SECTION 3

SPECIALIZED BROADCAST RADIO ENGINEERING

RECORDING SYSTEMS

309 E

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RECORDING SYSTEMS

GENERAL RECORDING PROCESSES

EARLY HISTORY.—The phonograph is credited to Thomas A. Edison, who invented it in 1876, although actual recording of sound waves had been done much earlier. Prior to Edison, however, nobody seems to have thought of using a record to operate the stylus and thus to reproduce the sound once again.

VERTICAL RECORDING.—The Edison phonograph consisted of a horizontal cylinder, which was covered with tin foil, and on which the recording was made by a steel stylus fastened to a diaphragm made of gold beater's skin, as shown in Fig. 1. When words were spoken in front of the horn, the diaphragm was caused to vibrate, thus causing the stylus to press more or less into the tin foil coating. A spiral groove in the cylinder simultaneously moved the horn, diaphragm, and stylus as a unit along the axis, thereby causing a helix to be described on the coating.

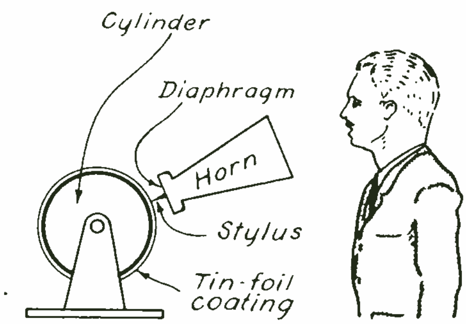


Fig. 1.—Original Phonograph.

The recording was in the form of a series of 'hills and dales' in the groove; i.e., the groove varied in depth. This type of recording, also known as vertical recording, was later superseded by the lateral cut record, but has of more recent years enjoyed a comeback in the form of an improved type of recording developed by the Bell Telephone Laboratories. Upon retracing the path, the hills and dales in the groove cause the stylus and diaphragm to vibrate in the same manner as when they recorded the sound, and thus the sound is reproduced and directed into the room by the horn.

The next step was by Bell and Tainter, who in 1887 produced the graphophone. Instead of *embossing* a groove in tin foil, they *cut* or *engraved* a groove in a layer of wax covering the surface of a pasteboard cylinder. However, even though Edison then adopted this idea, which made the phonograph a practical machine, there was one serious difficulty, and that was the making of duplicate records. These could be made by a sort of duplicating engraving machine, in which a stylus in the master record then actuated one or more other styli through mechanical coupling.

LATERAL CUT RECORDING.—It remained for Emile Berliner to develop, also in 1887, the gramophone. This employed flat discs (also considered by Edison but then discarded), and used the lateral type of recording. In this form of recording, the needle vibrates from side to side instead of up and down, and therefore produces a wavy groove of constant depth instead of a perfectly spiral groove of varying depth. A laterat-cut record is illustrated, in rather exaggerated form, Fig. 2.

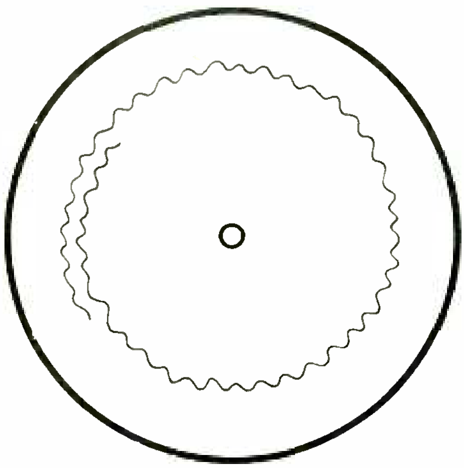


Fig. 2.—Lateral-cut record.

The flat disc is not only better suited for duplication, but also can be stored with less waste space, and has, therefore, practically superseded the cylindrical type of record. Lateral recording, while not used exclusively at the present time, appears to be the equal, if not the superior of hill-and-dale recording, and thus does not appear to be in danger of being supplanted by the latter.

MAGNETIC RECORDING.—Other methods of recording have been tried; among these are the optical and magnetic systems. The optical method has been brought to a successful conclusion in the form of sound-on-film motion picture recording. The magnetic type of recording was first introduced in 1900 by Poulsen and has had an indifferent history for many years.

In the last ten years or so it has experienced a revival of interest, and of late many magnetic recording systems have been developed that show considerable promise. The basic idea is to pass an iron wire or tape between two magnetic poles in whose windings flow the audio currents. The resultant pulsating magnetic flux magnetizes successive portions of the rapidly moving tape or wire to different degrees of flux density. The wire can then be passed between a similar set of poles, and by the cutting action of its flux, set up audio voltages in the windings surrounding these poles. These voltages can then be amplified and caused to operate a loudspeaker, telephone line, etc.

A simple schematic is shown in Fig. 3. The wire or tape unwinds

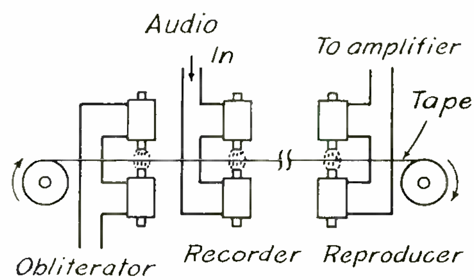


Fig. 3. —Magnetic recorder and reproducer.

from one reel and winds up on another. The obliterator head may require a.c. or d.c., depending upon the system. If d.c. is employed, the tape is brought to a fixed uniform magnetic induction, or else it is completely saturated; if a.c. is employed, all previous magnetism is removed.

In either case any previous magnetic recording is erased, and the recorder head can then proceed to record anew, and the reproducer head to reproduce the new recording. This is the most important feature of this type of recording, namely, the fact that where only temporary records are required, the same wire or tape may be employed over and over again.

PROCESSING.—Referring to the mechanical type of record once again, it is to be noted that although the records originally were duplicated by a mechanical copying process, as early as 1900 Edison employed a plating process to make a metal duplicate of the wax master, in order to stamp out duplicate copies of the original in thermoplastic material. In order to make the wax master conductive for the plating process, Edison sputtered or evaporated a very thin film of gold on the wax by means of a high voltage in a vacuum chamber. In other processes, graphite and fine metallic powders were brushed into the grooves, and the master then plated.

In an early process following the above, a master was employed consisting of a thin insulating film placed on a zinc disc, and engraved by the recording stylus, thereby exposing the metal surface. This could then be etched to form a groove, which was then burnished to remove some of the grosser imperfections produced by the etching process. The result was a master matrix. Then compounds of wax were melted onto the zinc disc, and after cooling, the resultant cast mold was removed and copper-plated after being rendered conductive by the application of graphite powder. The plating was then used to stamp out the final records.

ORTHOPHONIC RECORDING.—During the year 1926, the Bell Telephone Laboratories introduced through the Victor Talking Machine Company a new and improved phonograph known as the Orthophonic Victrola. This was employed in conjunction with the new technique of electrical recording. The phonograph was a vastly improved and scientifically designed mechanical instrument, i.e., one in which the record directly actuated the diaphragm in a sound box, from which the sound waves were coupled to the room by means of a folded exponential horn. The new instrument not only had a wider frequency range—about 115 to 5,000 c.p.s.,—but was freer from peaks in this range and sounded more natural.

Simultaneously RCA introduced through the Victor and also the Brunswick companies an all-electrical system, that not only employed electrical recording methods, but electrical reproducing means as well. The latter system ultimately superseded the mechanical or acoustic phonographs, except for portable applications, and represents the beginning of modern phonograph practice. Today the phonograph is usually part of a radio-phonograph combination, and in this form has staged a very impressive comeback.

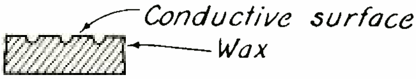
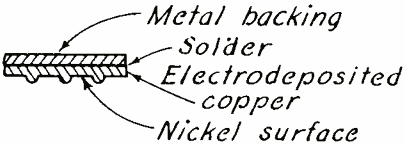
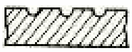
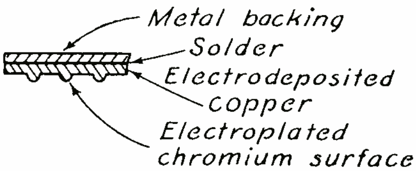
HIGH-FIDELITY SYSTEMS.—About the year 1932 the Bell Telephone Laboratories announced a new improved system of recording using vertically cut records, and embodying many additional (and probably more important) improvements. A much lighter pickup is employed, so that frequencies as high as 9,000 c.p.s. can be reproduced. Such high-frequency response is further aided by the use of a better record process, which reduces the surface noise sufficiently to allow such high frequencies to be heard.

Because of its importance, the processing method will be discussed next, but, in passing, it is of interest to note that other companies, notably RCA, have improved their lateral type recording until it is comparable to vertical recording, and while such improved techniques have been employed mainly in the broadcast and similar commercial fields, records for home use may be expected to attain as high a level of fidelity in the near future.

MODERN PROCESSING METHODS.—The modern process of producing duplicate records is one of remarkable accu-

TABLE I

RECORD MATRIX PRACTICE

Step No.	Name	Object	Material	Number Per Wax Disc	Used for
1	Original Wax Disc				Original recording and making master matrix.
2	Master Matrix			1	Making metal mold.
3	Metal mold		Electrodeposited copper	Any number desired.	Making Pressing Matrix.
4	Pressing Matrix			Any number desired.	Making final product, the record disc.

racy, and has for its basis the art of electroplating, which can register the most minute variations in a surface. The process consists of four fundamental steps, and is summarized in the preceding Table I, taken from 'Phonograph Record Recording and Reproducing', by A. D. Burt, and presented at the A.I.E.E. Summer Convention, Toronto, Ontario, Canada, in June, 1941.

In Step No. 1 the original, whether a wax disc or a so-called lacquer disc, is prepared for plating. Graphite and mettalic powders have been found to be too coarse and to produce too much surface noise, hence a coating of gold is usually sputtered on the insulating surface. This is done by placing the record in an evacuated vessel, and applying a high d.c. voltage between an electrode and another electrode of gold. The latter slowly evaporates, and a thin film is deposited on the record surface interposed in the path between the electrodes. The film does not melt or otherwise mar the record surface and follows the minutest convolutions in it.

Step No. 2 is to plate a substantial thickness of copper onto the gold surface, and the copper disc is then stripped from the wax. This, incidentally, destroys the original wax record. The copper ridges are then nickel-plated, and the back of the disc is soldered to a metal backing. The result is a master matrix.

Step No. 3 is to make as many metal molds as desired from the one master matrix. The metal molds have grooves in them just as the wax original, and therefore cannot be used directly for pressing records. Instead, they are used to make the stampers or pressing matrices which do the actual pressing.

The metal mold is made from the master matrix by a plating process. To prevent the plating from sticking to the master matrix, the surface of the latter is first treated with a chromate solution. This permits the metal mold to be stripped from it without damage to either.

The metal mold is then used to make the pressing matrices by a similar process (Step No. 4). The latter are also of electrodeposited copper, strengthened by a metal backing, and, in addition, chromium-plated on the recording ridges to withstand the wear and tear of the pressing process. As these wear out, new ones are made from the metal molds.

RECORD MATERIALS.—The original plastics used for records were essentially of a shellac base, and this is still employed where cost is an important consideration. The shellac is mixed with a finely divided clay-like material together with carbon black. The shellac is the binder, the clay is the filler, and the carbon black is the coloring. In addition, other ingredients are added to prevent sticking to the matrix during pressing to prevent warping, to increase the mechanical strength, and to absorb undesirable components in the shellac.

Apparently the clay acts as an abrasive material, for despite statements to the contrary, the needle wear on shellac records greatly exceeds that of other types. This abrasive action may be necessary to grind a steel needle to fit the record groove, but it is a detriment in the case of permanent styli of the sapphire and diamond type. Accordingly, new record materials have been developed that are much superior to the shellac record although more expensive and softer.

Among the more important of these are plasticized vinylite, and cellulose nitrate and acetate, properly plasticized. These materials, especially when used without fillers, are very quiet, but can be employed only with lightweight phonograph pickups—those bearing on the record with 1 ounce of force or less. The question of phonograph pickups will be discussed in greater detail further on. Recently RCA has announced a new record material for home use that is much quieter than the shellac composition previously used, and greatly improved reproduction may be expected from phonograph systems built to take advantage of this new material.

RECORD PRESSING PRACTICE.—A rectangular sheet of record material (biscuit) is placed on a hot plate, and heated until it is soft and semi-molten. It is then ready for the hydraulic press.

The latter contains one record matrix in a cover, and another record matrix in the body of the press. The two matrices are heated by steam prior to placing the pre-heated biscuit on the bottom matrix. The cover is then clamped shut and heated and pressure applied to the biscuit, so that it is forced evenly into the surfaces of the matrix above and below it. The matrices and the record pressing are then cooled by the circulation of water through chambers surrounding these, whereupon the record can be readily removed from the matrices after the pressure is released and the press opened.

Any fins around the periphery of the record are then removed and the record tested for eccentricity. If the hole is off-center by more than a few thousandths of an inch, the record is discarded. The labels are pasted on, and the record is ready for the market.

INSTANTANEOUS RECORDING.—Since the advent of sound broadcasting there has been a growing need for recording systems in which the record could be played back immediately after recording, if desired. Such instantaneous recording cannot be done on the wax original described above because it is too soft and would be destroyed by the pickup, but it can be done on cellulose nitrate and similar discs, and has proved to be a very important phase of recording practice.

It is desirable to record not only historic speeches but ordinary programs, so as to have a permanent record in case some question arises as to the propriety of some remark made, etc. Broadcast companies generally keep such records on file for some time in case any such question arises. Since only one copy is generally required, it is clear that the wax original and plating processes are out of the question owing to their expense. Instead, the engraving is done on a glass or aluminum (or even paper) disc coated with a film, usually of cellulose nitrate.

While the film is readily cut by the recording stylus, it is nevertheless sufficiently rigid and durable to permit a lightweight pickup to be operated from it, and the resultant electrical signal amplified and passed through a loudspeaker. While this technical assignment will be predominantly concerned with this process, nevertheless it is important to have a good picture of the ordinary commercial processes, because actually a large number of the smaller stations employ-the ordinary records, as well as special transcription records, and the above instantaneous recordings, as program material. Moreover, the basic principles are the same for all types of recording, and, therefore, can be studied with reference to all.

In passing, it is interesting to note that awakened interest has developed in this country concerning magnetic recording. This is because where a transitory record is to be kept, such as for sound effects, etc., for some particular program, it is unnecessarily expensive to record such material on a lacquer disc, thereupon rendering it useless for further recording. Instead, such transitory material can be recorded on magnetic tape and then erased by the obliterating head when the need for this recording has ceased, whereupon, the same tape can be employed for another recording. Magnetic recording has enjoyed considerable exploitation in foreign countries, notably England and Germany, and during and since the war has been considerably improved over here.

THEORY OF RECORDING

FUNDAMENTAL FACTORS.—There are at least six fundamental factors involved in the recording and reproducing of sound. These are:

1. Surface Noise
2. Band Width
3. Volume Range
4. Playing Time
5. Nonlinear Distortion, Flutter, etc.
6. Record Life

Of these, the first is probably the most important, and the first four are so closely interrelated that their effects must be evaluated as a unit. Thus, reduction in surface noise permits an increase in any or all of the other three, and for a given amount of surface noise, an increase in volume range, for example, requires a reduction in band width and/or playing time.

SURFACE NOISE.—Like any other communication system, the recording system is not free from a certain amount of extraneous signal known as noise. Some of it is owing to the microphone, some to thermal agitation of the air, thermal noise of coupling resistors, shot effects in the amplifying tubes, etc., but most of it is due to the granular structure of the record material itself. This source is known as surface noise or needle scratch, and it acts as a limit to the quality of the recording.

If there are minute irregularities in the record, these will actuate the needle similar to the undulations of a lateral-cut groove, or the hills and dales of a vertically cut groove. Since the disposition of these irregularities is entirely random, the signal produced is also a random series of pulses, somewhat like thermal or shot noise. However, unlike the latter, it does not have a uniform spectrum, but instead, is composed of frequencies having greater amplitudes at the higher frequencies. A representative spectrum is shown in Fig. 4, for a cellulose acetate record.

Observe that in this case the noise output tends to peak at 8,000 c.p.s., although generally the output continues to rise with frequency beyond possibly 20,000 c.p.s. The spectrum thus indicates that greater interference may be expected with the higher frequencies of a recording, so that these will have to be recorded at a higher level.

support the weight. Thus abrasive material of some sort was necessary for this purpose; unfortunately, this abrasive material was a prolific source of surface noise.

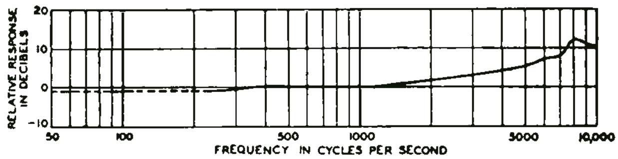


Fig. 4.—Energy distribution of surface noise from a cellulose acetate record.

Another source of noise is that of turntable rumble. This is due to the vibrations set up by the motor, gears, and bearings of the mechanism, and consists of very low-frequency vibrations, say from a few cycles per second up to 100 or 200 c.p.s. A contributing cause is that of building vibration, which may be appreciable in some locations.

Referring to the surface noise once more, it is to be noted that the shellac record containing a clay-like binder is very bad from this viewpoint. In the past it has been necessary to use relatively heavy pickups—4 ounces or more—whose weight on the fine needle point would cause the latter and the record groove to wear unduly unless the groove could wear down the needle point to an area sufficient to support the weight.

With the advent of pickups weighing one ounce or less, permanent sapphire or diamond styli could be used whose shape conformed to the record groove, and hence required no wearing-in process. It is, therefore, unnecessary to employ any abrasive material in the record, and consequently much quieter materials, such as vinylite, can now be used. Although they are softer than shellac, their life is satisfactory when a low-weight pickup is employed, and the only factor mitigating against their use is their greater cost as compared to the shellac record. This differential will probably be reduced in time, since the manufacture of plastics is steadily becoming more efficient and cheaper.

TYPES OF RECORDING.—In order to appreciate the frequency band-width requirements of a recording system, some note must be taken of the action of the pickup.

MAGNETIC PICKUPS.—A typical pickup is shown in Fig. 5. As shown by the dotted lines, the flux from

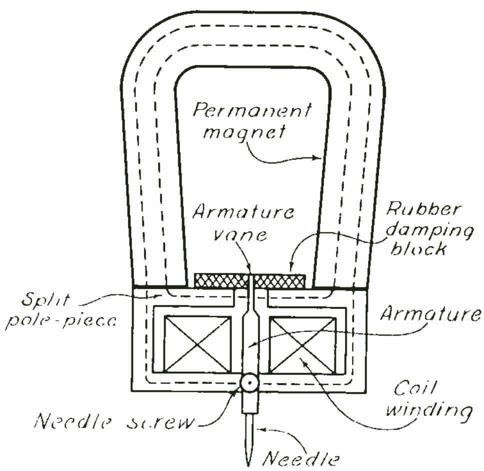


Fig. 5.—Basic pickup structure of the balanced armature magnetic type.

the permanent magnet traverses in part the upper halves of the split pole pieces, and in part the lower halves of the split pole pieces. The division of flux between these two halves depends upon the relative reluctance of the two paths, and usually the top air gaps are greater than the bottom ones, so that less flux traverses the top half, even though the length of path in the iron is somewhat less.

The soft iron armature pivots in a rubber bearing in the lower air gap. This is shown in greater detail in Fig. 6, where an exploded view of the armature and the pole pieces is shown. The rubber bearing consists of two thin sheets of rubber wedged between the armature bearing rod and the lower ends of the pole pieces, so that the armature pivots at this end. These two air gaps are therefore but the thickness of the rubber

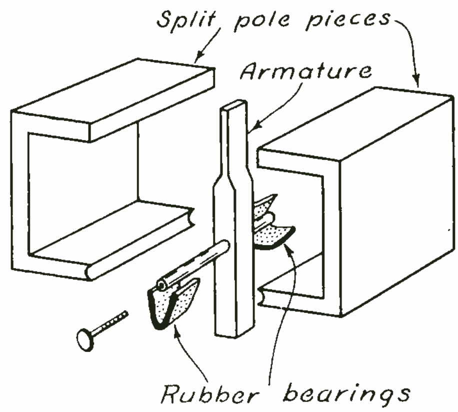


Fig. 6.—Exploded view of armature and split pole pieces.

sheet and hence are short.

On the other hand, the top end of the armature, in the form of a vane, vibrates between the longer air gaps at the top ends of the pole pieces, and thereby causes flux variations in the coil surrounding it and in this way induces voltages in it. It is this action that has to be analyzed to appreciate the band width considerations.

