MODERN GRAMOPHONES
AND
ELECTRICAL REPRODUCERS

Modern Gramophones and Electrical Reproducers

By

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With 120 Diagrams and Half-Tone Illustrations

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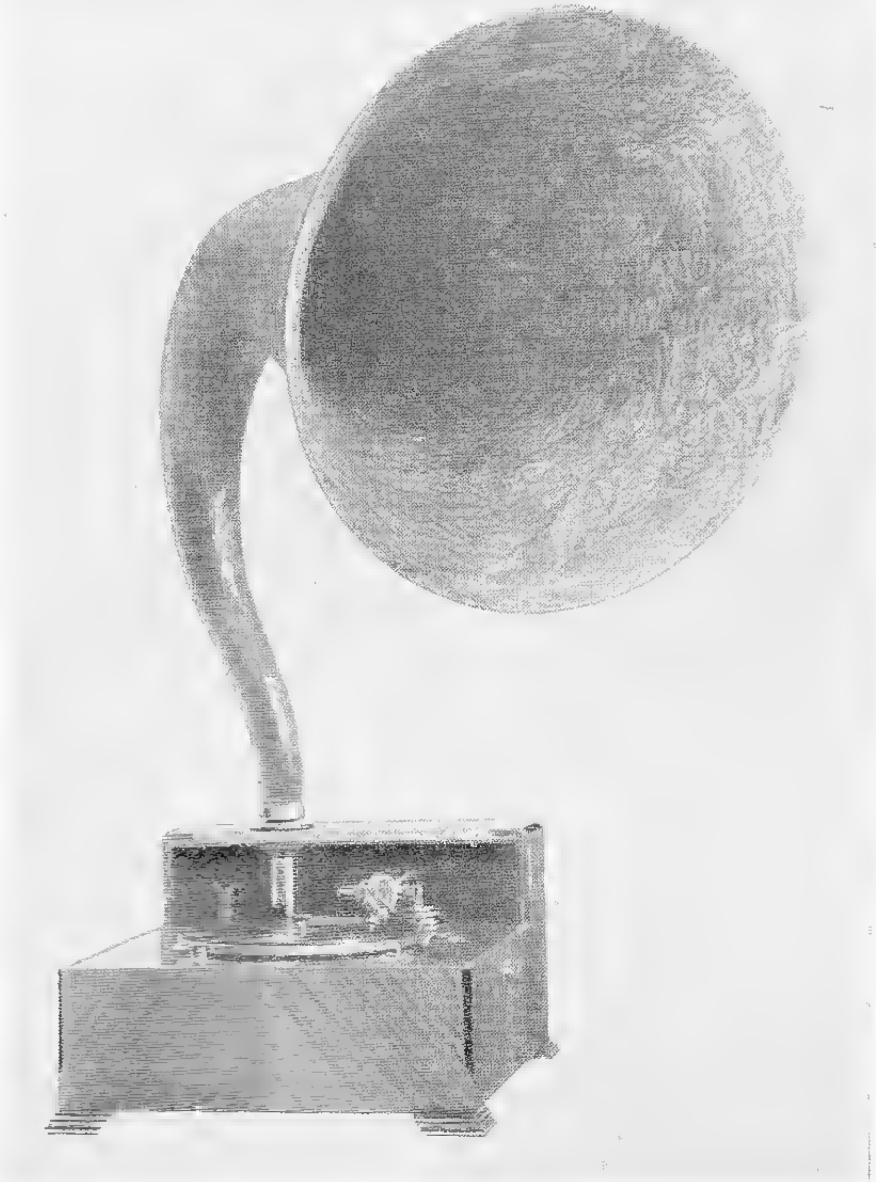

Fig. 24. E.M.G. External Horn Model.

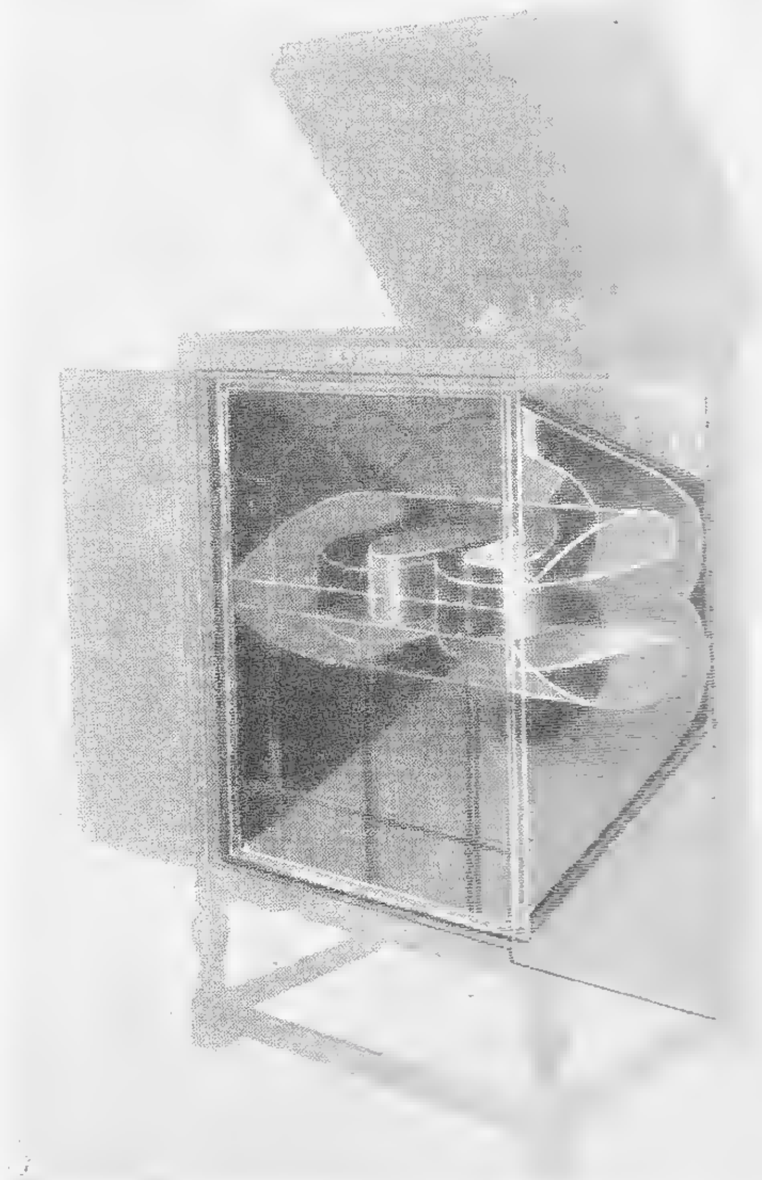

Fig. 25. H.M.V. Re-entrant (phantom view).

TWO MODERN GRAMOPHONES

Frontispiece]

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FOREWORD

There is little for the writer of a Foreword to say on behalf of a book which so completely fulfils its purpose as this one. A eombination of Mr. Webb's vast experience and knowledge, with Mr. Wilson's mathematical genius for being right could not be improved upon by any combination of experts of whieh I am aware. It has been my privilege and pleasure for some years now to rely upon the judgment of the two authors in all matters connected with the technicalities of the gramophone. What I should have done without their help and advice, when faced by the introduction of electric recording, I tremble to think.

The time has long passed when the writer of a Foreword to a book of this size, exclusively about the gramophone, would have begun his address by a defence of the instrument itself. We take for granted the value of the gramophone nowadays; but if anybody has any lingering doubt of the gramophone's importance, he has only to turn over a few pages of this book to be immediately reassured. Mr. Wilson and Mr. Webb would be the last people to claim that they have said the final word about the gramophone of to-day; but they have in this volume built up such a solid foundation that it is not rash to suggest that for some time to come it will not be shaken, and that further information will be in the nature of a supplement

The greatest practical advance of all has been in the development of an electrical system of recording; but this is not by any means the only benefit. The application of electrical "impedance" methods to mechanical theory has provided a new method of attacking difficult problems which promises to be one of great power. In one sense, it is merely a new notation, a new and simpler way of expressing complicated ideas in a sort of mental shorthand. But in the long run, discoveries of this kind are precisely those which have the greatest effect on technical progress.

In this book we have attempted to give an elementary account of the new principles. Though the subject matter is based on a practical experience of gramophones extending over twenty years, the actual arrangement of it, and the theoretical explanations which link together the mass of experimental facts, are the result of researches of the past five or six years only. It is only during that period that the art has also become a science. So far as the authors are aware, this is the first attempt that has been made to give a connected and balanced account of modern gramophone technique. There are a number of papers in various scientific journals, but these are either confined to generalities or deal only with certain aspects of the subject.

Naturally, in a first attempt of this sort, there will be many things that could have been better said, many ideas that time will show to be merely of ephemeral value, and many omissions to be rectified in the future. Developments are now taking place at such a pace, particularly in regard to electrical reproduction, that the near future may bring new apparatus as superior to our present instruments as these are to the gramophones and phonographs of yesterday. But the authors are confident that the fundamental principles are now well established and the paths of further progress clear. They trust, therefore, that their account will prove of service not only to the ordinary man who wishes to know the secrets behind this remarkable advance, but also to those who are their fellow-workers in the art. For this reason, the use of mathematical formulæ has not been avoided, though it has been kept within small limits and, wherever possible, a verbal explanation has been given to illustrate the particular principle under discussion. In addition, it has been thought desirable to reserve the more complicated ealculations for appendices rather than to interrupt the narrative in the text.

Acknowledgments are due, and are gratefully given, to the many people who have helped the authors in the preparation of the book: to the Gramophone Company ("H.M.V.") and the Columbia Graphophone Company, for their courtesy and kindness in supplying photographs and diagrams; to Mr. A. Hall, Chief Radio Engineer of Ferranti Ltd., for the oscillographs; to the *Wireless World* for permission to include pictures of the H.M.V. Electrical Reproducer and Pick-up which first appeared in that paper; and above all, to Mr. Compton Mackenzie, Mr. Christopher Stone and the "Expert Committee" of *The Gramophone* for encouragement and assistance both in the past and in the actual preparation of the book. To Mr. H. F. V. Little, B.Sc., Mr. J. Ainger Hall, B.Sc., who kindly read both manuscript and proofs, and to Mr. W. C. Wilson, who prepared the majority of the diagrams, we owe a special word of thanks.

CONTENTS

ERRATA

p. 32 *Fig.* 15 (*Caption*) : *For* Zc *read* Ze.

p. 39 *Line* 18 *should read :*

$$2\pi f L = \frac{1}{2\pi f C}, \text{ that is, when } f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

p. 40 *Add footnote to line* 7 :

It should be noted, however, that in combining impedances account has to be taken of phase relations. But by writing $Z = R + j X$, where j stands for $\sqrt{-1}$ and denotes that the reactance X is 90° out of phase with the resistance R, we can perform the algebraic operations indicated on pages 40, 41 and 42 and the phases will take care of themselves. If the resultant impedance is then expressed in similar form, this will indicate directly its resistance and reactance components.

p. 85 *Line* 11 : *Delete* cm^2.

Last line : *For* $\frac{A_0^2}{42{\cdot}8}$ *read* $\frac{A_0}{42{\cdot}8}$

p. 115 *Line* 20 *should read :*

where $m + n = M$. *etc.*

Line 26 *should read :*

$$m = \frac{\log (OP) - \log (op)_0}{1}$$

p. 217 *Fig.* 102 (*Caption*) :

5*th line :* *For* inpedance *read* impedance.

5*th*, 7*th and* 9*th lines :* *For* value *read* valve.

Footnote : *For* Davy *read* Davey.

p. 268 2*nd Col. line* 4 *should read :* ——, stiffness/mass ratio.

LIST OF ILLUSTRATIONS

HALF-TONE PLATES

DIAGRAMS IN TEXT

Modern Gramophones and Electrical Reproducers

CHAPTER I

SOUNDS AND SOUND-WAVES

I—1. Sound-waves.

When a body is set into vibration the material of which it is composed moves to and fro, dragging with it the surrounding air particles and thus rarefying or compressing the air in its vicinity. The motion of the air particles is communicated to adjacent particles which naturally move towards a rarefied space or away from a compression and this, in its turn, creates a compression or a rarefaction farther out. In this way a disturbance is propagated outwards to a distance, though the actual excursion to and fro of any single air particle is quite small. When this disturbance impinges on the ear the sensation of sound is produced.

If we were to take successive measurements of the pressure of the air at any point in the path of the disturbance, we should find that it increased up to a maximum, decreased again to normal and past normal down to a minimum, and then increased again up to normal and past normal to the maximum, and so on in succession. The propagation is in the form of a wave similar to the water waves with which we are familiar on the sea-shore except that in the latter case we are concerned with the height of the water above or below a standard level, whereas here we are concerned with the increase or decrease of pressure from normal atmospheric pressure; and that in the case of sound the wave may be propagated in three dimensions, whereas on the water surface there are only two.

I—2. Wave-front.

If instead of fixing our attention on a point in space and seeing what happens at successive instants of time at that point, we were to consider what is happening at different points at the same instant we should have a similar picture: at one place the wave would be at its crest (where the pressure is at its maximum), at another at its trough (pressure at its minimum). By this procedure, however, we can readily perceive an additional feature of interest: we can see what sort of shape a line of crests or a line of troughs takes up. It may be a straight line, as is not uncommon on a still sea-shore, or it may be a circle such as we get when we throw a stone into a pool, or it may be a complicated curve as on a rocky beach. In exactly the same way, the sound-wave from a vibrating body has a definite shape of "wave-front," but since in this case the wave spreads out through space and not merely on a surface, the wave-front is in the form of a surface instead of a line. Thus, we may have a "plane wave-front," in which case the points of maximum pressure all lie on a series of parallel planes, or a "spherical wave-front," in which case the crests lie on a series of concentric spheres, or a more complicated form which may be difficult to describe.

I—3. Velocity, Wave-length, Frequency, Amplitude.

Any disturbance which is propagated in the form of a simple wave has four fundamental characteristics :

(i) its *velocity* (v) is the speed with which the disturbance as a whole moves outwards.

(ii) its *wave-length* (λ) is the distance between successive crests or successive troughs.

(iii) its *frequency* (f) is the number of crests or the number of troughs which pass any point in a second ; that is, it is the number of times per second that the disturbance passes through its complete cycle of changes.

(iv) its *amplitude* (A) is the height above normal of any crest or the depth below normal of a trough.

The first three of these quantities, however, are not independent. Since f crests, distant λ from each other, pass any point in one second the distance travelled by the disturbance in one second is $f\lambda$, and thus the velocity of propagation $v=f\lambda$.

I—4. Simple and Complex Waves ; Phase.

The definitions just given apply, in strictness, only to the simplest form of waves. From certain mathematical properties which they possess these waves are known as "*sine-waves*" or "*simple-*

harmonic waves." Their shape is as shown in Fig. 1 below. All other forms of waves must be regarded as complex ; it can indeed be shown that

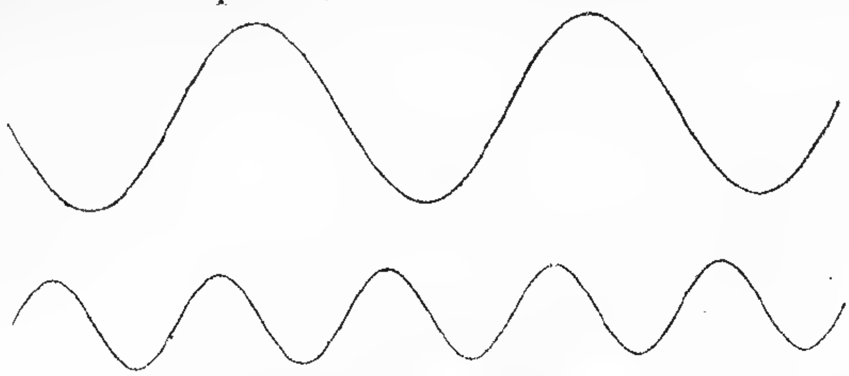


Fig. 1.—Sine-wave curves.

the most complicated form of vibration may be regarded as made up of a series of sine-waves of the type shown in Fig. 1, and that if a body vibrating

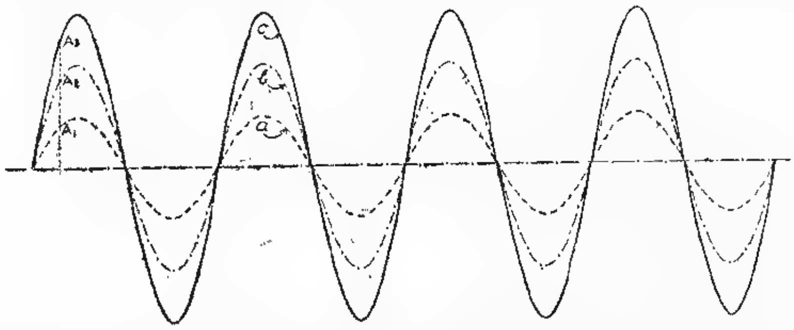


Fig. 2.—Addition of sine-waves of same frequency but different amplitudes.

in complicated fashion were suitably constrained any one of its simple constituent vibrations could be produced singly. Suppose, for example, we take

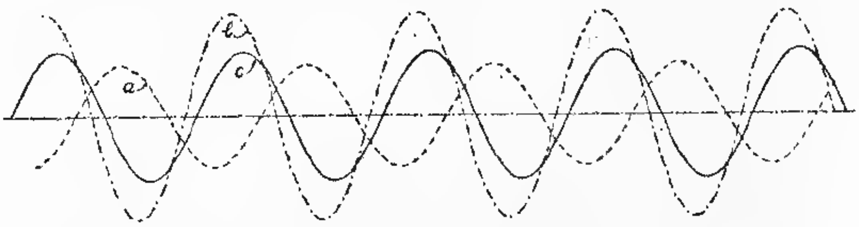


Fig. 3.—As in Fig. 2, but with difference of phase.

the simple waves shown in Figs. 2a and 2b and add together their effects ; the addition of the excursions A1 and A2 which occur at corresponding points give an excursion A3 in Fig. 2c, and if we perform the addition of the excursions for all points we get a wave as shown.

But now suppose that the wave 2b had been displaced a little to the right, that is that the crest of 2b does not occur at the same instant as the crest of 2a. In that case we should get a resultant wave

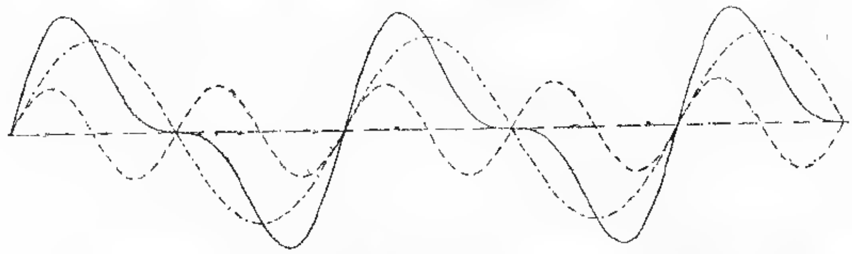


Fig. 4.—Addition of sine-waves of different frequencies and amplitudes.

as shown in Figs. 3a, 3b and 3c. In such a case as this the two simple waves are said to be " out of phase " by the interval between the two crests.

In these examples the simple waves had the same wave-length but different amplitudes. But it is equally possible to add together waves of the same amplitude and different wave-lengths or different

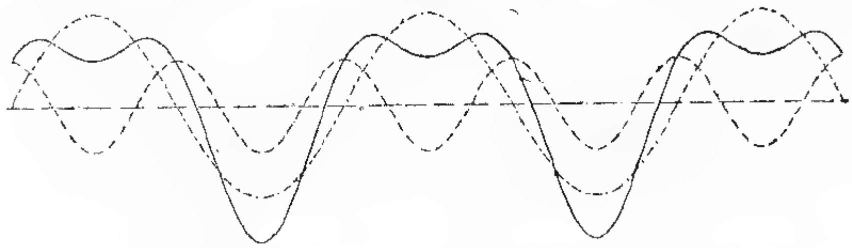


Fig. 5.—As in Fig. 4, but with difference of phase.

amplitudes and different wave-lengths. Thus, out of simple constituent waves a great variety of complex waves may be built up. In Figs. 4 and 5 the resultant waves obtained by adding simple waves of different wave-length and different amplitude are shown. It will be noticed that when the two constituent waves are in phase we get the maximum displacement for the resultant wave.

I—5. Analysis of Sounds.

Apart from mere duration, there are three properties by which we distinguish between sounds: *pitch*, *loudness* and *quality* or *timbre*. These properties must be identifiable in some way with the properties of the waves which produce the sensations. There are many simple experiments by which it may be shown that the pitch of a sound is dependent on the frequency of the wave. It is a natural assumption, too, and one which can readily be verified *a posteriori*, that the quality of the sound is determined by the wave-form or, in other words, by the characteristics of the simple sine-waves which are the constituents of the complex wave. Loudness is much more difficult to identify. Clearly a good deal depends on the sensitivity of the ear to different pitches, and it has been demonstrated that in this matter the ear does not act in any simple way. For scientific purposes it is usual to deal with a definite quantity known as the *Intensity*, with which the property of loudness is related. The intensity is a measure of the energy of the vibration and is proportional to the square of the frequency multiplied by the square of the amplitude (f^2A^2).

I—6. Musical Sounds.

Musical sounds being easily distinguished from mere noises by their quality, there is, as might be expected, a simple and definite connection between their constituent sine-waves; they have frequencies which stand to each other in the ratios of the natural numbers 1, 2, 3, etc. Every musical note is not compounded of simple notes in *all* these frequency ratios; some may be missing. It is a further property of musical sounds that for the same atmospheric conditions sounds of different pitches have the same velocity—about 1,132 feet per second at a temperature of 70° F.

Every musical note, then, can be split up into a number of simple notes, or *tones* as they are called, whose frequencies are in the ratios of whole

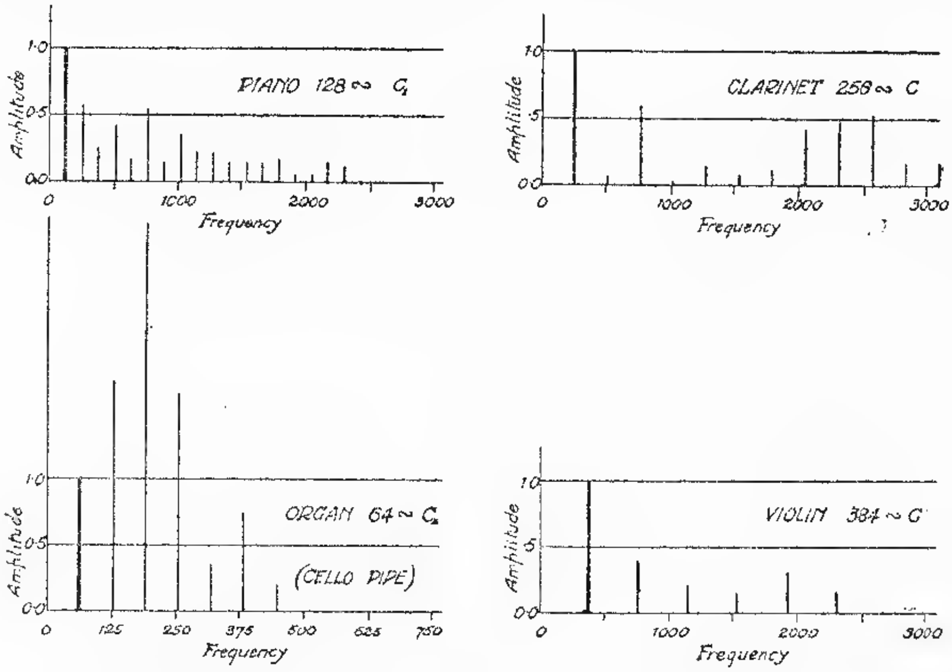


Fig. 6.—Relative strengths of overtones in musical instruments.

numbers. The tone of lowest frequency is called the *fundamental*; the others are called the *overtones*, *harmonics* or *upper partials*. We thus have the following sequence of tones which may be present in a musical note:

Frequency	f	$2f$	$3f$	$4f$	Etc.
Tone.	Fundamental.	Octave.	Twelfth.	Double Octave.	Etc.

The quality of a musical note depends on the presence or absence of overtones and the relative strengths of those that are present.

By way of illustration diagrams are given above showing the relative strengths of the tones in notes produced by various musical instruments.*

The pitch of a musical note is usually that of its fundamental tone. There are, however, circumstances in which the note may have the pitch of a fundamental tone which, in fact, is not present at all! This is due to certain peculiarities in the action of the ear, which apparently has the property of supplying a weak fundamental when both even and odd overtones are present in sufficient strength.†

The relative pitches of notes are thus determined by their relative frequencies. The standard of pitch is arbitrary. In scientific work it is usual to fix "middle C" at a frequency of 256 vibrations or cycles per second. The pitch of musical instruments varies slightly from this, a common standard being middle C=264 cycles per second. On these standards we get the following range of octaves from middle C, the octaves above middle C being denoted by indices C^1, C^2, etc., and those below by suffixes C_1, C_2, etc. (N.B.—To get the frequency of the octave above we multiply by 2; to get that of the octave below we divide by 2.)

C_4	C_3	C_2	C_1	C	C^1	C^2	C^3	C^4	C^5
16	32	64	128	256	512	1024	2048	4096	8192
$16\frac{1}{2}$	33	66	132	264	528	1056	2112	4224	8448

The range of audibility differs with different individuals. Normally it is from about 16 cycles to about 16,000 cycles. The fundamental tones in music do not extend beyond about 5,000 cycles.

* Martin and Fletcher: "Journal, A.I.E.E.," March, 1924.

† The discovery of this curious fact is due to Dr. H. Fletcher: "Physical Review," September, 1923.

The range of pitch for a human voice is from about 60 for a low bass to about 1,300 for a high soprano, these being the fundamental pitches. The overtones of instruments and voices, however, extend far above these limits and have frequencies of the order of 10,000 or more.

1—7. Transients.

Besides musical notes as described in the last section we are concerned in music with another kind of note in which the frequencies of the overtones are not necessarily simple multiples of the fundamental. They are said to be inharmonic to the fundamental. These notes are usually produced by percussion instruments—the drums, cymbals, triangle and even the piano—and owing to their physical nature do not persist so long as ordinary musical notes. For this reason they are known as "transients." These notes are perhaps the most difficult of all to reproduce artificially; their quality depends on the time during which they persist before being damped out and on the phase relationships as well as on the strength of their constituent overtones. Moreover, it is one of the easiest things in reproduction to introduce unwanted transients, and if they persist too long they give a muzziness and lack of detail to the reproduction which is most unsatisfactory.

1—8. Sensitivity of the Ear.

Since the war, a great deal of research work has been done upon the response of the ear to various kinds of sound-waves. It has already been mentioned in Section I—6 that the ear has the faculty of supplying a fundamental tone. This faculty is very fortunate so far as artificial reproduction of sound is concerned. Most reproducers respond very feebly or not at all to low notes. If therefore the absence of low tones in reproduction were to affect the pitch of the sounds heard, the result would be totally unrecognizable. For the ear is very sensitive to changes of pitch : a change of frequency of only 0.3 per cent. is perceptible to a normal ear. To changes of intensity the car is not nearly so sensitive. It is found that there is a certain " threshold " of intensity below which sounds are not heard at all. The amount of energy required to produce audible sound varies with the frequcncy. It is least between 2,000 and 4,000 cycles. At high and low frequencies it is very much greater. Above the " threshold of audibility " (i.e. for louder sounds or sounds with more energy) a definite percentage increase of intensity is required before a difference in loudness can be appreciated. For sounds just above the threshold the increase required is as much as 30 per cent. but for rather louder sounds it is only 10 per cent., at which figure it remains constant for larger intensities. As the intensity of the sound is increased, however, there comes a point where it produces a tickling or even painful sensation. There is thus a " threshold of feeling " as well as a " threshold of audibility," and between these two lies the " audibility area." At very high and very low frequencies these thresholds intersect each other ; the sensations of hearing and feeling become merged, and it is difficult to distinguish between them.

The following diagram (Fig. 7) shows the shapes of these threshold curves. It will be noticed that more than one million times as much energy is required to make a sound audible at 32 cycles as at 1,000 cycles, and more than 10 million times as much as at 2,000 cycles.

The fact that a certain *percentage* increase in intensity is needed before an increase of loudness can be

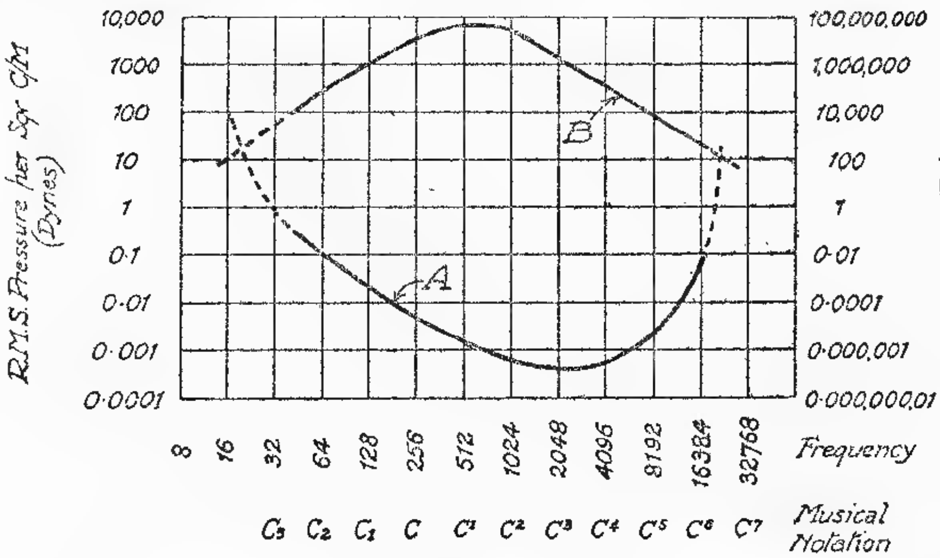


Fig. 7.—Audibility curves.
A. Threshold of audibility. B. Threshold of feeling.
Curves enclose audibility area.

detected has led to the use of a new scientific measure of loudness. This new unit is known as a Transmission Unit (T.U.), and is defined as follows :

Two pure tones of Intensity I and I^1 are said to differ in loudness by n transmission units where $n = 10 \log_{10} (I/I^1)$.

By using a logarithmic basis of computation percentage increases are converted into additive increments. Thus since the minimum percentage increase of intensity which can just be perceived is 10 per cent. we find that the smallest audible increase of loudness is $10 \log_{10} 1.1$ T.U. or about $\frac{1}{2}$ T.U.

From what has already been said, it will be anticipated that most of the energy of speech and music lies either in the very low tones or in the very high tones. Evidence is not wanting that in some voices (e.g. Madame Elizabeth Schumann's) the energy of the very high overtones does play an important part. As a rule, however, it is the low bass notes that give the body, the "naturalness" and the power to music. The high tones determine rather the articulation or intelligibility of the sounds. The curves given in Fig. 8 show the relative importance of different frequencies in respect of power and intelligibility. "The curve for intelligibility does not directly take into account the naturalness of the sounds. It is found, for example, that while a system which transmits only the frequency range from 500 to 2,000 cycles reproduces speech which can easily be understood, it leaves much to be desired from the standpoint of naturalness. . . . Results can be obtained for speech which are good for intelligibility and fairly good for naturalness with a frequency range from about 100 to 3,000 cycles, although appreciable improvement is obtained by the extension of the upper end of the range."*

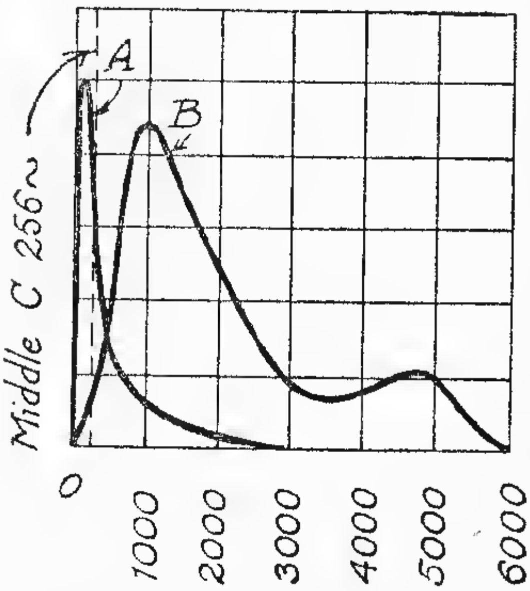


Fig. 8.—Frequency characteristics of speech.

Curve A. Energy distribution.
Curve B. Relative importance for intelligibility.

* Martin and Fletcher: "Journal, A.I.E.E.," March, 1924.

1—9. Requirements for Perfect Reproduction.

Expressed in a general way, the requirement for perfect reproduction is simply that the sounds heard should be indistinguishable from the original sounds. As "K.K.," one of the musical critics of *The Gramophone*, so tersely put it (Vol. VI, p. 87, July, 1928), "When I sit in an acoustically perfect hall (full of people), in the best seat for hearing, and listen to an orchestra, I hear such and such sounds. I want to hear precisely this effect from a record, if that be possible." In other words, the complex sounds which are produced by the reproducing instrument should contain at the original strengths all the tones which "K.K." would hear in his best seat, *and no others*. This, however, is a counsel of perfection, and in practice a certain latitude is permissible. All ears do not hear alike nor does an orchestra sound quite the same from two "best seats." As an illustration take the question of loudness. It is demonstrable that sounds reproduced at a greater strength than the original seem most unpleasantly distorted. Similarly a distortion is introduced if the sounds are much weaker than the original. In this case, however, it is possible to obtain a natural effect though it may be the effect of listening to the original from a greater distance. As the loudness of the reproduction is decreased more and more of the low notes sink below the threshold of audibility and the reproduction becomes thinner. This is precisely the sort of effect one gets on moving farther from the source; high notes are more directional and carry farther in a straight line than low notes. The point is of some importance in reproduction, whether by means of a gramophone or radio set; it is always difficult to reproduce low notes adequately. If the volume of the reproduction is not too great the absence of the low notes does not make itself felt so much; but if the volume is increased beyond a certain point the reproduction will become hard and unnatural and even painful.

In considering the requirements from a scientific standpoint, we should in strictness think of the recording instrument (or in the case of radio telephony, the transmitting instrument) and the reproducing instrument as one unit. A reproducing instrument need not be more nearly perfect than the recording instrument. In practiee, however, owing to commercial considerations, it is unlikely that it will be so good. We may assume, therefore, for our present purpose that the vibrations fed into the reproducer are the originals which we wish to reproduce without distortion.

Our requirements then become, firstly, that the reproduced sounds shall have component frequencies of the same *relative* intensitics as the originals, and secondly, that there shall be no components in the reproduced sounds which were not present in the originals. These requirements can be put in another form in the following way. Suppose the input intensity of a tone of any particular frequency is I_I and the output intensity of the corresponding sound is I_0. Then the ratio I_0/I_I should be (i) thc same for all frequencies over a wide range and (ii) should not be dependent on the particular value of the input I_1. If the *first* condition is not fulfilled we get " frequency distortion " and the apparatus does not give an even frequency response. This condition is not an easy one to fulfil in practice. All vibrating bodies such as we are dependent upon for our reproducing apparatus have favourite or " natural " frequencies to which they respond much more readily than to others. They have " resonances." The nature of these is dealt with in later chapters. The range of frequency response which is attainable with present apparatus is not much more than from about 50 cycles to 6,000 cycles, but this is quite sufficient to give a good simulation of the original.

If the *second* condition is not fulfilled we get what is known as " amplitude " or " non-linear " distortion. Most of the apparatus used for reproduction can be made free from this defect when dealing with a small energy input. But when the energy input is increased not only are the intensities of the original sounds reproduced in different proportions, but also components are set up which were not actually present in the original.

A third condition for good reproduction is that the duration of each of the original tones should be reproduced unchanged. If the duration is unduly prolonged the reproduction will become blurred and the quality of the transients (Section I—7) will be seriously affected. It is well known, for example, that the piano is very difficult to reproduce well—more so perhaps than any other instrument. The reproduction of transients is also affected by phase relationships, but this is a difficult aspect of the matter on which further research is required.

I—10. Permissible Errors in Reproduction.

It has been noted in the previous section that for ideal reproduction the loudness of the reproduced sounds should be within the range at which the listener is accustomed to hear the original sounds. This requirement, however, does not necessarily mean, as has sometimes been assumed, that the reproduced sounds should be just as loud as those which were actually produced in front of the recording or broadcasting microphone. This is merely the upper limit of loudness ; a reproduction of greater intensity will certainly sound distorted. But the range of intensity at which we are accustomed to hear music extends a considerable distance below this upper limit. In actual practice, the desirable intensity of reproduction depends partly on the surroundings of the reproducer, partly on the type of music being reproduced and partly on the amount of bass which the reproducer is capable of dealing with. In a small living-room there is clearly less objection to a " life-size " reproduction of a singer than there is to the life-size reproduction of an orchestra. We are accustomed to hear people sing in our drawing-rooms, whereas a full orchestra in a drawing-room would be an overpowering affair, apart, that is, from difficulties of accommodation. Similarly, if the response of the reproducing instrument is deficient in bass, it is most unwise to make the reproduction very loud. When the general level of intensity is such that bass notes down to a frequency of, say, 60 cycles should be above the threshold of audibility, absence of bass makes the reproduetion painfully "hard" and unnatural, whereas if the intensity level is kept lower the absence of bass notes is not so much felt, the general effect being that of listening to a performance from a distance. The point is one of considerable importance. Most owners of small gramophones and wireless sets try to get the reproduction far too loud, not realizing that the very nature of their apparatus prohibits the reproduction of bass notes and that undue loudness has an appalling effect upon quality.

The same conclusion forces itself upon us when we come to consider the permissible departures from a uniform frequency response or when we investigate the conditions for the avoidance of non-linear distortion. It has been remarked that a difference in loudness of about $\frac{1}{2}$ T.U. cannot be detected by the normal ear. It is, then, clearly permissible to have a departure from a uniform frequency response of $\frac{1}{2}$ T.U. In practice an even larger error is permissible. A difference of 3 T.U. is certainly discernible by direct comparison, but when we listen to reproduced music we judge quality by memory and not by direct comparison. The sensitiveness of individual ears varies greatly and the quality of two instruments of the same character (e.g. two violins, two pianos, etc.) is far from being invariable. Some authorities (e.g. Hanna and Slepian) place the permissible departure at as much as 10 T.U. (an intensity ratio of 10 : 1) before frequency distortion beeomes apparent. Such a large departure from the path of righteousness would not be tolerated by a purist, but it is certainly doubtful whether an ordinary person would detect anything very much wrong in a reproduction in which the loudness of some notes was 5 T.U. below the corrcct level whilst that of others was 5 T.U. above.

Non-linear distortion is another matter. So far as the authors are aware no definite experiments have been made to determine the extent to which distortion of this kind is permissible before the reproduction becomes appreciably affected. Attention so far seems to have been concentrated rather on methods of obtaining a more uniform frequency rcsponse. It seems, however, that the presence of even slight non-linear distortion, with its introduction of unwanted harmonic frequencies, is far more intolerable than quite a substantial departure from uniformity in frequcncy response. Most of the muzziness and lack of detail in the early loud-speakers, especially when used at too grcat a volume, can bc definitely traced to non-linear distortion. There are few mechanisms which will respond in the same way to a large amount of power as to a small one. A diaphragm, on which we are dependent at present for the conversion of our mechanical vibrations into sound, is certainly not one of them. Similarly, there is a definite limit to the amount of current that can be put through an electrical transformer before magnetic saturation takes place, and after that point is reached non-linear distortion is bound to take place. On page 203 is a photograph showing the current input and output of a transformer which was easily saturated.

The photograph was taken by means of a Duddell Oscillograph which automatically registers the wave form of the electrical vibration. The non-linear distortion shows itself in the appalling shape of the output wave.

From every point of view, then, it is madness to endeavour to obtain more volume or loudness from any piece of apparatus than that apparatus is capable of handling. Anyone who tries to make a portable gramophone or a portable wireless set sound as loud as a more generously designed instrument is asking for trouble. And as is the rule in such cases, he usually gets what he deserves.

CHAPTER II

RECORDS AND RECORDING SYSTEMS

II—1. Production of Mechanical Vibrations.

When a photograph is taken, the light waves coming from the scene in front of the camera are focused by the lenses and act directly on the sensitive material of the photographic plate or film. The recording of light waves is thus a direct process. With sound the matter is different; no direct method is known of making a permanent record. If such a process were to be discovered and at the same time some method of reversing the process were found, analogous to the projection of light through a cinema film, the problem of recording and reproducing sound would probably be much simplified.

In all the methods of recording hitherto developed the variations of air pressure due to the sound-waves are used to produce mechanical vibrations. These pressure variations being rapid and extremely small, relative to atmospheric pressure, a most delicate and sensitive receiving instrument is required to detect them. Usually a diaphragm is used in some form or other, its advantage being that for its mass it has a relatively large surface in contact with the air.

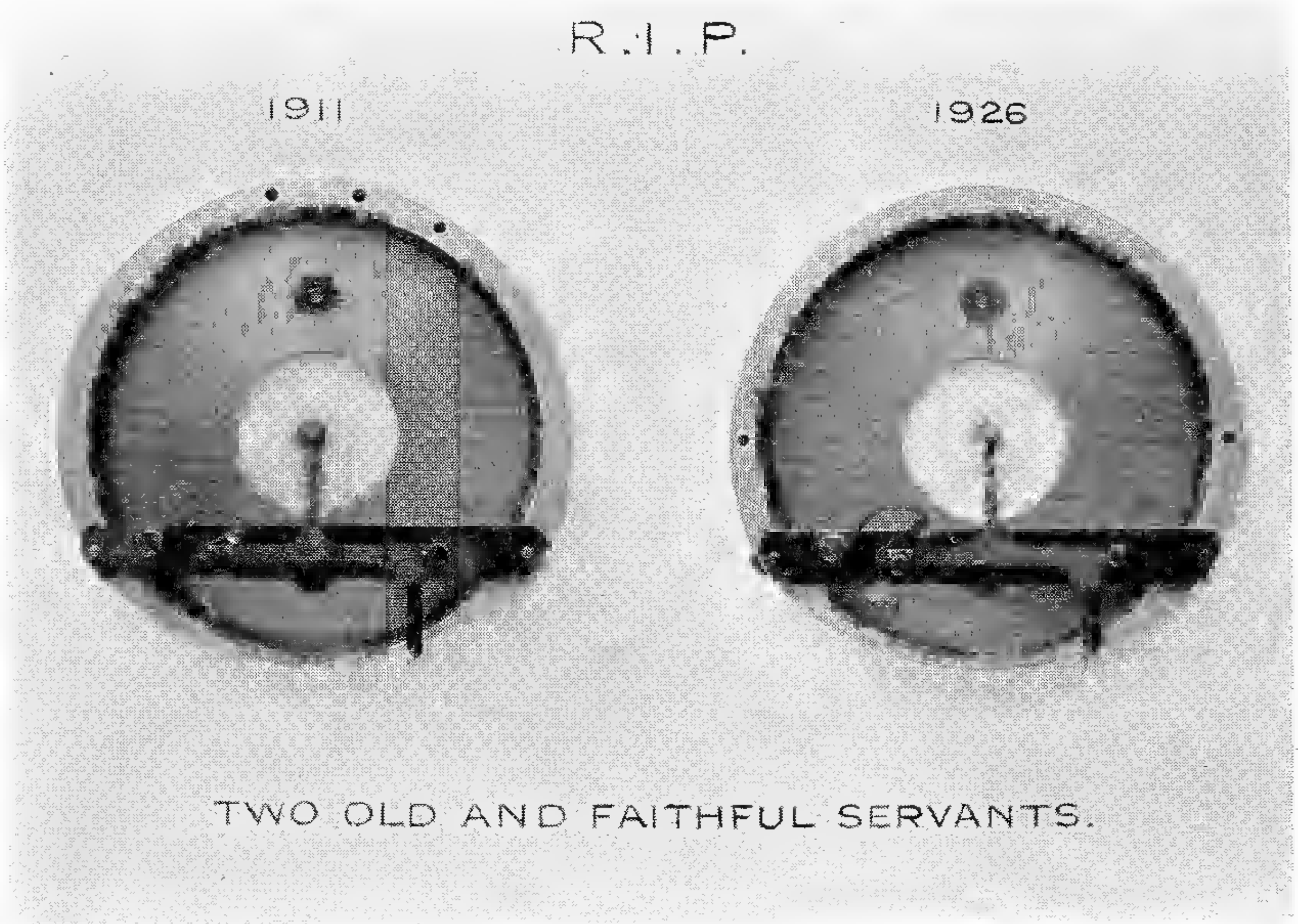


Fig. 9. Columbia Mechanical Recorders.

Reproduced by courtesy of the Columbia Graphophone Co.

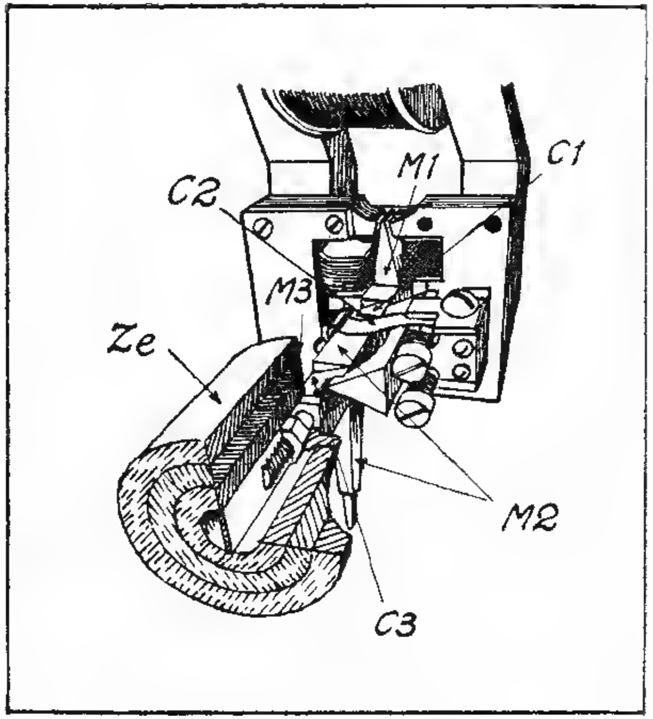


Fig. 14. Electromagnetic Recorder with rubber loading.

RECORDING INSTRUMENTS

A diaphragm, in fact, will respond with remarkable facility to extremely small and extremely rapid pressure variations. Its importance so far as the reproduction of sound is concerned can hardly be exaggerated. The telephone receiver has a diaphragm of sheet iron; in a microphone, carbon, mica and parchment are commonly used; for gramophones and loud speakers a very large number of different materials have been tried with success; whilst in some delicate scientific experiments a diaphragm in the form of a soap film has been employed.

II—2. Early Recording Systems.

The system of recording used commercially for the production of gramophone records until 1925 was identical, in all essential respects save one noticed in Section II—8 below, with that invented by Edison in 1877–8. In the interval, of course, many improvements were made in the actual design and operation of the recording instrument and very great advances indeed were made in the duplication of records; but the mechanical process of recording remained unaltered in principle. The recording instrument consisted essentially of a horn, usually conical in shape, at the apex of which a diaphragm was mounted. In the early days diaphragms of different materials and different sizes were used for recording different kinds of music, but in the end thin glass seems to have superseded all the other materials. The function of the horn was to concentrate the air-disturbances from a large to a small area and thus produce larger changes of pressure on the diaphragm. Sometimes, when the number of performers demanded it, as many as four horns all leading to the same diaphragm would be used. Attached to the diaphragm, usually at its ccntre, was a lever the other end of which carried a cutting stylus to inscribe the waves on a soft wax cylinder or disc which rotated under the point. Photographs of two of these recorders are reproduced in Fig. 9, Plate II, by courtesy of the Columbia Graphophone Co.

With all the mechanieal ingenuity which was bestowed upon it, this system of recording remained subject to several disabilities which there was scarcely any hope of ever removing. Perhaps the most serious of these was that the amount of energy available for cutting the record was limited to the small fraction of acoustie energy which could be picked up by the combination of horns and diaphragm. This was so small that the performers had to be closely grouped round the horns in a most unnatural way. The weaker instruments had either to be specially reinforced (e.g. a stroh-viol was often used in place of a violin) or to be placed close up to the recording horn, and the more powerful instrumcnts had to be removed to a distance or omitted altogether. To record with a large body of performers was virtually impossible; a full orchestra was altogether out of the question, and the arrangement of even the skeleton orchestras that were used was quite a troublesome affair. Moreover, for the performers themselvcs the conditions were far from comfortable; apart from the cramped conditions in which they had to play their instru-

Fig. 11. José Collins recording for Columbia.

Fig. 12. Jazz band recording.

OLD RECORDING CONDITIONS

Reproduced by courtesy of the Columbia Graphophone Co.

PLATE III

ments, the recording room was usually excessively hot. In such trying circumstances the best musical performances could hardly be expected. For vocalists alone were the conditions reasonably natural, and even in their case a slight movement of the head might completely spoil the quality of the record.

Another and scarcely less serious fault of this "acoustic" system of recording, as it has been somewhat inaptly called, was that the mechanical properties of horn, diaphragm and cutting stylus introduced serious distortion in the recording.

II—3. Ideal Response to Sound.

In the previous chapter it has been explained that for perfect reproduction the component tones of the reproduced sounds should have the same relative intensities as those of the original sounds recorded. Suppose a series of records were made of single pure tones all of the same intensity between the lowest and the highest audible frequencies. Then the individual tones reproduced from these records should all have the same intensity. By actual measurement of the shape and amplitudes of the grooves on the records it would be possible to determine whether the recording instrument by itself introduces any distortion. If it is distortionless the curves should all be sine curves, and since the intensity I is proportional to the square of the amplitude multiplied by the square of the frequency, that is to $(f\ A)^2$, the amplitude of the recorded sine curves should vary inversely as the frequency. (If the product f A is constant, A must be proportional to $1/f$.) Constant Note Records of this kind actually do exist and are of great value in testing and measuring the performance of reproducing instruments. In order to obtain perfect reproduction, however, it is not essential that the records made by the recording instruments should possess this property *provided it could be guaranteed that the reproducing instrument would exactly compensate for any departure from this condition in the recording.* For example, in the constant note records the amplitude A might be constant or it might be proportional to $1/f^2$, provided that in either case the reproducing instrument were designed to produce a constant intensity therefrom. The straightforward arrangement, however, is for both recording and reproducing instruments to have the same ideal characteristics, in which case the amplitude of cut in the records varies inversely as the frequency. This system of recording is known as the " constant-velocity " system since under it the speed of the recording stylus along its track is always the same. The other two systems referred to are known, for similar reasons, as the " constant-amplitude " and " constant-acceleration " systems and are mentioned here because they are, in fact, used to a limited extent in present day recording. The difference between the three systems is perhaps best shown graphically as in Fig. 10 (page 25). Here the scale of frequencies is represented by horizontal distances and the scale of intensity measured in Transmission Units by vertical distances. The horizontal line A shows the response that should be obtained with a constant velocity system of recording, the line B the ideal response for a constant amplitude system and the line C that for a constant acceleration system.

The old acoustic system of recording did not designedly aim at producing any definite form of response, though if the method used could have been freed from mechanieal difficulties the response should have been as in line A. Actually, however, the response was very far from this ideal. (Fig. 16a).

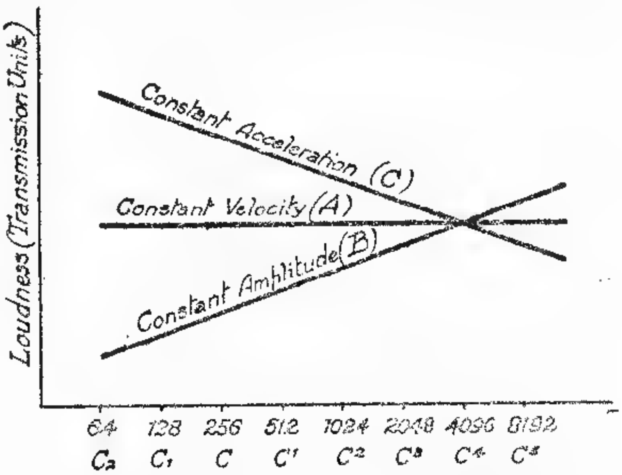


Fig. 10.—Frequency characteristics of recording systems.

II—4. Resonance and Damping.

Every vibrating body, whether it be a bar, a diaphragm or even a column of air, has one or more natural frequencies at which it vibrates most easily. As explained in the last chapter, the lowest frequency is the fundamental and the others are the overtones. In musical instruments the frequencies of the overtones are usually whole multiples of that of the fundamental, and it is the relative intensities of these overtones or harmonics which determine the quality of the instrument. By various artifices, sueh as stops and valves, the natural frequencies may be adjusted to different values though the relative intensities of the harmonics remain substantially the same. In most vibrating systems, however, the frequencies of the overtones are not whole multiples of the fundamental frequency ; they are *inharmonic*.

Usually, too, their intensities are much smaller than that of the fundamental.

If a body is set into vibration and the exciting cause is removed the body will vibrate freely in its natural frequency (or frequencies). The resulting vibrations will be strongest if the exciting cause happens to possess this same frequency; the two are then said to be in *resonance* or in tune. If the exciting cause is out of tune, the body may still be made to vibrate in its natural frequency though less strongly. If the vibrations are opposed or absorbed by some frictional force or resistance, their magnitude at resonance will be less strong, but in this case an exciting cause slightly out of tune will excite a stronger response than before. The greater the amount of energy which is absorbed by friction, etc. the less "sharp" is the tuning needed for resonance (see Section X—5) and the less pronounced is the strength of the vibration at resonance. In this case the vibration is said to be "*damped*."

If the exciting cause is continuously applied, the body will vibrate partly in its own natural frequency and partly in the frequency of the exciting cause. Its vibrations at its natural frequency are termed "free," while those at the frequency of the exciting cause are termed "forced." After a short time, however, the free vibrations will cease and the body will continue to vibrate at the frequency of the exciting cause. The natural vibrations are, in fact, "transients" (Section I—8) and the time for which they will endure depends upon the damping. In a heavily damped system the free vibrations die out very quickly.

In all the stages connected with the reproduction of sound we want our vibrating bodies to respond as uniformly as possible to the impressed vibrations and not to introduce any natural frequencies of their own. From this point of view, then, heavy damping would be highly desirable. But it should not be forgotten that damping absorbs energy and thereby reduces the sensitivity of the instrument. The old system of recording, limited as it was to the acoustic energy applied to the diaphragm, could not afford to employ sufficient damping; otherwise the amount of energy available for the cutting of the wax would have been totally insufficient.

