PROBLEMS CONCERNING THE DESIGN OF AN ELECTRONIC INSTRUMENT EQUIVALENT TO A PIPE ORGAN

by

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INTRODUCTION

In ancient times the Greek musical theorists applied the word "organic", as a general term, to instrumental music. Today the word "organ" is common to the language of most people comprising the western hemisphere group. For several centuries the term has been applied to musical instruments wherein the tones are generated by pipes blown by suitable means with air under pressure. The principle involved in obtaining sound from a pipe with wind pressure dates back to about 284 to 246 B.C. By 100 A.D. the organ embraced about three octaves and water was used to obtain a steady wind pressure. During this long period the organ was gradually improved and through constant experimentation the modern organ has evolved.

The modern organ is the grandest and the most magnificent of all instruments invented by human genius. It is an orchestra in itself and can express anything in response to a skilled touch.

There have been many attempts, especially in recent years, to devise an instrument which would obtain the effects secured by an organ and yet eliminate many of its undesirable features. The American Guild of Organists[1] published the statement, June, 1936, that the tone of the organ has never yet been successfully imitated by any other method of tone production. It is the purpose of this paper to take up the problems met in the design of an electronic instrument which is equivalent to the organ. Problems of this nature involve a survey of the standards acceptable to the American Guild of Organists and an understanding of the theory and operation of the organ.

PRINCIPAL FEATURES OF PIPE ORGANS

Tonal Properties

The beauty of organ tone arises from the combination at will of many ranks of pipes, each possessed of a large and varied number of harmonics. The harmonic content of the tone determines its character and is dependent upon the shape of the pipe and the air pressure. In some tones the third harmonic may have an amplitude five times the amplitude of the fundamental while another pipe, such as a Bourdon, shows that the amplitudes of the harmonic frequencies are quite small as compared to the fundamental.

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1. The American Guild of Organists is the accepted authority in the organ industry. RKO Building, New York, N. Y. This statement was mailed to members of the American Guild of Organists.

Figure 1 shows the wave form of a Flute D' Amour tone which is a small scale flute of the organ producing a tone of exceedingly lovely and fascinating quality. Figure 2 is a Viole D' Orchestra tone which is produced by open metal pipes of slender scale. It has a delicate orchestral string-tone quality and a 'cello effect in the bass. These figures are reproductions from cathode ray oscillograms made from actual organ tones[2]. The first has a low harmonic content, while the second has a relatively high content. Figure 3 represents the tone of a clarinet (C_3) and Figure 4 shows the harmonic content of the tone in Figure 3. It will be noticed that the amplitude of the tenth harmonic is 50 per cent that of the fundamental.

When two or more ranks of pipes are played at the same time the complex tones produced by one rank add to the others, forming a combination having a still different character. Thus, the characteristic tone colors of the organ are produced by ranks of pipes variously voiced and of different pitch, brought together to form an ensemble in which all of the parts perform a distinct auditory function. An organ to be complete must have several ranks of the same character but at a different pitch. For example, the organ may have a Diapason 16', Diapason 8', Diapason 4', and a

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2. The organ used was an Austin in the Kansas State College Auditorium.