In Fig. 7 (A) is shown the armature with the vane close to the left pole piece. The reduction in the left-hand air gap, and the simultaneous increase in the right-hand air gap, cause a certain amount of flux to pass *down* through the armature, as shown. Of course, flux also passes across the armature pivot via the lower halves of the pole pieces, and some flux traverses the upper right-hand air gap, as shown by the dotted lines, but the important feature is that some flux traverses the armature in a *downward direction.*

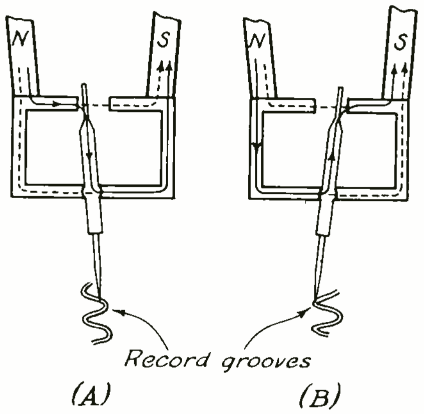


Fig. 7.—**Flux path in vibrating armature.**

In Fig. 7 (B), the armature is in the opposite position, and it will now be observed that the flux passes *upward* through the armature. When the armature is neither inclined to the right nor to the left, but is in an upright position (record groove not modulated) then the top air gaps are equal, and there is no tendency for the flux to seek a lower reluctance path either upward or downward through the armature. For the ordinarily small deflections produced by the record grooves, the flux passing upward or downward through the armature is *practically proportional to the amplitude of the undulation (waviness) of the groove.*

CONSTANT-VELOCITY CONSIDERATIONS.—The voltage induced in the coil surrounding the armature is proportional, however, *to the rate of change of the flux* alternating in the armature, rather than to the amount of flux itself. Thus, consider the case where the record groove causes the armature to deflect a certain distance A, whereupon a certain amount of flux ϕ is set up in the armature.

Suppose that a 100-cycle note has been recorded. Then the armature will deflect from +A to −A 100 times per second, and flux will be set up first of magnitude ϕ, and then of magnitude $-\phi$, the plus and minus corresponding to, say, the upward and downward directions of flow. The rate of change of the flux is from $+\phi$ to $-\phi$, or a total of 2 ϕ lines per cycle. For 100 c.p.s., there will therefore be 200 ϕ lines change *per second.* Corresponding to this there will be a 100-cycle voltage induced in the coil of amplitude e.

Now suppose that a 200-cycle note is recorded *of the same amplitude as the 100-cycle note.* The total change of flux per cycle will again be 2 ϕ, but since the number of cycles per second is twice as great, the total flux change per second will now be 400 ϕ lines change per second instead of 200 ϕ lines. As a result, twice the voltage, or 2e, (at twice the frequency) will be induced in the coil. The basic reason is that the *velocity* of the moving member has been doubled, thereby inducing twice the amplitude of voltage in the coil.

A desirable feature of any audio system is that it have a flat frequency response. This means in the case of the recording system that if sounds of *equal intensity*, but of *different* frequencies be produced in front of the microphone, the voltages induced in the pickups should all be of equal amplitude, although, of course, of correspondingly different frequencies.

Hence, for equal induced voltages, the amplitude of the 200-cycle groove undulation should be *one-half* that for the 100-cycle note; in short, the groove excursion amplitude should vary *inversely* as the frequency. In Fig. 8 the 100-cycle note has an amplitude of A units, the 200-cycle note of A/2 units; and, of course, the 100-cycle wavelength, λ_{100}, as recorded on the record, is twice that of the 200-cycle wavelength, λ_{200}.* Owing to their difference in amplitudes, the two will develop *equal* voltages in a magnetic type of pickup.

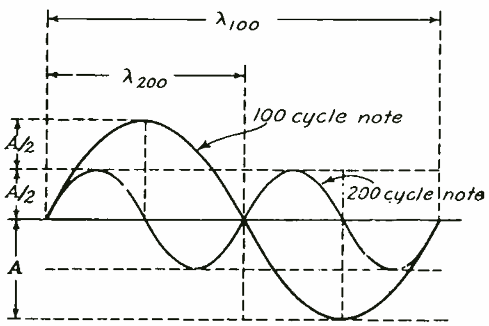


Fig. 8.—Comparision of amplitudes of 100-cycle and 200-cycle notes for constant-velocity recording.

A record recorded in this manner is known as a constant-velocity recording; it is exactly suited to pickups in which the voltage induced is *proportional to the velocity of the vibrating member.* The above balanced-armature pickup is one example; the old acoustic phonograph is another example.

CONSTANT-AMPLITUDE RECORDING.—On the other hand, certain pickups develop a voltage in proportion to the amplitude of the groove. In the previous technical assignment on microphones it was shown that a crystal microphone develops a voltage proportional to the amount of bending or twisting in the crystal element, depending upon the type of element employed. Similarly, a crystal pickup develops a voltage proportional to the deflection, i.e., to the amplitude of the record groove, and in this case, a flat frequency response is obtained only if the amplitude of the groove is *independent of frequency.*

Note that the above analysis is based on *equal* sound intensities impinging upon the microphone. Of course, if a high-frequency sound is louder than a low-frequency sound impinging upon the microphone, then the record groove may be of larger amplitude for the high-frequency sound than for the low-frequency sound, even for constant-velocity recording. This would depend upon the relative loudness of the two sounds and their relative frequencies.

In the very early days of sound recording, no particular thought was given to this factor. With the advent of the orthophonic victrola and of electrical recording, the question of constant-velocity or of constant-amplitude recording arose, and a form of recording curve was adopted that is a combination of the two.

*The actual wave length depends upon the speed of the turntable: 78 r.p.m. for ordinary commercial records used in home phonographs; and 33 1/3 r.p.m. for transcription records used in broadcast stations, etc.

Owing to the fact that acoustic phonographs were in use, it was decided to make the recording fundamentally constant velocity, in order that such phonographs would have an essentially flat response. Today it is rather difficult to define the actual type, or types, of recording employed, but since they have as their basis either of the above two fundamental types, it is necessary to understand what these are before any further features can be discussed.

RECORDING CHARACTERISTIC.—In order to appreciate the need for a recording characteristic, the dimensions of the record grooves must first be given. A typical pitch for the grooves is 112 lines per inch. Hence the center-to-center distance between grooves is 1' ÷112 = 0.00893' or approximately 9 mils. The normal groove has a semi-circular cross section of 2.5 mils radius. Hence the various dimensions will be as shown in Fig. 9. Note that the flat between the grooves is 4 mils.

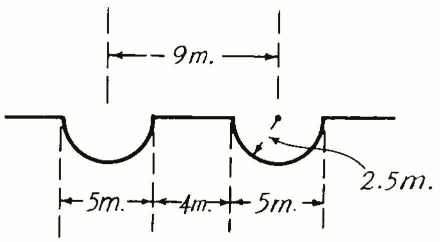


Fig. 9.—Cross section of a record showing typical dimensions for 112 lines per inch.

It is clear that the maximum excursion of either groove cannot exceed half of this, or 2 mils, and actually a lesser excursion is necessary inorder to preserve some side wall between the two grooves. However, for simplicity, assume that 2 mils is the maximum excursion.

HIGH-FREQUENCY LIMITATION.—Suppose this were the maximum excursion for a 50-cycle note *recorded at maximum loudness.* Then a 100-cycle note would have a maximum amplitude of 1 mil; a 1,000-cycle note of 0.1 mil; and a 5,000-cycle note of 0.02 mil, which is admittedly a small excursion. However, the above values were for the loudest sounds to be handled. Suppose the volume range from the loudest to the quietest sounds in 40 db., or 10,000 to 1 in power ratio. This corresponds to a voltage ratio of $\sqrt{10,000}$ to 1 = 100 to 1. *For a given frequency,* the amplitude of the groove varies in direct proportion to the voltage, hence the amplitude ratio would also be 100 to 1 for a 40 db. volume range. This means that the *quietest* 5,000-cycle note would have an amplitude of 1/100 of 0.02 mil or 0.0002 mil = 0.2 millionths of an inch!

METHODS OF OBVIATING THIS LIMITATION.—This is an exceedingly minute amplitude, and not only is it difficult to engrave to such precision, but it can easily be expected that the granular nature of even the smoothest recording material will produce irregularities exceeding this dimension. In short, the surface noise at 5,000 cycles will clearly 'swamp out' this high-frequency low-level signal.

Hence, some modification must be employed to permit the weak high-frequency notes to be heard. One method would be to cut down the volume range, say, from 40 to 20 db.

This would change the amplitude ratios from 100:1 to 10:1, and thus result in a 5,000-cycle note of 2 instead of 0.2 millionths of an inch minimum amplitude. Thus, *at the expense of volume range*, the frequency range can be extended to 5,000 c.p.s., and beyond.

Another possibility is to increase the spacing between the grooves. If this spacing is increased 10-fold, then the minimum 5,000-cycle amplitude will be 2 instead of 0.2 millionths of an inch, similar to the decrease in volume range. However, the distance between groove centers will now be 2.5 + (10x4) + 2.5 = 45 mils, and the pitch will now be only 1 ÷.045 = 22.2 lines per inch. As a result *the playing time will be reduced to* 22.2/112 - 0.1983 or about 1/5 of its previous value.

Either of the above methods of obtaining a satisfactory high-frequency response or band width is undesirable because of the adverse effect upon the other factors fundamental to recording, namely volume range and playing time. Hence another means has been adopted, and that is to record at constant velocity from 250 c.p.s. or thereabouts up to the highest frequency, and *at constant amplitude* below 250 c.p.s.

This characteristic results in a 2 mil *maximum* amplitude for all frequencies from *250 c.p.s. and down*, and a minimum amplitude at 5,000 cycles (for db volume range) of 250/50 = 5 times 0.2 = 1 millionth of an inch, and 0.5 millionth of an inch at 10,000 c.p.s., if a range out to this point is desired.

Before continuing the discussion of the high-frequency end, it is of interest to note that if the amplitude remains constant from 250 c.p.s. down, then at 125 c.p.s., for example, the voltage generated by a constant-velocity type of pickup, for equal sound intensity, will be one-half that generated at 250 c.p.s. This results in a four-fold reduction in power, or 10 log 4 = 6 db in power. Since 125 c.p.s. is one octave lower than 250 c.p.s., the constant amplitude type of recording is said to produce a 6 db loss per octave as one goes down the frequency scale.

However, such loss may easily be compensated for in the reproducing system by interposing an equalizer network between the pickup and the amplifier, so as to attenuate the frequencies in inverse manner and thus give an overall flat response. This is illustrated in Fig. 10. The recorder response falls

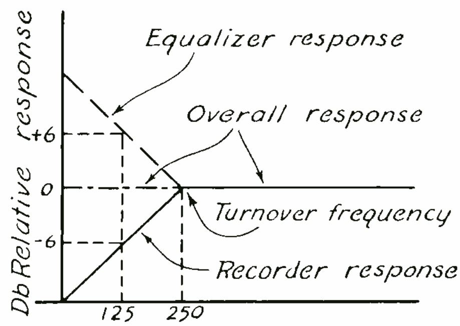


Fig. 10.—Recording and reproducing response curves, showing complementary attenuation characteristics that produce a flat response.

off 6 db per octave below 250 c.p.s., the turnover frequency. The equalizer response therefore has to rise 6 db per octave below 250 c.p.s. in order that the overall response be flat down, say, to 50 c.p.s.

Of course it must be appreciated that since the recorder response falls to very low values at very low frequencies, it is not possible in practice to equalize down to such low values owing to factors like noise, particularly turn-table rumble. However, equalization down to 50 c.p.s. is perfectly feasible, and this is a satisfactory lower limit to the audio response.

An important thing to note is that if the band width were reduced *at either end*, then the turnover frequency could be shifted so as to increase *either the playing time* or *the volume range*. For example, suppose the lowest frequency to be recorded was 100 c.p.s. instead of 50 c.p.s. Then the turnover frequency could be raised to 500 c.p.s. instead of 250 c.p.s. and still not require more than a little over 12 db equalization. But for the same upper frequency *minimum amplitude*, the *maximum amplitude* at 500 c.p.s. could be half of its previous value.

Thus, if 1 millionth of an inch is the minimum permissible amplitude at 5,000 c.p.s., then at 250 c.p.s. (for constant-velocity recording) the maximum amplitude is 2 mils for 40 db volume range. But of a constant-velocity characteristic is to be had only down to 500 c.p.s., and constant amplitude below this, then for the same 40 db volume range, the maximum amplitude will be only 1 mil. This means that the record grooves could be spaced more closely, and thus the playing time increased for a given size record.

On the other hand, if the same *2 mil* maximum amplitude were employed, instead of 1 mil at 500 c.p.s., the playing time would be unchanged, but the volume range would be increased $(2)^2 = 4$ times or 6 db, i.e., a total of 46 db instead of 40. Thus the band width, playing time, and volume range are all interrelated, and any change in one produces opposite changes in the others.

IMPORTANCE OF ELIMINATING SURFACE NOISE.—The foregoing discussion really points out a fundamental relationship, namely, that *reduction in surface noise* permits an improvement in frequency band width, and/or volume range; and/or playing time. For this reason high-fidelity records are practically impossible unless the recording and duplicating processes and the record material give the minimum amount of surface noise attainable today. Hence, substitution of the gold-sputtering process for the graphite coating preliminary to the plating of the original wax recording, elimination of the clay-like material in shellac, and, indeed, the substitution of the quieter vinylite and cellulose nitrate and acetate compositions for the shellac, are all necessary before records of really wide band, large volume range, and long playing time are possible.

CONSTANT AMPLITUDE CHARACTERISTIC.—Examination of Fig. 10 shows that the record is cut at constant amplitude up to 250 c.p.s., and then at constant velocity above this frequency, whereupon the amplitude begins to decrease as the frequency goes up, until at a very high frequency the amplitude is scarcely sufficient to override the surface noise. Apparently, the only reason for this constant-velocity portion of the curve is to permit the use of acoustic phonographs, and the like, that require such a type of recording for flat frequency response.

Since the low-frequency portion of the curve departs from constant velocity, and is constant amplitude instead, the question naturally arises, 'Why not record at constant-amplitude throughout the range, and employ an equalizer of the type shown in Fig. 10 for constant-velocity pickups, and use the record directly for constant-amplitude pickups, such as of the crystal type?'

While such a recording might require undue peaking of the lows compared to the highs in the equalizer, nevertheless some such arrangement might be feasible, and would result in the higher frequencies easily overriding the surface noise. However, a mechanical difficulty would arise, at least for *high-level high-frequency* tones. Reference is made to needle-tracking.

EFFECT OF NEEDLE SIZE.—It must be remembered that the record is essentially a *cam* that drives the needle at an audio-frequency rate. The ability of the record to drive the needle depends upon the size of the groove relative to the needle tip, the steepness of the groove excursion, and the mechanical impedance of the pickup mechanism.

Of paramount importance is the steepness of the groove excursion. In Fig. 11 (A) is shown a high-frequency wave of high-level, hence large amplitude. The needle tip is normally not a point, but a tiny spherical surface of about 2.5 mils radius. This is particularly true of the permanent type of stylus. For example, the diamond-point stylus used in the RCA MI-4856 reproducer has a radius of 2.3 ± 0.1 mil.

Note that owing to the steepness of the wave, the needle tip may not fit in the groove, and in addition, will experience difficulty in being driven nearly perpendicularly to the direction of motion *at the zero points of the wave.* Such oblique motion is difficult even if the needle tip fits in the groove. On the other hand, the low-frequency wave of (B) has no difficulty in accommodating the needle tip. If the amplitude of the high-frequency wave is reduced, as in (C) the wave can also accomodate the needle tip, so that no difficulty is experienced in making the needle track in the groove, and, in addition, the grooves are not as steep.

Thus the size of the needle tip

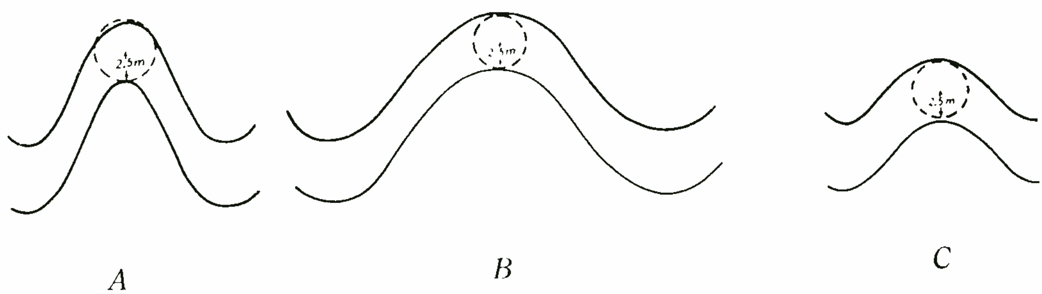


Fig. 11.—Effect of needle tip dimension on limiting high-frequency high-level response.

determines the highest frequency and level that can be reproduced. At the time electrical recording was introduced, it was felt that the higher frequencies could be successfully reproduced only if they were attenuated sufficiently in recording to obtain the effect shown in (C), Fig. 11, and hence a recording characteristic as shown in Fig. 12 was employed. Besides the turnover

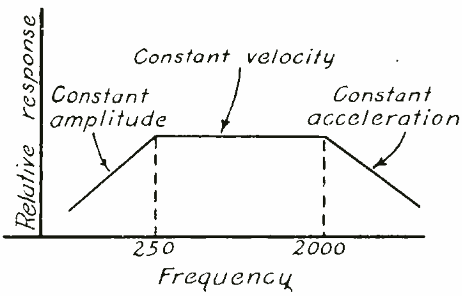


Fig. 12.—Overall recording characteristic.

frequency at 250 c.p.s., there was another at about 2,000 c.p.s. From this frequency on, the amplitude varied inversely as the *square* of the frequency, so that for a velocity type pickup the response actually dropped.

For a sine wave, if the amplitude varies inversely as the square of the frequency, the *acceleration* of the vibrating needle system is constant and independent of frequency, hence the upper portion of the curve is called a *constant acceleration characteristic.* The advantage is that if the acceleration of the moving system is constant, the amplitude shrinks with frequency in just the right manner with the *recorded* wavelength to be able to accommodate the needle tip in the groove. Refer to Fig. 11 (A) and (C) once again.

ORTHACOUSTIC RECORDING.—The above reasoning was sound but resulted in the amplitude shrinking so fast with frequency that the high-frequencies were easily swamped out by the surface noise, so that the fact that the needle tracked better in the groove at those frequencies was not of practical importance. It was not long before it was realized that from a practical viewpoint, there was no need to attenuate the higher frequencies as indicated in Fig. 12, and, in fact, it was of advantage to *peak* them.

This comes about from two facts. The first is that the surface noise increases in strength with frequency (see Fig. 4), so that if the same favorable signal-to-noise ratio that obtains at low frequencies is desired at high frequencies, it is necessary that the high frequencies be peaked to somewhat the same degree as the way the noise peaks. Then, if a high-frequency attenuation circuit is included in the reproducing equalizer, the high frequencies will be de-emphasized to the same relative level as the low frequencies, and the surface noise will be brought down below audibility.

The second fact is that the ordinary sounds encountered in practice contain most of their energy around 300 c.p.s., and very little above about 3,000 c.p.s., or below about 100 c.p.s. In Fig. 13 is shown the relative energies in the spectrum for a 75-piece orchestra on the basis of the most probable peak energy, since the actual frequencies generated depend upon the nature of the music. It will be observed that very little energy is encountered, particularly above 5,000, and below 70 c.p.s.

If this is the case, then there is no need to fear overcutting of the grooves at the low frequencies,

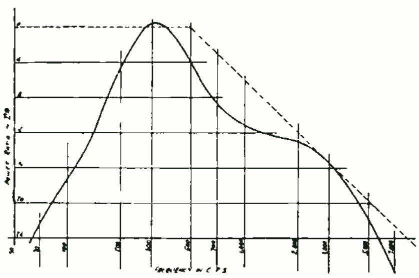


Fig. 13.—Spectral distribution of most probable peak energy for 75-piece orchestra.

or excessively steep wave fronts at the high frequencies. Instead, the recording characteristic can combine constant-velocity and constant-amplitude characteristics in any proportion desired; in short, the characteristic can be made to overcome practical difficulties that are encountered.

It was with this in mind that NBC developed their orthacoustic type of recording. The recording characteristic is given in Fig. 14, and the complementary reproducing characteristic in Fig. 15.

If the reproducing filter were not employed, then a perfect or ideal velocity-type pickup would have a frequency response similar to that of Fig. 14. This indicates that Fig. 14 is based roughly on a constant-amplitude characteristic.

There are, however, important deviations. One such deviation is that at 50 c.p.s. and below. Note that an approach to constant-velocity, with the attendant rise in amplitude, is employed here. In reproducing, very little attenuation is therefore employed in the equalizer below 50 c.p.s. This is done

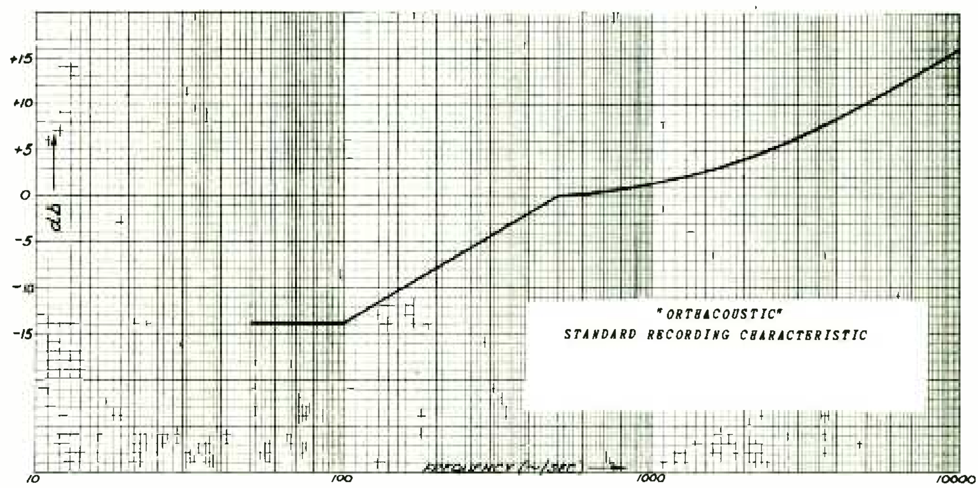


Fig. 14.—Orthacoustic recording characteristic.

so that turntable rumble will not tend to predominate over the low-frequency response, as would be the case if constant-amplitude recording were used in this part of the spectrum.

