Limiting Factors in Gramophone

I.—PLASTIC DEFORMATION AND WEAR OF GROOVE WALLS

THE stylus tip in a gramophone pickup is usually spherical and much more rigid than the record, so that the problems of determining the deformation of the record groove wall have much in common with those associated with hardness tests such as the Brinell, in which a ball is pressed into the surface to be tested. Under light loads any material will deform elastically, giving a small area of contact. On releasing the load the material springs back to its original position undamaged. With increasing load, the yield stress of the material will be reached and permanent plastic deformation will begin; on releasing the load the material will not return exactly to its original position, i.e. the record is damaged.

The equations for the elastic range are well known and were deduced by Hertz; they have been expressed in convenient form by Hunt[1].

$$p_m = \frac{0.45\,E_1^{\frac{2}{3}}\,W^{\frac{1}{3}}}{R^{\frac{2}{3}}}$$

$$\text{or } W = \frac{11\,p_m{}^3 R^2}{E_1{}^2}$$

Where p_m is mean bearing pressure between contacting surfaces in kgm/mm^2

$E_1 = E/(1-\sigma^2)$
E = Young's modulus of record material (kgm/mm^2)
σ = Poisson's ratio of record material
W = Load on stylus in grams
R = Stylus radius in mils (0.001in).

Because of the complex stress system, yielding occurs at a value of p_m = 1.1 times the simple tensile or compressive yield stress of the material. Hunt[1] quotes 11 milligrams as the limiting load for no plastic deformation for a stylus of 1-mil radius on vinyl. Although the stylus is supported by both groove walls at low signal levels, at extreme amplitude or acceleration one wall will be taking most of the load. As this is applied at about 45° to the surface, the playing weight must be increased by $\sqrt{2}$ before yielding can commence, i.e. to about 16 milligrams. In a modulated groove the stylus is in contact not with a flat surface but with concave and convex groove walls. This would reduce the load required for yielding by a factor of 0.77 if the driving wall were convex and the trace radius approached the stylus radius. However, at high frequencies where the trace radius may be small the inertia of the pickup will be a controlling factor rather than the stiffness, so that the load will be taken entirely by the concave outer wall (Fig. 1).

As the load on the indenter (stylus) is increased beyond the elastic range, yielding occurs not at the surface but below, at a distance of about half the radius of the circle of contact. With further increase in load, deformation will gradually spread throughout the area under the indenter. Eventually, plastic deformation of the surface will commence at the surface. With further increase in load, plastic deformation occurs over the whole of the area of contact (the condition has been termed "full plasticity") when the contact pressure is about three times the yield stress of the material. Further increase in load does not appreciably affect the contact pressure. This is the condition in normal identation hardness testing, where the load must exceed the minimum value for full plasticity for reliable hardness readings to be obtained.

From Hunt's results, the minimum load for full plasticity is 6-10 grams with a 1-mil stylus on a vinyl surface (Hunt's Fig. 2). Many commercial pickups therefore operate in the fully plastic range, and must cause considerable damage to the groove (Fig. 2). If each groove wall were deformed equally at all parts of the waveform, this would give no distortion and would not be serious. However, as the load is not taken equally by each wall, the deformation will be unequal, giving distortion of the waveform, with a decrease of low-frequency signals (where stiffness is operative) and an increase of high frequencies (where inertia is operative). Similar effects occur due to the elastic deformation of the groove walls, but in most if not all commercial pickups the elastic effects will be small compared with the plastic. A possible method of obtaining equal deformation of both groove walls would be to play the virgin record first at twice the normal tracking weight at a very low speed, so that the pickup arm could follow the whole of the wave form with negligible lateral loads, but this would hardly be practicable.

The ideal pickup would work entirely within the elastic range (16 mgm). Although it may not be possible to construct such a pickup it might still be possible to limit plastic deformation to the interior of the material, so that the surface of the grooves is undamaged[3]. The limiting tracking weight would be that at which plastic deformation just commenced at the surface. Unfortunately, this point cannot as yet be calculated. Under any stress

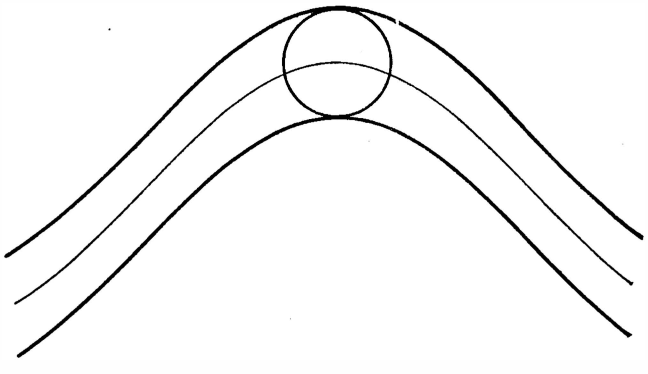

Fig. 1. Stylus supported by convex and concave groove walls.

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[1] Hunt, F. V. *J. Audio Eng. Soc.*, Vol. 3, No. 1, Jan. 1955.

[2] Davies, R. M. *Proc. Roy. Soc.*, Vol. 197, A1050. 22 June 1949

[3] Barlow, D. A. *J. Audio Eng. Soc.*, Vol. 4, No. 3. July 1956.

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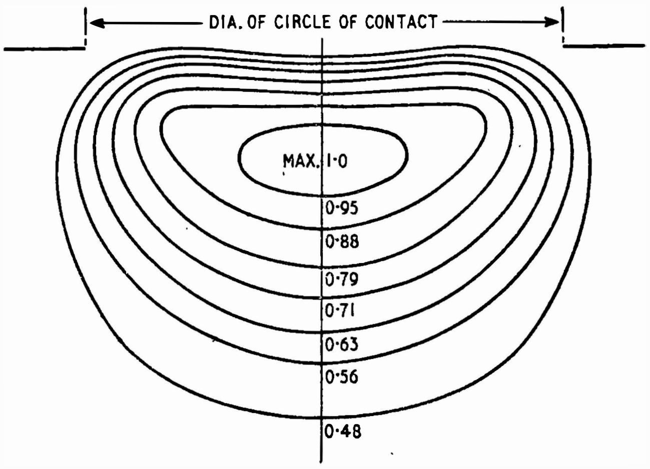

Fig. 3. Shear stress distribution in material under spherical indenter (after Davies[2]).

system, all materials yield according to some function of the shear stress. The shear stress contours in a material under an indenter at the moment of sub-surface yielding are shown in Fig. 3; they will vary somewhat with the Young's modulus and Poisson's ratio of the material. The shear stress at the surface is 0.33 of the shear yield stress, and is proportional to the cube of the load while the whole of the material is elastic. To obtain surface yielding therefore, the load will have to be raised by some unknown factor, probably greater than $(1/0.33)^3$, giving 0.3 gram for a flat surface, or 0.43 gram for a record groove.