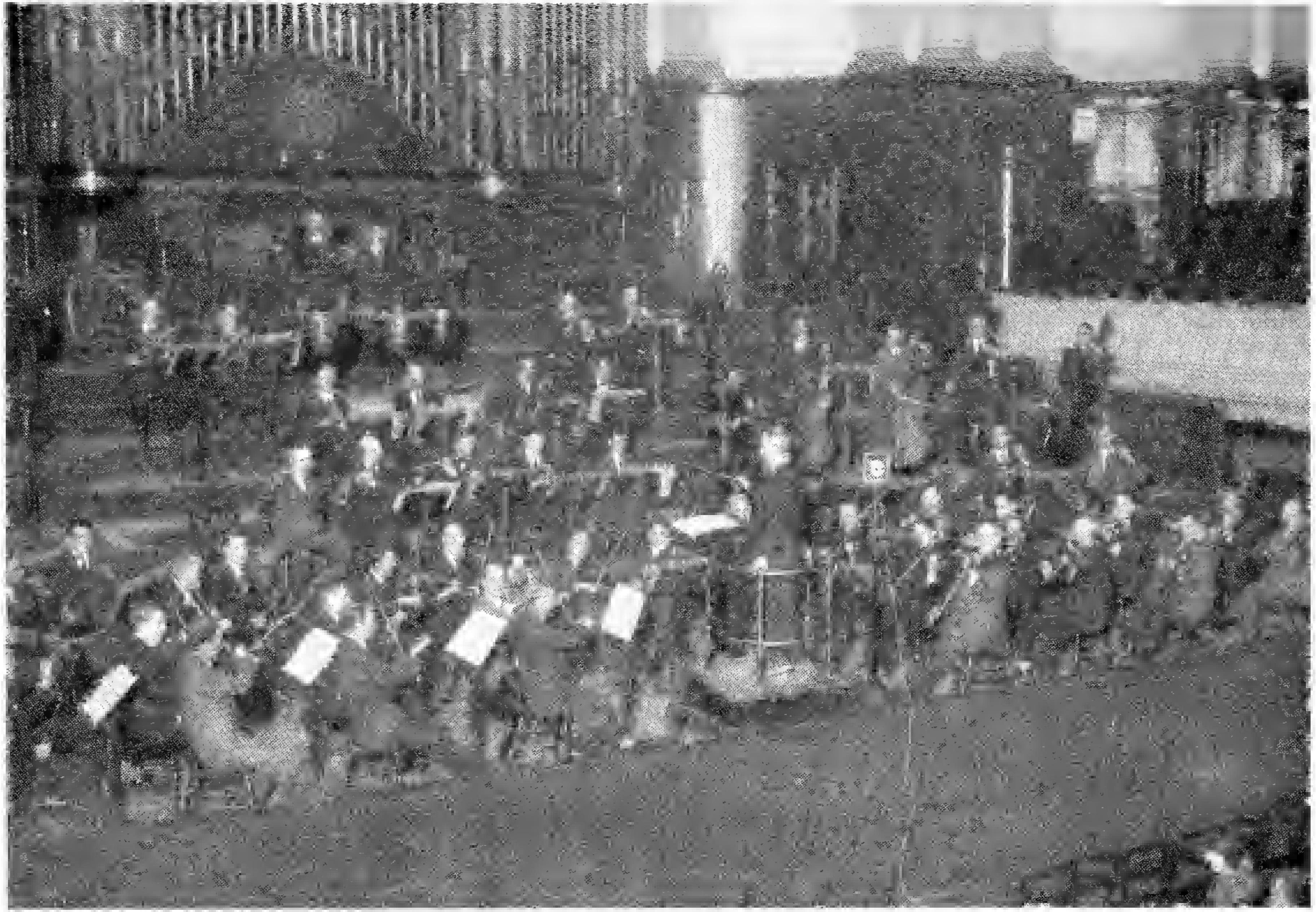
II—5. Electrical Recording.

Many attempts were made to increase the amount of energy available for recording, but it was not until the thermionic valve had been developed for wireless telegraphy and telephony and practically distortionless microphones had been invented that the problem was satisfactorily solved. The credit for the successful development of an electrical system of recording belongs to a group of telephone engineers at the Bell Telephone Laboratories in America. In this system the sound-waves impinge on a microphone of high quality, thereby producing electrical vibrations of similar wave-form. These electrical vibrations are amplified by a thermionic valve amplifier and then passed through an instrument known as an "attenuation equalizer" which is designed specially to correct any distortion which may have been introduced by the microphone and associated amplifier. Apparatus of this type had been designed many years before for use in Public Address Systems.* The electric current from the amplifier may then be transmitted, if need be, to a distance through telephone wires, a corrective " network " being inserted to counterbalance any distortion in the transmitters ; or it can be fed directly to the electromagnetic recorder. There is thus no difficulty in having the performance to be recorded in a theatre or concert-hall, the actual recording mechanism being still kept at the recording headquarters. When the electrical system was first introduced it was natural that most of the big scale work should be done in concert halls rather than in the small studios which had been used for the old system. This in itself introduced a certain " hall effect " into the recording which, being new, was most impressive. It cannot, however, be said that records made in these conditions are entirely satisfactory. The conditions of reverberation which are suitable for a concert performance are not the best for recording purposes ; records made in concert halls are apt to be blurred in their musical outlines and even the timbre of the various instruments seems to suffer.

The next development in the art of recording is to be looked for in the provision of special recording studios in which the reverberation conditions can be controlled. A good deal of research is at present (1929) being carried out on these lines.

In either case, however, the recording can now be

* E. C. Wente : " Physical Review," Vol. X, 1917, and Vol. XIX, 1922. I. B. Crandall : " Physical Review," Vol. XI, 1918. Green and Maxfield : " Trans. A.I.E.E.," Vol. XLIII, 1923.



[Photo: Graphic Photo Union.

Fig. 13. Electric Recording: Hallé Orchestra in Free Trade Hall, Manchester.

NEW RECORDING CONDITIONS

PLATE IV

done with the artists more nearly in their normal concert-room arrangement, and there is no limitation to the number of performers that may be employed. For special orchestral records (e.g. of Elgar's works, conducted by the composer) the Gramophone Company have often used over 90 instrumentalists, whilst special records of choirs with over 4,000 voices have been made by the Columbia Company; a marked contrast, this, to the dozen or so performers who were employed in the old days. Here we give photographs of recording conditions under the old system in Plate III and in modern conditions in Plate IV.

II—6. Electrical and Mechanical Analogies.

By the electrical system of recording, then, there is no important limitation to the subjects which can be recorded or to the amount of energy available. It therefore becomes possible to use a highly damped recording instrument, thereby mitigating the effect of mechanical resonance and producing a more even response. In the early experimental stages when electrical recording first became possible such a recording instrument was, in fact, used, and there is little doubt that substantial improvements could have been made on these lines. Before any commercial application was made, however, a new method of attack presented itself, and made it possible to design a recording instrument whose response is remarkably free from distortion.

It has long been known that a close analogy exists between electrical and mechanical problems.

Mechanical science is much older than electrical science, and on many occasions in the past the known solution of a mechanical problem has been used to indicate the solution of the corresponding electrical problem. In this way, Clerk Maxwell constructed the equations of the electromagnetic field and so gave an impetus to electrical science which culminated in wireless telegraphy and telephony. By an inverse process Lord Rayleigh used electrical analogies to solve some of the more difficult problems in Acoustics. During the past thirty years, largely under the pressure of economic necessity, electrical technology has developed at a tremendous pace, and in some respects has far outstripped its older companion. The properties of complicated elcetrical circuits have been thoroughly studied by telephone engineers and solutions of the more important problems have now been discovered. The corresponding mechanical problems have hitherto been of little physical interest.

Some of the important types of electrical circuits developed by the telephone engineers have been termed "wave-filters." They were invented by Dr. G. A. Campbell, of the Bell Telephone Laboratories, and are of three kinds: "low-pass filters," "high-pass filters," and "band-pass filters." A low-pass filter has the property of transmitting electrical vibrations with uniform attenuation below a certain critical frequency, known as the "cut-off" frequency, and suppressing all vibrations above that frequency. A high-pass filter will transmit vibrations above a critical cut-off frequency and suppress those below. A band-pass filter will transmit with uniform attenuation over one or more ranges or "bands" of frequencies and suppress vibrations outside those bands.

Clearly, if the mechanical analogy of a low-pass filter could be designed (or even of a band-pass filter with a low cut-off frequency in the neighbourhood of, say, 60 cycles, and a high cut-off frequency at about 5,000 cycles) the problem of recording sound with a uniform response over the most important range of musical frequencies would be solved. Moreover, the same method might be applied to a reproducing system with equally satisfactory results. This was the new method of attack developed by Maxfield and Harrison, two telephone engineers at the Bell Telephone Laboratories, and it is to the successful accomplishment of the task which they set themselves that the modern "electric record" and the comprehensive theory of the action of a gramophone is due.

The determination of the electrical analogue of any mechanism is not a difficult matter. The electrical equivalents of various mechanical quantities are shown in the table below, the units in which each quantity is measured being also given.

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

The term compliance perhaps requires a little explanation. It is used in the sense in which one speaks of the compliance of a spring and is the reciprocal of what scientists call elasticity or stiffness. In this sense, for example, a piece of indiarubber has great compliance but little elasticity.

But though it is easy by the use of these correspondences to see what is required mechanically as the analogue of an electric circuit, it is by no means so easy to make a practical mechanism which fulfils

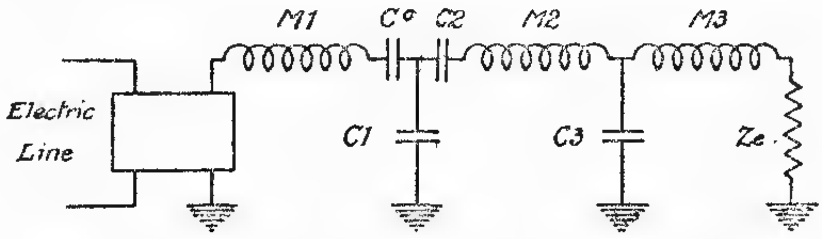


Fig. 15.—Equivalent electrical transmission line for Electromagnetic recorder.

M1. Armature. Co. Negative compliance of magnetic field. C1. Coupling shaft compliance. C2. Balancing springs compliance. M2. Cutting stylus mass. C3. Coupling shaft compliance. M3. Coupling disc mass. Zc. Rubber line.

the conditions. For example, it is possible electrically to have a capacity with negligible inductance; but mechanically it is hardly possible to have a compliance, e.g. a spring, without mass. Again, it may be a very difficult matter to make a mechanism work in one direction only; usually there are unwanted effects in other directions as well.

II—7. The Electromagnetic Recorder.

After several partially successful attempts, however, a recorder was evolved which had the required characteristics. Its general appearance is as shown in Fig. 14, Plate II, and the equivalent electrical transmission line in Fig. 15. Essentially the recorder consists of an electromagnet with a soft iron armature pivoted between the pole pieces. The currents from the electric amplifier pass through coils which surround the armature and produce a variable magnetic flux in it, causing it to be moved to and fro towards the pole pieces of the electromagnet. To the armature a shaft is attached, and on this shaft the stylus-holder and stylus for cutting the recording wax is mounted. The other end of the shaft is held firmly in a rod of rubber.

The response curve of this recorder is as shown

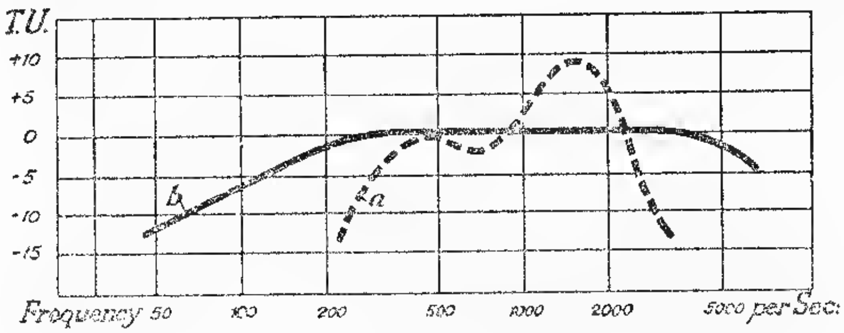


Fig. 16.—Recording instrument response curves.
a. Old recording. *b.* Electrical recording.

in Fig. 16b. A typical response curve of a mechanical recorder is shown for comparison in Fig. 16a. It will be observed that under modern conditions the response is practically uniform between 300 and 5,000 cycles. Below 300 cycles the response gradually falls off and cuts off altogether at 60 cycles; above 5,000 cycles, too, it falls away and cuts off between 6,000 and 7,000 cycles. The shape of the response curve at the two ends is deliberate and not accidental. For frequencies below 300 the recording is approximately at constant amplitude; between 300 and 5,000 it is at constant velocity; whilst above 5,000 it is approximately at constant acceleration. The playing time of a 12-inch record is only about 4 minutes, and if this time is not to be reduced, and if the loudness of the so-called "surface-noise" or "scratch" is not to be too great in comparison with that of the reproduced music, certain restrictions are imposed on the response at each end. If the bass notes were recorded in full, successive record grooves would run into each other, the amplitude of cut being inversely proportional to the frequency; and, on the other hand, if the high notes were recorded in full the curvature of the groove would become too acute for the reproducing needle to follow. It would appear, then, that with the present method of recording we have reached the limit of what is possible, until the technique of record manufacture is distinctly improved.

II—8. Lateral-cut and Hill-and-dale Records.

In the early days, long before electric recording, records were made on cylinders and reproduced on "phonographs." In these cylinder records the actual record of the sound was contained in the varying depths of the groove. The section of the groove was approximately of U shape, and had "hills" and "dales" on the bottom. When the disc record was invented by Berliner the cylinder soon went out of favour. At the same time Berliner introduced the form of "lateral-cut" record with which we are familiar to-day. In this the sound-record is in the horizontal instead of the vertical shape of the groove. This form of record has several advantages over the hill-and-dale cut, the principal one being that the resistance of the material to the cutting of relatively large amplitudes is less horizontally than vertically. It follows that bass notes are more easily and clearly recorded on a lateral-cut disc. On the other hand, the hill-and-dale cut possesses a number of advantages over its rival. Record wear is much less—the Edison and Pathé hill-and-dale reeords can be played with a permanent stylus—and whereas the lateral-cut disc is limited to about 100 grooves to the inch, the hill-and-dale can have 200 or more, so that the playing time can be increased. So far as the principles of recording and reproducing are concerned, however, there is no difference between the two types. In this book we are mainly concerned with lateral-cut records, but the remarks can be understood to apply equally well to hill-and-dale records unless a special exception is made.

II—9. Constant Amplitude Recording.

Since the playing time of a record is determined by the "number of grooves per inch," and since the distance between successive grooves is determined by the amplitude of cut, it would seem desirable, in order to increase the playing time, that records should be made on the "constant amplitude" system. Under this system the amplitude of the cut would be governed solely by the loudness of the sound and not at all by its pitch. Records made by this system would, of course, be deficient in bass, as can be seen from Fig. 10 on page 25. And if the curvature of the groove for high notes is not to be made too difficult for a needle to follow, the standard of amplitude would have to be that which applies to the highest notes recorded under the present constant velocity system. The reproducing system, too, would have to be designed in such a way as to correct for the deliberate distortion introduced in the recording. With an electrical system of recording it would be quite a straightforward matter to introduce an electrical network which would give the recording the required characteristics, and if an electrical system of reproduction were used a corrective device could be inserted in the electric amplifier in order to restore the balance. The system is quite a feasible one and would have a number of practical advantages, apart altogether from the great artistic advantage of having records with a longer playing time.

From what has been said above about the mechanical analogies of electrical circuits it might be thought that special mechanical reproducers of such records might also be made. But the realization in practice of the mechanical apparatus which would be required for the purpose is hardly possible at present. Even with our present gramophones, the great difficulty is to obtain an adequate response in the bass. Under the system proposed the lower frequencies would have to be over-emphasized by the reprodueer in order to balance the reduced response in the recording. It is therefore safe to say that the commercial possibilities of such a system will be very small until such time as the world equips itself with electrical reproducers. And when that state of affairs has come to pass, the time may be ripe for an entirely different system of recording—a recording on photographic films. This clearly is a promising line of development in the future.

APPENDIX

NOTE ON ELECTRICAL CIRCUITS

In subsequent chapters we shall make considerable use of analogies from electrical circuit theory. To clear the ground we give here a short explanation of some of the more common electrical principles and formulæ.

When we are dealing only with steady " direet " currents the fundamental quantities with which we are concerned are the current measured in *amperes*, the pressure or electromotive force (e.m.f.) measured in *volts*, and the resistance of a conductor measured in *ohms*. These are connected by a relation, known as Ohm's Law, which may be expressed in any of the following ways :

$$I \text{ (current)} = \frac{E \text{ (electromotive force)}}{R \text{ (resistance)}}$$

$$R = \frac{E}{I}; \quad E = I\,R.$$

The energy transmitted by a current is measured in *watts*, and is given by the following expression :

$$W = E\,I = E^2/R = I^2R$$

When two or more resistances are connected in series the total resistance is the sum of the individual resistances :

$$R = R_1 + R_2 + R_3 + \text{etc.}$$

When, however, they are connected in parallel, that is, when we connect together one end of each resistanee at one point and the other cnd of each resistance at another point, the reciprocal of the total resistance is equal to the sum of the reciprocals of the individual resistances:

$$\frac{1}{R}=\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\dots$$

The reciprocal of a resistance is known as a conductance, and is measured in *mhos*.

When we deal with alternating currents, that is, where the magnitude and direction of the current (and of the e.m.f.) varies (e.g. as in a sine-wave), we have to take account of other factors. Thus the current and voltage have a frequency, expressed in *cycles per second*, and the circuit through which the current passes may have inductance, measured in *henries*, or capacity, measured in *farads*. The typical example of a conductor possessing substantial inductance is a coil of wire; when a current flows through a coil it produces a certain amount of magnetism depending on the strength of the current and the size and number of turns in the coil. If the current changes, the alteration of the magnetic flux in the coil produces a back e.m.f. which tends to oppose the change of current. The typical example of a component possessing substantial capacity is a condenser, which consists of a number of metallic sheets placed close to each other, but not touching; but there is a certain amount of capacity between any two conductors of electricity.

For a given alternating e.m.f. the magnitude of the current which will pass through a circuit depends on the frequency, the resistance, the inductance, and the capacity. Analogous to Ohm's Law, there is a rule by which the current at any instant may be determined. The current will generally be out of phase with the e.m.f. by an amount depending on the inductance and the capacity. Its maximum value (amplitude) in terms of the maximum value (amplitude) of the e.m.f. is given by $I = \frac{E}{Z}$ where Z is a quantity, corresponding to the resistance in a direct current circuit, known as the *impedance.* In a circuit with resistance R, inductance L and capacity C in series the impedance (measured in ohms) is determined by an expression of the form

$$Z^2 = R^2 + X^2$$

where

$$X = 2 \pi f L - 1/2 \pi f C.$$

f being the frequency of the e.m.f.; $2 \pi f$ is usually denoted by ω. The quantity X is known as the *reactance* of the circuit; its magnitude depends upon the frequency. It becomes zero when $2 \pi f L = \frac{1}{2} \pi f C$, that is, when $f = \frac{1}{2} \pi \sqrt{\frac{1}{LC}}$ and this frequency is called the resonant frequency of the circuit. The impedance is then a minimum, being equal in magnitude to the resistance, and therefore the current being passed is a maximum. At resonance, when the reactance is zero, the current is in phase with the e.m.f.; the difference of phase at other frequencies depends on the ratio of the reactance to the resistance.

The impedance of an inductance L is $2 \pi f L$; that of a capacity C is $1/2 \pi f C$. It should be noticed that the impedance of an inductance increases with the frequency, and that the impedance of a capacity decreases as the frequency increases.

An inductance thus acts as a choke to high frequencies, while a capacity passes high frequencies easily, but presents an infinite impedance to direct currents (frequency zero).

The rules for finding the total impedance of a number of impedances joined together are the same as for resistances. We thus have :

SERIES CONNECTIONS.

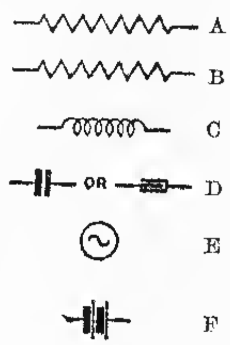
$$R = R_1 + R_2 + R_3 + \ldots.$$
$$Z = Z_1 + Z_2 + Z_3 + \ldots.$$
$$L = L_1 + L_2 + L_3 + \ldots.$$
$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots.$$

PARALLEL CONNECTIONS.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots.$$
$$\frac{1}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \ldots.$$
$$\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots.$$
$$C = C_1 + C_2 + C_3 + \ldots.$$

In diagrams of electrical circuits the following conventional signs are used :

Resistance is represented by A
Impedance ,, ,, ,, B
Inductance ,, ,, ,, C
Capacity ,, ,, ,, D



A source of alternating e.m.f. is represented by E. A " battery " or a source of constant e.m.f. is represented by F, the short thick stroke denoting the negative terminal.

The impedance, "looking into a network," at a point is the total or resultant impedance of the circuit beyond that point, and is such that the current flowing in the rest of the circuit would be unaltered if the single impedance were substituted for the network beyond the point. Thus, take the simple network shown in Fig. 17. The impedance Z, looking into it at the point A, may be calculated as follows:

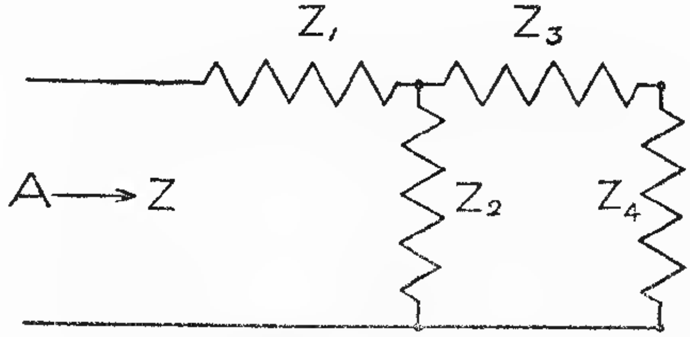


Fig. 17.—Impedance network.

Z_3 and Z_4 are in series, and their resultant $Z_A = Z_3 + Z_4$. Z_2 is in parallel with Z_A. The resultant Z_B is therefore given by

$$\frac{1}{Z_B} = \frac{1}{Z_2} + \frac{1}{Z_A} = \frac{1}{Z_2} + \frac{1}{Z_3 + Z_4}$$

So

$$Z_B = \frac{Z_2\,(Z_3 + Z_4)}{Z_2 + Z_3 + Z_4}$$

The circuit is now reduced to that in Fig. 18. Z_1

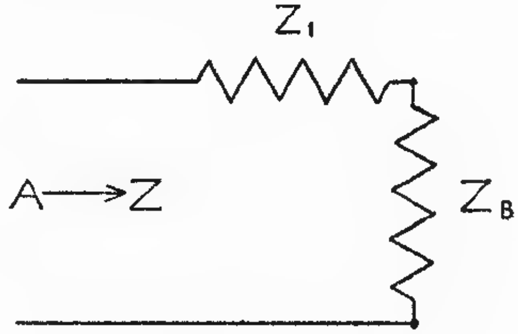


Fig. 18.—Reduced network.

is in series with Z_B. Their resultant Z is therefore given by

$$Z = Z_1 + Z_B$$
$$= Z_1 + \frac{Z_2 (Z_3 + Z_4)}{Z_2 + Z_3 + Z_4}$$

The electrical circuits with which we are most concerned in this book are those known as wave-filters. These have been defined in the text (page 30). A large number of circuits aet as wave-filters. The simplest form of low-pass filter is shown in Fig. 19.

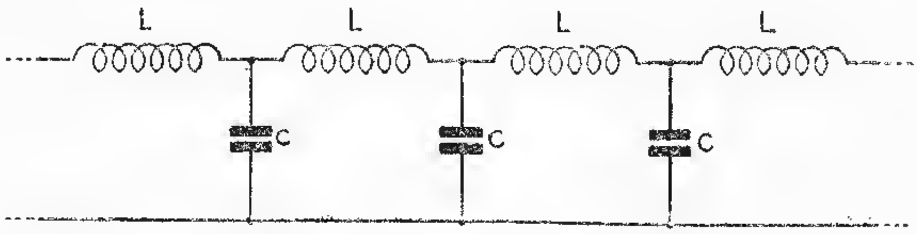


Fig. 19.—Low-pass wave-filter.

The "cut-off frequency" of a filter of this type is given by $f = \frac{1}{\pi \sqrt{L\,C}}$

The quantity $Z = \pi\, f\, L = \frac{1}{\pi\, f\, C}$ is known as the "characteristic" impedance or the "surge" or "image" impedance of the filter.

A constant resistance network is one in which the reactanee eomponent, i.e. the eomponent whieh varies with the frequency, of the impedance looking into the network is zero. The network then simulates a pure resistance. A wave-filter has a pure resistance characteristic over one or more ranges of frequencies and a pure reactance characteristic elsewhere.

CHAPTER III

REPRODUCING SYSTEMS

III—1. Historical Summary.

The trend of development of reproducing systems has been much the same as that of recording. The early talking machines were ungainly in appearance and crude in performance, but their principles of operation were but little different from those of the more imposing gramophones of to-day. In all, some form of stylus, tracking in a wavy groove, was employed to impart vibrations to a diaphragm, and the resulting sound-pulses were "amplified," in a way then obscure, by means of a horn. At first the stylus was directly attached to the centre of the diaphragm; later a "spider" was inserted between stylus and diaphragm so that the latter was operated not from its centre but along a ring. This method, however, was subsequently discarded and the use of a pivoted lever or "stylus-bar" between needle and diaphragm gradually became universal. For the diaphragm itself many different materials were tried—iron, copper, aluminium, paper, parchment, carbon, wood, glass, mica, besides a host of composite materials—but by 1920 practically all had given way in favour of mica.

Numerous, also, were the ways in which the diaphragm was mounted. At first rigidly clamped round the edge, later it was mounted between washers of paper, fclt and other matcrials, but ultimately rubber gaskets, whether solid or of the tubular variety, became almost general. In the early days, the instruments were hand-operated, though the speed of the reeord was to some extent regulated by a governor mechanism similar in form to that used to-day. The introduetion of a clockwork motor by Berliner and Johnson was a grcat stcp forward ; the speed of the record was madc much more uniform and the pitch of the reprodueed sounds thereby became more definite and regular. The horn was at first small and eonieal in shapc. One would naturally suppose that in thc first instanee the whole diaphragm would bc connected to the horn. This, however, appears never to have been the case, at any rate in eommereial instruments. Probably the reason is that the first "sound-boxes" were merely copics of Bell's telephone earpieee. In any case the advantage of having a sound-box with an aperturc less than the area of the diaphragm must have been discovered at a very early stage. The horn was gradually increased in size and a slight flare was introduced at its open end. By the year 1906 horns over 4 feet long with an open end nearly 2 feet aeross were not uneommon. Fig. 20, Plate V, shows one of the earliest gramophones of the hand-operated type. Fig. 21 shows an early cylinder phonograph, whilst Fig. 22 shows one of the earliest spring-driven models (the H.M.V. "dog" model).

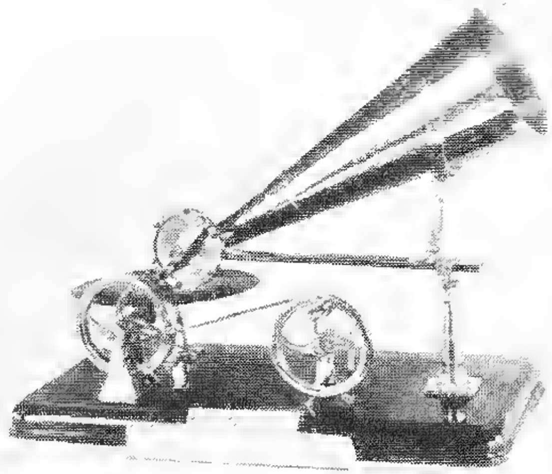


Fig. 20. Berliner's Gramophone No. 1. 1894.
The original is in the Gramophone Company's museum at Hayes. A slightly different model is in the South Kensington Science Museum.

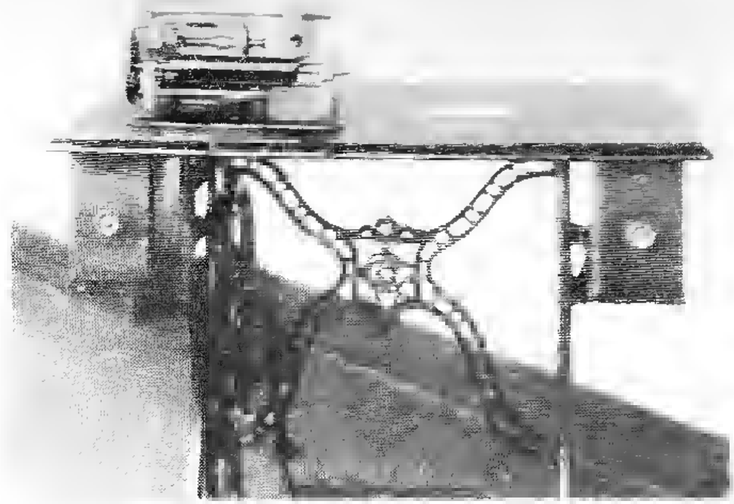


Fig. 21. Treadle Machine Graphophone.
American Graphophone Company's first product manufactured in the old Howe Sewing Machine Factory, Bridgeport, Conn., 1888.

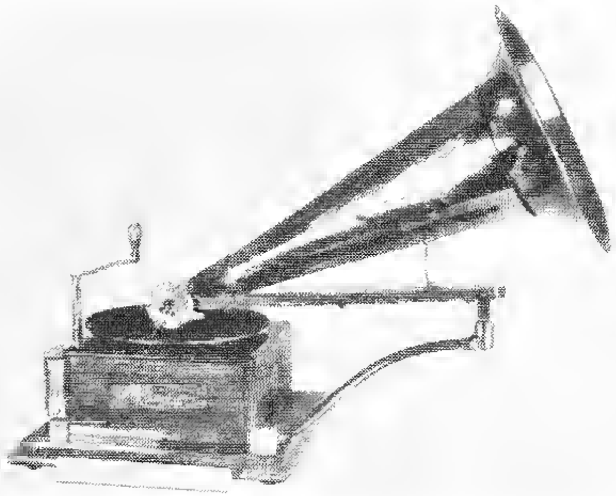


Fig. 22.
H.M.V. "Trade Mark" Gramophone.

Fig. 23.
H.M.V. "Senior Monarch" Gramophone.

HISTORICAL GRAMOPHONES

PLATE V

It will be noticed that in these early instruments the sound-box was coupled to the horn by an elbow and that the motion across the record was secured by pivoting the horn. This was a very cumbersome arrangement, though it had mechanical (and acoustical) advantages which were not appreciated at the time: e.g. the traverse of the sound-box across the record was not very far from that which the recording stylus followed, and there was only one bend in the sound conduit. Some quite well informed people are even now of the opinion that it would be well to go back to this early arrangement notwithstanding its cumbersomeness. There is no doubt that most of the changes in gramophone design which took place between 1912 and 1924 were dictated rather by a desire to improve the appearance and convenience of the instrument than by any consideration for the quality of the reproduction. It is no exaggeration to say that the external horn instruments of 1912 gave a finer quality of reproduction than any of the instruments of the succeeding period. Even to this day the most confirmed gramophone enthusiasts (the writers included) prefer to use an instrument with a large external horn, though the design of the instrument generally and of the horn in particular is different from that which was usual at the beginning of the century. Such instruments are cheaper to produce, and from an acoustical and mechanical point of view the design is straightforward and comparatively simple. But, and it is a big but, they are unquestionably clumsy. There can be little doubt that if the gramophone companies had been content to go on producing external horn machines, merely adding this or that refinement in design, the gramophone would never have achieved its present popularity. Mere efficiency is not the sole criterion of worth, and the public have a right to expect that the ingenuity and the skill of the gramophone expert will produce an instrument which is both efficient and easy to handle and at the same time no more incongruous in the home than an upright piano. The cabinet gramophones produced during the past few years show that this is not an unattainable ideal.

The first step in the direction of convenience of operation was the invention of the tone-arm. This enabled the horn proper to remain at rest during the traverse of the sound-box across the record. Claims were also made for it at the time that it improved the tone of the reproduction—hence its name ; but these claims had no substantial foundation. The tone of a gramophone may certainly be altered by the design of the tone-arm, and if the design is a bad one may be seriously impaired. But the authors know of no instance where a tone-arm may be said to have improved the quality *per se*, and certainly there appears to be no good acoustical argument for the claim. The most that can be said is that the tone-arm may be designed so as to have no deleterious effect on the quality of the reproduction, and that being so, the advantages which it confers in the convenience of operation of the gramophone and in the use of a stationary horn are not by any means to be despised.

An illustration of an H.M.V. gramophone of this period is shown in Fig. 23, Plate V. For some years after the invention of the tone-arm, external horn gramophones were the only ones made. For quality and volume these instruments could more than hold their own with all the instruments up to, at any rate, the 1926 models, and with a horn of rather larger size and different design, and with a suitable sound-box, will bear comparison with the finest instruments of 1928. Photographs of two modern instruments are reproduced in the Frontispiece (Figs. 24 and 25). About 1912, however, the so-called "hornless" gramophone was introdueed. The first models were puny affairs with little save their compactness to recommend them; the volume was poor and the tone was thin and wiry. Yet for some reason they were a commercial suceess, and the impression got abroad that the "internal amplifier" was in some way different from and better than a horn. The gradual development of the cabinet instrument soon put an end to that notion, however. The improvements that were made were almost entirely in the direction of bigger "amplifiers," and the bigger they grew the more nearly they came to resemble a horn, though now the horn was rectangular in section and bent so as to fit into a cabinet. Some manufacturers went the whole way and deliberately made long horns with a large number of bends.

III—2. The Scientific Stage.

Throughout this period the design of gramophones was purely empirical. Numerous experimenters had collected together a large number of seemingly unrelated facts, many of them at first sight mutually contradictory, but there was no unifying theory. In such circumstances it is not surprising that development soon came to a standstill; empiricism had reached the limit of its capacity, and for further progress a new impetus from scientific thought was required. It is true that in the early post-war years numerous new makes of gramophone were marketed, each with imposing claims to perfect reproduction. But these claims as a rule would not bear much scrutiny; any improvement in one respect, usually described as " mellowness," was only obtained at the expense of a loss of clarity and definition.

In retrospect the failure of the technical experts of the gramophone industry to formulate any definite principles of design for so long appears a little puzzling. The theory of the action of a diaphragm had long been known, and the elements of the theory of horns had been given by Lord Rayleigh in the early seventies. In 1919 a paper by Professor A. G. Webster, published in the Proceedings of the (American) National Academy of Sciences, carried Rayleigh's horn theory a good deal further, and actually worked out in some detail the properties of the particular kind of horn which has come to be regarded as the most satisfactory for reproduction purposes. But little notice appears to have been taken of Webster's work until in 1923 R. J. Hanna and Dr. Slepian, of the Westinghouse Eleetric Company, read a paper before the American Institute of Electrical Engineers in which the function and design of horns for reproducing purposes were thoroughly considered. Their results, though in some respects incomplete and in others merely a recapitulation of Webster's work, serve as the starting point for that theoretical development for lack of which gramophone design had come to a standstill. At about this time, too, Maxfield and Harrison and the other engineers of the Bell Telephone Laboratories who were responsible for electrical recording, applied the principles of electrical transmission theory to the analogous problems of the transmission of mechanical and acoustical vibrations. The standard design of sound-box and horn as it had been developed empirically corresponded almost exactly to the structure of an electric wave-filter, and the application by analogy of wave-filter theory enabled the telephone engineers to give a quantitative as well as a qualitative account of the action of a gramophone.* The work of these engineers has given the gramophone art a new impetus, if not a new orientation. Any development of this sort is usually followed by years of intensive work, rechecking the theory at every stage, introdueing various refinements and, most important of all, discovering better ways of approximating to the theoretical ideal in actual production. It is one thing to construct a laboratory instrument to satisfy an ideal but it is quite another to standardize the instrument for commercial production. In the laboratory elaborate precautions can be taken and, where necessary, delicate adjustments can be made regardless of time and expense. For

* "Trans. A.I.E.E.," March, 1926.

the factory every part has to be standardized and a technique of assembly has to be determined by experience ; if the cost of production is to be kept reasonably low, the necessity for minute calibration and adjustment of each individual instrument must be avoided. Even so, the best results can only be obtained if gramophone users will take the trouble to learn the principles on which the instrument

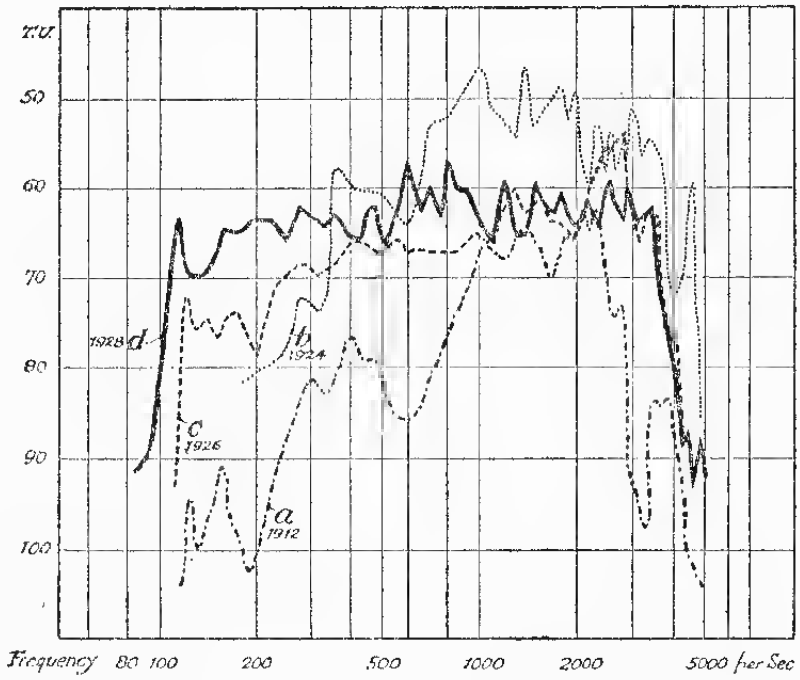


Fig. 26.—Typical response curves of H.M.V. gramophones.

works and the ways in which adjustments can be made.

The full fruits from this new soil, then, must not be expected immediately. But even the first fruits are not by any means unappetizing. The gramophones designed since 1926 have been unquestionably superior to those of any earlier period. By the courtesy of the Gramophone Company we are able to reproduce above the response curves of gramophones of four successive periods. It will be observed that there has been a marked improvement in the response to low and high frequencies and that "peakiness" due to resonances has been much reduced. In other words, the response has a longer range and is much more even within that range.

III—3. Even Response.

For records made under a constant velocity system of recording a uniform response in the reproducer is precisely what is wanted for perfect reproduction, and owing to the lack of uniformity in the sensitivity of the human ear a considerable departure from uniformity of response can be permitted before any appreciable difference will be noticeable. The response curve in Fig. 26(d) above is still far from perfect; there are numerous peaks and troughs. But it will be observed that for the most part there is not more than five transmission units between a peak and a trough so that the errors are not so important to the ear as they may appear to the eye. The exceptions are the trough at 130 cycles and the peaks at 600 and 800 cycles, the spread between which is 14 T.U. Still, there can be no question that the response of this instrument is markedly superior to that of the earlier commercial gramophones.

There is, however, one important point about an even response of this sort which should not be overlooked: the reproduction cannot in this case be better in any way than the recording. It was explained in Chapter II that, owing to geometrical difficulties, the response in the recording fell off below about 300 cycles and above about 5,000 cycles. The reproduction with a gramophone having an even response must therefore be deficient in the frequeneies below 300 and above 5,000. If it were possible, it would be desirable to have a reprodueer whieh, whilst maintaining a uniform response between 300 and 5,000, actually over-emphasized the response outside those limits.

There are, however, very serious difficulties in the design of a mechanical reproducer with such properties, and apart from this there is reason to think that if the response of the reproducer differs substantially from that of the reeorder severe reeord wear is introdueed. An eleetrieal reproducer would not be subjeet to such disabilities.

When we come to consider the reproduetion of records made by the old " aeoustic " process the argument is even more important. There the reeording response to different frequeneies was far from uniform and was not even approximately the same for reeords made at different times. It follows that for the best reproduction of these old records a reproducing instrument is required which has a different response from that required for electric reeordings.

Fortunately all that is necessary to make the desired ehange in the reprodueer is to substitute a different sound-box. It has long been the practiee of gramophone " fans " to have different sound-boxes " tuned " for different types of old recording, though the preeise function of the tuning has only recently been understood. Even for electric recordings, and more especially the early ones which were made when the calibration and adjustment of the recording instrument were not so well understood as they are now, differently tuned sound-boxes may be an advantage. It is much easier to tune a sound-box to give a uniform response within a short range of frequency than for a large range. It follows that special sound-boxes designed to reproduce solo violin records to perfection might be totally unsuitable for the longer range of an orchestra. A special sound-box for piano records is almost always an advantage, since here the effects of transients are so important.

III—4. Limitations of Mechanical Reproduction.

In an ordinary gramophone, the needle which tracks in the recorded groove imparts vibrations to the diaphragm and thereby creates sound pulses in the sound-box which are transmitted through the horn to the outer air. As explained in Chapter V the function of the horn is to enable the sound-box to vibrate with greater energy and to transmit a larger proportion of that energy to the outer air. The source of the energy which we hear as sound is not the record, as is often thought, but the motor which drives the record. The record merely determines at what rates and to some extent in what amounts the energy shall be imparted to the diaphragm. The amount of energy which the motor can give up without fluctuating in speed and the amount of energy which a record can pass on is very limited, however. Any attempt to increase the volume of reproduction above this level is foredoomed to failure. Now, although the loudness of a sound depends on the amount of energy in it, it does not by any means follow that a gramophone which produces more acoustic energy will necessarily *seem* louder. It has been pointed out that far more energy is required to bring a bass note above the threshold of audibility than to make a treble note audible. An instrument such as the one whose response curve was given in Fig. 26 (d) may have to pass more energy than the one with a response as in Fig. 26(a) in order to attain the same seeming loudness. The reproduction with the longer range is fuller, more natural and more satisfying, but although the energy eontent is greater, owing to the presence of low notes, the volume may seem smaller since the higher notes are not so strong. Thus, with the more nearly perfect reproducer, the possible range of secming loudness may not be so great as with a reproducer having a shorter range ; but whereas the loudness in the former case may be, and usually is, an advantage, in the latter case it usually brings the energy level for some frequencies up to the threshold of feeling and thereby makes the reproduction positively unbearable. Fortunately, however, the loudness of reproduction with the better type of response can be made quite sufficient for home purposes. It is only when the instrument is used in a very large room or before a large number of people that the available energy becomes inadequate.

There is, however, another disability of the mechanical system of reproduction which should be noticed. The response of a gramophone in the treble is determined by the design of the soundbox and hardly at all by that of the horn. In the bass, however, the most important factor is the horn. It will be shown in a later chapter that to pass frequencies of 100 cycles a horn has to be about 8 feet long and have an opening of nearly 3 feet diameter. To reach down to 60 cycles a horn 14 feet long is needed, whilst for 40 cycles the length has to be increased to 20 feet. The size of the instruments required to accommodate horns of these proportions is altogether too big for home use; and in any case sufficient energy cannot be supplied mechanically to operate them. Instruments of this size have been constructed for auditorium work, but these are operated electrically.

III—5. Electrical Reproduction.

In recording, the difficulties of a limited energy supply were overcome by using electric amplifiers, and a similar system is naturally suggested for reproducing. For this purpose we require an instrument, now known as a "pick-up," which will track in the record groove and convert mechanical vibrations into electrical vibrations, a valve amplifier to magnify the vibrations so produced and a loud-speaker to convert the electrical vibrations into sound. The amount of energy drawn from the motor through the record is now of no great importance, since an electric amplifier can be designed to give as much power as may be required. At the same time it should not be forgotten that this system is more complicated and, therefore, more expensive than the mechanical system, and that the more magnification required from the amplifier the greater the expense. It is not possible to produce a powerful and distortionless electric amplificr very cheaply. The growth of wircless has made it possible to obtain high quality electrical components at very moderate prices; but it has also flooded the market with cheap and flimsy apparatus for which there is no place in a first-class amplifier. The importance of using only thc best components cannot be insisted upon too strongly. Even one faulty component may ruin the over-all response.

The design of an electric amplifier to give a uniform response from 20 to about 8,000 cycles presents no serious difficulty. In the pick-up and loud-speaker, however, we are faced with mechanical problems which are not so easy of solution. Until 1926 loud-speakers were very imperfeet affairs. Their response was not nearly so good as that of the bcst gramophoncs, and the power-handling capacities of most of them were very limited. Now, however, the position is very different. The development of the "moving-coil" speaker by Rice and Kellogg has altered the whole outlook. A good coil-driven speakcr will reproduce notes down to about 40 cycles and up to 6,000 cycles and will stand great power without producing non-linear distortion. The early models were not so satisfactory as this, and thcre are still many inferior types on the market. But there is little doubt as to the excellence of the best of them. Their disadvantage is their relatively small efficiency, less than 1 per cent of the electrical input being converted into sound. Powerful amplifiers are, therefore, required to operate thcm, and for the power supply it is practically essential to have what is known as a " mains unit," deriving its energy from the electric light mains. In these circumstances the initial cost is substantial, but the cost of upkeep is small. The only serious rival of the moving-coil type of speaker at present is one with a large exponential horn. These may have a high efficiency ratio of acoustic output/electrical input and so require a less powerful amplifier to operate them. For the exponential horn speakers (14 feet long) used in the " Movietone," where the unit has a moving-coil drive, an efficiency of 50 per cent has been claimed. But these large horns are themselves expensive to make, and they are certainly not easy to dispose conveniently in an ordinary living room. However, progress in loud-speaker design is being made at such a rate that before this book is actually in a reader's hands new types with improved characteristics may be available.

As with the loud-speaker, so with the electrical pick-up. The earliest types were very crude, both in design and performance, and simply butchered records. The design of a pick-up involves several difficult problems. The theoretical requirements are clear, but the fulfilment of these requirements in a practical design is not easy. Substantial progress, however, is being made and there can be little doubt that pick-ups with a practically uniform frequency response and minimum record wear will soon be available.

III—6. Advantages of Electrical Reproduction.

The possibilities of obtaining a better response to low notes and a larger range of power by the electrical system have already been mentioned. One or two other advantages should now be noticed. The first is the ease of volume control. In a well designed gramophone the volume of the reproduction is almost rigidly determined by the record. Changing the needle, loud to soft or vice versa, alters the loudness, it is true; but it also affects the frequency response and therefore the quality. In an electrical amplifier it is possible to have a simple and convenient form of volume control which affects the frequency response but little. One has merely to turn a knob, that is all. Manipulation of quality is also feasible, though perhaps rather too tricky for general use. In many electrical reproducers, however, a "scratch filter" which suppresses all frequencies above about 4,000 cycles is deliberately introduced in order to obliterate surface noise. Unfortunately, it affects the quality of the music as well. A scratch filter with a cut-off at 6,000 cycles would be unobjectionable, since the recording rarely extends above that limit, but this would not remove all the scratch.

There is another feature of electrical reproduction with a good pick-up, amplifier, and moving-coil speaker which is both interesting and significant. The *pp* passages in a record are softer and the *ff* passages are louder when reproduced electrically than when reproduced mechanically. This may mean that the electrical system, properly managed, introduces less non-linear distortion; or it may simply be due to the fact that in a loud passage more bass notes actually come above the threshold of audibility, which they can do in the electrical system with a very low cut-off. Be that as it may, this feature of electrical reproduction is a very valuable one: one of the criticisms of gramophone reproduction made by musicians has been that too little distinction is made between loud and soft passages. Another has been that however loud the music may sound, one has always been able to talk through it: the loudness, in other words, is illusory. That is most certainly due to inadequate bass response. A moving-coil speaker operating at quite moderate volume can effectively drown all conversation.

The initial cost of a suitable electric amplifier and equipment generally is certainly a drawback. External horn gramophones, capable of giving most satisfactory reproduction at good volume and with negligible record wear, can be obtained for under £20. A good electric reproducer, including amplifier, loud-speaker, power supply, pick-up, carrying-arm, motor and cabinet, will certainly cost more than double if not four or five times that amount. But the extra expense is partly compensated by the fact that the same apparatus may be used for reception of broadcasting. The ordinary "wireless set" is a very inferior affair compared with an amplifier of the type discussed in these pages, and the extra initial expense of the first-class apparatus is well worth while.

There is, however, another disadvantage which is more serious. An electrieal reproducer is a more complicated affair than a gramophone. There are thus more parts to get out of order, and tracing a fault may be a difficult business. The ordinary gramophone is undoubtedly more fool-proof, and for this reason, if there is any truth in Carlyle's dictum on the ubiquity of fools, may be more suitable to the man-in-the-street. But the foree of this objeetion ean easily be exaggerated. To anyone who will take a little trouble to understand the apparatus he is using, there is no reason why an electrical reproducer should give any anxiety. And, in any case, progress often comes through complexity to simplicity.

CHAPTER IV

SOUND-BOXES

IV—1. Essential Features.

In its main features the gramophone sound-box has remained unaltered for over thirty years. But only during the last few years has anyone had more than a vague notion of the functions of the various parts. Even now, when a unifying theory is available, the determination of a practical design to carry out the theoretical requirements is by no means straightforward. But it is an interesting fact that of all the possible forms which a sound-box might have taken, the one which was developed happens to correspond closely with that which modern theory shows to be desirable.

Essentially, the sound-box consists of a stylus-bar, or needle-arm as it is now coming to be called, a diaphragm, and an air-chamber. One end of the stylus-bar is in the form of a socket into which a gramophone needle is inserted, whilst the other is attached to the diaphragm either directly or through some intermediate coupling such as a "spider." The stylus-bar is mounted so as to be more or less free to rock about some point in its length. At the present time, it is common practice to have a form of pivoting arranged in such a way that the rocking motion is not limited save by the tracking of the needle in the record groove and by the attachment of the diaphragm. But other methods are possible and in the past have been extensively used. A discussion of some of them will be found in Section IV—6 below. The general form of construction is illustrated in Fig. 27, which is a sectional drawing of a common type of sound-box. N is the needle-socket, P and P^1 are pivots on which the stylus-bar rocks, S is the upper arm of the stylus-bar, D is the diaphragm, G and G^1 are rubber "gaskets" in which the diaphragm is mounted at its periphery, A is the air-chamber behind the diaphragm and O in the casing C is the outlet communicating with the tone-arm and horn.

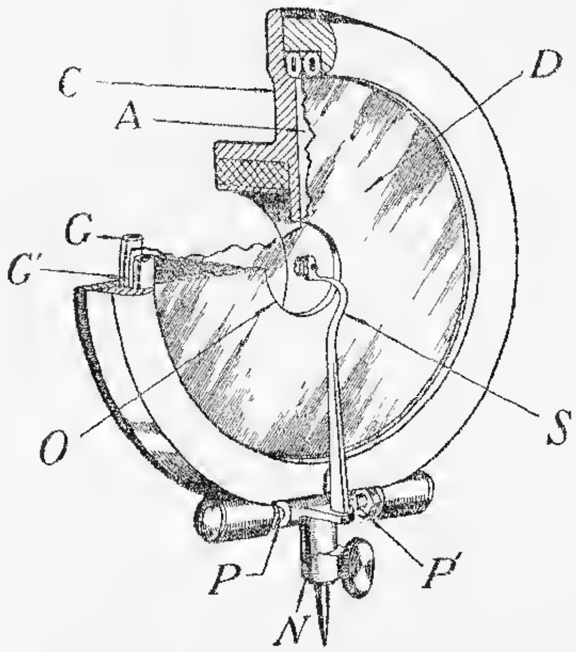
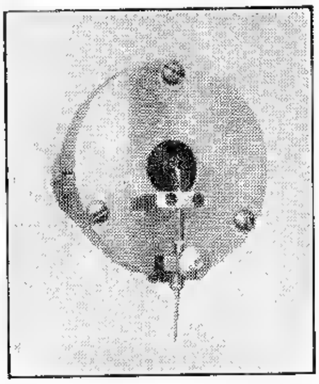
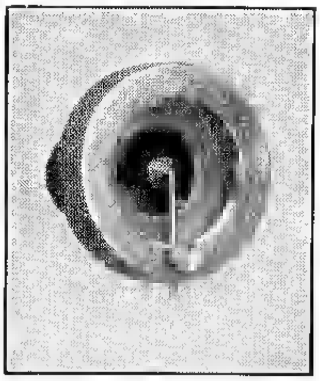


Fig. 27.—Sound-box diagram.

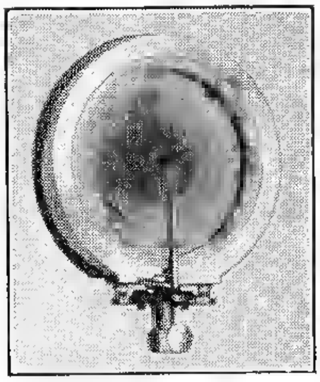
The action of a sound-box in producing the pressure variations which constitute sound is simply this. The groove cut in the record carries the needle point from side to side and thus causes vibrations to be communicated by the stylus-bar to the diaphragm. The motion of the diaphragm to and fro causes the air in the air-chamber to be alternately compressed and rarefied, and thus pressure changes are transmitted through the outlet to the air in the tone-arm and horn. It would



1898

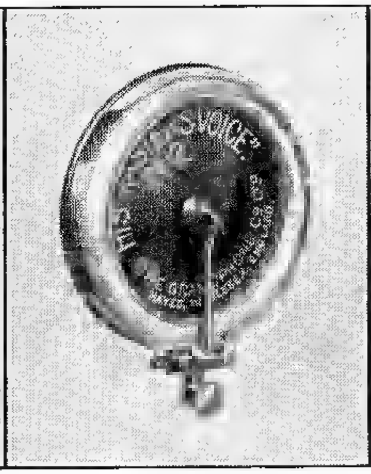


1901



1903

1919



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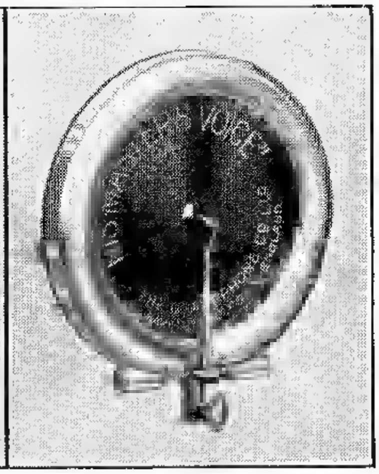

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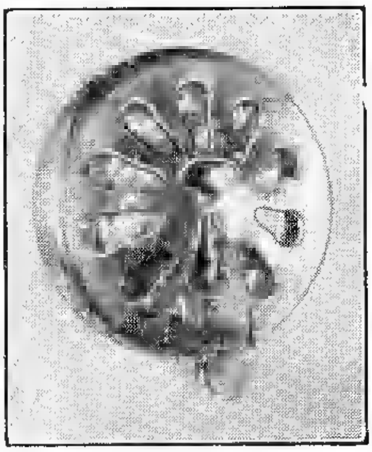
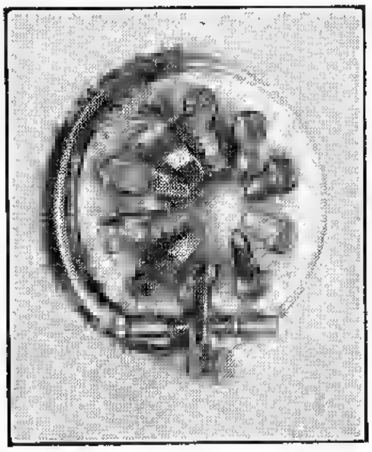


1927



1928

H.M.V. SOUND BOXES, 1898-1928

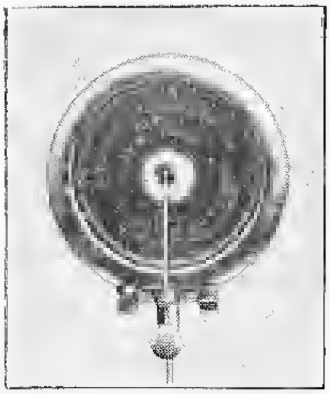
appear at first sight that a diaphragm with a large surfaee should eause a greater variation of pressure in the orifiee of the air ehamber than a smaller one, and that the sounds produeed by a large diaphragm should therefore be louder than those produced by a small one. This would be true if it could be assumed that the diaphragm had no mass and moved as a perfect piston, that is, without bending. These " ideal " circumstances, of course, are quite unattainable, and in practice we must take account of mass and compliance. Still, within limits, the conclusion is valid evcn in practical circumstances. What these limits are it is the object of the following seetions to explain.