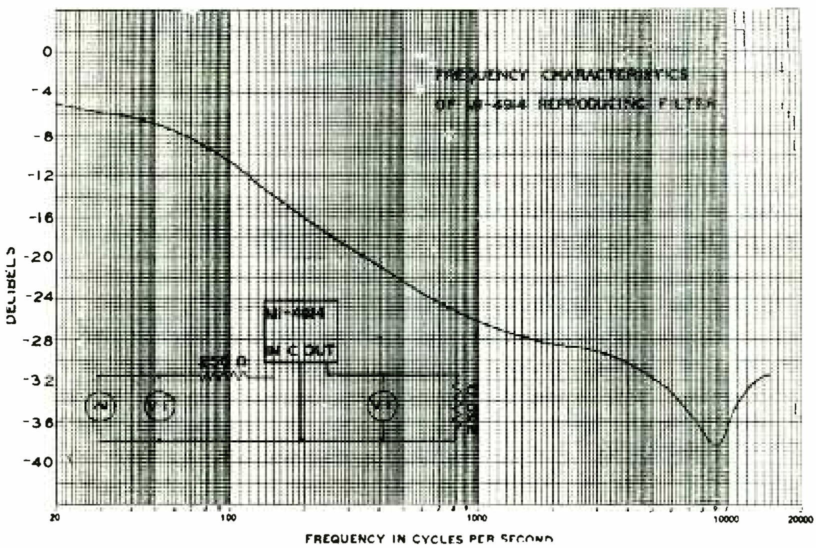


Fig. 15.—Orthacoustic reproducing characteristic.

At the high frequencies, roughly above 5,000 c.p.s., the recording response is peaked to a greater extent than would be the case for constant-amplitude recording, and must therefore be attenuated at a correspondingly greater rate. This—as explained previously—produces a more favorable ratio of signal to noise *at the higher frequencies*.

The pre-emphasis at the low and high frequencies in the orthacoustic system is based on the fact that the energy content at these frequencies is low—as shown in Fig. 12—so that no danger of overcutting from one groove to the other need be feared at the low frequencies, nor danger in failure to track at the high frequencies. However, there may be some question of excessive distortion if the high frequencies are peaked. This will be discussed further on.

In ordinary commercial practice, various recording characteristics are employed by different recording companies, and this makes it difficult to design a phonograph system that will reproduce satisfactorily records of different manufacture. The orthacoustic characteristic is an attempt at standardization on the part of one of the major broadcasting companies.

DISTORTION.—The recording process can very easily produce excessive distortion, both in engraving and in the retracing of the groove by the needle. These two mechanical activities seem to produce more distortion than the electrical amplifying processes, or even the loudspeaker and microphone units. Accordingly, it will be of value to analyze the distortion produced and to note its effects.

RECORDING VS. REPRODUCING STYLUS.—An important source of distortion is the difference between the shapes of the recording and the reproducing styli. Generally, especially in wax recording, the recording stylus is a chisel-shaped cutter, of the shape shown in Fig. 16, and the reproducing stylus

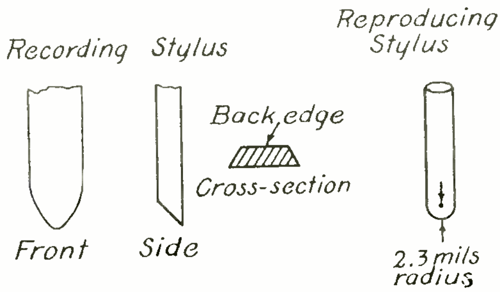


Fig. 16.—Shape of recording and reproducing styli.

is a cylinder with a spherical tip, of about 2.3 radius. If a steel needle is used, the shank tapers down to what may be a point, but after a few seconds playing the tip assumes a more or less spherical shape conforming to the record groove.

LATERAL-CUT TRACING DISTORTION.—Suppose the cutter engraves a sine wave groove. Since the cutter is flat and vibrates parallel to its long cross-sectional dimension, it cuts a groove which is narrower at the zero points of the sine wave than at the peaks. This is shown in Fig. 17. The solid trapezoidal figures represent the recording stylus; the dotted circles, the reproducing stylus.

It is clear from the figure that the reproducing stylus is pinched by the narrow parts of the groove and forced upward, so that a smaller segment of its spherical tip will rest on the groove at such constricted regions; whereas at the

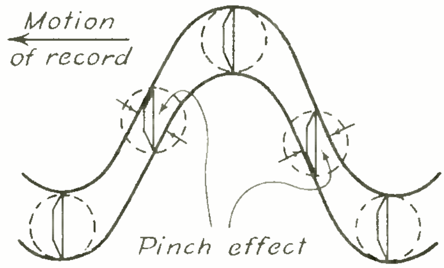


Fig. 17.—Shape of recorded groove for sinusoidal input.

peaks the needle will move downward, so that a larger segment of its spherical tip contacts the groove at these points. Thus, the needle not only vibrates laterally, as is desired, but also vertically, owing to the pinch effect, as this is called.

Many lateral pickups are designed today to have a certain amount of freedom of motion in the vertical direction to accommodate themselves to the pinch effect, while at the same time every effort is made in the design to prevent such vertical motion from producing any extraneous signal. This will be seen later. However, calculations made on ordinary record materials indicate that the groove walls have enough elastic 'give' to spread somewhat and thus permit the needle to ride at a perfectly even keel vertically. Indeed, it has long been observer that the output of a pickup is usually less than the groove excursion would indicate to be expected. This has been explained as owing to the *lateral* 'give' in the record walls. Hence, it is quite reasonable to expect that a similar vertical 'give' takes place to relieve the pinch effect.

However, even if this 'give' is present either in the record walls or in the pickup, it is also true that *the center of the needle tip,* in tracing the record groove, does not follow exactly the same path as did the recording stylus in the process of engraving the groove. This is owing to the *difference in cross-sectional shapes* of the two styli. The result is distortion; specifically, if a sine wave is recorded, something other than a sine wave is traced by the reproducing stylus. This is known as *tracing distortion.*

The distortion is most pronounced for high-frequency large-amplitude sounds, since for these the wave is steepest, and the pinch effect and the distortion are therefore greatest. This has raised the question in the minds of some engineers as to the advisability of peaking the high-frequency response, as indicated in Fig. 14, for example, because of the rise in tracing distortion with increase in amplitude. On the other hand, it was shown that the signal-to-noise ratio is benefited by such peaking, and so it is a question as to which is the more important consideration.

Probably the signal-to-noise ratio will be the more important until such time as a record material is found that is so free from surface noise that no concern need be felt about the high-frequency tones being lost in the background of noise. Consequently, it will be found that peaking of the high frequencies in recording and their subsequent attenuation in reproduction represents, in general, the best practice today, and very satisfactory results are obtained thereby.

VERTICAL-CUT TRACING DISTORTION.—When the high-fidelity vertical type of recording was introduced around 1932, one advantage stated for it was that it was free from the above pinch effect and attendant distortion, although another kind of tracing distortion was recognized. This arises also from the fact that the recording and reproducing styli are of different shapes.

In Fig. 18 is shown a chisel-

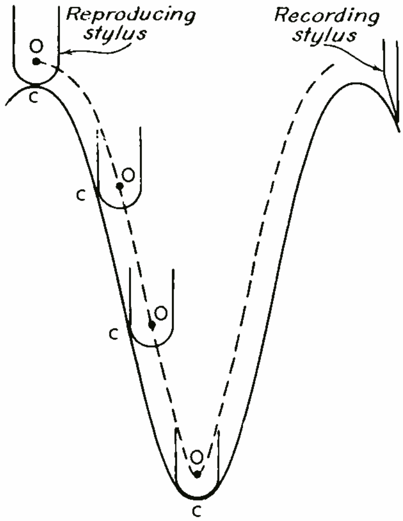


Fig. 18.—Tracing distortion for vertical-cut record.

shaped recording stylus cutting a sine wave groove. A reproducing stylus having a spherical tip is also shown tracing the same groove. Note particularly how the point of contact C between the record wall and the stylus, rolls back and forth, as it were, as the stylus drops down into the valleys and rises up to the peaks. The motion of the armature or moving coil actuated by the needle corresponds to the motion of the *center* O of the spherical needle tip rather than to the *point of contact* C. As indicated by the dotted line, the path followed by the center O is flattened at the tops and very peaked at the troughs, hence quite different from the sinusoidal wave recorded. The asymmetry of the dotted line curve denotes the presence of at least even harmonics, notably the second.

On the other hand, the path traced out by the center of the needle in Fig. 17 is one that is symmetrical, since conditions are the same at both peaks and different from the zero points of the recorded sine wave. This symmetry indicates the presence of odd harmonics, notably the third.

COMPARISON OF TWO TYPES OF RECORDING.—The distortion produces for either type of recording may be appreciable if the frequency is sufficiently high or the reproducing stylus is unduly large. An analysis of the tracing distortion for either type by Hunt and Pierce* indicates that the lateral-cut record groove acts in a push-pull manner, since first one wall acts on the needle in one direction, and then the other wall acts in the opposite direction, whereas the vertical-cut record acts more like a single-ended stage. This is borne out by the absence of even-harmonic tracing distortion in the case of the lateral-cut record.

The analysis indicates that the lateral cut record apparently produces less tracing distortion for a given size needle, amplitude of groove, and frequency, than does the vertical-cut record, particularly at high levels. There is thus, apparently, no reason to expect the lateral type of recording to be discarded in time. In actual practice, either type of recording, if carefully made, gives excellent results.

PLAYING TIME.—The relation between playing time, volume range, band width, and surface noise has been discussed above. One further point concerning playing time is apropos at this time, and that is the relative advantage of vertical over lateral recording in this respect.

In lateral recording sufficient space between the grooves must be allowed for their undulations, which are a maximum at maximum volume level and at the turnover frequency and below. A spacing of 4 mils has been indicated previously; this must be reduced if more than 112 grooves per inch are to be accommodated, whereupon the maximum level must be reduced.

In the case of vertical recording, the undulations are into the thickness of the record, so that presumably the grooves can be spaced more closely together without interfering with one another. Indeed, it has been proposed to have the grooves overlap one another somewhat, as is indicated in Fig. 19. Here a radial cross section of a portion of the record is shown. Note the variable depth of successive grooves, which is the characteristic of vertical recording. As shown in the figure, the side walls of any one groove are overlapped by those of its neighbors

*F. V. Hunt and G. N. Pierce, "Distortion in Sound Reproduction from Phonograph Records", Jour. Soc. Mot. Pic. Eng., Vol. 31, pp. 157-182; August, 1938.

and have therefore been cut away, so that only the bottom of the groove remains in many cases.

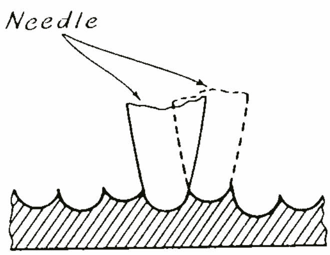


Fig. 19.—Overlapping of grooves in vertical-cut record.

However, the needle can still track in any one groove since there is sufficient support for it. This is indicated by Fig. 19, where the position of the needle in two successive grooves is indicated by the solid and dotted lines. Unfortunately, such close spacing of the grooves is not feasible in practice. It appears that when any one groove is being cut, the stresses set up are communicated to the neighboring areas and produce slight deformation in those regions. If the grooves are spaced too closely together, 'echos' of the one groove appear in the adjacent grooves, and thus produce interference.

Furthermore, the cutter stylus has a shape as shown in Fig. 16, and it is clear that as the stylus digs into the groove, the width of the latter is increased, particularly on a loud passage. Hence, while vertical recording permits a longer playing time or volume range than lateral recording, the improvement is not as great as was first anticipated, and it is possible to record nearly 15 minutes of material on a 16-inch disc using lateral recording at 33 1/3 r.p.m., just as in the case of vertical recording.

RECORDING AND REPRODUCING SYSTEMS

GENERAL LAYOUT.—The general layout of a recording system follows broadcast practice very closely. Thus the microphones, mixer, program amplifier, and audio bus in the broadcast system have their counterpart in the recording system. The latter is shown in Fig. 20. Across the audio bus are bridged several recorders, as well as the monitor amplifier and speaker. The object in using several recorders is to guard against failure on the part of one unit from necessitating a retake. This would mean the reassembling of expensive talent, and is, of course, to be avoided.

Even when film recordings are to be made, as for sound motion pictures, a separate disc recorder is usually also bridged across the audio bus. Instantaneous recording discs, such as of the cellulose nitrate type, are employed, and immediately after the performance these are played back. Any errors or poor quality in the recording can immediately be detected while the cast is still assembled.

Usually, the recorder consists of a bridging recording amplifier, a recorder head, and a high-grade turntable. In the wax-type recorders, a suction pump and nozzle is also furnished to suck off the shavings. In the case of the cellulose nitrate (or acetate, as they are often erroneously labeled) instantaneous records, the shaving is generally wound on the spindle, or else removed at intervals, although suction is being employed more and more, particularly for outside-in recordings.

RECORDING AMPLIFIER.—Recording amplifiers are often of the same type as monitor amplifiers. Representative output levels are from 8 to 12 watts, and a representive frequency response is from 40 to 10,000 c.p.s. The amplifier must be relatively free of noise and hum; i.e., the power supply must be well-filtered.

Very often, as in auditioning, a system completely separate from the broadcast equipment will be employed, including a microphone, an amplifier that can be used for recording or play-back, a recorder head, a reproducer (pickup), and loudspeakers. In such an arrangement the amplifier may very well have a gain of 110 db and may operate directly from the microphone, or the amplifier may have a gain of 90 db and be preceded by a mixer and individual pre-amplifiers of about 36 db gain, one for each microphone. This represents a more elaborate system that is in itself a small broadcast system.

In addition, a radio tuner may be furnished for off-the-air recordings. These may be made for clients and sponsers to give them an idea as to how the program sounded over the air. The tuner also obviates the need for tapping in on the studio lines. It must therefore be of the high-fidelity type, and a representative response characteristic is one that is flat from 50 to 8,000 c.p.s., and for a 1,000 kc carrier is down 5 db at ± 18 kc limits, to insure reasonably good selectivity in spite of the high-fidelity requirements. The output level is usually 0 db (.006 watt).

In general, the recording amplifiers are of typical design and are equivalent to those employed in broadcast practice or in high-grade public address systems. The same is true of the microphones and of the loudspeakers employed in reproducing

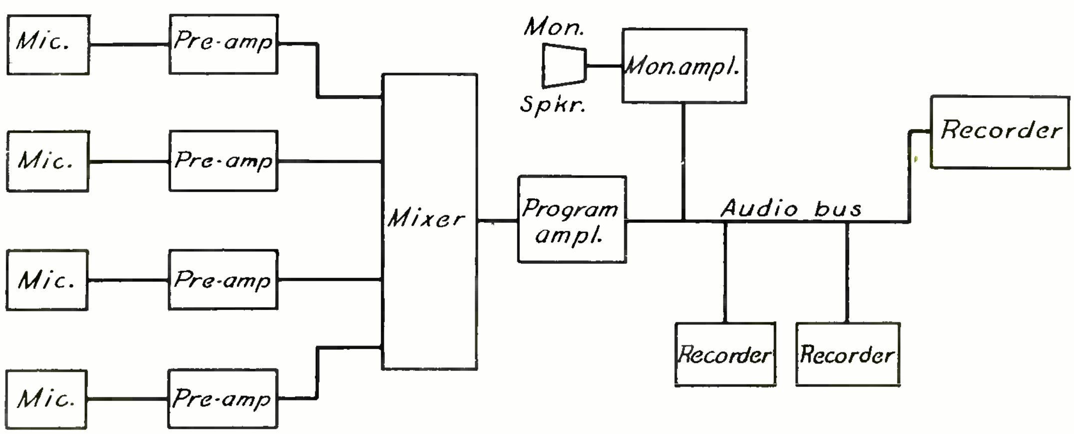


Fig. 20.—Typical recording system layout.

the recording.

TURNTABLE DRIVE.—The recorder is essentially a vertical lathe, but one of extreme precision, although of low power. Probably the most important requirement is that the turntable platter rotate at absolutely constant speed.

FLUTTER AND WOWS.—Variations in turntable speed can be classified in two divisions:

(1) Slow variations in speed that produce a variation in pitch heard as 'wows', and which are particularly objectionable. A slight but *constant* departure in the actual speed of the reproducing turntable from that of the recording turntable is not particularly objectionable, but the deviations from *constancy of speed for either turntable* must be held below a certain minimum.

Tests indicate that 0.3 per cent variation at a rate of from one to three times or cycles per second can be detected for a 1,000-cycle tone. For rates other than the above 1 to 3 cycles per second, a higher percentage is required to be just detectable by the ear. This then forms a maximum deviation in constancy of speed for 78 r.p.m. records, since 1 revolution is in between 1 and 3 cycles per second, and any variation per revolution will be, therefore, noticed if it exceeds the 0.3 per cent given above. A slightly greater variation is permissible for a 33 1/3 r.p.m. record.

(2) Rapid variations in speed that occur at a sufficient rate (number of times per second) so as to produce a flutter effect in the sound. If the rate is high enough (possibly 70 c.p.s. or greater) then all sense of pitch variation is lost, but constant-frequency recordings—such as test notes—develop sidebands that are not harmonically related to the frequency in question and produce a definite harshness in the tone. These sidebands can be regarded as produced by a kind of frequency modulation of the test tone, owing to the rapid fluctuations in speed from the average value.

TURNTABLE DESIGN.—In order to reduce both slow and rapid speed fluctuations below the minimum values that can be detected, it is necessary to design the turntable drive unit very carefully. Many designs are quite elaborate; others, surprisingly simple; but in all cases one difficulty that is encountered is that a drive which is initially 'wow-free', may in time develop appreciable speed fluctuations; in short, a good design must maintain its initial adjustment over a long period of time with a minimum of attention.

In order to eliminate 'wows', a fairly heavy platter must be used, that rotates upon perfectly uniform bearings, and is driven by pulleys or gears that run perfectly true. In order to eliminate flutter and higher frequency speed fluctuations, a heavy platter is also required, but it must not be directly gear-driven from the motor; instead, it requires a flexible drive coupling of some sort interposed between it and the final drive gear.

It appears that no two gears can be cut with sufficient accuracy to mesh without some vibration owing to tooth contacts, which would produce a high-frequency or flutter effect, and no gear is free from one or more high spots, which would produce a 'wow'. One attempt to solve this, employed by Western Electric in their highest grade wax recorder, is to use a worm gear driven by a worm.

WESTERN ELECTRIC DRIVE.—The worm gear is sliced into four laminations and then each of the four laminations or slices is given a quarter turn before being placed on the lamination beneath it again. This is shown at the left in Fig. 21. Any high spot on the original gear

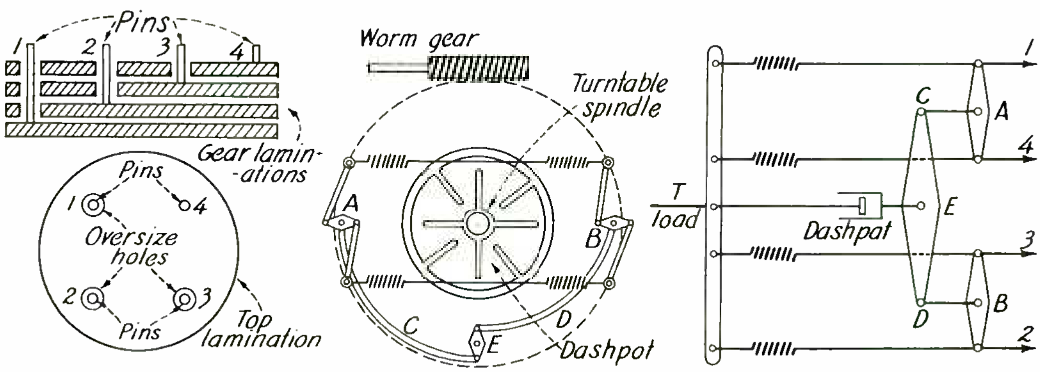


Fig. 21.—Diagrams illustrating averaging linkage described by Elmer and Blattner, and straight-line analogue. In actual structure, each gear lamina carried two pins, and equalizing links were in duplicate.

blank is thus distributed by the arrangement of the four laminations into four high spots of lesser magnitude. Moreover, four fluctuations per revolution are produced instead of one, and the mechanical filter used in conjuction with the above gear drive can more easily filter the higher-frequency fluctuations.

Another ingenious feature is the manner in which the four laminations drive the turntable shaft. The principle is based on the whiffletree type of drive used for a wagon drawn by several horses and is illustrated in Fig. 21.

Each lamination has a pin connected to it. This pin passes freely through oversize holes in the laminations above the one to which the pin is connected so that the lamination and pin can rotate slightly, relative to the other lamination if it so desires. Each pair of adjacent pins, such as 1 and 4, or 2 and 3, are connected to a center cross lever A or B by means of individual levers. The two center cross levers in turn pivot on curved lever arms, C and D which connect to a third cross lever E. This in turn pivots on an extension of a cylindrical dash pot and thereby rotates the latter. (Actually two such sets of levers are employed.

