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BY

J. P. MAXFIELD and
H. C. HARRISON

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BASED ON TELEPHONE RESEARCH

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Methods of High Quality Recording and Reproducing of Music and Speech Based on Telephone Research[1]

By J. P. MAXFIELD and H. C. HARRISON

Bell Telephone Laboratories, Incorporated

SYNOPSIS: This paper deals with an analysis of the general requirements of recording and reproducing sound without appreciable distortion. The storing or recording of sound requires, first, a mechanical system which will respond faithfully to the sound waves which are to be recorded. Then there is required some material in or on which this sound may be recorded and an intervening system which permits the sound waves to make the record in this material. In the usual case, and in that which is particularly discussed, there is a mechanical system which will vibrate in response to the sound which is to be recorded and directly through some mechanical linkage, or less directly through an electrical linkage, drives a cutting mechanism which will impress a wax record.

The amount of power available to operate the recorder directly from the sound in the recording room is so small as to make the use of high quality electrical apparatus with associated vacuum tube amplifiers of very distinct advantage over the acoustic method.

Where the question of reproduction is concerned, the same two alternatives mentioned for recording present themselves, namely, direct use of power derived from the record itself vs. the use of electro-mechanical equipment with an amplifier. In this case, however, the situation is materially different since the power which can be drawn directly from the record is more than sufficient for many uses. It is, therefore, generally simpler to design one single mechanical transmission system than it is to add the unnecessary complications of amplifiers, power supply and associated circuits. In cases where music is to be reproduced in large auditoriums, the power which can be drawn from the record may be insufficient and some form of electrical reproduction using amplifiers becomes necessary.

The paper points out, at length, how many of the heretofore unsolved fundamental problems of sound recording and reproduction have been readily solved by the application of a detailed knowledge of telephone transmission theory. The advances which have been effected in telephone transmission theory and in related electrical measuring apparatus in the last few years, have been so great as to surpass previous knowledge of mechanical wave transmission systems. The result is, therefore, that mechanical transmission systems of the type here considered, and perhaps other types, can be designed more successfully if they are viewed as the analogs of electric circuits. A detailed analysis is here made of the analogies between electrical and mechanical systems in the voice frequency range and a discussion of the resulting mechanical design is presented.

INTRODUCTION

THE problem with which this paper is concerned, in its broadest sense, may be stated as that of taking sound from the air, storing it in some permanent way and reproducing it again without appreciable distortion. It is immaterial from the general standpoint whether the means used are mechanical or electrical or a combination of the two. The choice of which method to use will depend largely upon the commercial requirements accompanying the specific purpose for which the reproduction is being made. For instance, it is quite probable that

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[1] As printed here this paper is essentially as read before the A.I.E.E. Feb. 8-11, 1926.

the means chosen for reproduction in residences would differ materially from those used in large ballrooms or in the presentation of synchronized motion pictures.

Before considering the methods and results referred to in the title of this paper, it may be well to make a rough division of the problem. The storing or recording of sound requires, first, a mechanical system which will respond faithfully to the sound waves which are to be recorded. Then, there is required some material in or on which this sound may be recorded and an intervening system which permits the sound waves to make the record in this material. In the usual case, and in that with which we are particularly concerned here, there is a mechanical system which will vibrate in response to the sound which is to be recorded and directly through some mechanical linkage or less directly through an electrical linkage, drive a cutting mechanism which will impress a wax record.

The first consideration, therefore, is the character of the sound which is to be recorded including all of the effects of reverberation and the general questions of studio design. Next to be considered is the manner in which the cutting instrument shall impress this speech or musical record upon the constantly rotating wax disk, which disk is commonly called the wax master. In this connection, there will be discussed also the relative value of the electrical and mechanical linking of the cutting knife with the mechanism which receives the sound waves. Following the discussion of these problems and a brief reference to the state of the prior art, there remains to be considered the reproduction of the sound which is stored in the cuts or grooves of the wax record.

In the case of reproduction also, there is required a mechanical system which will respond to these cuts in the wax and a system which will set up in the air-sound waves essentially identical to those picked up by the first mechanism of the recording system. Between these two systems, a mechanical linkage intervenes in the case under discussion, but reference is made to the relative advantages of this system compared with the use of an electrical linkage.

First to be described, is the character of the sound which is to be recorded and reproduced and the effects of reverberation and transients upon the listener's sensation of this sound.

STUDIO CHARACTERISTICS AND TRANSIENTS

Phonographic reproduction may be termed perfect when the components of the reproduced sound reaching the ears of the actual listener have the same relative intensity and phase relation as the sound reaching the ears of an imaginary listener to the original performance would have had. Obviously, it is very difficult, if not impossible, to fulfill all of these requirements with a single channel system, that is, with a system which does not have a separate path to each ear of the listener from the sound source.

The use of two ears, that is, two-channel listening, gives the listener a sense of direction for each of the various sources of sound to which at a given moment he may be listening, and, therefore, he apprehends them in their relative distribution in space. It has been found possible with a single channel system, however, by controlling the acoustic properties of the room in which the sound is being recorded, to simulate to a considerable degree in the reproduced music the effective space relationships of the original. In this case, with a one-channel system, the directional effect is, of course, entirely absent, and the spatial relationship which is apprehended is probably due to the increased apparent reverberation of the instruments situated at the far end of the room as compared with those in the near foreground.

In recording work, therefore, one of the important acoustic characteristics of a room is its time of reverberation. Although it is probable that this is the most comprehensive single factor, experiment has shown that the shape of the room and the distribution and character of the damping surfaces play a part in the excellence of music in such a room.

It has been shown by Sabine[2] that for piano music, studios should have a time of reverberation measured by his method of 1.08 seconds. Experience has indicated that this figure is also very closely correct for other types of music. This figure of Sabine's assumes binaural listening. With single-channel systems, such as most of the present reproduction systems, whether for radio or the phonograph, the ability of the listener to separate the reverberation from the direct music by means of the sense of direction is completely removed and there is thrust upon his attention an apparently excessive amount of room echo. Experiment has shown that a time of reverberation for the recording room ranging from slightly more than ½ to slightly less than ¾ of Sabine's figure affords in the reproduced music the effect of a room with proper acoustics. When this effect is accomplished, the person listening to the reproduced music has the consciousness of the music being played in a continuation of the same room in which he is listening and also has a sense of spatial depth.

Experiment has indicated further that any transients set up by the recording or reproducing system constitute a second cause of apparent

[2] Collected papers of W. Sabine.

increased reverberation. The data obtained thus far are insufficient to permit assignment of quantitative values to the importance of these two factors.

At the present state of the art, the most important requirement of a recording or reproducing system is its frequency characteristic. This involves two factors—intensity versus frequency, and phase distortion versus frequency. The effect of the second of these factors is not thoroughly understood but as it is closely related to the production of transients it has to be considered, as mentoined above. The system to be described is, however, relatively free from violent phase shifts within most of the range covered, but does have some undesirable phase-shift characteristics with small accompanying transients near its limiting cut-off frequencies.

Frequency Requirements

The frequency range which it would be desirable to cover if, it were possible, with relatively uniform intensity for the transmission of speech and all types of music including pipe organ is from about 16 cycles per second to approximately 10,000.

It may be interesting to examine the record requirements for a band of frequencies this great. For the purpose of this illustration, a lateral cut record will be assumed although in all the factors except the time which the record will run, the arguments apply in a similar manner to the hill-and-dale cut. Since, for mechanical reproduction, the sound at a given pitch is radiated by means of a fixed radiation resistance, it is necessary that the record must be cut with a device the square of whose velocity is proportional to the sound power. Under these conditions, it is seen that for a given intensity of sound the amplitude is inversely proportional to the frequency of the tone, and that a point will be reached somewhere at the low end of the sound spectrum where this amplitude will be great enough to cut from one groove into the adjacent groove, or in case of vertical cut, to cut so deeply that with present materials the wax will tear instead of cut away with a clean surface. This means that there is an inherent maximum amplitude beyond which it is not commercially feasible to go. Similarly the minimum radius of curvature of sine waves of various frequencies cut at constant velocity is inversely proportional to the frequency, so that as higher and higher frequencies are reached the radius of curvature becomes smaller and smaller until finally it becomes too small for the reproducing needle to follow. There is, therefore, an inherent limit at the upper end.