IV—2. Motion of a Diaphragm.

A diaphragm is a thin, usually eireular, plate of a light, stiff material whieh may be set into vibration by an external souree. Its manner of vibration is a rather complicated business. A mathematical analysis is given in Lord Rayleigh's " Theory of Sound," whcre it is shown that the diaphragm may vibrate in an infinite number of different modes, each with its own particular frequency. The position of thesc natural frequencies in the scale will depend upon the manncr in which the diaphragm is mounted and driven, as well as upon the size, thickness and material. For any particular material it may be shown that the fundamental frequency is proportional to the square root of the ratio of the stiffness to the mass ($\sqrt{s/m}$). If the diaphragm is clamped round the edge, it may also be shown that for vibrations up to the fundamental frequency the effect on the air is practically the same as it would be for a piston of 0·2 times the mass moving with a velocity of 0·3 times that of the centre of the diaphragm.* If the diaphragm-mounting at the edge is arranged so as to give more of a plunger motion, the piston-mass is practically unaltered, but the average velocity, and therefore the effective piston area, is increased. This also remains substantially true for vibrations up to double the fundamental frequency, but as the second natural frequency (which is about four times that of the fundamental) is approached the effect becomes much more complicated. Then, a considerable proportion of the energy is expended in setting up wave motion in the diaphragm itself, the waves travelling outwards from the centre to the edge and then being partially reflected back again. The motion of the outside of the diaphragm may be completely out of phase with the central portion, and may thus even be causing a rarefaction of air at the instant when the central portion is causing a compression.

It needs very little study of the behaviour of diaphragms to convince oneself that in designing a sound-box the aim should be to have as high a fundamental frequency as possible so as to obtain the benefits of piston motion, and that, subject to this requirement, the area of the diaphragm should be as large as possible. From the formula given above it is readily seen that to raise the fundamental frequency we must increase the stiffness/mass ratio. It follows that we should use a material

* I. B. Crandall: "Theory of Vibrating Systems and Sound," p. 41.



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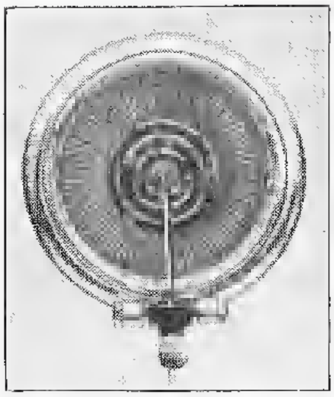
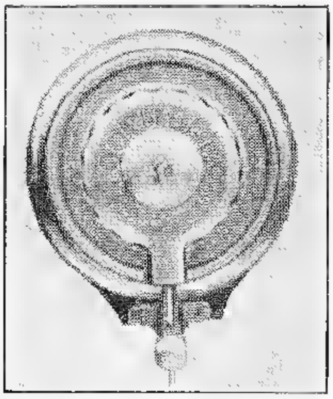
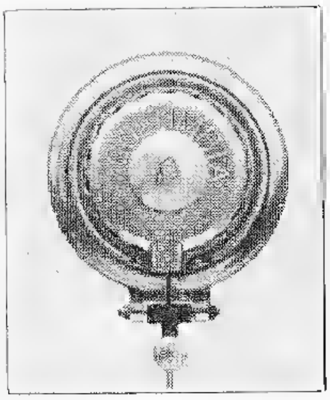


1910



1911



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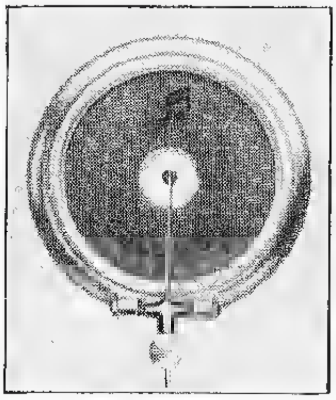
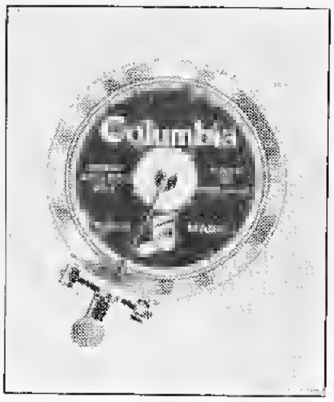
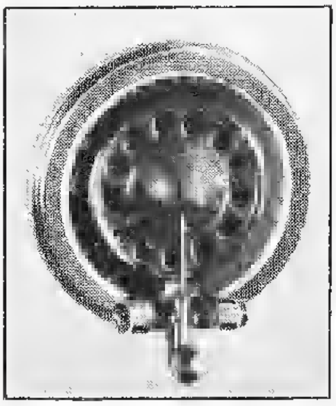


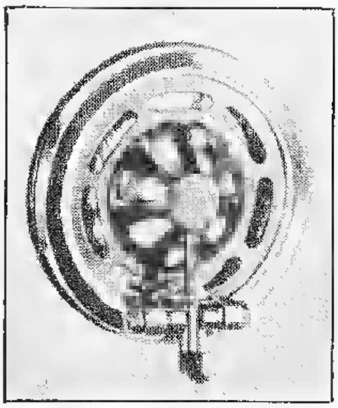
1913 (No. 6)



1923



1927



1928

COLUMBIA SOUND BOXES, 1909-1928

PLATE VII

whose inherent stiffness is as great as possible, and whose density is as small as possible. This consideration indicates in a general way what materials are the most suitable for our purpose. In flat sheets, miea and thin glass have a high stiffness/mass ratio, which aceounts for the suecess with which they have been used in the past. Composite diaphragms of paper, parchment, treated silk, etc., usually have a small stiffness/mass ratio and are thus not so suitable. Some of the aluminium alloys have a high stiffness/mass ratio, and by corrugating them in certain ways the ratio can be greatly increased. The introduction of corrugations, however, may give rise to other effects since they provide surfaces on which the vibrations may act in directions other than at right angles to the diaphragm proper. The stiffness can also be increased by putting the diaphragm under tension; the stiffness of a membrane is direetly proportional to the tension on it. It is interesting to note that Commander Bettini, who was a very active experimenter in the early days, took out a patent for stretched diaphragms over thirty years ago, and the principle has been employed again in the "eondenser transmitter" microphone.

This neeessity of keeping the stiffness/mass ratio as great as possible imposes limitations on the area of the diaphragm. The stiffness varies as the cube of the thiekness and inversely as the square of the diameter (t^3/d^2). The mass varies as the thickness and as the square of the diameter ($t\ d^2$). So the stiffness/mass ratio varies as t^2/d^4. Thus, if we double the diameter of the diaphragm we must have four times the thickness to preserve the same stiffness/mass ratio and this means that the mass itself is sixteen times as great. Now the mass of the diaphragm enters into the calculations for the rest of the sound-box, and these calculations all point to the desirability of having a small mass. This imposes a restriction on the area, apart altogether from the fact noticed above that with a large diaphragm the vibrations of frequency more than four times the fundamental are attenuated by the setting up of wave motion in the diaphragm itself.

So far, we have ignored the question of mounting. But clearly since our aim is to obtain piston motion, and at the same time to keep the air-chamber sealed, this question is of great importance. If the diaphragm is rigidly clamped at the edge we satisfy the second condition but we limit the piston motion. For this we require the edge mounting to have as great a compliance as possible. This is the main reason for the use of rubber gaskets, and it is clear that the quality of the gaskets and their state of compression must radically affect the response. In the H.M.V. No. 5 and No. 5a sound-boxes substantial piston motion has been obtained by the use of two kinds of corrugations. In the central portion of the diaphragm, which is made of a light aluminium alloy, there are concentric stiffening corrugations. Round the edge there are tangential corrugations giving the outer portion great compliance. Another device has also been used to obtain piston action. In sound-boxes produced in recent years, the diaphragm has been attached to the stylus-bar at its centre by means of a small screw. In the No. 5 sound-boxes the diaphragm is not driven from the centre ; instead, the designers have interposed a "spider" between diaphragm and stylus-bar, so that the diaphragm is driven along one of the corrugations rather more than $\frac{1}{2}$ inch from the centre. This is another interesting reversion to an old idea ; spiders of various shapes and sizes were commonly used in the early days of the phonograph.

IV—3. The Air-chamber.

Though a complete explanation of the functions of the air-chamber cannot be given until we come to consider the equivalent electrical circuit of the sound-box, it is possible to obtain some insight into its effects from ordinary mechanical considerations. When the diaphragm is set in motion in open space the air in front of it is given a certain velocity and, in consequence, pressure changes are set up. Due to the pressure produced there is a reaction force acting on the surface of the diaphragm, and it can easily be shown that this force is proportional to the air-velocity. Now this velocity and therefore the reaction force cannot but be quite small compared with the stiffness and inertia forces of the diaphragm itself. The diaphragm is thus working with a very small load, and, as is usual in such circumstances, its motion is determined almost entirely by its own stiffness and mass. Its own natural frequencies will thus be pronounced. If, however, we can introduce a load, the reaction forces on the diaphragm will come into play and introduce a damping effect.

To realize that this must be so one only need think of what happens when an electric motor is switched on: if there is no load the speed of the motor is unsteady, but when the motor is coupled to the machinery the load gives it stability. Again, a motor-car travelling light along a bad road is very lively; that is, it vibrates at the natural frequencies of the springs. But when it is loaded the vibrations are damped down.

When the diaphragm works into an air-chamber with a small outlet to a tube or horn, the air in the outlet is given a comparatively large velocity and greater pressure changes are developed. This increases the reaction force on the diaphragm, and so loads it and damps the natural vibrations. The effcct, in fact, is similar to that of the hydraulic press. It is not very difficult to show that in ordinary circumstances the magnitude of this reaction force is proportional to the square of the diaphragm area divided by the area of the outlet (A_1^2/A_0), so that by making the outlet small compared with the diaphragm area, the loading is increased. If the outlet is made too small, however, the changes of pressure become quite substantial compared with the atmospheric steady-state pressure. Other factors then begin to have an important effect. There is, in fact, a limit to the reduction in the size of the outlet. What that limit is, it is not very easy to determine by the line of argument so far adopted. Fortunately, however, the problem can be tackled in another and more serviceable way.

IV—4. Action of the Stylus-bar.

The function of the stylus-bar being to communicate vibrations from the needle point to the diaphragm, it might be thought that its shape should be such as to make it as stiff as possible. Here again the fundamental frequency varies as $\sqrt{s/m}$, so that if we design the bar to have a great stiffness with a small mass, the fundamental frequency will be high. Stylus-bars of the lattice-girder type with a great stiffness/mass ratio have been used in the past, but never with success. Experimenters have always found that the upper arm of the stylus-bar should have a certain compliance but that the needle-socket end should be rigid. Various explanations have been given of this curious empirical result, but none of them has been completely convincing. Thus it has been said that vibrations could be transmitted by the stylus-bar either by lever action or by transverse vibrations. In the latter case they would be transmitted along the bar in much the same way as vibrations travel along a stretched string. As proof of the existence of such vibrations, it was pointed out that even if the stylus-bar were firmly screwed to the casing of the sound-box some sound would be produced by the diaphragm. It was consequently argued that slower vibrations (bass notes) would be transmitted by lever action, and the faster ones by transverse vibrations. All of this is no doubt true, but still it does not explain why a very light stylus-bar as stiff as possible throughout its entire length should not have transmitted the vibrations as well as one which had a substantial compliance in the upper arm; a stiff bar should transmit high frequencies by transverse vibrations more efficiently than a flexible onc since its own natural frequency is higher.

It must be confessed that this problcm remained unsolved until the telephone cngineers produced their electrical analogy of the sound-box mechanism. This analogy makes the nature of the action quite clear and gives, besides, a basis for determining quantitatively the values of the masses and compliances involved.

IV—5. The Electrical Analogy.

It can be shown that the electrical analogue of

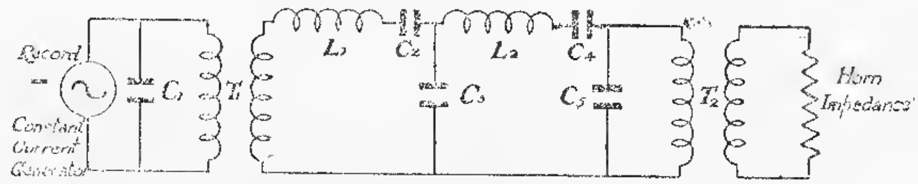


Fig. 28.—Equivalent electrical circuit of sound-box.

the sound-box shown in Fig. 27 is the circuit given in Fig. 28.

In this diagram the record is represented as a constant *current* generator (*N.B.*—The recording is assumed to be the constant *velocity* system) and the other quantities arc related as follows:

Capacity C_1 : compliance of needle point.
Transformer T_1 : leverage ratio of stylus-bar.
Inductance L_1 : stylus-bar mass viewed from point of connection to diaphragm.
Capacity C_2 : compliance of stylus-bar pivots.

Capacity C_3 : compliance of upper arm of stylus-bar.
Inductance L_2 : effective piston mass of diaphragm.
Capacity C_4 : edge compliance of diaphragm.
Capacity C_5 : compliance of air-chamber.
Transformer T_2 : air-chamber transformer.

It will be observed that the compliances C_1, C_3 and C_5 are in shunt across the line, whilst C_2 and C_4 are in series. It may be asked if one can determine on general grounds whether a compliance is in series or in shunt. The rule is quite simple: a compliance between moving parts is in shunt; a compliance between a moving part and a fixed part (e.g. the casing) is in series. Another way of looking at the matter is this. Consider what would happen if the compliance were made infinite. An infinite capacity will pass electric oscillations completely: it is in effect an electrical short circuit. So if the compliance is such that all motion would be stopped if its value were infinite, then it must be in shunt across the line.

Apart from the series capacities C_2 and C_4 the circuit diagram is precisely that of a low-pass wave-filter. The property of such a filter is that it will transmit vibrations below a certain "cut-off" frequency with practically uniform attenuation, and will suppress all vibrations above that frequency. The value of this cut-off will be determined by the values of the shunt capacities and series inductances. In other words, provided these values are rightly chosen, the circuit acts for frequencies below the cut-off as though it were a pure resistance. There will be uniform attenuation of energy within the filter itself, and provided it is terminated with a resistance of the same value there will be no reflection at the junction. By determining the values of the inductances and capacities (masses and compliances) so as to give a cut-off of, say, 5,000 cycles we can thus design a sound-box which, when used with a suitable horn, will give a uniform response up to 5,000 cycles and suppress all vibrations above that limit. An example of the calculations involved is given as an appendix to this chapter. Here we will content ourselves with some general observations.

The effect of the series compliances C_2 and C_4 is to introduce a low-frequeney cut-off in addition to the high-frequency cut-off. This cut-off should be made as low as possible, and for this it is necessary that both the pivot compliance C_2 and the diaphragm edge compliance C_4 should be made as great as possible.

The two transformers are necessary at each end of the circuit so as to " match the impedances " at the junctions. At one end we have the " needle-arm transformer " to match the impedance of the needle compliance to that of the diaphragm. At the other end we have the " air-chamber transformer " to match the impedance of the diaphragm to that of the horn to which the sound-box is attached.

The filter as shown has only two sections. The ideal filter has a large number of sections with equal series inductances and equal shunt capacities. But if the filter ends in a series element that element should have only half the normal series impedance, and if it ends in a shunt element, that element should have double the normal shunt impedance.

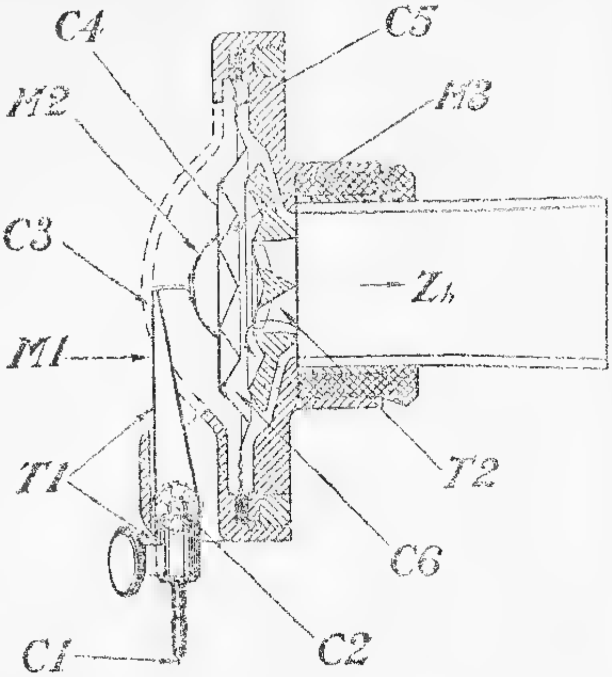


Fig. 29.—H.M.V. No. 5 Sound-box.

It will now be seen why the upper arm of the stylus-bar should have a certain compliance: it is required to provide the shunt element in that section of the filter.

The introduction of a "spider" of the standard mass and compliance between stylus-bar and diaphragm improves the analogy by adding another section to the filter. A sectional picture of the H.M.V. No. 5 sound-box and a diagram of the corresponding filter circuit are given in Figs. 29 and 30.

It should be noticed that the design formulæ involve such quantities as the density of the air and the velocity of sound. These quantities vary with temperature and humidity. Hence even a

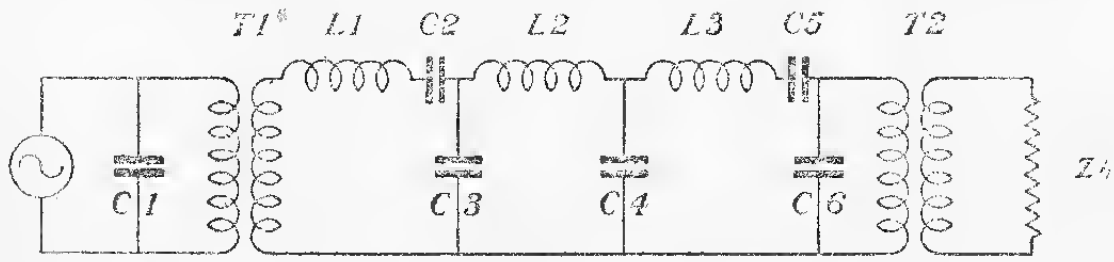


Fig. 30.—Equivalent electrical circuit of No. 5 sound-box.

perfectly designed sound-box cannot give exactly the same response for all atmospheric conditions.

The first stage in the design of a sound-box is the choice of a suitable diaphragm. As explained before, this should be as light as possible and yet should have a substantial piston area. When this has been chosen it is necessary to determine its effective piston mass and its equivalent piston area, or what comes to the same thing, the average velocity over the surface compared with the velocity at the centre. These can best be found by actual measurement. Given these values, the characteristic impedance of the filter is determined, and from that the values of the masses and compliances in the various sections. The various parts have then to be designed to possess these values. This may be a matter of considerable difficulty, particularly so far as the stylus-bar is concerned. There is great need at present for a reliable method of measuring mechanical impedances. Until this is invented, the full fruits of this comprehensive theory of sound-box action cannot be expected to mature.

IV—6. Stylus-bar Mountings.

In the sound-boxes previously illustrated, the stylus-bar is mounted on the casing by means of end-pivots. When accurately adjusted, the series compliance of these pivots is quite large (as it should be), but the method has a number of practical disadvantages. It is a matter of some delicacy to adjust the pivots so that the stylus-bar is firmly held without being subjected to frictional forces. Any end or side play in the pivots gives rise to chattering. Again, the expansion and contraction of the metal in different atmospheric conditions begin to affect the most accurate adjustment after a comparatively short time. Further, it is hardly possible, in view of the heavy back-plate required in the sound-box, to arrange the centre of gravity of the mass exactly above the needle point. When, therefore, the sound-box is placed on a record, there is a torque acting on the stylus-bar and being counter-balanced only by the diaphragm: as the needle tracks in the groove this torque varies in magnitude with the displacement. This is apt to strain the diaphragm, and in those cases where the upper arm is fixed directly to it by means of a small screw, this part of the diaphragm, if of metal, alters its structure under the oscillating strains.

For these reasons the authors prefer to have a different form of mounting, in which the stylus-bar is designed to rock on knife edges or steel balls, being kept in contact by means of light springs. These springs reduce the value of the series compliance at C2 in Fig. 28, but that is not so important as might be thought. In the first place this reduction of compliance is partly off-set by the tendency of the pressure of the sound-box on the record to overbalance the stylus-bar, and in the second place there is already a series compliance due to the diaphragm edge-compliance in another section of the filter, and so long as the pivot compliance is not less than this, it cannot do any harm. Indeed, it is probably of some advantage to make the net pivot compliance exactly equal to the diaphragm edge compliance, since then the filter is more perfectly balanced in each of its sections. Certainly the authors have found that the introduction of springs at this point does, in fact, improve the quality of the reproduction besides protecting the diaphragm from strain. Fig. 31 shows a form of mounting which has proved itself suitable. End springs are shown holding the stylus-plate on to the knife edges, and mild cross tension springs, similar to but weaker than those which were used in the H.M.V. Exhibition Sound-box, are used to provide a series compliance.

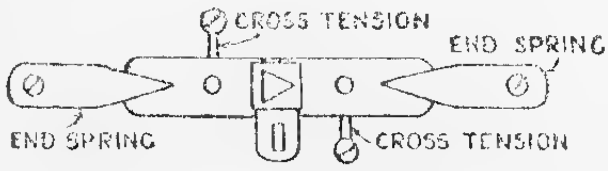


Fig. 31.—Stylus-bar mounting.

IV—7. Back-plate and Gaskets.

In the explanations so far given it has been tacitly assumed that the back-plate of the sound-box, its material, shape and mass have no effect on the transmission of vibrations. This would be strictly true if the back-plate were rigid and had very great elasticity (*N.B.*, *not* compliance) and mass. In practice the mass is limited to something like 4 to 5 ozs. This, however, is quite sufficient to remove any effects beyond the audibility range, provided that a material such as brass or one of the harder die-casting alloys is used. Some sound-boxes have aluminium or even vulcanite backs. These have certain absorptive properties depending on the porosity of the material. In a sound-box faulty elsewhere, this absorption may be of advantage, but in a well designed and well constructed sound-box it can hardly be tolerated.

In some sound-boxes the shell is made in one piece, the diaphragm being inserted from the front. This method cheapens production to some extent and is satisfactory provided that sufficient care is taken not to damage the diaphragm in assembling. The authors, however, favour a sound-box in two pieces, the stylus-bar being mounted on the " front-rim " and the back-plate being attached by means of *three* small screws. There are a number of important advantages in this method of construction.

1. The stylus-bar and diaphragm can be mounted (without gaskets) in the front-rim before the back-plate is attached, and care can be taken to see that the diaphragm lies perfectly evenly with a uniform clearance between the edge and the front-rim.

2. In these circumstances, when the gaskets are put in (the front gasket being carefully inserted from the front) and the back-plate screwed on, there is no strain put upon the diaphragm. Many commercial sound-boxes are so badly assembled in this respect that the diaphragm, if of mica, is cracked at the centre, or, if of metal or other material, is kinked and distorted. There is no doubt whatever that a bad assembly in a sound-box may destroy the virtues of an otherwise excellent design.

3. The attachment by three screws enables the pressure on the gaskets to be made quite uniform all round the edge. In a mica sound-box the effect of this in prevention of strains may be readily seen by holding the sound-box at an angle and observing the

reflection of a light at different points on the mica diaphragm ; any strain shows itself by a distortion of the refleetion.

4. By putting two soft rubber washers (e.g. made from gasket tubing) on each of the three screws, one between the head of the screw (separated from it by a metal or fibre washer) and the back-plate and the other between the back-plate and front-rim, a valuable adjustment can be made in the quality of the reproduction. A certain compliance is introdueed between the back-plate and gaskets and the gaskets and front-rim. This has two effeets. It inereases the diaphragm edge eomplianee, which for theoretically perfect results should be infinite, and thereby allows the diaphragm to move more as a plunger, increasing the response in the bass. At the same time it acts in *series* with the compliance of the air-chamber, thereby *reducing* the effect of that complianee and enabling the depth of the chamber to be increased so as to restore the proper value. Now an increase in the depth of the air-chamber is a very desirable thing, since it improves the chances of making the pressure uniform throughout the ehamber and of having the pressure variations in phase across the outlet. Further, since the baek-plate and front-rim are not actually in metallic contaet, there is less likelihood of the transmission of vibrations to the tone-arm and into the horn by metallic conduction.

There is, however, one danger in the use of washers between the back-plate and front-rim: they may introduce a leak in the air-chamber, and this has a marked filtering effect on low notes. This danger, however, can be avoided to a large extent by having the back-plate raised slightly in such a way that the raised portion will make contact round the sides of the back gasket and compress it laterally to a small extent. This slight lateral compression in itself is an advantage since it assists in increasing the diaphragm edge compliance. A form of back-plate which is suitable for this purpose is shown in Fig. 32.

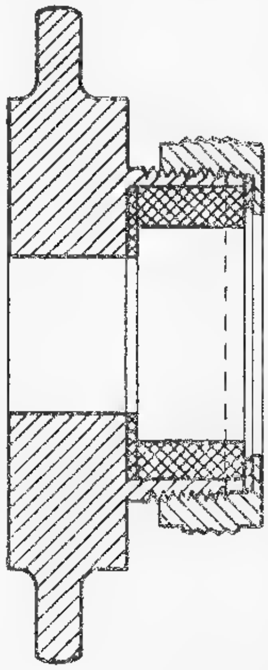


Fig. 32.—Shape of sound-box back-plate, showing method of connection to tone-arm.

From what has already been said it will be realized that the gaskets play an important part in a sound-box. Rubber has been universally recognized as the most suitable material, principally because of its great compliance. Its disadvantage is that it alters its qualities so easily under the effect of light, heat and changing atmospheric conditions. Rubber gaskets in a sound-box should be renewed at least once a year, and probably it will be necessary, if the best quality is to be maintained, for the sound-box to be "re-tuned," as indicated in (4) above, oftener than that. A good deal depends on the quality of the rubber. Some gasket rubbers are highly adulterated and lose their resilience after a very short time. Others maintain their quality for quite a long period. As regards shape, the authors prefer to use tubular gaskets of 3 millimetres external and 1 millimetre internal diameter, cut exactly to the proper length to fit in the front-rim of the sound-box without gap and without tightness. The gaskets when assembled in the sound-box should be just air-tight and no more. If they are too long, they do not rest quite evenly, but kink up against the diaphragm and exert an uneven pressure ; if they are too short the air is not imprisoned in the tube, with the result that some of the compliance is lost, and in addition a leak may be formed in the air-chamber. The size of the front-rim of the sound-box should be just sufficient to leave a clearance of $1\frac{1}{2}$ millimetres all round the diaphragm ; in these circumstances the diaphragm is held at its edge in the centre of the gaskets.

In the H.M.V. No. 2 and No. 4 sound-boxes, gaskets in the form of a continuous split ring were used. This ring could be put on the diaphragm before assembly, and when in position, prevented contact between the edge of the diaphragm and any part of the case. This device no doubt cheapened the cost of assembly, but in the authors' experience was never so satisfactory as tubular gaskets properly used. In the No. 5 sound-box, felt gaskets have been used with tangential corrugations at the edge of the diaphragm itself. This method gives sufficient compliance at the edge and avoids the difficulties due to the perishing of rubber.

IV—8. Miscellaneous Attachments.

The method of fixing the sound-box to the tone-arm varies a good deal. In some sound-boxes the back-plate is directly attached, metal to metal. Usually, however, some form of rubber attachment is used. In the old H.M.V. Exhibition Sound-box there was a special " rubber-back " screwed to the back-plate of the sound-box. In the later H.M.V. sound-boxes, however, the back-plate had a special projection into which a rubber sleeve was fitted, and inside that a metal sleeve to fit on the tone-arm. In the Columbia sound-boxes a special form of spring-plate back-fitting is used. Perhaps the neatest fitting the authors have come across is that illustrated in Fig. 32. Here a rubber sleeve is inserted in a projection on the baek of the sound-box and over this projection a screw cap is fitted. The rubber sleeve fits directly on the tone-arm, and when the cap is screwed up it compresses the rubber endwise and so secures a good fit without danger of any air leak.

The use of rubber in this position has two effects. It avoids metallic contact between sound-box and tone-arm, and so prevents transmission of vibrations along the metal itself; the frequencies most easily transmitted in this way would be those of high pitch and in particular those which constitute surface-noise or " scratch." In addition it gives the sound-box, as a whole, a certain compliance, and since this is associated with the mass of the sound-box itself there must be a resonance effect. The effeet in fact is that of a large inductance and a fairly large capacity shunted across the transmission line as in Fig. 33.

The resonance is clearly one of low frequency. With the fitting illustrated in Fig. 32 the value of the compliance is slightly adjustable, and therefore the resonance may be tuned within narrow limits. There is a device on the market known as the "Life-belt," consisting of a rubber neck with an adjustable collar, which may be inserted between sound-box and tone-arm. This, too, appears to have the

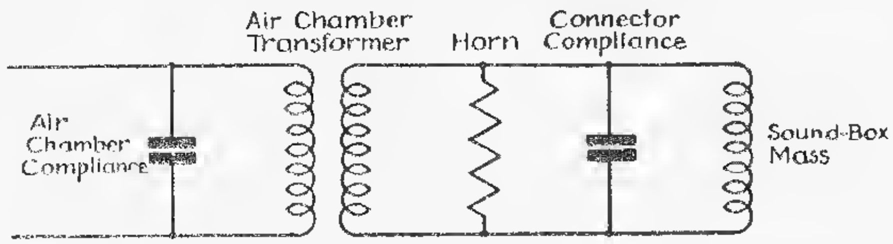


Fig. 33.—Circuit diagram showing electrical equivalent of flexible sound-box connection.

function of increasing and adjusting the compliance, thereby tuning the resonance to a lower frequency.

It is becoming a fairly common practice to have a metal cover on the front of the sound-box. In some sound-boxes this cover also forms the front-rim and has the stylus-bar mounted on it. Its function is simply to protect the diaphragm from damage. In theory it has no other advantage. Indeed, unless it is carefully designed it may form a resonance chamber on the free side of the diaphragm with decidedly unsatisfactory effects on the response of the sound-box. In some cases the front of the sound-box has been enclosed with a small aperture leading to a second horn. The notion seems to be to take energy from both sides of the diaphragm, thereby, it is presumed, doubling the loudness of the sound reproduced. But, of course, the pressure variations on the two sides of the diaphragm are out of phase, and if allowed to enter the same space would interfere with one another and tend to cancel out, particularly at low frequencies. The effect on the response of the sound-box itself is even more serious. The idea is as old as the gramophone itself and its fallacy has been demonstrated on many occasions. The history of the gramophone is full of such ill-considered ideas. They seem to rise Phœnix-like from their ashes and to appear in new plumage again and again. Perhaps it is as well. If there is nothing new under the sun, the old ideas must contain in themselves the secret of progress.

APPENDIX

EXAMPLE OF SOUND-BOX DESIGN

To determine the values of the masses and compliances required in a sound-box, we require a number of formulæ both from the theory of sound and from the theory of wave-filters.

These are, in C.G.S. units :

ρ = density of air = ·00129 grm/c.c.

a = velocity of sound = $3{\cdot}33 \times 10^4$ cm/sec at 15° C.

$\rho a = 42{\cdot}8$.

e = elasticity of air = $\rho a^2 = 1{\cdot}43 \times 10^6$ per square cm per cm length.

Z = characteristic impedance of wave-filter (sometimes called the " surge " or " image " impedance).

f = cut-off frequency of wave-filter.

L = normal series inductance = $Z/\pi f$.

C = normal shunt capacity = $1/\pi f Z$.

As explained in the text, we start with the design of the diaphragm, keeping its mass as small as possible and its stiffness as great as possible, and so arranging matters that the motion shall be as nearly piston-like as possible. The values of the effective piston-mass and area are best determined experimentally. In order to illustrate the principles we will work out designs on the two extreme assumptions: namely, that of a clamped diaphragm, in which case the effective mass may be taken to be 0·2 times the total mass and the mean velocity 0·3 times that at the centre, so that the equivalent piston area is 0·3 times the full area; and the ideal case of a piston of the full area and mass of the diaphragm.

We will assume that the material has a density of 2·75 (which corresponds to either mica or aluminium and is not far out for glass) and that the full diameter and thickness are 4·8 cms. and 0·1 mm. respectively. The total area is $\pi \times 2{\cdot}4 \times 2{\cdot}4$ cm^2 = 18·1 cm^2 and the total mass is $2{\cdot}75 \times 18{\cdot}1 \times 0{\cdot}01$ = ·4978 grm.

The calculations given below relate to:

(a) diaphragm action, cut-off frequency 5,000 cycles.

(b) piston action, cut-off frequency 5,000 cycles.

(c) diaphragm action, cut-off frequency 4,000 cycles.

(d) piston action, cut-off frequency 4,000 cycles.

$Z = \pi f L =$ (a) $5{,}000 \times \pi \times \cdot 4978 \times 0{\cdot}2 =$ 1560 dyne sec/cm.

(b) $5{,}000 \times \pi \times \cdot 4978 =$ 7800 dyne sec/cm.

(c) $4{,}000 \times \pi \times \cdot 4978 \times 0{\cdot}2 =$ 1250 dyne sec/cm.

(d) $4{,}000 \times \pi \times \cdot 4978 =$ 6250 dyne sec/cm.

We now require the impedance looking into the small end of a horn. For the range in which the horn acts as a pure resistance this is $Z_0 = \rho a \ A_0 \text{ cm}^2 = 42{\cdot}8 \ A_0$.

If the full area of the diaphragm worked into the horn the value of this impedance would be $42{\cdot}8 \times 18{\cdot}1 = 775$ dyne sec/cm which is much too small to match the impedance of the filter. The air-chamber transformer therefore becomes necessary.

To find the transformer ratio we assume that the pressure changes in the air-chamber are all in phase and that there is no loss of energy. If V_1 is the average velocity of the diaphragm and V_0 that of the air in the outlet

$V_0 = A_1 V_1/A_0$ (piston) $V_0 = 0{\cdot}3 \ A_1 V_1/A_0$ (diaphragm).

As in the corresponding electrical problem, the energy is proportional to the impedance multiplied by the velocity (current) squared.

So $$Z_0 V_0^2 = Z_1 V_1^2$$

or $$\frac{A_0^2}{Z_0} = \frac{A_1^2}{Z_1} \text{ (piston) or } \frac{0{\cdot}09 \ A_1^2}{Z_1} \text{ (diaphragm).}$$

Hence

$$\frac{A_0^2}{42{\cdot}8} = \frac{A_1^2}{Z_1^2} \text{ (piston) or } \frac{0{\cdot}09 \ A_1^2}{Z_1^2} \text{ (diaphragm).}$$

This gives $A_0 =$ (a) 0·8 cm² (b) 1·8 cm² (c) 1·01 cm² (d) 2·24 cm². For these values the diameter of the outlet $d_0 =$ (a) 1·0 cm (b) 1·5 cm (c) 1·13 cm (d) 1·89 cm.

We now want to find the depth of the air-chamber. For this we note that the compliance is a terminal shunt compliance and that therefore $C = 1/2\pi f Z$ = (a) 2×10^{-8}; (b) $0{\cdot}4 \times 10^{-8}$; (c) $3{\cdot}2 \times 10^{-8}$; (d) $0{\cdot}64 \times 10^{-8}$.

The compliance of the air-chamber

$$= \frac{\text{Displacement of diaphragm}}{\text{Change of pressure.}}$$

For adiabatic expansions this is equal to $\dfrac{V}{\rho\, a^2 A^2}$ where V is the volume of the air-chamber and A is the equivalent piston area. Hence the depth of air-chamber required is $\rho\, a^2 A^2 C/A_1$. For the piston cases, $A^2/A_1 = A_1$. For the diaphragm cases, $A^2/A_1 = 0{\cdot}09\, A_1$. From this we find that the required depths in the four cases are (a) 0·5 mm. (b) 1·03 mm. (c) 0·75 mm. (d) 1·66 mm. If we collect our formulæ we get the following results :

A =	effective area of diaphragm	(cm²)
M =	,, mass ,, ,,	(grm)
V =	Volume of air-chamber	(cm³)
d =	diameter of outlet	(cm)
f =	cut-off frequency	(cycles/sec)

$$Z = \pi f M \quad C = \frac{1}{\pi^2 f^2 M} \quad C^1 = \frac{1}{\pi^2 f^2\, 2M}$$

$$A_0 = \frac{42{\cdot}8\, A^2}{Z^2}$$

$$\pi\, d^2/4 = 42{\cdot}8\, A^2/\pi^2 f^2 M^2$$

$$\therefore d = 2{\cdot}35\, \frac{A}{f M}$$

$$\frac{V}{\rho\, a^2\, A^2} = \frac{1}{\pi^2\, f^2\, 2M}$$

$$\therefore V = \frac{\rho\, a^2\, A^2}{\pi^2\, f^2\, 2M} = 72450\, \frac{A^2}{f^2\, M}$$

The values obtained here for the size of the outlet and the volume of the air-chamber show clearly the advantage of having a large piston area and a small mass, apart altogether from the fact that in that case the fundamental frequency of the diaphragm is higher. The smaller we make the outlet and the depth of the air-chamber the more complicated are the pressure changes (eddies may be set up) and the less reliable are the assumptions on which the various values have been calculated. With certain diaphragms made by the authors of the size and thickness assumed in this example, the best response was obtained with an outlet of about 1·4 cm. and a depth of air-chamber of from 1 to $1\frac{1}{4}$ mm. But in this case the device described in (4) of Section IV—7 was used.

The mass, compliance and transformer ratio of the stylus-bar remain to be dealt with. It should be noticed that if the distance l_1 from the needle point to the pivots is less than the distance l_2 from the pivots to the diaphragm connection the velocity at the diaphragm end is greater than at the needle end in the ratio l_2/l_1. The *pressure* is therefore *stepped down* from the needle to the diaphragm in the ratio l_1/l_2. This is the "turns ratio" of the transformer. The "impedance ratio" is the square of this.

The stylus-bar compliance is not a terminal compliance. Hence $C = 1/\pi f Z$ and therefore has double the value calculated for the air-chamber.

The mass of the stylus-bar is the mass viewed from the diaphragm. If I is the moment of inertia of the stylus-bar this mass is equal to I/l_2^2. The value of this fraction should therefore be equal to the effective piston mass of the diaphragm.

The transformer ratio is determined by the value of the needle-point compliance, and this in its turn determines the power taken from the record. In view of the variety of needles available, and of the complicated structure of the stylus-bar itself, it is clear that the design of a stylus-bar by ealeulation alone is virtually impossible. The only part that can be determined with certainty is the compliance of the upper arm. At present probably the best method of dealing with the rest of the design is by experiment with needle-sockets and needles of different masses and different lengths.

If a spider is inserted between stylus-bar and diaphragm its mass and compliance will be normal elements. The mass should therefore be the same as the effective piston mass of the diaphragm and the compliance double the air-chamber compliance.

It might at first sight be thought that the number of sections in the filter could be increased by using several diaphragms, one behind the other, the air-chambers between each diaphragm providing the necessary shunt compliances and the masses of the diaphragms being all equal. But since the diaphragms on each side of an air-chamber will be in motion, the necessary compliances could not readily be obtained, and the analogy with the electric wave-filter would break down. Still, there is here a possibility of development in the future.

CHAPTER V

HORNS

V—1. Function of the Horn.

For a long time the part played in a gramophone by the horn remained obscure. Some people spoke of it as an amplifier, thereby begging the whole question ; others committed themselves more deeply and referred to it as a resonator, thereby implying that its function was simply to resonate and thus increase the response whenever the frequency of the forced vibrations happened to coincide with one of its own natural frequencies. But one of the things we wish to avoid is undue prominence to particular notes in the scale.

The preceding chapters have indicated two ways of looking at the matter. In one place it was remarked that the horn acted in conjunction with the air-chamber of the sound-box to load the diaphragm, thereby making the diaphragm resonances less prominent, and extracting more energy from the record. From this point of view the important requirement of a horn is that it should impose equal loading on all notes, from the bottom to the top of the musical scale, and this implies that the horn itself should be as free as possible from resonances.

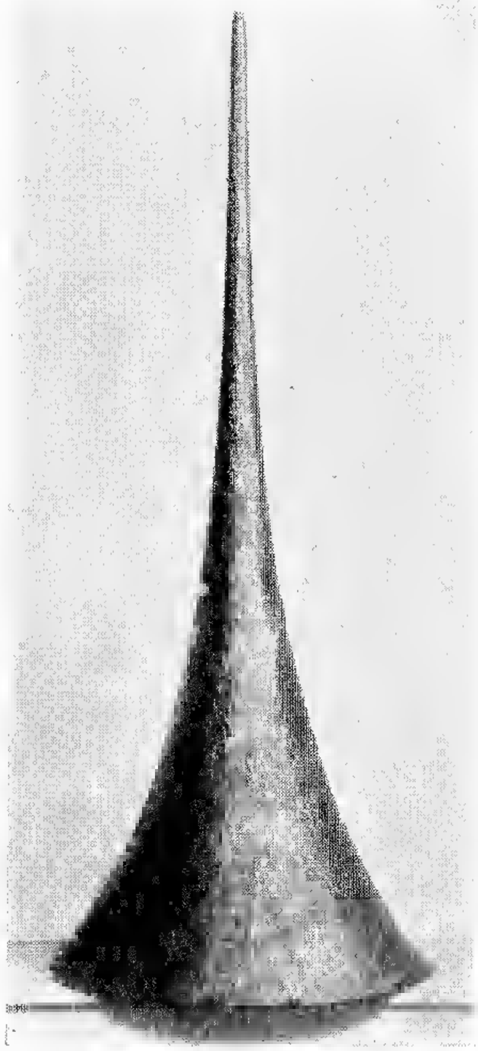


Fig. 38. 5-ft. Exponential Horn

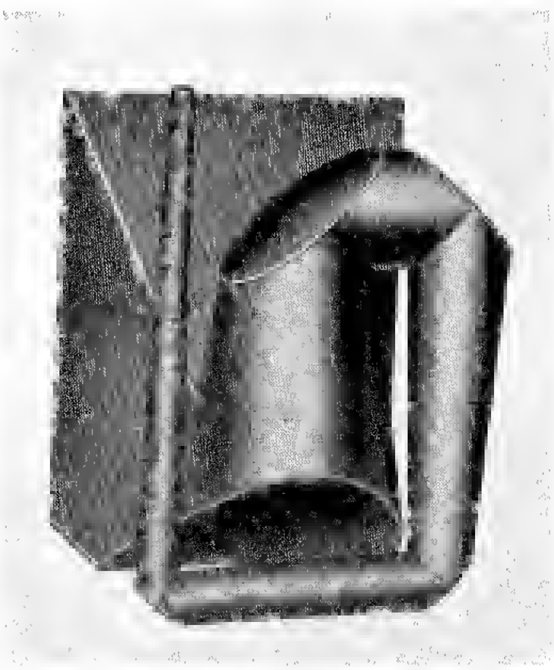


Fig 39.
Columbia " Plano-reflex " horn

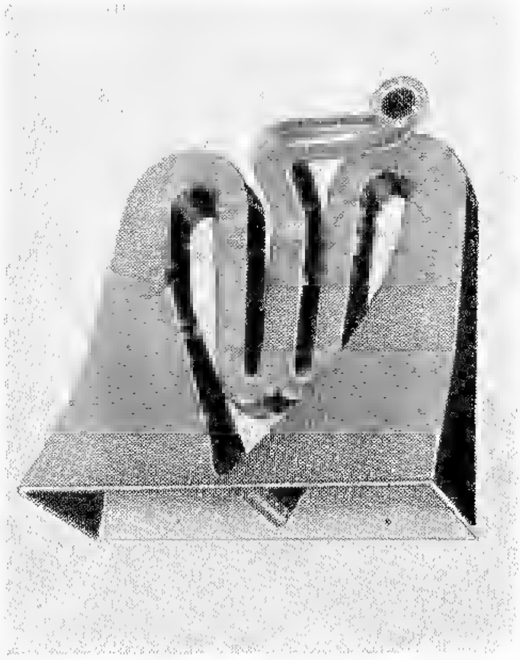


Fig. 45.
Columbia Bifurcated horn

HORNS

The other view of the same function of the horn was that it provided the terminating impedance of the sound-box wave-filter and should therefore act as a pure resistance over the range of frequencies under consideration. It is not a very difficult matter to demonstrate that these two views of the function of the horn in effect really amount to the same thing. Constant loading implies constant resistance. Resonance implies a reactance component. The only form of conduit known which satisfies the requirements completely is a tube of uniform bore and great length—a sort of speaking tube in fact. That does give a pure resistance with constant loading provided that the walls of the tube are quite rigid.

In a gramophone, however, we want something more than this: we want the sound produced in the loading tube to be transmitted to the outer air with a minimum of distortion in the process. Now in a tube with small diameter at the open end or mouth sound-waves are largely reflected back again. The only waves which can get through the opening without difficulty are those with frequencies so high that their wave-lengths are not large compared with the diameter of the tube. (*N.B.*, wave-length $\times$ frequency $=$ velocity of sound.) The existence of these reflections from the mouth of a tube must mean that resonances are set up. The only low notes which will be heard are therefore those that happen to correspond with the resonances of the tube. The arrangement will thus act as a musical instrument and impose its own character (due to its resonances) on all the sound-waves passing through it.

To explain more fully what happens at the open end of the tube we cannot do better than quote a passage from Hanna and Slepian's paper, read before the American Institute of Electrical Engineers in February, 1924.

"Consider a half wave length of sound, in which there is positive pressure and forward velocity travelling along the tube. While progressing within the tube it is uniformly confined and occupies a constant volume. Hence the pressure and velocity in it remains constant. As it leaves the open end of the tube, however, it expands into an approximately hemispherical shape, Fig. 34. There is thus an increase in the volume occupied by the wave as it leaves the tube. Evidently a fall in pressure must result. But if the pressure just outside the tube remains lower than that within the tube, the velocity of the air just within the tube will be increased; this causes the pressure just behind to decrease, and the velocity to increase, and so we have produced a wave travelling back in the tube, which near the open end reduces the pressure and increases the velocity in the oncoming wave. This is the familiar phenomenon of reflection.

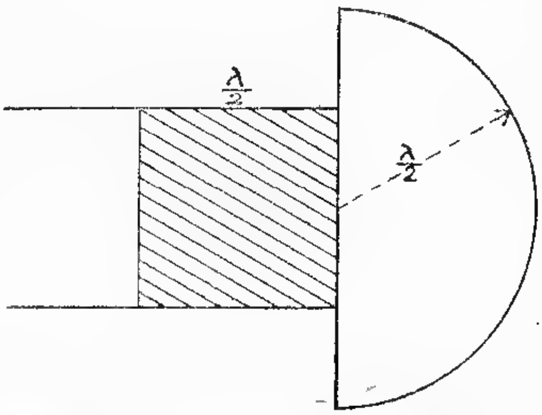


Fig. 34.—Reflection of waves at open end of a tube.

"The reflected wave not only represents power which does not get out into the air but, depending on the phase in which it reaches the diaphragm, it may produce resonance or dissonance. Obviously, the less intense the reflection is, the less marked will be the resonance or dissonance.

"It is now easy to see what influence the size of the final opening of the tube has upon the intensity of the reflection. It is evident from Fig. 34 that thc larger the section of the tube is, the less will be the relative increase in volume occupied by a half wave length just within and just without the tube, and therefore the less intense will be the reflection. For wave lengths which are less than the diameter of the tube, Fig. 35, the increase in volume on passing out of the tube is slight, and therefore the reflection is negligible; but for wave lengths which are greater than the tube diameter, Fig. 34, the increase in volume becomes considerable, and the reflection becomes appreciable."

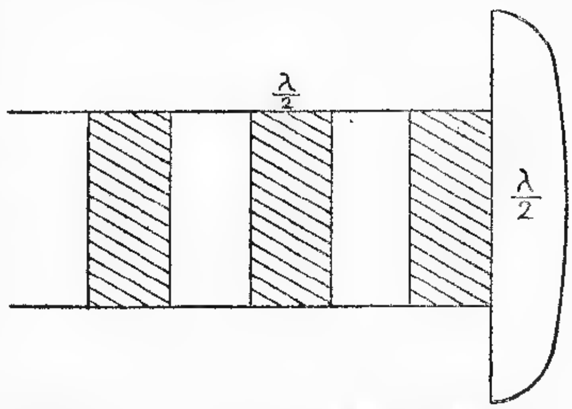


Fig. 35.—Reflection of waves at open end of a tube.

V—2. Properties Required of a Horn.

We are now in a position to state the three requirements of a horn:

(1) The throat should be small, to correspond with the outlet from the sound-box.

(2) The mouth should be large, to transmit the sound with negligible reflection to the open air.

(3) The whole arrangement should be sueh as to give a constant loading, or, in other words, to act as a pure resistance.

It is not very diffieult to see that these requirements are ultimately ineonsistent with each other. To proceed from a throat of small area to a mouth of eonsiderable area, we must taper the tube and thus allow the sound-waves to spread out laterally. Low notes will spread much more than high notes. This lateral dispersion introduces a phase differenee between the pressure and velocity of the air in the tube, and this in its turn reduces the loading on the diaphragm. It has already been explained that the loading at any instant is proportional to the power being transmitted. Now just as electrical power (watts) is the product of the electromotive force (volts) and the current (amperes), so in our present problem the power being transmitted past any seetion of the horn is the product of the pressure and the velocity, and if these are out of phase the transmitted power is redueed. It is, in faet, equal to the product of the maximum values of the pressure and velocity multiplied by a quantity known as the "power faetor." This is equal to the eosine of a certain angle which measures the amount by whieh the two are out of phase. When they are in phase this angle is zero and the power faetor is unity. When they are eompletely out of phase the angle is 90° and the power faetor is zero, which means that no power is transmitted.

From the preceding argument it will readily be appreciated that the more slowly the horn opens up to its large mouth opening, the more uniform will be the loading on all notes. If we wish to go very low in the seale we shall require a very long horn with a very large opening.

V—3. Contour of a Horn.

It will naturally be anticipated that the shape or contour of a horn will matcrially affect its loading properties. The only case which has been fully trcated mathematically at present is that of a conical horn, in which the radii of successive sections at constant intervals along the axis inerease by a constant *amount*. The properties of this type of horn were worked out over fifty years ago in Lord Rayleigh's "Theory of Sound." It can be shown from Rayleigh's formulæ that the power or loading factor at various frequencies is as drawn in Fig. 36 (A). The loading falls off rapidly as we come down the scale. This type of horn, then, is clearly not suitable for our purpose, espccially with a constant velocity system of recording. If the recording could be done on a constant acceleration basis (see Fig. 10 on page 25) a conical horn would be more suitable, though even then it would not be effective in damping out diaphragm resonances.

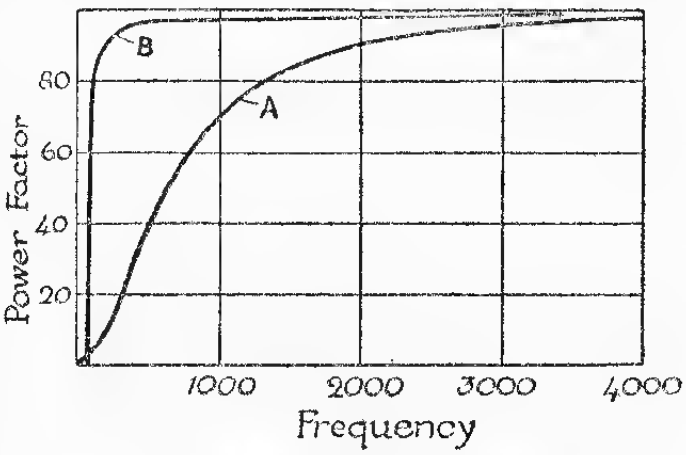


Fig. 36.—Loading factors of conical and exponential horns.

In 1919 Prof. A. G. Webster, acting upon a hint given in Article 265 of Rayleigh's treatise, worked out an approximate theory for other types of horn. His formulæ indicated that one type would probably be more suitable for sound-reproduction than any other, and since then very good reasons, though not quite rigorous proofs, have been advanced to show that that is indeed the case. In this type of horn the areas of successive wave-fronts increase by a constant *percentage* at constant intervals along the axis. It ean be shown that for such a horn the power (or loading) factor is as shown in Fig. 36 (B). The loading is practically uniform for a long range of frequency, and then begins to fall off, and finally cuts-off quite rapidly. The frequency at which this occurs is known as the "cut-off frequency." The following table will indicate how rapidly the power factor incrcases from zero at the cut-off frequeney to unity at higher frequencies. The frequency scale is in octaves.

Frequency ..	f	2f	4f	8f	16f
Power factor	0	0·866	0·966	0·992	0·998

V—4. The Exponential or Logarithmic Horn.

The definition already given, however, does not in practice enable us to specify the actual shape of the horn. We are in something of a dilemma. The areas of successive wave-fronts intercepted by the horn should increase by a constant percentagc. In order to determine the proper shape of horn we require to know thc shape of the wave-fronts ; and the shape of the wave-fronts depends on the shape of the horn. There are certain ways in which a problem of this sort may be tackled. Many similar problems havc been rigorously solved mathematically. But this particular problcm has so far resisted attack in this way. The othcr method that is available is to make a series of approximations, first assuming a shape, working out a wave-front, then correcting the shape, working out a corrected wave-front and so on.

The usual assumption made is that the wave-fronts are all plane. In this case we get what is known as an exponcntial or logarithmic horn which is of the shape shown in Fig. 37.

If we measure distances x along the axis of the horn Ox, and distances y at right angles to the axis, we can get a formula which determines y in terms of x. Thus if P M P^1 represents a section of the

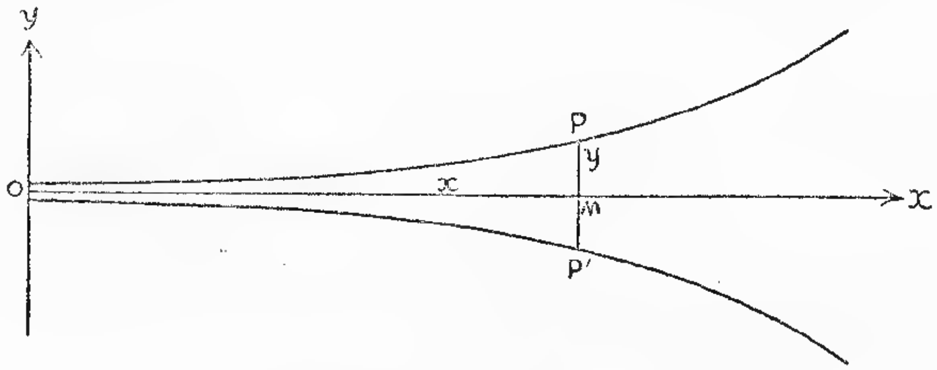


Fig. 37.—Outline of exponential horn.

horn (assumed to be circular for the present) distant x from O, and P M = M P^1 = y

$$\log y = \log y_0 + mx$$

where y_0 is the value of y at the origin O, and m is known as the linear rate of taper of the horn. From this equation the value of y can be computed for different sections by the use of ordinary log tables.