Each pin also connects through a spring and lever to one of two pins on the vanes of that part of the dash pot that is fastened directly to the turntable. If any one of the four gear pins say No. 1 tends to move faster or slower than the three others, because perhaps a high spot on its lamination happens at that moment, to connect with the worm gear, its spring stretches so as not directly to communicate this difference in speed to the turntable spindle. At the same time such differential motion also causes the cross lever A to rotate slightly on its pin, so that the latter and the curved lever on which it is mounted have only about half of this irregularity of motion imparted to them.

The curved lever C then causes a slight rotational effect of the cross lever E to which it is connected, thereby imparting only about

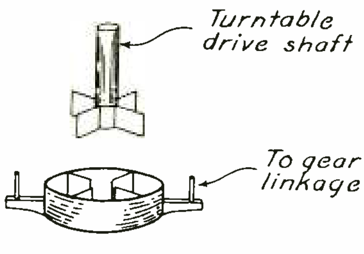


Fig. 22.—Dash pot arrangement for recorder.

half of its irregulatity in motion to the cylindrical dash pot. The dash pot therefore moves with very nearly constant speed, too. It is further illustrated in Fig. 22. The vanes on the turntable drive shaft fit between those of the other cylindrical member, and the latter is filled with oil of suitable viscosity. Any relative motion between the two sets of vanes produces a swirling of the oil in the narrow passages between them, and the viscous forces set up thereby rapidly damp out such motion. The amount of damping is sufficient to prevent free oscillations between the springs and the masses involved, particularly that of the turntable.

This turntable drive is admittedly very elaborate and expensive, but it reduces speed variations to probably below 0.1 per cent at 33 1/3 r.p.m. Such a low value, and the care and expense in obtaining it, are justified on the basis that greater tolerance is thereby possible in the reproducing machines, which greatly outnumber the recording machines. The above recorder

Fig. 23.—High quality transcription turntable.

exhibits very clearly the various components required for a successful drive, namely, the gear arrangement, the spring assembly, and the damping mechanism.

RCA TRANSCRIPTION TURNTABLE.— A correspondingly elaborate turntable for broadcast transcription purposes is shown in Fig. 23. This unit is of sufficiently high quality to be used not only for reproducing purposes, but for recording attachment is required and will be described later.

The drive mechanism consists of a high torque synchronous mo-

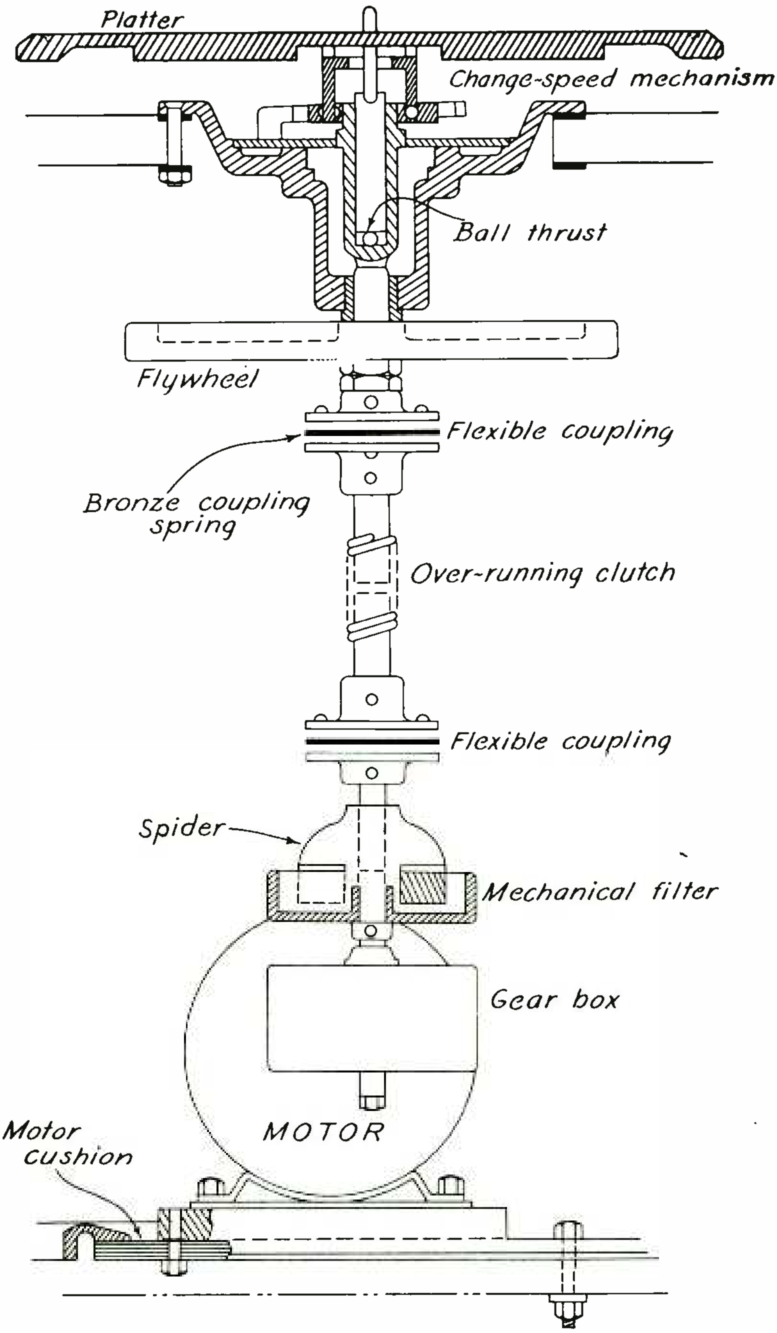


Fig. 24.—Drive mechanism of RCA transcription turntable.

tor, cushion-mounted at the bottom of the cabinet, and which drives the platter (upon which the record rests) through a worm reduction gear, a mechanical filter, two couplings an over-running clutch, a flywheel stabilizer, and finally a ballbearing type of speed-change mechanism. The arrangement is shown in Fig. 24.

The mechanical filter consists of a cup-like arrangement with two vanes, fastened to the gear box shaft. Into this cup projects a spider, keyed to the shaft above, and having two vanes that fit in between the vanes of the upper shaft. Between the sets of vanes are felt pads saturated in oil. These pads act both as spring couplings and as dampers, since the structure of the felt makes it have high internal viscosity as well as elasticity. The oil produces a uniform frictional effect that makes the damping smoother.

The flexible couplings take care of slight misalignments in the series of shafts, and also help filter out some of the vibration. Each coupling consists of two flanges with respect to one another. These pins fit in holes in a central bronze disc or coupling spring which transmits the motion from the lower to the upper shaft.

The over-running clutch is a coil spring arrangement that acts like a ratchet. The platter can be turned clockwise with respect to the drive shaft, the spring permitting such relative motion. Thus the record can be set at any position desired before the turntable motor is turned on.

If it is attempted to turn the platter in a counterclockwise direction, the spring clutch engages and prevents such motion, because this would require the worm mechanism in the gear box to be driven in the reverse direction. Perhaps the most important reason for the over-running clutch is with reference to the gear box; if the heavy platter and flywheel are revolving at normal speed, and the motor is shut off, the relatively high friction in the gear box, etc., causes this part to tend to decelerate faster than the platter. As a result, the platter tends to run the gear box, which is irreversible, and hence may set up strains in the gears and cause damage. By the use of an over-running clutch, the platter can over-ride the gear box and thus obviate such possible damage.

Although a sixteen inch platter

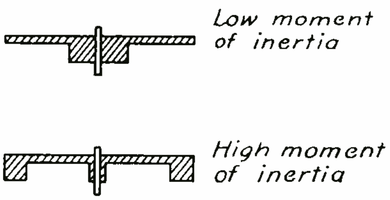


Fig. 25.—Two wheels of equal weight having different moments of inertia.

is employed, additional inertia is provided by the flywheel shown. This aids greatly in maintaining constancy of speed, *particularly since the flywheel rotates at all times at 78 r.p.m.* In connection with this it is important to note that it is not the mass of the flywheel or platter, but rather its *moment of inertia,* that promotes constancy of speed. The moment of inertia is popularly known as the flywheel effect, and in Fig. 25 are shown two wheels of equal mass and weight that have different moments of inertia or flywheel effect. From the figure it is clear that to obtain maximum moment of inertia for a given weight of flywheel and diameter, the material should be distributed as far away from the center as possible.

The change-speed mechanism is of a rather novel design. If this were of a gear shift type *located in the gear box*, then the mechanical filter following it would remove any of the gear vibrations, but the flywheel would then rotate at 331/3 r. p.m. if a platter speed of 331/3 r. p.m. were desired, and the flywheel effect would be reduced. This would prevent as perfect an elimination of 'wows' compared to a flywheel speed of 78 r.p.m., although either speed would probably be adequate for removal of the higher frequency flutter effect.

On the other hand, if the change speed mechanism is located *after* the flywheel, as is actually the case, then if it is of the gear type, it will introduce flutter into the platter, unless additional filtering is employed, whereupon the flywheel would be of little value since it would be mechanically decoupled by such a filter from the platter.

Hence the change-speed mechanism, interposed between the flywheel and platter (so that the flywheel can rotate at all times at the higher speed of 78 r.p.m.) is of a gearless type. Specifically, it is a ball bearing assembly operating as a kind of friction planetary drive. It is shown in Fig. 26. The top ring is actually part of the platter and rotates with it as one unit. The three nibs in it fit between the three balls in the ball race shown below it. The locking ring shown below actually fits around the outer ball race.

A lever arrangement (not shown), operated by a pawl in a slot in the platter, either locks the locking ring and outer race to the platter for 78 r.p.m., or to a stationary

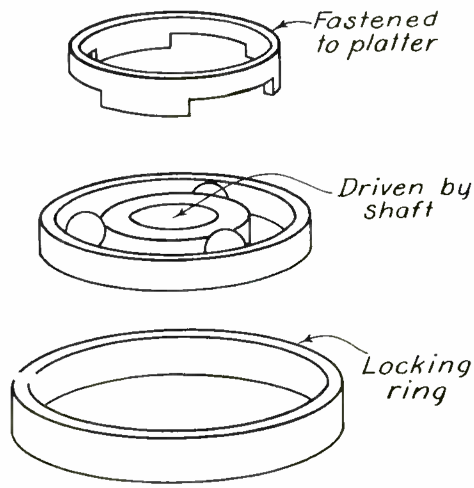


Fig. 26.—Speed-change mechanism.

part of the housing structure for 33 1/3 r.p.m. Consider the 78 r.p.m. position, in which the outer race is fastened to the platter. Since the nibs between the three balls are also fastened to the platter, it is clear that the balls and outer race must revolve at one and the same speed.

If this common speed were to be different from that of the inner race keyed to the drive shaft, then the balls would have to slide, rather than roll on the inner face, and owing to the precision fit in a ball-bearing, the friction is far too great to permit such slipping for any reasonable load on the platter. Hence, the platter, outer race, balls, and inner race all revolve at the speed of the drive shaft, which is 78 r.p.m.

Next consider the 33 1/3 r.p.m-position. Now the outer race is *fixed in space,* rather than fixed to the platter. The inner race is being driven by its shaft at 78 r.p.m. The only way the three conditions above can be satisfied is by having the balls roll between the two races, as shown in Fig. 27. The balls *roll* on their own axes counterclockwise, and therefore revolve in space at the slower speed of 33 1/3 r.p.m. as

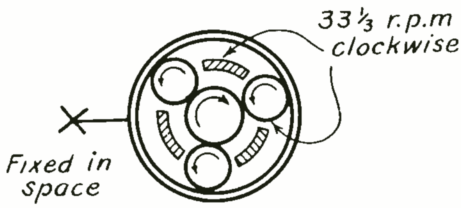


Fig. 27.—Planetary action of change-speed mechanism.

compared to 78 r.p.m. for the inner race. The 33 1/3 r.p.m. *is still in a clockwise direction.*

The action is practically as positive as if gears were involved. But the friction drive is far smoother, *provided the mechanism is clean,* and can therefore be safely interposed between the flywheel and the platter without introducing any 'wows' or flutter on its own account.

Some idea of the constance of speed can be gained from the following figures:

Speed Regulation (Wows)
0.2% r.m.s. at 33 1/3 r.p.m.
0.09% r.m.s. at 78 r.p.m.

These are well within the permissible values given previously.

FRICTION TYPE DRIVES.—Many manufacturers, notably Presto, have employed friction drives between the motor and the platter. These vary in design from one model to another, but are essentially of two types:

(1) Drive through an intermediate rubber roller.

(2) Direct drive on rubber rim of turntable platter.

The drive through an intermediate idle roller is shown in Fig. 28. The motor has a two-step steel pulley of the proper diameters re-

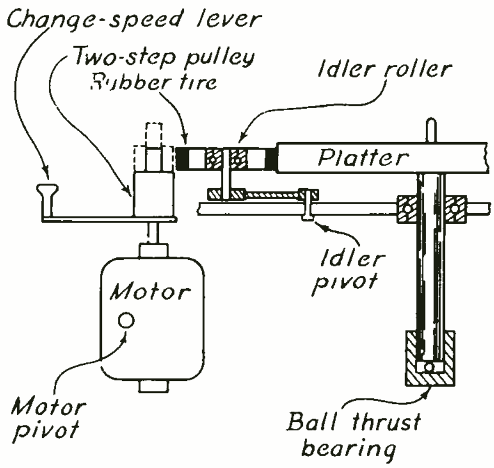


Fig. 28.—Idler roller type of friction drive.

lative to the turntable platter to give the two desired speeds, 78 and 33 1/3 r.p.m. The motor pulley does not drive the platter directly, however, but instead drives it through the intermediary of a rubber-tired idler roller. This is mounted on a pivoted frame, and the motor is similarly pivoted, so that its pulley swings against the roller, causing it in turn to press against the rim of the platter.

In the arrangement shown in Fig. 28, the motor pulley can be shifted in a vertical direction so that either step engages the idler roller, as desired, and in this way either speed is obtained.

In an actual layout, the motor is suspended from the motor board by springs or rubber cushions, so that its vibration is not transmitted to the platter. In the same way, the rubber tire on the roller acts as a cushion between the motor pulley and the turn table platter, thereby absorbing the vibrations that are present in the motor pulley. In this design the rubber tire may be regarded as both the spring member and the damping member of a mechanical filter; the damping being a result of the high internal viscosity or friction of the rubber.

One difficulty that has been experienced in the past is that the idler roller develops a flat on its rubber tire if the motor pulley is left pressing against it for any length of time when not in operation. Hence, present designs incorporate a mechanical lever arrangement such that in the process of switching off the current to the motor, the pressure of the latter against the idler is also removed.

In one RCA model two synchronous motors and two drives are employed. This tends to equalize the effects of vibration and rumble and thus results in a more uniform speed of rotation. The values given for speed fluctuations are remarkably low:

0.14% r.m.s. at 33 1/3 r.p.m.
0.07% r.m.s. at 78 r.p.m.

The above refers to *deviations* from the *average* speed. The average speed in itself may not be exactly 78 or 33 1/3 r.p.m. For the particular machine the accuracy of the average speed is guaranteed to within ± 1/2 per cent.

In another design by RCA, one motor is employed to drive two idler roller. The speed regulation (wows) in this case is somewhat higher, namely, 0.15% r.m.s. max. at 33 1/3 r.p.m. and 0.1% r.m.s. max. at 78 r.p.m. It will be appreciated that these values are also exceptionally low, particularly in view of the maximum allowable value of 0.3% for 78 r.p.m., as mentioned previously.

The Presto Recording Company uses a similar arrangement. In one model the motor step pulley is inside of the platter as indicated in Fig. 29. By shifting the spring-mounted motor laterally, either of two idler

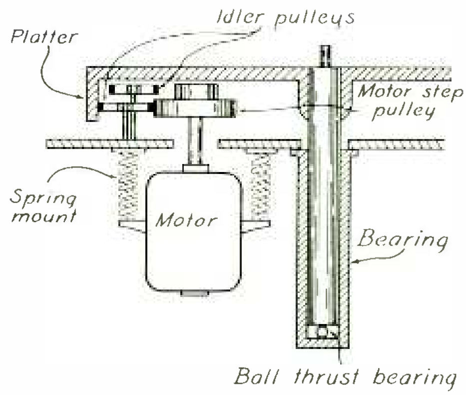


Fig. 29.—**Presto drive mechanism.**

pulleys may be engaged by the corresponding step of the motor pulley, thus providing either of the two speeds desired. This arrangement keeps the moving parts covered and protected from dust, shavings, etc.

In another design the motor drive pulley is external to the rim, as in Fig. 28. To obtain the lower 33 1/3 r.p.m. speed, a sleeve is slipped over the motor pulley, thus increasing its diameter and hence reducing the speed.

A third arrangement is shown in Fig. 30. Here the rim of the platter is fitted with a soft rubber tire

Courtesy Presto Recording Corp.

Fig. 30.—Rubber-tired platter drive.

which is directly driven by the steel motor step pulley. Thus the idler rollers are eliminated. The speed is changed by moving the motor carriage to engage either section of the drive pulley.

Maintenance consists in oiling the motor at 90 day intervals, occasional adjustment of the drive pressure, and replacement of the tire once yearly. It is interesting to note that Presto states that the accuracy of the speed of their turntables is 0.5% both at 78 and 33 1/3 r.p.m., and that the speed regulation within a single revolution is accurate to 0.25%.

OTHER TYPES OF DRIVE.—There are, of course, many other types of drive. The main point in any case is to employ a heavy platter or associated flywheel and to drive it through a flexible driving means. This can be a spring assembly, a rubber tire, a rubber or felt drive shaft, or a rubber or other flexible type of belt. The drives to be described here will illustrate further this basic principle.

In Fig. 31 is shown a very simple drive system for use in a reproducer (phonograph). The platter and turntable shaft form one unit, that rotates in the sleeve ball

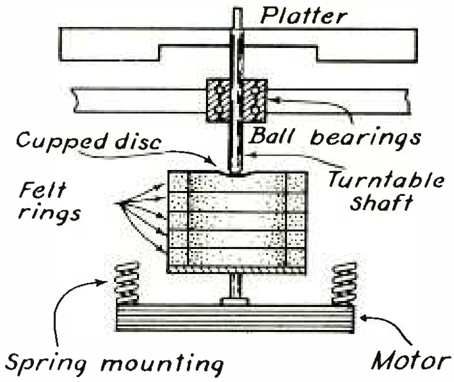


Fig. 31.—Felt transmission shaft.

bearing and can slide through it. The motor may be of any type used in phonograph drives; the one shown in Fig. 31 is a flat model and has a speed reduction gear integral with it, so that its drive shaft rotates at the desired platter speed. A change-gear may be employed in it to give the desired speeds of 78 and 33 1/3 r.p.m.

Above the drive shaft is a series of felt rings placed one above the other as shown. They are cemented together to form a felt tube of about 2 inches in length and about 1/2 inch wall thickness. On top of this tube is cemented a disc with a center spherical depression or cup. The end of the turntable spindle is also rounded, and the weight of the platter forces the spindle against the cup.

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When the motor is turned on, the friction between the cupped portion of the disc and the rounded end of the spindle causes the latter and attached platter to come up to speed after some preliminary slipping. Once up to speed the friction is sufficient to hold the two parts locked as one unit since the drag of the pickup on the record represents an exceedingly light load.

In this device all vibrations of the motor are damped out both in its spring or cushion mounting, and in the felt drive shaft, so that practically no speed irregularities are imparted to the heavy platter above.

Another type of design is that of a belt drive. This is shown in Fig. 32. Here the motor vibrations are filtered out by the flexible belt. As in the case of the felt shaft of Fig. 31, the belt acts both as a spring drive and damping member (owing to its internal viscosity), so that any tendency for free oscillations is damped out. The belt may be of rubber or of soft cloth, and may be flat (as shown in Fig. 32) or round. The writer has had good results using a 12-pound platter, well balanced, a synchronous motor of adequate power, and two vee pulleys and a round rubber sewing machine belt.

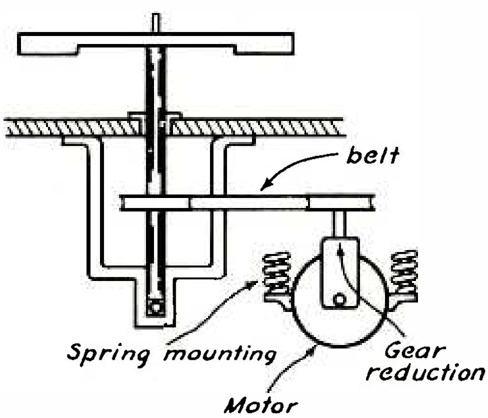


Fig. 32.—Flexible belt drive.

FURTHER CONSIDERATIONS.—A precaution that must be employed is to have some slip-clutch arrangement in these drives because of the worm reduction-gear in the motor. Just as in the case of the RCA Transcription Turntable, so here some sort of overrunning clutch is advisable. Where a flat belt is employed, the belt itself can be permitted to slip and provide the safety feature. This scheme is used in some makes of recorders.

Other points to note are that all pulleys must run true, the bearings must be smooth and tight, and where a belt drive is employed, the joint in the belt must be perfectly smooth, as otherwise a speed variation will occur each time the joint passes over either pulley.

Turntable platters have in general been covered with velvet cloth. In commercial work a rubber mat is generally employed as a cushion between the record and the metal platter. This helps to absorb any vibration, and particularly rumble that may get through the mechanical filter of the drive mechanism.