In order to extend these limits, it is necessary in the case of the low end to make the spiral coarser and in the case of the high end to run the record at a higher speed. Both of these changes tend to decrease the time which a record of a given size can be made to play. The only alternative of these methods is to cut the record less loud than is the present standard practise and make the reproducing equipment more sensitive. This could easily be done if it were not for the "record noise" or "surface noise," as it is commonly called. Since this surface noise is already loud enough in comparison with the reproduced music to be somewhat objectionable, no appreciable gain in this direction can be made until the technique of record manufacture has been distinctly improved.

In this connection, there is one other interesting point. It has been suggested that if electric reproduction were used, it would be possible to cut the record with a characteristic other than uniform velocity sensitiveness and correct for the error by an electrical system whose characteristic is the inverse of the characteristic of record. If the change which is made in the recording characteristic tends toward cutting at uniform acceleration sensitiveness, the amplitude varies inversely as the square of the frequency and hence the difficulties at the low end of the scale are greatly enhanced. Similarly, if the records are cut more nearly at constant amplitude, the radius of curvature of the sine waves decreases as the square of the frequency, hence the difficulties are placed at the upper end. In the process which is being described in this paper, these limitations have been met commercially by having a frequency characteristic of the uniform velocity type between the frequencies of 200 and approximately 4000 cycles per second. Below 200 it has been necessary to operate at approximately constant amplitude with a resulting loss in intensity which loss increases as the frequency decreases. Above 4000 it has been necessary to operate at approximately constant acceleration with its consequent slight loss in intensity at the very high overtones. With a characteristic of this type, a range of frequencies from 60 cycles to 6000 can be recorded with reasonable success although the very low and very high range are slightly deficient. (See Fig. 14) With a record having such a frequency characteristic, the inherent limitations are divided between the two ends of the frequency band and where electrical reproduction methods are used, it is possible to employ a reproduction system whose frequency characteristic compensates for that of the record.

It should be pointed out that an attempt to record notes lower than the low cutoff of the above mentioned apparatus would result in recording only those harmonics of the notes which lie above the cut-off. This in no way prevents the listener from hearing the notes, reproduced by means of the harmonics only, as notes with the pitches of the missing fundamentals although it does somewhat change the quality of the tone.[3] It it were not for this ability of the ear to add the fundamental pitch of a note, of which only the harmonics are being reproduced, most of the older phonographs and loud speakers would have been totally useless for the reproduction of speech and music.

MECHANICAL VERSUS ELECTRICAL RECORDING

In attacking the recording part of the problem, two ways at once present themselves; first, the direct use of the power of the sound being recorded to operate the recording instrument; and second, the use of high quality electric apparatus with vacuum tube amplifiers in order to give more freedom to the artists and better control to the process. The amount of power available to operate the recorder directly from the sound in the recording room is so small as to make it extremely difficult to make records under natural conditions of speaking, singing, or instrumental playing. As the use of high quality electric apparatus with associated amplifiers has a very distinct advantage over the acoustic method, they have been adopted for the recording part of the process. Fig. 1a shows a picture of a group of artists recording by

Fig. 1a—Picture of an orchestra recording by the acoustic process. This picture was furnished through the courtesy of the Victor Talking Machine Company, Camden, New Jersey

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[3] Physical Criterion for Determining the Pitch of a Musical Tone, H. Fletcher *Phys. Rev.*, Vol. 23, No. 3, March, 1924.

means of the sound power directly, while Fig. 1b shows a record being made by the same artists with the electric process.

It will be noticed in Fig. 1a that the artists are grouped very closely about the horn. In the case of the weaker instruments such as violins, it has been possible to use only two of standard construction. The rest of the violins are of the type known as the "Stroh" violin which is a device strung in the manner of a violin but so arranged that the bridge vibrates a diaphragm attached to a horn. The horn is directed toward the recording horn, as shown by the player in the foreground.

Fig. 1b—Picture of the same orchestra shown in Fig. 1a, but recording by the electric process. This picture was furnished through the courtesy of the Victor Talking Machine Company, Camden, New Jersey

With such an arrangement of musicians, it is very difficult to arouse the spontaneous enthusiasm which is necessary for the production of really artistic music. In Fig. 1b the musicians are sitting at ease more nearly in their usual arrangement and all are using the instruments which they would use were they playing at a concert. Furthermore, the microphone is now sufficiently far away from the orchestra to receive the sound in much the manner that the ears of a listener in the audience would receive it. In other words, it picks up the sound after it has been properly blended with the reflections from the walls of the room. It is in this way that the so-called "atmosphere" or "room-tone" has been obtained.

In the old process, it sometimes happened that after the instruments had been arranged in such a manner that the relative loudness of the various parts had been balanced correctly, it was found that the whole selection was either too loud or too weak. This usually meant a complete rearrangement of the players. With the flexibility introduced by the use of electrical apparatus including amplifiers, the control of loudness is obtained by simple manipulation of the amplifier system and is in no way related to the difficulties of the relative loudness of one instrument to another. The only problem for the studio director in this case is to obtain the proper balance among the various musical instruments and artists. The advantages derived from this added ease of control are also made manifest in that it is much easier and less tiresome for the artists and it is usually possible to make more records in a given time.

Mechanical Versus Electrical Reproducing

Where the question of reproduction is concerned, the same two alternatives mentioned for recording present themselves, namely, direct use of power derived from the record itself versus the use of electromechanical equipment with an amplifier. In this case, however, the situation is a little different as the power which can be drawn directly from the record is more than sufficient for home use. Since any method of reproducing from mechanical records by electrical means involves the use of a mechanical device for transforming from mechanical to electrical power and a second such device for transforming from electrical back to mechanical power, that is, sound, it is necessary to use two mechanical systems, one at each end of an electrical system. Where the power which can be supplied by the record, is sufficient to produce the necessary sound intensity, as in the case of home use, it is in general simpler to design one single mechanical transmission system than it is to add the unnecessary complications of amplifiers, power supply and associated circuits. In cases where music is to be reproduced in large auditoriums, the power which can be drawn from the record may be insufficient and some form of electric reproduction using amplifiers becomes necessary.

Brief Description of Recording System

The system used for recording consists of a condenser transmitter, a high quality vacuum tube amplifier and an electromagnetic recorder. Fig. 2 shows the calibration of the condenser transmitter and the associated amplifiers. The condenser transmitter and amplifiers are so designed that the current delivered to the recorder circuit is essentially proportional to the sound pressure at the transmitter diaphragm. The electromagnetic recorder, which will be described later, is designed to work with this type of system. With the exception of this electromagnetic recorder, apparatus of this type has already been described in the literature.[4] In addition to this equipment which might be called the recording amplifier system, there is a volume indicator for measuring the power which is being delivered to the recorder and also an audible monitoring system. The audible monitoring system consists of an amplifier whose input impedance is high compared with the recorder impedance and a suitable loud speaking receiver. The monitoring amplifier is bridged directly across the recorder and operates the loud speaking receiver so that the operator may listen to the record as it is being made.

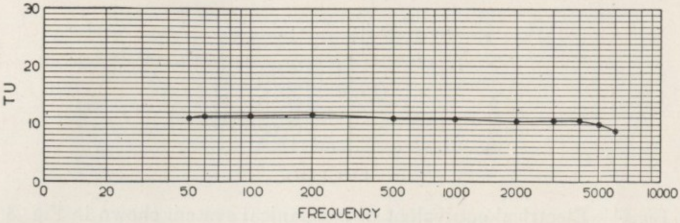

Fig. 2—Calibration of the condenser transmitter and associated amplifiers
This curve shows merely the relative frequency sensitiveness of the system, the zero line having been chosen arbitrarily.