The cut-off frequency is determined by the value of m. If this cut-off frequeney is denoted by f it can be shown that

$$f = ma/2{\cdot}7288 = {\cdot}3665\ ma$$

where *a* is the velocity of sound in the units we use for measuring our distances.

To construct a horn with a given cut-off, then, we first of all determine the value of m from this formula. We then use this value in the equation to give the value of y at any distance we choose from the throat, the value y_0 being determined by the radius of the opening in the sound-box. This method will give us the radius of the cross section of the horn at *any* point. Sometimes, however, it is convenient to use a different method. We start by marking off equal distances 0-1, 1-2, 2-3, etc., along a line. At the points 0, 1, 2, 3, etc., we erect perpendiculars. At 0 we make the length of the perpendicular equal to the radius of the throat; at 1 we double that length; at 2 we double the length at 1; at 3 we double the length at 2, and so on. The extremities of these perpendiculars determine the shape of the horn. Under this method of construction the cut-off frequency is determined by the distances apart of the points 0, 1, 2, 3, etc., at which we double. The cut-off, in fact, will have a wave-length of 9 times the distances apart. Thus, if the distance between perpendiculars is 6 inches, the wave-length of the cut-off will be 4 ft. 6 ins., which is just below middle C (wave-length 4 ft. 3 ins.), whilst if the perpendiculars are a foot apart the cut-off will be an octave lower.

V—5. Another Approximation.

The exponential horn is an approximation to the shape we are aiming at, derived upon the assumption that the wave-fronts in the horn are plane. Clearly, however, such an assumption cannot be true. The wave-front along the axis of the horn must gain on that at the boundaries so that in practice the wave-front must present a convex surface at the mouth of the horn.

In a conical horn it may be shown that the successive wave-fronts are spherical with centres at the apex. In a straight tube of uniform bore the wave-front is plane. In both cases, it should be noticed, the wave-fronts cut the sides of the conduits at right angles. It is therefore natural to inquire whether we cannot find a shape of horn with the characteristic property of constant percentage increase of area of wave-fronts, assuming these to be spheres cutting the horn at right angles. Such a shape can be determined. It approximates very closely to the ordinary exponential horn but, on the whole, lies inside the contour of it. The shape of the modified horn can in practice be deduced from that of the exponential horn by measuring the angle which the latter makes with the axis at successive points along its length. The diameter (or radius) of the exponential horn at each point must be reduced in a ratio which depends on the value of that angle. The following table gives the ratio of reduction for various angles up to 45°:

Angle of slope	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°
Ratio ..	1	·999	·996	·991	·985	·976	·967	·957	·945	·930

Thus, at a point where the slope of the exponential horn is 20° to the axis, the diameter (or radius) of the modified horn is ·985 times that of the exponential horn. The formula on which this table is based will be found in Appendix II to this Chapter.

The following table gives, for different distances from the throat along the axis, the lengths of the radii of an exponential horn with a cut-off at 64 cycles per second—two octaves below middle C. If the distances along the axis were halved, the cut-off would be 128 cycles, whilst if they were doubled, the cut-off would be 32 cycles. It should not be assumed, however, that the horn will give uniform loading down to its cut-off. The table given on page 96 shows that even at the octave above the cut-off the loading is only ·866 of the full amount.

TABLE

Details of Exponential and Modified Exponential Horns with Cut-off 64 Cycles.

(1) Distance from throat (inches)					0	4	8	12	16	20
(2) Radius of section (exponential) (inches)					0·25	0·28	0·32	0·36	0·4	0·45
(3) Radius (modified exponential) (inches)					0·25	0·28	0·32	0·36	0·4	0·45
(1)	24	28	32	36	40	44	48	52	56	60
(2)	0·51	0·57	0·65	0·73	0·82	0·92	1·04	1·17	1·32	1·48
(3)	0·51	0·57	0·65	0·73	0·82	0·92	1·04	1·17	1·32	1·48
(1)	64	68	72	76	80	84	88	92	96	100
(2)	1·67	1·88	2·12	2·38	2·68	3·02	3·40	3·83	4·31	4·85
(3)	1·67	1·88	2·12	2·38	2·68	3·02	3·39	3·82	4·30	4·84
(1)	104	108	112	116	120	124	128	132	136	140
(2)	5·46	6·15	6·93	7·80	8·78	9·89	11·13	12·53	14·11	15·89
(3)	5·44	6·13	6·89	7·75	8·71	9·81	11·03	12·39	13·9	15·6
(1)	144	148	152	156	160	164	168	—	—	—
(2)	17·89	20·15	22·68	25·54	28·76	32·38	36·46	—	—	—
(3)	17·5	19·6	21·9	24·5	27·3	30·5	34·0	—	—	—

In the table the radii of the modified exponential horn with a cut-off at 64 cycles are also given. It should be noticed that for the modified horn we cannot alter the cut-off simply by altering the distances along the axis. To get the modified horn for other cut-offs we must first draw the corresponding exponential horn and then apply the reduction factors for angle of slope.

V—6. Size of Mouth Opening.

In a horn, just as in a uniform tube, sounds of large wave-length compared with the diameter of the mouth are largely reflected and do not emerge to the open air. If we are to pass bass notes we must, therefore, make the diameter of the mouth large. Clearly, however, we need not bother about the reflection of sounds below the cut-off of the horn determined by its rate of taper. We are thus naturally led to inquire whether there is a size of mouth which will give a minimum reflection for the frequencies above the cut-off. Hanna and Slepian investigated this in their paper previously referred to, and found that on certain assumptions as to the shape of the emerging wave-front, the reflection would be a minimum when the slope of the horn at the mouth was 45° to the axis. Another investigation on similar assumptions, but by a different method, was made by P. B. Flanders (see British Patent 245,415) with almost exactly the same result. Now it may be shown that the assumptions made in both these investigations must lead to rather too large an angle of slope. In any case, for the modified horn a slope of 43° corresponds to one of 45° in the exponential horn. By experiment the authors have found that a final slope of about 42° gives the most satisfactory results, but that even a slope of 40° is not greatly inferior. To design a horn with a specified cut-off it is thus most convenient to begin at the throat (whieh should correspond with the outlct in the sound-box), draw the appropriate exponential curve as previously deseribed, measure the angles of slope, and thus form the eurve for the modified shape. This curve should then be continued until a point is reaehed where thc slope makes an angle of 42° with the axis.

The length of horn required to give the best loading is thus seen to depend partly on the rate of taper and partly on the size of the mouth neeessary to give minimum refleetion. As previously indicated, substantial refleetion at the mouth gives rise to pronouneed resonances. It is, therefore, bad practice to make a horn with a small rate of taper and cut it short before reaehing the size of mouth requisite for minimum reflection. In small gramophones, such as portables, where size of opening is very limited, horn resonanees have to be tolerated ; in this ease a small rate of taper eombined with a relatively small mouth is the best compromise that ean be effected. But the volume of reproduction should be kept eomparatively low so that the resonanees do not become too prominent. In a gramophone with any pretensions to accuracy of response, however, a long horn with a large opening is essential. If the eut-off is to be an oetave below middle C a length of 5 feet and a mouth of 2 fect diameter are nccessary. A photograph of a straight horn with these characteristics is reproduced in Fig. 38, Plate VIII. For a cut-off at 100 cycles the length must be increased to 8 feet and the mouth diameter to 3 feet 6 inches, whilst for a cut-off at 64 cycles the length must be 14 feet and the mouth diameter 5 feet 6 inches. In all these cases, the throat diameter has been assumed to be $\frac{1}{2}$ inch.

V—7. Non-circular Section.

So far it has been assumed that the cross-section of the horn is circular in shape. The transmission in a horn of any other form of section is doubtless a more complicated affair. No complete theory is available. Experiment shows, however, that provided the cross-section is not unduly elongated in any direction, the response is not very different to the ear from that of a circular horn of equal area at corresponding cross-sections. In a rectangular horn there are probably eddy currents set up at the corners, and the effective area is rather less than the full area, so that for close correspondence with the circular horn a rather greater length will be necessary. Moreover, when the horn has flat sides there is always a risk that these sides will be set into vibration and give a "drumming" effect. A circular section is always more rigid than a flat-sided section; hence the use of circular tubes for the underground railways. Many manufacturers deliberately stiffen the sides of a rectangular horn either by means of corrugations or by external bands. Others deliberately make use of the drumming effect to give an added response to certain notes in the bass. The drumming is due to a resonance in the material, and if the natural frequency of this resonance is below the cut-off of the air-column some advantages may be gained. This is a delicate business, however, and is fraught with a great many dangers.

If the section of the horn is much elongated the response may be substantially different. One curious fact about an elongated opening should be noticed: when the waves emerge into the room they expand more in the direction of the shorter dimension. Thus the sound waves emerging from a gramophone with a mouth in the form of a horizontal slit spread more vertically than horizontally.

V—8. Folded Horns.

The fact that a very long horn is required for an adequate response to bass notes at once raises the question whether folding a horn will alter its characteristics. The answer is that it does. Even in a straight horn the precise shape of the wave-front is not easily ascertained, but we have the assurance that at any rate it is always at right angles to the centre-line, and is symmetrical on each side of it. A folded horn is not symmetrical with respect to the centre-line, and we can only make more or less intelligent guesses at the shape and position of the wave-front. Accurate calculations to determine the contour so that the areas of successive wave-fronts will increase by a constant percentage are therefore quite out of the question. One must proceed by making assumptions as to the shape of the wave-fronts and then check the design a posteriori. The large gramophone companies actually measure the acoustic response of their instruments and modify the design until the right response is obtained. This, of course, is the safest method of procedure but it is naturally very costly.

Certain principles of design ean, however, be dedueed from general eonsiderations. To design a folded horn to give as uniform a response as a straight exponential horn involves great expenditure of both time and money. For this reason an external horn gramophone, where the bends are few and are all in the narrow part of the horn, can be designed to give a uniform response much more easily and more eheaply than a cabinet gramophone. But provided suffieient time is given to the aetual design, checking and re-cheeking the drawings, it is quite possible, even for an amateur, to make a folded horn with many of the excellent qualities of the straight exponential horn. The principal difficulty is to determine the probable positions of suecessive wave-fronts. Our design must aim at wave-fronts proeeeding steadily out to the mouth with eonstant pereentage inerease of area. We must guard against twisting the wave-front aeross the horn. Dr. A. H. Davis's experiments with water waves in ripple tanks, at the National Physieal Laboratory*, lead to the inference that at a sharp bend in a horn eross vibrations may be set up, and that these will derive their energy from the main flow through the conduit, thus filtering out all notes of a wave-length corresponding with that of the cross-vibration. In a uniform tube the cross-

* See "Proc. Phys. Soc." Vol. 40, p. 91.

vibrations have a fundamental wave-length equal to 1·7 times the diameter of the tube. Thus, if the diameter is 2 inches, notes in the region of 4,000 cycles will be filtered, whilst if the diameter is 4 inches, the effect will be on notes of about 2,000 cycles. There may also be other effects due to reaction at the walls of the tube depending principally upon the nature of the material.

The twisting of the wave-front across a sharp bend is due to the differencc in the lengths of the paths round the inside and outside of a bend. The wave-front is the surface along which the pressure is the same. At the inside curve of the bend, therefore, the position of the wave-front is in advance of the position at the outside curve. Now, as soon as the wave-front ceases to cut the outside curve at right angles, a reflectcd wave is set up equally inelined to the reflecting surface, which in this case is the outer wall of the conduit. If the bend is so designed that the reflected wave strikes the inner wall and is reflected back again to the outer wall cross reflections ensue. We can guard against this by designing the bend in such a way that the extreme portions of the wave-front are all reflected outwards towards the mouth of the conduit. One method of doing this is illustrated in Fig. 39, Plate VIII, which shows the Columbia Plano-reflcx horn. Here flat surfaees are made at the bends to act as reflectors.

It is clear, however, that this method does not give us any means of ensuring that the areas of successive wave-fronts shall increase by a constant percentage. What are the successive wave-fronts for this purpose at a bend ? One or two methods of avoiding this dilemma may be suggested. Lord Rayleigh has shown that bends in a tube of constant cross-section will have no effect on sounds whose wave-lengths are large compared with the diameter of the tube. If, therefore, we can keep our most acute bends at the part of the horn where the cross-section is not more than 2 inches, and make them of uniform bore, we can confine any deleterious effects to the region above 4,000 cycles. It should not be forgotten in this connection that the ear is most sensitive in the region between 2,000 and 4,000 cycles. Even if we cannot afford the additional length required to make the horn of uniform bore at the bends, it is well to arrange for the expansion to be in one direction only, preferably in the direction across the bend, and not along it. Alternatively, we may endeavour to accelerate the wave-front along the outside curve of the bend. Thus, in a horn normally of square cross-section, we may make the section across the bend in the shape of a trapezium (Fig. 43, page 118), the longer parallel side being at the outside of the bend. If the section is normally circular the corresponding section at the bend would be egg-shaped, the broadest portion being at the outside. This method of procedure is especially useful when the bends are in the form of long sweeping curves. In any case, however, it is probably an advantage to spread out the change of section to the trapezium or ovoid form over a length of the horn and not merely confine it to the actual bend. An example of this method, illustrated in Figs. 40-43, is worked out in the first appendix to this chapter.

V—9. Bifurcated Horns.

It has been explained that the difficulties of folding a horn arise from the fact that the inside and outside curves are not of the same length, and that in consequence of this the position of successive wave-fronts becomes difficult to determine. It has also been mentioned that cross-reflections may be set up with a filtering effect on notes of wave-length in the region of 1·7 times the diameter of the horn at that point. If we can split up the horn into two or more separate channels the diameter can be kept small, thereby confining any filtering effect to very high frequencies, and at the same time we can make the lengths of the inside and outside curves more nearly equal.

Now it can be shown (see Rayleigh, Art. 264) that bifurcating a conduit will have no effect on the transmission of sound, provided that :

(1) The lengths of the two portions are equal.

(2) The sum of their areas at corresponding points is equal to that of the original conduit.

A bifurcated horn can thus be designed to have the same loading properties as a single exponential horn, and the separate conduits being of small section, the horn may be folded into a smaller space without deleterious effects. It is clearly desirable to bifurcate as soon as the diameter of the cross-section of the horn reaches a value which would bring the frequency of any cross-reflections below 5,000 cycles. The wave-length for 5,000 cycles is

1130 × 12/5000 or 2·7 inches. Dividing this by 1·7 we learn that it would be well to bifurcate the horn, if we can manage to do so, as soon as the diameter *across* a bend exceeds 1·6 inches, though not much harm will be done if we have to wait until the diameter reaches 2 inches. Bifurcations where the diameter is smaller than 1·6 inches will not be of any assistance to us. After a bifurcation we can design each portion of the horn, retaining the original rate of taper *m*, and proceeding on the basis that the area of cross-section just after bifurcation is the "initial area" for the succeeding portion. It is convenient, of course, that the two conduits after a bifurcation should be symmetrical, since then the design is the same for both.

It is not proposed here to go into details regarding the design of these succeeding conduits. Each one can be dealt with by the methods described in the last section. It should be emphasized, however, that the joining up of the various portions should not take place until all bending has been finished; otherwise the advantages of bifurcation will be lost.

The general arrangement of the several portions of the horn will naturally depend on the skill and ingenuity of the designer. The 1927 Columbia gramophones illustrate a straightforward method of bifurcation. A photograph of this is shown in Fig. 45 (Plate VIII). A more elaborate, and at the same time more compact, method is employed in the H.M.V. re-entrant (1928) models. This method was devised by Mr. H. C. Harrison, of the Bell Telephone Laboratories, and is illustrated in Fig. 25 (Frontispiece). An even more elaborate method, devised by the authors, is shown in Fig. 46. Here the horn bifurcates into two portions a and b, and each portion subsequently bifurcates into two: a′, a″, b′, b″; a′ joins up with b′ and a″ joins up with b″ at the rear of the cabinet, leaving two portions which eventually unite at the front. The arrangement is not so complicated in practice as it seems at first sight, since the shape of a′ is exactly the same as that of b″, and the shape of a″ is the same as that of b′.

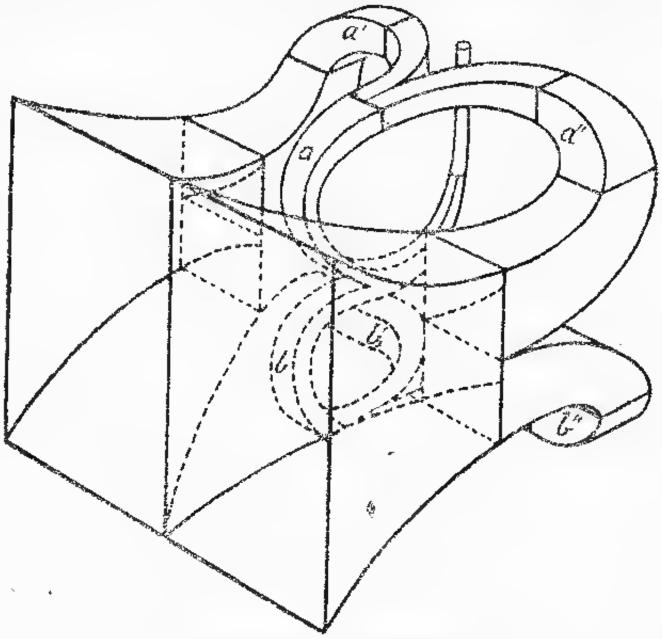


Fig. 46.—Authors' bifurcated horn.

V—10. Material of Horns.

Up to now we have been solely concerned with the shape of the air-column of the horn. It remains to discuss what effect the material has on the properties of the horn. In a straight horn, provided the walls are rigid and smooth, the material of which they are made has little or no effect on the transmission. If the walls are rough or yielding, however, there is a certain attenuation, roughness principally affecting high notes and lack of rigidity the low notes.* In a folded horn, where the possibilities of reflection at the walls cannot be ignored, the effects may be much more complicated. The

* Lamb: "Dynamical Theory of Sound," Section LXII. Rayleigh: Brit. Assoc. Report, 1893, p. 690.

walls of the horn will have resonances and at each reflection will emphasize the notes of their own frequency. These resonances will be more marked in a flat-sided horn than in one of circular section. Some gramophone manufacturers deliberately make use of these resonances to increase the response of the horn to certain frequencies; others bind their horns with rubber tape or other non-resonant materials—as previously mentioned.

The current notion that a horn made of metal must necessarily give a metallic tone to the reproduction is quite untenable. It may or may not according to the way in which it is used. Metallic tone in reproduction is usually due to over emphasis of frequencies between 2,000 and 3,000, and for this it is much more likely that the sound-box or loud-speaker unit or electric amplifier will be responsible. A bad electrical transformer, for example, will give a metallic quality to the reproduction, whatever the nature of the material of the horn used for the loud-speaker.

Provided one or two simple rules are observed, the material does not appear to be a really vital factor in the construction of a horn, unless indeed a deliberate attempt is made to fill out the response of the sound-box and air-column by resonances in horn material. This, however, is a very tricky business, and hardly one to be recommended, unless there are ample means for measuring the response actually produced. A few exceptionally gifted people may be able to obtain an even response by aural tests, but in the ordinary way it is much more likely that the resonances will be placed at wrong places. In the authors' experience it is better practice to avoid resonances as far as possible, and to place those which cannot be avoided either very low or very high in the scale. Some forms of papier mâché have very low resonances, but they have the disadvantage that the surfaces are not very rigid. Ebonite is a good material, but is brittle and very expensive to mould. Ply-wood, which was commonly used in the past owing to the ease with which it can be bent, is a poor material for several reasons; the cementing or gluing of the layers is often inadequate, and this causes a rattle to be set up; the joints are very difficult to make satisfactorily; and in any case it is not easy to avoid surface resonances within the normal range of reproduction. Ordinary tin-plate is often used nowadays, principally because it is fairly easy to work, and in a long folded horn ease of working is an important consideration, not only on account of expense, but also because the exact shape required may be more accurately obtained. But unless it is of heavy "gauge," and is specially stiffened either by corrugations pressed in the walls or by external stiffening members soldered to the outside, it has a tendency to "drum" on notes in the middle register. For this reason some manufacturers use sheet zinc, again suitably stiffened. Having regard to cost, ease of working and general response, perhaps terne-plate is as good a material as any at present available.

The simple rules referred to are thus:

(1) The material should be as rigid as possible: this means heavy gauge.

(2) It should not easily buckle.

(3) Any resonances introduced by it should either be very low or very high. The latter is the more easily obtained in practice by use of stiff and fairly thick materials.

(4) Flat surfaces should be stiffened.

(5) The material must not be difficult to work.

(6) It should be such that all joints can be made firm and air-tight.

As regards the method of fixing horns in a cabinet little need be said. Some people prefer to have the horn free (or "floating") at the mouth and fixed only at the throat. This is probably an advantage for horns which depend for part of their effect on the resonance properties of the material. The purist, however, who aims simply at air-column loading and wishes to avoid resonance, will prefer to have the horn mounted as rigidly as possible. Some have even gone to the extreme of setting it in cement. This certainly avoids wall and cabinet resonances, but is hardly likely to become popular until the gramophone or wireless set ceases to be a personal luxury and becomes a landlord's fixture. There does seem, however, to be some possibility that in the future huge horns may be built into the fabric of places of public entertainment—theatres, cinemas, dance-halls and the like, especially when used with electrical reproducing instruments. A horn forty feet long, with a suitable electrical loud-speaking unit, is the most efficient loud-speaker and has the longest range of response that we can ever hope to obtain.

APPENDIX I

EXAMPLE OF FOLDED HORN DESIGN

The method of design outlined on page 107 will best be understood if we indicate the stages to be followed in a particular case. We will therefore study the design of a horn folded as in Fig. 40.

We will neglect the effect of the twisting at right angles to the paper (it is very small in any case) and concentrate on the main bend whieh affects the

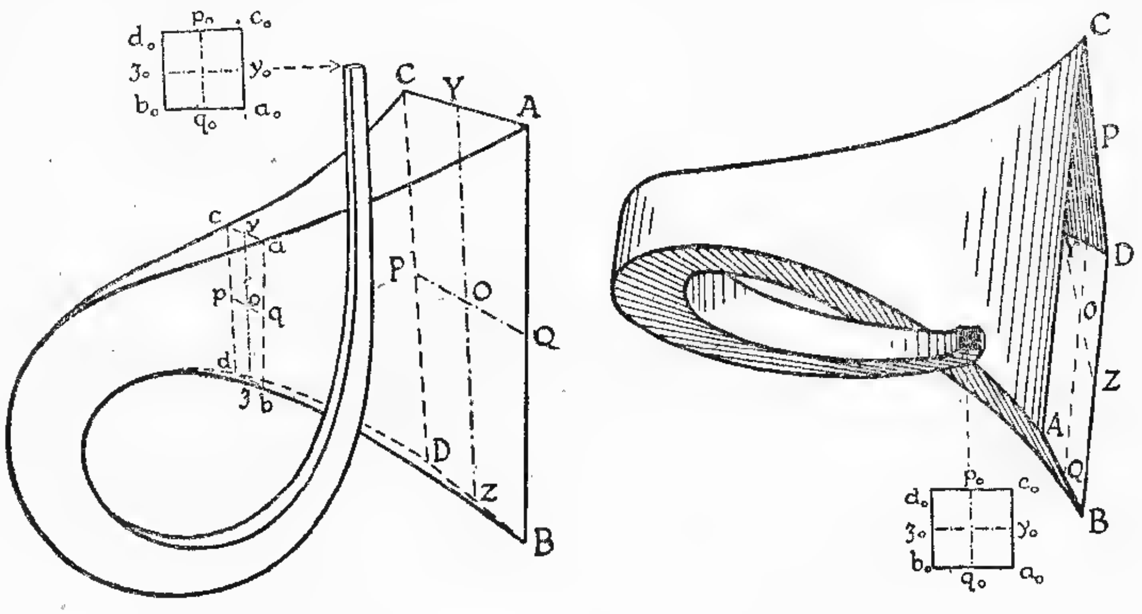


Fig. 40.—Design for simple folded horn.

lengths and shapes of the faces ending in the lines A C and B D. Thus it is clear that the face which ends in A C is longer than that which ends in B D. So our first aim must be to determine these two lengths measured along the centre line of the faces. This is equivalent to determining the shape of the central section which ends in the dotted line Y Z.

The throat area is fixed by the design of the sound-box (or loud-speaker unit), as explained in the previous chapter. For the present purpose it is assumed to be square; when the design is finished it can be pressed into circular shape of equivalent area. We choose our cut-off frequency to suit our requirements and thus determine the axial length (l) of the horn (ending at o) and the area of the mouth opening. For economy in cabinet construction it will probably be convenient to have the depth A B rather greater than the breadth A C; these two are chosen to give the required mouth area.

The area of successive sections is given by a formula of the type:

$$\log A = \log A_0 + M x$$

Since at any section $A = (ab) \times (pq) = 4\,(op) \times (oy)$
$\log A = \log 4 + \log (op) + \log (oy)$.

It is therefore suggested that the formula for oy should be of the form $\log (oy) = \log (oy)_0 + nx$ while that for op will be $\log (op) = \log (op)_0 + mx$ where $mn = M$. The value of n is determined by the axial length of the horn and the initial and final openings.

Thus

$$n = \frac{\log (OY) - \log (oy)_0}{l}$$

and

$$m = \frac{\log (op) - \log (op)_0.}{l}$$

Having worked out these values of n and m we can now construct a table giving for various axial distances x from the throat the successive cross-sectional areas and the successive lengths of oy and op.

We are now in a position to draw the central section of the horn ending in YOZ. We draw the central line in the form shown in Fig. 41 and at the successive distances x along it we draw perpendiculars. Along these perpendiculars on each side of the central line we mark off the lengths oy given by the table.

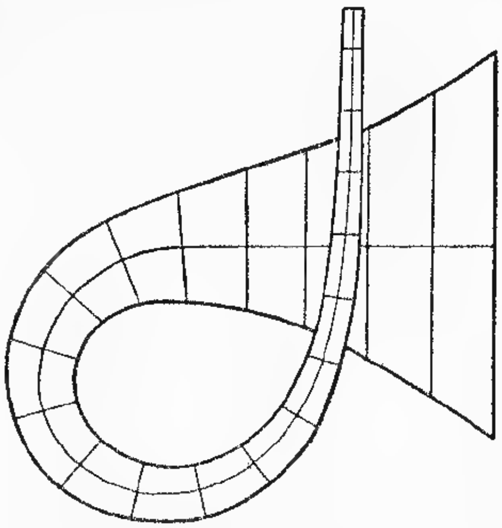


Fig. 41.—Central section of folded horn.

Then by means of an instrument, such as a map measurer, which measures distances along a curved line, we measure the actual distances l_0 and l_1 along the outside and inside curves of this contour. These are the centre lines of the faces ending in AC and BD. We now determine the shapes of these faces so that the lengths yc and zd increase *at the same rate* as the lengths op.

Thus

$$\log (yc) = \log (yc)_0 + mx_0$$
$$\log (zd) = \log (zd)_0 + mx_1$$

Since the total length l_0 along the centre line of the outside face is greater than l_1, the length along the inside face, we arrive at a length YC for the opening which is greater than the length ZD. Also at corresponding points yc is always greater than zd, so that the horn is constricted round the inside of the bend.

We must now re-determine the values of the lengths oy in such a way that the *areas* of successive sections have the right value, as given by the tablc of areas previously constructed. We havc for the area of the trapezium abcd (sce next page),

$$A = \tfrac{1}{2}\, yz\,(ca + db)$$
$$= 2\, oy\,(yc + zd).$$

Hence

$$oy = \frac{A}{2\,(yc + zd)}$$

A is given by the table of areas and yc and zd have just been determined for the corresponding axial distance x.

The distances oy, yc and zd have all been dcter-mined for an exponential horn. To get the modified form we reduce these lengths in the ratios given by the table on page 99.

The procedure described determines the shapes of the faces ending in AC and BD *on the flat*, that is, as they should be cut from a flat sheet ready for bending. It also determines for the centre lines of these faces the distances apart to which they should be bent. So far, however, it has been assumed that these centre lines are in the same plane, so that the narrow end of the horn pierces through the centre of the bell portion. To allow for the displacement to one side it is only necessary in laying out the faces to curve the centrc line thus :

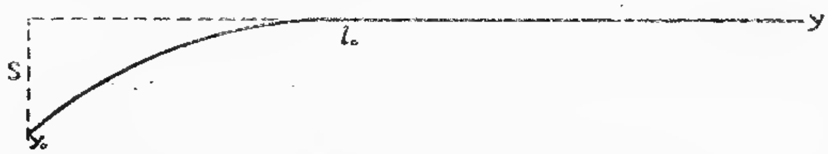


Fig. 42.—Laying off the centre line.

The distance *s* by which yo or zo should be dis-placed from the straight should be rather more than the distance AY, so as to ensure that the throat portion will clear the bell portion. In order that the normals to this centre line should be readily determined it is well to make the curve in the form of a circle of large radius.

It remains to determine the shapes on the flat of the faces ending in AB and CD. To do this we require to know the lengths along the centre lines corresponding to the successive distances x along the axial line of the horn. For this we consider the central section which ends in PQ. We draw the axial line though O and mark off our distances x along it. We then measure the distance op or oq at each of these distances. Since the cross-section of the horn is in the form of a trapezium op = oq = $\frac{1}{2}$ (yc + zd). We can now draw curves through the points so obtained, thereby determining the shapes and lengths of the centre lines of the side faces. We mark these lengths along a line of the same form as the axial line of the horn and draw perpendiculars. To find the lengths to measure off along these perpendiculars we must draw the trapezium for each point of the horn. The distances we require are aq (or bq or cp or dp). Thus the shape on the flat of the side faces is determined.

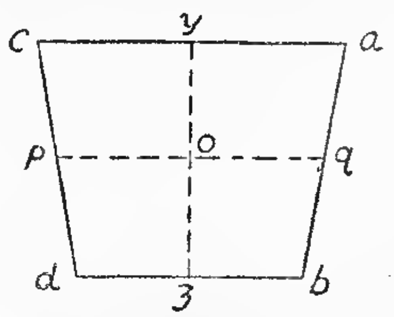


Fig. 43.—Trapezium section for folded horn.

APPENDIX II

THEORY OF THE MODIFIED EXPONENTIAL HORN

The theory of the exponential horn is discussed in several of the papers referred to in the bibliography. The suggestion for a modified exponential horn is new. The formula is derived as follows :

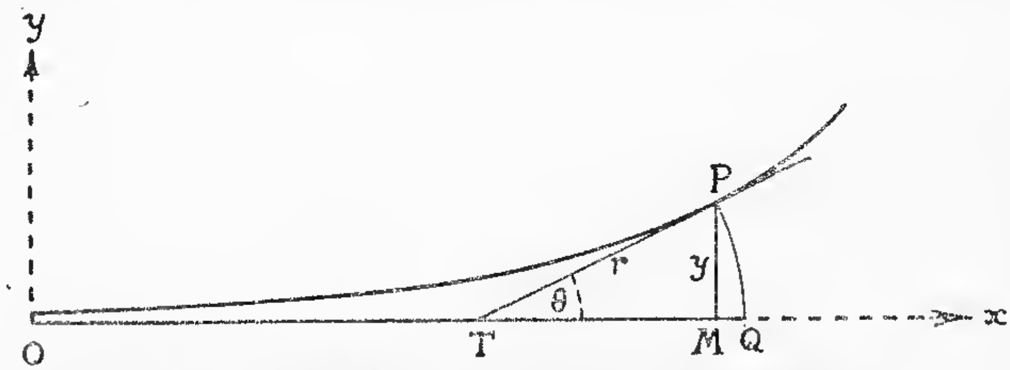


Fig. 44.—Diagram for modified exponential horn.

P T is the tangent to the contour, angle of slope θ. O M = x is the distance from the throat and P M = y is the radius of the section at P. P Q represents half of wave-front assumed to be spherical and of area A.

$$A = 2\pi r^2 (1 - \cos\theta)$$

$$= 2\pi y^2 \frac{1 - \cos\theta}{\sin^2\theta}$$

$$= \pi y^2 \sec^2 \theta/2$$

Initially, $A_0 = \pi y_0^2$

In the modified exponential horn,

$$A = A_0\, \varepsilon^{2m(x + MQ)} = A_0\, \varepsilon^{2mx}\, \varepsilon^{2my\tan\theta/2}$$

So, $\quad y^2 \sec^2 \theta/2 = y_0^2\, \varepsilon^{2mx}\, \varepsilon^{2my\tan\theta/2}$

whence $\quad y = y_0\, \varepsilon^{mx} \cos\theta/2\, \varepsilon^{my\tan\theta/2}$

In the ordinary exponential horn which assumes a plane wave-front, $y' = y_0\, \varepsilon^{mx}$.

So, $\quad y = y' \cos\frac{\theta}{2}\, \varepsilon^{my\tan\theta/2}$

For all the values with which we are concerned m is small and θ is less than 45°. It follows that my. $\tan\frac{\theta}{2}$ is small, and we may, therefore, write $\varepsilon^{\,my\tan\theta/2} = 1$ for a first approximation, and $1 + my\tan\theta/2$ for a second approximation.

To the first approximation, therefore,

$$y = y'\cos\frac{\theta}{2}$$

To the second approximation,

$$y = y'\cos\frac{\theta}{2}\left(1 + m\,y\tan\frac{\theta}{2}\right)$$
$$= y'\cos\frac{\theta}{2}\left(1 + m\,y'\sin\frac{\theta}{2}\right)$$

It is clear that the second term is so small as to be negligible. θ relates to the modified horn. However, since it is less than 45°, $\cos\theta/2$ lies between 0·924 and unity, so that the contour of the modified horn lies just inside that of the ordinary horn and very close to it. The shape of the modified horn can, therefore, be determined by a series of approximations, measuring θ first for the ordinary horn, deducing a first approximation to the modified horn, measuring the slope of that, deducing a second approximation and so on. In practice, even the first approximation will be found to be very close.

N.B.—The symbol m in this appendix is related to Naperian logarithms, while m in the text is related to common logarithms. Thus,

m (in text) $= \log \varepsilon \times m$ (in appendix).

CHAPTER VI

TONE-ARMS

VI—1. Record Groove Characteristics.

The function of the tone-arm is to carry the sound-box across the record and to provide the link between sound-box and horn. Its design can accordingly be studied from three different points of view: geometrical, acoustical and mechanical. In the first we examine the geometrical requirements so that the sound-box may be carried across the record in the proper direction; in the second we look upon the tone-arm merely as a conduit for transmitting sound-waves; whilst in the third we inquire what effects the mechanical structure may have upon reproduction and record wear.

When a record is made, the wax matrix rotates at a constant speed, and at the same time the motor which is driving it moves at a constant speed under the recording stylus. If no mechanical vibrations were being impressed upon the stylus it would cut a groove in the wax in the form of a plain spiral—what mathematicians call an Archimedean spiral, after the Greek philosopher who investigated its properties. This spiral may, therefore, be fitly described as the mean line of the groove, since the effect of the vibrations of the stylus is merely to cut a sinuous curve about the spiral as a centre line. Usually there are about 100 convolutions of the spiral per inch across the radius of the disc, and in consequence we usually talk of a gramophone record as having about "100 grooves per inch." The distance between the middles of successive grooves is thus $\frac{1}{100}$ of an inch, and since the groove itself occupies about half this distance, we have only about $\frac{1}{200}$ inch available for the excursion of the two adjoining grooves from the mean lines. This means that the maximum amplitude which can be obtained without risk of grooves running into each other is only $\frac{1}{400}$ inch. It is this which accounts for the difficulty mentioned in Chapter II of recording bass notes at their full value.

VI—2. Geometrical Requirements.

The recording stylus in its vibrations to and fro across the mean line is always moving radially, that is towards or away from the axis about which the matrix is rotating. Its motion across the matrix (or rather relative to the matrix, since as a rule it is the matrix which moves under the stylus) is likewise always in a radial straight line. For exact correspondence between the conditions of recording and reproducing we should therefore arrange, in strictness, that the gramophone needle in its path across the record should move in a radial straight line, and that the axis about which it vibrates should be at right angles to this straight line. This axis is parallel to the plane of the diaphragm, so that the second requirement becomes that the plane of the diaphragm should be at right angles to the radius through the needle point and therefore tangential to the mean line of the groove at that point. (Note: the error in assuming the groove to be geometrically equivalent to a series of concentric circles is quite negligible. Its length is, in fact, equal to the combined lengths of the circles, and the angular difference at any point between the Archimedean spiral and the circle is never more than one minute of arc).

The only satisfactory way of ensuring that the needle point shall move in a straight line across a record is to attach the sound-box directly to the horn and move the whole arrangement straight across on some form of carriage. The favourite gramophone of Mr. Compton Mackenzie, the Editor of *The Gramophone*, works in this way. It is constructed in accordance with a patent of Mr. C. Balmain (177,215). The horn is pivoted on a carriage provided with floats similar to those on the undercarriage of a seaplane. The floats are supported in troughs of mercury, and the carriage and horn have side arms carrying ball-bearing wheels which engage with upright bearing surfaces of glass to ensure straight line motion. A photograph of a skeleton Balmain gramophone with a five-foot exponential horn is shown in Fig. 47, Plate IX.

If we use a pivoted horn or a pivoted tone-arm the needle must move in an arc across the record. If the distance between pivots and record centre is small the curvature of this arc will be considerable. We must therefore inquire what effects this curvature will have. They are two. Firstly, the friction of the record on the needle point will introduce a side pressure tending to push the needle across the record towards the centre; the importance of this will be dealt with later. Secondly, the radial line joining the needle point to the centre will always lie between the arc and the pivot (unless, that is, the needle point falls far short of the record centre—a contingency which is so patently undesirable that we pass it over without further comment). This means that in its motion across the record the needle always has a motion along as well as across the groove.

There will consequently be a continuous flattening of pitch of the reproduced sounds. A simple calculation, however, shows that the amount of this flattening must be so small as to be utterly imperceptible; between consecutive grooves it is no more than 1 in 400,000. From this point of view, then, there is no disadvantage in using a pivoted tone-arm instead of allowing the needle and sound-box to travel straight across the record.

The second requirement, namely, that the plane of the diaphragm should be at right angles to the radius through the needle point, is more important. If it is not fulfilled, the sound-box will be skewed across the groove and the needle will not fit evenly; it will ride on the top of one wall of the groove with its point resting against the other wall, Fig. 51. Moreover, since the needle point can vibrate only in a direction at right angles to the diaphragm, and since for exact reproduction the groove should move it to and fro along a radius, stresses are introduced between needle and groove which can only result in record wear. An instrument in which this second requirement is fulfilled, or nearly fulfilled, is said to have good "needle-track alignment"; and the angular error between the position of the diaphragm and the ideal position, measured on the record surface at the needle point, is called the "tracking error."

Until a few years ago tone-arms were frequently designed in sueh a way that the line through the needle point parallel to the diaphragm passed

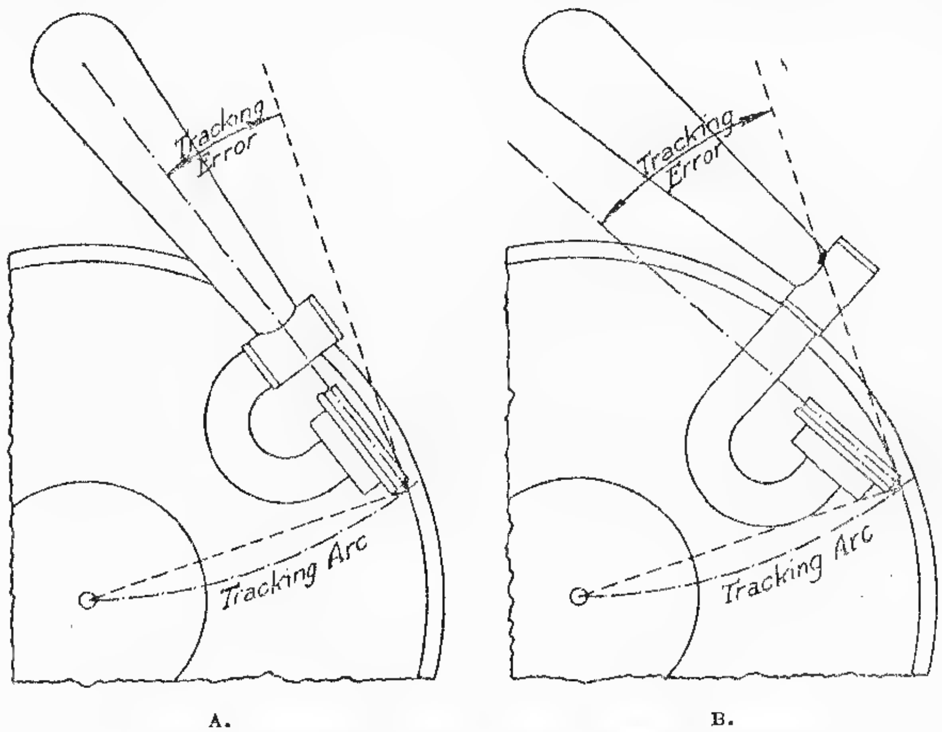


Fig. 48.—Tracking error of goose-neck tone-arms.

through the tone-arm pivot, and that the needle point reached exactly to the centre of the turntable spindle over which the hole in the centre of the record fits, Fig. 48 (A). With these tone-arms the tracking error was bound to be substantial. With a 9-inch tone-arm the error was as much as $19\frac{1}{2}°$ at the outside of a 12-inch record, decreasing to about $6\frac{1}{2}°$ at the inside grooves. It was never zero at any part of the recorded surface. Then, immediately after the war, a new type of tone-arm with a "trombone goose-neck," Fig. 48 (B), was introduced in order that the sound-box could be folded back alongside the tone-arm when not in use; in this way the lid of the gramophone could be made shallower. This type of tone-arm sometimes had atrociously bad alignment. At the outside of a 12-inch record the error was often as much as 30°, decreasing to 18° at the inside grooves.

In 1924 one of the authors, in an article published in *The Gramophone*, investigated the problem analytically, and derived a formula by which the tracking error could be reduced to less than 2° at every point of a 12-inch record. Geometrically, the system of tone-arm and sound-box is equivalent to Fig. 49. Here P represents the back pivot of the tone-arm, O the record centre, N the needle point, and ND the plane of the diaphragm. The distance PO (=a) may be called the "base" line, the distance PN (=p) the "vector," the distance ON (=r) the "radius" and the angle DNP (=d) the "divergence." If we denote the tracking error by x we obtain by simple trigonometry

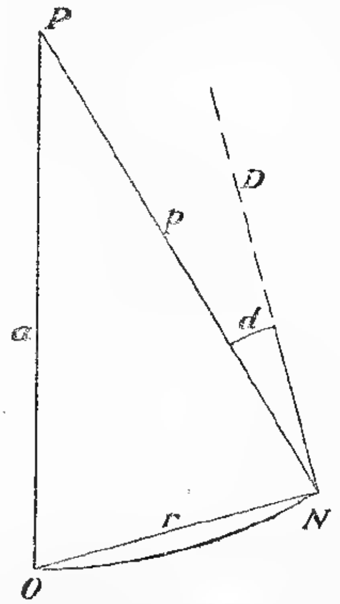


Fig. 49.—Tone-arm diagram showing tracking error.

$$\sin (x + d) = \frac{p^2 - a^2 + r^2}{2\,pr}$$

From this formula the tracking error under any conditions of mounting of a tone-arm and sound-box may be calculated, for every point across a record. Thus for a tone-arm of the type shown in Fig. 48 (A), with a base and vector of 9 inches, the divergence being zero, the error works out to be:

r =	2″	3″	4″	5″	6″
x =	$6\frac{1}{2}°$	$9\frac{1}{2}°$	13°	16°	$19\frac{1}{2}°$

The effect of introducing divergence by twisting the sound-box through an angle in the direction indicated in Fig. 49 is to reduce the error by a constant amount for all points across the record. Thus if we make d = 13° we should get the following table of errors:

r =	2″	3″	4″	5″	6″
x =	$-6\frac{1}{2}°$	$-3\frac{1}{2}°$	0	3°	$6\frac{1}{2}°$

The negative sign denotes that the error has been over corrected and is now in the opposite direction. The arrangement in Fig. 48 (B) has a negative divergence, the sound-box pointing to the left of the back pivot, and this increases the error at each point. Thus if d = -13° we get:

r =	2″	3″	4″	5″	6″
x =	$19\frac{1}{2}°$	$22\frac{1}{4}°$	26°	29°	$32\frac{1}{2}°$

It can be shown, though the working is rather long, that the minimum tracking error is obtained when p, a and d are related to each other by the following formulæ:

$$a^2 = p^2 - 12$$

$$d = \frac{1}{2}\left[\sin^{-1}\left(\frac{3{\cdot}4641}{p}\right) + \sin^{-1}\left(\frac{4}{p}\right)\right]$$

From these two formulæ, given any value of p, we can deduce the appropriate values of a and d, and then from the formula previously given we can calculate the tracking error at every point across the record. The following table gives the corresponding values in various cases:

TABLE I

p = Distance between back pivot and needle point.	a = Distance between back pivot and centre of turntable spindle.	d = Angle which plane of diaphragm makes with p.		X = Maximum tracking error.	
Inches.	Inches.	Degs.	Mins.	Degs.	Mins.
8	7·21	27	50	2	10
9	8·31	24	30	1	52
10	9·38	21	55	1	39
11	10·44	19	50	1	29
12	11·49	18	7	1	20
13	12·53	16	41	1	14
14	13·57	15	28	1	8
15	14·6	14	24	1	4

For tone-arms in which the distance between the back pivot and needle point is not less than 9 inches, the maximum tracking error is less than 2 degrees. Several other points about the arrangement should be noticed.

(1) In all cases a is less than p, which means that when the sound-box is brought to the centre of the record, the needle point will come in front of the turntable spindle. As will be seen later, this is not altogether a desirable feature, but fortunately its disabilities can be compensated in another way.

(2) The direction of the sound-box must always be to the right of the back pivot. If the needle point is made to overlap the spindle, and the right amount of divergence is not used, the tracking error may be considerable.

(3) It can be shown that the maximum error in one direction occurs at both the outside and inside grooves, and that there is an equal error in the opposite direction at a point 3·46 inches from

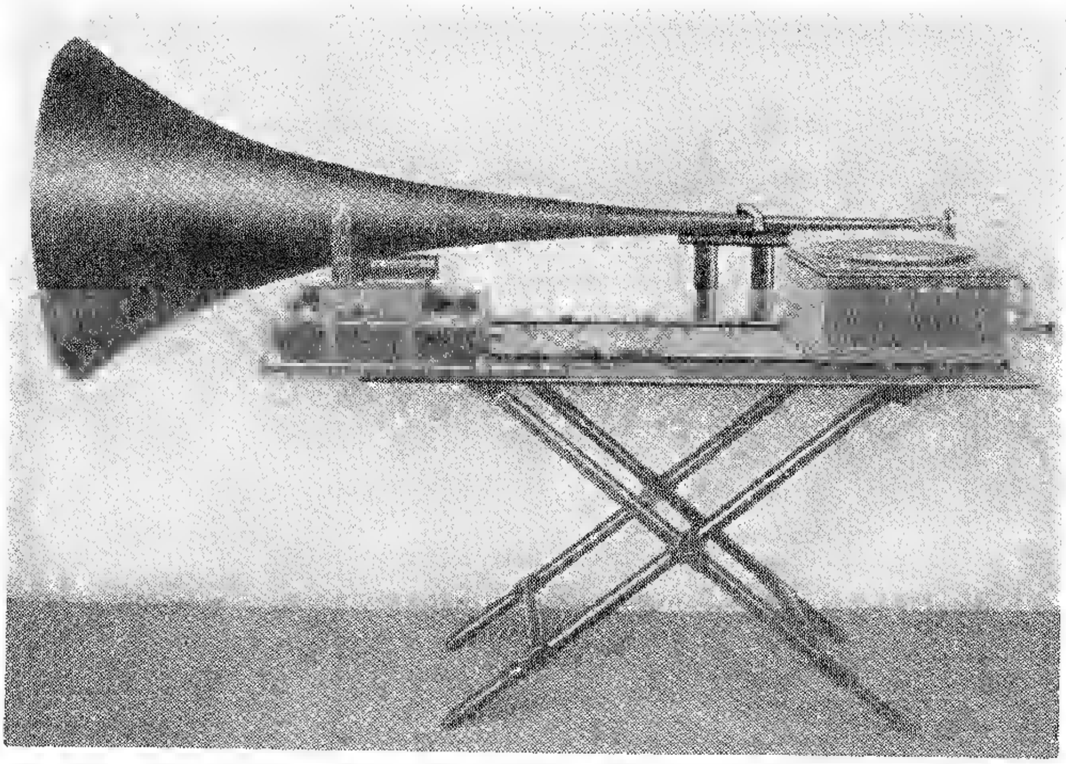


Fig. 47. Balmain Gramophone with straight horn.

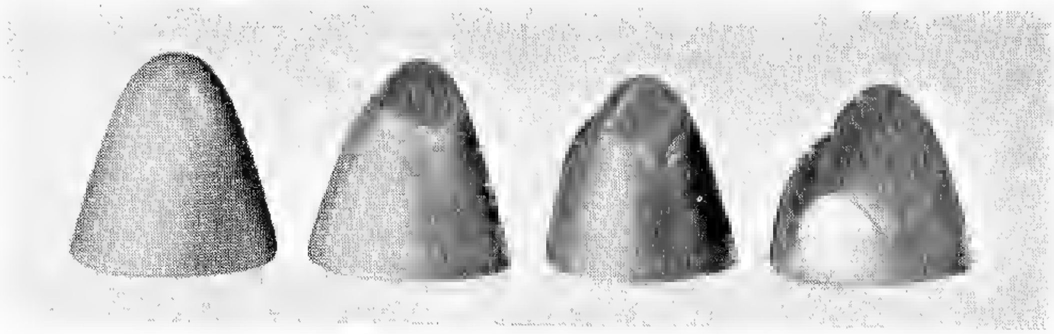


Fig. 50. New and worn needle points.

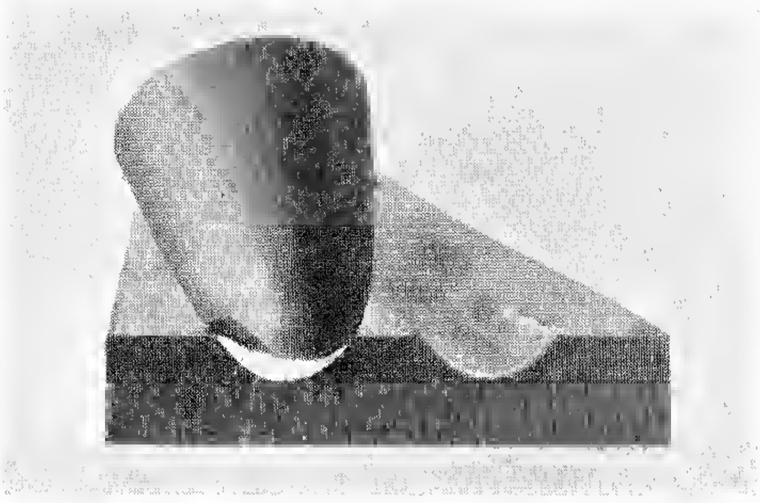


Fig. 51.
Worn needle skewing across a record groove.

PLATE IX

the record centre. Hence, the *change of error* as the needle travels across the record is double the maximum tracking error. When the tracking error is arranged to be a minimum the change of error is also a minimum. This is important for a reason not previously mentioned. As the needle tracks in the groove it is gradually worn to a chisel point. Very few needles have a point fine enough to reach to the bottom of a groove; they usually ride on the walls, as shown in Fig. 51, Plate IX, and facets are worn upon the needle as shown in Fig. 50. If the change of tracking error is large, the record has to extend these facets so as to obtain a fit between needle and groove. If the change of error is small the facets are small, and the chisel point is not so sharp and dangerous to the sinuosities in the record groove.

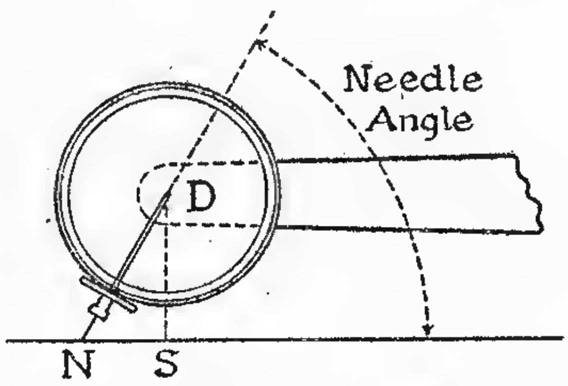


Fig. 52.—Needle angle diagram.

It should be noticed that this method of ensuring good alignment (and it is the only method that can be used with a swinging tone-arm unless complicated mechanisms are used) depends on the distance between back pivot and needle point and not directly on the length of tone-arm. In other words, the size of the sound-box and the length of the needle and the needle angle all enter into the problem. This is easily seen from the elevation in Fig. 52. The tone-arm reaches only to the centre of the sound-box diaphragm, but the needle point projects farther than that by a distance which depends partly on the distance between the centre of the diaphragm and the needle point and partly on the needle angle.

The following table gives the length of the added distance NS for various values of ND and needle angle SND. It has, of course, been calculated from the formula

$$NS = ND \cos SND.$$

TABLE II

ND = distance between centre of diaphragm and needle point.	Needle angle.			
	50°	55°	60°	65°
	Added distance NS.			
Inches.				
1·5	0·96	0·86	0·75	0·63
1·6	1·03	0·92	0·8	0·68
1·7	1·09	0·98	0·85	0·72
1·8	1·16	1·03	0·9	0·76
1·9	1·22	1·09	0·95	0·8
2·0	1·29	1·15	1·0	0·85

It will be gathered from this table that, having arranged the tone-arm to give the best alignment for one particular sound-box, length of needle and needle angle, the alteration of any one of these factors will alter the alignment. But it is possible to get the best alignment with different sound-boxes or lengths of needle provided that the needle angle is adjusted accordingly. Thus, altering the length ND from 1·5 inches to 1·7 inches will have no effect on the alignment, provided that in the former case the needle angle is 55° and in the latter 60°. Similarly, 1·5 inches at a needle angle of 55° will give the same results as 2·0 inches at a needle angle of 65°.