A simple method of testing a turntable for noise and rumble is shown in Fig. 33. The screwdriver helps to transmit mechanical vibration directly from the platter to the ear. This is a very sensitive test. A well-designed turntable

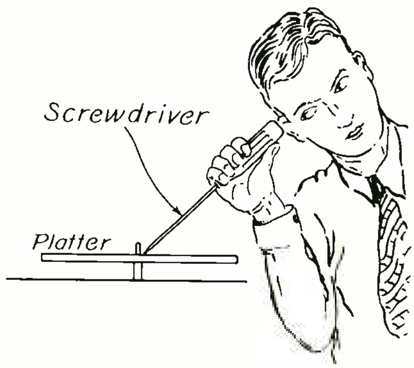


Fig. 33.—Test for turntable vibration and rumble.

should be practically quiet. One source of noise and hum is that of the motor. If this is not properly suspended from the main board, or it happens to touch the main assembly, then considerable vibration can get into the record.

Sometimes the noise is due to a poor turntable spindle or bearing. This can be differentiated from a motor vibration by allowing the platter to come up to speed, and then shutting the motor off. Any subsequent noise as the platter coasts to rest must be due to the bearings, etc. One difficulty with most drives is that when new they are excellent, but as they grow older, they get out of adjustment and produce 'wows', flutters, etc. For that reason such equipment should be tested at regular intervals to see if it is still functioning properly.

FEED SCREWS AND ACCESSORIES.—A good phonograph turntable, like the RCA Transcription Turntable described above, can be used for recording purposes. The speed must be sufficiently constant, and the motor must have adequate power to take care of the slightly greater load of the recording head. The actual cutting load is small (although appreciable in the case of instantaneous recording blanks), but the weight of the head (about 4 ounces), exceeds the weight of present-day pickups (1 ounce or thereabouts).

PRESTO RECORDERS.—In order to record, certain additional accessories are required. The most important is the feed screw that moves the recording head slowly across the rotating record and thus causes the head to cut a fine spiral groove in the disc. The feed screw is a precision device, and is normally located on top of the motor board and arranged to be driven by the turntable spindle. In Fig. 34 is shown a Presto Model 'A' Recorder. This is their deluxe equipment and is a precision device.

Each overhead cutting mechanism is mounted on a 60-pound cast iron base equipped with shock-proof mountings. The turntable platter weighs 20 pounds and is accurately machined and dynamically balanced. It has a hardened steel shaft that rotates in a bronze shaft well, and rests on a single steel ball at the bottom of the well. The bearing can be tightened to compensate for wear. The drive system consists of a heavy duty self-starting synchronous motor, which drives the inner rim of the turntable through either of two rubber-tired idlers, — one for each speed. This drive has been described above.

The cutter mechanism consists of a heavy machined bar which pivots on a post secured to the base of the machine. The feed screw is made of stainless steel, and is driven through a worm and gear from a flange mounted on the turntable shaft. The standard feed screw furnishing 96, 104, or 120 lines per inch by simply loosening one thumb screw. A special feature is the provision for cutting various spirals by manual operation of a hand wheel. A rachet arrangement in the screw permits it to be rotated at a faster rate than that provided by the turntable spindle, so that grooves with a spacing up to 1/2' can be cut. This is useful for separating selections recorded on the one disc, and also for the runout grooves at the end of the record.

A time scale is furnished to indicate the amount of elapsed recording time, and can be seen at the rear of the cutter mechanism. It consists of a four-sided cylinder with white markings engraved on the black background. A pointer that moves with the recorded head thus indicates the elapsed time. The four pitches mentioned above to be measured on the basis of elapsed time.

The microscope is a 40 power and accurately focuses 7 grooves of the disc at any one time. It is furnished with a lamp and reflector

Courtesy Presto Manufacturing Company.

Fig. 34.—Presto Model "A" Recorder showing feed mechanism, turntables, recorder heads, and microscopes.

to afford the high illumination necessary for the magnified image. Inspection of the grooves is necessary to insure that the depth of cut is not excessive, that the groove is not one-sided, and that the cutting tool is cutting smoothly.

Records may be cut from the inside-out or the outside-in, as desired, although separate feed screws are required for each direction and pitch in the above recorder. Originally transcription records were cut inside-out, i.e., from the center to the rim of the disc. The main advantage was that in reproducing such a record, the inside grooves, which had the shortest (recorded) wavelength for a given high frequency, were reproduced by a steel needle that was sharpest at the start and therefore best suited to track in these short wavelengths. With the advent of the light-weight pickup having a permanent stylus, the above consideration was eliminated.

There is, however, another advantage in recording inside-out, and that is that as the cutter head moves radially outward, the shavings can be wound on the center spindle without interfering with the cutting action of the stylus. On the other hand, if the recording is made outside-in, then if the shavings are collected on the turntable spindle, they will tend to accumulate ahead of the cutter and interfere with its action.

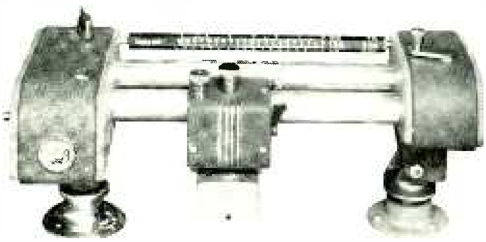
Recording outside-in, however, has certain advantages, such as that the record is the same as the standard commercial records and is handled in the same way, and also that it is easier to start the phonograph pickup at the outside groove of the record than at the inside groove. To take care of the shavings (which, incidentally, are very inflammable) a suction tube is placed directly adjacent to the cutter, and connected to a suction pump, so that the shavings are sucked into this tube just like in the case of the ordinary vacuum cleaner. A suction feed is invariably used in the case of a wax recorder but is not adapted for portable use, as is so often required of an instantaneous disc recorder.

In a somewhat cheaper model of the Presto line, the feed-screw mechanism is located below the motor board, and operates the cutter through a kind of tone arm assembly. While this has the advantage of keeping dust and dirt away from the mechanism, it does not afford the precision of groove spacing that the overhead mechanism provides, and—as has been seen previously—accurate spacing of the grooves permits maximum level to be safely recorded without the danger of cutting into adjacent grooves. Since the grooves are normally spaced about 4 mils apart, the importance of accuracy is apparent.

RCA RECORDERS.—In Fig. 35 is shown a feedscrew mechanism that can be attached to the RCA Transcription Turntable. As is clear from the figure, it is driven directly from the turntable spindle through a flange that fits over the latter. It is arranged to swing clear of the platter when not in use, and can easily be removed.

An important feature of the mechanism is that the cutter carriage does not ride directly on the feedscrew, but instead on a metal tube enclosing it, and, in addition, another tube serves as a guide for the carriage. This arrangement not only reduces wear on the feedscrew but protects it from dust and dirt.

Recordings can be made at 33 1/3 or 78 r.p.m., inside-out or outside in, and at 96, 112, and 136 lines



Courtesy RCA

Fig. 35.—Recording attachment for transcription turntable.

per inch, without requiring any change in lead screws or gears. A timing scale will be noted at the back; this is a hexagon in shape to take care of the various speed and pitch combinations. At the upper right will be seen a hand crank. This is for the purpose of producing spiralling grooves, similar to the method used in the Presto recorder.

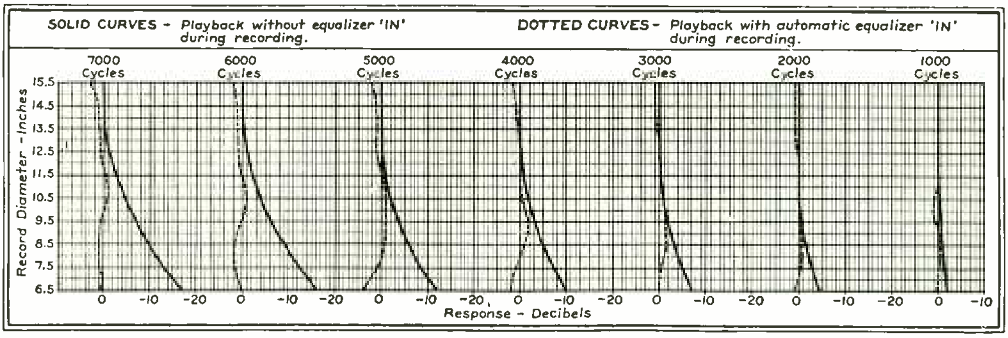
A feature that is becoming increasingly more common is that of an automatic equalizer for the recording head. The finite, instead of ideal infinitesimal size of the tip of the recording stylus, makes it more difficult to record the higher frequencies for which the *recorded* wavelength is shorter. A similar difficulty exists in the case of reproduction of these higher frequencies by a reproducing stylus having a finite tip.

The *recorded* wavelength depends upon the *linear* groove speed. Since the record revolves with uniform *angular* velocity, it is clear that the outer grooves have a greater *linear* speed than the inner grooves, so that the recorded wavelength is least for the inner grooves. The result is that the 'highs' are attenuated at the inside of the record. This is particularly true at the lower turntable speed of 33 1/3 r.p.m. Indeed, at this speed it is inadvisable to record to a diameter less than 6 1/2'. as the surface noise and distortion will become relatively excessive.

To compensate for the progressive attenuation of the 'highs' as the cutter approaches the center of the record, a variable equalizer is provided progressively to peak the 'highs' compared to the middle and low frequencies. This equalizer is preferably varied automatically by the feedscrew, either directly, or through the agency of the cutter head that it is actuating. In the above RCA model the equalizer control is contained in the guide rod and is actuated by the recorder head.

A representative set of curves (for a Presto automatic equalizer) is shown in Fig. 36. For each frequency, such as 7,000 c.p.s., 6,000 c.p.s., etc., the attenuation in db, as the reproducer approaches the center, is shown without the equalizer 'IN' and then with the equalizer 'IN'. At 7,000 c.p.s. an attenuation of 17 db will be noted from the rim (15.5 inches) to the innermost groove (6.5 inches), whereas at 1,000 c.p.s. a difference of 2 db is all that is noted.

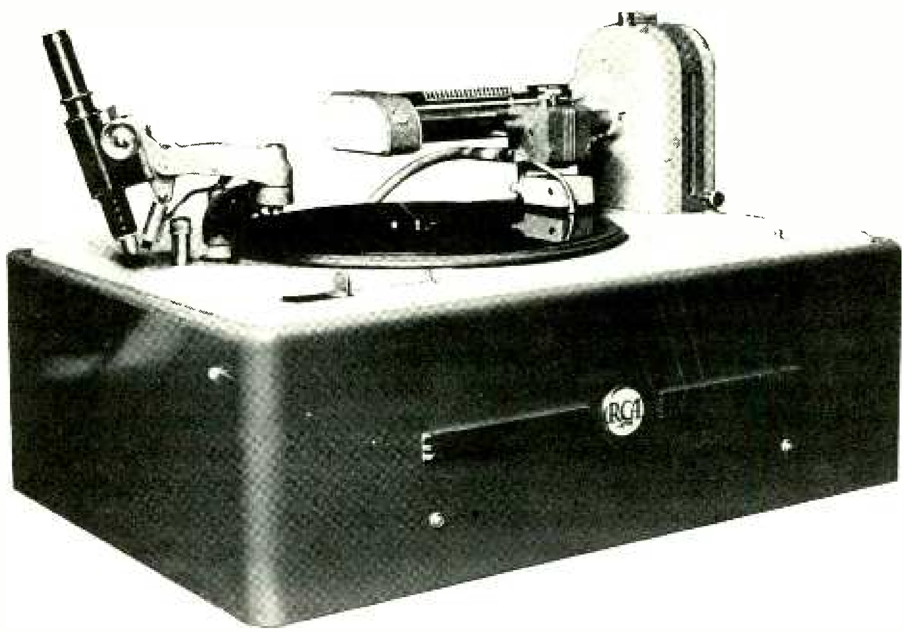
In Fig. 37 is shown the RCA Professional Recorder Type 73-B. This has some interesting fearures. One of these has been described previously, namely, the use of two motors for the turntable drive. Another feature apparent from the figure is that the feedscrew is driven from the far end through gearing underneath the motor board. This eliminates the need for placing a driving flange on the turntable spindle, and thus permits the records to be placed on the platter and taken off without removing the feed mechanism.



Courtesy of Presto Manufacturing Co.

Fig. 36.—Playback curves at different frequencies before and after equalization.

The single feedscrew is within



Courtesy RCA

Fig. 37.—RCA Professional recorder type 73-B.

the hollow tube that supports the cutter head. A second hollow tube acts as a guide and also can have the automatic equalizer placed within it, if desired. This is similar to the design of the recording attachment previously described.

The single feedscrew can be set to provide from 96 to 152 lines per inch in steps of eight lines. This is accomplished by employing a friction drive, as indicated in Fig. 38.

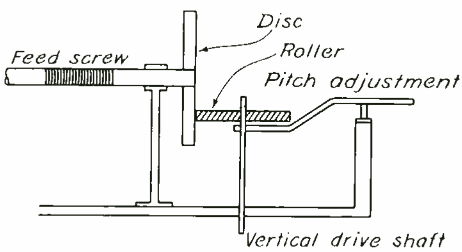


Fig. 38.—Details of variable pitch drive mechanism.

The vertical drive shaft, driven underneath from the turntable spindle, has a roller keyed to it, but able to move up or down on the shaft. The roller (rubber-tired) bears against a friction disc, which is keyed to the feedscrew. As the roller is raised, it bears against a smaller circumference on the disc, and therefore drives it and the disc at a higher speed, thus decreasing the number of lines per inch.

If the roller is raised to a position above the feedscrew, then it turns the latter and the disc in the *reverse* direction. Thus inside-out and outside-in feeds of various pitches can be obtained in the one mechanism. Since the operating speed and load are very small, no difficulty from slippage need be experienced. Actually a planetary drive mechanism is employed, but the above is essentially the principle of operation. When the cutter head carriage is raised to the rest position, the drive roller is automatically disengaged from the driving disc to obviate any flats on the rubber tire. The number of lines per inch is indicated by an illuminated scale in the drive housing, and four spring-released time scales are provided to cover all combinations of turntable speed and groove spacings.

Another interesting feature is the use of a separate, 'spiralling motor', controlled by a push button, for overdriving the lead screw to provide the various spirals desired. At 78 r.p.m., and for 96 lines per inch, the spiralling device furnishes 4 lines per inch, and a proportionate lower pitch for 33 1/3 r.p.m. recording.

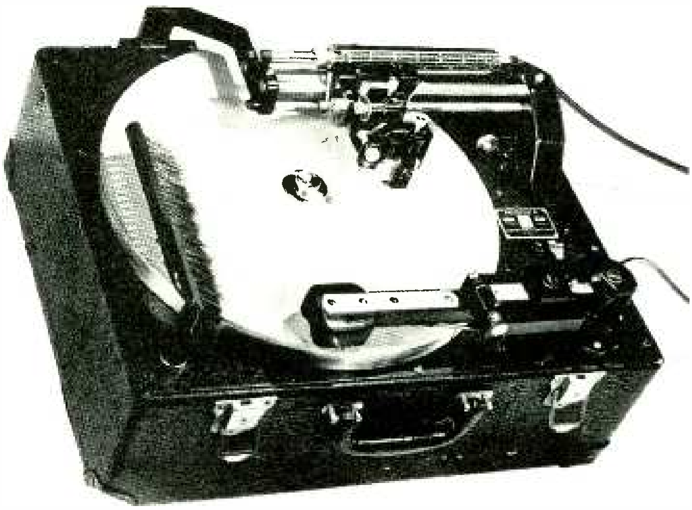
The microscope is a 36-power instrument, and has a calibrated eyepiece having 50 divisions, each .001'. The instrument is provided with a small shielded lamp, and the whole device is readily adjusted to observe any part of the record. The entire recorder is equipped with a heavy cast base and is well shock-mounted; indeed, the entire recording mechanism is isolated from room vibration by rubber mounts.

Miscellaneous features are the rubber mat on the platter, an adjustable suction nozzle attached to the carriage mechanism, a single driving pin in the platter to enable any type of blank to be used, with the further provision that the pin can be pushed into the platter against a spring if a disc without driving holes is employed, and provision for the use of an advance ball on the cutter head when making wax recordings. This will be described more fully further on.

FAIRCHILD PORTABLE RECORDER.— In Fig. 39 is shown the Fairchild Portable Recorder for use in schools, speech correction, music recording, etc. It consists of a special 1,800 r.p.m. synchronous motor, geared down by a 54 to 1 gear- and worm-drive to 33 1/3 r.p.m. for the platter. To obtain 78 r.p.m. a ball bearing planetary drive is used between the turntable spindle and the platter, similar to that employed in the RCA Transcription Turntable.

As will be observed from the figure, the drive for the feedscrew is from below, rather than from the turntable spindle, so that the records can easily be put on or taken off the platter without requiring the recording mechanism to be swung out of the way. Another interesting feature is the long brush employed to sweep the shavings from the record, instead of a suction nozzle.

It is possible to record either inside-out or outside-in at any of the following four pitches: 98, 118, 141, and 161 lines per inch, in addition to the two speeds available, namely, 33 1/3 and 78 r.p.m. A calibrated scale shows the elapsed recording time as well as the minutes remaining.



Courtesy of Fairchild Camera and Instrument Corp.

Fig. 39.—Fairchild portable recorder.

The magnetic recording unit is rated as flat within ± 2 db up to 8,000 c.p.s., and the amplifier-equalizer furnished with the equipment permits an average boost of from 0 to 20 db in two parts of the spectrum: 20 to 100 c.p.s., and 4,000 to 10,000 c.p.s. It will be recalled that in these two parts of the spectrum the energy content of the sounds picked up is low, so that pre-emphasis in recording, followed by de-emphasis in reproduction can give a better ratio of signal-to-surface noise and signal-to-rumble at the high and low ends, respectively.

RECORDING HEADS.—The recording head is, in general, the same as the reproducing or pickup unit described earlier in this technical assignment, except that it operates in reverse fashion; i.e., it converts electrical energy into mechanical energy.

There are some important differences in the design of the two units. The recording head has to cut into the record, hence its weight must be sufficient for this purpose. A pickup, on the other hand, must be light enough so that the pressure of its stylus in the record groove does not destroy the groove.

A second point is that the operating levels are widely different. The output level of a pickup may be- 50 db (0 db - 6 mw.), whereas the power into a recorder may be in the order of a watt or more. This means that not only must the recorder unit be able to dissipate more incidental I^2R losses, but also magnetic saturation effects (in the case of a magnetic recorder), or electrostatic saturation effects (in the case of a crystal recorder) must be minimized. In the past a surprising amount of distortion has been generated right in the recorder head itself.

A third difference is that uniformity of performance between different recorders is more important than in the case of pickups. Today, different recorders of the same may vary by as little as 2 or 3 db, one from the other. A recorder unit that has a little more mechanical output for a given electrical input than another unit, may easily overload the record and cause cutting into adjacent grooves, because of the small spacing between grooves and the desire to record at as high a level as possible in order to have as high a signal-to-surface-noise ratio as possible. In the case of a pickup, variation in output level is never sufficient to overload the electrical system, since this is in general oversize, and, moreover, any overloading that might occur causes no permanent damage.

DAMPING FOR WAX RECORDER.—In the case of a wax recorder, the mechanical load imposed by the wax is very variable (nonlinear), but also very small. It is therefore customary to damp the mechanical system of the recorder with a rubber line, or other suitable material, such that this damping predominates over that of the wax itself, and makes the variability of the wax loading of no consequence.

A typical example of a wax recorder with rubber damping line is shown in Fig. 40. The rubber line,

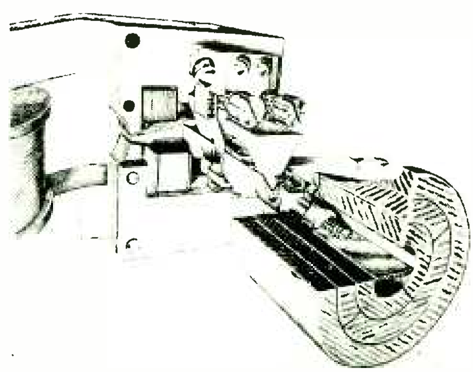


Fig. 40.—Section of Electrical recorder.

as it is called, consists of a series of concentric gum rubber tubes, about 10 inches long, and split into sections, as shown. The recorder stylus and shaft are shown directly behind this line. A vane, attached to the recorder shaft, transmits vibrations to the rubber line, causing torsional vibrations to take place in the latter.

The speed with which these vibrations travel down the line is 100 feet/sec. This makes the 10-inch rubber line equivalent to an *electrical line 1,500 miles long*, for which the speed of transmission is close to that of light, namely, 186,000 miles/sec. As a result, by the time the mechanical vibration has reached the far end and been reflected back to the beginning (vane) end, the motion has been so greatly attenuated that practically no appreciable energy is left to be re-reflected and thus set up standing waves and resonance. The rubber line thus acts like a pure mechanical resistance, in spite of its inertia and elastic reactions.

VISCALOID DAMPING.—While such a device is very satisfactory as a mechanical resistance unit, it has the disadvantage of being rather bulky. Where more moderate (and also more approximate) values of damping are satisfactory, a simpler arrangement, shown in Fig. 41, is satisfactory. The armature is part of the balanced-armature magnetic unit previously described in the form of a pickup unit. Essentially the same form can be used in reverse as a recorder. The shaft on which the armature pivots is fused at one end into a viscaloid sheet. This is a plastic material that has rather high internal viscosity or friction, as its name suggests. It therefore acts to damp out resonant peaks in the vibration of the armature and thus flattens the frequency response.