As the record moves under the stylus, the system is not the same as the static indentation case so far considered. Poritsky[4] has shown, for cylinders in contact, that the effect of an additional tangential force, as represented by friction, is to shift the point of onset of yielding nearer to the surface. The influence of stylus-groove friction would doubtless be similar and would affect yield loads, but if friction is low, as is probably the case, the effect will be small.

Scratch Tests.—Hunt's scratch tests were conducted by dragging 1-mil and 3-mil radius styli over flat vinyl surfaces. No trace was detected below about 6.7 grams for the 3-mil stylus; the corresponding load for the 1-mil stylus should be 0.75 gram, but no tracks were detected below 1.5 grams, probably because of the difficulty of detecting such very fine traces. The limiting loads for plastic deformation just to appear at the surface with a 1-mil stylus will thus be between 0.3 and 0.75 gm for a flat surface, or 0.4 and 1 gm for a pickup, say, half a gram.

Shellac Records.—From hardness tests, the yield strength of shellac is about twice that of vinyl. From cantilever loading tests, the modulus of elasticity of shellac is about three times that of vinyl. The increased yield stress is therefore more than offset by the increased modulus, giving a smaller area of contact (and hence higher stresses) for a given load. The limiting load for no plastic deformation of shellac will thus be slightly less than for vinyl (for the same size stylus). For a 2.5-mil stylus the load will be about 90 milligrams, and the corresponding load for plastic deformation to just appear at the surface will be 1.75 grams. Loading tests on shellac with a 2.5-mil sapphire stylus showed tracks at less than 3 grams, corresponding to a pickup weight of about 4 grams. We may thus take the limiting load as about 2½ grams.

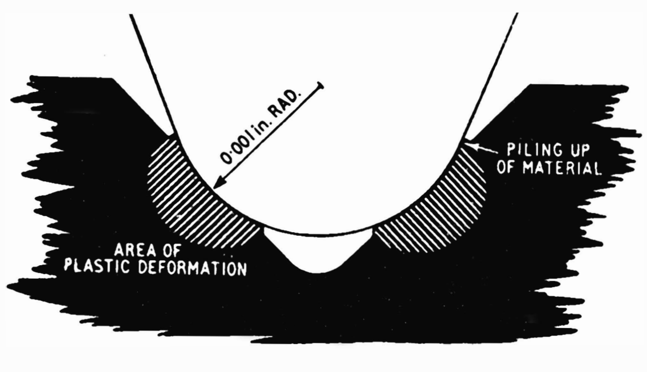

Fig. 2. Stylus-groove contact in the fully plastic range.

It will be noted that at low loads, for a given stylus, shellac will actually be damaged more than the vinyl, but around 15 grams for a 2½-mil stylus the track width or damage will be similar for each material, and above this load the damage to shellac will be less—the track width will be about 0.7 of that on vinyl in the fully plastic range. Shellac is therefore the better material for the old type of heavy pickup, but vinyl will be superior for lightweight pickups. This would explain conflicting reports on the relative damage of vinyl and shellac discs. There is no technical reason why, in these days of lightweight pickups, 78 r.p.m. records should not be made in vinyl.

Deterioration on Repeated Playback.—When any material is deformed the area of contact increases, and, beyond the elastic limit, the material work hardens until it is able to support the load, unless the load is so high as to cause fracture. Once a record has been played at a given weight, provided that this is not too great, there will be no further plastic deformation on continued playback (at the same weight); the record will sound the same as at the first playing, although it may be heavily deformed, and there is no knowing what the virgin record would sound like. The claim that a certain record sounds the same after 1,000 playings as it did with the first playback does not mean that it is undamaged.

It used to be the practice of record companies to monitor the original wax or lacquer disc before plating to make the master. If the original has been damaged in this way, the final record will not sound any different for being played with a very lightweight pickup. It would be interesting to know if the record companies still monitor the original disc before plating now that the original recording is usually done on tape. If we are to take advantage

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[4] Poritsky, H. *J. Appl. Mech.*, Vol. 17, No. 2. June 1950

of very light-weight pickups which will not give plastic deformation of the surface not only must we purchase virgin records but it is essential that any monitoring at any stage during manufacture be done with equally light pickups (or with styli that are weaker than the groove walls).

Nevertheless, with heavy pickups progressive deterioration does take place on continued playback. This is due to creep and fatigue. At high stresses the material continues to deform slowly, so that on repeated replay the groove continues to be deformed slightly each time. Fatigue is the fracture of a material by varying or repeated loads at stresses lower than the static strength. As the highest stresses are sub-surface, failure will take place by sub-surface cracking, giving flaking and pitting of the groove walls. This gives the increase in noise characteristic of heavily played records. It is interesting to note that Max[5] obtains this type of failure on repeated playback of polystyrene and occasionally vinyl records at 10 grams load with a 1-mil stylus. If there is a rest period between replays the material partly recovers, and does not fail.

Wear.—Up till now we have been discussing damage or plastic deformation of perfect surfaces, although it is often referred to as wear. Wear may be defined as the attrition of contacting surfaces due to relative sliding. The nature of friction is as follows. Under light loads no two surfaces contact at more than a few high spots or asperities, however accurately thay may be finished. Local pressures at these asperities are therefore high, and ploughing, welding and shearing occur on relative motion. This is the normal mode of wear of styli. If there is no bulk surface plastic deformation of a record, the stylus is supported by the asperities, which may be stronger than the bulk material[1,3] and will give a lower rate of frictional wear of record and stylus than a heavier pickup working in the fully plastic range, where the whole of the mating surfaces are in intimate contact. Diamond is known to give lower coefficients of friction with most materials than sapphire or cemented carbide; it might therefore be expected to give less frictional record wear.

Noise.—The noise level will depend on the tracking weight of the pickup as well as on other factors such as sensitivity for degrees of freedom other than lateral. Also Hunt[1] has pointed out that there are the following components in the noise from a gramophone record.

(1) *Surface roughness.* The grooves of modern records are very highly finished, the roughness as low as 50 A.U. (10^{-7} mm). This is as low as is obtainable on the most highly finished surfaces. In the case of shellac, the filler is of course responsible for considerable roughness, and hence noise. This can be reduced somewhat by the use of superfine fillers.

(2) *Welding and shearing of asperities.*

(3) *The associated plastic deformation.* This may also give rise to noise as plastic deformation is not a continuous process, but on a microscale, it occurs by discontinuous slip.