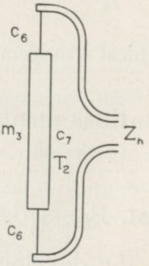

Fig. 3—Schematic mechanical arrangement of diaphragm and air chamber

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[4] Wente, E. C., "Condenser Transmitter as a Uniformly Sensitive Instrument for Measuring Sound Intensity," *Phys. Rev.*, Vol. 10, 1917.

Crandall, I. B., "Air-Damped Vibrating Systems," *Phys. Rev.*, Vol. 11, 1918.

Wente, E. C., "Electrostatic Transmitter," *Phys. Rev.*, Vol. 19, 1922.

Martin, W. H. and Fletcher H., "High Quality Transmission and Reproduction of Speech and Music," Trans. *A. I. E. E.*, Vol. 43, 1924, p. 384.

Green, I. W. and Maxfield, J. P., "Public Address Systems," Trans. *A. I. E. E.* Vol. 43, 1923, p. 64.

In the design of the recording and reproducing systems each part of the system has been made as nearly perfect as possible. Errors of one part have not been designed to compensate for inverse errors in another part. Although this method is the more difficult, its flexibility, particularly as regards the commercial possibilities of future improvements justifies the extra effort.[5] There is, therefore, no distortion in the record whose purpose is to compensate for errors in the reproducing equipment; the only intended distortion in the record being that required by the inherent limitations mentioned above. See Figs. 2, 14 and 20.

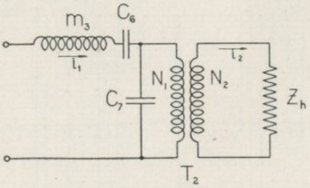

Fig. 4—Electrical equivalent of mechanical system shown in Fig. 3

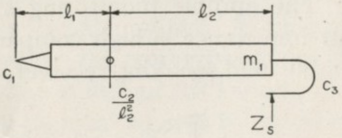

Fig. 5—Schematic mechanical arrangement of needle arm transformer

GENERAL BASIS OF DESIGN

An interesting feature of the development of the mechanical and electromechanical portions of the recording and reproducing system is their quantitative design as mechanical analogs of electric circuits. Both the recording and reproducing systems are good examples of the use of this type of analogy.

The economic need for the solution of many of the problems connected with electric wave transmission over long distances coupled with the consequent development of accurate electric measuring apparatus has led to a rather complete theoretical and practical knowledge of electrical wave transmission. The advance has been so great that the knowledge of electric systems has surpassed our previous engineering

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[5] Green, I. W. and Maxfield, J. P., "Public Address Systems," Tras. A. I. E. E., Vol. 42, 1923, p. 64.

knowledge of mechanical wave transmission systems. The result is, therefore, that mechanical transmission systems can be designed more successfully if they are viewed as analogs of electric circuits.

While there are mechanical analogs for nearly every form of electrical circuit imaginable, there is one particular class of electrical circuits whose study has led to ideas of the utmost value in guiding the course of the present development. This class of circuits consists of infinitely repeated similar sections of one or more lumped capacity and inductance elements in series and shunt and are commonly known as filters. The study of filters began with the work of Campbell[6] and a recognition of their importance as frequency selective systems in telephone repeaters, carrier systems, radio, signalling systems, etc., led to their intensive study. In the available literature is to be found a fairly complete statement of their properties and details of their design.[6]

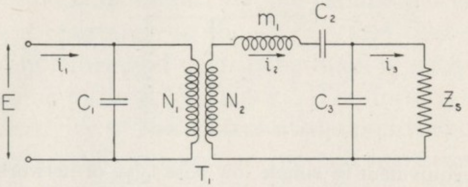

Fig. 6—Electrical equivalent of system shown in Fig. 5 with its termination

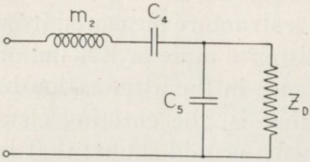

Fig. 7—Electrical equivalent of the spider section

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[6] Campbell, G. A., "On Loaded Lines in Telephonic Transmission," *Phil. Mag.*, March 1903.

Campbell, G. A., U. S. Patents 1,227,113; 1,227,114; "Physical Theory of the Electric Wave Filter," *Bell System Technical Journal*, November 1922.

Zobel, O. J., "Theory and Design of Uniform and Composite Electric Wave Filters," *Bell System Technical Journal*, January 1923.

Peters, L. J., "Theory of Electric Wave Filters Built up of Coupled Circuit Elements," Trans. *A. I. E. E.*, May 1923.

Carson, J. R. and Zobel, O. J., "Transient Oscillations in Electric Wave Filters," *Bell System Technical Journal*, July 1923.

Zobel, O. J., "Transmission Characteristics of Electric Wave Filters," *Bell System Technical Journal*, October 1924.

Johnson, K. S., and Shea, T. E., "Mutual Inductance in Wave Filters with an Introduction on Filter Design," *Bell System Techincal Journal*, January 1925.

Johnson, K. S., "Tansmission Circuits for Telephonic Communication," D. Van Nostrand, 1925.

It will be recalled in the case of the telephone circuit that the introduction of inductance coils at regular intervals in the circuit produced a remarkable change in the transmission characteristic. Over a broad band of frequencies the attenuation was reduced and made fairly uniform over that range while beyond a critical frequency called the cut-off frequency the attenuation became very high. In the ideal filters with zero dissipation the transmission characteristics are of the same nature but more clear cut. Structures of this type with infinitely repeated sections will have one or more transmission bands of zero attenuation and one or more bands having infinite attenuation. The impedance characteristics of such a structure measured from certain characteristic points will be pure resistance more or less uniform in the transmission bands, and pure reactance in the attenuation bands. These terminations are mid-series; that is, the entering element being one-half of the normal series element; or mid-shunt; that is, the entering element being twice the impedance of the normal shunt element. The corresponding impedances are called the mid-series and mid-shunt characteristic or iterative impedances.

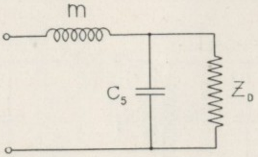

Fig. 8—Electrical equivalent of simple low pass type of network which occurs frequently in this work

If we retain the first few sections of such a structure and terminate them with a resistance which is equal to the resistance impedance of the infinite line from which they were taken, the characteristics are substantially unchanged. It is understood, of course, that this resistance equals approximately the resistance impedance of the remainder of the infinite line at most of the frequencies in the transmission band in which we are interested.

The presence of small amounts of damping in the various elements also has but slight effect on the general characteristics. These results could in general be readily applied to the various telephone transmission problems because the source and load between which the filter system was inserted generally had or could be made to have a resistance impedance nearly equalling the mid-series or mid-shunt impedance of the filter within the transmission band. The filter and terminating impedances may then be said to be matched. Where adjacent sections in the filter have impedances similar in character but different in absolute magnitude they may be joined by a suitable transformer.

Many early attempts were made to design mechanical transmission systems having a wide frequency range in which highly damped single or multi-resonant systems were employed. In these attempts both of the obvious methods of increasing the damping were used, namely, that of adding a resistance to the system and that of increasing the value of the compliance and decreasing mass in such proportion as to maintain the same natural frequency. The former of these methods reduces the sensitivity of the system at the point where it is most efficient (See Fig. 9), while the second method increases the response at the points where the system is less sensitive, namely, away from its resonance point. Fig. 9 shows four curves—first, a singly resonant system, Curve A; second, the same system with friction added, Curve B; third, the same system without the added friction but with an increase in compliance and a decrease in mass such that the natural period remains the same, Curve C; and fourth, a band pass type of circuit whose resistance impedance is the same as that of the system shown in Curve A. (See Curve D.)

