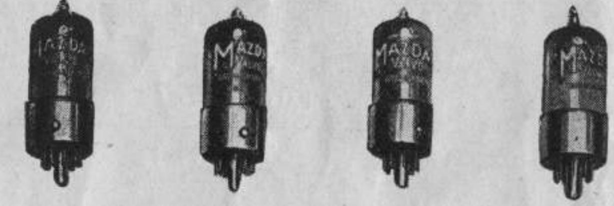
1901895 Ranger
1901896 Ranger
1905996 Coupleux and Givelet
1929027 Miessner
1929028 Miessner
1947020 Ranger
1957392 Coupleux and Givelet
1958866 Severy
2035836 Ranger
2105318 Goldsmith
2142580 Williams
2173888 Smiley
2203569 George
2221188 Hammond and Meinema
2221814 Reid
2227068 Curtis
2229755 Manatt
2233258 Hammond
2241027 Bumstead
2241363 Hammond
2245337 Hammond
2245338 Hammond
2245354 Mroz
2251051 Hammond
2251052 Hammond
2253782 Hammond and Stevens
2254284 Hanert
2287105 Kannenberg
2294178 Hanert
2295524 Hanert
2296125 Traub
2297829 Hammond
2301870 Hancock
2310429 Hanert
2323242 Rienstra
2323392 Hammond and George
2327720 Koehl
2332076 Hammond and Hanert
2382413 Hanert
2392184 Phillips
Re 20825 Smiley

# INDEX

*Names of persons are shown in italics.*



---

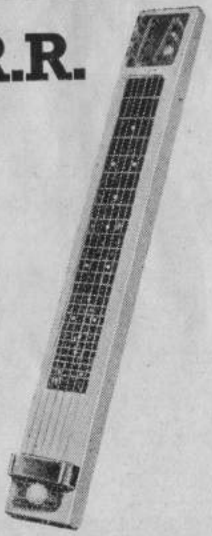


**ENGLISH & AMERICAN TECHNICAL BOOK SPECIALISTS**

We have the Finest Stock of Radio and Electronic Engineering Books in the Country

*WRITE OR CALL FOR COMPLETE LIST*

**THE MODERN BOOK CO.**
**19-23 PRAED STREET**
**LONDON, W.2.**
Telephone : PAD 4185



**R.R.** "*Falcon*"

**ELECTRIC HAWAIIAN GUITAR**

● The R.R. "Falcon" Electric Hawaiian Guitar has been scientifically designed by a team of expert electrical and mechanical engineers working in close collaboration with a group of noted musicians, in order to produce an instrument of the finest possible performance.

The body, strings, magnet and coil assembly together form the most sensitive, efficient and distortionless unit which has yet been produced, and when used in conjunction with a good quality amplifier this instrument will give the finest possible results.

A specially designed 10 watt AC/DC amplifier is available for use with the "Falcon" Electric Hawaiian Guitar.

EVERY R.R. "FALCON" ELECTRIC HAWAIIAN GUITAR IS GUARANTEED AGAINST FAULTY MATERIALS AND WORKMANSHIP INDEFINITELY.

Price **£27 12s. 9d.** Plus Purchase Tax **£12 5s. 8d.**

*PLEASE SEND FOR LEAFLET No. 103*

**R.R. DEVELOPMENT LABORATORIES LTD.**
**BARNARD ROAD · BRADFORD · YORKS.**

---

B T-H

**VALVES FOR RESEARCH**
**AND**
**ELECTRONIC CONTROL**

Photo-cells, Ignitrons, Thyratrons, Rectifiers, Safety Gaps.

• •

**VALVES FOR THE CENTIMETRE WAVE BAND**

Magnetrons, Klystrons, Crystal Rectifiers.

• •

**ELECTRONIC EQUIPMENT**
**for all Industrial purposes**

**BTH RUGBY**
THE BRITISH THOMSON-HOUSTON COMPANY LIMITED, RUGBY, ENGLAND.

A3637N

---


Remember the ROLA G.12?
now
it's back - the
G12 plus

Electronic Engineering Electronic Engineering Electronic Engineering Electronic Engineering

# Electronic Engineering

## THE MODERN BRITISH JOURNAL
## for
## INDUSTRY AND RESEARCH

Original articles appear regularly from leading authorities on the theory and application of electronic science.

**PRICE 2/- MONTHLY**
Annual Subscription 26/- post free

A series of technical monographs on specially interesting electronic subjects is issued at intervals.

Published by
**MORGAN BROTHERS (PUBLISHERS) LTD.,**
**28, Essex Street, Strand, London, W.C.2.**
(Proprietors of THE ENGINEER)

Electronic Engineering Electronic Engineering Electronic Engineering Electronic Engineering

---

# *Important Books*

## Electronics - To-day and To-morrow
By JOHN MILLS
(Sometime Member Technical Staff, Bell Telephone Laboratories)
Lg. Post 8vo 178 pages 12s. net

## Television Simply Explained
By R. W. HALLOWS, T.D., M.A. (Cantab.), A.M.I.E.E.
Crown 8vo 200 pages Illustrated 9s. 6d. net

## The Path of Science
By C. E. K. MEES, D.Sc., F.R.S.
with the co-operation of
J. R. BAKER, M.A., D.Phil., D.Sc.
Demy 8vo 250 pages 6 figures 18s. net

## Horology
THE SCIENCE OF TIME, MEASUREMENT AND THE CONSTRUCTION OF CLOCKS, WATCHES AND CHRONOMETERS
By J. ERIC HASWELL, F.B.H.I.
Demy 8vo 288 pages 111 figures 19 plates 16s. net

## Radio's Conquest of Space
THE EXPERIMENTAL RISE IN RADIO COMMUNICATION
By D. McNICOL
(Past President of the Institute of Radio Engineers, U.S.A.)
Demy 8vo 384 pages 53 figures 18s. net

**CHAPMAN & HALL, LTD.**
**37-39 ESSEX STREET, LONDON, W.C.2**