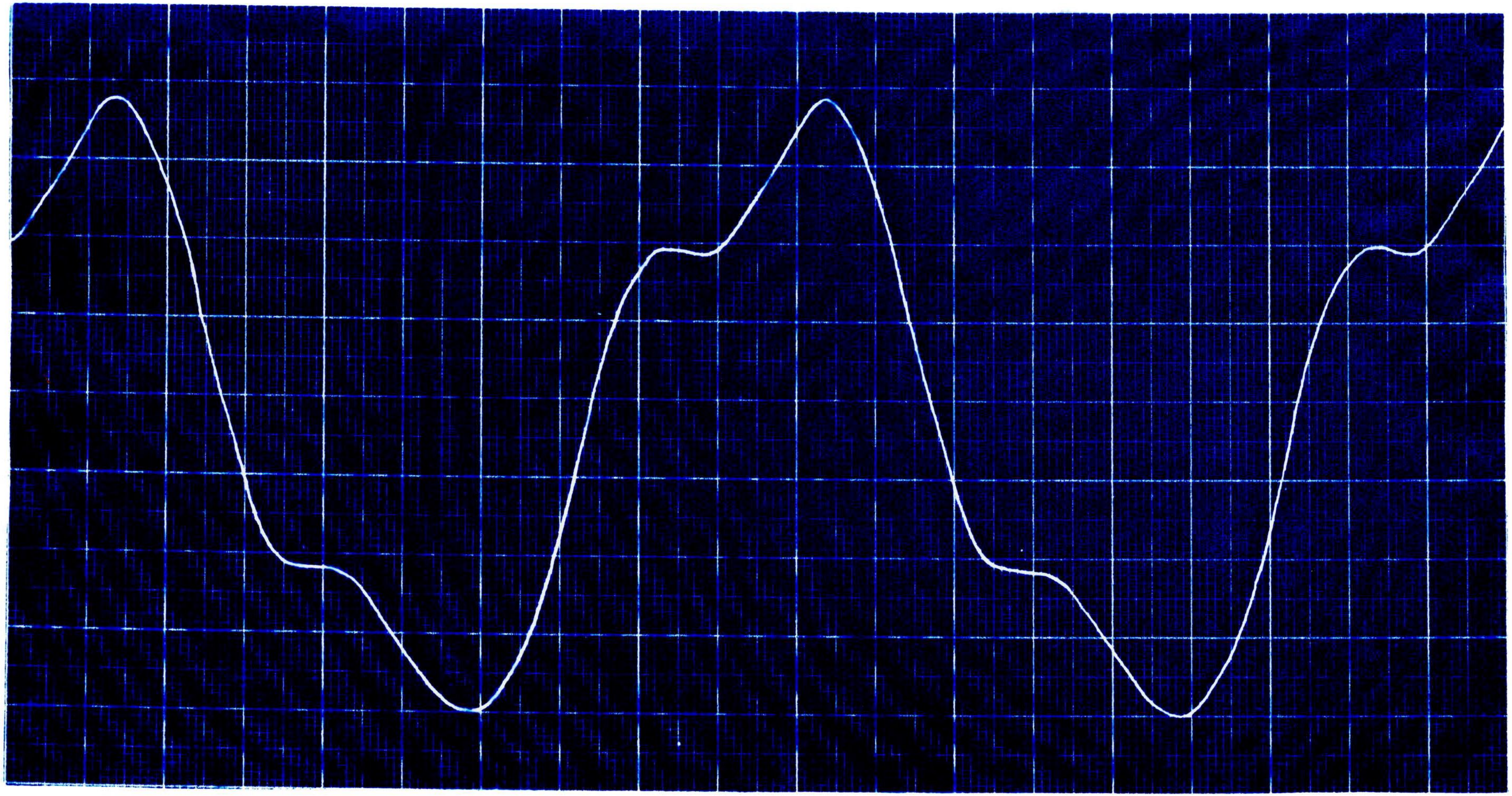

Figure 1. Flute D'Amour.

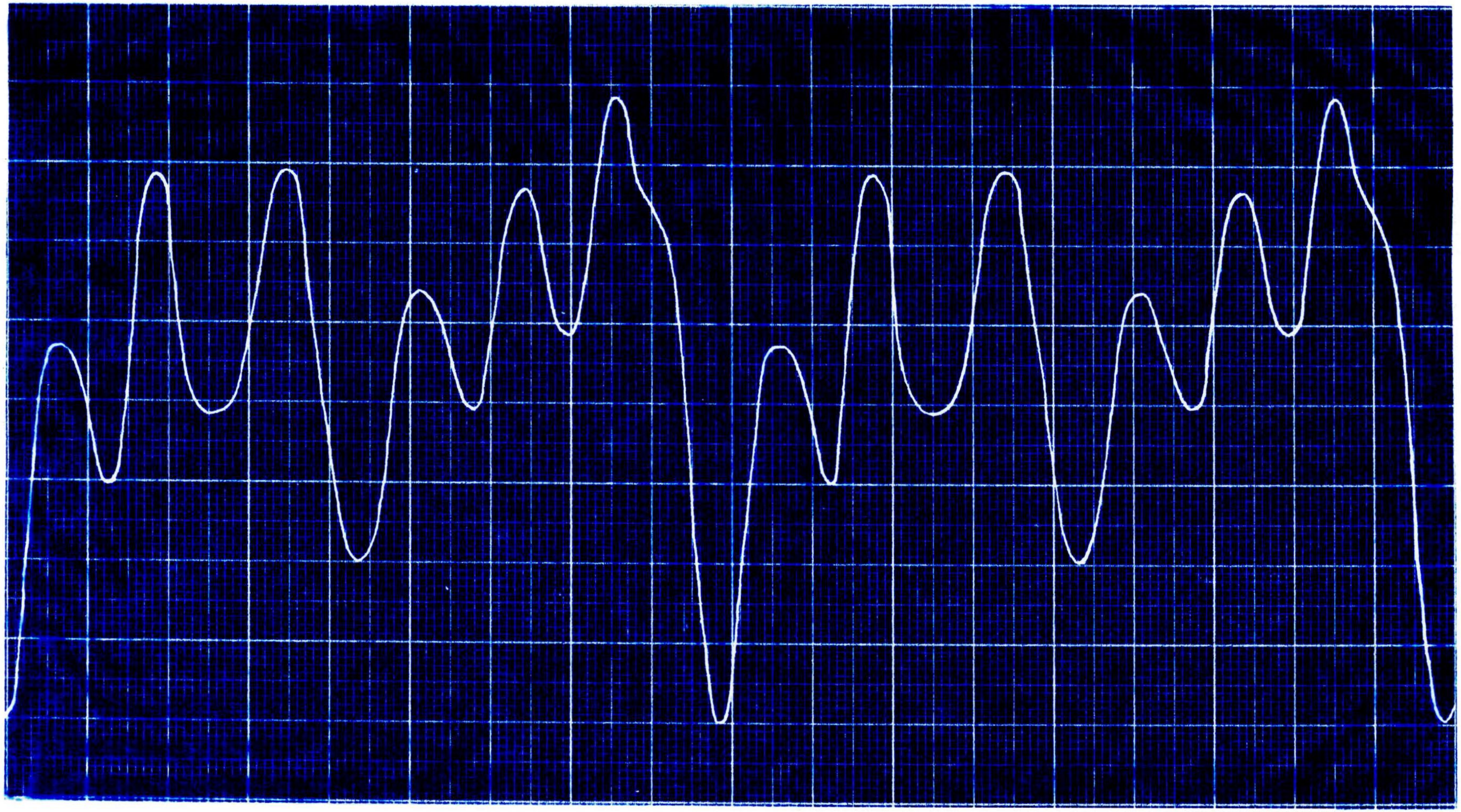

Figure 2. Viole D'Orchestra.