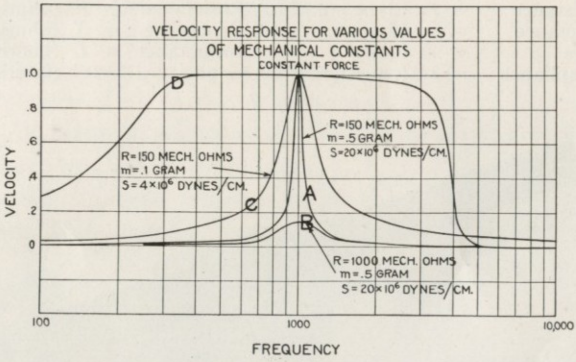

Fig. 9—Velocity response for various values of mechanical constants

The results of filter theory have shown how these resonances should be coordinated so that when a proper resistance termination is used high efficiency and equal sensitivity are obtained over a definite band of frequencies by elimination of response to all frequencies outside the band. With the electrical case of a repeated filter, each section considered by itself resonates at the same frequency but when combined into a short-circuited filter of n sections, there will be n natural frequencies. However, when such a system is terminated with a resistance which equals the nominal characteristic impedance in the transmission band, uniform response in the terminating resistance is obtained over the entire band.

DETAILED ANALYSIS OF MECHANICAL AND ELECTRICAL ANALOGS [7]

Before going on with a detailed treatment of the electrical analogs of the mechanical structures used in the problem of phonographic reproduction, a list of the corresponding quantities used in the two systems will be given, together with the symbols employed.

Mechanical			Electrical		
Force	= F	(dynes)	Voltage	= E	(volts)
Velocity	= v	(cm./sec.)	Current	= i	(amperes)
Displacement	= s	(cm.)	Charge	= q	(coulombs)
Impedance or mechanical ohms	= z	(dyne sec./cm.)	Impedance	= Z	(ohms)
Resistance	= r	(dyne sec./cm.)	Resistance	= R	(ohms)
Reactance	= x	(dyne sec./cm.)	Reactance	= X	(ohms)
Mass	= m	(gms.)	Inductance	= L	(henries)
Compliance	= c	(cm./dyne)[8]	Capacity	= C	(farads)

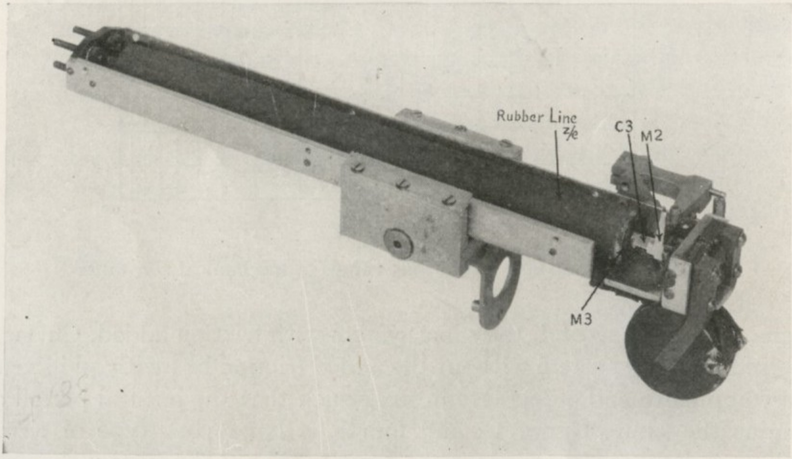

Fig. 10—This figure shows an electromagnetic recorder complete except for the bottom of the case

In addition to the above certain other quantities such as angular displacement, pressure and impedance per unit area, and a few others which have no direct electrical analog will be used. These quantities,

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[7] The authors wish to express their appreciation to Mr. E. L. Norton for his courtesy in working out the mathematics of the mechanical and electrical analogs which are shown in this paper.

[8] H. W. Nichols, "Theory of Variable Dynamical Electrical Systems," *Phys. Rev.* Vol. 10, 1917.

however, are either standard in the literature or may always be reduced to those given above.

As illustrations of the general methods employed certain important portions of the reproducer will be considered in detail. Considering first the electrical analog of the air chamber[9] between the diaphragm and horn, we make use of the following list of symbols (see Figs. 3, 4, 15 and 16):

m_3 = Effective mass of diaphragm in grams;
A_1 = Equivalent area of diaphragm in cms^2;
c_6 = Compliance of edge of diaphragm;
c_7 = Compliance of air chamber;
A_2 = Area of throat of horn;
z_h = Impedance of horn—Vector ratio of applied force at the throat of the horn to the resultant linear velocity of the air;
s_1 = Displacement of diaphragm;
v_1 = Velocity of diaphragm;
s_2 = Displacement of air in throat of horn;
v_2 = Velocity of air in throat of horn;
P_0 and V_0 = Initial pressure and volume of air-chamber;
F = Force applied to diaphragm;
p = Small change of pressure in air-chamber.

For a small change p in the pressure within the air-chamber we have:

$$p = \frac{n(A_1 s_1 - A_2 s_2)P_0}{V_0} \tag{1}$$

where $n = 1$ for an isothermal change and 1.4 for an adiabatic change. For the case under consideration $n = 1.4$ very nearly.

If the horn opening is closed, $s_2 = 0$, and we get for the compliance of the air chamber as measured from the diaphragm

$$c_7 = \frac{s_1}{pA_1} = \frac{V_0}{np_0 A_1^2}.$$

We have the two force equations

$$m_3 \frac{dv_1}{dt} + \frac{s_1}{c_6} + pA_1 = F \tag{2}$$

$$z_h v_2 - pA_2 = 0 \tag{3}$$

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[9] The use of the air chamber to increase the loading effect of the horn on the diaphragm has been appreciated for a number of years. It has been used in telephone receivers, phonographs, and loud speaking receivers since their earliest developments. A treatment of the force equations of the air-chamber was given by Hanna & Slepian, "The Function and Design of Horns for Loud Speakers." Trans. *A. I. E. E.*, 1924, p. 393. The equivalent structure, however, was analysed as a compliance and resistance in series instead of in shunt.

or substituting the values of p and c_7

$$m_3\frac{dv_1}{dt}+\frac{s_1}{c_6}+\frac{1}{c_7}\left[s_1-\left(\frac{A_2}{A_1}\right)s_2=F\right] \tag{4}$$

$$z_h v_2+\frac{1}{c_7}\left[\left(\frac{A_2}{A_1}\right)^2 s_2-\left(\frac{A_2}{A_1}\right)s_1\right]=0 \tag{5}$$

If $v_1=j\omega s_1$, etc.

$$z_1v_1-z_mv_2=F$$
$$z_2v_2-z_mv_1=0$$

where

$$z_1=j\left(\omega m_3-\frac{1}{\omega c_6}-\frac{1}{\omega c_7}\right),$$

$$z_2=\left[z_h-j\left(\frac{A_2}{A_1}\right)^2\frac{1}{\omega c_7}\right],$$

$$z_m=-j\left(\frac{A_2}{A_1}\right)\frac{1}{\omega c_7}.$$

Considering now the analogous electrical circuit, and assuming the velocity, current, force and voltage to vary sinusoidally, we have the parallel relationship for the steady state conditions:

$$L_3\frac{di_1}{dt}+\frac{q_1}{C_6}+\frac{1}{C_7}\left[q_1-\left(\frac{N_2}{N_1}\right)q_2\right]=E,$$

$$Z_h i_2+\frac{1}{C_7}\left[\left(\frac{N_2}{N_1}\right)^2 q_2-\left(\frac{N_2}{N_1}\right)q_1=0.\right.$$

where $\dfrac{N_2}{N_1}$ = turns ratio of ideal transformer (Fig. 4).