One disadvantage of most damping materials, particularly viscaloid, is that its viscosity varies with temperature, and even with humidity, so that the frequency response of the unit may vary with the above factors. The above is also true for the damping or loading imposed by the cellulose nitrate lacquer film used in instantaneous disc recording, and unlike wax blanks, the lacquer blanks impose an appreciable load on the recorder unit. Nevertheless, in actual operation the recorders appear to be at least reasonably satisfactory in their performance.

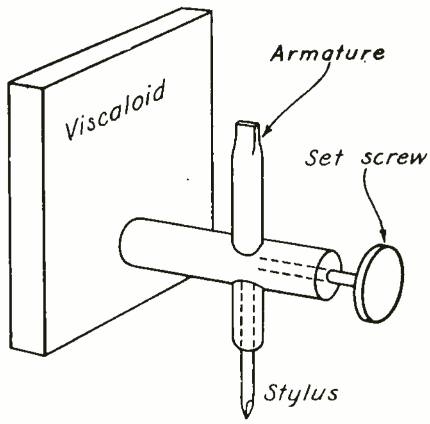


Fig. 41.—Use of viscaloid for damping.

HIGH-FREQUENCY RESPONSE.—At the high frequencies, the vibration of the armature or other vibrating member is determined, in general, by the moment of inertia of the part. This will be made clearer by referring to Fig. 42. The arrows marked F, F', represent the forces acting on one end of the armature, and since it is pivoted at approximately the center, the other end, representing

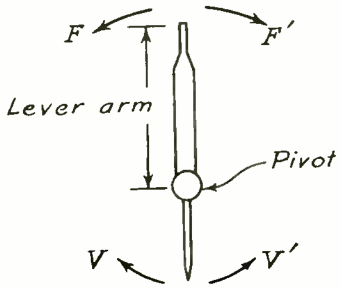


Fig. 42.—Motion of armature.

the cutting stylus, moves with the velocity V, V', as shown. Thus the armature and stylus rotate back and forth through a small angle about the pivot. This may be a rubber bearing or a knife edge, depending upon the design.

In such a case, the amount of motion imparted to the structure depends upon the force developed multiplied by the lever arm, or torque, as the product is called, and also upon the *moment of inertia*, rather than the *mass* of the moving element. The difference is that two armatures might have the same mass, but because in one the mass is concentrated close to the pivot, and in the other close to the far end away from the pivot, the latter will not move through as great a distance as the former *because its moment of inertia is higher, even though its mass is the same.*

As a result the amplitude of recording will be less at any given frequency, and the effect will be more pronounced, the higher the frequency. Particular difficulty is experienced at frequencies of 5,000 c.p.s. and above. An appreciable contribution to the moment of inertia of the vibrating member is the set screw that secures the stylus to the armature. If this is located on the axis of rotation, as indicated in Fig. 41, then its contributing moment of inertia is at a minimum. Hence, this is the usual location for this part, and often an improvement in response can be obtained by eliminating the small rim or disc on it and substituting a slotted screw instead. More will be said concerning moment of inertia in the discussion of pickups.

Another factor of importance is that the vibrating member may or may not move as one rigid unit. This is analogous to an r.f. choke coil, which at some frequency may resonate with its own distributed capacity and then resonate at still higher frequencies in sections. Another example is that of a transmission line, which can show multiple resonance effects; in short, the mechanical member, like the electrical unit, may exhibit distributed circuit characteristics.

This comes about from the fact that any member, such as a long rod, for example has a certain amount of compliance and mass distributed throughout its length. It, therefore, is analogous to the transmission line, which has series inductance and shunt capacitance throughout its length. Moreover, mechanical systems are usually characterized by very low internal damping, which corresponds to a transmission line of high Q.

As a result, several resonant

peaks and dips may occur—in the case of a mechanical system—at various frequencies in its audio response. It is necessary to design each component so as to have a maximum of stiffness and a minimum of mass, so that its first resonant frequency is at the top end, or preferably beyond the audio spectrum. In this way the member will act essentially as a rigid member—corresponding to a lumped electrical circuit component—and thus behave in a predictable manner in the audio range. Any resonance that then occurs can be damped down to a reasonably flat response by the damping material employed.

LOW-FREQUENCY RESPONSE.—At low frequencies, the excursions of the recording stylus may be limited by elastic (spring) members. In Fig. 43 is shown a balanced-armature unit

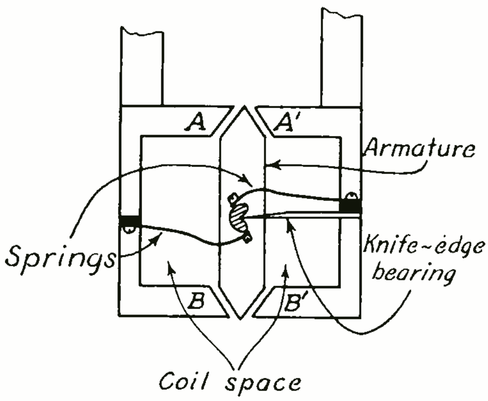


Fig. 43.—Use of restoring springs.

once again, together with the restoring springs. One of these may also be seen in the previous Fig. 40. The shaft through the armature has a V-groove, in which fits the knife edge bearing to act as a pivot. On the same shaft is mounted the stylus, but this is ommitted in Fig. 43 for clarity.

In this particular design the pivot is at the center of the armature rather than near one end, and while this reduces the moment of inertia, it requires that the stylus be longer, so that it can be fastened to the shaft and yet clear the bottom end of the armature. Therefore, this design is not necessarily superior to the one where the armature pivots near one end, as suggested in Figs. 41 and 42, so far as high-frequency response is concerned.

One function of the springs is that of counteracting the tendency for the split pole pieces A, B', or BA', to pull the armature against them if it is displaced initially from its center equilibrium position. However, the springs are made stiffer than is required merely to provide the above required restoring force. As a result, if it is attempted to vibrate the armature at low frequencies, then even though its moment of inertia effects is small, appreciable force has to be exerted to deflect it against the action of the restoring springs.

The force required in this low-frequency range will, therefore, be independent of the frequency, since it involves the flexing of springs rather than the inertia effects of the moving elements. But the force is produced by the interaction of the audio current in the coil surrounding the armature and the magnetic field. For constant current at all frequencies (sufficiently low) the force will be constant, too, and *therefore the deflection of the armature and its stylus will be the same at all frequencies.* Thus, *constant-amplitude recording* can be obtained at the lower frequencies, as is normally desired.

OVERALL RESPONSE CHARACTERISTIC.—At some intermediate frequency the springs and the moment of inertia of the armature will produce a series resonance effect and consequently excessive amplitude of vibration. It is here the damping material is of value in holding the stylus excursions down to a reasonable value. At this frequency, and for a range considerably above it, the damping may be the predominating reaction in the system.

This corresponds to resistance in an electrical system. If an electrical circuit is resistive in nature, then the current is equal to E/R, and is independent of frequency. Similarly, if in a mechanical circuit, the mechanical impedance is resistive (frictional) in nature and of value R_m, then the *velocity*, corresponding to current, is equal to F/R_m (F=Force) *or is independent of frequency*. Thus *constant-velocity recording* can be obtained in this range.

At the higher frequencies the inertia of the moving elements will limit the amplitude of vibration, just as in an electrical series resonant circuit the net inductive reactance of the circuit limits the current flow. If it is possible to move the resonant frequency to the top of the audio range, then the behavior of the unit beyond that point is of no consequence. In many cases it is possible to 'build out' the unit in the following manner:

In Fig. 44 (A) is shown an armature, shaft, and stylus, designed as far as possible to act as one rigid unit. Hence the velocity of all members is the same, and the equivalent electrical circuit is that shown in (B).* Note that the mass of the armature M_a, of the shaft M_sh, and of the stylus M_{st}, are all in series with one another and with the damping components, namely, that of the damping material, R_d, and that of the record, R_r. It is clear that the velocity of the members will be small at the higher frequencies.

If the shaft is constricted, for example, where it joins the armature, as indicated in Fig. 44 (C), so that it is not as rigidly coupled to the armature as in Fig. 44 (A), then not all the motion of the armature is conveyed to the shaft. The effect is as if some of the motion were by-passed at this point by the 'give' in the constriction, and is represented by the compliance C_1 in Fig. 44 (D). Another constriction at the point where the cutter joins the shaft gives rise to compliance C_2.

The effect of these two compliances is to separate the various masses and make them parts of separate filter sections. As such, they will transmit higher frequencies from one to the other owing to the very agency that at first thought would prevent such transmission, namely, the by-pass compliances C_1 and C_2. The latter really promotes the transmission of the higher frequencies up to a certain cutoff value by resonating with the masses.

The difference in frequency response between the two systems is illustrated in Fig. 45. Note that for the normal system, the stylus velocity v (which is the one of interest) drops off gradually with

*Mechanical analogies of electrical circuits have been discussed in the technical assignment on microphones.

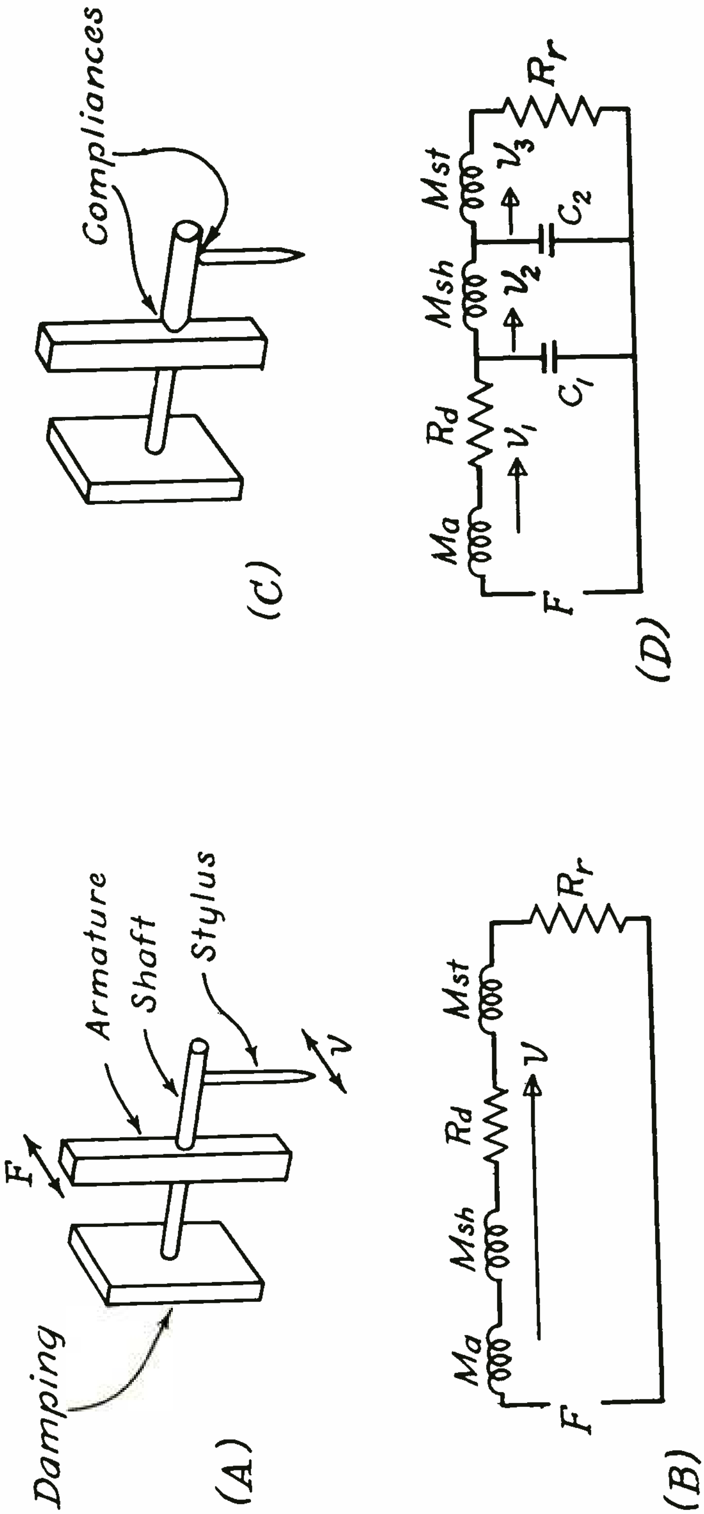


Fig. 44.—Method of "building-out" a mechanical vibrating system.

frequency, whereas for the 'built out' system the stylus velocity, now v_3, is fairly flat up to a certain frequency and then drops off sharply.

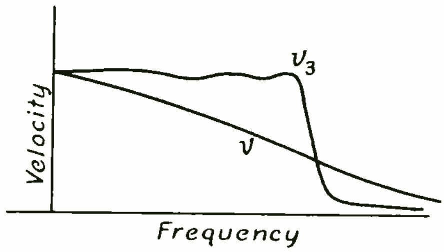


Fig. 45.—Difference in frequency response of "built out' and normal system.

Another effect not shown in Fig. 45 is that there is a progressive phase shift through the sections; i.e., velocity v_3 lags v_2, which in turn lags v_1 in Fig. 44 (D), whereas in (B), there is only one common velocity v. Ordinarily the presence of a progressive phase shaft in an audio system is of no consequence. It may be remarked here that the design of a pickup is based on the same consideration.

ELECTRICAL COMPENSATION.—The above discussion was based on the assumption that the force F is independent of frequency. But F is produced by the audio current through the windings, and if the current is less at the higher frequencies owing to inductance in the windings, then the high-frequency response of the unit will be decreased because of this factor.

One means of compensation is that shown in Fig. 46 and is used in an RCA recorder. It consists simply of 10-ohm resistor connected in series with the 15-ohm terminals of the output transformer and the recorder, whose impedance is represented by Z_r. Since Z_r is primarily inductive in nature, its reactance is considerably less than 10

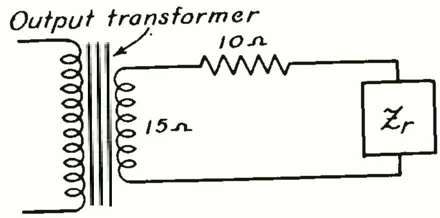


Fig. 46.—Coupling of recorder to amplifier output.

ohms except at the higher frequencies. Thus the output current over the greater part of the audio range is determined mainly by the 10-ohm resistance and is fairly constant and independent of frequency. Hence, the force developed in the recorder is also fairly constant over most of the frequency range.

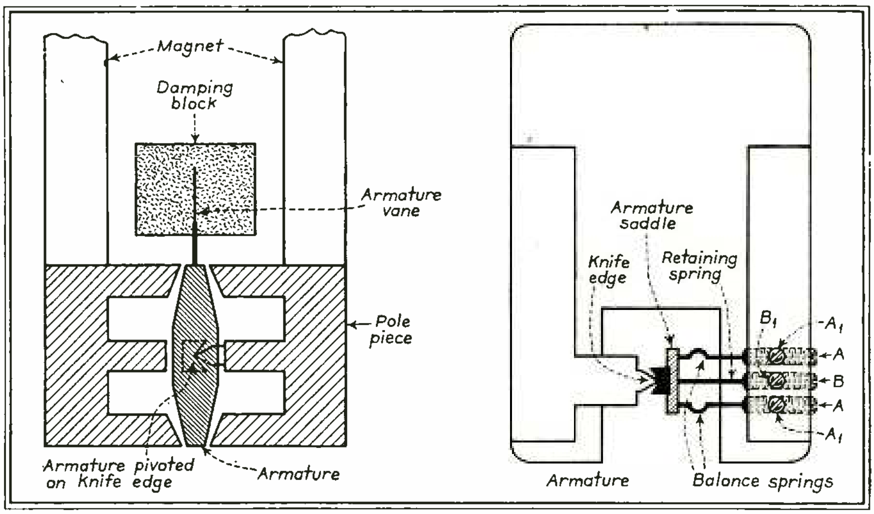
Any decrease in amplitude of cutting of the recorder at the higher frequencies could be compensated for by peaking the recording amplifier. This is not, in general, advisable; i.e., it is preferable to have the recorder as flat as possible. The reason is that peaking of the recording amplifier is required anyway to obtain the special features, say, of the orthacoustic system of recording, so that additional peaking demanded by an inherent drop-off in the recorder output would require excessive compensation in the amplifier.

Another factor is that peaking tends to accentuate the harmonics produced in the amplifier, relative to the fundamental frequencies. This can be minimized by producing the peaking in the low-level stages, where the production of harmonics is very small, rather than *after* the output stage, where the high-level of signal may produce appreciable harmonics.

REPRESENTATIVE RECORDERS.—The above principles are embodied, in one form or another, in the various recorders available today. It will be of interest to examine these units in the light of the preceding remarks.

PRESTO RECORDER.—In Fig. 47 are shown simplified drawings of the Presto recording head. This is of the balanced armature type. The damping block provides the additional amount of damping required in conjunction with that supplied by the lacquer disc. The disc material offers much more damping than does a wax blank, hence, the additional damping need not be as great as that furnished by the rubber line in Fig. 40.

The main feature claimed for this recorder is the knife-edge bearing. The V bearing and the knife edge are very accurately milled out for a perfect fit. Then the center spring, known as the retaining spring, is put under compression by adjusting screw B fastened to it, thus forcing the armature against the knife edge. The contact area is then inspected under a microscope, and when correct, set-screw B-1 is



Courtesy Comm. and Broadcast Eng.

(A) Cutter having the armature pivoted at the center.

(B) Rear view of the new cutter showing armature mounting.

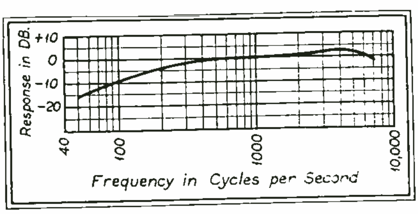
Fig. 47.—Structural details of Presto recorder.

used to lock B, and is then sealed. Once made, this adjustment need never be tampered with.

The balance springs then are adjusted by means of their screws A until the armature is perfectly balanced, and then set-screws A-1 are used to lock the adjustment. Presumably very little further adjustment of the centering screws will be required thereafter. It is felt that this type of bearing is far superior—as regards high-frequency response—to the rubber bearing shown in Fig. 6.

The cutter requires an input of 0.242 watt which corresponds to + 16 db (o db = 6 mw.). Since this is rather small, an amplifier of 2 watts maximum output will easily handle the head. At this level, 112 lines per inch will be fully utilized, and the surface noise will be 40 db below the recorded sound, which is about 10. db better than the surface noise from a shellac pressing and compares favorably with the best acetate transcription disc.

The frequency response is from about 50 to 7,000 c.p.s., with the turnover frequency at about 400 c.p.s. In Fig. 48 is shown the re-



Courtesy Comm. and Broadcast Eng.

Fig. 48.—Frequency characteristic of the cutter.

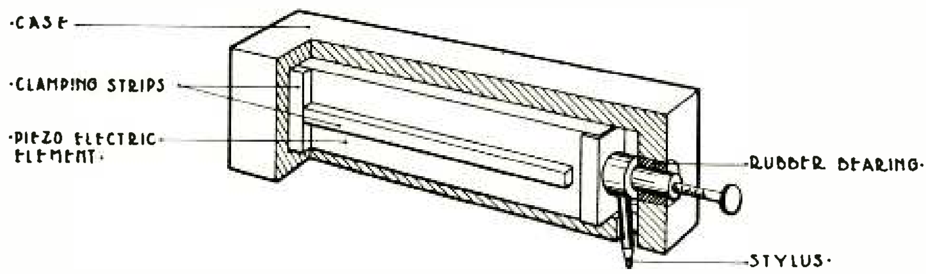
sponse curve. It will be observed that there are no sudden peaks or dips, which indicates that the unit is well damped. The linear drop-off below 400 c.p.s., the turnover frequency, provides constant-amplitude recording, while the response above 400 c.p.s. furnished constant-velocity recording. The recording amplifier can then be peaked so as to furnish orthacoustic or any other desired type of recording.

A later improved type operates at a maximum input level of +20 db, is flat to 8,000 c.p.s., and by means of suitable equalizers, can be extended to 10,000 c.p.s. The harmonic distortion is stated to be negligible compared to that generated by the best pickups and needles. Values given are 4% at 100 c.p.s., 1.5% above 1,000 c.p.s. Measurements are taken from a fully modulated groove cut at a pitch of 96 lines per inch. A picture of the recorder is shown in Fig. 49.

Courtesy Comm. and Broadcast Eng.

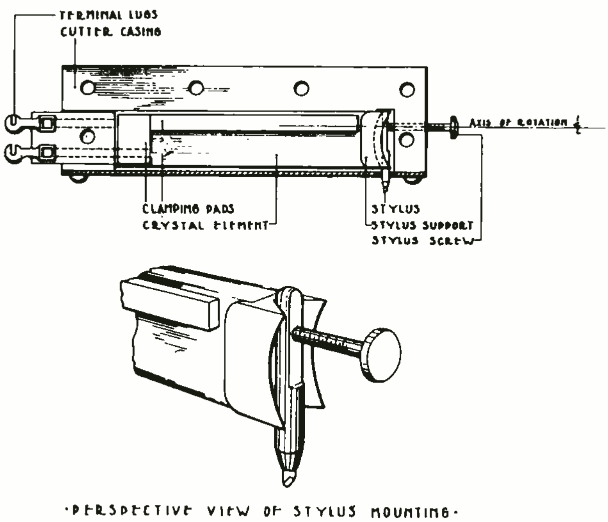
Fig. 49.—External view of Presto Recorder.