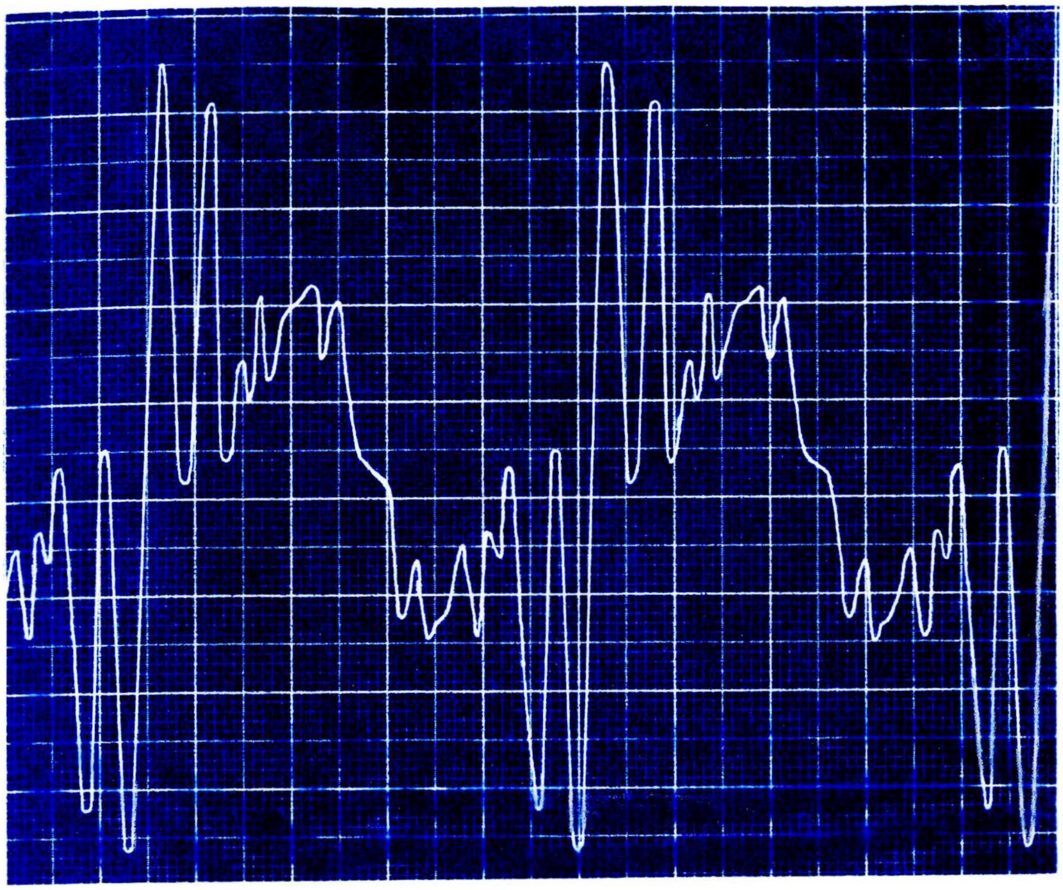

Figure 3. Clarinet C_3.

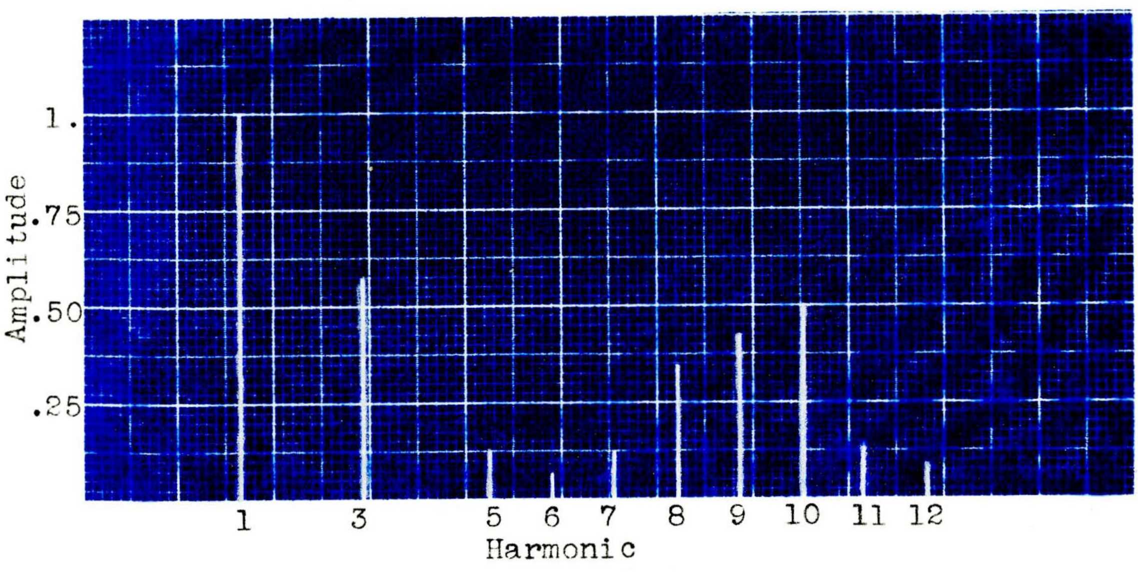

Figure 4.

Diapason 2', thus comprising a chorus of Diapason pipes. The 16' indicates the tone sounds one octave lower than played, 8' indicates the tone sounds in unison with the pitch represented by the key pressed, 4' shows the tone sounds one octave higher, and 2' indicates the tone sounds two octaves higher than the key played. Thus, if all four stop tablets were pressed in this case and the (C_3) key pressed on the console, there would be four tones sound (C_2, C_3, C_4, and C_5).

Some smaller organs attempt to get a choral effect by using one rank of pipes so connected to the console that it is possible to draw the stop at several pitches. This is undesirable, however, since if a chord is being played, one pipe may be called upon to act as a 16' pipe and an 8' pipe at the same time, which, of course, is impossible, and one or more tones that should be in the chord will be lacking. A still further addition to the warmth of organ music is obtained by making a stop consist of two sets of pipes, one set being tuned a trifle higher or lower than the other, producing through beats a wavering, undulating effect which is very beautiful. An example is the Voix Celeste stop consisting of two sets of open metal pipes of small scale and delicate tone.

The actual voicing of the organ is largely a matter of opinion and a consideration of the use that will be made of the organ. The theatre organ needed many "trick" effects which, of course, would be out of place on a concert organ, but lines are drawn much finer than that in organ tonal design. An organ designed for a Methodist church would be of little utility to a Catholic church. The following rules, however, are applicable to good organ design in general.

1. All stops employed are strictly musical in character. That is to say, the harmonic development is neither under nor overdone, but lies within well defined limits.

2. The stops maintain such harmonic development throughout their compass.

3. The relative power of Octave and Mutation[3] Ranks to the Unison lies within definite limits and follows a logical order in all cases.