If $i_1=\mathrm{j}\omega q_1$, etc.

$$Z_1i_1-Z_mi_2=E$$

$$Z_2i_2-Z_mi_1=0$$

where

$$Z_1=j\left(\omega L_3-\frac{1}{\omega C_6}-\frac{1}{\omega C_7}\right),$$

$$Z_2=\left[Z_h-\mathrm{j}\left(\frac{N_2}{N_1}\right)^2\frac{1}{\omega C_7}\right],$$

$$Z_m=-j\left(\frac{N_2}{N_1}\right)\frac{1}{\omega C_7}.$$

The last five equations in each case give the complete solution of the network. By analogy between the two sets of equations, therefore, the air-chamber corresponding in the electrical case to a shunt capacity, c_7 is spoken of as a shunt compliance, $c_7=\frac{V_0}{nP_0A_1{}^2}$, together with a transformer inserted before the horn, which has an equivalent turns ratio equal to the ratio of the areas of the diaphragm and horn openings.

Taking up now the somewhat different illustration of the needle arm, the following symbols are needed (Figs. 5, 6, 15, 16):

l_1 = Distance from pivot point to end of needle;
l_2 = Distance from pivot point to center of "spider" (Fig. 15);
I = Moment of inertia of needle arm;
m_1 = Apparent or equivalent mass of arm as measured from the center of the spider

$$=\frac{I}{l_2{}^2};$$

c_1 = Compliance of needle point;
c_2 = Compliance of bearing to turning of the needle arm, as measured from end of arm at the spider;
c_3 = Compliance of end of needle arm attached to spider;
s_1 = Displacement of tip of needle;
s_2 = Displacement of end of arm at the spider;
s_3 = Displacement of spider;
z_s = Mechanical impedance of spider and remainder of structure = Vector ratio of applied force to resultant velocity;
θ = Angular displacement of needle arm;
F = Applied force at needle point.

We have the three force equations:

$$\frac{s_1-l_1\theta}{c_1}=F \tag{6}$$

$$I\frac{d^2\theta}{dt^2}+\frac{(l_1\theta-s_1)l_1}{c_1}+\frac{\theta l_2{}^2}{c_2}+\frac{(l_2\theta-s_3)l_2}{c_3}=0 \tag{7}$$

$$\frac{s_3-l_2\theta}{c_3}+z_s\frac{ds_3}{dt}=0 \tag{8}$$

Replacing θ by $\frac{s_2}{l_2}$ and I by $m_1 l_2^2$ gives:

$$\frac{s_1 - \frac{l_1}{l_2} s_2}{c_1} = F \tag{9}$$

$$m_1 \frac{d^2 s_2}{dt^2} + s_2 \left[\left(\frac{l_1}{l_2} \right)^2 \frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3} \right] - \frac{l_1}{l_2} \frac{s_1}{c_1} - \frac{s_3}{c_3} = 0 \tag{10}$$

$$\frac{s_3 - s_2}{c_3} + z_s \frac{ds_3}{dt} = 0 \tag{11}$$

Considering now the parallel mechanical electrical circuits, and assuming as before sine functions for v, i, F, and E, we have:

Mechanical Case, substituting $v_1 = j\,\omega\, s_1$, etc., in the last equations:

$$-j \frac{v_1}{\omega c_1} + j \frac{l_1}{l_2} \frac{v_2}{\omega c_1} = F,$$

$$j v_2 \left[\omega m_1 - \left(\frac{l_1}{l_2} \right)^2 \frac{1}{\omega c_1} - \frac{1}{\omega c_2} - \frac{1}{\omega c_3} \right]$$

$$+ j \frac{l_1}{l_2} \frac{v_1}{\omega c_1} + j \frac{v_3}{\omega c_3} = 0,$$

$$j \frac{v_2}{\omega c_3} + v_3 \left(z_s - j \frac{1}{\omega c_3} \right) = 0.$$

Electrical Case, with ideal transformer of turns ratio $\frac{N_2}{N_1}$:

$$-j \frac{i_1}{\omega C_1} + j \left(\frac{N_2}{N_1} \right) \frac{i_2}{\omega C_1} = E,$$

$$j i_2 \left[\omega L_1 - \left(\frac{N_2}{N_1} \right)^2 \frac{1}{\omega C_1} - \frac{1}{\omega C_2} - \frac{1}{\omega C_3} \right] + j \left(\frac{N_2}{N_1} \right) \frac{i_1}{\omega C_1} + j \frac{i_3}{\omega C_3} = 0,$$

$$j \frac{i_2}{\omega C_3} + i_3 \left(Z_s - j \frac{1}{\omega C_3} \right) = 0.$$

The analogy between the two sets of equations is quite obvious. It will be noticed that the effect of the lever arm is to introduce an equivalent transformer of a turns ratio which is the reciprocal of the corresponding lengths of the arms.

The general method of deducing the equivalent electric circuits should be clear from the above illustrations of the air-chamber and of the needle arm. For example, in the spider section, Fig. 15, the mass is driven directly by the force from the needle-arm compliance, there being a small series compliance in the connection owing to bending of connecting rod. The diaphragm is connected through the compliance of the prongs of the spider. The equivalent circuits are shown in Figs. 7 and 16.

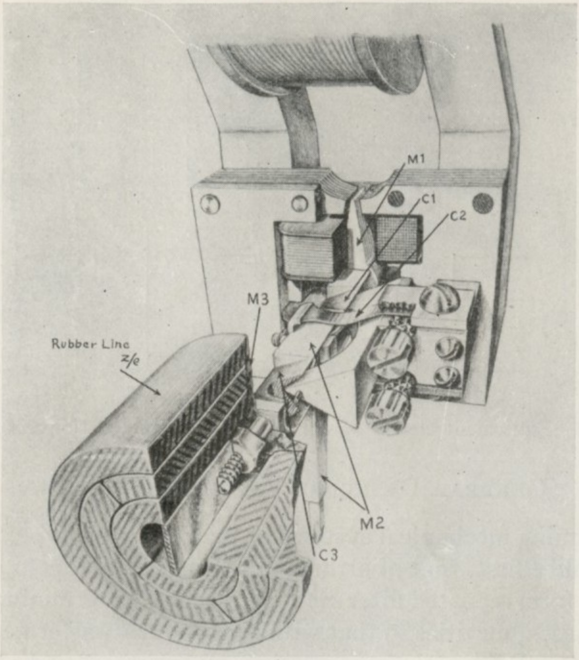

Fig. 11—Detailed drawing of the mechanical filter of an electromagnetic recorder. (Lettering same as in Fig. 12)

The equations of this network may be obtained from the equations for the needle arm by placing c_1 equal to zero, taking a unity ratio transformer, and substituting m_2 for m_1, c_4 for c_2, c_5 for c_3 and z_d for z_s.

Another type of network which occurs frequently in the building of mechanical vibrating systems is represented diagrammatically in Fig. 8. This is clearly a particular case of Fig. 7 with c_4 made infinite.

By combining Fig. 6 representing the needle arm, Fig. 7, representing the spider section and Fig. 4 representing the diaphragm, air-chamber and horn, the complete reproducer may be built up. The resultant network is shown in Fig. 16. Since methods are available in the theory of electric wave filters to determine the proper values of the elements of the complete network for a free transfer of energy throughout an assigned frequency band, the analogous mechanical elements may be determined in the same manner.