To reduce wear and noise, therefore, improvements can be made only to items (2) and (3), given a homogeneous record material. In addition to using a diamond stylus, the obvious method would be to use polytetrafluorethylene (p.t.f.e.) for the record[1] or the stylus, although its yield stress and modulus may be too low. This gives low friction with all materials, but if the pickup works in the fully plastic range a coefficient of friction of only 0.04 represents welding of stylus to groove over 25% of the contact area[3]. This will obviously give relatively high wear and noise level, so that the situation with more readily weldable materials, such as vinyl, can well be imagined. Polyethylene usually has a lower coefficient of friction than other plastics (apart from p.t.f.e.) but its yield strength and modulus may be too low; however, Smith[6] has used polyethylene and reports that it gives a lower noise level than vinyl. Polyethylene is said to be too expensive for records; polytetrafluorethylene would be very much more so. It would be interesting to know what proportion of the cost of a record is represented by the plastic and its processing—it has been said that the cost of producing a record pre-war was about 3½d. If so, a more expensive plastic giving lower noise level could obviously be used without appreciably increasing the cost of a record.

Other possible means of reducing friction would be the use of graphite for styli, or porous metal or ceramic impregnated with graphite, oil or p.t.f.e.

Another method of reducing wear and noise due to items (2) and (3) would be by lubrication of the record[1,3]. For this purpose, a solution of calcium petroleum sulphonate in a light petroleum fraction has been suggested. This would be wiped on to the record immediately before each playing, the solvent evaporating and leaving an adsorbed film, only a few molecules thick, on the groove walls. This would probably give adequate boundary lubrication, and would not obscure the high frequencies. Flake graphite, as has been used in the past, would not be adsorbed on to the groove walls, and would have no effect other than to increase noise by reason of particles trapped under the stylus.

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[5] Max, A. M. *J. Audio Eng. Soc.*, Vol. 3, No. 2. April 1955

[6] Smith, O. J. M. *Audio Eng.*, Vol. 32, No. 9. Sept. 1948.

Limiting Factors in Gramophone

2.—PICKUP DESIGN: CONTINUITY OF STYLUS-GROOVE CONTACT:

HAVING examined, in the first part of this article, the nature of record deformation and wear, we can consider the design of a suitable pickup. The limiting tracking weights are ½ gram for vinyl and 2½ grams for shellac. The lightest commercial pickups track at 2-3 grams for vinyl and 4-6 grams for shellac. It would be difficult to reduce the tracking weight to the desired value for vinyl, but it would be fairly easy to halve the tracking weight for shellac, as the design is in any case easier than for vinyl. If the desired low weight for tracking on vinyl could be achieved, the resultant pickup would doubtless be fragile, and have low output voltage, but before ruling out such a pickup as impossibly difficult and expensive, it should be remembered that only a few years ago pickup manufacturers considered that anything with a tracking weight of less than 30 grams was a fragile, expensive, specialists' instrument. With the advent of microgroove records, and the necessity of reducing tracking weights to about 8 grams, if reasonable record life was to be obtained, pickup manufacturers have produced, apparently without difficulty or complaint, pickups which not only operate at this weight but are fairly cheap and have a high output voltage; even record changers have been redesigned to treat records with more care.

The Arm.—This must have low friction and low inertia, particularly with warped records, and torsional resonance which will influence response must be avoided. A single vertical pivot bearing is at once the simplest and cheapest, is robust, has the lowest friction, and torsional resonance is avoided. If desired, an anti-vibration mounting can be used between head and arm to further reduce the effect of arm resonance. The only disadvantage of the single-point bearing is that very thin flexible leads must be used to reduce drag. To reduce the torque on the arm to a minimum, the armature should be positioned (at the correct angle for minimum tracking error) with the stylus on the axis of the arm (Fig. 4). To obtain the correct tracking weight the arm may be counterbalanced either by a weight or by a spring—in the case of a single pivot, a weight only is possible. The weight is much more convenient and more easily adjusted, but it is sometimes argued that a spring is better in that it saves weight and hence inertia of the arm. However, although the saving of weight is considerable, the saving of inertia is very small. Thus if the head is of mass m, distant l from the pivot, its moment of inertia about the point is ml^2; this must be counterbalanced by a mass of say $5m$, distant approximately $\frac{l}{5}$ from the point, having a moment of inertia of $5m \times (\frac{l}{5})^2 = \frac{ml^2}{5}$, i.e., for the convenience of using a counterbalance as opposed to a spring, there is an increase of only 20% in the inertia. As the inertia of the tube forming the arm has been ignored the increase in the total inertia will be somewhat smaller. As the inertia of the arm will usually be only a fraction of that of the head, particularly if a magnetic head is used, there is no point in making the arm absurdly flimsy.

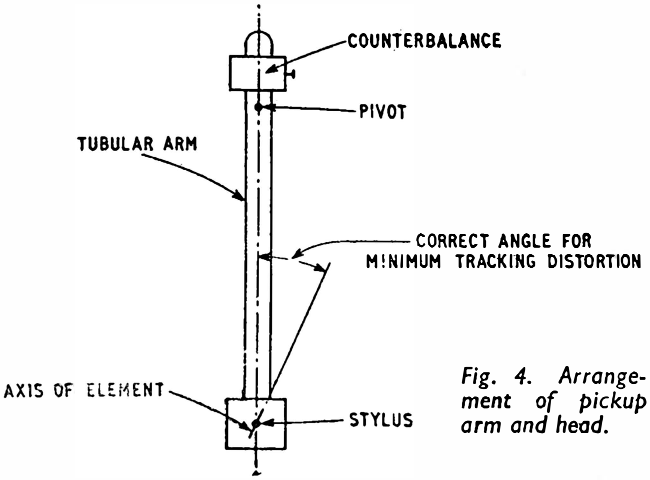

Fig. 4. Arrangement of pickup arm and head.

The Head.—The limiting weight of the head will depend on the degree of warping of the record to be played, the accuracy of the centre hole and the accuracy of the turntable. The inertia of a 60-gram head is not excessive at a tracking weight of 2 grams; it is thought, therefore, that at a tracking weight of ½ gram, a head weight of 15 grams would not be excessive. In a magnetic head it is doubtful whether this weight of magnet would give saturation in the size of gap likely to be used, but sufficient flux to give useful output should be obtainable. With shellac records, with the greater weight allowable, there should be no difficulty. Where a crystal movement is used there will be less difficulty in attaining a small head weight. The type of movement used is partly a matter of choice. The moving coil system is easily designed and has fewer objections than moving iron and crystal systems. The coil would preferably consist of several turns of fine wire giving a higher output voltage than a ribbon or single turn, so as to be well above the hum level picked up by the leads[7, 8]. The coil would preferably be a bifilar push-pull winding, feeding into a centre-tapped coupling transformer, thus reducing hum. A strain-gauge system in which the electrical resistance of a fine wire is varied by the strain it receives is attractive, as it is simple and can be made in small sizes. However, circuit arrangements are a little complex, and the signal level would almost certainly be so low that noise and hum would be serious problems. Carbon composition strain gauges would be unsatisfactory, due to self-generated noise. Other methods, such as magneto-striction and frequency modulation, would seem to offer no advantages. The recently

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[7] Baxandall, P. J., Letter, *Wireless World*, Sept., 1950.