BRUSH CRYSTAL RECORDER.—A piezo-electric crystal can be used for a recorder just as well as for a pickup. A representative design is given in Figs. 50 and 51. This is the Brush Type RC-20 Crystal Cutter. It employs a 4-ply crystal element, held by koroseal pads, which provide both a stiff mounting support and damping for the peak at the resonant frequency of the crystal. The crystal is of the 'twister' type, and when a voltage is applied to its terminals, the free end to which the needle chuck is attached twists to-and-fro and furnishes the motion



A. L. Williams, Courtesy Brush Development Co.

Fig. 50.—Brush Type RC-20 crystal cutter.



A.L. Williams, Courtesy of Brush Development Co.

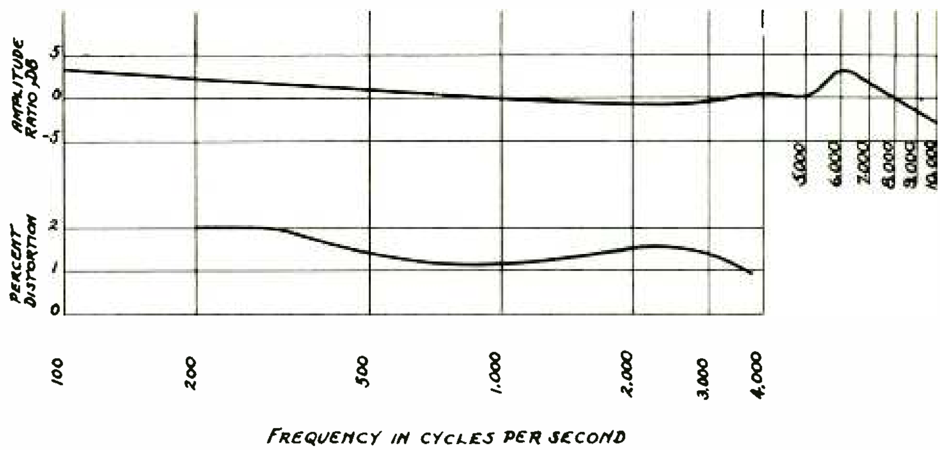
Fig. 51.—Construction views of RC-20 crystal cutter

necessary for lateral recording.

Note from Fig. 51 the chuck for holding the stylus. Observe first that the set-screw is in the axis of rotation and therefore contributes very little to the moment of inertia of the system. The chuck itself is V-shaped, but the notch is in the form of an arc, so that the stylus is supported close to each end. This reduces the elastic 'give' of the stylus and increases the high-frequency response.

With 60 volts applied to the cutter, the amplitude of the cut is 0.5 mil at 500 c.p.s. For constant voltage at all frequencies, the amplitude tends to remain constant; i.e., the crystal inherently records on a constant-amplitude basis. It has been remarked previously that this tends to increase the signal-to-noise ratio for the higher frequencies. Hence, this cutter needs very little further equalization, at least at the high end, to produce recordings of an orthacoustic nature or similar.

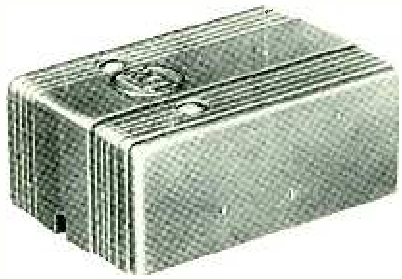
The amplitude response and also the distortion curves are shown in Fig. 52. It will be observed that on an *amplitude* basis, the response is essentially flat to 9,000 c.p.s., or even to 10,000 c.p.s., and that the distortion is very low. One criticism of the crystal cutter is that its characteristics vary appreciably with temperature. However, as pointed out by the Brush engineers, the characteristics of the damping materials used in a recorder, even of the magnetic type, are much more variable. Furthermore, it is possible to temperature-control the crystal so as to maintain its performance at a fixed level.



A. L. Williams, Courtesy Brush Development Co.

Fig. 52.—Frequency response and distortion characteristics of crystal cutter.

RCA HIGH FIDELITY RECORDER.—In Fig. 53 is shown the RCA Type MI-11850-C recording head. Its construction is similar to that of the Presto recorder. It has a laminated magnetic field together with a driving coil and permanent magnet, an armature (complete with damping material), pivoted on knife edge bearings and centered by means of a

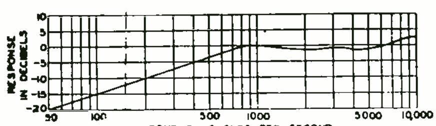


Courtesy RCA

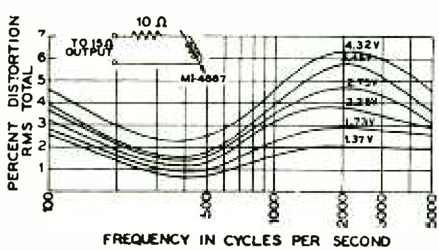
Fig. 53.—RCA Type MI-11850-C recording head.

steel-centering spring. Its input impedance is 15 ohms nominal, and it requires approximately 3 watts for a stylus deflection *velocity* of 5 cm per sec. at 1,000 c.p.s.

The frequency response is shown in Fig. 54(A), and the distortion



Typical frequency response of MI-11850-C and MI-4887 based upon optical measurements of the stylus tip motion for constant input



Courtesy RCA

Fig. 54.—Frequency response and distortion characteristics of the RCA Type MI-11850-C recording head.

characteristics for various input voltages in Fig. 54(B). Note from (A) that the turnover frequency is approximately 800 c.p.s. It is also of interest to note how the distortion begins to increase appreciably as the input voltage is increased. The percent distortion, however, is at no time objectionable.

MISCELLANEOUS CONSIDERATIONS.—Several auxiliary components are necessary for successful recording. One of these is a mechanical arrangement for lowering the recorder head gently on the blank. The cutter stylus employed, especially if made of sapphire, is brittle and easily damaged or broken if the head is lowered too abruptly, or it is lowered *before the disc starts rotating*. In addition, the depth of the first groove may be excessive.

DEPTH OF GROOVE.—The depth of groove is normally determined by the net weight of the recorder head on the record blank. A thumb screw is usually employed to adjust the tension on a restraining spring, and thus the net weight of the head. In addition, another screw adjustment permits the recorder head to be revolved in its cradle so as to adjust the cutting angle. The average proper angle is about 96°, as shown in Fig. 55, although this angle

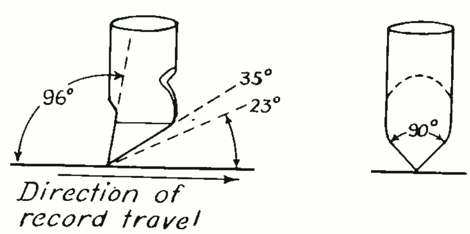


Fig. 55.—Details of needle construction.

should be varied somewhat in any particular case if any noise is heard during cutting, because the same noise will later show up as excessive surface noise in reproduction.

The front angle of the stylus should be somewhere between 87.5° (standard) and 90°. For 90° the depth of groove will be exactly half of the width of the groove, as measured by the microscope. In addition, the cutting edges are generally dulled or 'dubbed' ever so slightly so as to produce a burnishing and polishing effect on the groove by the surface of the stylus immediately behind the cutting edge.

Styli are generally made of steel, stellite, or sapphire. The sapphire is hardest and best, but most expensive. It can be used for about 5 hours after each sharpening and can be resharpened about 10 times. Stellite needles are next in hardness, but their life is 2 hours between sharpenings, and they may also be resharpened several times. Steel cutters are recommended for home recording only. The surface noise of the cut is higher, and they can be used for only one-half hour. Moreover, it does not pay to resharpen them.

In wax recording the depth of groove is determined by a small sapphire 'advance ball' this is fastened to the recorder head directly in front of the stylus, and rides on the surface of the wax. In acetate or instantaneous recordings it is not always desirable to use such an advance ball, because the lacquer surface is not as even as the wax surface, which has had a preliminary turning with a special shaving cutter.

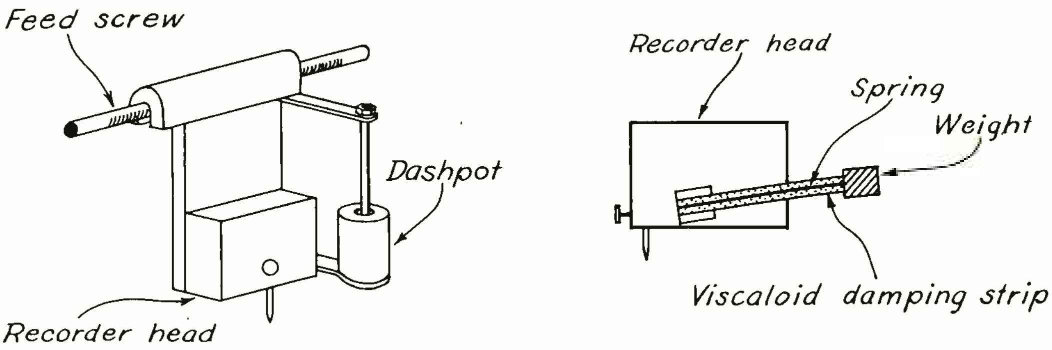
DAMPING MECHANISMS.—Instead, the net weight of the recorder head (never exceeding 4 ounces) is used to determine the depth of cut. However, oscillations may be set up that cause the cutter head to vibrate up and down, either once per revolution, or even several times per revolution of the disc. The result is an uneven depth of recording from one side of the record to the other, or in the latter case, the depth may vary several times around the record and give rise to a series of spokes when the record is viewed in the light.

To prevent this a dashpot form of damping is used, as shown in Fig. 56 (A). Any motion of the recorder head relative to the feed screw mechanism, which is in fixed position with respect to the record, causes the dashpot plunger to move in the oil-filled cylinder, thereupon producing a damping effect.

In portable recorders this form of liquid dashpot is not so feasible, and, hence, an inertia type of damping is employed instead. As illustrated in Fig. 56 (B) it consists of a spring strip covered with damping material, such as viscaloid, one end of which is fastened to the recorder head, and the other end to a large mass or weight. Any sudden motion of the recorder head cannot be followed by the weight owing to its inertia, so that the damping strip is flexed instead, and thereby introduces damping into the system.

It is possible to minimize oscillations of the recorder head by mounting it properly. By placing the pivot or fulcrum of its mounting arm about 2 1/2" behnid the stylus and no more than 3/4" above the record surface, the tendency for the recorder head to move up and down is reduced to a point where the damping in the bearing is sufficient to prevent such motion.

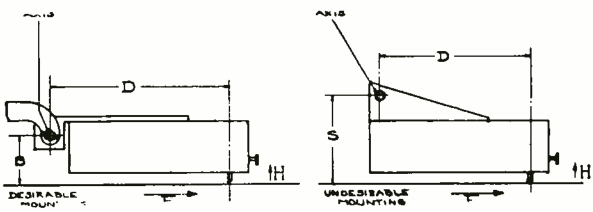
increasing D and decreasing S, H will be decreased, since H = FS/D,



(A) (B)

Fig. 56.—Methods of damping the recorder head.

Referring to Fig. 57, the reaction of the record to the cutting force of the stylus is denoted as F, and may be made sufficiently small to allow the friction in the pivot to absorb its effect. In the re-



Courtesy Institute of Radio Engineers

Fig. 57.—Desirable and undesirable mountings.

and this force, multiplied by its lever arm, which is S, or FS, produces a counterclockwise torque. This must be balanced by H, part of the weight of the head on its stylus, multiplied by its lever arm D, or HD; that is, HD = FS. If a sudden hard spot in the record passes by, FS will suddenly become greater, and thus increase H, the upward thrust on the stylus. This impulse may cause the head to oscillate. By

corder shown in Fig. 37, RCA, by using a special flat recorder head, mounted close to the record, has been able to do away with this damping mechanism.

PICKUPS.—A typical form of reproducing unit or pickup was described earlier in Fig. 5. A modified form of damping using a sheet of viscaloid was shown in Fig. 41, and is applicable to pickups as well as to recorders. The pickup differs from the recorder head in several important respects:

(1) It is driven by the record groove. If the walls are perfectly rigid, then the needle tip will be forced to follow the groove undulations, except that at the higher frequencies the needle may partially jump out of the groove and 'skate' along its tip, thus failing to follow its undulations.

(2) The electrical output can be quite low, as sufficient gain can normally be provided electrically to bring the level up to loudspeaker requirements. Danger of magnetic saturation on loud passages is remote.

(3) The weight of the pickup is supported by the area of contact between the needle tip and the record groove. Owing to the small area involved, a weight of 4 ounces may produce a *pressure* of as high as 100 tons per sq. inch on the tip and on the groove, particularly before the (steel) needle has worn to fit the groove. After the needle has been worn in, the supporting area is greater, and the pressure may drop to 25 tons per sq. in. for a 4 ounce weight.

PICKUP PRESSURE.—Even a pressure of 25 tons per sq. in. is too great for the record material to withstand, particularly the acetate discs. The present trend is toward a pickup of 1 ounce or less in weight, resting on a sapphire or diamond stylus of the correct tip radius (about 2.3 to 3 mils) so that no further grinding-in of the stylus is required. Tests indicate that the resultant pressure is below that which will cause permanent deformation of the record material or of the stylus. Although a diamond stylus is harder than a sapphire stylus, the latter is satisfactory for the above weight and has the advantage over the diamond of being much cheaper and also of being able to be more highly polished than the diamond. Probably most pickups will employ a sapphire rather than a diamond stylus, and the life will be in the neighborhood of 500 hours (playing time) as compared to 1,000 hours playing time for the diamond stylus.

The low downward pressure required to prevent excessive record and stylus wear requires in turn a vibrating system that has a very low mechanical impedance, particularly at the higher frequencies. The main impedance at the higher frequencies is, as in the case of the recorder, the inertia or moment of inertia of the vibrating members. Unless this is kept below a certain minimum, the needle tip will be unable to follow the high-frequency undulations of the groove unless the downward force is increased from 1 ounce to as high as possibly 4 ounces, whereupon excessive wear will result. Thus, in order to obviate such wear, it is not sufficient merely to counterbalance the weight of the pickup; in addition, its mechanism must be designed to have a sufficiently low impedance to track in the groove.

MECHANICAL IMPEDANCE.—Tests made with steel needles indicate that if they alone were used as the armature of a magnetic pickup, their moment of inertia, even when pivoted at the center (for which the moment of inertia is a minimum), would be too great to permit them to track in a 10,000-cycle groove for a downward force of 1 ounce. In short, for a lightweight pickup having a response up to about 10,000 c.p.s., the steel needle must be discarded and a lightweight jewel stylus employed instead.

EXAMPLES OF PICKUP DESIGN.—Several examples of pickup design will be given to illustrate constructional features.

CRYSTAL PICKUP.—In Fig. 58 is shown the vibrating system of a

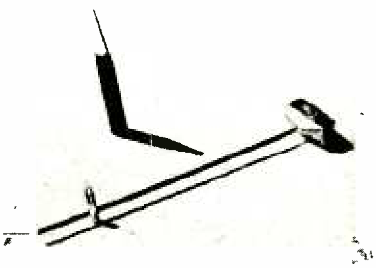


Fig. 58.—Brush pickup assembly, shown in comparsion with a standard steel needle.

Brush PL-50 pickup, with a standard steel needle behind it for comparison. The sapphire stylus is mounted in a nickel tube which is connected to one end of a thin drive wire of 0.021' beryllium copper. The other end of the wire is connected to the crystal, which is a 4-ply torsion element. Practically only the wire and stylus move, and their inertia effects are so low that no damping is required to eliminate resonant effects, since the record groove walls are in themselves sufficiently unyielding to constrain the above members to vibrate according to the degree of groove undulation. As an indication of the lightness of the design, perfect tracking can be had with only 7 to 8 grams of stylus force, and in actual practice a weight of but half an ounce is employed. The record wear is practically negligible, even in the case of the soft instantaneous discs.

The output is .16 volts (open circuit) per .001' amplitude of record modulation within ± 1.0 db from 30 to 5,000 c.p.s., and within ± 1.5 db from 30 to 10,000 c.p.s. The crystal type of pickup is inherently adapted to constant-amplitude recording, since the voltage is in proportion to the pressure on the crystal, which is inherently proportional to the amplitude of the cut. Hence, for constant-amplitude recording the pickup operates directly into a one megohm load, whereas for constant-velocity recording an equalizer must be employed. In the latter case, for a record modulation of .001' at 400 c.p.s., the output is approximately .01 volt.

MOVING COIL PICKUP.—In Fig. 59

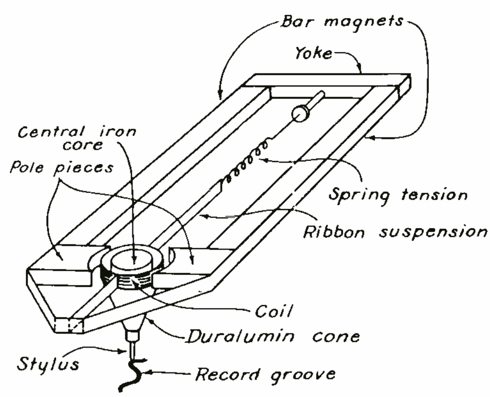


Fig. 59.—Moving coil pickup.

is shown a moving coil type of pickup manufactured by the Altec Lansing Corporation. It is essentially a D'Arsonval meter movement adapted to be rocked to and fro by a stylus. The coil is wound on a hollow duralumin cone, into whose bottom end or apex is fastened a sapphire stylus. The cone is about 6mm in diameter and 5 mm in altitude, and its walls are about .04 mm thick. The stylus is ground to an angle of 40 degrees, and the tip has a radius of 2 mils.

The cone is held in place by a suspension consisting of a ribbon .1 mm by 2 mm that passes through a slot in the cylindrical portion of the cone and is held under a spring tension of approximately 7 kg. Thus, as the record groove moves the stylus back and forth, the cone and coil pivot on this ribbon suspension laterally, but cannot move up or down.

The pole pieces each surround 90 degrees of the coil's surface. A soft iron core within the coil, fixed to the pole pieces (means not shown in figure) cuts down the reluctance to the magnetic flux, just as in a meter movement. Two permanent bar magnets and a soft iron yoke complete the magnetic circuit, although a horseshoe permanent magnet could be used instead. The flux density is 5 kilogauses.

The record groove causes the coil to rock about the ribbon suspension, thus causing the coil sides to cut the magnetic flux and hence generate a voltage. The action is illustrated in Fig. 60, (A) and (B). Note that the front and back portions of the coil are parallel to the flux and do not cut it, so that no voltage is induced in these parts and they act similar to end connections in the meter or armature coil. Nevertheless the unit has a fairly high output level of -40 db.

Some idea of the low moving masses involved can be gained from the fact that the cone weighs 2 mg; the stylus, 2.4 mg; and the coil, about 60 mg. The assembly, in con-

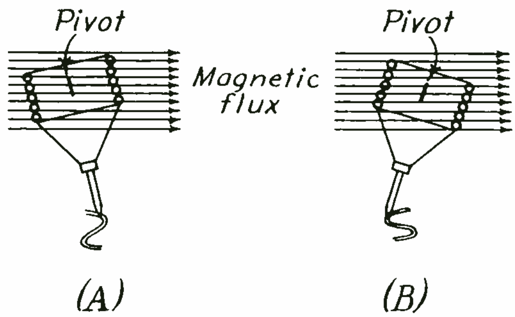


Fig. 60.—Cutting action of moving coil in a magnetic field.

junction with the ribbon suspension, has a natural frequency of 1,300 c.p.s., but its mechanical impedance is so low throughout the range that no damping is required, since the record groove can, of itself, force the unit to vibrate at the recorded frequency. The net weight or force of the stylus on the groove can be adjusted from 6-30 grams, or one ounce or less is required for proper tracking. The frequency range is given as from 30-10,000 c.p.s., and the output impedance as 50 ohms.

UNIVERSAL PICKUP.—Both RCA and Western Electric have introduced pickups that can operate on hill and dale or on lateral cut records, as desired, by merely changing connections by means of a switch. It is necessary that the reproducer respond to one or other type of recording as desired, but not to both kinds simultaneously, because a lateral cut record has a surprising amount of surface noise recorded vertically in it,—sufficient to blanket the lateral recording.

In Fig. 61 are shown simplified drawings of the device in order to exhibit the salient features. In (A) is shown an exploded view of the magnet structure. The two half-round, or rather oval pole pieces marked NN, fit into the corresponding two half-round slots in the other member marked S. One or both long strips can be permanent magnets, and the yoke Y completes the magnetic circuit when the three are assembled. In the lower view are shown the flux paths, which are radial acroos the air gap and hence at right angles to the coil form that will fit in the gap. Thus the right-hand generator rule will apply if the coil is moved up or down in this air gap.

The two coils and the duralumin form on which they are wound are shown in (B), Fig. 61. The duralumin form is of Tee shape, with the vertical member containing the diamond stylus at its bottom end. Also around this is a damping disc of viscous material to damp out any resonances in the system. The traingular spring shown permits the tee assembly to move up or down, or to rock about the vertex of the spring as a pivot. The restraining wire at the bottom permits all motions of the stylus except a forward motion, as would be produced by the drag of the record groove of the stylus.