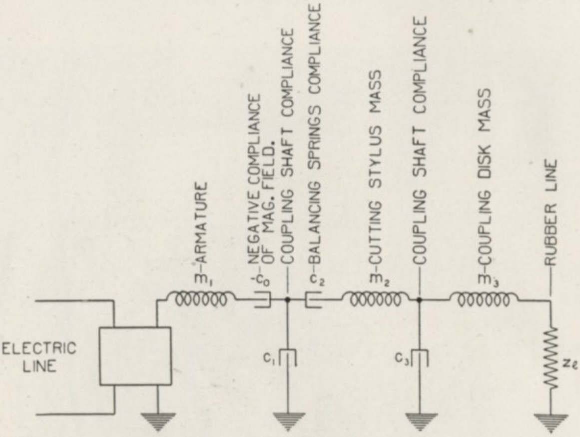

Fig. 12—Equivalent electric circuit of the electromagnetic recorder

GENERAL DESIGN OF MECHANICAL SYSTEMS

In designing mechanical systems of the band pass type, the problem is three fold—first, that of arranging the masses and compliances such that they form repeated filter sections; second, determining the magnitude of these quantities so that with or without transformers the separate sections all have the same cut-off frequenceis[10] and characteristic impedances; third, to provide the proper resistance termination. Where the transmitted mechanical power has not been radiated as sound this third part has been one of the most difficult to fulfill.

In designing these systems, practical difficulties arose—first, the difficulty of insuring that the parts vibrated in the desired degrees of freedom only, and second, the difficulty of determining the magnitudes of the various effective masses, compliances and resistances. Before the work to be described could be carried out practically it became necessary to develop a method of measuring mechanical impedances[11].

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[10] It is of course permissible to have a section having a higher cut-off than the others provided its characteristic impedance is the same as that of the others over the transmission band of those having the lower cut-off.

[11] Kennelly, A. E. and Affel, H. A., "The Mechanics of Telephone Receiver Diaphragms, as Derived from their Motional Impedance Circles," *Proc. A. A. A. S.*, Vol. 51, No. 8, November, 1915.

Kennelly, A. E. and Pierce, G. W., "The Impedance of Telephone Receivers as Affected by the Motion of their Diaphragms," *Proc. A. A. A. S.*, Vol. 48, No. 6, September, 1912.

Such a method has been developed which at the present time covers a range of frequencies from somewhere below 50 to about 4,500 pps. Work is still being continued to extend the method to the higher frequencies. This method of measurement has been very useful not only in determining the magnitudes of the impedances in the degrees of freedom in which it is desired that they shall operate, but in determining the impedances to motion of the various parts in directions in which they should not be permitted to vibrate. In connection with the measurement of the magnitudes of the parts in the desired degrees of freedom this method enables us to determine the constants of the mechanical networks under their conditions of operation. Experience so far has indicated that when all the degrees of freedom have been taken into account and when the dynamic axes of vibration have been properly chosen, the static and dynamic constants of the parts are the same, and it is then possible to check the parts by simple static measurements. In the early attempts to build these systems very large discrepancies between the static and dynamic characteristics were found.

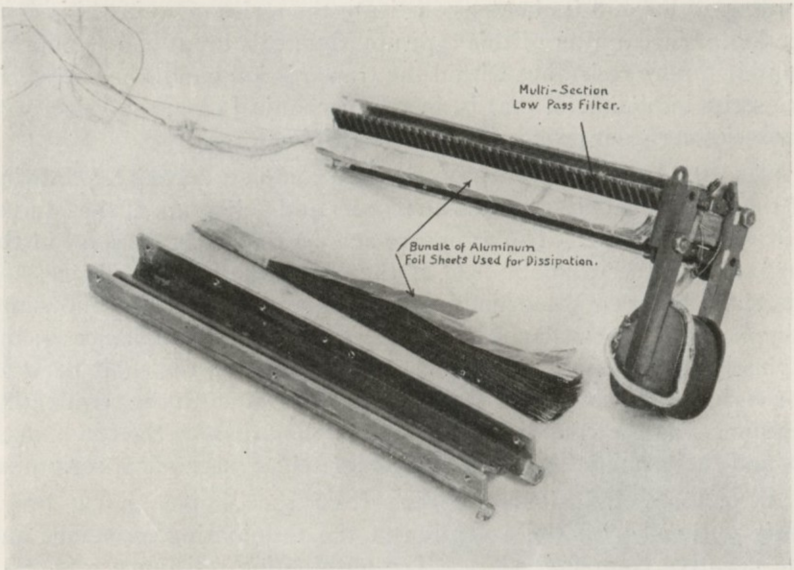

Fig. 13—Electromagnetic recorder using lumped loaded termination
The method of furnishing dissipation to the lumped loaded line is shown

THE RECORDER

One of the early practical phonographic applications of electric filter design to mechanical problems was the development of an electromagnetic recorder. The instrument as finally constructed is essentially a properly terminated three-section mechanical filter in which the recording stylus and its holder constitute the series mass in the second section. Since a filter of this type appears at its input end as approximately a pure resistance within the transmission band, the current in the series inductances, that is, in the mechanical case, the velocity of the series masses is proportional to the driving force.

Figs. 10, 11 and 12 show respectively, a complete recorder, a drawing of the mechanical filter of such a recorder and a diagram of the equivalent electric circuit. The armature acts as the series mass m_1 in the first section; the magnetic field as the series negative compliance, $-c_0$; the shaft between the armature and the stylus holder as the shunt compliance c_1; the balancing springs as the series compliance c_2; the stylus holder and the stylus as the series mass m_2; the shaft between the stylus holder and the disk, coupling the system to the terminating resistance, as the compliance c_3; the coupling disk as the series mass m_3 and the terminating line as approximately a mechanical resistance.

All of these equivalents are seen from the simple analog previously outlined with the exception of the terminating resistance and the negative compliance, $-c_0$. The terminating resistance was originally made up of a series of filter sections of lumped series masses and shunt compliances with a small amount of damping added to the motion of each of the series masses. Fig. 13 shows one of the early recorders equipped with this type of resistance termination. The reason for using such a complicated termination lies in the fact that most of the known mechanical resistances have values which are functions of frequency or of amplitude or both. Also in most cases, the mechanical resistance is accompanied by either a mass or compliance reactance. By using a multi-section filter which is sufficiently long so that a wave entering it will be essentially absorbed before it has reached the far end, been reflected and returned to the entering end, it has been possible to use imperfect types of damping for this line and still obtain over the desired band, an essentially pure resistance at the input end.

More recently a continuous line has been developed which is much easier of practical attainment than the complicated lump-loaded filter. The recorder shown in Fig. 10 is so equipped.

Fig. 14 shows calibration curves of three types of recorders. The bottom curve shows an early type of highly damped singly resonant system. The middle curve is a calibration of a low pass mechanical filter type using lumped loading in the resistance line. The upper curve shows the calibration of the recorder shown in Fig. 10.

The compliance $-c_0$ is a mechanical quantity for which there is no simple electric analog. In a balanced armature type of structure such as that shown in Fig. 11, the action of the field on the armature, when it is at its center point, is balanced. If, however, the armature be deflected, a small distance from this equilibrium, there is exerted by the magnetic field a torque tending to pull the armature further away from its center position. The value of this torque for small amplitudes is proportional to the angular displacement. It is therefore seen that this quantity is of the nature of a compliance but that the back force is in a reverse direction to that required for a positive compliance.