[8] West, R. L., Letter, *Wireless World*, Sept., 1950.

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TRACING DISTORTION

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introduced magnetomotive system[9] consisting of a moving magnet with a stationary coil on a soft iron core is attractive, as the moving parts are simple and robust and high impedance with high output voltage is obtainable without a coupling transformer.

The tracking weight has been discussed by Mallett[10]. It is governed by three factors, the lateral stiffness, the lateral inertia and the vertical stiffness. The lateral stiffness is operative at low frequency so that the inner surface of the groove will take most of the load; at high frequencies the inertia of the moving parts is operative and the outer wall of the groove takes the load. In a complex waveform stiffness or inertia may be operative over different parts of the wave, but the full load will be taken at any instant by only one groove wall, so that stiffness and inertia loads are complementary. The maximum stiffness load is reached at maximum amplitude; the maximum inertia load may not always be reached at maximum amplitude, depending on the waveform; the maximum load due to vertical stiffness when vertical amplitude is greatest is at the mid-point of the wave. These three components of load, therefore, lateral stiffness, lateral inertia and vertical stiffness, are largely complementary rather than additive. Vertical inertia is not in itself important as will be shown later. Longitudinal movement of the stylus must be a minimum, otherwise distortion and rounding off the steep wave fronts will occur. Lack of longitudinal rigidity is the probable reason for needles trailing rather than being set vertically[11]. A vertically set needle will judder longitudinally if it is not rigid in that direction. The maximum angle of the trace to the direction making a tangent to the groove at the stylus contact must be less than the half angle of the groove (approx. 45°), otherwise the stylus will ride up the groove wall regardless of tracking weight. The angle of the trace in the $33\frac{1}{3}$ r.p.m. extended play records appears to approach this limit as a result of the greater amplitudes employed.

Lateral Stiffness.—This must be such that the lateral load for the maximum recorded amplitude is not greater than the tracking weight, i.e., lateral compliances must be more than 6×10^{-6} cm/dyne for vinyl and 4×10^{-6} cm/dyne for shellac. This should not be difficult to arrange.

Resonances.—There will be a number of resonances due to the mass of the armature, head, etc., with the lateral, vertical, and longitudinal compliances of the suspension, and record-stylus. The armature should be sufficiently rigid longitudinally for resonances with this compliance to be ignored. The other resonances are examined below. Any damping material must be added with caution, as it may cause intermodulation distortion[12].

Lateral Low-frequency Resonance.—This is the resonance of the mass of the head and arm and the lateral stiffness of the movement, and the frequency is given by

$$f_1 = \frac{1}{2\pi\sqrt{M_p C_a}}$$

Where M_p is the lateral effective mass at the stylus of the head and arm (gm) C_a is the lateral compliance of the movement (cm/dyne).

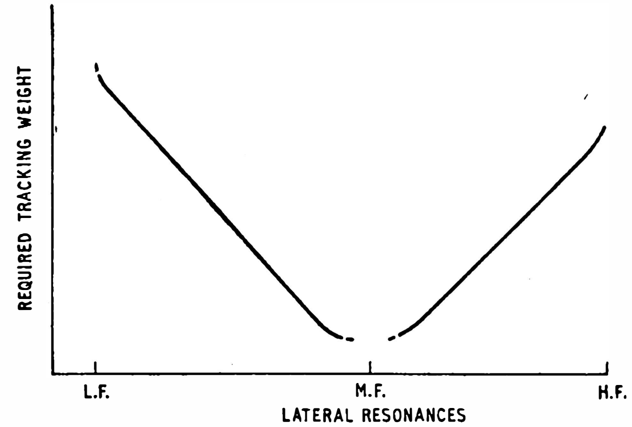

Fig. 5. Effect of lateral resonances on required tracking weight.

The effective mass at the stylus is:

$\frac{I}{l^2}$ where I is the moment of inertia about the particular axis, and l is distance of axis from stylus (cm).

This resonance has been used in cheap pickups to boost the bass; it should, of course, be below the recorded range in a high-quality pickup. For vinyl with a head weight of 15 grams, the resonance would be at about 17 c/s; for shellac with a 75-gram head, the resonance would be about 9 c/s.

Lateral Mid-frequency Resonance.—This is the resonance of the mass of the movement (coil or armature) with its own lateral stiffness (restoring force), and generally occurs at the mid-frequencies. Unlike most other resonances, it is not deleterious. It is a series resonance and at the resonance frequency the stylus point impedance tends to zero (Fig. 5.). It simply means that at this frequency no power is required to move the armature except that required by damping. The physical significance of this can be easily seen—the stylus will always try to move at this frequency so that at lower frequencies it tends to return to the mid-point faster than the trace allows, so that it is always pressing on the inner wall of the groove; at high frequencies

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[9] Wittenburg, N., *Philips Tech. Rev.*, Vol. 18, Nos. 4/5 and 6, 1956/57.

[10] Mallett, E. S., *Electronic Eng.*, May, 1950.

[11] Rabinow, J., and Codier, E., *J. Acous. Soc. Amer.*, Vol. 24, No. 2, March, 1952.

[12] Roys, H. E., *Audio Eng.*, May, 1950.

it tends to return to the mid-point slower than the trace allows, so that it is always being forced back by the outer wall of the groove. This resonance is given by

$f_2 = \frac{1}{2\pi\sqrt{M_a C_a}}$ where M_a is lateral effective mass of element at stylus.

Lateral High-frequency Resonance.—This is the resonance of the mass of the element with the compliance of the record and stylus. It is well known that if this frequency is in the audio range, excessive noise will result from shock excitation of this resonance, and there may be accompanying distortion, even if the resonance is thoroughly damped. This resonance is given by

$f_3 = \frac{1}{2\pi\sqrt{M_a C_n}}$ where C_n = lateral compliance of stylus and record materials (cm/dyne).

For this resonance to be above say 20 kc/s, M_a must be less than about 1 milligram for vinyl and 3 milligrams for shellac.

Lateral Inertia.—The maximum accelerations recorded are about 1500 *g* for microgroove records and 500 *g* for 78 r.p.m. records[1][3]. The corresponding limiting lateral effective mass at the stylus is 0.33 milligrams for vinyl, which would be hard to achieve, and 5 milligrams for shellac, which would be easy to achieve.