It remains to discuss the practical method of using these tables. Suppose we wish to design a tone-arm, or a carrying arm for a pick-up, which shall give the best possible alignment with a particular sound-box, or pick-up, how shall we proceed? Here is the method which we have found to work best. First of all decide what length you want between back pivot and spindle centre. Draw a line PO of this length on the left-hand side of a sheet of drawing paper. Look up, from Table I, the corresponding value of PN. With centre P and radius PN draw an arc of a circle as in Fig. 53. Take a convenient point on this arc; it does not matter geometrically where you take it, but for other reasons it is usually convenient to have it three or four inches to the right of O. Join NP and draw the line NS at the angle PNS read off from Table I. Along NS mark off the distance to S according to the length given in Table II for the particular stylus-bar length and needle angle you wish to use. Draw SL at right angles to SN, and along it mark off a distance to L corresponding to the thickness of the sound-box from the needle point to the place where the end of the tone-arm comes when the sound-box is in position. Through L draw a line ALB at right angles to SL. The tone-arm should then be

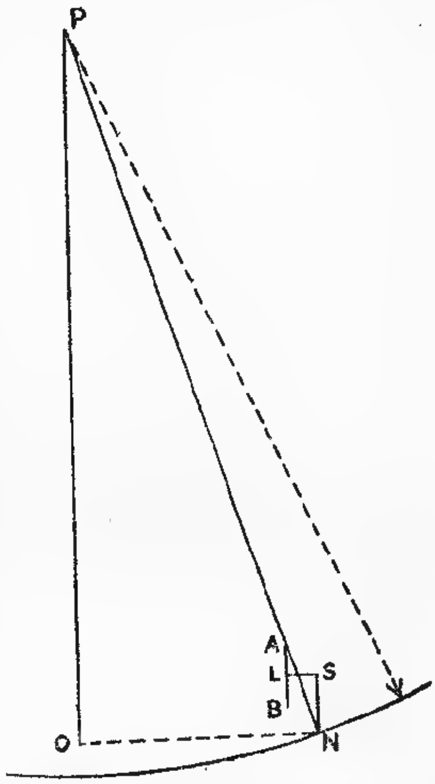


Fig. 53.—Geometrical construction for tone-arm design.

designed to go from the back pivot P to the point L in such a way that its cross section at L is in the direction ALB.

For measuring errors in alignment a special form of protractor has been devised by one of the authors, as below.

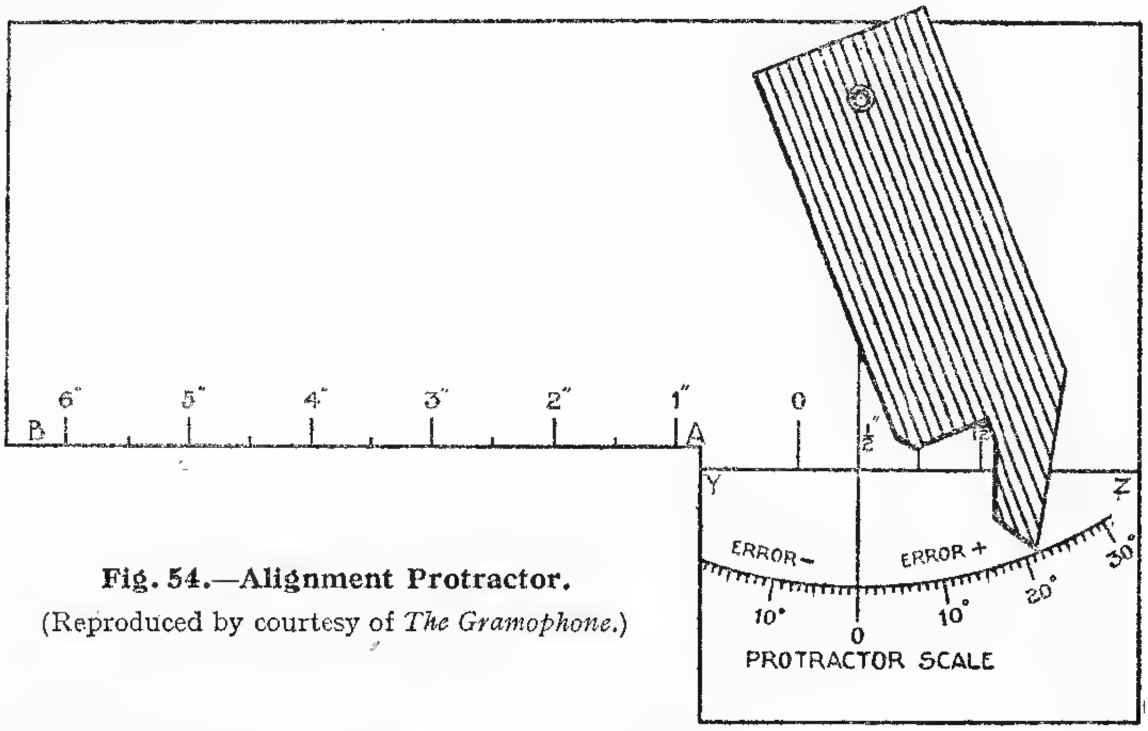


Fig. 54.—Alignment Protractor.
(Reproduced by courtesy of *The Gramophone.*)

VI—3. Acoustical Requirements.

As the link between sound-box and horn, the tone-arm must naturally be regarded as part of the horn itself. From this point of view the rate of expansion of the air-column in the tone-arm should correspond with that in the horn. It follows that any particular tone-arm is only really suitable for one particular design of horn. In practice, of course, this is an awkward conclusion. The size of a horn in a gramophone is determined by the size of cabinet, selling price, and other faetors besides the acoustic response, and to have special tone-arms for different models adds greatly to the cost. The tools for making a good tone-arm may cost as much as £1,000. Provided two conditions are fulfilled, however, some departure from the ideal requirements is permissible. These conditions are:

(1) That the opening at the base of the tone-arm should be exactly the same as that at the throat of the horn. This simply means that each horn should be designed to have the same throat opening as the standard tone-arm.

(2) That the rate of taper of the tone-arm should be less than that in the horn. As explained in the last chapter, the rate of taper determines the cut-off frequency, so that it is clearly desirable that the tone-arm should pass all frequencies which the horn can handle.

Apart, however, from these considerations, there is another possibility which is worthy of attention. The tone-arm may be designed to have re-action effects upon the sound-box. Thus, for example, it would be possible to extend the sound-box wave-filter into the structure of the tone-arm. G. W. Stewart* devised a transmission conduit which is the analogue of a low-pass wave-filter. This is shown in Fig. 55.

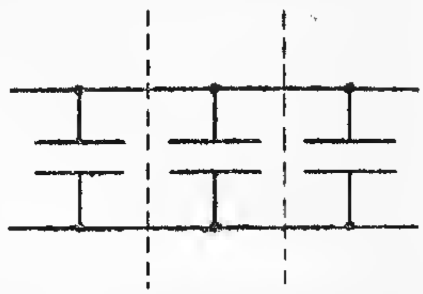


Fig. 55.—Stewart low-pass acoustic wave-filter.

The conduit is in the form of a tube with internal barriers pierced by short tubes of smaller diameter. The filter properties depend on the conductivity of the orifices and the volume of air between the barriers. So far as the authors are aware, no advantage has yet been taken of this principle in

* *Phys. Rev.*, March, 1921, and December, 1922.

gramophone design. Another kind of filter, however, has been employed. This is known as a Quincke filter, an account of which is given in Article 318 of Rayleigh's treatise.* This is exemplified in the goose-neck tone-arm with " dead-end " shown in Fig. 48, page 125. The dead-end acts as a Quincke filter and attenuates notes of the frequency to which it is tuned. This is a useful device for use with sound-boxes where the fundamental resonance frequency of the diaphragm is fairly high, since then the response at this frequency can be reduced and the effective uniform transmission range of the sound-box extended.

It should be noted that in the tone-arm illustrated the goose-neck is of uniform bore. This is an important feature. Tapered goose-neck tone-arms have been used in the past, but have proved themselves altogether inferior to the non-tapered kind. We are thus led to inquire what is the effect of introducing a tube of uniform bore between sound-box and exponential horn. The first point that should be noticed is that if the diameter of a uniform tube is small the sound-waves passing through it will ultimately become plane (Rayleigh, Art. 301). This is just what we want at the throat of an exponential horn. The waves emerging from the sound-box, however, and particularly those of low frequency, will be slightly convex. The effect of the non-tapered tube is thus all to the good. Experiments have been made by the Victor Talking Machine Company to test the effects.† The fre-

* See also A. H. Davies : " Proc. Phys. Soc.," Vol. XL, p. 90.

† Williams : " Journal Franklin Institute," October, 1926.

quency response curves are shown in Figs. 56 and 57. It should be noted at the outset that the curves are not horizontal, but have an upward and then a downward slope. These features were due to the conditions in which the experiments were made and have nothing to do with the response of the horn. They can be ignored for our present purpose, which is to compare the response of a horn with and without an initial straight section. The response curves with the straight section are shown dotted, the original curves being in thick line. It will be observed that apart from a slight loss at 400 cycles, the bass response with a 6-inch initial straight section is much superior to that without

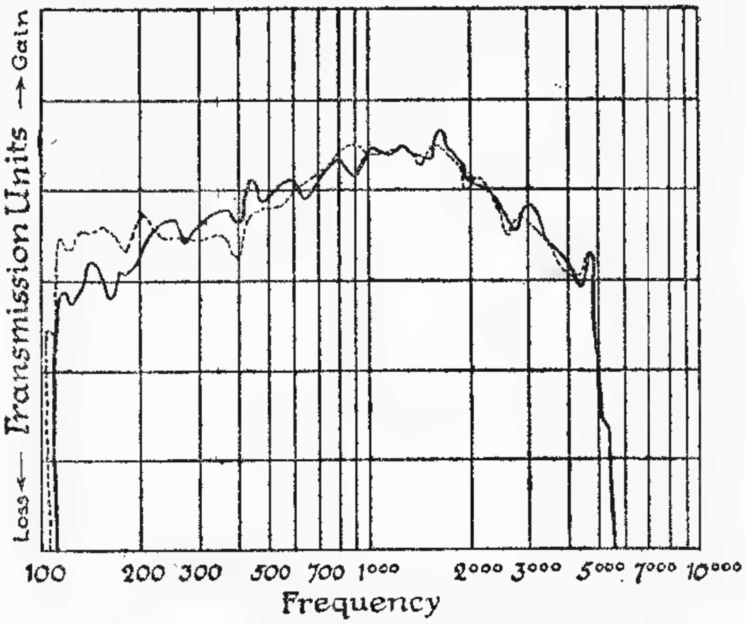


Fig. 56.—Response curve for horn with straight section.

Response curve of 72″ horn, showing effect of adding 6″ straight section at narrow end. (Full line shows response of original horn.)

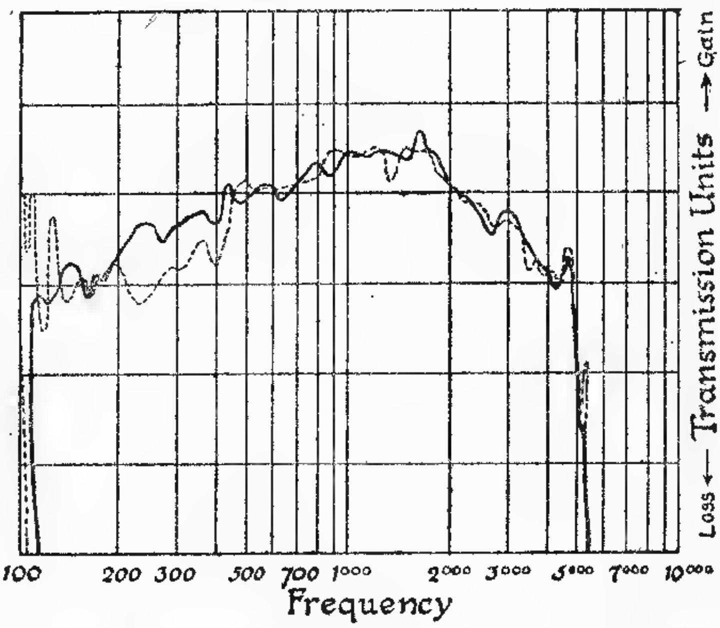


Fig. 57.—Response curve for horn with straight section.

Response curve of 72″ horn, showing effect of adding 12″ straight section at narrow end. (Full line shows response of horn without straight section.)

it. The response with the 12-inch section is not so uniform, but in view of the falling response of the recording in the region below 250 cycles the increase of bass shown may be a decided advantage.

Another point about the use of a tube of uniform bore in the tone-arm should also be noticed. The bore is bound to be quite small compared with the wave-lengths of the sounds we are transmitting, and therefore we can bend the tube without much danger of affecting the response (see page 107).

VI—4. Mechanical Considerations.

The forces which act upon a sound-box and tone-arm when a record is being played may conveniently be grouped under six heads.

(1) The force due to the friction of the record on the needle point.

(2) The frictional forces of the tone-arm bearings.

(3) Side pressure of the groove upon the needle.

(4) The force due to faulty centring of the record.

(5) Gravity and the reaction to gravity at the needle point.

(6) The forces due to the recording. These may be resolved into two components: those at right angles to the diaphragm, which are responsible for the vibration of the diaphragm and the production of sound; and those parallel to the plane of the diaphragm, which should have no effect on reproduction, but may have a decided effect on record wear.

The force due to friction is tangential to the mean line of the groove. It is balanced partly by a stress in the tone-arm (which refuses to bc elongated) and partly by side-pressure between needle and record. It is an easy exercise in mechanics to show that this side pressure must increase the more the needle point is made to overlap the spindle, and that at the critical setting for best necdle-track alignment it is practically thc same at every position of the needle across the record. There are two other causcs of side pressure: a stiff back bearing of the tone-arm and a bearing which is not exactly vertical so that the tone-arm has a tendency to swing one way or the other. The side pressure due to a stiff back bearing will be irregular and it is therefore highly important to make this bearing as frec as possible. The side pressure due to gravity may be as large or as small as wc choose to make it, and it may be in either direction. We can consequently use this property to neutralize the side-pressure due to friction, leaving the needle in contact with the groove without sidc-pressure either inwards or outwards. Thc method of doing this is described in Section XI—7.

A tone-arm must have two bearings: one to allow it to move across the record and one to allow the sound-box to move up and down slightly; very few gramophone turntables are exactly lcvel, and there is always a possibility that a record may not be of uniform thickness and may even be warped. These bearings should be designed in such a way that the motion is as frictionless as possible, and that the conduit is air-tight. Leaks in a conduit act as a high-pass filter—that is, they attenuate low notes and pass only those above a critical frequency. In G. W. Stewart's paper, already referred to, the acoustic analogue of the electrical high-pass filter employed a series of leaks. The effect can also be seen in the response curves reproduced from S. T. Williams's paper, Fig. 58.

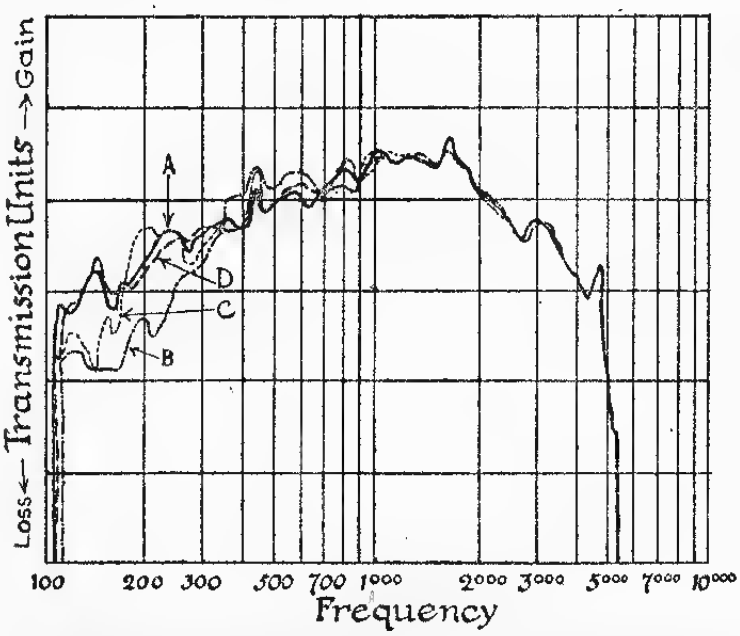


Fig. 58.—Response curves showing the effect of leaks.

A = no leak.
B = ¼″ diameter leak 1″ from throat.
C = ½″ diameter leak 15″ from throat.
D = ¾″ diameter leak 29″ from throat.

There are four types of bearing in common use in gramophone tone-arms :

(*a*) *Pivot bearings*, in which the tone-arm is supported above and below on conical pivots, the lower pivot being carried on a bar which is mounted inside the tone-arm, Fig. 59. This form can be made remarkably free and air-tight if a little vaseline is inserted between the tone-arm and the casing. But many people object to the internal cross-bar which must have some effect on the transmission of the sound-waves. Observation shows, however, that if the cross-bar is fairly narrow the effect is negligible.

(*b*) *Ball-bearings*, which can be made free and air-tight without the use of any internal cross-bar. Unless an external pivot bearing at the top of the tone-arm is used, however, the thrust on the ball-race is not even all round, and in these circumstances the tone-arm is apt to move in a series of little jerks which are specially bad for record wear. The best design the authors have come across is that shown in Fig. 60, where there is an adjustable conical seating.

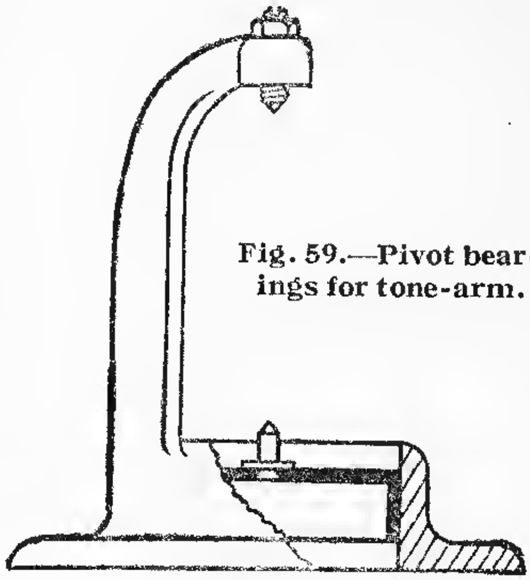


Fig. 59.—Pivot bearings for tone-arm.

(*c*) *Screw-bearings*, in which the end of the tone-arm has an external screw thread engaging in an internal screw in the base fitting. The authors have never found these to be satisfactory for the back bearing. They are usually air-tight, but are rarely free, owing to the large friction surfaee and the strain imposed by the weight of the tone-arm. For the horizontal bearing which allows the sound-box to move up and down, however, they are quite satisfactory; here the same degree of freedom is not so essential, but is more easily secured since the bearing has not to take so much strain.

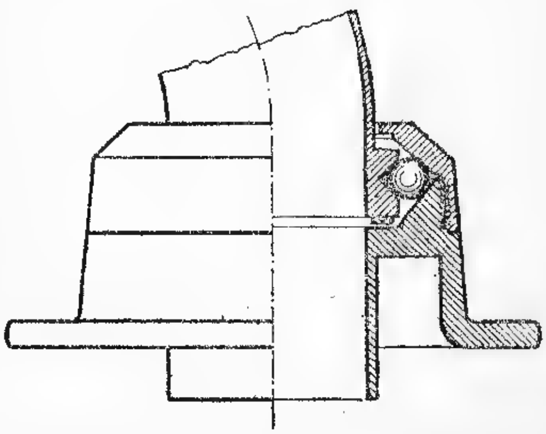


Fig. 60.—Ball bearings for tone-arm.

(*d*) *Sleeve bearings*, in which one tube simply slides inside another. The remarks in (*c*) apply to this type also.

The design of the horizontal bearing is of importance from another point of view. Unless its axis is at right angles to the vertical plane through the needle (which is usually the same as the plane of the diaphragm) difficulty may be experienced in getting the sound-box and needle, viewed edgewise, to be at right angles to the record. Only for one particular length of needle will that be the case, and if the turntable is not quite level or if the record is warped, the position of the sound-box will be right only at one position of the record. As the sound-box is raised it does not go up parallel to itself; its face begins to tilt over. This is a serious fault, since it means that the needle will not enter the groove properly.

The horizontal bearing, then, must have its axis at right angles to the face of the sound-box. It is not very easy to design a tone-arm with this property and at the same time to secure good alignment. The most straightforward method is to have the horizontal bearing in the same position as the vertical bearing at the back. In the authors' experience, however, a tone-arm of this kind is not really satisfactory. Apart from the fact that the whole of the weight of the tone-arm, as well as that of the sound-box, is pressing down on the record, tone-arms of this kind seem to have other ill effects, particularly as regards record wear. Experiments carried out by the authors show quite clearly that it is better to have the horizontal bearing not more than 3 or 4 inches behind the sound-box, though what the explanation of this empirical conclusion may be they have not yet satisfied themselves. Fig. 61 below shows a method by which the two requirements may be satisfied in a goose-neck tone-arm. Fig. 62 shows an inverted " S " tone-arm

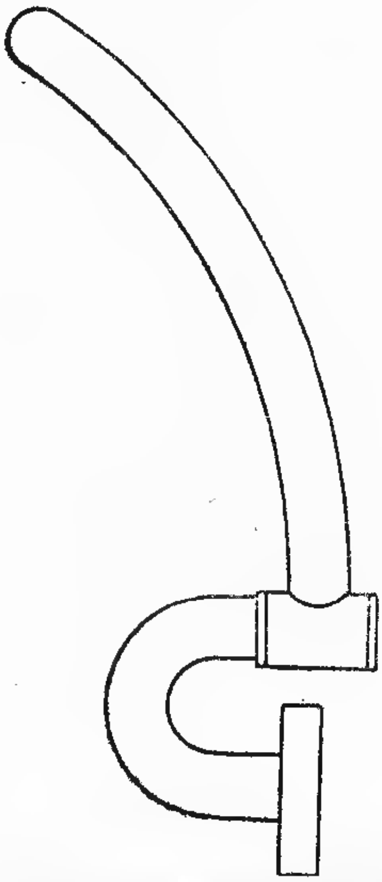


Fig. 61.—" Goose-neck " tone-arm corrected for alignment.

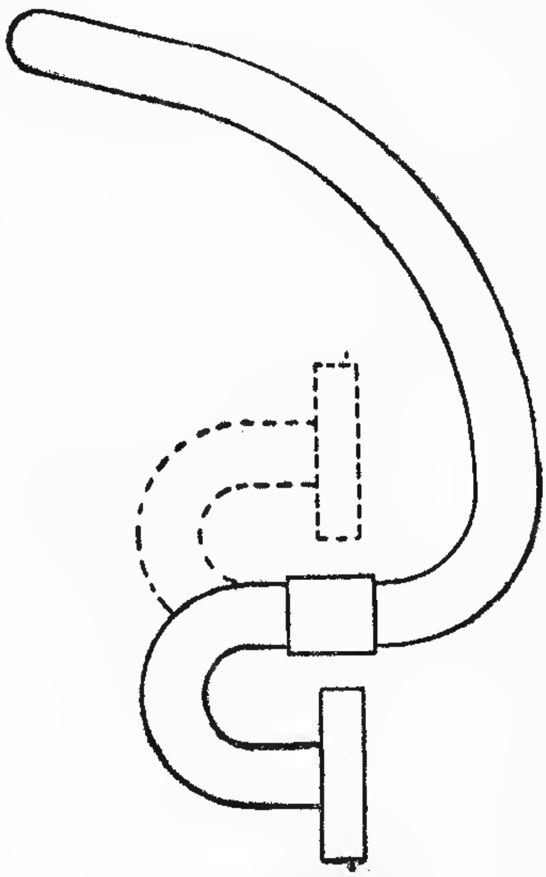


Fig. 62.—Inverted " S " tone-arm.

which also fulfils the conditions. This also has the practical advantage that when the gramophone is not in use the sound-box may be folded back alongside the tone-arm, without danger that the lid of the instrument will hit the needle and damage the sound-box.

VI—5. Tone-arm Material.

The bore of the tone-arm being fairly small, it is important that the material should be rigid and smooth, otherwise viscosity effects will become important. Moreover, the tone-arm may have a number of fairly sharp bends. The diameter is small, it is true, but that does not affect the possibility of resonance from the material. The material of which a tone-arm is made does have an appreciable effect on the response. The authors definitely prefer to use drawn-brass of fairly substantial gauge —not lighter than 20 S.W.G. (0·032″).

Claims have been made in the past that wood, ebonite, aluminium and even papier mâché tone-arms are superior, but these have never been substantiated and the experience of the authors is definitely against them.

VI—6. Carrying-arms for Electric Pick-ups.

In the design of pick-up arms, the same principles apply as for tone-arms, save that here we need not provide an air-tight conduit proceeding in smooth curves. The mechanical problem is therefore easier, and it is possible to make a really serviceable arm quite simply. It would be foolish in making a carrying-arm for pick-ups to saddle ourselves with the mechanical difficulties of tone-arm design; it is much better to consider the design afresh from first principles.

A practical design for a carrying-arm, which satisfies all the requirements discussed in Section VI. 4, was described by one of the authors in the issue of *The Gramophone* for September, 1928. A photograph of an arm based on that design is shown in Fig. 63 (Plate XI).

CHAPTER VII

RECORD WEAR, NEEDLES, SURFACE-NOISE

VII—1. Frictional Wear.

There are two kinds of record wear. The typical sign of the first is an increasing amount of surface-noise, particularly at the outside grooves of a record. It is due to a roughening of the walls of the groove by the friction of the needle. In the old days, when the record material was coarser than it is to-day, frictional wear was far more common. The record manufacturers deliberately incorporated a small quantity of abrasive matter, such as rotten-stone, in the records, with the idea, apparently, that it was better for the record to wear the needle than for the needle to wear the record. In recent years record material has been improved very considerably. The constituents are now more finely ground, and therefore the surface texture is more uniform. The introduction by the Columbia Company of their " New Process " records, in 1922, marked the beginning of a new era. In this process the material used on the record surface is finely ground, passed through a 200 mesh sieve and finally sifted by means of an air current which blows the lighter particles over a series of barriers.

In these days frictional wear can be reduced to quite negligible proportions. It obviously depends partly on the smoothness of the record, partly on the hardness of the needle, partly on the pressure of the needle upon the record, and partly on the method of contact. It has been mentioned in the last chapter that few gramophone needles reach to the bottom of the groove ; the sapphire recording stylus is ground to a much finer point than a steel needle. Moreover, the sapphire point is nearly vertical, whilst the reproducing point is inclined at an angle of about 60° in the reverse direction. In consequence the needle may ride on the walls of the groove without touching the bottom, and in these circumstances more or less flat surfaces are worn on the sides of the needle (see Plate IX). These surfaces would be of little account if there were no sinuosities in the groove ; owing to these sinuosities, however, and to the faet that the needle is not vertical, different parts of the needle are in contact with the walls of the groove at different instants, and to accommodate itself to the groove the needle may have to ride up and down the walls.

Clearly the pressure between needle and record affects the amount of wear, since the frictional force is proportional to it. For other reasons, however, it is not advisable to reduce this pressure below about 4 oz, and in the authors' experience a pressure of 5 to 5½ oz is preferable. But on no account should the pressure be increased beyond about 7 oz.

Other factors tending to increase this kind of wear are faulty alignment and side-pressure between

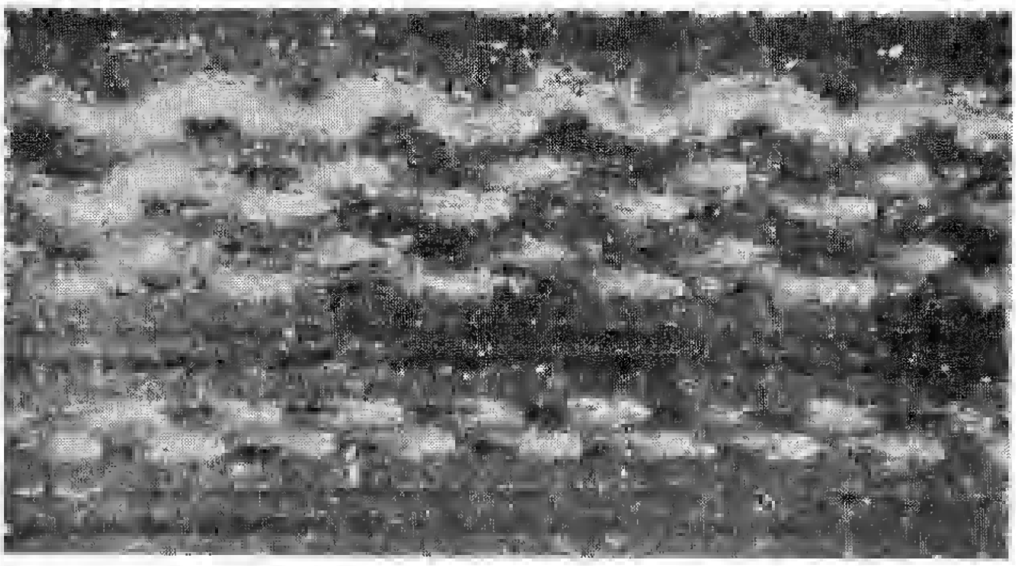


Fig. 64. In this photograph record wear appears in a more or less equal amount on alternate sides of the groove. A very common form of breakdown.

Reproduced by courtesy of the Gramophone Company.

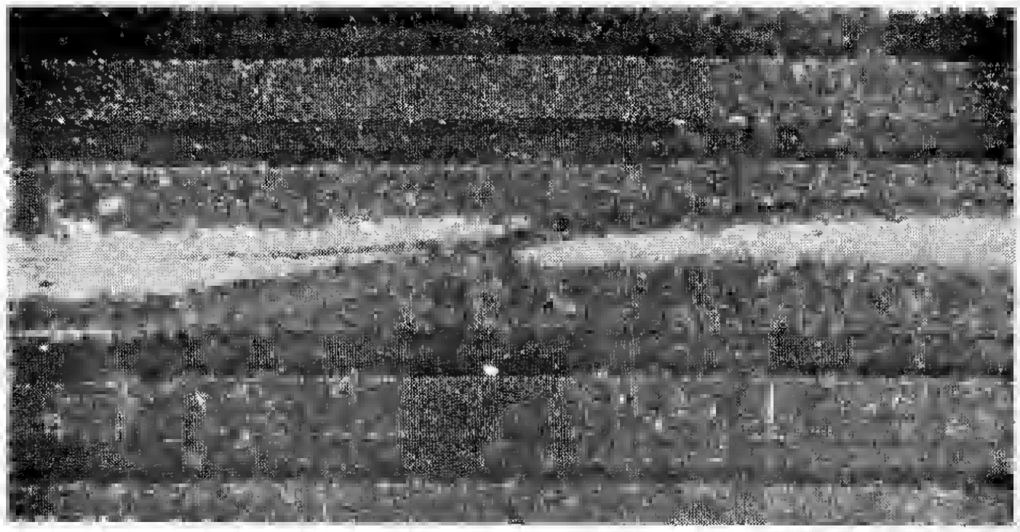


Fig. 65. A severe straightening out of the path of low frequency waves occurs on bass orchestral records to the extent of almost doubling the width of groove.

Reproduced by courtesy of the Gramophone Company.

RECORD WEAR

needle and groove ; these are even more important in connection with the second kind of wear to be noticed presently, and since they can be almost entirely obviated there can be little excuse for their existence. Perhaps the surest way of avoiding wear of this kind, however, is to use either steel needles with a fine point or fibre needles. But here another matter must be borne in mind. A fine point has a greater compliance than a blunter one and account must be taken of this fact in the design of the sound-box. Unfortunately most of the fine pointed needles have to be used with a special grip ; this increases the mass of the stylus-bar very considerably and may thus upset the whole balance of the sound-box.

VII—2. Reactive Wear.

The second kind of wear is much the more important, even as it is the more difficult to avoid. The typical sign of it is a series of grey lines to be seen when the record is viewed at an angle. These lines mean that the walls of the groove have been either broken down or cut away by the needle. The effect is precisely similar to the wearing down of a river bank by a strong current. Two pictures of reactive wear are shown in Figs. 64 and 65 (Plate X).

It is tolerably obvious that this kind of wear occurs whenever the needle experiences exceptional difficulty in following the groove, and the measure of this difficulty is the pressure required to drive the needle. If the pressure exceeds the amount which the walls of the groove are capable of imparting, either the record or the needle must give way. If the needle material is stronger than the record material the record is worn. With a fibre needle, however, the record material is the stronger and the point of the needle breaks off. From this simple consideration it is clear that record wear is most likely where the walls are thinnest or where the groove has the sharpest curvature. Since with constant velocity recording the amplitude varies inversely as the frequency, consecutive grooves approach nearest to each other for deep bass notes. The curvature is greatest for high treble notes and for transients. Record wear thus occurs most often at sudden heavy passages which contain notes of both high and low frequency sounding together. It has long been recognized that records wear quickly at heavy bass passages, but the importance of curvature has not generally been appreciated. Yet it is not uncommon to find that a powerful tenor record, or one containing florid passages of coloratura soprano airs, is peculiarly prone to excessive wear. One or two other points in this connection are worth noticing. If the weight on the record is too small the needle has greater difficulty in traversing places of sharp curvature; it will dance about in the groove and even ride over the walls. A similar effect is encountered if the alignment is faulty. Again, if the needle rides upon the upper parts of the walls, the strains have to be taken at the weakest points.

The manner in which excessive strains are produced is not so easily elucidated. Until recently a complete explanation has not been possible. Here again, however, the electrical analogy has come to our aid. Clearly the strains may be partly due to the mechanical design and partly to the changing acoustical reactions. In one sense this variable part is the more important of the two, since it is less easily controlled. It has its greatest effeet, however, when the other part is large, for thcn the margin of safety is reduced. The mechanical strains take the form of side-pressure between needle and groove, and are due either to stiff tone-arms, faulty lcvelling, or even to the use of such contrivances as automatic stops or repeating mechanisms. Anything which imposes a strain between needle point and groove is therefore best avoided.

The acoustical reactions depend on the sound-box and horn. The transmission of vibrations through the masses and compliances which make up the acoustical system may be a very complicatcd affair, and the reactions upon thc driving point may be quite considerable. At one time it may require considerable pressure for the groovc to move the needle point at all; at another, very little power will be required. The impedance to motion at the needle point will usually have a resistance component which does the useful work of transmitting the vibrations to the outer air in the form of sound and a reactance component which does no useful work and varies with the frequency. Analogous to the extended form of Ohm's Law for alternating currents wc have :

$$V=\frac{F}{Z}$$

where V is the velocity of the needle point, F is the force betwecn needle and groove, and Z is the impedance. Z is made up of a resistance R and a reactance X, $Z^2=R^2+X^2$.

Under the constant velocity system of recording V is constant relative to the record groove. The magnitude of the force F will thus depend partly on the magnitude of R, which is the measure of the loudness of the reproduction, and partly on the value of X. It is this reactance X which is responsible for most of thc trouble; its magnitude fluctuates greatly both with the frequency of the vibrations and from instant to instant. It may even be so great as to swamp R completely. For minimum record wear, then, the impedance of the acoustical systcm, viewed from the needle point, should have no reactance component.* It should be a pure resistance. But this is precisely the condition for a uniform frcquency response. To obtain such a response the masses and compliances have to be so related that the system simulates a pure resistance over thc requircd range of frequeneies. That is the fundamental property of a wave-filter on which the design is based. In this case, then, there is no reactance and thc power from the record will be expended in doing useful work. For a given volumc of rcproduction, therefore, record wear will be at its minimum when the instrument is designed and adjusted to give the bcst quality. No conclusion could be happier!

One or two other corollaries of this argument should be noticed. Below the cut-off frequency of

* Another way of looking at the matter is this. Record wear may be said to be due to phase differences. If the needle velocity and the pressure are in phase there is no reactive wear; this reactive wear only occurs when the difference of phase is appreciable. It can be shown that with a perfectly uniform frequency response phase differences of this kind do not occur. It is also interesting to note that in such circumstances transients can be perfectly reproduced.

a gramophone the impedance becomes a pure reactance. The resistance component vanishes and no useful work is being done. Record wear may thus be substantial since, as we have seen, the walls of the record groove are weakest at bass passages. Another indication of the presence of reactance is the existence of resonances. In an electrical circuit resonance occurs for the particular frequency at which the reactance component vanishes. The existence of resonances at particular frequencies thus implies the presence of reactance at other frequencies. Portable and other gramophones with small horns must have a fairly high cut-off frequency, and therefore dangerous reactance at frequencies below the cut-off; and if the horn is made long, but the mouth small, powerful resonances are set up which mean substantial reactance elsewhere. For these reasons record wear is bound to be more substantial on small gramophones than on large ones, even though the actual volume of sound reproduced is less.

Since the simulation of a perfect wave-filter is only exact when all the masses and compliances in the acoustical system are adjusted to precise values, we are naturally led to inquire whether there are any precautions we can take so that in a resonant system the reaction between needle and record may be kept within reasonable limits. This is a question which is very difficult to answer with any degree of certainty. Generally speaking, of course, the conditions are, firstly, that the horn should be large both in length and in mouth opening; and secondly, that the resonances should not be too pronounced. We can, however, deduce two fairly safe rules merely by considering the forces on the stylus-bar. Suppose the displacement of the needle point from the mean line of the groove is x and the corresponding displacement of the upper arm of the stylus-bar is y. If c is the needle point compliance and l_1/l_2 is the leverage ratio of the stylus-bar, l_1 being the distance between needle point and pivot, then the instantaneous value of the pressure p is :

$$p = \frac{1}{c}\left(x - \frac{l_1}{l_2} y\right)$$

We may write this :

$$pc/x = 1 - \frac{l_1}{l_2}\frac{y}{x}$$

The value of y depends on the reactance component and to a certain extent therefore on the values of c and l_1/l_2. For our present purpose, however, we can ignore this variation in y. It is usually small compared with x. In that case it is easily seen that to keep the value of p low we may increase the value of c or the value of l_1/l_2. A large value of c means a flexible needle point, and a large value of l_1/l_2 is most easily secured in practice by increasing l_1, that is by using a longer needle. Within limits both these methods are found in practice to be effective in reducing record wear, though they usually mean a reduction in volume as well.

VII—3. Needles.

From the acoustical point of view the two things of importance in a gramophone needle are its length and the compliance of its point. In Chapter IV it was explained that to match the compliance of the needle point to the impedance of the diaphragm, air-chamber, etc., the needle-arm transformer became necessary. The length of the needle and its mass must therefore be considered as part of the stylus-bar. For any particular design of sound-box the length of needle, its mass and the compliance of its point must be interrelated. The same type of needle will probably not suit another design of sound-box. By experimenting with different types of needle we are thus able to control the response in some measure. To " tune " a sound-box thoroughly we may also have to adjust the mass of the stylus-bar and the compliance of its upper arm, as well as the depth of air-chamber and size of outlet to the horn. Another point should be noticed about the needle compliance. The theory assumes that in effect it is situated at the needle point and not in the shank. We might therefore expect to obtain the best results from our design with a needle which is comparatively stiff for the greater part of its length and flexible only at the point. The needles which fulfil this condition most exactly are Tungstyles, those spear-pointed needles which have a fine taper beyond the spear, and fibres. A needle which is flexible along most of its length has a tendency to " whip," and this has ill effects both on reproduction and record wear. The only disadvantage of concentrating the compliance at the tip of the needle seems to be that the tip is thereby made more fragile. A Tungstyle consists of a rigid metal sheath with a small projecting point of fine tungsten wire which will buckle if carelessly used. The fragility of fibre points is well known, though when they are properly used, in a sound-box specially made for them, it is surprising how well they will stand up to seemingly impossible strains; and in these circumstances, as might be expected, they give excellent quality of reproduction. The important point to remember with regard to any needle is that its performance will be controlled entirely by the sound-box in which it is used; and conversely, the performance of a sound-box will partly be governed by the type of needle used with it.

From the mechanical point of view the fundamental requirements of a gramophone needle are: firstly, that the point should be just sharp enough to reach to the bottom of the record groove; and secondly, that the material of which it is made should either be softer than the record material or as hard as it is possible to make it consistent with obtaining the required degree of compliance. In every box of needles there is inevitably a number of bad points. British needle manufacturers examine a certain percentage of needles in a projector and reject whole batches if the samples are not up to standard. It would be quite out of the question for them to examine every one: millions of needles are sold every week. Before using the needle, therefore, it is always advisable to examine the point under a light. Some meticulous gramophiles examine every point under a magnifying glass whenever they buy a box of needles; that is carrying the "safety first" principle to extremes.

A needle which is weaker than the record material will, of course, break down before the record is damaged. This is at once the virtue and the annoyance of fibres. It follows that a fibre needle, in a sound-box specially made for it, gives us an excellent method of judging whether the mechanieal conditions are such as to cause record wear. It is significant that stiffness in a tone-arm, too great a compliance in the conneetion between sound-box and tone-arm, the existence of side-pressure, a record which is not centred properly, or a motor which pulls unevenly will break a fibre point with ease. One disadvantage of this type of needle, however, is that the debris worn from the needle, particularly after a few breakdowns, will eventually clog the groove. And if dust and grit are allowed to remain on the record they will embed themselves in the needle and act as an abrasive.

If the needle is harder than the record material it had better be very mueh harder, sinee then not only is it possible for it to be ground to a finer point, but the very hardness causes it to wear into a chisel less readily. A very hard needle will show less signs of wear after half a dozen playings than a soft needle does with one. This does not mean, however, that such needles ought to be used half a dozen times. Thc counsel of perfeetion is to use them once only, particularly if the alignment of the gramophone is faulty, for in this ease the faces worn on the needle at the end of a record would not fit the groove at the beginning of the record if the needle were used again.

VII—4. Surface-Noise.

Next to the extended frequency range aehieved by electrical recording, the reduction of surface-noise during the past few years has been the most important improvement in record manufacture. As already mentioned, the improvement was initiated by the Columbia new process. The next improvement was made by electrical recording. Quite a large amount of the " scratch " one used to hear was actually due to the recording process. It consisted of noises with a frequency in the region from about 5,000 cycles upwards. The electrical wave-filter recorder attenuates most of the frequencies in this region. To attenuate those which happen to lie below 5,000 cycles would mar the quality of the reproduction.

The same disadvantage attaches itself to the suppression of these frequencies in reproduction. For the best reproduction a certain amount of scratch must be tolerated. It is fortunately very small in these days. The only legitimate way of avoiding excessive surface-noise in the gramophone itself is to arrange matters so that the needle should not pick up unwanted vibrations from the record surface. The circumstances in which this may be ensured are precisely those for absence of frictional wear discussed in the first section of this chapter.

CHAPTER VIII

ELECTRIC PICK-UPS

VIII—1. Functions.

The first process in the electrical reproduction of gramophone records is the conversion of the mechanical vibrations imparted by the record to the gramophone needle into electrical vibrations. These electrical vibrations are in the form of variations of voltage or electromotive force at the terminals of the electrical "pick-up." When variations of this sort are applied between grid and filament of a thermionic valve a magnified version of the variations is created in the plate circuit of the valve, and this applied between the grid and filament of a succeeding valve creates in its turn still greater voltage variations in the plate circuit of that valve. In this way, by proper choice of valves and circuits, the voltage fluctuations can be magnified many times, and the resulting currents from the last stage of the amplifier can be used to operate a loud-speaker at any desired volume. The design of an amplifier to give uniform amplification of all frequencies within the range with which we are concerned presents no serious theoretical difficulties. The current output may be made to correspond in wave-form quite closely with the input to the amplifier.

For distortionless reproduction, then, our first requirement is that the voltage variations induced in the electrieal pick-up should exaetly eorrespond in wave-form with the vibrations of the needle point as it traeks in the record groove. The second requirement is that the needle point should be able to follow the groove without difficulty; for if too much strain is imposed upon it, not only will the record be badly worn, but the mechanical vibrations will be distorted. Here, as in the ordinary gramophone, the conditions for best reproduction are precisely those for minimum record wear. It should be noticed at this point that it is not at all necessary that the voltages induced in the pick-up should be large, sinec we can amplify them electrically as much as wc please. Of course, the larger we can make them, without distortion, the better off we shall be when wc come to dcsign an amplifier to give a desired output. In prineiplc, however, we are not really eoneerned to make the piek-up specially cfficient in the mechanical sense. This consideration is of importance sincc, as we saw in the last chapter, record wear is detcrmined by the magnitude of the driving force at the needle point. By redueing the power taken from the gramophone motor through the record, wear may thcrefore be reduced. We should be on our guard, however, against supposing that a pick-up which gives the smallest output voltage neeessarily wears records less than others. If the mechanieal impedance of thc pick-up looking in at the needle point has a large reactance component compared with its resistance component, the output voltage may be very small and

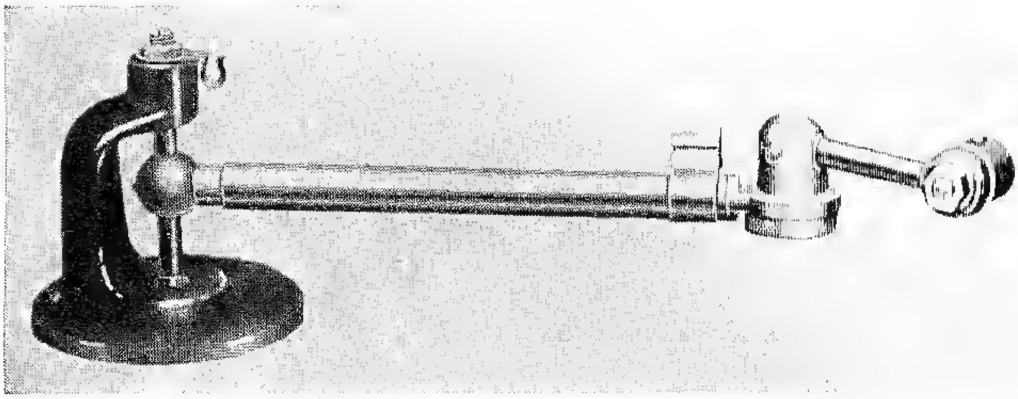


Fig. 63. Meltrope Pick-up arm.

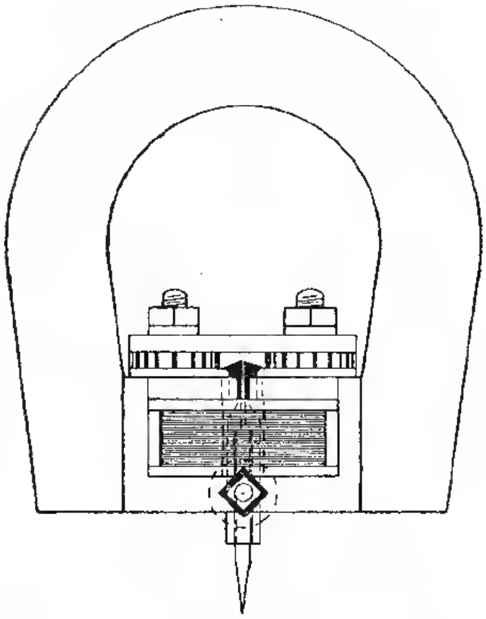


Fig. 67. Kellogg Pick-up.

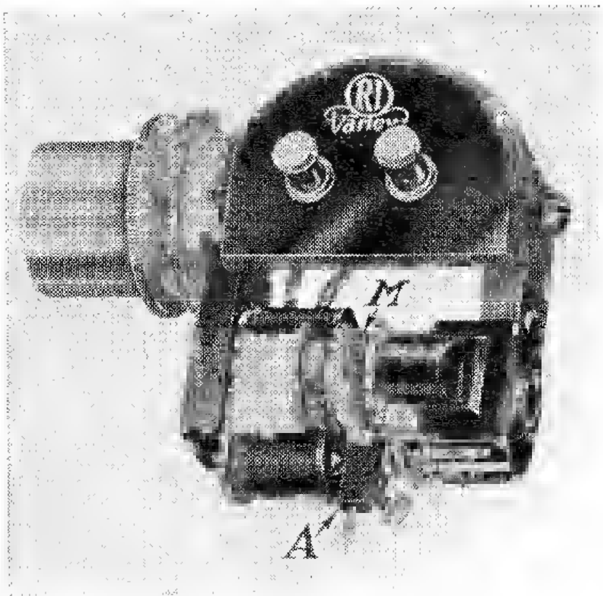


Fig. 70. Varley Pick-up.

yet the driving force substantial. This, in fact, has been the chief fault of all the early forms of pick-up. In order to obtain a reasonably accurate correspondence in wave-form between the output voltage and the vibrations of the needle point, heavy damping has been employed, and the reactance component at the needle point has been very great, particularly at low frequencies. Notwithstanding this, the output power of the pick-up has been not more than about 1/100th of that of a good gramophone sound-box.

VIII—2. Types.

Before we proceed to consider the mechanical problems involved in the design of a pick-up, it will be well to examine a few of the methods which may be adopted to convert the mechanical vibrations into electrical vibrations. There are in general two classes of device which may be used. In the electromagnetic type the mechanical vibrating member may be arranged to induce an electromotive force in a coil of wire through the intermediary of a magnetic field. If the magnetic flux through a coil is varied, either by movement of the coil or by movement or variations of the magnetic field, an e.m.f. is induced in the coil. This is the method which has been employed in nearly all the pick-ups now available. The second method employs a different principle. The current flowing in an electrical circuit depends upon the impedance of the circuit. This impedance may be a resistance, an inductance, a capacity or any combination of the three. If, therefore, we pass a current through a circuit and so arrange our mechanical vibrating device as to vary the resistance, induetance or capacity in the circuit, we shall modulate the current in the circuit and thus produce electrical vibrations which may be fed to the electric amplifier. This method has not been fully explored up to the present. " Electrostatic " pick-ups, which depend for their action on the variation of the capacity of a condenser, have been produced, but it cannot be said that they have met with much success. The " condenser transmitter," which acts on the same principle, however, is a very succcssful form of microphone. The hot-wire microphone, in which the temperature and therefore the resistance of a hot wire is varied by the air currents created by sound pulses, is an example of the use of a varying resistance to convert mechanical or acoustic vibrations into electrical vibrations. So far as the authors are aware, however, no attempt has been made to devise a gramophone pick-up on this principle.

VIII—3. Velocity and Displacement Devices.

Another point about the design of a pick-up should be noticed at this stage. According to the design the output voltage may be proportional either to the mechanical displacement or to the velocity of the meehanical motions. In the case of an electrostatic (condenser) pick-up, if the plates of the condenser are kept charged through a very high resistance, so that the charge upon them does not change appreciably, the voltage across them varies inversely as the capacity or directly as the distance between the plates. Hence, if the distance between the plates is varied mechanically, the voltage will be directly proportional to the mechanical displacement. On the other hand, as Kellogg points out,* if a low resistance (compared with the capacity reactance of the condenser) is shunted across the condenser the charge will flow to and fro in the resistance, and the current (or voltage across the leak resistance) is proportional to the rate of change of charge, which in turn is proportional to the velocity of the moving plate. The electrostatic pick-up can thus be used as a velocity device. In the electromagnetic type the voltage induced in the coil is proportional to the rate of change of magnetic flux and this in its turn is proportional to the velocity of the mechanical motion.

For reproducing modern records made on the constant velocity system a pick-up of the velocity type is required. If records were to be made on the constant amplitude system a pick-up of the displacement type would be necessary. Notwithstanding Kellogg's tentative statement to the contrary, there are a number of considerations which suggest that for electrical reproduction a constant amplitude system of recording would be better than the present system, though it certainly would have the disadvantage that the records could not be used for mechanical reproduction. Record wear would certainly be diminished (unless, that is, the constant amplitude were made as large as the amplitude at 200 cycles under the present system), since the thickness of the walls of the groove and, therefore, the power of withstanding strains would be increased. There is also reason to think that surface-noise would

* "Journal, A.I.E.E.," October, 1927.

be to some extent reduced. Under this system notes of high frequency would in effect be over emphasized in recording. To obtain the proper balance throughout the scale in the final result, therefore, the reproducing instrument must attenuate the high frequencies, and this would be accompanied necessarily by a reduction in surface-noise.

VIII—4. Electromagnetic Pick-ups.

The possible types of electromagnetic pick-up are very numerous. Here we can only illustrate the general principles by a description of the more common examples. The essential feature of all is that the mechanical motion should create a change of magnetic flux through a coil. This object may be attained either by making the coil move in a magnetic field or by arranging for a magnetic armature to alter the flux through a fixed coil. The difficulty about the first method is that the mass of a coil with sufficient inductance (determined by the diameter of the coil and the number of turns in it) is relatively so large that the response falls off substantially at high frequencies. Moreover, it is not at all a straightforward matter to dispose a small moving-coil so as to be operated by the gramophone needle and yet remain quite rigid. In view of the success of the moving-coil speaker, most experimenters must have conceived the idea that a moving-coil pick-up should be superior to a " moving-iron " type. But a moving-coil speaker works on an altogether different scale both of motion and of force, and the errors are not subsequently magnified as they are in the case of a pick-up. It would be rash to assert that there is no future for a moving-coil pick-up, but it is clear that any such device would either have to be designed with much bigger and more expensive magnets and lighter coils than are used in the iron-armature type, or some compensating electrical network may have to be provided. No successful design has yet been produced commercially.

In the moving-iron or armature type, the coil may be arranged either round the armature or on the pole-pieces of the magnet. The Round (Marconi), Celestion (Woodroffe), Varley, Brown and H.M.V. pick-ups are of the latter type, whilst the Kellogg (B.T.H.), G.E.C. (Hopkins), Phonovox (Igranic), and Crosley Merola are examples of the former. Again, there are three possible motions for the armature: translation, half-rocker and full-rocker. These possibilities are illustrated diagrammatically in Fig. 66, which is reproduced from Kellogg's paper previously mentioned. The following summary of the advantages and disadvantages of the various arrangements is quoted from Kellogg's paper, the present authors' comments being added in brackets.