The modern view of the tremolo as held by some of the finest organists in America is that it is a most useful device and one which they frequently employ, but that it is often used to excess. The most common use of the tremolo is the Vox Humana stop. It is a fact that of all of the instruments of music none produces a more pleasingly vi-

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3. By Mutations is meant all the ranks of pipes in an organ that do not speak the prime tone or some octave of the prime. Their purpose is to fill in the harmonics not produced by the prime tone pipes or to reenforce weak harmonics.

brant tone than a fine human voice. This vibrant quality is the chief attraction in most stringed instruments.

A vibrating effect may be produced in a tone by doing one or both of two things. First, its tone may be caused to waver in pitch about the point intended to be heard as the definite pitch. Second, the tone may increase and decrease in intensity, the pitch remaining constant. The usual organ tremolo produces the latter result. Though it is not done in all cases, it is desirable to have the tremolo more pronounced on the higher notes with less movement of the bass.

The power input to an organ varies from about 350 to 10,000 watts and the output will range from about 1/2 to 600 acoustical watts, depending upon the size of the instrument. Figure 5 shows the average results of experiments by Fletcher[4] regarding the pressure spectrum of pipe organ music.

Flexibility

A great deal could be said regarding the flexibility required in the manipulation of an instrument as complex as

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4. Fletcher, Harvey
   Speech and hearing. New York. D. Van Nostrand. p. 95, Fig. 55. 1929.

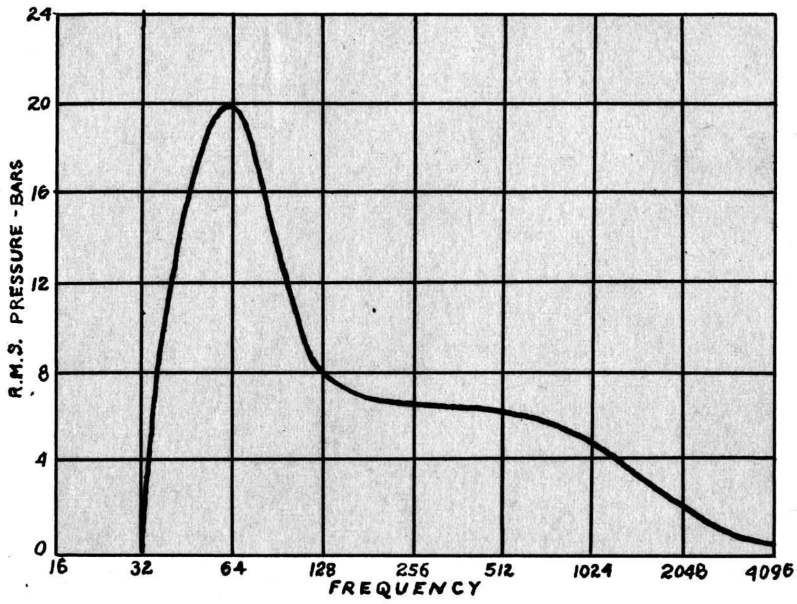

Figure 5

an organ and it can be treated only very briefly here. The usual range of the keyboard is 61 keys (CC-C_4) and 32 foot pedals (CCC-G). In reality, however, the tone range of the organ is as high as eight octaves or more through the use of super-octave and sub-octave couplers, or due to the fact that some stops play higher or lower by an octave or more than the key or pedal indicates.

Needless to say, a large variety of stops is desirable in an organ but there are certain foundations tones upon which the remainder of the tonal structure is balanced. Barnes[5] gives a very good discussion of tonal design. The number of stops placed in an organ is limited by the expense, the space required, and the possible shapes of pipes to produce different desirable tones.

Expression

An organ may be made up of several divisions depending upon the size of the instrument. It may have from one to five manuals and pedals and for each manual and set of pedals there are one or more organ sections. For example, on a three-manual organ there may be a Great Organ, a Choir Organ, and a Swell Organ for the manuals, and a Pedal Organ for the pedals. In addition there may be an Echo Organ division which, while not having a manual of its own in this case, is playable upon either of the three manuals or the pedals through the use of couplers.

The reason for the division is to obtain greater flexibility in expression and to obtain separate control for the solo, accompaniment, and pedal. Sometimes there is no actual division so far as separate chambers for all sections are concerned and then, of course, the same swell pedal

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5. Barnes, William H.
   The contemporary American organ. New York. J. Fischer & Bro. p. 139-184. 1930.

controls the expression of more than one section at once. It is helpful to be able to control the volume of tones played by each manual and the pedal section with swell pedals.

Couplers make it possible to switch divisions to different manuals or to different octaves of the division.

Another essential feature of the console is a series of combination pistons which make it possible to pre-set combinations of stops and control them as groups with the pistons.

Standardization

The American Guild of Organists has, since 1903, taken successive actions leading to the creation of the present standard measurements for organ consoles. It has standardized the relative positions of the manuals and pedals, the preferred locations of stops, couplers and pistons, the spring tension in the keys, and so forth. The serious student of the organ demands that the console of any instrument designed for his practice be controlled in a similar fashion to the standard arrangement prevailing on organs. Any instrument designed for use as a substitute for the organ should conform to these standards of console measurement and control.

Physical Properties

Among the disadvantages of the pipe organ are its bulk, weight, initial cost, inefficiency, sluggish response to keying, change of tuning with temperature and humidity changes, and cost of upkeep.

The space required for an average three-manual organ is about 6000 cubic feet. The weight of organs ranges from 1 to 30 tons and the cost from $750 to $25,000 or more. Some fast passages of music cannot be properly played on the organ because there is an appreciable lag from the time the key is pressed until the tone is heard.

GENERAL STANDARDS

While considerably more could be said regarding organ technique, it is possible from the foregoing discussion to draw general conclusions as to the standards which should be met by any instrument which is to be considered an accepted equivalent to a pipe organ.

1. The instrument should be able to produce any continuous tone with extreme fidelity. It should be possible to produce tones of every musical instrument which produces a continuous tone, similar to the timbre of the finest octave, or finest note, or similar to the instrument over

its entire range. The range of the instrument should be complete.

2. The harmonic content of the tones should be such as to fulfill the above requirement and thereby eliminate the necessity of mixtures or mutations.