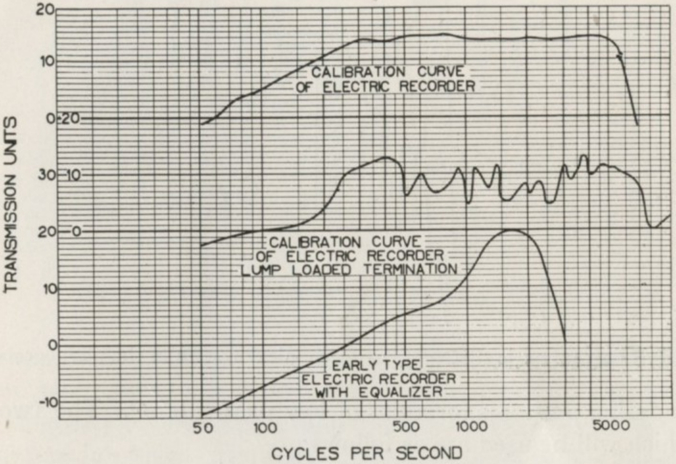

Fig. 14—Calibration curve of three types of electromagnetic recorders

Design of the Reproducing Apparatus

As the analogy between the mechanical and electrical filter is more perfectly shown in the case of the reproducing equipment, its detailed quantitative description will now be given. Figs. 15 and 16 show respectively a diagram of the reproducing system and its equivalent electric circuit. From these diagrams it is evident which units in the mechanical system correspond to the various electrical parts. As the series compliances c_2, c_4 and c_6 have been made so large that the low frequency cut-off caused by them lies well below the low frequency cut-off of the horn, an inappreciable error is introduced in using for design purposes formulas of low pass filters[12]. The two formulas which will be used are as follows:

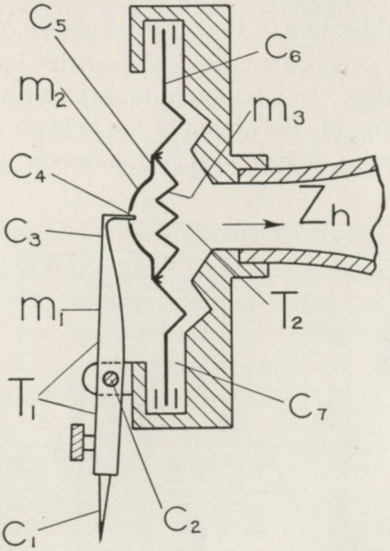

Fig. 15—Diagrammatic sketch of the mechanical system of the phonograph

$$f_c = \frac{1}{\pi}\sqrt{\frac{1}{mc}} \qquad (12)$$

Where

f_c = cut-off frequency of a lumped transmission system in cycles per second
c = shunt compliance per section in centimeters per dynes
m = series mass per section in grams

$$z_o = \sqrt{\frac{m}{c}} \qquad (13)$$

where z_0[13] is the value of characteristic impedance over the greater part of the band range.

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[12] Campbell, G. A., "On loaded lines in Telephonic Transmission," *Phil. Mag.*, March, 1903.

[13] z_0 may be called nominal mid-shunt or mid-series impedance. Their actual values in the transmission band being at any frequency *f*.,

$$\text{mid-series} = z_0\sqrt{1-\left(\frac{f}{f_c}\right)^2} \qquad \text{mid-shunt} = \frac{z^0}{\sqrt{1-\left(\frac{f}{f_c}\right)^2}}$$

Equations (12) and (13) which form the basis of the design work contain four variables, f_c, c, m and z_0. It is, therefore, necessary to determine two of them by the physical requirements of the problem after which the other two are determined. The upper cut-off frequency f_c was arbitrarily chosen at 5000 pps. as a compromise between the highest frequency occurring on the record and the increase in surface noise as the cut-off is raised. The choice of the other arbitrarily set variable came after considerable preliminary experimenting and was fixed by the difficulty of obtaining a diaphragm which is light enough and has a large enough area. Hence the effective mass of the diaphragm m_3, (Figs. 15–16) was fixed at 0.186 grams which value can be obtained by careful design. The effective area can be made as large as 13 square centimeters. For convenience let the arbitrary value chosen for $f_c = \bar{f}_c$ and the value of $m = \overline{m}_3$.

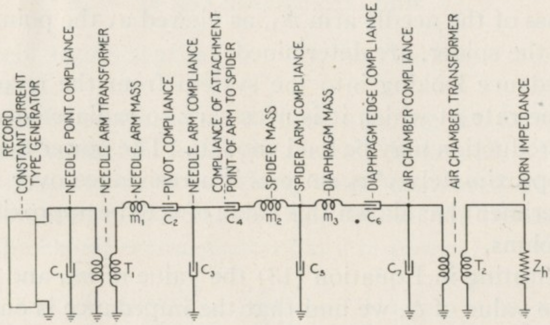

Fig. 16—Electric equivalent of the system shown in Fig. 15

Solving Equations (12) and (13) for c and z_0, we get

$$c = \frac{1}{\pi^2 \bar{f}_c^{\,2} \overline{m}_3}, \tag{14}$$

$$z_0 = \pi \bar{f}_c \overline{m}_3; \tag{15}$$

also

$$z_0 = \frac{1}{\pi c \bar{f}_c} \tag{16}$$

In order to obtain the low value of mass mentioned, with a large enough area, it was necessary to make the diaphragm of a very stiff light material. An aluminum alloy sheet 0.0017 in. thick was chosen and concentrically corrugated as shown in Figs. 17 and 18. These corrugations are spaced sufficiently close so that the natural periods of the flat surfaces are all above $\bar{f}_c$. To insure that this central stiffened portion should vibrate with approximate plunger action, which is more efficient than diaphragm action, it is driven at six points near its periphery.

Reference to Figs. 15 and 16 and Equation (14) shows that the compliance of the air chamber c_7, of the spider legs c_5 and shunt tip of the needle arm c_3 are determined. Also the mass of the spider m_2 and the effective mass of the needle arm m_1, as viewed at the point where it is attached to the spider, are determined.

The impedance looking into the system from the record is determined by the rate at which it is necessary to radiate energy in order that the reproduction may be loud enough. The power taken from the record is approximately $v^2 z_0$ since z_0 is a resistance over most of the band. Experiment has shown this value of z_0 to be approximately 4500 mechanical ohms.

But substituting in Equation (13) the value of $\overline{m}_3$, and from Equation (14) the value of c_5, we find that the impedance is only 2920 mechanical ohms. It is, therefore, necessary to use a transformer whose impedance ratio is $\frac{4500}{2920}$. From this and a knowledge of filter structures the needle-point compliance can be determined. The value obtained is easily realized with commercial types of needle.

It will be noted that the record is shown in Fig. 16 as a constant current generator, *i. e.*, a generator whose impedance appears high as viewed from the needle point. That this is necessary is obvious when it is remembered that, if the impedance looking back into the record were to equal the impedance of the filter system, the walls of the record would have to yield an amount comparable with one-half the amplitude of the lateral cut. This would cause a breakdown of the record material with consequent damage.

The design of the system is, therefore, complete except for the resistance termination which is supplied by the horn for all frequencies above its low frequency cut-off. The characteristics of the horn will be dealt with later. The resistance within the band looking in at the small end of the horn is $G A_2$ where G equals the mechanical ohms per square centimeter of an infinite cylindrical tube of the same area, and A_2 equals the area in square centimeters of the small end of the horn.

Let A_1 = the effective plunger area of the diaphragm (as previously mentioned this is 13 sq. cm.). The impedance looking back at the diaphragm is

$$z_0 = \pi \bar{f}_c \overline{m}_3 = 2920 \text{ mechanical ohms}$$

from Equation (15), and the impedance looking at a horn whose small end area equals A_2 is

$$z_h = r_0 = A_2\,G \tag{17}$$

Substituting

$$A_2 = 13 \text{ sq. cm.}$$
$$G = 41 \text{ ohms per cm.}^2$$

we get

$$z_h = r_0 = 533 \text{ mechanical ohms}$$

This is entirely insufficient so that the air-chamber transformer becomes necessary.