(1) " It is better to place the windings around the armature than around the poles, for much of the flux change in the armature involves only a slight shift of the flux from the pole pieces and does not cut all the turns of a coil wound on the pole." (This argument is only concerned with the desirability of obtaining as great a variation of output voltage as possible. As we have already pointed out, this is a secondary consideration, compared with

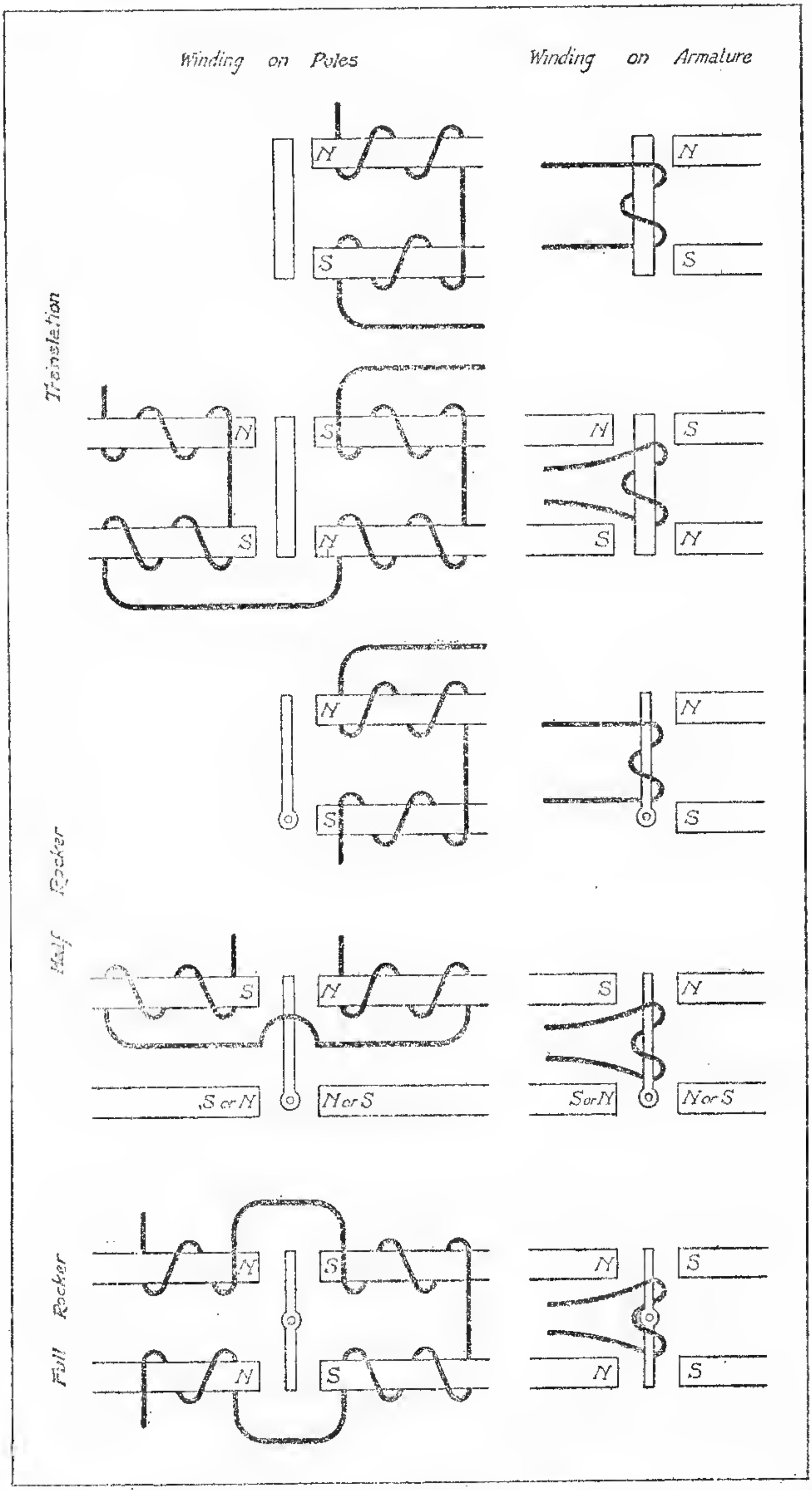


Fig. 66.—Diagram showing possible types of electromagnetic pick-up.

the necessity of obtaining a uniform frequency response coupled with minimum record wear.)

(2) “ Adding two poles on the left-hand side of the armature (as well as two on the right) has doubled the magnetic effeet which results from a given motion of the armature, for there are just twice as many air-gaps whose reluetance is varied.” (This argument again is coneerned solely with the magnitude of the output.)

(3) “ By plaeing opposite poles on the two sides we have redueed the steady flux which the armature has to carry, leaving only the residual or alternating flux. Hence the armature may be lighter in this case.” (This is an important eonsideration from the point of view of both frequency response and record wear.)

(4) “ The rocker type armature has an advantage over the translation type armature in which both ends move in the same direetion. It is only the motion of the ends of the armature opposite the poles which is effective to produee flux change. In the translation type all parts of the armature move equally, whereas in the rocker type, the middle has only a slight motion for a given motion at the ends.” (This again is an important consideration. For a given mass in the armature the momentum of the roeker type is much smaller than that of the translation type, and it is in the form of momentum that mass enters into the motion.)

(5) “ The middle point of the armature of the full-roeker is a point of constant magnetie potential. If we imagine the armature eut in two, and only the upper end removed, we should still get as mueh

flux change through the upper end of the armature as we did in the full-rocker, provided we could keep the lower end of the moving portion at constant magnetic potential. In other words, we might say that in the full-rocker type the motion of the upper half gives rise to the flux change and that the motion of the lower end is required to keep the middle at constant magnetic potential. In the half-rocker the pivot end of the armature can be kept at *nearly* constant magnetic potential by making the reluctance of the air-gaps at this end low compared with that of the gaps of the moving end."

VIII—5. Half-Rocker Moving-Iron Pick-ups.

As a result of these arguments, Kellogg concludes that the best design, from an electromagnetic point

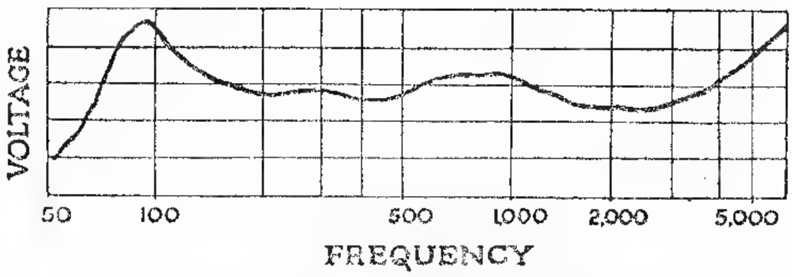


Fig. 68.—Frequency response of Kellogg pick-up.

of view, is a half-rocker type with the air-gap at the pivot very small and with the coil windings round the armature. His design (which has been largely followed in essential respects by other designers) is shown in Plate XI. He gives a mathematical analysis of the motion, and from that analysis concludes that the various masses and eompliances may be chosen so as to give a frequency response as shown in Fig. 68. Unfortunately his analysis omits to take account of one or two features of some importance. Thus, account is taken of the compliance of the needle point, but not of the compliance of the upper end of the armature between the pole pieces; also, the stiffness of the armature mounting is assumed to be concentrated at the end along with the damping arrangements. When account is taken of all factors, the theoretical response may be made more uniform than is shown by Fig. 68. But when we proceed to calculate the driving force at the needle point required to maintain the motion, we find that at low frequencies it is relatively large, and from the point of view of record wear this is undesirable. This large driving force is necessitated partly by the use of stiff rubber springs, both at the pivot and at the upper end of the armature, in order that the resonant frequency of the arrangement shall be very high—in the region of 6,000 cycles—and partly by the use of relatively heavy damping so that that resonance shall not be too prominent. With constant-velocity recording, this stiff spring and heavy damping call for a considerable driving force from the record, in order that the necessary amplitude of motion of the needle point may be obtained.

Is there any escape from this dilemma?

To answer this question it is necessary to examine in great detail the motion of the armature and the forces acting upon it. The formulæ are so intricate that it is impossible in this book to do more than indicate the nature of the problem to be solved. This problem is to choose values of the masses and compliances which are realizable in a practical design and which will ensure that:

(1) The ratio of the motion of the upper end of the armature to the motion of the needle point shall be as nearly eonstant as possible for the frequeneies within the reeording range.

(2) The ratio of the driving foree to the needle velocity demanded (particularly at low frequencies) does not beeome unduly large.

The formulæ connecting the various quantities are set out in the Appendix to this chapter for the convenienee of those readers who wish to pursue the matter in detail. It can be said at onee that there is no obvious solution to the problem. The only way of tackling the question seems to be to assume possible values of the various quantities involved and determine by trial how the results work out. But the authors have found, both theoretically and in practice, that if the design is based primarily on a needle with a flexible point, e.g. a fibre needle, a reasonably uniform response ean be obtained without requiring too great a driving force, though the output beeomes rather small.

VIII—6. Other Types.

The question may be asked: Since a sound-box eonstrueted on a wave-filter analogy has proved so sueeessful, why not eonstruct a piek-up on the same principle? It would give a uniform response and at the same time the impedance looking in at the needle point would have no reactance component. The answer is that this would certainly be done if anyone knew how to do it in practice. It must be remembered that the form of the gramophone was developed long before the wave-filter theory was elaborated ; the mechanical methods existed ready for the theory to adopt. In particular it should be noticed that the gramophone horn provides the resistance termination of the sound-box wave-filter ; the filter would be of little use without it. No one has yet thought of a satisfactory method of providing a proper resistance termination to a pick-up wave-filter. The nearest approach to it seems to be the oil-damping system used in the H.M.V. "electric sound-box." An illustration of this is shown in Fig. 69. A magnetic pole is placed close to a steel diaphragm (less than three-thousandths of an inch thick), which is clamped round its edge to

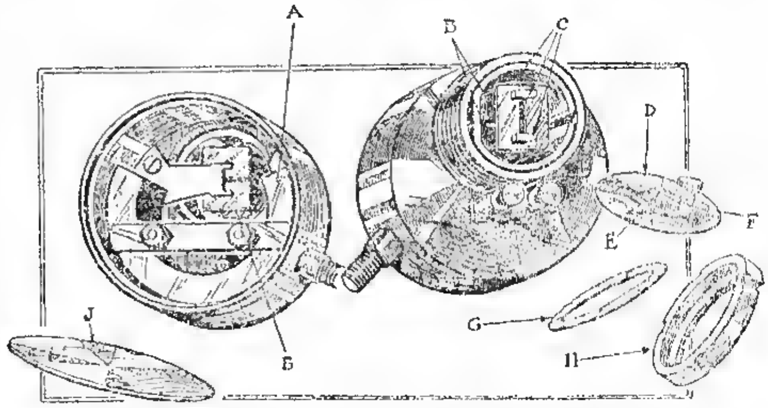


Fig. 69.—H.M.V. oil-damped pick-up.

A, field magnet ; B, bobbins on divided end of magnet pole ; C, the poles ; D, the steel diaphragm ; E, iron attachment for needle holder ; F, brass end to prevent needles sticking ; G, oil-retaining washer ; H, diaphragm clamping ring ; J, back cover ring.

(Reproduced by courtesy of *The Wireless World*.)

the opposite pole, which is in the form of a cylinder. To this diaphragm the needle holder, which is made partly of brass and partly of iron, is attached. The vibration of the diaphragm produces the change of flux in a coil disposed on the central pole piece. The whole of the interior is filled with a viscous oil.

Another form of pick-up has recently been developed by the Varley Company. An illustration of its mechanism is shown in Plate XI. The armature A is mounted at the middle of a thin steel spring, the ends of which are attached to a shaped member M of soft iron. This is pivoted in a line with the spring upon a pole piece attached to one leg of a horse-shoe magnet. The coils are mounted on two pole pieces, of the same polarity, attached to the other limb of the magnet. Between the armature and the shaped member there is a pad of rubber, and between the shaped member and the magnet are two other pads. When the needle is vibrated, the armature can either rock on the spring, or the armature and the shaped member can rock on the pivots. The magnetic flux passes through the armature to either of the pole pieces on which the coils are mounted, according to the increase or decrease of air-gap caused by the rocking of the armature.

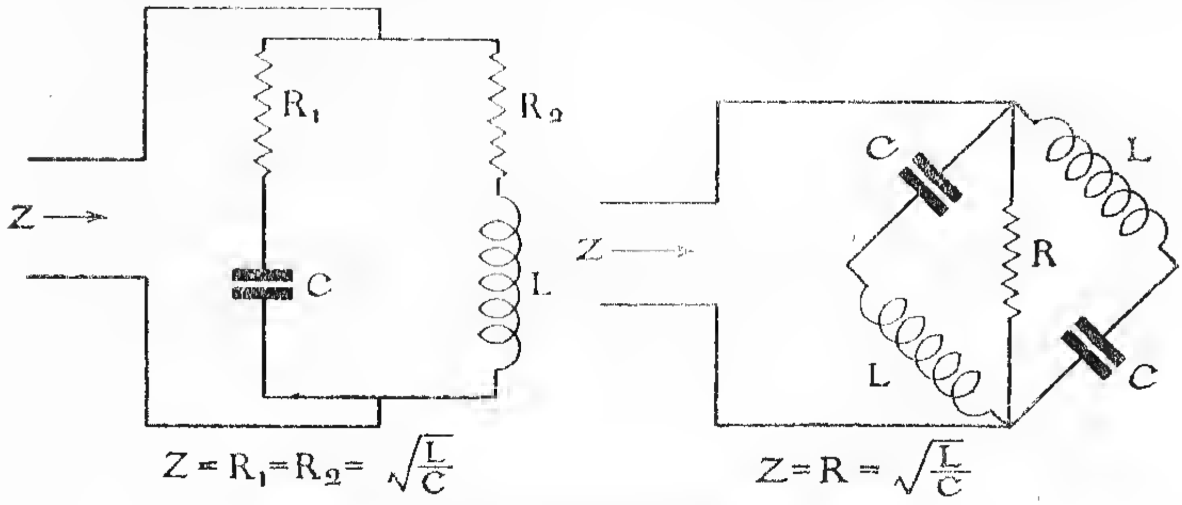
VIII—7. Possible Developments.

At the present stage in the development of the electrical pick-up it is hardly possible to forecast what form the successful pick-ups of the future will take. The most one can do is to indicate in a general way some of the difficulties to be faced and some possible ways of approach.

(1) Whatever the remainder of the mechanical system may be like, there must always be compliance in the needle point and mass in the armature. It follows that the mechanical system must be a resonant system.

(2) There are three possible ways of dealing with a resonant system:

(*a*) The masses, compliances and resistances may be arranged in such a way as to produce a mechanical transmission line which will simulatc a pure resistance. This is what is achieved in the sound-box wave-filter. But a low-pass wave-filter is not the only "eonstant resistance circuit." Two circuits which simulate a pure resistance *at all frequencies* are shown in Figs. 71 and 72, where the quantities are connectcd by the relation $R^2 = L/C$. Other circuits with similar properties are described in works on clcctrical transmission lines. A pick-up constructcd as the exact mechanical



Figs. 71 and 72.—Constant resistance circuits.

analogue of one of these eircuits should give an even response independent of the frequency.

(*b*) A heavily damped resonant circuit. This has the disadvantage of causing severe record wear.

(*c*) A resonant circuit in which the resonances are either above or below the recording range. Thus, resonances at 50 cycles and 6,000 cycles *only* would actually compensate for some of the falling off of response in the recording.

(3) In any moving-iron pick-up aecount must be taken of the negative compliance due to the magnetic field. As the armature is displaced from its central (neutral) position the magnetic field tends to pull it

farther over. This effect can be compensated by a spring which would tend to pull it back. The magnitude of the negative compliance depends on the strengths of the magnetic poles. In any commercial design these strengths can hardly be standardized. Hence, it would appear necessary either to make the compensating spring adjustable and to adjust each pick-up individually or, alternatively, to arrange for the compensating spring to be automatically provided by the magnet itself. One method of doing this, which has been used with success by the authors, is to make the pole pieces hollow and to insert soft-iron plungers, backed by grease, in the pole pieces so as to bear against the armature through some slightly resilient material.

(4) The frequency response need not be perfectly uniform for all frequencies provided it is free from resonances. An ascending or descending response in the pick-up can be compensated later by an electrical network. A moving-coil pick-up with a compensating network appears to be quite a feasible proposition, and it would have the advantage of requiring no compensating spring for the negative compliance of the magnetic field.

(5) There are a number of theoretical advantages in having comparatively large air-gaps and strong magnets. There appears to be no good reason, apart from expense, why quite large magnets should not be used; if necessary, they could form part of the carrying arm, so that the downward pressure on the record is not unduly increased. Up to now designers seem to have been hypnotized by the size and general appearance of the gramophone sound-box.

APPENDIX

FORCE EQUATIONS OF THE HALF-ROCKER PICK-UP.

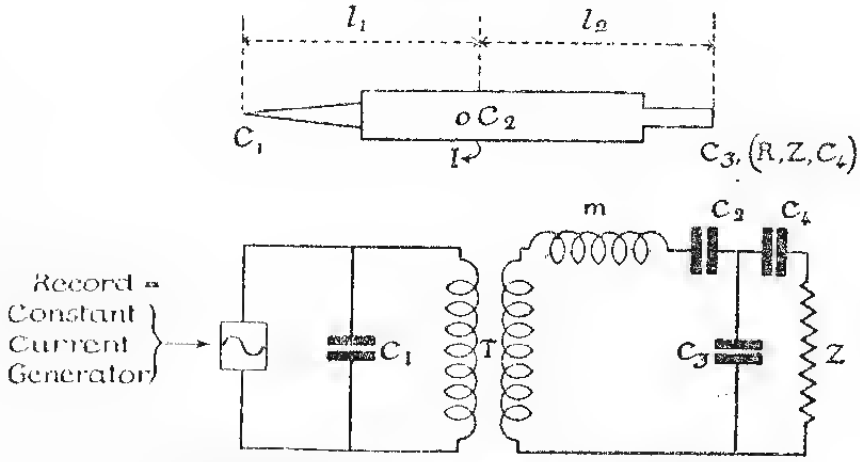


Fig. 73.—Force diagram of half-rocker pick-up.

C_1 = needle point compliance.

T = armature transformer ratio $\dfrac{l_1}{l_2}$

m = mass of armature viewed from $C_3 = \dfrac{I}{l_2^2}$ where I is the moment of inertia of armature.

C_2 = pivot compliance.

C_3 = compliance of upper end of armature.

C_4 = negative compliance of magnetic field.

Z = impedance of damping arrangements which may be considered to be equivalent to a compliance C_5 in series with a resistance R.

S_1 = displacement of needle point.

S_2 = displacement of upper arm before C_3.

S_3 = ,, ,, ,, ,, after C_3.

θ = angle of deflection at pivot $= \dfrac{S_2}{l_2}$

$$\frac{S_1 - l_1\theta}{C_1} = \text{driving force } F.$$

$$I\frac{d^2\theta}{dt^2} + \frac{l_1\theta - S_1}{C_1}\,l_1 + \frac{\theta\, l_2}{C_2}\,l_2 + \frac{l_2\theta - S_3}{C_3}\,l_2 = 0$$

$$\frac{S_3 - l_2\theta}{C_3} + Z\,\frac{d\,S_3}{dt} = 0$$

From these we obtain, putting $l_1/l_2 = n$,

$$\frac{S_1}{S_3}\frac{n}{C_1} = \left(1 + \frac{C_3(C_5 - C_4)}{C_4\,C_5}\right)\left(-m\omega^2 + \frac{n^2}{C_1} + \frac{1}{C_2}\right)$$
$$+ \frac{1}{C_5} - \frac{1}{C_4} + j\,\omega\,C_3\,R\left(-\,m\omega^2 + \frac{n^2}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right).$$

For perfect transmission $\frac{S_1}{S_3}$ should be constant for all values of ω $(= 2\,\pi\,\times$ frequency) within the recording range.

The driving force

$$F = \frac{1}{C_1}\,(S_1 - n\,S_2)$$

and

$$S_2 = S_3\left(1 + j\,\omega\,C_3\,R + \frac{C_3}{C_5} - \frac{C_3}{C_4}\right).$$

For minimum record wear $\frac{F}{\omega S_1}$ should be small and as uniform as possible.

CHAPTER IX

LOUD-SPEAKERS

IX—1. General Principles.

Having converted the mechanical vibrations, either in a broadcasting microphone or a gramophone pick-up, into electrical vibrations of corresponding wave form, the next stage in electrical reproduction is the amplification of the electrical vibrations. The amount of amplification necessary depends, of course, upon the sensitiveness (or mechanical efficiency) and the power-handling capacity of the loud-speaker. It is therefore convenient to postpone for a while the discussion of amplifier design and to deal first of all with the loud-speaker problem.

It is not so long ago that the only type of loud-speaker consisted of a modified form of telephone ear-piece attached to a short horn. The value of a large horn for sound reproduction has been realized, if not fully understood, in gramophone work for over twenty years. But for radio, in the early years, this previous gramophone experience seems to have been ignored. Or perhaps it was that the amplifying apparatus commonly used in those times gave insufficient power to operate a large horn speaker effectively. Certainly gramophone reproduction, even with records made under the old acoustic process, was for several years far superior both in point of quality and of power to the loud-speaker radio reproduction. The development of better valves and electrical components generally, however, soon demonstrated the shortcomings of the loud-speakers. Even now it is not untrue to say that the loud-speaker is the weakest link in the broadcasting chain, notwithstanding the enormous improvements that have been effected in recent years.

The main defect of small horn loud-speakers is not so much that the response is full of resonances, as is commonly supposed, though that in itself is serious enough, but that the frequency range is so short. Few of them, and those the largest, can reproduce any notes below middle C. Attempts to increase the range in the bass have been made by the use of large diaphragms in the telephone element, but exactly as in the corresponding case of the gramophone the result is only to increase the resonances and make the response more uneven. The alternative of using a small light diaphragm and a long horn never seems to have been favoured, at any rate in commercial instruments, notwithstanding the experience of gramophiles that that was the most effective method of obtaining an increased range and a more uniform response. In radio circles in Great Britain, Hanna and Slepian's work is even now almost unknown, though the success of the modern gramophone with a large exponential horn has demonstrated that the development of large folded horn loud-speakers would be

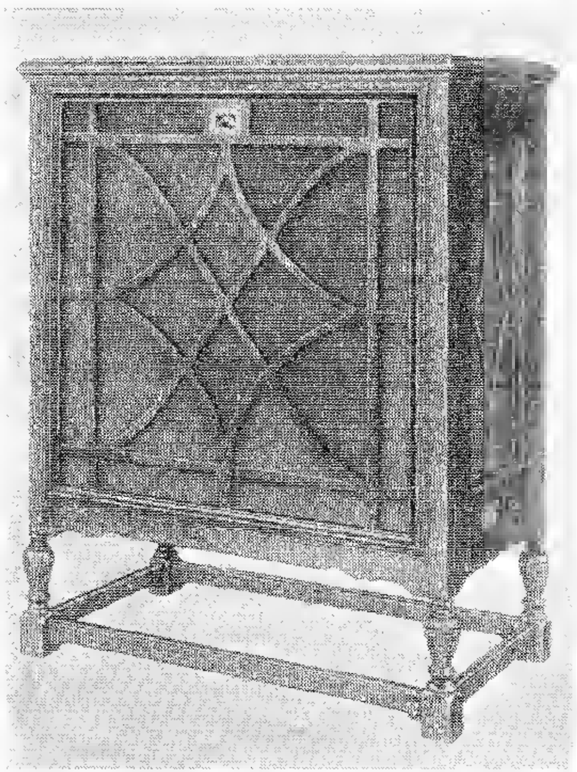


Fig. 83. Loud Speaker Unit.

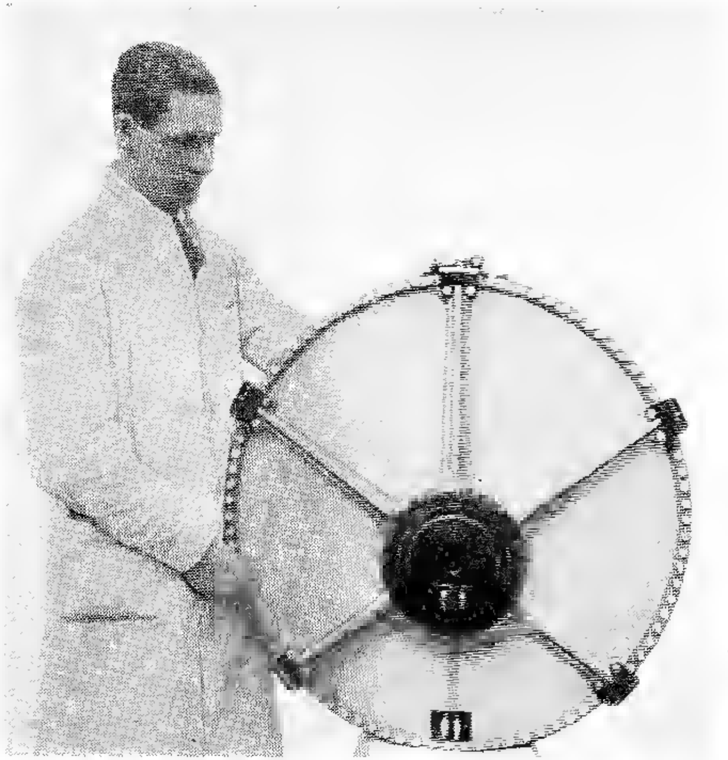


Fig. 83b.
Schlenker Loud Speaker removed from case.

Fig. 83c. Pick-up unit.

H.M.V. ELECTRICAL REPRODUCER

PLATE XII

well worthy of attention. Speakers of this type are remarkably efficient in the sense that they give a fairly large output of sound for a comparatively small input of electric power. As soon as the methods of folding horns have been more thoroughly explored, this type of speaker will no doubt come into favour.

At present, however, it is undoubtedly overshadowed by the diaphragm type. In this a large diaphragm, usually in the form of a cone, is actuated at its apex by an electromagnetic reed mechanism, and communicates vibrations directly to the air in the room. This form of speaker can be made quite compact, and it certainly gives a better bass response than the small horn type. But the response to higher frequencies is often deficient and, besides, it is peculiarly prone to non-linear distortion. This is most readily seen when the speaker is called upon to reproduce a large number of instruments or voices; the instruments are apt to be far from clear and distinct, their timbre is not preserved and the perspective is lost. The same criticism, however, does not apply to the better examples of the more recently developed form of diaphragm speaker, now known as the "moving-coil" type. Here the driving mechanism is a light coil of wire attached to the diaphragm. When the signal currents from the amplifier pass through the coil, it is drawn in and out of a magnetic gap in a special form of cylindrical magnet. A mechanism of this kind may be used either to work into a horn or to operate directly on the air in the room. In the latter case, however, it is necessary, if low notes are to be reproduced, that the air on the two sides of the diaphragm should be separated by a considerable distance, preferably over 8 feet; otherwise the circulation of air between the front and back of the diaphragm will cause the pressure variations created by low notes to cancel out. The separation is usually effected by mounting the speaker in the centre of a large board known as a "baffle"; but a more effective way is to mount it in an aperture in the wall of a room so that one side of the diaphragm is working into the room and the other into another room or the passage outside.

Other types of loud-speaker have been developed in recent years, particularly for auditorium use. Thus there is an electrostatic loud-speaker, based on the same principle as the electrostatic pick-up or the condenser microphone; there is an induction type, in which the driving force is spread almost uniformly over the area of the diaphragm; and there are multiple-unit devices. An account of many of these types will be found in the paper read before the American Institute of Electrical Engineers in April, 1925, by Rice and Kellogg. Reference should also be made to the elementary handbook on "Loud Speakers," by Dr. N. W. McLachlan.

IX—2. Reed-Driven Mechanisms.

The earliest form of loud-speaker mechanism was that used in the Bell Telephone. In this a thin disc of iron was mounted in front of bobbins of wire disposed on the poles of a permanent magnet. The modern form of this mechanism is shown in Fig. 74.

The telephonic currents in the coils on the pole pieces increase or decrease the magnetic flux and thus the attraction between the diaphragm and pole pieces is varied and sound pulses are created. The disability of this form of mechanism is that the diaphragm has a strong fundamental resonant frequency, usually at about 900 cycles per second, and marked but less pronounced over-tones at higher frequencies. In a telephone ear-piece the resonances are partially damped by the air cavity between the diaphragm and the ear, but they are still too marked for good frequency response. Similar conditions apply when a mechanism of this type is coupled to a horn. A typical response curve of an undamped telephone diaphragm is shown in Fig. 75.

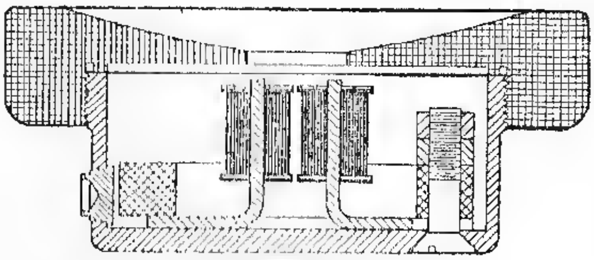


Fig. 74.—Bell telephone ear-piece.

From what has been said in the chapter on sound-boxes, it will be readily appreciated that what is required to improve the response characteristic is an intermediate mechanism between diaphragm and driving force, so that the diaphragm itself may be made to move more

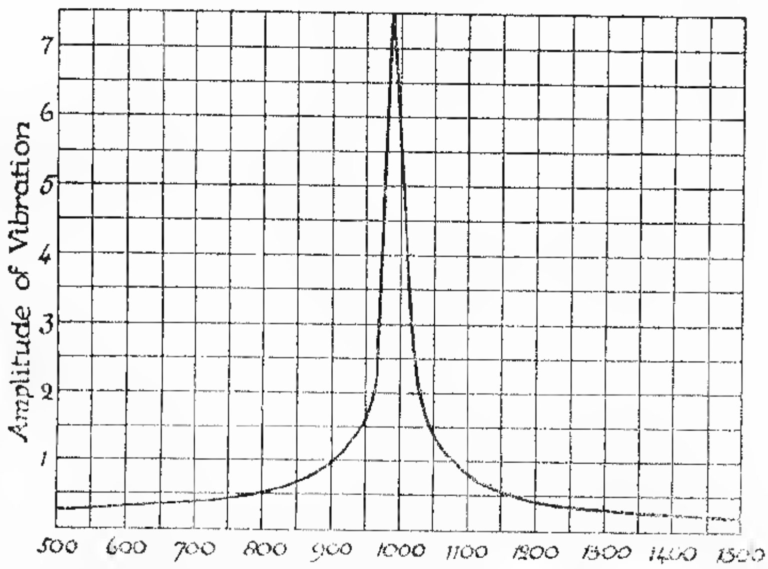


Fig. 75.—Typical response of telephone diaphragm.

Typical response of telephone diaphragm showing resonance at 980 cycles per second. The next natural frequency is about 2,000 cycles per second.

as a piston, and that an eleetrical resistance nctwork may be more easily simulated. Up to a certain point the first requircment was achievcd in S. G. Brown's ear-pieee of 1910, the structure of which is shown in Fig. 76. In this example the driving force is on a flat reed to which a light cone-shaped diaphragm is attached. The periphery of the diaphragm is mounted on a flat ring of flexible material which bridgcs the gap between the circumference of the cone and the shell of the ear-piece. A small cone diaphragm of this type acts substantially as a piston over a largc range of frequency and the diaphragm rcsonances are vcry high.

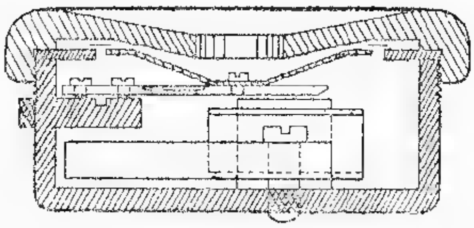


Fig. 76.—S. G. Brown ear-piece.

This arrangcment is subject to two disabilities. In the first place, the gap between the pole pieces and the rccd has to be quite small ; largc displacements of the diaphragm are therefore impossible. Secondly, the magnetic pull on the reed varies with the distance between the reed and the pole pieces, so that for large displacements there is not a linear relation betwecn the displaccment and the signal current passing through the coils on the pole pieces. The importance of these two considerations naturally depends on the displacement required, and therefore partly on the strength of the signal current and partly on the volumc of sound produced. In a telephone ear-piece the signal currcnts, the displacements, and the volume of sound are all quite small and the disabilities mentioncd are of little importance. So, too, they are not of much moment when the mechanism operates into a large exponential horn, since then a comparatively large volume of sound is obtained for a small displacement of the diaphragm, the requisite energy being obtained from the large force then required to move the diaphragm over a small distance. The position is quite different when the diaphragm has to operate on a small load, as, for example, when it works directly into the open air or when it is attached to a small horn. Then, a a large movement is necessary in order to obtain a considerable volume of sound, and the non-linear relationship between the signal current and the displacement of the reed introduces distortion.

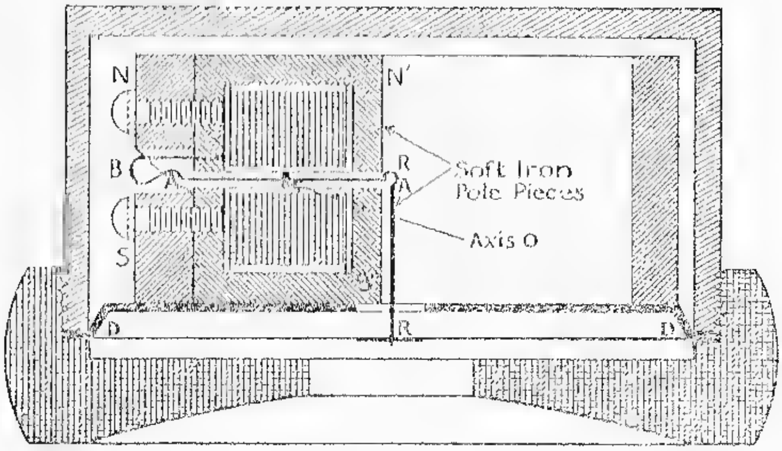


Fig. 77.—Baldwin balanced armature.

Another type of mechanism with similar characteristics is exhibited in the Baldwin telephone, the structure of which is shown in Fig. 77. Here a signal coil receiving the telephone current magnetizes an iron armature A A which is supported within the coil and is free to oscillate about an axis at O. The armature A is held between permanent magnet pole pieces N S, N′ S′ by a spring B at one end and a light rod R R at the other. The rod is attached at its other end to a diaphragm D D. When no currents pass through the coil the armature A A is in equilibrium ; but as soon as the telephone currents pass through the coil the armature is magnetized, first in one direction and then in the other, and oscillates under the attractions of the magnetic pole pieces about the pivot O, and these oscillations are transmitted to the diaphragm through the rod R R. The distinction between this and the Brown earpiece is that there is no permanent magnetic pull on the armature when no signal is passing through the coil. This type is therefore known as a "balanced armature." Moreover, since there are four air-gaps, the arrangement is more sensitive. But the relation-

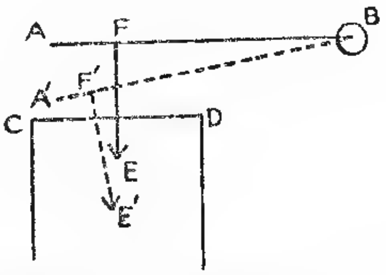


Fig. 78.—Diagram of common form of reed mounting.

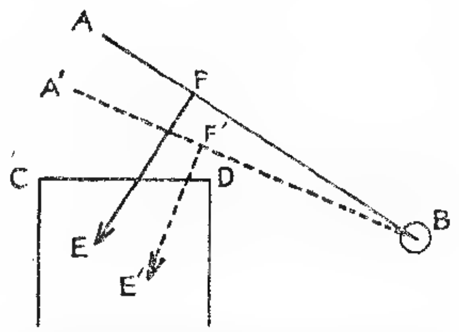


Fig. 79.—Diagram of "Lion" reed mounting.

ship between the signal current and the displacement is still non-linear owing to the variation of the magnetic force with the distance between armature and pole pieces. Other forms of balanced armature have been devised, but the majority are similar in principle to the Baldwin phone and are subject to the same disabilities.

Recently (1928) an attempt has been made in the Amplion "Lion" speaker to mount a reed in such a way that the increase of magnetic pull due to the decrease of air-gap is compensated by a decrease in the leverage of the reed, thereby achieving a displacement proportional to the current. The principle is illustrated in Figs. 78 and 79. In the ordinary arrangement (Fig. 78), in which the end A of a reed pivoted at B is pulled down towards a magnet C D, the gap decreases more towards A than towards B. The resultant magnetie pull therefore tends to concentrate towards A, so that not only is the magnitude of the pull increased by the shorter air-gap but its leverage ratio is increased. In the new arrangement the pivot B is arranged slightly below the pole face C D, as in Fig. 79, and when the recd is pulled down the concentration of magnetic pull shifts towards the smaller air-gap, that is towards B. Hence in this case, although the pull itself is increased the length of the leverage arm F B is decreased, and by adjusting the location of the pivot B with regard to the magnet the undue increase of magnetic pull is offset by a decreased distance F'B, leaving a remaining increase of torque proportional to the increase of signal current.

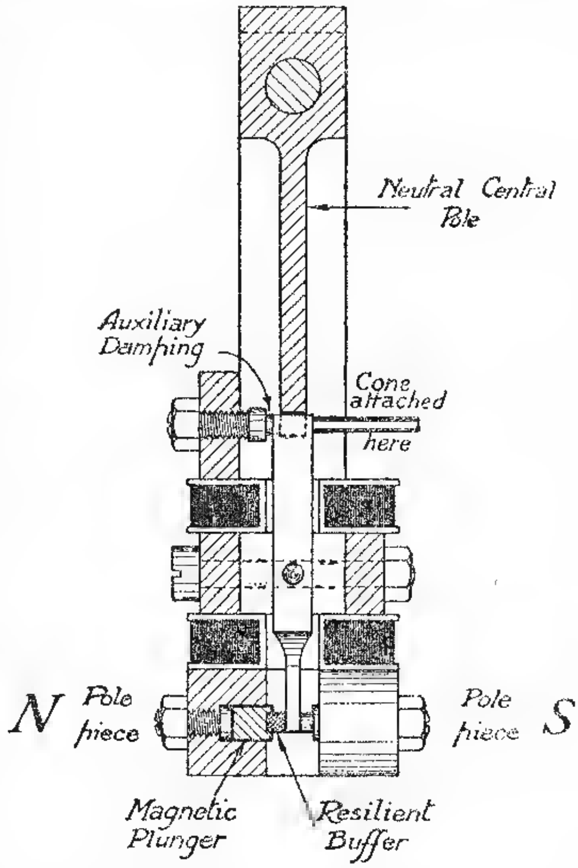


Fig. 80.—Loud-speaker unit with magnetic plungers.

Another method of compensating for the extra pull on the reed due to the reduction of air-gap has been devised by the authors and is shown in Fig. 80. In this, movable magnetic plungers are disposed in the poles of the magnet (whieh are hollowed for the purpose) and bear against the reed through a pad of soft resilient material. As the reed approaches the pole piece the plunger is attracted towards it and exerts a force on the reed compensating for the undue increase in the magnetic pull towards the pole piece.

IX—3. Moving-Coil Mechanisms.

The invention of a moving-coil drive for a loud-speaker is usually attributed to Sir Oliver Lodge (British Patent 9712 of 1898), but the authors have recently discovered a full description of a moving-coil speaker in an earlier patent by Dr. Siemens (No. 4685 of 1877). The device, too, has been used in a number of scientific instruments, of which Hibbert's Magnetic Standard is a well-known example. Essentially it consists of a small coil of wire disposed in an annular magnetic gap. The usual arrangement is shown diagrammatically in Fig. 81. The coil is attached to a diaphragm, usually of conical shape, and the signal currents from the amplifier are fed into it. An electromagnet is normally used to give the magnetic flux across the annular gap in which the coil is suspended ; a permanent magnet arrangement can be employed, but the flux and therefore the sensitivity of the speaker is not so great

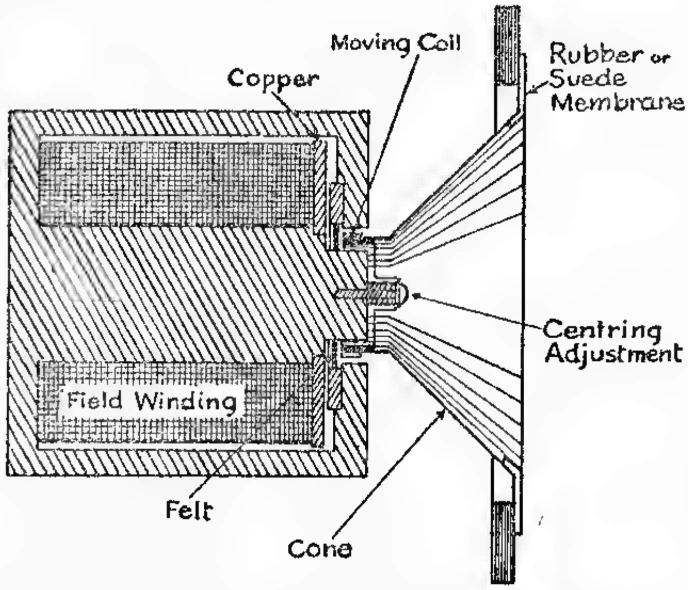


Fig. 81.—Moving-coil speaker mechanism.

as when an electromagnet of reasonable proportions is used. When the signal currents pass through it the coil is drawn in and out of the annular gap. There is no permanent pull on the coil and therefore quite large displacements can be tolerated. With one qualification, to be noticed presently, the relation between current and driving force is linear. This type of speaker may therefore be used to give a much greater sound output than the ordinary small horn or diaphragm types, and owing to the permissible amplitude the bass response when a baffle is fitted is very impressive. These are all solid gains. When, however, we come to examine the arrangement more closely we find that it is still subject to a number of disabilities. Thus, although there is no permanent magnetic pull on the coil there is a back e.m.f. induced in it when the coil is in motion. The effect of this is the same as if there were a capacity in series with the inductance of the coil, and the combination of the two gives a resonance effect. This motional capacity, as it has been termed, has an approximate value in microfarads $C = \frac{M \times 10^{15}}{S^2}$ where M is the mass of the moving parts and $S = \pi d n H$, where d is the diameter of the coil, n the number of turns and H the strength of the magnetic field expressed in lines per square centimetre. If L is the inductance of the coil resonance occurs at the frequency

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{d n H}{2} \sqrt{\frac{1}{L M 10^{15}}}$$

For efficiency of output L must be fairly high and the coil fairly massive; moreover, the diaphragm must have a substantial area, if it is to work into free space and not through a horn. The presence of the factor 10^{15} in the denominator also makes the value of the quantity under the square-root sign very low. It follows that very large values of d, n and H would be required to ensure a very high resonant frequency. In actual commercial designs the resonance occurs well within the musical range, usually at a frequency of about 1,500 cycles, though in some it may be as low as 500 cycles. When a moving-coil arrangement is used to operate a horn, however, the mass and inductance of the coil may be made quite small, the width of the annular gap can be reduced very considerably, and therefore for the same field current the value of H can be made much greater. In these circumstances the resonant frequency can be made very high.

IX—4. Diaphragm Effects.

In Chapter IV it was explained that for uniform response combined with relatively high efficiency the diaphragm should have a large stiffness/mass ratio and as large an area as possible, and that the edge should be as free as possible, though air circulation between the two sides of the diaphragm should be prevented. In this way the diaphragm can be made to act sensibly as a piston throughout the important frequency range, and diaphragm resonances will be removed to frequencies above that range. So long as we confine ourselves to diaphragms of not more than about 50 mm. in diameter the required stiffness and mass conditions can easily be secured by using aluminium diaphragms, either corrugated or in the form of a cone. The modern sound-box uses the former, whilst the latter is to be seen in the Brown ear-pieces and loud-speaker units. When the diaphragm is coupled to a horn, therefore, no serious difficulty is experienced in fulfilling the required conditions, though little attempt appears yet to have been made to match the impedances of the mechanical system as in the corresponding gramophone design. The most interesting example of a loud-speaker with a large exponential horn is to be found in the "Movietone." Here a moving-coil drive, specially designed by E. C. Wente and A. L. Thuras for the American Telephone and Telegraph Company, is used. The method of coupling the diaphragm to the horn is as shown in Fig. 82. A dished aluminium diaphragm is used and the throat of the horn is flared annularly to the point where it meets the edge of the dished diaphragm. In this way the pressure variations are made to reach the throat of the horn from the inner and outer portions of the diaphragm approximately in phase up to very high frequencies. The diaphragm is made of aluminium ·002 inches thick, and the outer edge has tangential corrugations which give it a large edge compliance. The moving-coil, which is attached

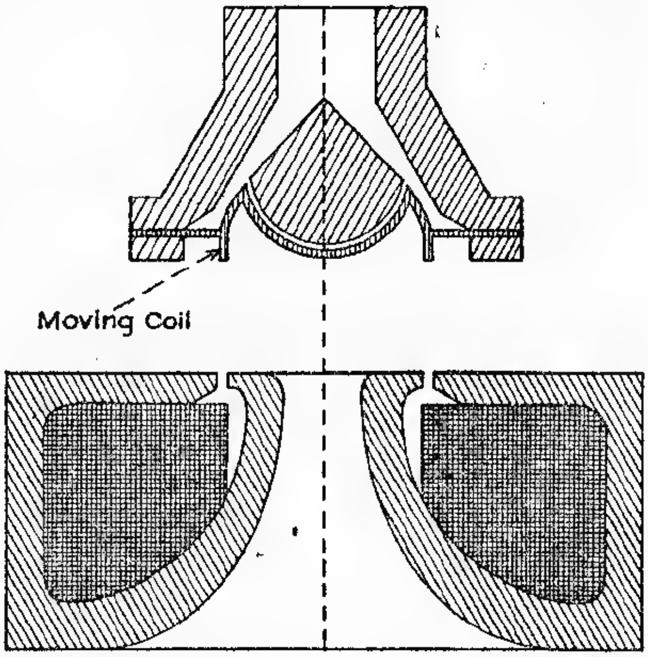


Fig. 82.—Moving-coil drive for horn speaker.

to the diaphragm near its outer edge, consists of a single layer of aluminium ribbon 0·015 inches wide and 0·002 inches thick, wound on edge, the turns being held together by a film of insulating lacquer. With this unit attached to an exponential horn of length 14 feet or more a sensibly uniform frequency response from 60 to 7,000 cycles has been obtained, and the mechanical efficiency of sound output to electrical input is relatively high.

IX—5. Large Diaphragms.

When the diaphragm has to work into free space, however, the conditions are very different. The mechanical impedance of the diaphragm is fairly large whilst that of the air in free space is very small. This is bound to mean inefficiency of transmission, and to obtain sufficient sound output we must use a large surface and, for low frequencies, a considerable amplitude of motion. The problems raised by the latter in connection with the driving mechanism have already been discussed. As regards the former, it should be noticed that a large area presents peculiar difficulties of its own. The mass of the diaphragm is substantial, thereby detracting from the mechanical efficiency, and at low frequencies this mass is further increased by the reaction of the air in front of the diaphragm. This reaction is in two parts, one proportional to the acceleration of the diaphragm, and therefore equivalent to an addition to its mass, and the other proportional to its velocity and therefore equivalent to a resistance. It is through this resistance, known as the radiation resistance, that useful work is done in creating sound.

The magnitudes of this added inertia and radiation resistance can be calculated from formulæ developed by Lord Rayleigh.* They vary both with the size of the diaphragm and with the frequency. For frequencies below about middle C the added inertia is equivalent to the mass of air which would be contained in a cylinder with a base of the area of the diaphragm and a height of $8/3\pi$ times the radius. At high frequencies (above about 2,000 cycles) it is negligible. The radiation resistance is practically constant for low frequencies, but falls off rapidly above 1,000 cycles. The power radiated as sound is equal to this radiation resistance multiplied by the square of the current in the coil and this, as remarked in the last section, has a resonant frequency owing to the inductance and motional capacity of the coil. The combined effect of these two quantities may be calculated, but the process is long and laborious. The general result, as a rule, is that both the very low and the very high frequencies are attenuated in the acoustic output.

So far piston motion has been assumed for the diaphragm. In actual practice, however, this cannot be achieved for all frequencies, even with the relatively stiff cone of 90° angle at the apex. Even if the edge were quite free a paper cone of this type with an edge diameter of 6 inches would exhibit a fairly large resonance between 3,000 and 4,000 cycles. With larger cones the resonant frequency would be lower. In an ordinary moving-coil speaker the existence of this resonance is of advantage owing to the reduction of radiation resistance at high

* "Theory of Sound," Vol. II, Art. 302.

frequencies. Normally, however, it is too pronounced and some additional means of stiffening the cone, such as radial corrugations or flutes, would no doubt be of advantage. There is, however, another method by which piston motion may be obtained even with a flexible diaphragm. This is to distribute the driving force over the area of the diaphragm. Examples of this method are to be found in the Hewlett induction-coil speaker and in the Siemens-Halske "Blatthaller" loud-speaker. In the former the diaphragm is a thin aluminium sheet loosely supported between two pancake-type coils wound with venting spaces. In the latter the diaphragm consists of a large plate on which is mounted a shaped band of copper edge on. This works into a series of annular gaps in an electromagnet.

Another interesting form of speaker (Plate XII) is that used in the H.M.V. electrical reproducer. Here the diaphragm is in the form of a flat sheet of duralumin 29½ inches in diameter and 0·002 inches thick, stretched almost to its elastic limit. It is driven by a moving coil mounted eccentrically. In this way modes of vibration which have nodal diameters are not suppressed. A typical response curve of this electrical reproducer is shown in Fig. 84.

With the H.M.V. type of speaker no special difficulty arises with regard to the edge mounting; clamping to maintain the tension is the only requirement. In the other cases, however, it is necessary at one and the same time both to prevent circulation between the two sides of the diaphragm and to have a very large diaphragm edge-compliance. If the compliance at the edge is too small it will combine with the mass of the diaphragm as a whole to give a resonance at the lower end of the musical range—usually just below 100 cycles. If the frequency of this resonance is lowered by increasing the edge compliance too much, however, difficulties are usually experienced in keeping the motion of the coil axial in the gap of the magnet pot. The coil jumps about, particularly at large amplitudes or for sudden increases of current, and there may be

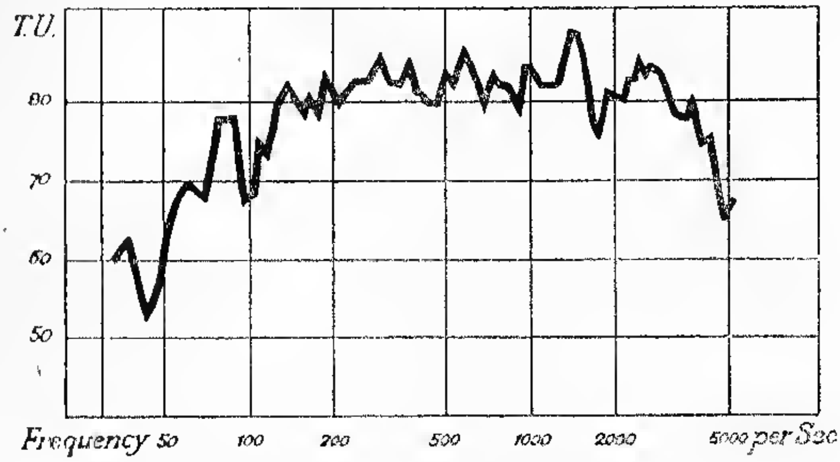


Fig. 84.—Typical response curve of H.M.V. electrical reproducer.

chattering of the coil in the pot. In some moving-coil speakers the coil is kept central in the gap by means of a " spider " attached to the central pole. This enables the gap to be reduced, thereby increasing the flux density across it, and the chattering due to wobble is not experienced. But the diaphragm edge-compliance is in effect increased and the low frequency resonance becomes rather marked.

In reed-driven diaphragm speakers, the limitation to the amplitude of motion severely reduces the power-handling capacity. Attempts are sometimes made to increase the power radiated and at the same time to give a more adequate bass response by using a cone diaphragm of 18 inches or even 24 inches diameter. But in these circumstances, whilst the bass is undoubtedly increased, the response is full of resonances in the middle range up to about 2,000 cycles and is very poor above that limit.

One other point should be mentioned before we bring this section to a close. It is sometimes claimed that with a reed-driven mechanism the reproduction of " transients " is bctter than when a moving-coil drive is used. This is said to be shown by the better " attack." The authors have certainly heard moving-coil speakers in which the attack is blurred and the general quality indistinct. But on the other hand they know of other moving-coil speakers in which the attack leaves little to be desircd. In theory there appears to be no reason whatever why a moving-coil speaker should not be effective in dealing with transients, and the excellent rcproduction of piano music which a good moving-coil speaker gives seems to the authors to be adequate testimony to its effectiveness in this particular respect. The truth is that this question of attack is much misunderstood ; the term is very loosely applied to quite a number of essentially different charaeteristics. Thus a speaker which has a decided resonance at about 2,000 cycles will appear to give a very brilliant tone, and by comparison another speaker which has no such resonance is said by some to be lacking in attack. Again, non-linear distortion with its introduction of overtones to every powerful note will seem to blur the attack.

IX—6. The Outlook.

In the preceding sections of this chapter emphasis has been laid, perhaps too strongly, upon the faults of existing designs of loud-speakers rather than upon their virtues. It would be idle to claim that perfection of response, or anything like it, has yet been achieved. Indeed, frequency measurements definitely show that so far as the general level of response is concerned even the best commercial

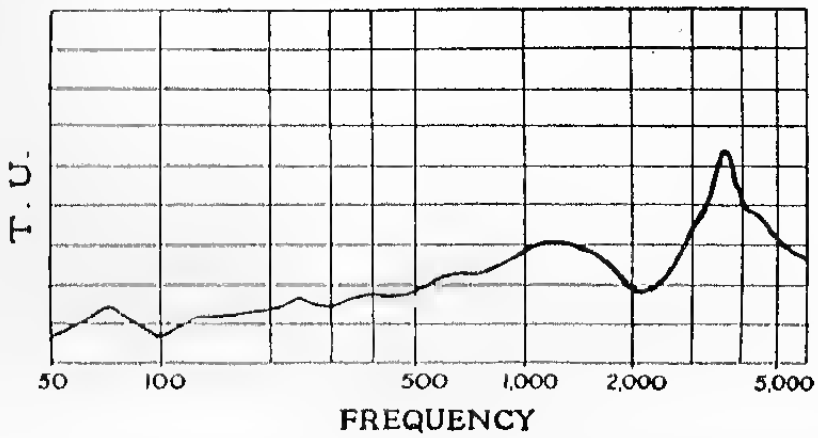


Fig. 85.—Response curve of moving-coil speaker.

loud-speakers are not so good as the best modern gramophones. Compare, for example, the curve in Fig. 26, page 50, with the curve (Fig. 85 above) of the frequency response of a typical moving-coil speaker. The general level of the gramophone curve is certainly more satisfactory than that of the loud-speaker curve. On the other hand the moving-coil curve is not so " peaky " and is decidedly better in bass response. If it were possible to reduce the diaphragm resonance at 3,500 cycles and at the same time to fill up the trough at 2,000 cycles the over-all response would become very good indeed. Possibly this might be achieved by decreasing the elements of mass of the diaphragm from the eentre or apex to the edge and increasing the eomplianee in such a way that the produet of the two were the same at all distances from the apex. There are some moving-coil speakers whose response eurves are decidedly better than that of the typical example given above, and to hear the reproduetion with one of these speakers, either of speeeh or of music, is one of the most impressive experienees that one ean have to-day. For it must not be forgotten that the ear is a very lenient instrument, and will tolerate quite a considerable amount of frequeney distortion before beeoming dissatisfied. One thing whieh it eannot tolerate is too mueh power in a reproduction in which low notes are missing. So long as low notes are present in suffieient strength it is really remarkable how mueh power the ear will stand without discomfort. These then, are the really great aehievements of modern designs: low notes and power. And they are aehievements in directions in whieh the obstaeles to advance have always been regarded as very formidable. Having regard to the nature of the problem, every well-informed person is bound to admit that a new era is dawning.

CHAPTER X

ELECTRIC AMPLIFIERS

X—1. Thermionic Valves.

The development of electric amplifiers, by which electrical oscillations may be magnified, dates from the invention of the thermionic valve by Professor J. A. Fleming, in 1904. In its original form the valve had no magnifying properties but, as its name implies, was simply a device which permitted currents to pass in one direction only. It consisted of a " kathode " in the form of a filament of fine wire heated by an electric current and an " anode " in the form of a plate of nickel. These two " electrodes " were disposed in a glass bulb from which the air had been exhausted. When the kathode was connected to the negative terminal and the anode to the positive terminal of a battery, a current flowed in the circuit ; when, however, the positive terminal was connected to the kathode and the negative terminal to the anode no current flowed.