3. Complete specification containing 16', 8', 4', and 2' stops should be possible without undue complexity, and other stops, such as 32', 10-2/3', 2-2/3', 1, 1-3/5', and celeste stops, should be possible if desired. The stops should be brought into play in the conventional manner.

4. A large number of stops in a small space is desired.

5. Borrowing, duplexing, or unification should not be utilized.

6. Tone response should be as rapid as the finger can work the key and yet not be percussive by speaking with a click or a thump.

7. The console should be built according to A.G.O. specifications.

8. The organ should be properly divided with adequate expression control. Individual stop volume control would be an advantage in voicing the organ to fit a given auditorium.

9. A tremolo for each division, controllable by the

musician in both intensity and speed, is valuable. The tremolo should have its greatest effect upon higher tones.

10. The pitch of the instrument should be established through some synchronous means to prevent pitch variation.

11. The instrument should be small, light, economical in operation, and contain as few moving parts as possible.

12. Percussion tones, though not a necessity, are to be desired for chimes, bells, harp, and so forth.

13. The instrument should be practical and as trouble-free as possible.

14. The power output must be adequate for the auditorium without distortion while operating at full capacity.

15. Close regard should be made to accepted practice in tonal design and all other properties of the organ.

TYPES OF ELECTRONIC ORGANS

Oscillator Type

Although many attempts have been made to produce an electronic instrument comparable to an organ, no instrument announced to date has been successful. Some instruments have enjoyed a period of popularity but mainly because of their novelty, and as a result their popularity was short. Such an instrument was invented by a Russian named Theremin.

This instrument produced tones through the use of vacuum-tube oscillators causing a beat frequency in the audible range. Its 'cello-like tone was controlled in volume and pitch through capacity effects of the body and the musician played by ear. It really was not intended to be an organ but rather a solo instrument. Using the same fundamentals, Ranger[6] built an instrument with a large number of vacuum-tube oscillators and keys to control the pitch. The beat frequencies of several channels were mixed to synthesize the resultant tone. The pitch of the instrument was dependent upon fixed parameters in the various circuits to which other parameters could be added or subtracted. The instrument required so many tubes and circuits for its limited flexibility and range that it was not practical.

Photo-Electric Type

A second type of electronic instrument is based upon the modulation of a light beam by means of recorded sound on film or by a chopper wheel, thus producing sounds. Many patents have been issued on this type. The major patents are held by the Bell Telephone Laboratories and Ivan Eremeef of Philadelphia. Potter[7], of the Bell Laboratories, devised

6. Captain Richard Ranger, Newark, N. J.
7. Patent 1,678,872, July 31, 1928.

an instrument whereby a film record in the form of a cylinder was rotated about a photo-electric cell. There were small sound tracks side by side along the cylinder and extending around it in rings. A light to one side of the drum was allowed to pass through shutters connected to their respective keys and then through the proper sound track to the photo cell inside the drum. This instrument met standards 1, 2, 6, 10, 11, and 13, as previously set forth in this thesis, but due to the space required for the sound recordings it became impractical to meet standards 3, 4, 5, 8, and 9. The instrument had some fine features but could not be equivalent to an organ and remain simple.

Eremeef[8] worked along similar lines by making various tone bands side by side on a wide piece of film which passed from one reel to another between the light source and the photo cell. Every few minutes the film reversed. When it was desired to play tones of different timbre the film was shifted sidewise so that new sound tracks fell into the light channels.

It can be seen even from this brief description that the instrument is very limited and is apt to be troublesome to operate. Along similar lines Eremeef made another with

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8. Patent 1,990,023, Feb. 5, 1935.

simple sine waves recorded on the film and means for blending these waves to form complex tones. This instrument was very complicated and was still limited in its results. Standards 3, 5, 8, 9, and 11 were among the standards not met.

Eremeef made a still different instrument which he called the Photona. In this instrument there was a standard six-volt automobile headlight bulb for each key. As the key was pressed the lamp glowed and its beam of light passed through slits in a rotating disc to a photo cell. There were 900 lamps, 10 photo cells, and 12 discs. The discs acted as light choppers and modulated the light beams from the lamps. Of the fifteen standards this instrument met only 6, 10, and 11.

Electromagnetic Type

The Hammond[9] Clock Company, of Chicago, has produced an instrument that is enjoying popularity with small churches and homes but has not been accepted by the professional organists. In their professional magazine, <u>The American Organist</u>, a recent questionnaire[9a] revealed that not one of the leading organists of the country considered

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9. Patent 1,956,350, April 24, 1934.
9a. Henney, Keith
    Editorial in Electronics, New York. McGraw-Hill. March, 1936.

the Hammond instrument in any way a satisfactory substitute for the pipe organ.

The Hammond instrument contains 92 small generators of the electromagnetic type which generate approximate sine waves. Tuned circuits are used in conjunction with each of the majority of the generators in order to eliminate unwanted harmonics. The voltages of these generators are mixed in a manner that permits complex tones to be synthesized. Each generates a different frequency of the tempered scale, so, for example, one generator may be used for A_1 (110.00); another generator may be used for A_2 (220.00) and also the second harmonic of (A_1). The generator for E_3 (329.627), due to slight error in gearing, will have an actual frequency of 329.552 and will be used as the third harmonic of A_1 which should be 330.000.

The generator for A_3 (440.000) will be used as the fourth harmonic of A_1. For the fifth harmonic the generator for $C\#_4$ (554.365) which as produced by the instrument is 554.146, should be 550.000. The sixth harmonic is obtained exact from A_4 (880.000). The seventh is omitted and the eighth is A_5 (1760.000). It is seen that the odd harmonics as produced by the instrument are not true harmonics and they have been termed "tempered" harmonics. Such appropriate pitches will not combine adequately to produce foundation tones of well varied or truly musical character. The so-called tempered harmonics are believed to cause beats with the true harmonics generated by the non-linear characteristics of the ear and have a tiring effect upon the listener. It is obvious that the tone in Figure 3 could not be synthesized by this instrument if it did have true harmonics for none can be obtained past the eighth, and Figure 4 shows the wave to have appreciable ninth, tenth, eleventh, and twelfth. Furthermore, only the fundamental and second harmonic are made available in the pedal section, which is inadequate. The pedal tone of an organ possesses real variety of color and volume and should be able to furnish suitable bass for the wide variety of tonal effects possessed by the manuals. An examination of this instrument will show that of the fifteen desirable standards it meets only No. 10 and possibly No. 13.