Vertical Stiffness.—The need for vertical movement is of course to allow for the pinch effect. The groove is cut with a chisel-edged stylus and traced with a spherical stylus, as a consequence of which the stylus of an ideal pickup must move vertically at twice the frequency of the trace. The maximum vertical amplitude is about 1/9th of the lateral for microgroove and 1/6th for 78 r.p.m. records. The vertical stiffness must therefore be not greater than 9 times and 6 times the lateral stiffness respectively, i.e., a compliance of 0.67×10^{-6} cm/dyne in each case.

Vertical Resonances.—Although the pickup may not generate any voltage for vertical movement, vertical resonances are best avoided in the recorded range, or, rather, at twice these frequencies, as the vertical movement takes place at twice the recorded frequency of the trace. Where the lateral loads are not shared equally by each groove wall, as is always the case except at zero amplitude, any vertical forces will cause movement of the stylus not vertically but at some angle—in extreme cases up and down the side of one of the groove walls, and will thus generate a signal, even though true vertical movement generates no signal. The normal vertical movement may therefore generate a signal, although it may be very small, but vertical resonances may be serious.

Vertical Low-frequency Resonance.—This is not the resonance of the mass of the head with the vertical compliance of the movement or cantilever, and should be below the recorded range. It will be about 50 c/s for vinyl and 22 c/s for shellac (corresponding to lateral recorded frequencies of 25 and 11 c/s) for the pickup considered here.

Vertical High-frequency Resonance.—This is the resonance of the vertical effective mass at the stylus point with the compliance of stylus and record, and should be above the recorded range, i.e., above 40 kc/s (corresponding to 20 kc/s lateral). The vertical compliance of record and stylus is unknown, but will probably be about half the lateral, as the load is now taken by both walls of the groove. The limiting vertical effective mass at the stylus will thus be about 0.5 mgm for vinyl and 1.5 mgm for shellac.

The above two resonances will influence each other's frequencies slightly, but as they are a long way apart the interaction will be very small and can be ignored. With suitable design there will be no other vertical resonance, and the stylus will maintain contact with the groove at all times, except when severe tracing distortion occurs, due to overmodulation, when the trace radius approaches the stylus radius. When this occurs, and contact with the groove is not maintained, there will obviously be acoustic rattle or needle-talk, and the output may be affected. In addition, when the stylus point is free, there may be a further vertical resonance, falling in the mid-frequencies (see later). The vertical inertia of the system is not, in itself, of importance, as the high-frequency resonance is above the recorded range.

Cantilever Movements.—To achieve the above very small effective vertical masses in practice, a cantilever type of movement is essential, as only the cantilever and stylus contribute to the vertical mass, the axis of the generating element being vertical. In most other designs, the whole of the element must move vertically, and the total mass is limited to the allowable vertical mass. The cantilever movement has the added advantages that vertical movement is obtained with the minimum of longitudinal movement, and the system can be easily designed to minimize damage due to accidental dropping on the record. The use of a cantilever, however, introduces its own lateral, vertical and torsional resonances. The lateral resonance can probably be avoided, as the cantilever must be stiff laterally if appreciable signal loss is to be avoided. The torsional stiffness could be increased for a given cantilever mass by making it of tubular form, and its magnitude reduced by placing the stylus tip as near as possible to the axis of the cantilever. Vertical resonance of the cantilever will occur when the stylus is not in contact with the groove, and in any practical design this resonance will fall within the audio range. However, when the stylus tip is in contact with the groove, and provided the generating element itself has negligible vertical compliance, there will be no resonance in the audio range. Considering vertical movement only, the system has two degrees of freedom, Fig. 6(a), and the only resonances will be the low and high frequency ones already listed. If there is appreciable vertical compliance between armature and head, the system will have three degrees of freedom, Fig. 6(b), and there will be three resonances, the additional one of the mass of the armature with the cantilever compliance being within the recorded range. The armature vertical compliance can be made very small if the top end of the armature forms a cup-and-cone bearing with the head; in the case of a torsional crystal element it may be firmly fixed to the head.

The cantilever would best be made in a hard rigid

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[3] Cosmocord Ltd., Private communication.

plastic, perhaps phenol-formaldehyde, as this would have the greatest stiffness/weight ratio of any practical material, this being proportional to modulus/(density)^2. Sapphire and diamond would be too heavy for tips, at least for microgroove, so that a one-piece replaceable plastic moulding could be used for stylus plus cantilever.

Soft Styli.—In passing, it should be noted that the usual objections to soft needles will not apply here; as the yield stress and modulus of the stylus will be appreciably greater than those of the record material, there will be no serious deformation of the stylus, and fairly accurate tracing with reasonable life would be obtained. Conditions would bear no relation to those of the conventional thorn under, say, 40 gm playing weight, under which the point is deformed to contact almost the whole of the groove, with consequent distortion and top loss. The other conventional objections to thorn are the possible embedding of either sharpening or other dust with consequent abrasive wear of the grooves, the thorn acting as a lap. The possibility of dust from sharpening being embedded is much exaggerated; every day in industry, millions of sand-papering and grinding operations are carried out on all types of material and particles of abrasive are virtually never embedded in the work. It is possible to get embedding of abrasive, particularly with certain soft and ductile metals, but it occurs only with unsuitable grinding conditions, and virtually never occurs with the free-working non-metallic materials. Regarding the embedding of ordinary dust, if the record is cleaned sufficiently well each time for the noise due to dust to be inaudible, it is difficult to see how such dust as remains could become audible, and the rate of wear, if any, would be extremely small. Further, it is by no means certain that abrasive wear by such means actually occurs; for lapping to take place, the lap must normally be much softer than the material to be lapped. In the present case, the plastic will be harder than vinyl or (unfilled) shellac.

The relatively low modulus of soft styli, compared with sapphire or diamond, will increase the stylus-record compliance, which will lower the lateral and vertical high-frequency resonances. Again, a high-modulus plastic must be chosen, when the effect will probably be slight, but, if necessary, a further reduction in mass at the stylus point must be made.

Tracing Distortion.—This is by far the most serious form of distortion in record reproduction. It can be very distressing on shellac records, and is tolerable on vinyl only by reason of the elastic deflection of the groove walls, which reduces the tracing distortion but introduces a further type of distortion which is less serious. Severe record damage will result from overmodulated traces, however light the pickup. When the trace radius is equal to or less than the radius of the stylus at the point of contact with the walls, the stylus is required to change its direction instantaneously, which requires infinite deceleration and acceleration thus giving groove deformation and rattling. On 78 r.p.m. records an elliptical stylus is essential to reduce tracing distortion to tolerable limits. Thus a 3-mil bottom radius/1-mil lateral radius stylus can be used, reducing the tracing distortion by a factor of 6; the tracking weight must be reduced to about half that for a 2.5-mil stylus. With microgroove records no such course is possible, and tracing distortion is more serious than on 78 r.p.m. records played with an elliptical stylus.