This uni-directional property is due to the fact that, when heated, certain substances such as tungsten and thorium, and to a lesser extent carbon, emit negatively-charged particles or " electrons." If the anode is at a sufficient positive potential relative to the kathode, the electrons traverse the intervening space to the anode. There is thus a *negative* current inside the valve from kathode to anode.* Up to a certain limit determined by the ability of the kathode to emit electrons the higher the potential difference the greater the current that will flow.

It is usual to heat the kathode filament by passing a small electric current through it. That is why a "low-tension" battery is required in a "wireless set." The difference of potential between the kathode and anode is supplied by the "high-tension battery." But this is not the only method that can be employed. In some modern valves the kathode is in the form of a small cylinder inside which is a filament heated by an alternating current drawn from the electric-light mains, and the kathode is heated by radiation from this filament. In either case, however, it is usual now to arrange the anode so as to surround the kathode as completely as physical considerations will allow. In this way the electron emission from the kathode is almost entirely collected by the anode, or "plate," as it is sometimes called.

In 1908 Lee de Forest introdueed a third electrode into the valve between plate and filament. This electrode, which is known as the "grid," is in the form of a wire spiral or mesh, through the interstices in which the ncgative electrons from the kathode have to pass. If the grid is kept at a nega-

* In considering valves it is more convenient to speak in terms of *negative* currents than to adopt the usual practice and think in terms of *positive* currents. A negative current in one direction is the same, of course, as a positive current in the opposite direction.

tive potential relative to the kathode it will repel the electrons and thus reduce the current passing through the valve. As the potential of the grid is made less negative the repulsion is less, and a greater current is permitted to pass between kathode and anode. The potential of the grid thus controls the current passing in the " anode circuit " of the valve. If the grid potential is made positive relative to the kathode, however, some of the electrons will pass to it rather than to the anode and there will thus be a current in the " grid circuit " (e.g. from kathode to grid) of the valve. In all the applications of the valve with which we are concerned in this book, however, the existence of a grid current is detrimental to the proper working of the amplifier. It will therefore be assumed without further ado that the potential of the grid will always be adjusted so that no grid current can flow.

X—2. Valve Characteristics.

A three-electrode valve (or " triode ") of this kind may be used as an amplifier. The current flowing in the anode circuit depends partly on the positive potential (or voltage) applied to the anode and partly on the voltage of the grid. A small change of voltage of the grid will produce a greater change of anode current than a change of the same amount in the anode voltage. If we keep the anode voltage V constant then we can plot a curve showing for different values of the grid voltage v the magnitude of the anode current I. This curve is known as a " characteristic curve " of the valve. If now we alter the anode voltage V, and go through the same process again we should obtain a different characteristic curve. The series of curves obtained in this way for a typical modern valve is shown in Fig. 86. Now we might have proceeded in a different order by keeping v constant and plotting the values of I for different values of V. In this way we could have obtained a different series of curves, as illustrated in Fig. 87. Both sets of curves really give precisely the same information, namely, the value of the anode current

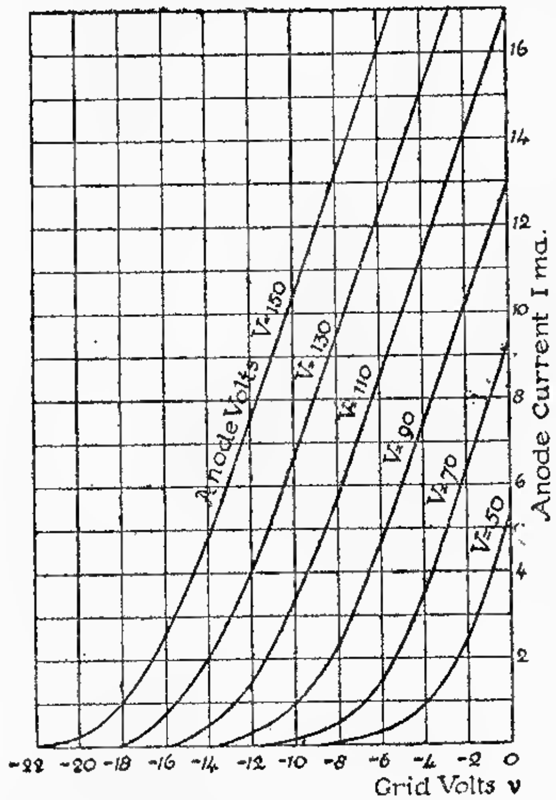


Fig. 86.—(I, v) Valve characteristic.

I for different values of V and v; but for some purposes it is more convenient to use the first set and for other purposes the second.

It will be observed that over a considerable distance the characteristic curves are practically straight lines and that over the straight-line portions the different curves in each series are parallel to each other, that is, the slopes are the same. Mathematically, this means that over the range of values denoted by these straight

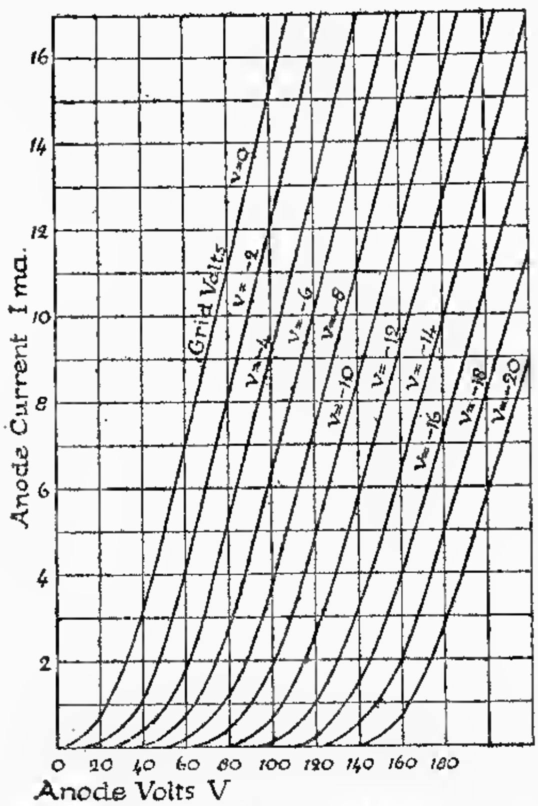


Fig. 87.—(I, V) Valve characteristic.

portions the relation between I, V and v can be expressed in the form

$$I = K_1 v + K_2 V$$

where K_1 and K_2 are constants, depending on the design of the valve, which measure the slopes of the two sets of characteristic curves. K_1 is called the *mutual conductance* of the valve and K_2 the *plate conductance.* The reciprocal of K_2 is often called the *impedance* or *A.C. resistance* of the valve. If V is kept constant a unit increase of voltage in v will increase the anode current I by K_1 units. Similarly if v is kept constant a unit increase in V will increase I by K_2 units. The ratio K_1/K_2 is, therefore, a measure of the voltage amplification of the valve. It is denoted by μ and is called the *voltage amplification constant*, or, more shortly, the *amplification factor* of the valve. Denoting the valve impedance by R we may, therefore, write our valve equation in the form

$$I = K_2 \left(\frac{K_1}{K_2} v + V\right)$$

$$= \frac{1}{R} (\mu v + V)$$

At first sight it might be thought that the value of μ is a measure of the goodness of the valve as an amplifier. If we could ignore the external circuit of the valve this would be the case. But the conditions in which the valve is to be used must clearly be taken into account. Owing to certain considerations, explained later, it is as a rule desirable to have a low value for R and, therefore, a high value for K_2. If μ is to be large, therefore, K_1 must be as large as possible. For this reason the magnitude of the mutual conductance ($=\frac{\mu}{R}$) of a valve is usually a truer measure of its goodness than the amplification factor.

It is important to remember that the linear valvc equation referred to above only represents the actual circumstances when the voltage changes are such that the valvc is being operated over a portion of the characteristic which is sensibly straight. As soon as voltage changes, either in the grid or the anode circuit, are such that the anode current is denoted by a point on the curved portion of the characteristic, the linear equation no longer represents the action of the valve. Save in one particular case, discussed later, wc are concerned in this book only with the straight portions of the characteristics. If other portions are used distortion will ensue.

X—3. Intervalve Couplings.

We have seen that a change in the voltage applied to the grid of a valve may produce a comparatively large change in the anode current. We want to use that changing anode current to apply an increased voltage variation to thc grid of a second valve. If we put a resistance R_A in the anode circuit of the first valve thcre will be a drop of voltage across the resistance equal to the resistancc in ohms multiplied by the current passing in amperes. As the anode current is varied by the changing grid voltage the voltage drop across this resistance will likewise vary. When a source of constant voltage is used to supply the positive potential through the anode resistance to the anode of the valve, the actual voltage at the anode will vary with the current being passed. Denoting the battery voltage by V_o we thus have

$$I = \frac{1}{R}(\mu v + V)$$

$$V = V_o - R_A I.$$

From these we find

$$I = \frac{1}{R + R_A}(\mu v + V_o)$$

Hence the change in voltage across R_A due to a change v' in the grid potential $= R_A \times$ change in I $= R_A \times \frac{1}{R + R_A} \times \mu v'$. So the actual voltage amplification $\mu_1 = \mu \frac{R_A}{R + R_A}$ which, of course, is less than the nominal amplification factor μ.

If we couple the anode of the first valve to the grid of the second valve the voltage variations in the anode circuit of the first valve control the emission of electrons in the second valve. But here we have to be careful. It is convenient to heat the filaments of both valves from the same battery and, therefore, to have the filaments at the same potential. The anode of the first valve is at a high positive potential relative to the filament, and we do not want to give the grid of the second valve a positive potential since in that case grid current would flow. Hence we must insert a device between the first anode A_1 and the second grid G_2 which will allow us to communicate *changes* of potential from A_1 to G_2, but will cut off the high positive potential. Now a condenser will pass alternating currents whilst blocking direct currents or voltages. Hence we insert a condenser C and resistance R_G in series from A_1 to the common filament terminal and connect G_2 to the junction between them as indicated in Fig. 88. B_1 is the battery which simply heats the filaments. B_2 is the battery which provides the difference of potential between anode and kathode, and thereby causes the current to pass from kathode to anode through the valve. No steady current can pass through C, but the varying part of the current (created by the varying potential on G_1) can proceed via C and R_G to the filament again. Due to this current there is a varying potential difference between the two ends of the resistance R_G, and this potential difference is applied to G_2 and controls the operation of the second valve. It will be noticed that a small battery is shown between one end of R_G and the filament lead. The object of this is to make the potential of G_2 always negative relative to its filament, thereby preventing grid current. If this battery were omitted the changes of potential passed on from A_1 would make G_2 alternately positive and negative ; with the battery they only increase or decrease the negative potential applied by the " grid bias battery," as it is called. In other words, the negative grid bias allows the valve to be operated along the straight

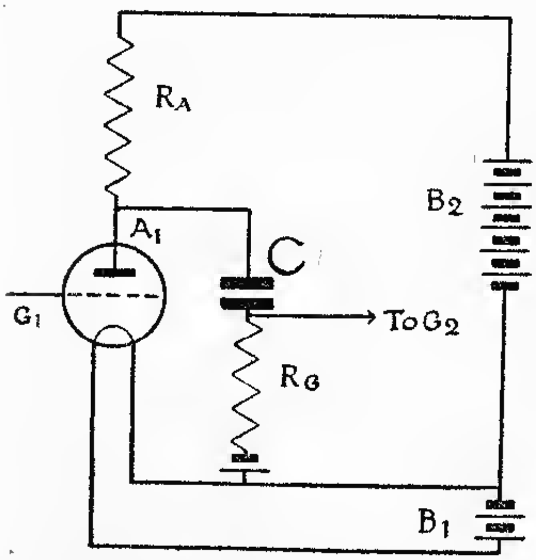


Fig. 88.—Resistance-capacity coupling.

portion of its characteristic curve as shown in Fig. 86 on page 196. It should be observed that if no grid current is flowing in the second valve no current is aetually taken from the grid bias battery : there is no completed circuit round which it could flow ; in one direction it is blocked by the condenser C and in the other by the second valve.

The method of coupling just described is known as " resistance-capacity coupling." In place of the resistances R_A and R_G, however, we might have used iron-cored " low-frequency chokes." These have a comparatively low resistance to direct currents with a high impedance to the varying currents in the anode circuit. When a choke is used in place of the anode resistance, therefore, practically the full voltage of the high-tension battery is applied to the anode. In the first stage of an amplifier, however, a comparatively low anode voltage is no disability, and since for the last stage a high voltage is needed, the use of a choke in place of a resistance to save reducing the voltage on the first valve is of no real advantage.

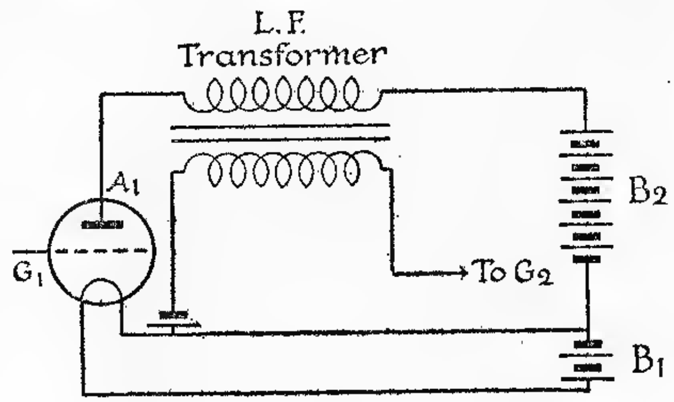


Fig. 89.—Transformer coupling.

There is another method of intervalve coupling which has definite advantages : transformer coupling. This is shown in Fig. 89. If the primary of a low-frequency transformer is connected between the H.T. battery and the anode any changes in current through it will induce an alternating voltage in the secondary. By having a larger number of turns in the secondary winding than in the primary winding the voltage across the secondary may be made greater than that across the primary. Whereas a resistance- or choke-capacity coupling decreases the nominal valve magnification transformer coupling increases it. There is, however, a limit to the step-up which may be obtained in this way. This limit is attained in commercial transformers when the number of turns on the secondary is about three or four times that on the primary, so that the

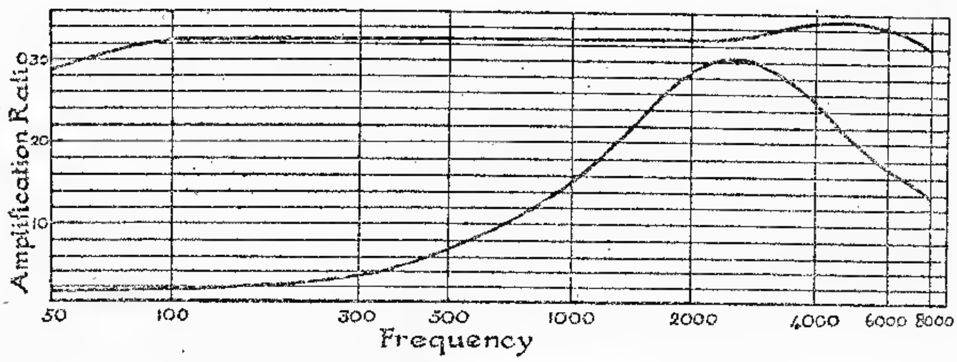


Fig. 90.—Response curves of transformers.

voltage amplification ratio is 3 or 4. If the ratio is increased above this limit, either the primary inductance must be redueed, in which case low frequencies suffer and, in addition, non-linear distortion becomes pronounced; or the number of turns on the secondary must be increased, in which case the self-capacity between the turns and the magnetic leakage begin to reach a point where frequencies of the order of 5,000 cycles are by-passed. Early types of intervalve transformers gave rise both to frequency distortion and to non-linear distortion. Fig. 90 shows the amplification ratio for different frequencies of an old transformer of a poor type, and a modern transformer of good design, the latter, of course, being the upper curve. Figs. 91 and 92 are oscillograph photographs which show the input wave-form and the output wave-form of these two transformers. It will be noticed that the poor transformer not only over-emphasizes the middle frequencies but also distorts the wave-form by introducing harmonics. The modern transformer, on the other hand, when used in suitable conditions, gives a practically uniform frequency response from 50 cycles to 5,000 cycles and the output wave shows no obvious sign of non-linear distortion.

Fig. 91.—Oscillograph of transformer output.

X—4. The Output Stage.

In the last section we have indicated briefly the manner in which intervalve couplings are arranged so that the voltage applied to the grid of the first valve is instrumental in causing greater voltages to be applied to the grids of succeeding valves. We have yet to consider the principles of design in order that voltages of all frequencies within the range 50 to 5,000 cycles, with which we are here concerned, may be amplified in the same ratio. Before we consider this question, however, we should draw the reader's attention to certain important general considerations regarding the characteristics required of each valve. Suppose the voltage applied to the grid of the first

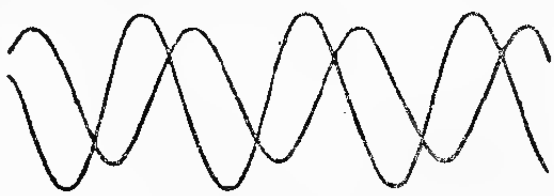


Fig. 92.—Oscillograph of transformer output.

valve is of sine-wave form (Fig. 1, page 4) and that its amplitude or peak value is v volts. Then the " grid swing " on this first valve must be from v volts positive to v volts negative, a total of 2v volts. The grid bias applied to this valve must, therefore, be such that during this swing of 2v volts we are operating the valve along the straight portion of its (I, v) characteristic; we must neither run into grid current at the upper end of the characteristic by making the grid positive nor must we run into the curved portion (" the bottom bend ") of the characteristic during the negative part of the applied voltage wave. In the first valve of the amplifier the total voltage fluctuation 2v is usually very small —not more than 1 or 2 volts at the most—and the straight portion of the (I, v) characteristic of most valves is larger than our maximum requirements. The voltage fluctuation on the grid of the next valve, however, will be $\mu' \times 2v$, where μ' is the over-all voltage amplification factor of the first valve and of the intervalve coupling which succeeds it. A much greater grid swing is therefore required on the second valve. We can deal with the situation either by using for the second stage a valve which permits a large grid swing or by reducing the voltage amplification of the first stage. If we use a transformer to follow the second valve it must be capable of taking a large current in its primary since the valves which have a large grid swing also have a large anode current. On the other hand, if we use resistance coupling the drop of voltage through the anode resistance when a large anode current is passing is substantial, so that in order to obtain the required grid swing we must use a fairly high external battery voltage. The other alternative is to regulate the voltage applied to the second grid. Since in some circumstances the voltage applied to the first grid may be much smaller than in others, it is wise in any case to control the voltage on the second grid by means of a "volume control" incorporated in the coupling between the first and second valves. This should be such that the voltages for all frequencies are reduced in the same ratio. The possible methods are discussed later.

When we come to the third valve the necessity of having a large grid swing is greater still. We now have a voltage fluctuation of $\mu' \times \mu'' \times 2v$, where μ'' is the net amplification factor of the second valve and its succeeding coupling. We can, as it were, shirk the difficulty in the first stage, as already explained, but we cannot shirk it here if we are ever going to obtain sufficient power to feed our loud-speaker. We have already had two stages of amplification, and for a number of reasons connected with the practical construction and operation of an amplifier it is not advisable to have more than three stages unless special screening is adopted and very high external voltages are available. Nor is it really necessary, since for all ordinary purposes we can get all the amplification we require from these three stages.

In the last stage our requirements are different from those in the preceding stages. Up to the last stage we want to magnify *voltages* uniformly. In the last stage we want to use the voltage applied to the grid to give a large alternating *power* output to operate the loud-speaker. Now the current in the anode circuit will consist of a large direct current (which is of no use to us), and superposed on it an alternating current due to the grid control. We want a device for sorting out the alternating current from the direct current. As before, we can either use a condenser or a transformer. In the former case, the usual arrangement is as shown in Fig. 93. A choke of large current-carrying capacity is used in place of a resistance in the anode circuit and a condenser of 2 or 4 microfarads capacity is used as the blocking condenser. For this stage a special type of valve with a long straight characteristic is essential.

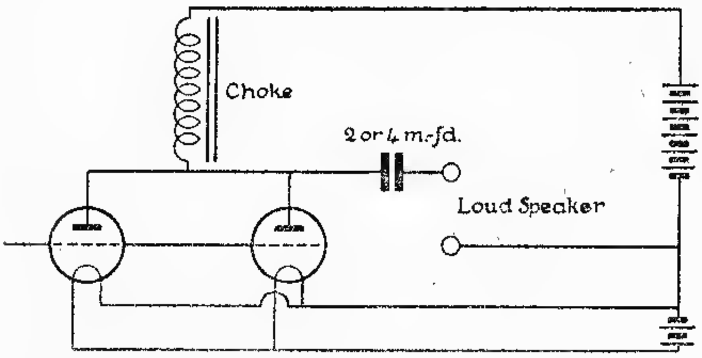


Fig. 93.—Choke-condenser output coupling.

If an output transformer is used, the arrangement might be as shown in Fig. 94. This, however, would have the disadvantage of requiring a large current through the primary of the transformer and either a very large transformer would be required or the low notes would suffer owing to magnetic saturation of the iron core. A better arrangement is that which is known as "push-pull." The connections in this are as shown in Fig. 95.

Here a transformer T_1, whose secondary is centre-tapped, is used before the last stage. This splits the voltage in the secondary into two halves; one half is applied to the grid of one of the output valves and the other half to the grid of the other output valve. Each valve has therefore to take only a half of the total grid swing. The anode currents from the two valves are combined in a transformer T_2 whose primary is centre tapped. The currents flow

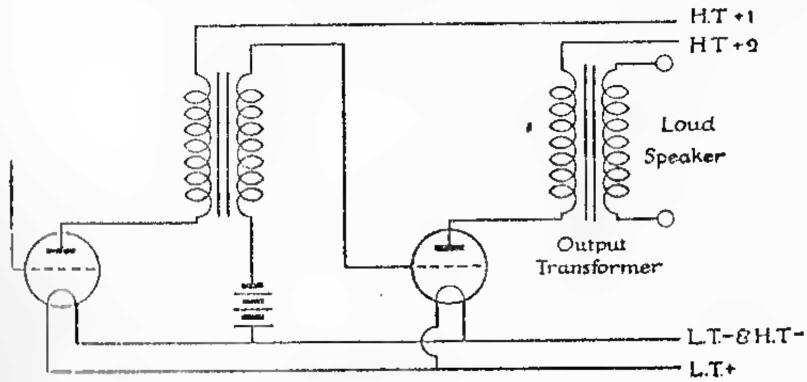


Fig. 94.—**Transformer output coupling.**

in the two halves of T_2 in opposite directions, with the result that there is no steady current through the primary of the transformer as a whole and therefore no danger of saturating the iron core. This system has other important advantages. Thus, if we follow out the directions of the currents in the two halves of T_1 and in the two output valves we find that whilst one output valve is being

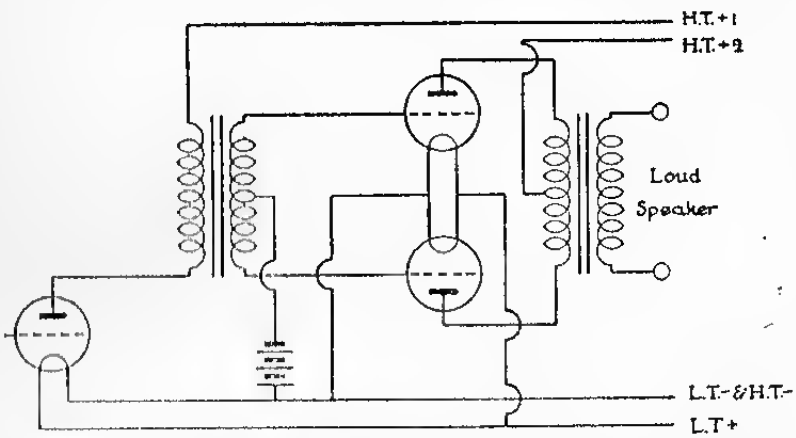


Fig. 95.—**Push-pull transformer output coupling.**

operated on the upper part of its characteristic the other is being operated on the lower part; when the voltage on the grid of the one is above the mean that on the grid of the other is below the mean. Hence, if the characteristics of the two valves are identical, slight curvatures in them tend to cancel out, and the net result is the same as if the characteristics were straight.

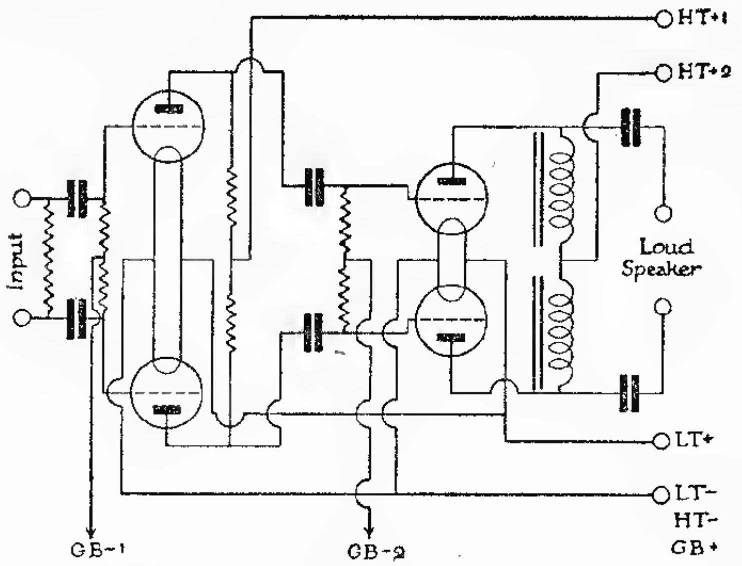


Fig. 96.—Push-pull resistance coupling with output chokes.

Other methods of operating valves in push-pull have been devised, using resistances instead of intervalve transformers and chokes instead of output transformers. One such arrangement is shown in Fig. 96.

X—5. Special Conditions for Reception of Broadcasting.

So far we have been solely coneerned with the amplification of electrical oscillations, of frequencies ranging from 50 to 5,000 cycles, in the form of voltages applied between grid and filament of the first valve of the amplifier. This is all that we are concerned with in the electrical reproduction of gramophone records, the voltages being those induced in the eleetrical pick-up. For reception of broadcasting, however, something more than this is required. Clearly, if every broadcasting station simply sent out waves of these frequencies —" audio frequencies," as they are called—it would be impossible to distinguish one station from another.

The wave sent out by a broadcasting station is a continuous wave of high frequency—somewhere between 500,000 and 15,000,000 cycles per second. This wave is the "carrier wave," and on it the audio-frequency waves are superposed, the process being termed "modulation." Suppose a carrier wave of frequency f is being modulated by an audio frequency f′. Then the composite wave sent out is of the form shown in Fig. 97, and is the resultant of three waves: one of frequency f, one of frequency (f—f′) and one of frequency (f+f′). These last two are known as the "side-bands."

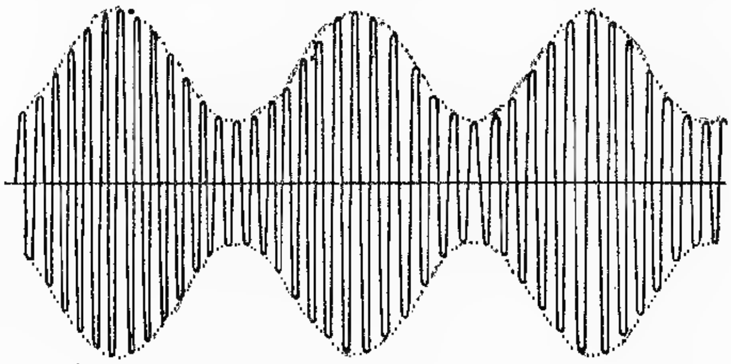


Fig. 97.—Modulated carrier wave.

When a receiving aerial is tuned by means of a coil and condenser of variable capacity so as to have a resonant frequency at f, the frequency of the carrier wave, a current will be induced in it by the transmitted broadcast wave. This current will be a composite current composed of the three frequencies f, f—f′ and f+f′. But since the resonant circuit is tuned to f the current at frequencies less than or greater than f will be attenuated; the more removed the frequeney from f the greater the attenuation will be. Since for high notes the side-band frequencies are further removed from the carrier frequency than for low notes, it follows that there will be a relative loss in high notes, and if the resonant circuit is sharply tuned this loss may be considerable. As in the case of the mechanical resonances in a gramophone, discussed in previous chapters, this loss may be mitigated by adding damping to the resonant circuit. In this case the response of the resonant circuit to various frequencies on either side of the carrier frequency would be as shown in curve B of Fig. 98 instead of as in curve A. If we were concerned with only one broadcasting station, this might be a satisfactory solution of the difficulty. But there are so many broadcasting stations in Europe that it has only been found possible to keep their carrier-wave frequencies 9 kilocycles (9,000 cycles) apart. The range on each side of the carrier frequency for any station is thus only 4,500 cycles and a heavily damped circuit would be affected not only by the particular station to which it is tuned but by adjoining stations as well. For perfect reception we want a tuning curve such as C in the figure. This cannot actually be attained, but a good approximation to it can be got by having two or more tuned circuits, tuning the first to a frequeney slightly below f, the second to a frequency slightly above f and the third, if there is one, to f. This process requires very delicate tuning, but fortunately it is possible to devise a means by which one can see with very little trouble whether it has been correctly done. This consists in getting correct readings on a milliammeter placed in the anode circuit of the detector valve and will be described whcn we come to that part of our discussion.

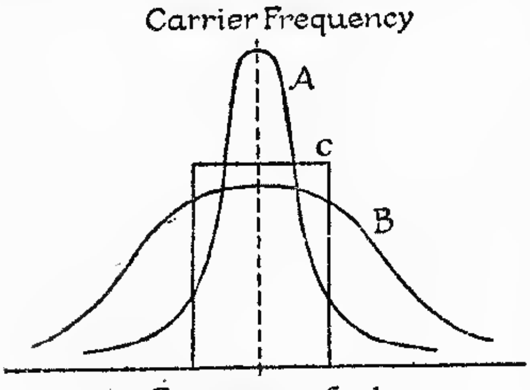


Fig. 98.—Tuning curves.

Assuming for the moment that our tuned circuit has received a current of the required wave-form, we have now two courses open to us. We can either demodulate, so as to sort out the audio frequency from the carrier wave, or we can amplify the signal first and demodulate afterwards. For various reasons, which we have no space here to discuss, it is desirable to include at least one stage of amplification before demodulation.

Later we give some designs which include stages of high-frequency amplification, as it is called, but it would be beyond our scope to enter into any detailed discussion of the problems involved. For that the reader should consult works dealing specially with reception of broadcasting. In some respects the problem of H.F. amplification is more difficult and requires greater care than the corresponding L.F. problem, since for high frequencies quite small stray capacities, whether in wiring, components or even in the valve itself, may be far from negligible. The introduction of a special four-electrode valve with an extra grid between the control grid and the anode has simplified the problem to some extent. By keeping this grid at a suitable positive potential the internal capacity of the valve has been made quite small, and provided the external wiring is carefully arranged and the various components are suitably screened, the high-frequency signals can be amplified to quite a considerable extent, without delicate adjustments to avoid oscillation.

For demodulation, or "rectification," as it is sometimes rather inaptly termed, a number of methods are available. These are fully described in standard works. The only one we propose to concern ourselves with is that known as "anode-bend rectification." This depends for its action on the fact that the bottom bend of the (I, v) characteristic of a valve is curved. If, therefore, we adjust the grid bias on the valve, so that the operating point is on this bend, the voltage swing on the grid will affect the anode current unsymmetrically. Thus, suppose we use a valve whose characteristic is as given in Fig. 99, and choose an operating point at O. When the radio signal is received the voltage on the grid rises and falls above and below the mean voltage in the manner indicated by the waves from E to F. When the carrier wave is modulated the voltage on the grid varies as in the waves at F G H. When we plot the changes in anode current we get the curve in the diagram on the right. If now we smooth out the very rapid pulses in the anode current we obtain a mean current as indicated by the line X Y Z. This is achieved by inserting a very small condenser of value about 0·0001 microfarads between anode and kathode of the valve. This by-passes the rapid pulses of the carrier wave and leaves the slower audio frequencies

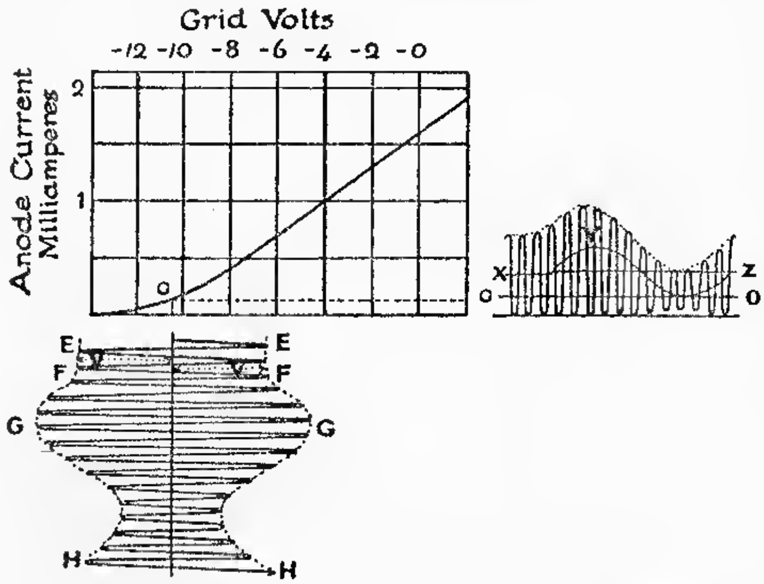


Fig. 99.—Demodulation with anode-bend rectifier.

to proceed by another path. If we put a milliammeter in the plate circuit of the valve it will give a reading corresponding to the point O when no signal is applied to the grid of the valve. As soon as the carrier wave is received, however, the reading will go up to the level represented by the line X Z. The first reading is therefore a check on the grid bias; grid bias should be adjusted so as to give a reading of about 0·1 to 0·2 milliamps. The second reading is an indication of the strength of the signal being applied to the grid; this should be adjusted so that there is never any danger of the grid being made positive relatively to the kathode: with most valves used as anode bend detectors, a reading of more than about 0·6 milliamps is inadvisable, and the strength of the signal on the grid should be adjusted by means of a volume control in the H.F. stage so that the reading does not exceed this value. This reading on the milliammeter may also be used to find the resonant points on the tuning condensers in the H.F. stage. Thus, suppose we have two tuned circuits with variable condensers C_1 and C_2. When C_1 and C_2 are brought near their resonance points the reading on the milliammeter goes up. At the resonant points the reading is a maximum provided that the volume control is set to such a low position that the reading never exceeds 0·6 milliamps. These points on the condenser dials can then be noted down for future reference; they should be checked from time to time in case some slight alteration has taken place in the aerial capacity. It will then be found that the best quality is attained when C_1 is detuned very slightly on one side of its resonant point, whilst C_2 is detuned an equal amount on the other side of its resonant point.

It should be noticed that if the signal applied to the grid is too weak, the valve will be operated wholly on the curved portion of its characteristic, even during the positive half of the carrier wave. In that case, the demodulation will be accompanied by non-linear distortion, and at the same time the amplification in the detector valve will be reduced below what it should be.

After the detector stage the audio frequencies may be amplified by a low-frequency amplifier in the manner already indicated. Where a set is to be used both for electrical reproduction of gramophone records and for radio, it is possible by means of a change-over switch to convert the radio detector valve into a low-frequency amplifier. This scheme is incorporated in the designs given later.

X—6. Low-Frequency Amplifier Design.

The secret in designing a low-frequency amplifier so as to give sensibly uniform amplification from 50 cycles to 5,000 cycles lies partly in the choice of suitable valves for each stage, partly in the choice of components for the intervalve couplings, and partly in the care which is taken to allow for the "stray" capacities in the wiring, the components and the valves. Since the part played by these stray capacities to some extent limits the choice of valve it is convenient to consider their bearing on the matter first of all. Suppose we take the resistance-capacity coupling illustrated in Fig. 100.

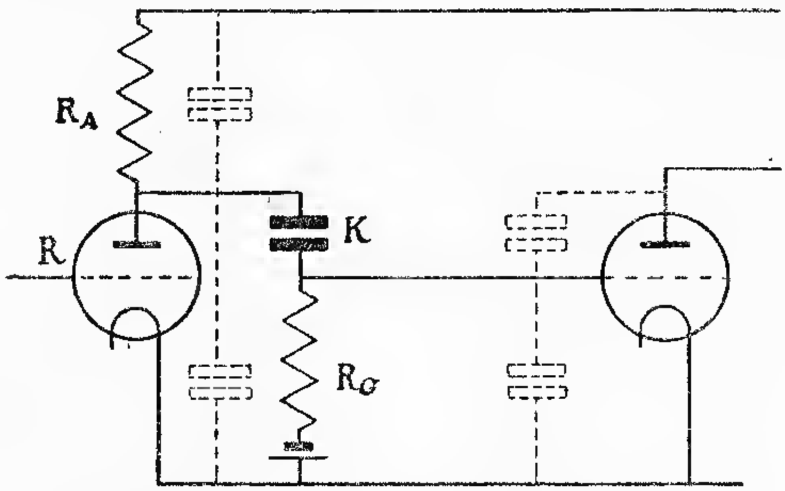


Fig. 100.—Resistance-capacity coupling, showing stray capacities.

There are four stray capacities as shown dotted; they may be in the valves, the valve-holders, the wiring or the components. A. L. M. Sowerby has discussed their effects in a noteworthy series of articles in the *Wireless World* (February-March, 1928). He shows that in effect these capacities may be lumped together into a larger capacity between anode and filament so that the impedances

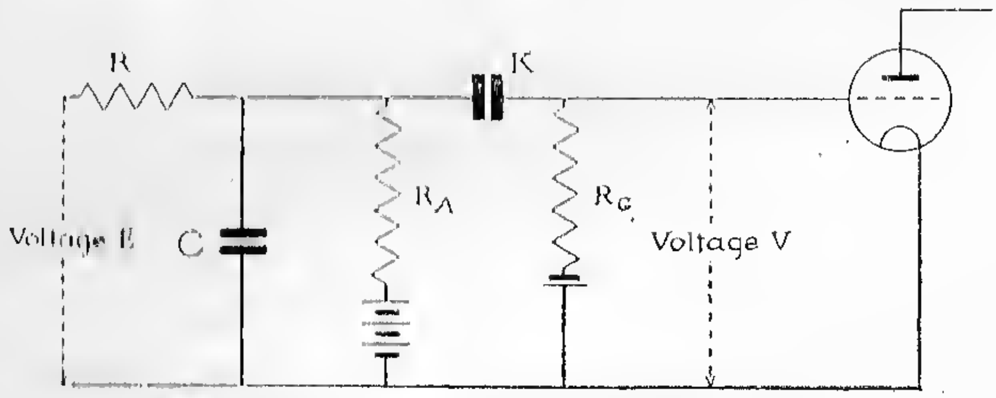


Fig. 101.—Equivalent circuit, as in Fig. 100.

in the output circuit of the first valve are equivalent to the network in Fig. 101.

For this network it can be shown that, if R_G is great compared with R_A:

(1) For high notes (where the effects of K and R_G can be ignored).

$$\frac{V}{E} = \frac{R_A}{R + R_A} \frac{1}{\sqrt{1 + k^2}} \text{ where } k = \frac{\omega C R R_A}{R + R_A}$$

(2) For middle notes (where the effects of C and K can be ignored).

$$\frac{V}{E} = \frac{R_A}{R + R_A} \text{ (c.f. the formula on page 199).}$$

(3) For low notes (where C can be ignored).

$$\frac{V}{E} = \frac{R_A}{R + R_A} \frac{p}{\sqrt{1 + p^2}} \text{ where } p = \omega K R_G$$

Thus, taking the middle-note ratio as unity, we find that there may be a reduction of high notes in the ratio of $\frac{1}{\sqrt{1 + k^2}}$ and a reduction of low notes in the ratio $\frac{p}{\sqrt{1 + p^2}}$. From these formulæ we find that if we take as a standard of good performance that the reduction is not to be more than 5% at extreme frequencies of 32 and 8,000 cycles then

$K R_G > \cdot015$ where K is in microfarads and R_G is in megohms.

and $\frac{R + R_A}{C R R_A} > 0\cdot15$ where C is in micro-microfarads and R and R_A are in megohms.

As in Sowerby's analysis the value of C may be taken approximately to be $25 + 7 \mu_o$ where μ_o is the amplification factor of the succeeding valve. R is the *working impedance* of the valve and not its rated impedance given by the makers. The latter is usually measured with no load in the plate circuit and zero grid bias; in working conditions the impedance is increased owing to the reduction in the voltage which actually reaches the anode. In any particular case it can be worked out, with sufficient accuracy for our present purpose, from the (I, V) characteristic for the particular grid bias used by measuring the slope at the voltage which actually reaches the anode. This has first of all to be estimated by allowing for the drop in voltage (R_A I) in the anode resistance. Then the increase of current I′ for a small increase of voltage V′ is found and R = V′/I′.

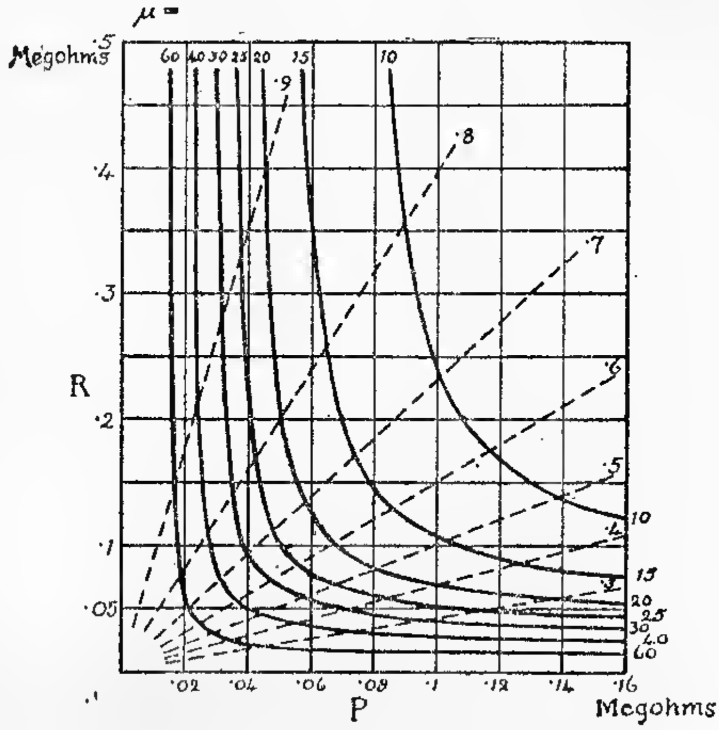


Fig. 102.—Anode resistance curves.

Curves showing :—

(a). (thick lines). The maximum permissible values of anode resistances for negligible high-note loss.

R. = Value of anode resistance.

P. = Working inpedance of preceding value.

μ. = Nominal voltage amplification factor of succeeding value.

(b). (broken lines). Fraction of nominal amplification factor of preceding value, which will be obtained.

Having found this with an assumed value of R_A we then determine from the formula

$$\frac{R + R_A}{C\,R\,R_A} > 0{\cdot}15$$

what is the *maximum* value of R_A which may be used. This can be read off at once from the curves* given in Fig. 102. If the assumed value of R_A is

* For these curves and for the formulæ on which they are based the authors are indebted to Mr. F. G. G. Davy.

less than this, all will be well, so far as the uniformity of amplification is concerned, though perhaps onc might do better in the actual magnitude of the amplification. To get the best possible values, having regard to both considerations, a series of approximations will be necessary.

A consideration of the formula for high-note loss shows at once that if we are to preserve quality with resistance coupling we must not expect a very high magnification per stage. A valve with a high magnification factor usually has a high impedance, so that low anode resistances must be used, thereby reducing the net amplification of the stage. It is best never to use more than one such valve (and that in the detector stage) unless the mutual conductance is of the order of 2 micro-mhos.

The condition for good quality at low frequencies is easily satisfied. Thus a coupling condenser K of ·05 microfarads and a " grid leak " R_G of 500,000 ohms gives an ample margin and works well. So would a coupling condenser of ·01 mfd. and a grid leak of 2 megohms. But there are other reasons connected with reproduction of transients which make a small value of condenser and a large value of grid leak less satisfactory. The grid leak should have a value not less than 5 nor more than 10 times the anode resistance.

When transformer coupling is to be used the amplifier designer is almost completely in the hands of the transformer manufacturers. Care should therefore be taken to ensure that the type of transformer used is one whose frequency characteristic with a specified type of valve in the following stage is guaranteed, preferably by a eertifieate from the National Physical Laboratory. The valve preceding the transformer should not have a working impedanee greater than about 20,000 ohms and yet the eurrent passed by it should not be so great as to saturate the iron-core. Most transformers, even of the better kind, will not take more than about 3 milliamps; but there are a few that can safely stand more. In the upper curve of Fig. 90 on page 202 the frequency response of a transformer of this type is shown. It will be observed that the high frequeneies of the order of 5,000 are slightly exaggerated. In view of what was said when we discussed resistance-capaeity eoupling about the by-passing of high frequencies by stray capaeities in wiring, etc., it will be readily appreciated that this slightly rising charaeteristic may be (and usually is) a decided advantage.

The eonsiderations whieh apply to the last stage of the amplifier are different from those applying to the earlier stages. Here we want maximum undistorted power output into the loud-speaker. If the effeetive eleetrical impedance of the speaker and associated output circuit were constant for all frequencies, it is easy to show that for maximum power output the valve impedance should be equal to this eonstant output impedance. For maximum *undistorted* output, however, the valve impedance should be half the constant output impedanee.* This arrangement would permit the greatest possible grid swing without running into grid eurrent on the one hand or into the bottom bend on the other.

* Browne: "Proc. London Phys. Soc.," Vol. XXXVI, 1924.

No loud-speaker yet invented has this ideal constant-impedance characteristic. Notwithstanding this the rule is still a valuable guide. Thus if we find that when paralleled output valves are used a moving-coil speaker with a certain number of turns on the coil gives the best results, we can conclude that with a push-pull output stage a 2 : 1 step down transformer is required. The impedance of two valves in parallel is half the single valve impedance ; in push-pull, however, the valves are effectivcly in series and the impedanee is doubled. To correct for this we use a transformer of 2 : 1 turns ratio, which gives a 4 (i.e. 2^2) : 1 impedance ratio. Similarly, if we have facilities for actually measuring the working impedance of the speaker at various frequencies we can choose our output transformer or our choke coupling to make the output impedance twice the valve impedance at a low frequency where the grid swing is greatest. In other cases the easiest plan is to experiment with output transformers of different ratios.

The importance of operating the amplifier only within the straight portions of the valve characteristics has already been mentioned. If the valves are suitably chosen there is normally no danger of overloading the valves before the last stage. In the last stage, however, the danger is very real ; in fact, it can safely be asserted that 99 per cent of radio sets are habitually overloaded in the last stage. In order to guard against overloading it is desirable to insert a milliammeter in the H.T.+ lead of the last stage at the point nearest to the H.T. supply. The arrangement is shown in the diagrams given in the appendix. When the output valve is being operated within its linear range the milliammeter needle remains steady ; if too little grid bias is being used the grid voltage will swing over the upper bend of the characteristic sooner than round the lower bend. In this case the anode current during the positive swing will not be proportionately increased, with the result that the net reading of the milliammeter will be reduced momentarily and the pointer will kick down the scale. On the other hand, if too much grid bias is used the current during the negative half of the swing will be reduced, and the average current shown by the milliammeter will be momentarily increased and the pointer will kick up. When the grid bias is correct and too strong a signal is being fed to the grid the needle will oscillate about a mean position. When the bias is adjusted to this position the amplifier is capable of giving its maximum output. The volume should henceforth be controlled so that the milliammeter needle remains steady even on loud passages.

X—7. Volume Controls.

There are many possible ways in which a volume control may be incorporated in an amplifier. Most of them, however, introduce distortion in one form or another. One of the worst methods is to shunt a variable resistance across the loud-speaker terminals. Another unsatisfactory method is to shunt a variable resistance or potentiometer across the secondary of a modern transformer ; with the poor transformers of yesterday the response could be improved in this way, but with a good transformer it cannot help but be worsened. In an L.F. amplifier two methods can be recommended with confidence. If there is a resistance capacity stage the grid leak can be a potentiometer of 500,000 ohms rcsistanee, the slider of the potentiometer being connected to the grid of the succeeding valve. If an L.F. transformer is used a variable resistance of 50,000 or 100,000 ohms maximum, with good current-carrying capacity (say, 5 milliamps), may be shunted across thc *primary*. This cannot but do good to the rcsponse. For connecting the gramophone pick-up between grid and kathode of the first valve a potentiometer of 500,000 ohms maximum may be used connected as shown in the diagram later. For the rcasons explained earlier, a volume control in thc H.F. stage is also desirable. If the kathode filament is heated by direct current from batteries a rhcostat of 15 ohms maximum in the negative filament lead serves admirably. Alternatively a potentiometcr of 250,000 ohms maximum may be connected between the grid cnd of the tuning-coil and carth and the slider taken to the grid of the valve. Detuning should only be used for the purpose already explained and never as a volume control.

X—8. Mains Units or Battery Eliminators.

In the early days of broadcasting, the valves and designs used made fairly heavy demands for low-tension currcnt and very low dcmands on the high-tension battery. As the design of valves developed, however, the position changed ; very much less L.T. current was required and rather larger H.T. current.

More recently, with the development of powerful amplifiers and loud-speakers which will reproduce deep bass notes, another change has taken place. For the early stages of an amplifier it is still possible to use valves with a low consumption of both L.T. and H.T., but for the last stage, voltages and eurrents are now used which would have been undreamt of a few years ago. This change has led to the development of methods of taking the current supply from the lighting mains. The initial cost of a good mains unit is fairly substantial, but the upkeep costs, even with the heavy currents taken, are much less than those of accumulators and batteries, whilst the convenience of operation is an inestimable boon.

At present the electric supply available is sometimes direct current and sometimes alternating current. For electric amplifier work, as for most other things, there is no doubt that an alternating current supply is the more convenient. The facility with which the voltage can be stepped up or down by means of a transformer makes it particularly suitable for both H.T. and L.T. supply. Moreover, alternating current supply is usually reasonably consistent. D.C. supply is often far from regular and in some cases it is virtually impossible to smooth out the irregularities. In any case the voltage available, without the assistance of a motor generator, is limited, and if a motor generator is to be used it is preferable to have one to convert from D.C. into A.C. at a standard voltage, so that high voltages need not be conveyed in wires about the house, but can be confined to the immediate vicinity of the transformer in the amplifier cabinet.

For these reasons, as well as for the reason that before long all D.C. supplies are to be converted to A.C., we propose to confine ourselves here to mains units for converting A.C. lighting current to our service. For low-tension current the simplest (and in the authors' view the best) plan is to use valves which can be heated by alternating current. The use of A.C. on ordinary battery-type valves usually introduces a hum of the frequency of the A.C. mains. The principal exceptions are the so-called super-power valves for the output stage, which take a filament current of 0·25 amps or more. These valves have thick filaments which can be used with A.C. without trouble. For the other stages special valves are now available. Some are indirectly heated by radiation from the filament to the kathode, as previously explained, whilst others, which take a low filament voltage and a fairly high current, are directly heated, the filament acting as kathode. It should be remarked, however, that difficulty may be experienced in avoiding hum if a directly heated valve is used as an anode-bend detector. For that position, at any rate, an indirectly heated valve is preferable. In either case, the mains voltage is stepped down to that required by means of a transformer and the negative H.T. and positive grid bias connection is taken either to a centre tapping on the secondary (low voltage) side of the transformer, or to the slider of a 400-ohm potentiometer, the two ends of which are connected to the end terminals of the secondary.

For H.T. supply the mains voltage is first of all stepped up to that required for the last stage of the amplifier, a margin of 25 per cent being allowed for subsequent losses. The current at this high voltage has then to be "rectified" and "smoothed." The process of rectification is best illustrated by the following oscillograph photographs. In Fig. 103 we have a picture of an alternating current of sine-wave form, the current increasing from zero up to a maximum positive, falling to zero again, then changing direction and increasing to a maximum negative and then coming back to zero again, the whole cycle of operations being repeated at the frequency of the electric supply (usually 50 cycles per second). If the supply is connected to the kathode and anode of a two-electrode valve, current will pass in one direction only, and will therefore be of the form shown in Fig. 104. In this case half the current is wasted. Two simple two-electrode valves, however, may be so arranged as to collect both halves of the wave, and in that case the resulting current will have the form shown in Fig. 105. But in this case the resulting voltage is only half that developed by the transformer, so that if this method of "full-wave" valve rectification is employed the transformer should give a voltage $2\frac{1}{2}$ times that ultimately

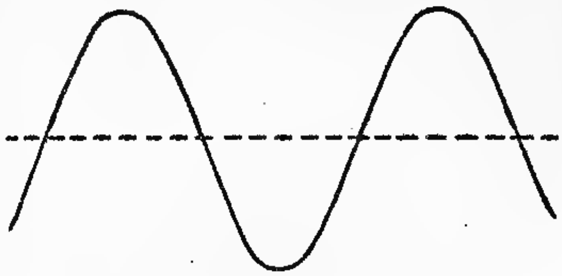


Fig. 103.—Oscillograph of A.C. current.

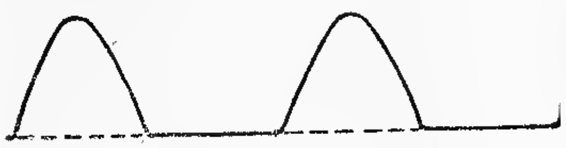


Fig. 104.—Oscillograph of half-wave rectification.

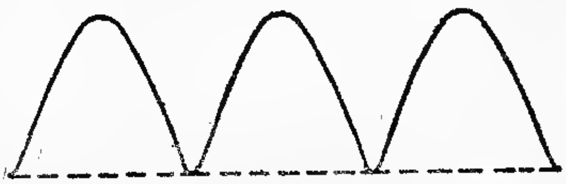


Fig. 105.—Oscillograph of full-wave rectification.

required. The circuit for full-wave valve rectification is shown in Fig. 106. Another method of full-wave rectification is available, which docs not halve the voltage. In this a special form of metal rectifier is used. These metal rectifiers, however, are more expensive than the valve rectifiers.

The rectified current has then to be smoothed. This is achieved by shunting condensers of large capaeity between positive and negative leads and inserting iron-cored chokes in the leads. The

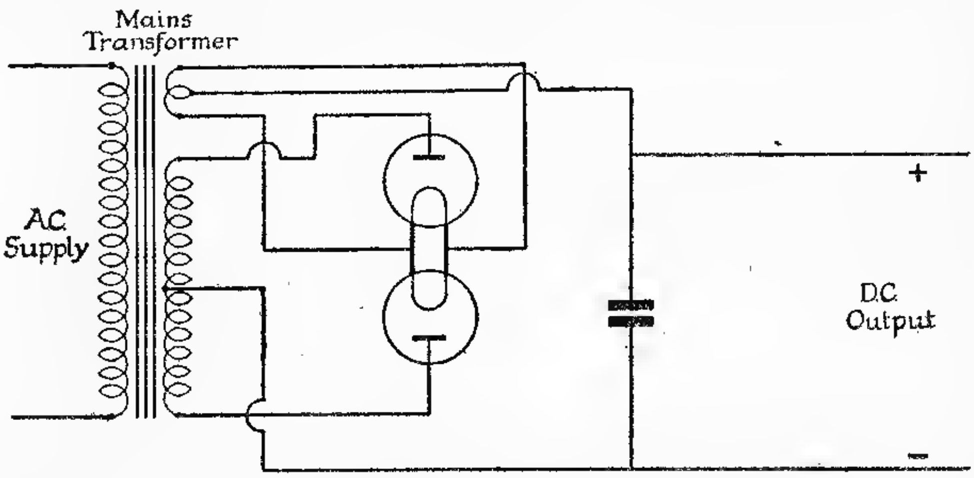


Fig. 106.—Circuit for full-wave rectification.

chokes offer a high impedanee to changes of current but a low impedance to direct current. The condensers may be looked upon either as reservoirs which store up electricity and give it out again when required or, more accurately, as devices which offer a low impedance to variable currents and infinite impedance to direct currents. After passing through a suitably designed network of this kind the current appears at the other end with most of the variations smoothed out.