Firestone[10] disclosed a method similar to Hammond's except electrostatic generators were to be used instead of electromagnetic type. His disclosure does not show any features not obtained by Hammond and in addition to the inherent disadvantages of the Hammond type, there will be the added disadvantage that the equivalent electrostatic generators would require more space than the electromagnetic

10. Patent 1,953,753, April 3, 1934.

type.

ELECTRONIC STANDARDS

The organ is so complex that it is difficult to know all the facts concerning it and it is troublesome to make a substitute for something not well understood. On the other hand, even though the designer be well versed on the standards to be met, there is yet considerable difficulty in making the proper electronic substitutions. If a scientific approach is made to the entire problem, the substitution is made much easier. That is to say, if each of the requisites is thoroughly understood and properly fitted into the problem as a whole, many impossible solutions are at once eliminated and a possible solution is more readily deduced. Of the many possible solutions which might be reached to meet the general standards previously itemized, some would, of course, possess more merit than others. In attacking the problem it is essential that the practical side be kept in view at all times for, above all, the instrument must be practical. Often it is tempting to compromise with a few of the standards unmet if a practical instrument results that has commercial promise.

It was the belief of the author that an electronic instrument could be designed which would omit none of these standards so no solution was accepted if any of the standards seemed impossible. Eventually a satisfactory design was completed.

Conjugate electrical standards may now be selected to fit the general requirements listed on pages 13, 14, and 15.

1a. By synthesis or from pre-recorded complex tones, the instrument should be able to generate any continuous tone with extreme fidelity. Having been generated it must be amplified and transduced into sound by means of loud speakers without appreciable distortion. The frequency range for best results should be 30 to 15,000 cycles per second.

2a. If synthesis is used, there should be sufficient range of true harmonics available to construct desired tones. If recorded tones are reproduced, the recording and reproduction should be such that none of the desired harmonic content is lost.

3a. A large number of different tones should be generated in a small space and in a manner which makes the selection of any individual tone simple.

4a. If recorded tones are reproduced, they should be recorded in the smallest possible space in order that a large variety may be used.

5a. If rule 3a above is followed, it will not be necessary to utilize borrowing, duplexing, or unification unless desired.

6a. If keying is done in electric circuits it should be done in a manner to prevent the generation of transients, or if they are unavoidably generated they should be adequately damped. It would be preferable to key in such a way as not to cause the tone to have instantaneous response, thereby preventing the generation of unwanted transients.

7a. Tone generation, selection of tones, and mixing of tones should be done in such a way that a standard console arrangement could be used.

8a. Several channels should be provided with tremolo and volume control for each channel. There should be as many channels as there are manuals and, better still, a separate channel for the pedal section.

9a. Means should be provided to periodically vary the amplitude of the signal in each channel and this should be done in a manner having the greatest effect upon treble notes.

10a. The tone generating units should be driven by a synchronous motor. The power should be uniformly transmitted from the motor through a speed changing device to the tone generating unit.

11a. All the foregoing rules should be obeyed through the simplest possible devices.

12a. It would be desirable that the tone producing units be capable of producing percussion tones but this feature should not be made a major premise due to the complicated manner in which percussion tone is developed. Consideration should be given to the possible addition of this feature.

13a. All mechanism must be as free as possible from delicate parts or any parts possessing inherent instability.

14a. A sufficient number of well designed loudspeakers, which include proper baffle, should be provided to furnish adequate acoustical power at all frequencies and with as little distortion as practicable.

15a. A professional organist well acquainted with the subject should be consulted by the engineer designing the instrument.

A NEW PHOTO-ELECTRIC DESIGN

As an illustration of an application of the foregoing rules, let us examine a design which was one of the several rejected.

In this design, for better flexibility and compactness the conventional photo-electric method was reversed. That is, instead of moving the film past a slit of light in order to reproduce the sound recorded thereon, the slit of light was moved and the film held stationary. By scanning the film in this manner several important advantages were made possible.

In order to make a detailed study of the qualities of this method, a model was constructed and tested.

Figure 6 is a photograph of the arrangement used showing from left to right the scanning drum with lamp in center, the film holder, a condenser lens, and a photo-electric cell. In the background to the right is a sound recording head constructed to record sound on film for the experiments. On top of the recording head may be seen the film drums and mechanism for timing the exposure. The scanning drum was 8 inches in diameter and had 20 lenses accurately spaced around it. The double convex lenses were 1 inch in diameter and of 2-inch focal length. Each lens was held in an individual holder and the spacing was done optically through the use of a dividing head. The film holder was curved on a circle 16 inches in diameter and concentric with the scanning drum. The condenser lens was used to focus light passing through the film to an essentially stationary spot on the cathode of the photo-electric cell. The light source was a standard exciter lamp having a coiled filament approximately .01 inch in diameter.