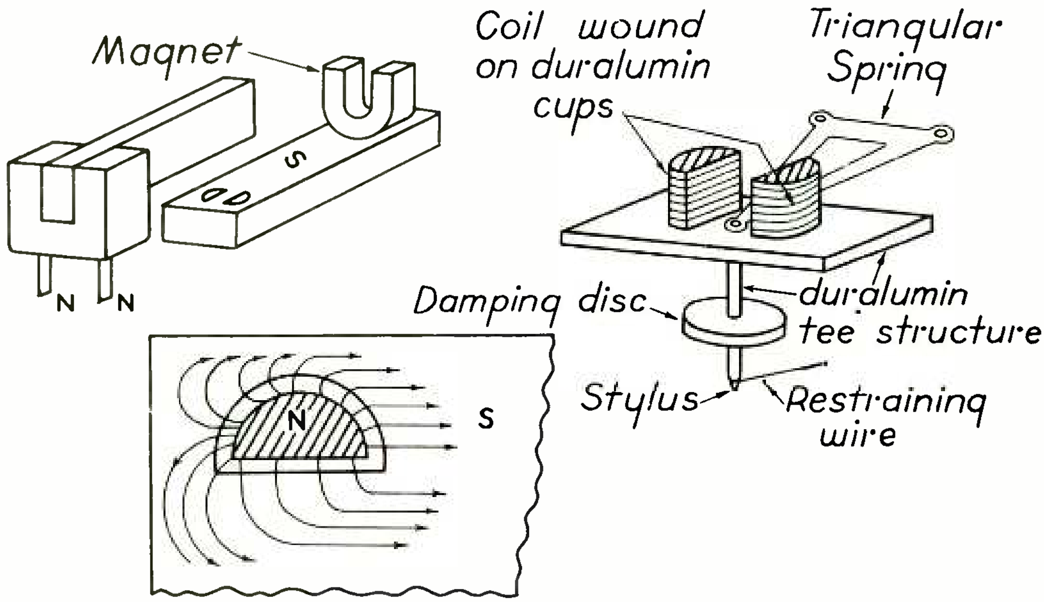


Fig. 61.—Details of universal pickup.

In the case of a lateral-cut record, the motion of the coils are opposite directions as indicated in Fig. 62 (A). (The amount of tilt is small, so that there is no danger of the coils scraping against the pole pieces.) Owing to the opposite motions of the coils, the voltages induced in them are of opposite polarity. Hence, their terminals must be connected together correctly to make the voltage additive.

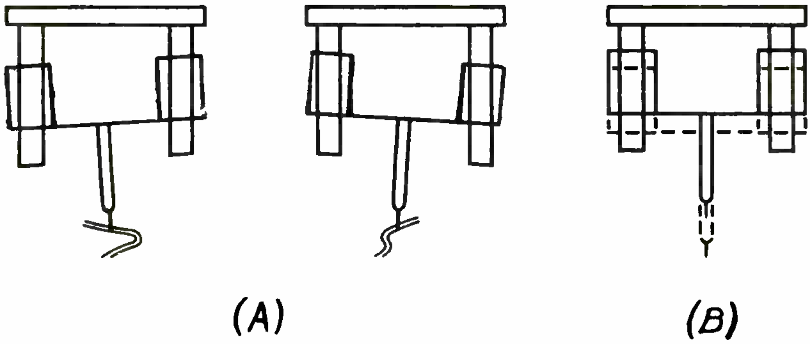


Fig. 62.—Action of Universal pickup for lateral-and vertical-cut records.

In (B), it will be observed that the coils are made to move either *both up* or *both down* by the record groove. Hence, the induced voltages will be of the same phase in both coils, and consequently they must be connected in opposite polarity to that which produces an additive effect for lateral recordings.

It is therefore clear that if a suitable reversing switch connects the coils for lateral recording, they will be insensitive to vertical surface noise; and if they are connected for vertical recording, they will be insensitive to lateral surface noise. The change from one type of recording to another is by electrical switching rather than by turning the head mechanically through 90 degrees. Any error on the part of the recording engineer can, therefore, be instantly corrected by snapping the switch without having

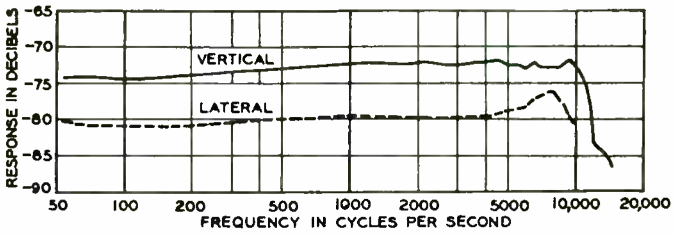


Fig. 63.—Frequency response curves of W. E. 9A Universal pickup.

to lift the pickup off the record.

The frequency response curves for both vertical and lateral re-recordings are shown in Fig. 63. It will be seen that in either case the response is substantially flat up to 10,000 c.p.s. Owing to the lower level of recording usually employed for vertical cut records, the output of this pickup for vertical recording has been purposely made higher to afford substantially the same output to the common amplifier for either type of recording;

The needle force is less than 1 ounce for either type of record, and consequently the record wear is very low. This pickup may very well be the ultimate type employed in broadcast studios.

TONE ARMS.—A surprisingly important component of the reproducing system is the tone arm, so-called from the early acoustic phonograph days, when it conveyed the sound from the sound box to the horn. Today it merely acts as the support for the pickup, but at least three factors are involved in its design.

RESONANCE.—One difficulty that is experienced is that of tone-arm resonance. At some low frequency the pickup may act as the lumped mass, and the tone arm as the spring or compliance member, in conjunction with compliances in the pickup itself, to form a resonant system. The result is an excessive response at this frequency.

The remedy is in part to afford sufficient damping in the system to reduce such a peak to the normal response value, and also, as far as possible, to lower the resonant frequency to below the audio range. Care must be taken in the design to see that the unit is not resonant in the low-frequency range—say around 50 c.p.s., or thereabouts—in order that rumble frequencies be not unduly amplified. It is thus clear that a coordinated design is necessary; the pickup and tone arm must be designed as a unit.

TRACKING ERROR.—This is further emphasized by the need for minimizing tracking error. It will be recalled that the recording head is guided *radially* acroos the record blank by the feed-screw, whereas the pickup is normally swung in an arc acroos the record by the tone arm. The difference is illustrated by Fig. 64. It is clear from the figure that the pickup arc has a radius tangent to it at only one point, A, and hence is only at this point in the correct position to be vibrated laterally by the groove. At other points the plane of the vibrating assembly makes an angle with the radius, and the result is poor tracking of the stylus in the groove and hence distortion, particularly at the higher frequencies.

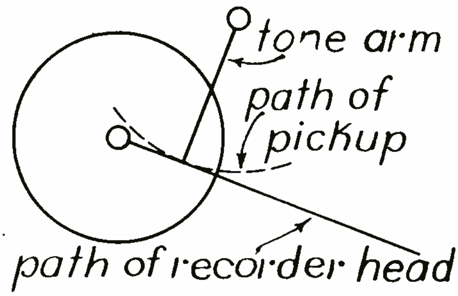


Fig. 64.—Difference in path of recorder head and pickup.

The amount of distortion is small if the above angle is reasonably small, as will be the case if the tone arm is long. For shorter tone arms, the tracking error can be made small by very simple means, and hence such means are worthwhile employing.

Thus, as shown in Fig. 65, let R_1 and R_2 be the minimum and maximum radii on the record, respectively; and R_c, the radius of a groove halfway between the above limits. The

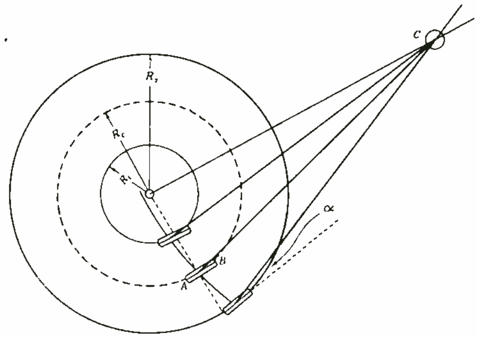


Fig. 65.—Use of off-set pickup with overhand beyond spindle.

pickup length is shown as L, and its pivot point as C. The latter is so chosen that the stylus of the pickup swings past the record spindle by an amount of overhand D. Furthermore, the pickup is mounted at an angle ∝ with respect to the tone arm.

Optimum values of ∝ appear to be from 19 to 26° for a 12-inch arm, and a correspondingly suitable value for D is approximately 1/2 inch. The exact values depend upon the length of the pickup arm, turntable speed, etc., and compromise values must be employed if the device is to operate under a variety of conditions. In Fig. 65 it will be observed that the pickup axis of vibration of the stylus, projected in one position on the record groove as AB, is very nearly tangent to the groove for practically all values of the groove radius. (The angle between AB and the tangent to the groove corresponds to the angle previously given for the tracking angle error.)

HORIZONTAL PIVOT.—The position of the pivot on which the tone arm and pickup swing in the vertical plane is of importance, too. This pivot permits the pickup to follow irregularities in the record surface. As shown in Fig. 66(A), the tone arm is pivoted directly over the bearing on which it swivels in a lateral direction in order to follow

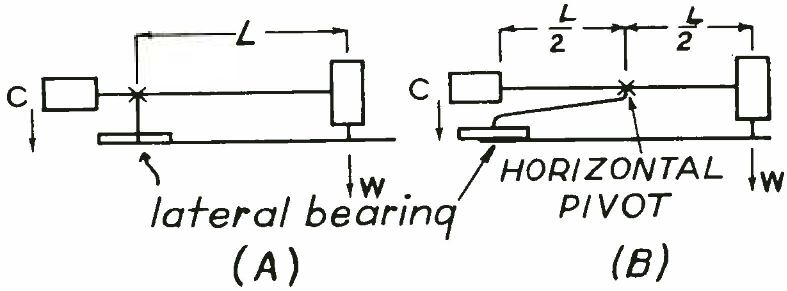


Fig. 66.—Position for horizontal pivot for minimum moment of inertia.

the pitch of the grooves. The counter-weight C balances the weight W of the pickup to within the desired stylus force on the groove, usually about 1 ounce.

When an irregularity in the record passes by, the pickup is momentarily raised, and then it drops down again at a rate proportional to the net weight of one ounce, and inversely proportional to the moment of inertia of the system with respect to the horizontal pivot. Since the net weight is very small to preserve the record life, the moment of inertia should also be as small as possible to permit the stylus to follow the drop in the record without losing contact with it. A low moment of inertia also means that it can be lifted quickly by the irregularity without undue force being exerted against the stylus by the upward force of the irregularity.

If the total weight W is large, then C must also be large to counterbalance it to the point where the net weight is small, the moment of inertia can be quite high. Thus an upward force on the stylus of about one-half pound by a warped record has been noted in some cases. This can cause breakdown in that part of the record groove, and it is also clear that the pickup will fail to drop into the low parts of the warped record.

The moment of inertia in Fig. 66(A) is approximately

$$I = WL^2$$

This assumes that the moment of inertia owing to C is negligible because it is so close to the horizontal pivot, and also that the tone arm mass is negligible. In 66 (B), however, a curved arm from the lateral bearing permits the horizontal pivot to be located half-way along the tone arm. Note that for minimum tracking angle distortion the tone-arm length should be a maximum, but for the horizontal pivot it should be a minimum to give minimum moment of inertia. The construction of Fig. 66(B) facilitates this. Thus the total moment of inertia is now

$$I = C(L/2)^2 + W(L/2)^2 = \frac{L^2}{4}(C + W)$$

For the half-way position shown, C approximately equals W (differs from it by one ounce). Hence the above equation can be written as

$$I \cong WL^2/2$$

As the horizontal pivot approaches the pickup, the moment of inertia decreases, so that the most desirable construction would appear to be to have a long curved member extending under the tone arm up to the pickup. This is an awkward construction, so that generally the horizontal pivot is located about one-third to one-half the distance from the lateral bearing.

Another type of mounting, however is often used, in which the pivot is placed close to pickup, and a balancing spring is employed instead of the counterweight. The construction is indicated in Fig. 67.

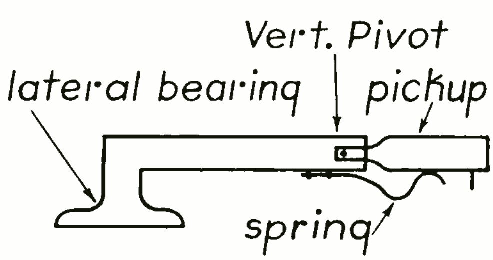


Fig. 67.—Spring counterbalance.

While the moment of inertia here is far less, and the construction considerably simplified, this arrangement has one objection, and that is if the pickup is inadvertently dropped on the record, then the full weight of the pickup acts for most of the distance of travel, and is opposed by the spring only over the last portion of the travel. As a result, the pickup may strike the record with sufficient force to damage the grooves and possibly break the stylus. A further objection is that the spring effect varies with the height of the pickup over the record. This may vary with the thickness of the record, and in any event varies during the revolving of the record if it is warped.

TECHNIQUE OF RECORDING

Several features of recording have already been noted. The following additional hints or pointers will be found of value:

PRELIMINARY PROCEDURE.—The turntable must be absolutely level, and the record blank must be absolutely clean. Use a soft cloth to remove dust and dirt, and avoid finger marks, as these increase the surface noise. particularly if the blank is to be processed for copies. The machine should be checked for noise and rumble, and the feedscrew and other parts must be operating properly and smoothly.

It is always advisable to make an unmodulated test cut on a portion of the disc which will not be used, and then to examine this groove under a microscope for depth and appearance. Start the turntable before lowering the cutter, and then lower it gently onto the disc. For 112 lines per inch, the ratio of groove to wall width should be 65/35; for 96 lines per inch, it should be 60/40. The microscope should be in a vertical position when making these measurements.

Also examine the thread cut from the groove. It should be about the thickness of a human hair, and be straight and shiny. If it is kinked or curly, then either the stylus is defective, the cut is too deep, or the vertical angle should be changed slightly from its normal value of 96°. Finally, play back the unmodulated groove to note whether or not the level of the surface noise is excessive.

RECORDING PROCEDURE.—During recording be sure to observe the precaution of not allowing the thread to touch the stylus, as otherwise baffling 'pops' and 'squeals' will be heard during the playback. The stylus may be even lifted from the groove in spots by the waste thread.

Try to keep the recording as close to the outer edge as possible, although for a long program the entire usable width will have to be employed. In any event, for 33 1/3 r.p.m. recordings, do not record to a diameter less than 6 1/2 inches.

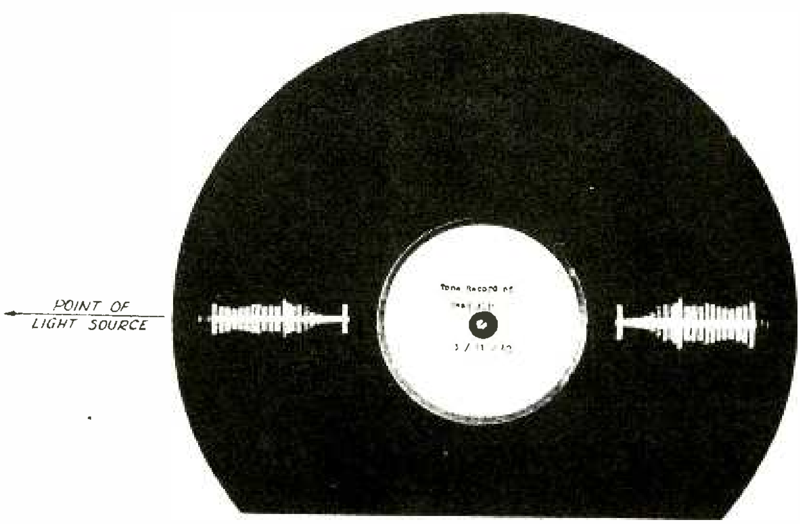
One of the worst causes for distortion, at least in commercial pressings, appears to be due to overmodulation. A limiting amplifier is of great value in preventing such an occurrence, but care should be exercised in checking the level at the recorder to insure that it is not excessive. Owing to change in temperature, or even humidity, the damping material may change its characteristics sufficiently to cause overcutting. On the other hand, if the program is recorded at too low a level, the surface noise may be relatively excessive. Hence careful monitoring of the program during the recording is of prime importance.

It is often found advisable to advance or retard the stylus with respect to the radius along which it moves. This radius, parallel to the line of feed, is called the center line. When cutting inside-out, the recorder head should be moved from 1/8 to 1/4 of an inch from the center line in the direction of rotation; i.e., the stylus should be retarded. On the other hand, when cutting outside-in, the stylus should be advanced about the same amount. The actual amount depends upon the mechanical design, upon the frequency response, and whether the speed is 33 1/3 or 78 r.p.m. An appreciable difference in the quality of recording can be noted with change in setting in many cases. Where no provision for this is made by the manufacturer, it may be assumed that he has chosen an average optimum position.

FREQUENCY RESPONSE.—If various frequencies, from the lowest to the highest, are recorded on the disc, and the latter then viewed while illuminated by a point source of light, a series of striations of light that resembles a Christmas tree pattern can be seen on the record. This is shown in Fig. 68.

The width of each band indicates the amplitude of the voltage which an ideal *velocity-type* pickup would generate when playing this record. This is owing to peculiar optical conditions that obtain when light shining on these grooves is reflected by them. Thus there is available an optical method for measuring the frequency response *as recorded on the record itself.*

The method of making such a record is to record each frequency selected for 10 seconds and then 5 seconds of silence (no modulation). The high frequencies should be recorded at the outside of the record.



Courtesy Broadcast News

Fig. 68.—Optical pattern of a tone record.

The reference frequency is 1,000 c.p.s., and should be recorded at the beginning and end of the test run, as well as at its proper place in the band, where it should also be recorded at 2 db below and above its normal value to furnish relative amplitudes for comparing the other frequencies.

Two patterns are formed, as shown in Fig. 68. The one closer to the light source can generally be measured more accurately. The light source should be of small area and high brightness, and should be located to the left of the record and slightly above it. The observer should stand directly over the pattern about 3 feet above it, and use a pair of dividers to measure the amplitude.

Note from Fig. 68 how the lower frequencies (actually below 500 c.p.s., the turnover frequency) decrease in width. This is because they are cut at constant amplitudes, and the light pattern shows them on a velocity basis. Because they decrease markedly, it may be preferable to measure their response with a high-grade pickup, since most pickups of good quality are flat in the lower range. The higher frequencies can be easily measured on the record. Note in Fig. 68 that the response is fairly uniform at the higher frequencies for the record shown. The optical method is thus a valuable recording aid, because it requires no auxiliary equipment except a pair of dividers for measuring the frequency response.

RESUME'

This concludes the assignment on recording. First a general historical review was given, followed by a general analysis of recording theory. The need for various recording curves, such as the Orthacoutic response, was shown, and then the various parts of a recording system were described. In particular, methods of obtaining uniform turntable speed were described, then feedscrew mechanisms, recorder heads, and finally representative recording mechanisms were discussed.

The reproducing pickup was then analyzed, and its differences from a recording head studied, as well as its coordination with the tone-arm design. Finally, a general analysis of recording technique was given, with pointers on the recording of instantaneous playback records.

RECORDING SYSTEMS

EXAMINATION

1. (A) Describe the four fundamental steps in processing a wax recording.

   (B) What is the objection to the use of graphite and similar powders in making the wax master conducting?

2. It is desired to record at a pitch of 130 lines per inc. The groove cross section is a semi-circle of 5-mil diameter.

   (A) What is the maximum amplitude of recording possible?

(B) Suppose the turnover frequency is 500 c.p.s., and above this frequency constant-velocity recording is employed. What is the maximum amplitude at 5,000 c.p.s.?

(C) A volume range of 46 db is desired. What is the minimum amplitude?

3. Refer to Problem 2.

(A) For the turnover frequency at 500 c.p.s., how much peaking is required at 50 c.p.s. in the reproducer equalizer response to obtain an overall flat response?

(B) Referring to the 5,000 c.p.s. response, it is desired to peak this frequency in recording by 12 db. What will be the amplitude of the minimum recorded sound at this frequency?

4. (A) What benefits can be derived from a reduction in the high frequency surface noise of the material? Explain briefly.

(B) What type of noise is encountered at the low-frequency end of the spectrum?

5. (A) What difficulty will be encountered in attempting to reproduce a *high level*, 10,000 c.p.s. note at 33 1/3 r.p.m.?

(B) How is it that in spite of the above difficulty, high-frequency peaking can, nevertheless, be employed in recording?

(C) Describe the important features of the orthacoustic system of recording.

6. (A) Discuss briefly the tracing distortion occuring in lateral, and in vertical recording.

(B) How does this affect the peaking of the high-frequency sounds in recording?

7. (A) Discuss the difference between flutter and 'wows'.

(B) What are the important principles involved in a turn-table drive? Choose some particular make of recorder, and show how these principles are employed.

8. (A) Describe the method employed in the RCA Professional Recorder for obtaining various pitches and recordings out-side-in or inside-out.

(B) Describe the construction of a Presto recorder head.

(C) How does RCA obtain an electrical equalizer effect in their recorder?

9. (A) What is the advantage of light weight in a pickup?

(B) In order to have a lightweight pickup, what characteristic must its vibrating system have?

(C) Describe the universal pickup, pointing out its method of operation for lateral and for vertical-cut records.

(D) What three considerations are involved in the design of a tone arm? Explain briefly.

10. (A) Describe briefly the process of making an instantaneous recording.

(B) How can the recorded frequency response be measured on the record?

(C) How can the mechanical damper be eliminated by suitable recorder design?