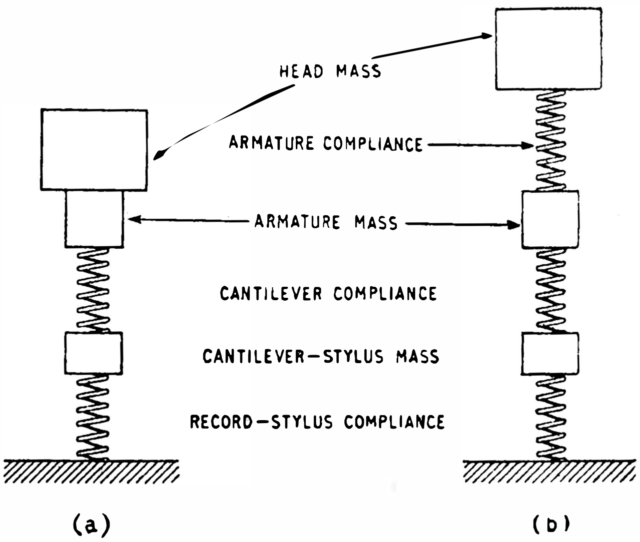

Fig. 6. Vertical systems with two and three degrees of freedom.

The high tracing distortion of microgroove records is due to the excessive high-frequency pre-emphasis used, as the de-emphasis in playback only partly offsets the distortion caused by pre-emphasis. The NAB characteristic, giving 16 dB rise at 10 kc/s is particularly bad—to quote Hunt, it "effectively guarantees excessive distortion." As a result, the A.E.S. standard curve, giving 12 dB rise at 10 kc/s, was adopted. The purpose of the pre-emphasis is of course to reduce surface noise; as the noise of good vinyl records is barely audible, it seems that even the 12 dB rise could be reduced without surface noise becoming objectionable. The noise level is reduced by about 6 dB for the 12 dB boost; if this were reduced to 6 dB, there would be an increase of 3 dB in noise level, which would be barely noticeable, with a reduction in tracing distortion by some factor approaching 4, which would be a very noticeable improvement. If there were no pre-emphasis, the noise level would be 6 dB higher than the A.E.S. standard, which would still be very much lower than shellac, and tracing distortion would be drastically reduced. This point has been well made by Viol[16].

An attractive alternative to dropping pre-emphasis would be 78 r.p.m. microgroove records—there would still be sufficient playing time per side that breaks would come between movements of symphonies, etc. The use of high-frequency pre-emphasis perhaps has more justification for shellac records where surface noise is high, but even here the gain may be largely offset by the increased tracing distortion. In any case, with a lightweight pickup, say less than 10-15 gm, there is no reason why 78 r.p.m. records should not be made in vinyl.

Dutton[17] has shown that for a given maximum level of tracing distortion, disc diameter, and average groove spacing, there is an optimum speed of rota-

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[14] Watts, C. E., Reported in *Wireless World*, Dec., 1949.

[15] Pierce, J. A., and Hunt, F. V., *J. Acous. Soc. Amer.*, Vol. 10, No. 4, July, 1938.

[16] Viol, F. O., *Proc. I.R.E.*, Vol. 38, No. 3, March, 1950.

[17] Dutton ,G. F., *Wireless World*, June, 1951.

tion of the turntable, giving the longest playing time. He states that at a groove speed of 16in/second, on standard 78 r.p.m. records, tracing distortion is apparent (this is rather an understatement), but that quality is not noticeably impaired at 22in/sec. The corresponding velocities for microgroove records (presumably allowing for high-frequency pre-emphasis, etc.) are stated to be lower by a factor of 1.6, i.e., 10in/sec and 13.75in/sec respectively; at this latter speed distortion is about 4% and it increases very rapidly to about 16% at 10in/sec. On the basis of a minimum speed of 10in/sec., a 12in disc gives a maximum playing time of 22 minutes at an optimum speed of about 33⅓ r.p.m. However, if we take the preferred minimum speed of 13.75in/sec., the maximum playing time is about 16 minutes at a speed of about 45 r.p.m.; 33⅓ r.p.m. gives a playing time of 15 minutes, and 78 r.p.m. gives 14 minutes. In other words, on the basis of work done by a well-known record manufacturer, if good quality is to be obtained, 15 minutes is about the limit of playing time, for a 12in disc, and the speed of rotation makes very little difference. In fact, the differences are so small that the trouble and expense of changing speeds and obtaining new turntables (usually more expensive than for 78 r.p.m., owing to the need to reduce rumble) was quite unjustified—the microgroove vinyl 78 r.p.m. record was the obvious choice, and speeds were doubtless changed only because the Americans had already done so. It has been argued that the slower speeds have the advantage of giving more margin for squeezing in an extra minute or so to enable the item to be completed; this is justified if the passage is a quiet one, but this does not often happen at the conclusion of a work. The fact that most 12in l.p. discs run for 20-25 minutes, and some for as much as 32 minutes, shows that this advantage is in fact a very serious disadvantage if high quality is to be obtained; with 78 r.p.m. microgroove discs, excessive squeezing in would be prevented by the label. There are even some gramophone enthusiasts who consider that on certain l.p.s, the musicians were persuaded to hurry through the work in order to squeeze it on to one side of a very long playing l.p. disc, when it would have been better to take two sides. If high-frequency pre-emphasis were not used on microgroove discs, it would be possible to go to a lower minimum groove speed, say 8½in/sec, for good quality, when a playing time of about 26 minutes would be obtained on a 12in disc, run at 22 r.p.m.

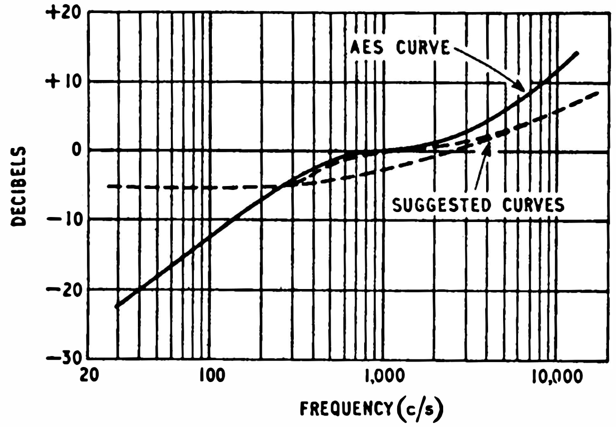

Fig. 7. Suggested revision of recording characteristics.

On the subject of recording characteristics, it is interesting to note in passing that Hunt[15] has pointed out that the maximum output for both speech and music drops off at rather more than 6 dB per octave below 250-300 c/s, i.e., the usual bass cut in recording is unnecessary. The advantage of no bass cut is obvious—less equalization required, i.e., less waste of precious output volts from the pickup, with the elimination of hum and rumble problems. There is some doubt about published curves for maximum output, as it is possible that transients and organ notes reach higher levels; nevertheless it would be interesting to know if bass cut is really necessary to avoid overcutting, or whether it is simply a hang-over from the days of acoustic recording, when the recording equipment unavoidably gave such a cut. The suggested recording characteristics are given in Fig. 7.