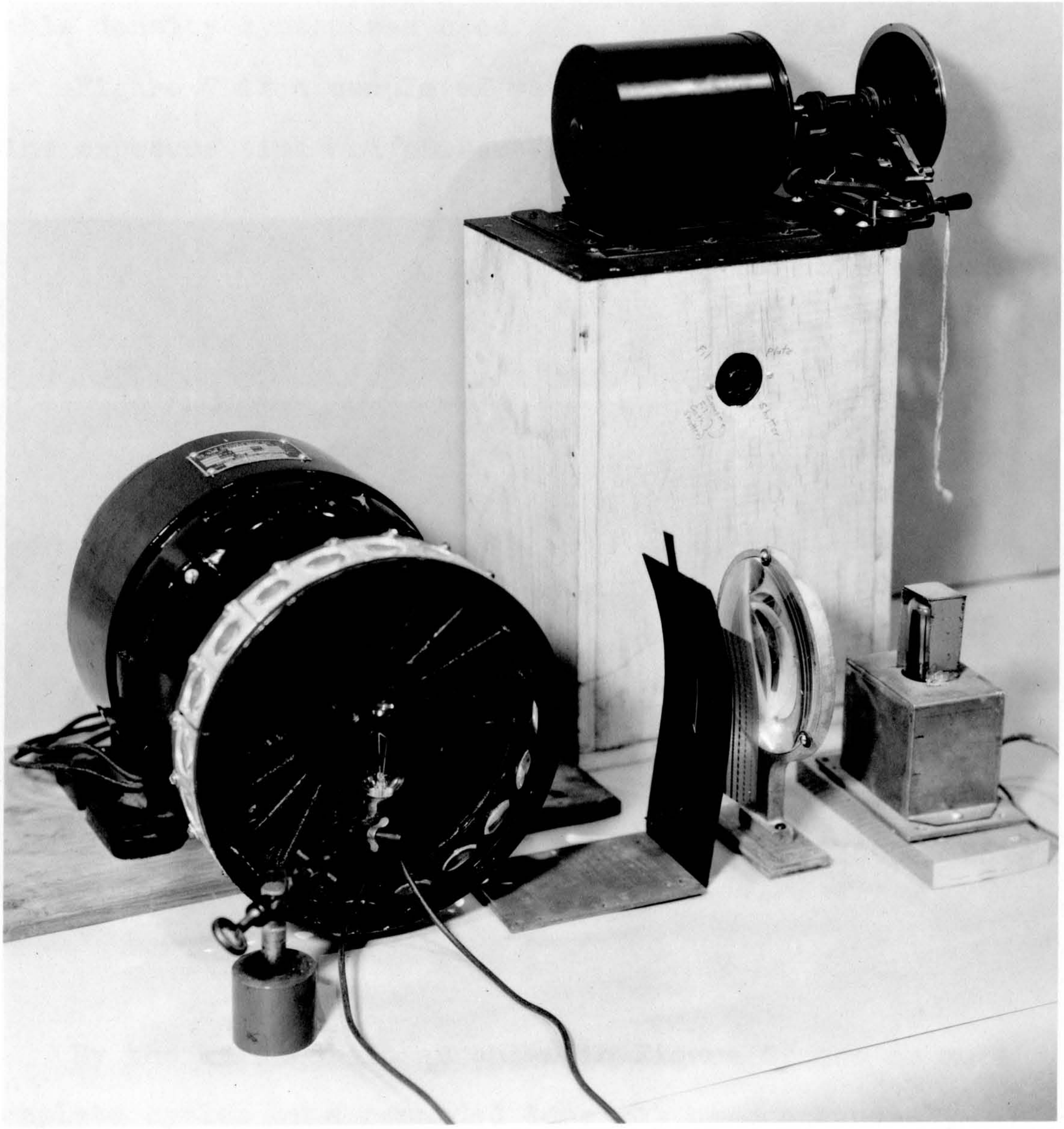
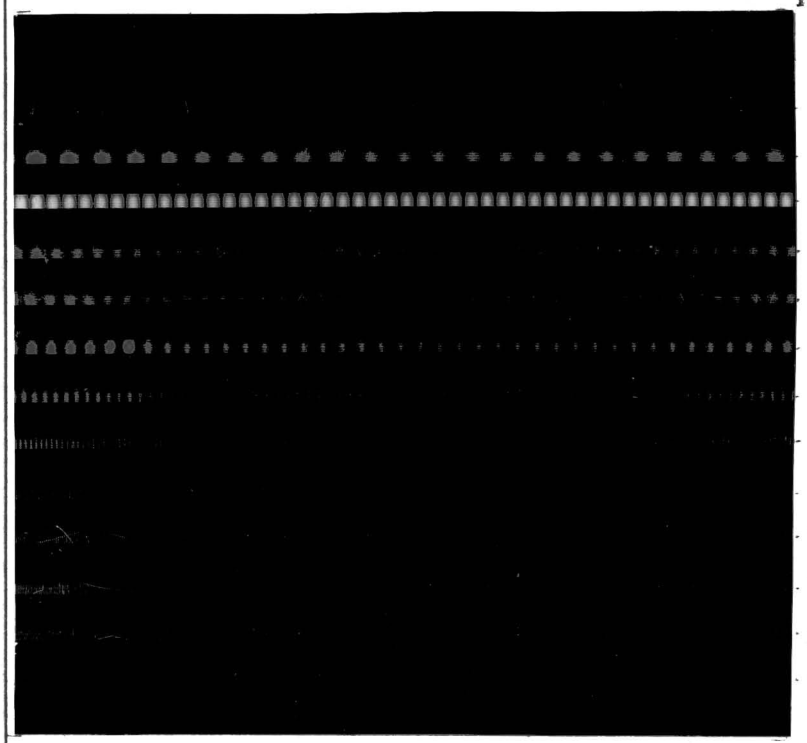


Figure 6.

For recording the sound on film the conventional variable density system was used.

Figure 7 is a sample of various tests made to determine exposure time and correct bias for the recording lamp.



R.P.M.	FREQ.	VOLTS
480	1000	25
120	500	25
120	125	25
60	62	25
120	125	20
120	125	15
120	125	30
120	500	25
120	1000	25
120	2000	25
120	2500	25
120	3000	25
120	3250	25
120	3500	25

Figure 7

By the arrangement as shown in Figure 6, one or more complete cycles of a recorded tone may be continuously scanned to produce a continuous wave whose character is dependent upon the recording. Thus, if one cycle of a flute tone were being scanned at a given speed by the light beams, an electric wave, whose shape is similar to the wave produced by the flute, will be produced at the photo-electric cell. If exactly two cycles of recorded tone were placed in the position occupied previously by one cycle and the rate of scanning held constant, a tone of double the former frequency would develop. It is possible to place, say five recordings side by side, scan them with the same light beams, and produce five different tones. They may be five octaves of the same tone or tones of different character at the same pitch.