To calculate the necessary ratio of areas on the two sides of the air-chamber transformer, the following formula is needed. The formula assumes the chamber to be relatively small compared with all wave lengths of the sound to be transmitted, that is, the pressure changes throughout the chamber are substantially in phase.

$$\frac{z_0}{z_h} = \left(\frac{v_2}{v_1}\right)^2 = \left(\frac{F_1}{F_2}\right)^2 = \left(\frac{A_1}{A_2}\right)^2 \tag{18}$$

where

z_0 = the impedance of the primary side of the transformer in mechanical ohms;

z_h = the impedance on the secondary side of the transformer in mechanical ohms, *i.e.*, the horn impedance;

v_1 = mechanical current, *i.e.*, velocity on the primary side of the transformer in centimeters per second;

v_2 = mechanical current on the secondary side of the transformer in centimeters per second;

F_1 = alternating force on primary side of air-chamber transformer in dynes;

F_2 = alternating force on secondary side of air-chamber transformer in dynes;

A_1 = effective area working into the primary side of the air-chamber in centimeters squared;

A_2 = effective area working into the secondary side of the air-chamber in centimeters squared.

The characteristic impedance of the line on the diaphragm or primary side of the air-chamber as shown by equation (15) is

$$z_0 = \pi \bar{f}_c \bar{m}_3. \tag{19}$$

From Equation (17) the characteristic impedance on the horn or secondary side is

$$z_h = GA_2. \tag{20}$$

Therefore,

$$\left(\frac{A_2}{A_1}\right)^2 = \frac{z_h}{z_0} = \frac{GA_2}{\pi f_c m_3} \tag{21}$$

and solving this for A_2, we get

$$A_2 = \frac{GA_1^2}{\pi f_c m_3} \tag{22}$$

The equivalence of the air-chamber to a transformer shunted by a compliance is shown earlier in the paper.

In applying the foregoing method of design to a practical structure, a number of design problems had to be solved. The construction of the diaphragm and the method by which it is actuated have been already described, except for the tangential corrugations constituting the series compliance. The use of these corrugations results in the value of the series compliance being practically independent of the nature of the clamping, and has eliminated a tendency to "rattle" introduced by unevenness in the clamping surfaces.

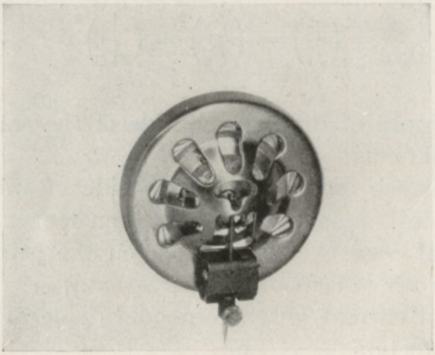

Fig. 17—Photograph of mechanical reproducing system without the horn

Another feature in connection with the sound box is the needle-arm bearing shown in Figs. 17 and 18. Ordinary knife-edge bearings are not sufficiently rigid as fulcrums and the rotational reactance as well as the rotational resistance is undesirably large. A construction which has been found to meet the necessary requirements is the ball bearing type with the steel balls held in position by magnetic pull. By making the ball-containing case of soft steel and magnetizing the shaft, it has been possible to manufacture this bearing reliably and cheaply.

The horn which has been used as a terminating resistance to the mechanical filter structure is a logarithmic one. The general properties of logarithmic horns have been understood for some time.[14]

There are two fundamental constants of such a horn—the first is the area of the large end and the second the rate of taper. The area of the mouth determines the lowest frequency which is radiated satisfactorily. The energy of the frequencies below this is largely reflected if it is permitted to reach the mouth.

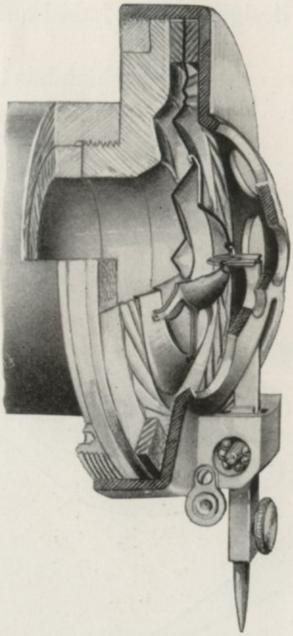

Fig. 18—Sectional drawing showing construction of the system shown in Fig. 17

From the equations given by Webster, [14] it can be shown that all logarithmic horns have a low frequency cut-off which is determined by the rate of taper. If the rate of taper is so proportioned that its resulting cut-off prevents the lower frequencies from reaching the horn mouth, the horn will then radiate all frequencies reaching its mouth and very little reflection will result.[15] It is, therefore, possible to build a horn having no marked fundamental resonance.

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[14] Webster, A. G., "Acoustical Impedance and Theory of Horns and Phonograph," *Proc.* Nat. Acad. of Sci., 1919.

[15] The authors wish to express their appreciation in this connection of the work of Mr. P. B. Flanders who carried out the mathematical investigation of these relationships and to Mr. A. L. Thuras who checked experimentally the mathematical theory.

Since the characteristics of the horn are determined by the area of its mouth and by its rate of taper the length of the horn is determined by the area of the small end. This area is determined in turn by the mechanical impedance and effective area of the system which it is terminating, as shown in Equation (22). It is seen, therefore, that the length of the horn should not be considered as a fundamental constant. A paper describing the design of horns based on these principles is being prepared.

An interesting feature of the horn which has been built commercially is its method of folding. The sketch in Fig. 19 shows a shadow picture of the horn. It will be noticed that the sound passage is folded only in its thin direction, which permits the radius of the turns to be small and thereby makes the folding compact.

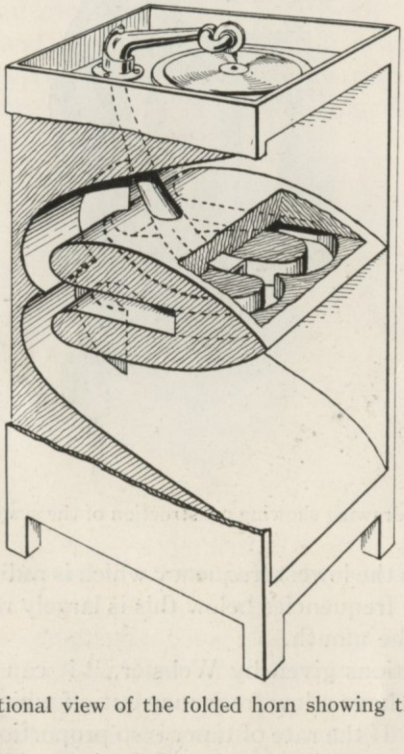

Fig. 19—Sectional view of the folded horn showing the air passage

Fig. 20 shows the frequency characteristic of a phonograph designed as shown above with a logarithmic horn whose rate of taper and area of mouth opening place the low cut-off at about 115 cycles. It also shows the characteristics of one of the best of the old style phonographs. Curve *A* represents the new machine, while Curve *B* represents the old style standard machine. Since the vertical scale used in this graph is logarithmic the full difference between the two instruments does not appear at first glance. Some idea as to the magnitude of this difference can be obtained, however, by noting that the points P_1 on the curve of the old machine stands at a power level about 250 times as great as P_2.

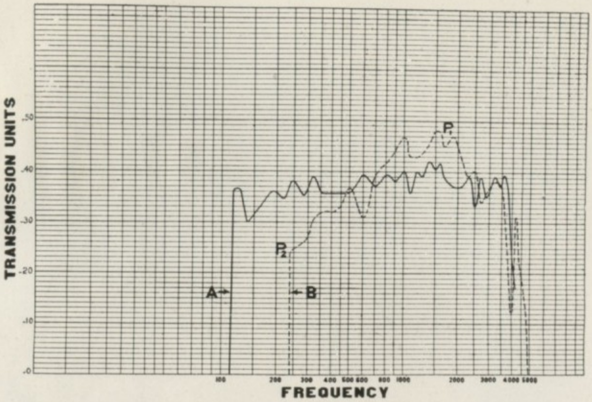

Fig. 20—Response frequency characteristic of two phonographs. Curve *A* shows the characteristic of the band pass filter type described. Curve *B* shows the characteristic of one of the best commercial machines previously on the market

Fig. 21—Bridge for measuring mechanical impedance, being used for determining the impedance of a phonograph horn