Returning to the problem of tracing distortion, together with pinch effect and the need for vertical motion of the stylus, the whole difficulty would disappear if the original groove were impressed with a spherical stylus, a duplicate of the reproducing stylus, instead of being cut with a chisel. As the area of contact of the groove with the stylus would now be greatly increased, deformation and wear from existing pickups would be almost eliminated. The limiting tracking weight for an impressed groove is difficult to calculate but would be about 0.9 gm for vinyl for *the elastic range*. With a comparatively slight reduction in existing tracking weights of the best pickups, there would be no damage whatsoever to record grooves and frictional wear of both groove and stylus would be very low. It might be necessary to use very close tolerances on dimensions of both recording and reproducing styli, to avoid an oversize stylus being forced into the groove, or an undersized one from " skating," but this would be a very small price to pay, especially as the reproducing stylus would be virtually everlasting for normal users. Alternatively, a V-groove could be impressed with a conical stylus, which would give a greater contact area and hence even higher limiting tracking loads. By making the bottom radius of the reproducing stylus larger than that on the recording one, skating would be avoided and a universal stylus becomes possible.

An impressed type of groove would doubtless require considerably more power for recording than a cut groove, but this might be offset by recording at a high temperature, either by means of a heated stylus or by heating the blank. Thus the normal hard type of recording wax or lacquer could be impressed while hot and soft. There are doubtless other difficulties, but the advantages to the record user would be so great that every effort should be made to produce impressed-groove records.

The impressed type of groove, with the high tracking weights possible without serious groove damage, makes the acoustic gramophone once more possible as a high-quality reproducer. Although there may be many limitations on the quality obtainable, some improvement in design is doubtless possible, and it should be remembered that the best acoustic gramophones have a clarity of reproduction which is not matched by many commercial radiograms.

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INVESTIGATIONS OF THE PHILIPS INDUSTRIES

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, NETHERLANDS

A MAGNETODYNAMIC GRAMOPHONE PICK-UP

I. CONSTRUCTION.

by N. WITTENBERG.

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Professional gramophones are commonly equipped with pick-ups of the electrodynamic type (moving coil and fixed magnet). A magnetodynamic type of pick-up will shortly be marketed in which the coils remain fixed while the magnet moves. The new pick-up has various advantages compared with the electrodynamic type, greater sensitivity and lower price amongst them, which make the new pick-up suitable for non-professional equipment. The article below deals the construction of the magnetodynamic pick-up. Its frequency characteristic and some other properties will be treated in a further article.

Of the various types of gramophone pick-up in use the most common is the piezo-electric type [1]). For professional purposes (in broadcasting studios, and for testing purposes in the manufacture of gramophone records) use is often made of the electrodynamic system: in this, a small coil located between the poles of a permanent magnet follows the movement of the gramophone needle, the signal voltage being induced in it as a result. The construction of the system is in principle the same as that of a moving-coil meter, the gramophone needle taking the place of the pointer moving across the scale.

There are disadvantages inherent in the electrodynamic system. They are manifested particularly when it is desired to employ the system in pick-ups for non-professional equipment of which a high fidelity is required. In such cases the coil must be of extremely light construction, in order to keep the mass of the moving system of the pick-up down to a minimum; otherwise, the resulting accelerations (which may be hundreds of times greater than the acceleration g due to gravity [2])) will give rise to inertia forces that will cause severe wear of the gramophone record. To keep wear within acceptable bounds, the mass of the moving system must not be more than a few milligrams. This implies a coil of extremely thin wire with only a few turns. Consequently the voltage induced in the pick-up is only a fraction of a millivolt. In order to get a good signal-to-noise ratio at the output of the amplifier in spite of this, the amplifier must be provided with a step-up input transformer which has been carefully screened against external magnetic fields (e.g. from the gramophone motor or the amplifier mains transformer). This all adds to the cost.

In order to increase the voltage induced in the moving coil the magnetic field in which the coil moves should be as strong as possible: a rather large permanent magnet is therefore required. The magnet is necessarily situated immediately above the record and hence above the turntable on which the record lies. The turntables of non-professional gramophones are frequently of iron, this being a cheap material and at the same time a heavy one, giving a flywheel action. The magnet exercises an attraction on the iron turntable, increasing the needle pressure on the disc. (The weight of the pick-up may be balanced by a spring or counterpoise.) Often the turntables of non-professional gramophones have a diameter of less than 12″; during the playing of the outer part of a 12″ disc, the pick-up is not directly over the turntable and the needle pressure is lower than it is further inwards, where the pick-up is directly above. The variation in the vertical needle

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[1]) See for example L. Alons, New developments in the gramophone world, Philips tech. Rev. **13**, 134-144, 1951/52.

[2]) J. L. Ooms, Philips tech. Rev. **17**, 101-109, 1955/56.

force sometimes amounts to several grams in ordinary electrodynamic pick-ups. The increase in the force exerted by the needle results in heavier wear of both needle and disc, and causes losses in the reproduction of high frequencies.

The disadvantages of the electrodynamic system — the need for an input transformer and the unnecessarily high needle pressure on part of the gramophone record — are entirely absent in the magnetodynamic pick-up, which will now be described.

Design of the magnetodynamic pick-up

In the magnetodynamic pick-up, the magnet and coil exchange their rôles; the magnet moves while the coil is fixed to the body of the pick-up.

A diagram illustrating the principle is given in *fig. 1*. A rod-shaped permanent magnet *M* is located in the air-gap of a yoke *J* of magnetic material, on which the coils *S* are wound. The rod is magnetized in the direction of the arrow, *perpendicular to a plane through its axis,* and can turn about that axis, being held in two bushes *P* and *R*. At its lower end the rod has an arm *L* (the needle arm) fixed to it, and this arm carries the needle *N*. The lateral movement of the needle point as it follows the modulated groove in the disc, causes the magnet to turn about its axis.