If the circle in which the film holder is located be divided into twenty equal parts and a film holder holding five recordings be placed in every other division, the same scanning beams can now develop fifty different tones. These tones may be utilized conveniently by generating five tones of octave relationship of the same timbre at one division and five octaves of another timbre at the next division.

Now, for still better space utility, let the recordings be recorded with less than 100 per cent modulation. That is to say, the darkest portions of the film are not opaque. Then one recording may be placed behind another and the same beams passed through both films simultaneously. Both films will then have their effects upon the modulation of the beam passing from the lamp to the photo-electric cell. This procedure would double the number of different tones so that one hundred would then be possible with the one drum.

Since the scanning drum can be used only for the generation of one pitch or multiples thereof (octaves), it would be necessary to have a drum for each of the twelve intervals of the scale and each scanner would rotate at a different speed. If the slowest speed drum rotated at 1.6 revolutions per second to generate 32 cycles per second, then the adjacent drum would rotate at 1.6 x $\sqrt[12]{2}$, the next at 1.6 x $\sqrt[12]{2^2}$, the next at 1.6 x $\sqrt[12]{2^3}$, the next at 1.6 x $\sqrt[12]{2^4}$, and so on up to the twelfth drum, which would rotate at 1.6 x $\sqrt[12]{2^{11}}$.

The twelve drums would have 600 film positions available and it is possible to put more than one film at each position, so the number of different tones possible would be a multiple of 600 as far as practicable.

Clear positive stock film showed an absorption of 10 per cent by experiment. If one film is used in each position, 10 per cent of the useful light is lost in the film. If two films are used, 19 per cent is lost, and so on. As high as ten films in one position at a time would be possible and would allow 6,000 tones, which is far above average for a pipe organ.

In calculating the necessary output from the photo-electric cell, 75 decibels was considered the lowest value that could be permitted. With an output impedance of 600,000 ohms, the voltage required to be generated would be

$$E = \frac{\sqrt{.006 \times 600{,}000}}{5620} = .010 \text{ volt.}$$

Lumens change required = 2 x .010 x .02 = 2.8 x 10^{-4} lumens.

Assuming 10 films in position,

$$\text{Lumens on slit} = \frac{2.8 \times 10^{-4}}{2.8 \times 10^{-2}} = .01 \text{ lumen.}$$

The efficiency of the scanning arrangement used was .1 per cent and the lamp emitted approximately 600 lumens so about .6 lumen reached the film. Allowing for loss in the film and means for directing it into the photo-electric cell, there was still plenty of light to cause the output to be above the low limit set. A smaller drum with fewer lenses of shorter focal length would give even greater efficiency but would offer disadvantages pertaining to available film positions.

Provision must be made to start and stop the tones at will so shutters may be provided in front of each film position. When more than one film is to be used in the same position, means may be arranged to slide the films sidewise, presenting a clear portion of the film in the opening when the tone on that particular film is not wanted.

The keys could connect directly to the shutters in the same fashion that they connect to relays in pipe organs. Stop tablets could cause their respective films to be moved in and out of playing position which is also analogous to a pipe organ. If means were provided to cause any desired film to move only partially into its speaking position, the tones on that film would sound at a fraction of their volume, allowing individual stop volume control.

If a single cycle is placed in the film holder it must be 2.51 inches long which, with a .01-inch scanning beam, would allow the 125th harmonic to be reproduced at about 100 per cent amplitude. The frequency cut-off, then, would be above 4,000 cycles per second on the slowest drum and above 7,660 cycles per second on the fastest drum.

The amplifier used should pass 30 to 10,000 cycles per second with not more than $\pm$ 1 decibel change, and the loudspeakers should handle these frequencies with as little frequency discrimination as is practical. At least three different speakers should be used, one for frequencies between 30 cycles and 100 cycles, another for 100 to 5,000 cycles, and a third for frequencies above 5,000 cycles.

Power output required for auditoriums ranges from 1 to

2 acoustical watts per 1000 people. The theory involved in loudspeaker design is too complex to be considered here but it is of extreme importance in the design of the instrument. McLachlan[11] is an excellent reference on loudspeakers.

The design of this instrument was treated in a much more detailed manner than described here but enough detail is given to analyze the possibilities of its being acceptable as a substitute for a pipe organ, as follows:

1. It is possible to generate from pre-recorded complex tones any continuous tone with reasonable fidelity. The frequency range is 30 to 8000 cycles.

2. Recorded tones may be reproduced with essentially their full harmonic content.

3. A reasonable number of tones may be generated in a comparatively small space and in a manner which makes the selection of any individual tone satisfactory.

4. The recorded tones require small space as compared to other electronic instruments.

5. Borrowing, duplexing, or unification is not necessary.

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11. McLachlan, N. W.
Loudspeakers. Oxford at the Clarendon Press.
399 p. 1934.

6. Keying is done in such a manner as to be fast and yet not instantaneous, thus producing no clicks or thumps in the tones.

7. Standard console may be used.

8. Separate channels may easily be provided.

9. Tremolo may be provided in separate channels.

10. The tone generating units may be driven by a synchronous motor.

11. All the foregoing rules are obeyed in a fairly simple manner.

12. Percussion tones are not producible by this generating method but may be added separately.

13. Tone generating mechanism requires very critical adjustment and must be sealed with a "breather" to keep dust out. The lamps, photo-electric cells, shutters, lenses, and movement of the film are apt to give trouble.

14. Loudspeaker design was properly engineered.

15. A professional organist was consulted frequently.

Therefore, the design meets all requirements reasonably except No. 13. This does not necessarily lead to the conclusion that the method has no value for it is possible that further work would lead to improvements, and, except for a few disadvantages, it has commercial possibilities.

CONCLUSION

It is believed by electronic specialists[12] and by the author that an instrument using vacuum tubes can be built which will satisfy the standards of the pipe organ and which will still be cheaper, more flexible, and capable of better music in the best sense.

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12. Henney, Keith
    Editorial in Electronics. New York. McGraw-Hill. March, 1936.

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