If we intended only to supply the H.T. for the output stage in this way nothing further need be said. When we want different voltages for different stages, however, we must proceed with caution. We can obtain the different voltages, of course, by putting a number of resistances across the line from positive to negative and taking tappings from the joins as in a potentiometer. That is the most straightforward method and it is the one most often adopted. This method, however, is subject to one very serious disadvantage. When a mains unit designed on these lines is connected to an amplifier there is a path for the signal currents, as amplified in the last valve, back from the anode, through the potentiometer resistance (aeross which a variable voltage is developed) and so to the anodes of preceding valves, to go through the amplifier and be magnified again. This vicious circle causes the amplifier to go into self-oscillation, showing itself in the loud-speaker first as a high-pitched whistle and then as a loud popping noise similar to that made by a motor boat. For this reason the phenomenon is called "motor-boating." It can occur in an ordinary H.T. battery when that has been in use for some time and has developed a substantial internal resistance, but it is more common in mains units. An oscillograph photograph of a sine-wave current fed to an amplifier and the output wave when motor-boating occurs is shown in Fig. 107.

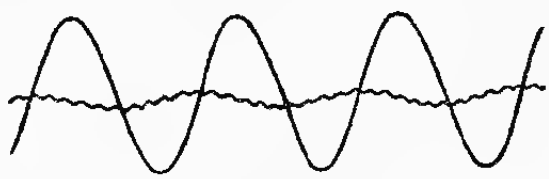


Fig. 107.—Oscillograph of "motor-boating."

By obtaining our various voltages in another way, however, we can avoid this result. The reductions in voltages are obtained by passing the current through resistances of suitable value in the positive leads and providing for any oscillatory currents fed back a low impedance path by means of condensers taken from each resistance to the negative lead. This method has come to be known as the "anode-feed" method. It appears to have been devised originally by the Western Electric Company of America, but its development more recently has been due to Messrs. Ferranti, Ltd. For the best quality of all, especially if low values of resistances have to be used, it is wise to go even a step farther and smooth every voltage lead separately. When the voltage of the output stage is of the order of 400 volts, whilst those of the other stages are 120 to 200, separate smoothing is of little, if any, advantage, since in this case the resistances are of high value.

It is possible to obtain grid bias from the mains as well as L.T. and H.T. voltages. But here again there is danger of feed-back, and sinee for the earlier stages very small amounts of grid bias are needed, small dry batteries, renewed at least once a year, are preferable; no current is taken from them if grid current in the amplifier is prevented. For the last stage it may be an advantage to obtain grid bias from the mains. Two resistances of suitable values are joined in series across the positive and negative H.T. for this stage, and the filaments of the output valves are connected to their join instead of to the common negative H.T. The grids of the output valves are connected to negative H.T. and are thus made negative relative to the filament. In this case the voltage from anode H.T. to negative H.T. should be designed to be the required H.T. voltage for the valves *plus* the grid bias voltage.

Alternative designs for an amplifier and mains unit are given in the appendix to this chapter.

APPENDIX

DESIGN OF AMPLIFIER UNITS

In this appendix alternative designs are shown of a gramophone amplifier and broadcast receiver, worked entirely from the mains, which the authors have found to give superlatively good results. The design consists of four parts:

Fig. 108: A high-frequency amplifier unit with switches to change from long to short wave lengths.

Fig. 109: An anode-bend detector unit.

Fig. 110-111: A low-frequency amplifier with either push-pull transformer coupling or resistance-capacity, choke output, coupling.

Fig. 112-113: A mains unit supplying H.T. and L.T. current from A.C. mains.

In Fig. 112 a metal rectifier is used giving a maximum output of 100 milliamps at 200 volts. In Fig. 113 a full-wave valve rectifier is used to give, if necessary, 120 milliamps at 600 volts. In this case the 1,000-ohm field-winding of a moving-coil speaker is used as the choke in the smoothing system and grid bias is obtained for the output valves by connecting the filaments to a point of positive potential in the H.T. smoothing system. In this latter case the connection marked GB – in Fig. 110 or Fig. 111 should be taken to HT – which is at earth potential. With the mains unit shown in Fig. 112 the lead GB – is taken to the appropriate negative tapping on a dry battery, the positive of the battery being connected to HT –.

The change-over from radio to gramophone pick-up is effected by means of a switch (shown on the left of Fig. 109) which is also coupled with the switch short-circuiting the milliammeter in the H.T. lead to the detector valve. When the switch is over to gramophone pick-up, the bias to the detector valve is automatically changed, so that the valve becomes a L.F. amplifier and not an anode-bend rectifier. For radio, therefore, we have a screened grid H.F. stage, an anode-bend detector, a L.F. stage and an output stage. For gramophone we have two L.F. stages and an output stage.

A potentiometer is shown connected across the pick-up so that the input to the valve may be controlled and overloading avoided. It is found that if this potentiometer has too low a value (say, 50,000 ohms) some reduction of high notes occurs. On the other hand, if it has too high a value (say, 1 megohm) the A.C. valves begin to cause hum in the reproduction. The best compromise is between 250,000 to 500,000 ohms.

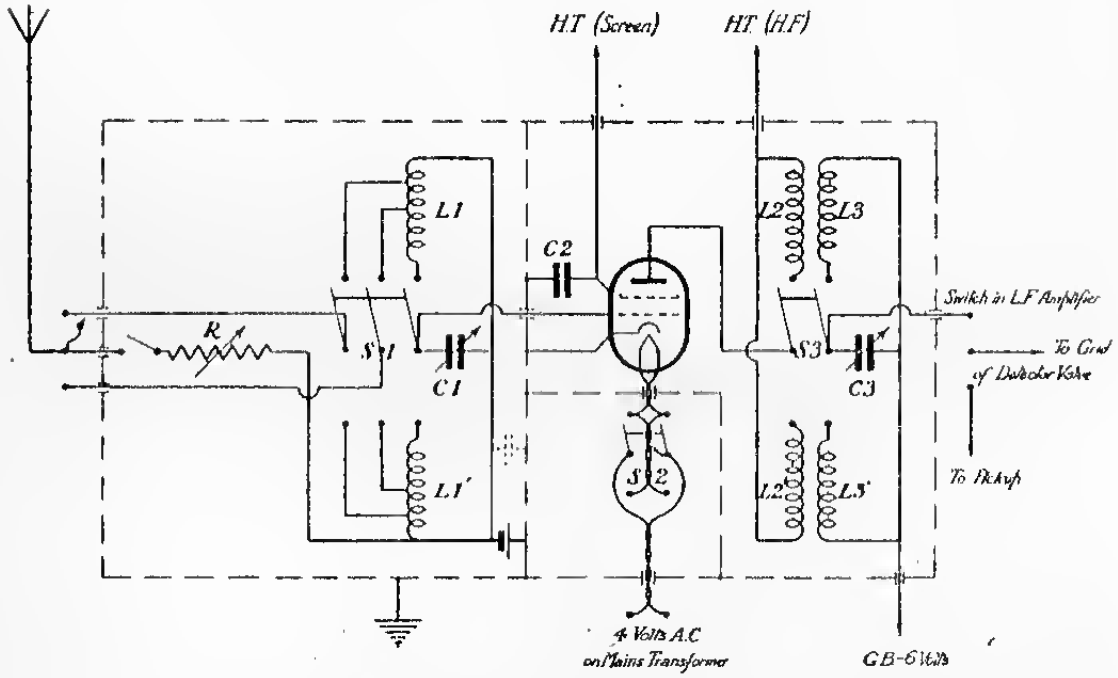


Fig. 108.—H.F. amplifier unit.

Circuit for H.F. stage employing indirectly heated A.C. screened-grid valve.

R : 25,000 ohms variable resistance to control signal strength. For weak signals this resistance can be cut out by means of a switch.

L1, L2, L3 : Coils for broadcasting band 250-500 metres.
- L1 : No. 60 coil with taps at 15th and 30th turn.
- L2 : No. 75 coil.
- L3 : No. 60 coil.

L1', L2', L3' : Coils for broadcasting band 1,000-2,000 metres.
- L1' : No. 200 coil with taps at 100th and 50th turn.
- L2', L3' : No. 200 coils.

C1, C3 : 0.0005 mfd variable condensers.

C2 : 0.1 mfd mica condenser.

S1, S2, S3 : Switches for changing over from long to short waves.
- S2 : Switches off the A.C. filament current to the valve when the switch is in the central position.
- These three switches may be ganged and operated by one control.

The whole unit is enclosed in a metal box with a partition and a smaller internal box to enclose the A.C. switch. The box is shown dotted.

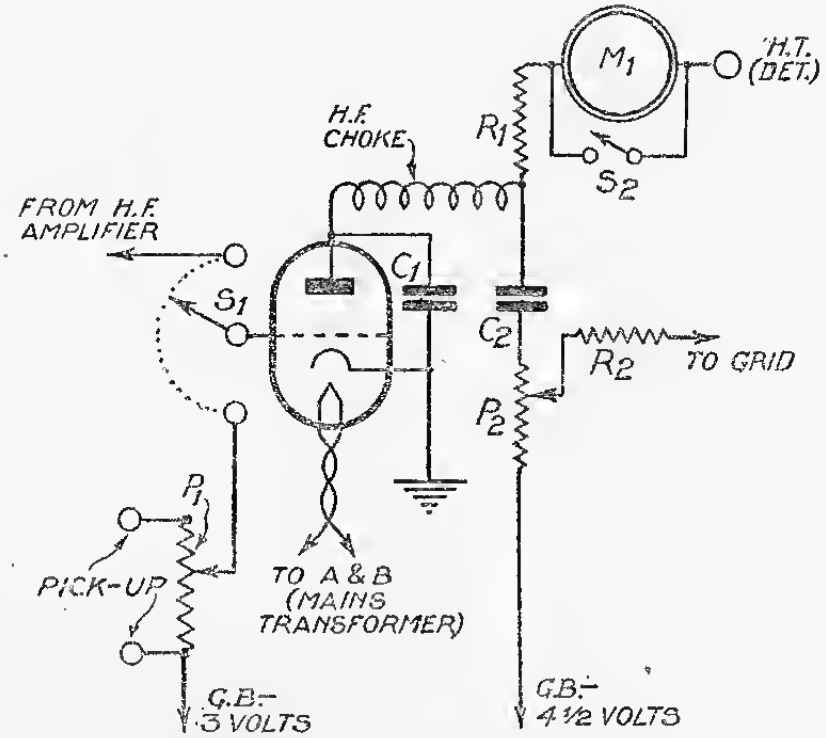


Fig. 109.—Anode-bend detector unit.

Detector unit with resistance-capacity coupling to L.F. unit.

S1 : Switch from radio to gramophone coupled to

S2 : Switch to short-circuit milliammeter on gramophone (a single D.P.D.T. switch is used for S1 and S2).

M1 : Milliammeter reading to 1 or 2 m.a.

P1 : Potentiometer value $\frac{1}{4}$ or $\frac{1}{2}$ megohm (see text).

P2 : Potentiometer value $\frac{1}{2}$ megohm.

R1 : 100,000 ohms wire-wound anode resistance.

C1 : 0.0001 mfd mica condenser.

C2 : 0.1 mfd mica condenser.

R2 : 100,000 ohm series grid resistance.

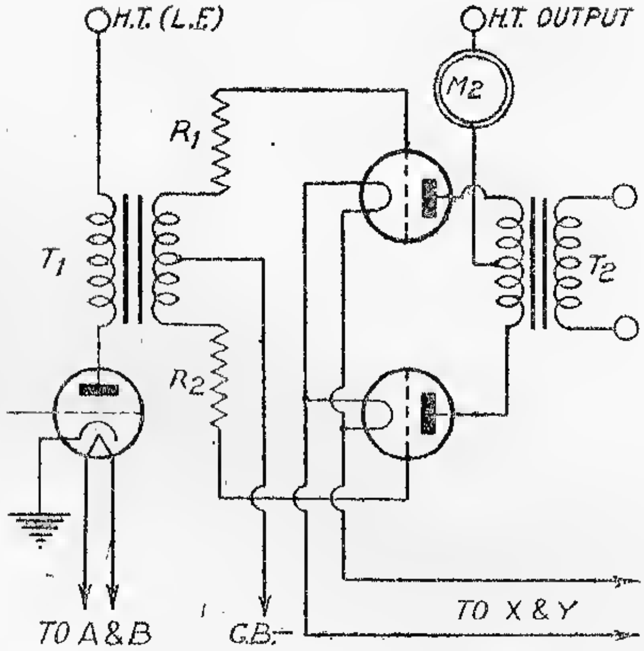


Fig. 110.—L.F. amplifier push-pull transformer coupling.

L.F. amplifier with push-pull transformer output stage.

T1 : Push-pull intervalve transformer.

T2 : Push-pull output transformer of ratio to suit loud-speaker impedance. As to this the makers of the speaker should be consulted.

M2 : Milliammeter reading to 100 or 150 milliamps.

R1, R2 : Series grid resistances, 100,000 ohms each, to safeguard against interaction between output valves.

Note :—If the mains unit used is that shown in Fig. 113 the lead marked G.B.— should be taken to earth. Suitable valves for the output stage are Mazda B12 or Mullard DO20, the L.T. voltage at X and Y being $7\frac{1}{2}$ volts.

For the other mains unit G.B.— is taken to the appropriate tapping on a grid bias battery. Suitable valves for the output stage are Osram P.625 or Mazda PX 650, the filament voltage being 6 volts.

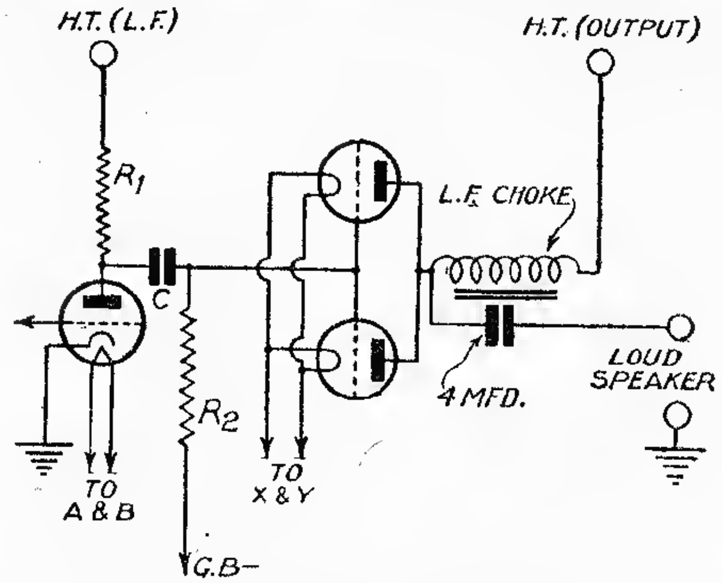


Fig. 111.—L.F. amplifier resistance-capacity coupling, choke output.

L.F. amplifier, resistance-capacity coupled, with choke output stage.

R1 : 50,000 ohms wire-wound anode resistance.
R2 : ½ megohm grid leak.
C : 0.1 mfd mica condenser.
Note :—(As in Fig. 110).

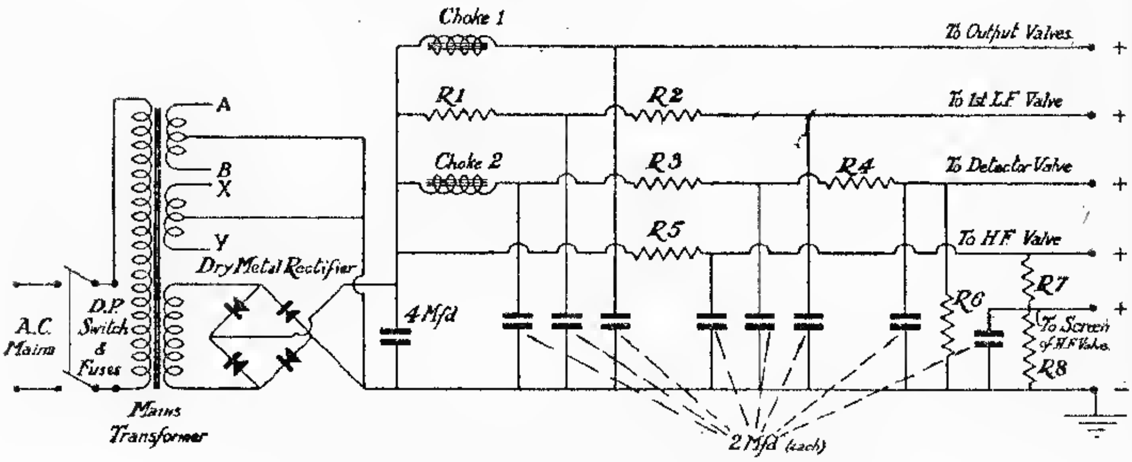


Fig. 112.—Mains unit with metal rectifier.

Mains unit with metal rectifier delivering 100 m.a. at 200 volts.

The mains transformer should give 2 amps at 6 volts at X and Y.
4 amps at 4 volts at A and B.
100 milliamps at 230-250 volts for H.T.

Choke 1 should have an inductance of not less than 8 henries at 100 m.a., and the D.C. resistance should not be more than 500 ohms.

Choke 2 should have an inductance of about 30-50 henries at 10 m.a.

The values of the resistances depend on the current and voltage required at each tapping. For the amplifier here illustrated the following values are approximately correct for the valves indicated below :—

R1 and R2 : 25,000 ohms. R3, R4 and R5 : 8,000 ohms.
R6 and R7 : 40,000 ohms. R8 : 50,000 ohms.
H.F. valve : Metro-Vick AC/S.
Detector and L.F. valves : Metro-Vick AC/G.
Output valves : Osram P625 (grid bias—27 volts).
Mazda PX 650 (grid bias—45 volts).

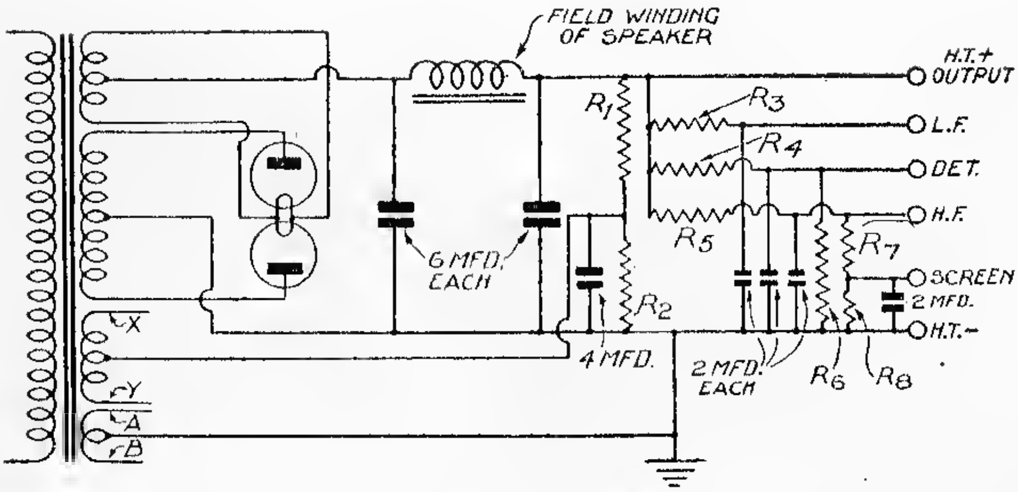


Fig. 113.—Mains unit with full-wave valve rectifier.

Mains unit with full-wave valve rectifier, with 1,000 ohm field coil of moving-coil speaker as choke and with automatic grid bias for output valves.

The mains transformer should have centre-tapped secondaries giving

$7\frac{1}{2}$ volts, 4 amps for Mazda RH1 rectifying valves.

$7\frac{1}{2}$ volts, 4 amps for Mazda B12 output valves at X and Y.

4 volts, 4 amps at A and B.

1200 volts, 100 m.a. for H.T.

The resistance values are as follows :—

R1 : 10,000 ohms. R2 : 1,000 ohms (rated to carry 100 m.a.).

R3 : 80,000 ohms. R4 : 40,000 ohms. R5 : 30,000 ohms (rated to carry 20 m.a.).

R6 : 40,000 ohms. R7 : 40,000 ohms. R8 : 50,000 ohms.

CHAPTER XI

MISCELLANEOUS HINTS

XI—1. Practical Considerations.

In previous chapters we have been concerned primarily with the design of the apparatus so that the vibrations imparted to the needle point through the record should be converted into sound-waves of corresponding wave-form. We have pointed out that the fundamental condition for good reproduction and minimum record wear, whether in a gramophone or in an electrical reproducer, is that the mechanical impedance of the system looking in at the needle point should be as nearly as possible independent of the frequency, that is, should approximate to a pure resistance. We have seen that the fulfilment of this condition involves careful calculation and design. But however good the design may be it is unlikely that the finished product will give the best results unless means are provided for fine adjustment. It might be expected that the chances of obtaining the critical adjustment required are not very hopeful ; and certainly great patience is necessary to achieve the best results. This fact, however, need not depress us unduly. Similar considerations apply to all delicate mechanisms—

—even the human body—and in all such cases experience provides a number of practical rules of conduct which enable us to avoid serious error. The important thing to notice from the start is that there can be no single golden rule, no universal panacea for all ills. If a delicate mechanism goes wrong, to diagnose the complaint with any degree of certainty may only be possible to a person of long experience and even then only after an elaborate examination.

These limitations should be kept constantly in mind when considering the topics dealt with in this chapter. We shall assume that the reader has an instrument of good design and shall try to explain the various points which our experience has taught us to be of the greatest importance if the instrument is to be kept in good working order ; but nothing we can say or do will enable the reader to become expert at diagnosis or treatment unless he is prepared to go to some little trouble to ascertain for himself exactly how things work out.

XI—2. Motors.

It has previously been remarked that the motor in a gramophone is the source of all the energy which we ultimately hear as sound. The record merely determines the rate of flow of energy. The first requirement of a motor, then, is that it should be able to yield up energy in varying amounts and at varying rates, and it should do this without varying in speed. The speed at which the record on the turntable rotates determines the pitch of the vibrations imparted to the gramophone needle and therefore that of the notes reproduced. The speed of rotation of the turntable should be exactly the same as that at which the original record was made. At other speeds the pitches of the reproduced sounds will be flat or sharp, according as the speed is too slow or too fast. Not only so, but the musical intervals between the various tones reproduced may be altered. The pitches of tones which are harmonic to each other will be altered in the same ratio and, therefore, no difference in the quality of a compound note composed entirely of harmonic tones should be perceptible. But the quality of notes which have inharmonic tones will be modified. The reproduction of transients will likewise suffer. The most noticeable effect will probably be in the reproduction of piano records, since the harmonic ratios of the notes on the pianoforte keyboard are deliberately modified so that the same strings can be used for the scales of different keys. For a full explanation of the necessity of the " even-tempered " scale in a pianoforte we must refer readers to text-books on sound or on music. The point we are trying to emphasize here is simply that the *quality* of the music, as well as its pitch, may suffer unless the speed of the motor is exactly right. If the speed of the turntable is uneven the effects are even more distressing. For then we get a periodic variation of pitch in addition to other faults. Here, again, the effect is most noticeable with piano records which sound " catty "—almost like Hawaiian guitars. Long-drawn-out top notes of soprano singers, too, show a very marked tremolo.

This requirement of constancy of speed of the motor, whatever the amount of energy drawn from it, is by far the most important of all our demands. Unless this is satisfied the reproduction cannot possibly be satisfactory. The first substantial advance was made in gramophone reproduction when spring-driven motors with reasonably constant speed came into use. It must not be supposed, however, that all, nor even the majority of, gramophone motors that are sold to-day do fulfil this demand. A really reliable motor is rather expensive, much too expensive for the cheaper sort of gramophones. The reason is that to obtain sufficient reserve of power, and yet make the motor practically noiseless in running, requires large and strong springs, careful design, accurate workmanship and delicate adjustment. Then, too, the question of the wear of the various parts has to be considered. There are many motors which run well for a period of three months or so and then become both noisy and unsteady. The absence of noise in the first instance is sometimes obtained by the use of soft material which wears rapidly as the motor is used.

The wearing properties of a motor can only, of course, be determined by experience. Some general hints, however, can be given. When buying a gramophone or a motor the first thing to test is the constancy of speed. For this two suitable records are H.M.V. D1065 (Chopin *Scherzo* played by Moiseiwitch) and Col. L2089 (*Andante :* Haydn's " Clock " Symphony). In the former there are heavy chords which may slow up the motor appreciably ; in the latter, about two inches from the beginning of the first side, there is a long-drawn-out wood-wind note which will waver in pitch if the motor is unsteady. It is best to use a fibre needle for this test, since with a fibre the friction on the record is rather greater than with a steel needle ; it is desirable too, to test the motor both when it is wound to the top and when it is half run down.

The next thing to notice is whether the noise made by the motor is regular and continuous. A discontinuous noise—crr, crr, crr, every revolution of the turntable—indicates that the motor is badly adjusted. The reason for this noise (which is fairly common) will be explained later. Here it is important to notice that unless the fault is remedied it will soon get worse and will lead to chronic instability of speed.

Thirdly, the turntable should fit tightly on the spindle and should run fairly evenly. To test the fitting, press gently round the rim of the turntable with the fingers. You should not be able to rock it on the spindle. Very few turntables run absolutely evenly, but there is no reason why the up-and-down motion should be more than just perceptible to the eye.

XI—3. Parts of a Spring Motor.

There are two main types of spring motor in use at the present time. Specimens of these two types are illustrated in Figs. 114 and 115. In the first type the springs (which are enclosed in a metal casing) drive a worm-wheel which meshes in a worm on the spindle. In the second type the gear on the spring casing drives an intermediate gear which engages with a pinion at the foot of the spindle. The advantage of the first type is its simplicity and the fact that there are fewer wearing parts. Its disadvantage, compared with the seeond type, is that a worm drive of this kind wastes at least half the power. Specially strong springs are therefore needed.

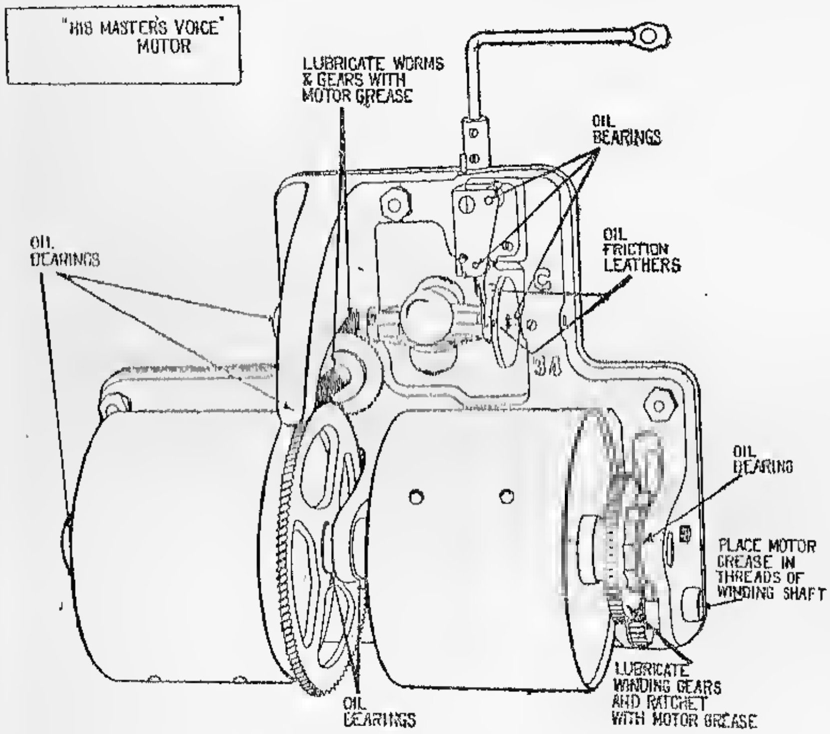


Fig. 114.—H.M.V. 4-spring motor.

In both cases the speed control is by means of a three-ball governor mounted on a separate shaft. At one end of this shaft is a worm driven by a worm-wheel on the spindle. The three balls are attached at the centres of thrce delicate flat springs. At one end these springs are fixed to the governor shaft and at the other to the governor disc, which is permitted to slide along the shaft. When the motor is running the balls move outwards and draw the governor disc against a small brake pad made sometimes of soft felt and sometimes of leather. If the motor is running at constant speed, the

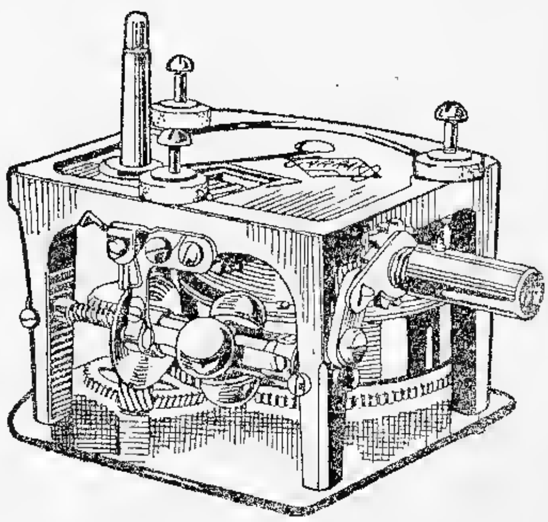


Fig. 115.—Garrard motor.

pressure between the pad and disc is constant. As soon, however, as the motor tends to lose speed the pressure between the disc and the governor pad decreases and the speed is restored again; on the other hand, if ever the speed tends to become greater the pressure between disc and pad is instantaneously increased and the tendency is thus checked.

Most of the troubles with poor motors arise from the design or adjustment of the worm-wheel on the spindle and of the worm and governor mechanism. The governor springs and the governor balls have to be delicately balanced. Sometimes one of the springs breaks, and in that case it is always wise to replace all three. In a good motor the balancing of the springs and governor balls is very accurate. Another important adjustment is that of the worm to the worm-wheel on the spindle. In order to minimize noise, the worm-wheel is often made of fibrous material supported between two metal discs. In the best motors this material is very hard and the gear is very cleanly cut. In a poor motor it may be a soft composition which will absorb oil and begin to warp. It is essential that this worm-wheel shall mesh with the worm at exactly the same depth at all positions. This means that it has to be mounted quite centrally on the spindle and that the spindle itself must be exactly at right angles to the governor shaft. As a rule, means are provided by which the direction of the governor shaft and the depth of mesh between worm and worm-wheel can be adjusted. If the adjustment is not quite accurate the motor will give the intermittent noise mentioned in the last section. This means that part of the worm-wheel is coming into closer mesh with the worm than the rest, and this is bound to cause excessive wear.

The art of adjusting a motor lies principally in obtaining the proper contact between the governor worm and the worm-wheel. The expert sometimes makes the adjustment with the motor running, but this is too dangerous a proceeding for the amateur to attempt. If he makes the slightest mistake he may either strip the gears or get his hand caught in the mechanism. If the worm and worm-wheel are too tightly enmeshed, the motor will become sluggish; if there is too much play, it will be noisy and possibly irregular. The amount of vertical play in the spindle is also important. The bottom of the spindle bears on the bottom plate through a steel ball; this ball should be the only part in contact with the plate bearing, There should also be a slight vertical play in the spindle but no side-to-side play.

The springs in the spring barrels each have one end hooked to the casing and one end to the central shaft. They are packed in graphite grease. This grease is usually made up of a mixture of vaseline, Rangoon oil and finely powdered graphite. Good quality spring grease has the appearance of being quite soft, smooth, almost liquid, and yet it should be sufficiently viscous to adhere, say, to a screw-driver, when a small quantity is picked up on it. Some forms of graphite grease are gritty and others are sticky or even hard. These should be avoided. The working of the springs inside the spring barrel after a time forces the grease out and tends to make sticky the little that remains. When this occurs the convolutions of the spring tend to stick together and then separate suddenly. This is the cause of the rather loud bumping noise which one sometimes hears when winding up a motor or allowing it to run down. When this happens it is time for the springs to be taken out of the barrel, thoroughly cleaned with paraffin or petrol, dried so that no trace of paraffin remains, replaced in the barrel and repacked with fresh grease. The method of performing this operation is not one that can be readily described in a book, and in any case the amateur is not advised to attempt it for himself. Unless the spring is handled in the right way it may do a great deal of damage. In any case there is always the possibility of distorting the shape of a spring barrel, and when that has occurred the motor can never be satisfactory again. Good mechanics can remove a spring by hand without damaging either themselves or any part of the motor. Bad mechanics, who are half afraid to tackle the job, sometimes put the spring barrel into a sack, pull on the spring with a piece of cord and trust to fortune as to what happens to the spring and barrel inside the sack. In such circumstances fortune is not usually kind. The important point for the amateur to remember is that as soon as he hears even the smallest bumping in the motor then he should seek out a good mechanic and have the spring attended to. If he neglects to do so the probability is that one or more of the springs will break. If a spring does happen to break it is usually advisable to have all the springs in the motor replaced, and not merely the broken one; it is a general experience that if only the broken spring is replaced the rest will also break within a very short time and the motor will have to be taken to pieces again.

XI—4. Care of the Motor.

When using a gramophone motor the following rules should be borne in mind:

1. Let the motor run when winding, but do not put the sound-box on to the record until you have finished winding. Do not wind whilst playing.

2. In winding turn the handle with an even, steady motion. Do not wind in jerks. When the motor is nearly fully wound, slow up the speed of winding and be careful not to overwind and so unhook the spring.

3. Find out how many records your motor will play and let it play so many. Do not rewind after each playing, unless the motor will not last another side. There is no objection to a few turns of the handle after eaeh playing, but get into the habit of using the whole of the spring and not merely the top or middle part of it. This keeps it in good temper.

4. Do not assist the turntable to start by giving it a flick on the edge with the fingers. This strains the tender governor springs. Similarly, do not put on the brake fiercely at the end of a record. It is a good habit to stop the motor gently with the fingers before applying the brake.

5. Never leave the motor half or fully wound. Run it to the bottom when you have finished playing,

and then give the winding handle a few turns. Better still, try to find out, by listening to the noise of the motor, when it is nearly run down and stop it just before it gets to the bottom.

6. Oil the motor regularly, say, once in three months. At the bearings of the spindle and governor shaft use a light oil of superfine quality; do not forget the bearing of the spindle under the turntable. For the teeth of the various gear-wheels use a non-gritty motor grease or vaseline. For the worm on the governor shaft and the worm-wheel on the spindle liquid oil must *not* be used; here, it is of great importance to use a non-gritty grease. The governor disc against which the pad presses should be kept scrupulously clean; a trace of grit or dust will upset the speed completely. Clean the disc carefully with a clean cloth damped slightly with petrol and put a drop of clean light oil on the pad. If the pad is made of felt examine it from time to time to see that it has not gone hard. Sometimes the face which presses against the disc goes glassy; when this happens the pad should be renewed.

7. Automatic stops, especially those which go on with a jerk, are apt to strain the governor springs. They are best avoided.

8. Never press heavily on the turntable; the spindle is easily strained and when once that has happened the motor cannot run steadily.

XI—5. Electric Motors.

There seems to be considerable difficulty in making a reliable electric gramophone motor. The speed of rotation is relatively small and yet it has to be kept quite uniform under a rapidly varying load. This is quite a different problem from that with which manufacturers of electric motors usually have to deal. Most of the electric motors which the authors have come across have either failed to keep a steady speed or have become over-heated. In an electric motor the most difficult problem seems to be to secure a satisfactory governor mechanism. On a slow-running electric motor a mechanical governor of the type used in spring motors rarely seems to give satisfaction. What appears to be needed is either a purely electrical control or a simple method of gearing so that a high-speed motor can be used to drive a slow-running turntable which is controlled by an independent governor. In that case the governor would act, as it were, "in shunt" with the power taken through the record, and in this way would tend to equalize the load on the motor. There are electric motors which act more or less on this principle, and these have been the most successful. The least successful motors have been those in which the governing mechanism has been mounted on the driving shaft.

One or two other points about electric motors should also be noticed. It very rarely happens that the voltage of an electric supply is constant. It is therefore necessary that the motor should be comparatively insensitive to fluctuations in the supply voltage. On account of the heat which is developed in the motor, the question of lubrication becomes of great importance. An electric motor certainly requires attention in this respect much oftener than a spring motor. It is a common practiee to drop the mains voltage to that required by the motor through a resistance. Sometimes an electric incandescent lamp is used for this purpose, but this has the disadvantage of varying its resistance with the current taken. A wire-wound resistance, arranged so as to dissipate heat quickly, is much better for the purpose. Resistance mats woven in asbestos can now be obtained and answer admirably.

XI—6. Speed Regulation.

The speed of a motor is adjusted by altering the distance between the governor pad and the governor disc; the pad is mounted on a bent lever the other end of which is in contact with a speed control and indicator fixed to the motor-board. On some H.M.V. motors there is a separate tiny brake pad on the governor disc which controls a pointer on the speed indicator. Either type of indicator, of course, will only show the correct speed if it is properly set.

There are a number of ways by which the actual speed at which the motor is running may be measured. The most straightforward way is to place a strip of paper on the turntable so as to project beyond the edge, lay a record on top and start playing. Count the revolutions of the strip of paper with your watch in hand for a full minute; start off by counting 0 (*not* 1) as the seconds hand reaches 0 on its dial. The speed indicator can then be adjusted so that it registers the actual speed at which the motor is running, or, alternatively, marks can be placed on the dial to indicate the position at which the indicator should be set when the speed is 78 and 80 revolutions per minute.

Both the H.M.V. and Columbia Companies have issued instantaneous speed testers. Both depend for their action on the centrifugal force acting on a weight revolving round the spindle. They work reasonably accurately if kept clean and oiled.

Those who have electric light from A.C. mains can construct a remarkably accurate stroboscopic speed tester on a piece of cardboard. The light from an incandescent lamp on alternating current varies its brilliancy at twice the frequency of the current, since in its heating effect the negative half of the current-wave is just as effective as the positive half. Thus, on a 50 cycle supply the light is momentarily extinguished every $\frac{1}{100}$ of a second. If, therefore, we rule a disc in black and white sectors, as in Fig. 116, and place this on the turntable over the spindle, the sectors may either appear to be stationary when the turntable is rotating, or they may appear to move with the turntable or in the opposite direction according to the speed of the turntable and the number of sectors on the disc. If there are 77 equally spaced black sectors on the disc and the electric supply is 50 cycles, the sectors will appear to be stationary when the turntable

Fig. 116.—Speed stroboscope.

speed is 78 revolutions per minute. The reason for this is that at 78 revolutions per minute a black sector will move to the place occupied by its neighbouring black sector in $\frac{1}{100}$ of a second. (*Note :* 78 revolutions per minute = 1·3 revolutions per second and $1{\cdot}3 \times 77 = 100{\cdot}1$). Simple calculations of this kind show that the number of sectors required to give the appearance of no motion when the turntable is revolving at 78 and 80 revolutions per minute is as shown in the following table :

Frequency of supply		25	30	40	50	60
Record Speed.	78 revolutions per minute	38½	46·2	61·5	77	92·3
	80 revolutions per minute	37½	45	60	75	90

This method of adjusting speed enables one to see at a glance whether the motor is running steadily, since any fluctuation in speed immediately shows itself in the pattern of the stroboscope. Since electric supplies are to be standardized at 50 cycles there seems to be no sound reason why a stroboscopic diagram should not be printed on the label of every record.

XI—7. Levelling the Gramophone.

It was remarked in Chapter VI that unless the axis of swing of the tone-arm is vertical there will be a tendency for the tone-arm to swing either inwards towards the centre of the record or outwards towards the edge, and that this tendency would create a side pressure between groove and needle. This side pressure is one of the important causes of record wear, or of the breaking of fibre points. There are other causes of side pressure besides a faultily mounted tone-arm. Thus, the gramophone or the floor or table on which it is placed may not be exactly level. If the tone-arm joints are quite free, as they should be, the friction between the record and needle will always tend to swing the tone-arm inwards.

It is best therefore to balance out all these causes by levelling the gramophone on the place in which it is used in such a way that side pressure is avoided. A spirit level is of no use for this purpose. The method recommended is as follows:

Set a 12-inch record moving on the turntable and gently lower the sound-box (with needle), first on to the outer blank rim and then on to the unrecorded portion just outside the label. Choose a record, if possible, which has a lot of blank unrecorded space (or the smooth back of an old single-sided record, if one is available). Note if the sound-box tends to swing inwards or outwards. If it swings inwards, then you must put a little packing (paper or bits of cardboard) under the feet of the gramophone either at the left or at the front—the former if the tendency for inward swing is greatest at the inside of the record and the latter in the opposite event. If, on the other hand, it swings outwards, then packing on the right or at the back may be required. It is really quite a simple and quick matter to level the gramophone in this way, so that there shall be no inward or outward swing anywhere.

XI—8. Record Faults.

Apart from record wear by use, there are three or four major record faults against which precautions must be taken if the best reproduction is to be obtained. The most important of these is an eccentric centre hole, or a hole which is too big for the spindle of the turntable. Unless the record is placed on the turntable in such a way that its axis of rotation is exactly at the centre of the recording grooves, the linear speed of the groove under the needle will vary and a fluctuation of pitch will result. An acute ear can detect a centring error even as small as $\frac{1}{100}$ of an inch. Record manufacturers as a rule take great pains to make the spindle hole central, but when records are being turned out by the thousand it is not an easy matter to ensure that each one is exactly right. Only too often one finds that the hole is slightly eccentric, and then we get what is known as a "swinger." A record of this kind can be identified at once by noticing whether the sound-box is swayed from side to side once every revolution of the turntable when the record is being played. Some records move the sound-box in little jerks; these are particularly vicious.

Another point to note is that in making the test, care should be taken to see that the record is placed so that the hole is concentric with the spindle; if the spindle is appreciably smaller than the hole, the record may appear to be a swinger simply because it is not placed on the turntable properly. To guard against this, some people place a thin piece of silk over the spindle and then press the record over that ; others place a size o celluloid capsule, such as chemists use, over the spindle before putting on the record. A better procedure, however, is to place the record on the turntable and watch the sound-box carefully while the needle is in the first groove or two ; then if the sound-box sways from side to side give the record a gentle push with the thumb-nail towards the spindle just as the sound-box is swaying outwards ; the push, of course, should be just opposite the sound-box. After a little practice one becomes quite expert in centring a record in this way before the music actually begins. Always avoid buying a record which cannot be adjusted centrally on the turntable in this way. If by chance you happen to have one, the best plan is to enlarge the hole slightly with a reamer so that there is a greater margin for adjustment. It is worth while, however, to take a great deal of trouble to ensure correct centring. Nothing is so distressing in reproduction as a record in which the pitch wavers. For electrical reproduction at considerable volume, exact centring is essential.

Another serious fault in manufacture is known as "cold pressing." The stampers which press records have to be kept at a certain temperature in order that the record material will flow properly. If they are too cold, the record surface becomes uneven, and when the record is played an irregular and rather disturbing kind of surface noise is heard. With a cold pressing of this sort, the grooves are not properly formed and there is actual distortion in the reproduction. On the other hand, if the stampers are too warm the record surface may be wavy: there will be a sheen on it of the kind one sees on watered silk. Both types of record should be avoided. Similarly, records which have bubbles or pin holes on their surface should be rejected. For faults such as these there is no cure.

Records which have been badly stored, either in the factory, the shop, or the private collection, very often become warped. A warped record is almost as bad as a swinger in the effect it has on reproduction. To flatten a warped record the most satisfactory method is to heat it *slightly* on both sides in front of a fire—preferably a gas or electric fire—and then place it between two sheets of plate glass which have been thoroughly washed, dried, and then polished with french chalk. For heating, the record should be held by its edge between the fingers of the two hands, the fingers pointing directly towards the fire and about eighteen inches away from it. Work the fingers round the edge so that the record actually rotates with its surface in front of the fire. When one side has become just warm—no more—turn the record over, still holding it round the edge, and warm the other side. A few heavy books placed on top of the sheets of plate glass with the warmed record between them will flatten it out in a very short space of time.

XI—9. Record Storage and Indexing.

The best method of dealing with warping, however, is to avoid it altogether by a satisfactory method of storage. After rather costly experience in this matter, the authors have come to the conclusion that the cheapest method of storing records is also the best. They have long ago ceased using record albums, or ingenious cabinet devices. The method which they strongly recommend is to stack the records in manilla envelopes *on edge* in a suitable cupboard with the open edges at the front, and to keep them tightly packed against each other. No attempt should be made to arrange the records in any predetermined order such as Orchestral Records, Vocal Records and so on. In that case gaps would have to be left between each group and the records could not be kept tightly pressed against each other ; this is essential if warping is to be prevented. Ten-inch records should be kept separate from 12-inch records for the same reason.

The record envelopes are numbered consecutively at the top corners either in manuscript, or by means of a rubber stamp or by gummed labels. The records being round, the corners of the envelopes are all empty, so that it is quite a simple matter to run one's fingers along the top and find any number. It is also easy to grasp the top corner of the envelope between finger and thumb and pull it forward from the stack. The record can then be extracted, and the empty envelope left in position to show where the record has to be returned after it has been played.

The records are identified by means of an index compiled in a loose-leaf note book. This index can be arranged in any way to suit the taste of the particular user. Thus, vocal records, instrumental records, orchestral records and so on, can each be grouped together ; alternatively an alphabetical list or a list of composers or works can be kept. The essential thing is that the index should enable the user to find the number of any record he wants quickly.

To store records on a systematic plan like this is far more satisfactory than either leaving them about in a more or less haphazard fashion or keeping them in some definite or indefinite order in albums. It is convenient, economical of time and money, and compact. It keeps the records clean and prevents warping, and at the same time there is little temptation for the user to leave records lying about. To store 1,000 records, four shelves 3 feet long and at least $\frac{3}{4}$ inch thick and 13 inches deep are required; there should be supporting partitions up the middle to prevent the shelves from sagging. The back should be boarded and the front closed in either by cupboard doors or by a curtain sliding on a rod.

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IV. *Patents :*

[*Note.*—In the following list the authors have merely selected those British Patents which appear to them to be of special technical or historical interest. They believe that the list is fairly representative of the important patents up to 1925. A few patents of later date have been added, but the number of recent patents is so large, and their ultimate value so uncertain, that a representative selection is at present quite out of the question. It should be noted that in many cases the corresponding American patents are more comprehensive than the British.]

1876	4,765	Bell	Telephone.
1877	2,909	Edison	Phonograph.
	4,685	Siemens	Telephone mechanisms (includes balanced armatures and moving coils).
1878	1,644	Edison	Phonograph.
	3,647	Hunnings	Carbon microphone.
1880	91	Berliner	Microphone.
1886	6,027	Bell and Tainter	Graphophone.
1887	15,232	Berliner	Gramophone.
	17,175	Edison	Electric phonograph.
1889	11,304	Deckert	Carbon microphone.
	12,762	Bettini	Stretched diaphragm and spider.
1895	9,526	Ferguson	Recording by light.

Patents—continued:

1897	2,430	Obelt	Multiple diaphragms.
1898	7,843 15,297 15,298	E. R. Johnson	Gramophone motor.
	9,712	Lodge	Moving-coil mechanism.
1899	11,747	Bowley	Tubular gaskets and conical diaphragm.
	13,959	Conn	Sound-box with horn on each side.
	14,287	H. Jones	Sound-box with spring mounting.
	16,085	Korytowski	Needle magazine.
1901	1,294	Petit	Double-sided record.
	3,393	Stroh	Corrugated diaphragm, conical centre.
	9,472	E. R. Johnson	Stylus-bar mounting.
	25,172	H. Jones and Gibson	Stylus-bar mounting.
1902	21,799	Johnson and Denison	Tone-arm.
1903	8,401	E. R. Johnson	Tapered tone-arm with goose-neck.
	9,910	G. W. Johnson	Stylus-bar mounting.
	10,468	Parsons	Compressed air sound-box.
	19,507	Douglass	Flexible connection to tone-arm.
1904	24,850	Fleming	Thermionic valve.
1905	6,050	English	Tangential tracking.
	23,213A	Boult	Spring motor wound electrically.
1907	1,915	Preszter	Internal horn gramophone.
	6,611	American Graphophone Co.	Record with shellac surface on paper discs.
	21,087	Coombs	Dished diaphragm.
	24,932	Hall	Fibre needles.
1908	1,427	de Forest	Three-electrode valve.
1909	11,015	Lumière	Pleated diaphragm.
	22,784	Fischer	Reflectors in tone-arms.
1910	29,833	Brown	Telephone ear-piece with conical diaphragm.
1911	2,985	Lumière	Shape of back-plate of sound-box.
	18,993	Diehl	Moulded rubber gasket.
1912	3,814	Edison	Diamond reproducer.

Patents—continued:

1914	16,602	Hopkins	Large conical diaphragm.
1915	275	Western Electric Co.	Push - pull amplification. (See also 141,047—convention date, May 18th, 1914.)

Note.—Since 1916, Patents have been numbered consecutively. The date from which they run is given in brackets.

102,726	(11/12/15)	Moyer	Tungstyle needle.
116,163	(9/ 6/17)	Armstrong and Bindloss	Tangential tracking.
120,715	(12/11/17)	E. R. Johnson	Stylus-bar mounting.
127,014	(7/11/16)	Brillouin and Beauvais	Resistance - capacity coupling.
134,872	(20/ 9/18)	Western Electric Co.	Condenser microphone.
141,033	(28/ 3/19)	Western Electric Co.	Potentiometer across L.F. transformer secondary.
142,115	(15/ 7/15)	G. A. Campbell	Wave-filters.
145,421	(31/ 5/16)	Siemens and Halske	Screened-grid valve.
151,140	(5/ 8/19)	Western Electric Co.	Attenuation Equalizers.
160,223	(18/11/19)	Sykes	Electromagnetic microphone. (See also 224,936.)
177,215	(14/12/20)	Balmain	Floating horn with radial tracking.
179,688	(17/ 2/21)	Brown	Folded logarithmic (exponential) horn.
195,589	(30/ 3/22)	Western Electric Co.	Combined wireless and gramophone sets.
195,782	(12/ 1/22)	Western Electric Co.	Filter circuits.
213,528	(2/ 2/25)	Western Electric Co.	Re-entrant horn.
217,192	(8/ 6/23)	Siemens and Halske	Blatthaller Loud Speaker.
206,518	(6/11/22)	Huguet d'Amour	Double cone connected base to base. (See also 222,152 and 239,245.)

Patents—continued:

221,105	(19/10/23)	Forse and Columbia Graphophone Co.	Record face material.
230,876	(8/10/23)	Western Electric Co.	Matching mechanical impedances.
231,216	(23/11/23)	Western Electric Co.	Mechanical wave-filter.
231,409-10	(23/11/23)	Western Electric Co.	Electric recorders and reproducers.
231,420	(27/ 3/24)	British Thomson Houston Co.	Moving-coil speaker. (See also 269,804.)
231,421	(27/ 3/24)	British Thomson Houston Co.	Baffle for loud speaker.
231,798	(30/11/23)	Western Electric Co.	Free-edge diaphragm.
241,676	(11/ 9/24)	GramophoneCo.	Form of record tracks.
242,821	(7/ 1/25)	British Thomson Houston Co.	Optical apparatus, electrical and magnetic sound-boxes.
245,415	(24/12/06)	Western Electric Co.	Re-entrant horn.
252,657	(29/ 5/25)	Western Electric Co.	Sound-box design.
254,403	(4/ 4/25)	Round	Pick-up.
258,530	(25/ 7/25)	Standard Telephones	Springs to correct negative compliance of magnetic field.
258,542	(19/ 9/25)	Reisz	Microphone.
260,148	(28/10/26)	British Thomson Houston Co.	"Kellogg" pick-up.
260,946	(3/11/25)	Western Electric Co.	Pick-up (note horizontal magnet acting as part of carrying-arm).
261,698	(18/ 1/25)	Hopkins Corporation	Pick-up.
262,839	(25/ 6/25)	Western Electric Co.	Rubber loading for recording instrument.

Patents—continued:

263,411	(22/11/25)	Standard Telephones	Tangential diaphragm corrugations.
264,103	(26/ 9/26)	British Thomson Houston Co.	Piezo-electric pick-up.
266,395	(22/ 9/25)	Western Electric Co.	Shape of back-plate.
268,723	(4/11/26)	GramophoneCo.	Conical pleated diaphragms.
268,759	(1/ 4/26)	British Thomson Houston Co.	Damping vibrating reed.
269,170	(1/ 4/26)	British Thomson Houston Co.	Felt and liquid damping.
269,978	(27/ 1/26)	Columbia Graphophone Co.	Electromagnetic damping.
272,637	(26/ 3/26)	GramophoneCo.	Fluid damping.
275,567 / 571	(4/ 8/26) / (4/ 8/26)	Electrical Research Products	Moving-coil drive for horn loud-speaker.
276,466	(19/ 6/26)	Lea	Pick-up with needle only as armature.
277,193	(15/ 9/27)	Columbia Graphophone Co.	Bifurcated horns.
279,826 / 280,534	(30/10/26)	British Thomson Houston Co.	Optical recording apparatus.
282,628	(24/12/26)	Vogt	Electrostatic speaker.
285,315	(22/ 7/27)	Dubilier Condenser Co.	Electrostatic pick-up. (See also 301,158.)
287,065	(12/ 3/27)	Siemens and Halske	Loud-speaker diaphragms. (See also 289,887-8.)
289,161	(22/ 1/27)	Woodroffe	Pick-up.
289,804	(2/ 5/27)	Philips Lamp Co.	Use of paramagnetic material in magnet system of speaker or pick-up.
290,235	(11/ 5/27)	Electrical Research Products	"Schlenker" stretched diaphragm speaker with moving-coil drive. (See also 305,543.)

Patents—continued:

290,264 290 559	(13/ 5/27) (14/ 5/27) (14/ 5/27)	Electrical Research Products	Pick-up with diaphragm and liquid damping.
292,893	(30/ 7/27)	Igranic Electric Co.	Phonovox pick-up.
294,285	(22/ 4/27)	Round and Rust	Moving-coil speaker.
295,625	(15/ 8/27)	Whitmore	Double linen diaphragm speaker.
295,687	(17/ 8/27)	Electrical Research Products	Diaphragm designed as wave-filter.
297,559	(27/ 8/27)	Wright	Tone-arm connection.
299,537	(5/ 8/27)	Trouton	" Lion " loud-speaker mechanism. (See also 305,429.)
299,822	(2/ 7/27)	Trouton	Cotton-wool edging to diaphragm.
302,190 216	(11/ 7/27)	Columbia Graphophone Co.	Electromagnetic pick-up.
306,166	(18/10/27)	Mitchell	" Plano-reflex " horn.
306,839	(25/ 2/28)	Beyer	Moving-coil speaker with coil at outer edge.

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