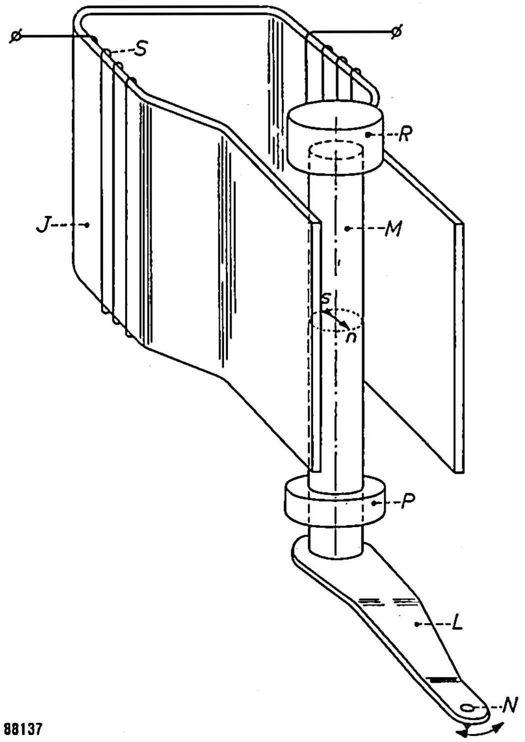

Fig. 1. The essentials of the magnetodynamic pick-up. *M*: ferroxdure rod, magnetised in the direction of the arrow *s*-*n*. The rod magnet is located between the ends of the yoke *J* carrying the coils *S*, by means of the rubber bush *R* and the polyvinyl chloride bearing *P*, which allow it an angular degree of freedom. The needle arm *L* converts the lateral movement of the needle point *N* into an angular displacement of the magnet about its axis.

The upper bush *R* is made of rubber. The magnet fits into it tightly and thus suffers a restoring couple when displaced that gives it a definite position of equilibrium. The equilibrium position is made to coincide as far as possible with the position of magnetic symmetry (*fig. 2a*), in which the lines of force form a symmetrical pattern, some passing through the air-gap and the ends of the yoke, others through the air only. If the magnet is turned from the equilibrium position the symmetry of fig. 2*a* is upset, and a portion of the flux passes right round the yoke to complete its circuit (fig. 2*b*). The direction of the flux passing round the yoke is dependent on the direction in which the magnet is turned. Lateral movement of the needle point thus produces alternations of flux through the yoke and these induce the signal voltage in the coils.

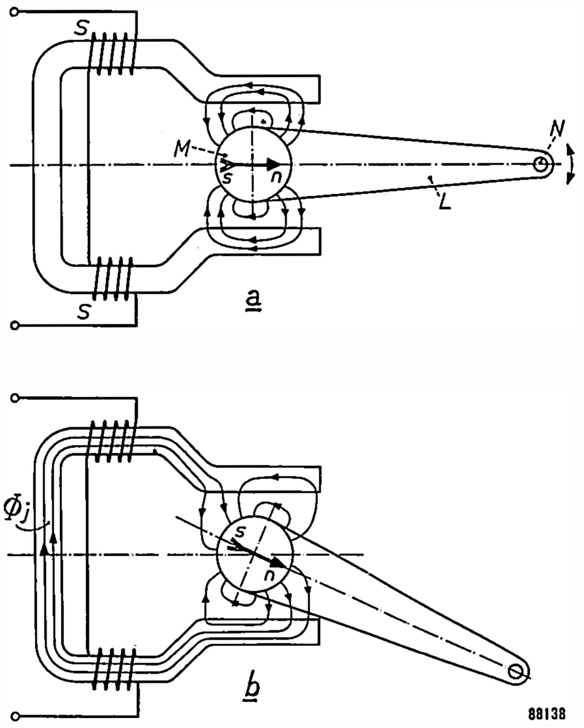

Fig. 2. The magnetodynamic pick-up seen from above (not to scale). (*a*) Magnet in position of rest; no flux passes through the coils. (*b*) Magnet turned out of position of rest; a flux Φ_j passes through both coils. The letters have the same meaning as in fig. 1.

Two important properties of the above arrangement may be deduced from the following experiment. The magnet, driven by a small motor, is made to *rotate* between the ends of the yoke, and the voltage set up in the coils is examined. It is found that the voltage is very nearly sinusoidal, this being due to the relatively large air-gaps. From this fact one may anticipate that the signal voltage induced by the small angular movement of the magnet during actual use will exhibit only extremely slight deviations from linearity (the magnet departs from its position of symmetry by not more than 1° for standard 78 r.p.m. records, and by not more than 0.5° for microgroove records). In the matter of linearity, then, the magnetodynamic pick-up does not fall short of the electrodynamic type, which in theory is strictly linear.

Of the total flux provided by the magnet, a portion Φ_m reaches the yoke, while the remainder completes its entire circuit in the air as a stray flux. The second property that may be deduced from the experiment with the rotating magnet is the magnitude of the flux Φ_m. For this we require only to know the speed with which the magnet rotates (n in revs. per sec) and to measure the induced voltage E (r.m.s. value). The flux is then given by

$$\Phi_m = \frac{E}{4Fnw} \text{ volt.second,}$$

where F is the shape factor of the voltage function (for a sine wave, $F = \pi/2\sqrt{2} \approx 1.11$) and w is the total number of turns on the coils. For $n = 50$ revolutions per second and $w = 4000$, we find a voltage $E = 0.65$ V, from which it follows that $\Phi_m \approx 0.7$ µVsec. This method can be employed in manufacture for testing the magnets.

From the fact that the rotating magnet produces a sinusoidal voltage it follows that Φ_j, the flux passing through both coils when the magnet is displaced through an angle α from the position of symmetry (*fig. 3*), can be written as $\Phi_j = \Phi_m \sin \alpha$. If y is the displacement of the needle point corresponding to α, and l is the distance between the axes of magnet and needle, $\sin \alpha = y/l$. Hence

$$\Phi_j = \frac{y}{l}\,\Phi_m.$$

If the motion of the needle point is sinusoidal, that is, if $y = \hat{y} \sin \omega t$, then $\Phi_j = (\hat{y}/l)\Phi_m \sin \omega t$. This flux induces an alternating voltage e in the coils given by

$$e = -w\frac{\mathrm{d}\Phi_j}{\mathrm{d}t} = -\frac{w\Phi_m\hat{y}\omega}{l}\cos \omega t = -\frac{w\Phi_m\hat{v}}{l}\cos \omega t, \quad . \; . \; . \; . \; . \; . \quad (1)$$

where $\hat{v}$ is the peak value of the velocity of the needle point.

The ratio between the voltage and the velocity is termed the sensitivity of the pick-up; it is usual to take the r.m.s. value of the voltage in millivolts and the peak value of velocity in cm/sec. Insertion of the values $w = 4000$, $\Phi_m = 0.7 \times 10^{-6}$ V sec, $l = 0.5$ cm in equation (1) gives us a sensitivity of about 4 mV per cm/sec. For $\hat{v} = 5$ cm/sec — a typical value for microgroove records — this sensitivity gives an r.m.s. voltage of 20 mV. The sensitivity is considerably better than that of electrodynamic pick-ups (without input transformer), but not so good as that of the piezo-electric type. Hence, if the magnetodynamic pick-up is to be connected up to a conventional radio receiver, an extra amplification stage is necessary. A suitable pre-amplifier using a transistor will be discussed in a subsequent article.

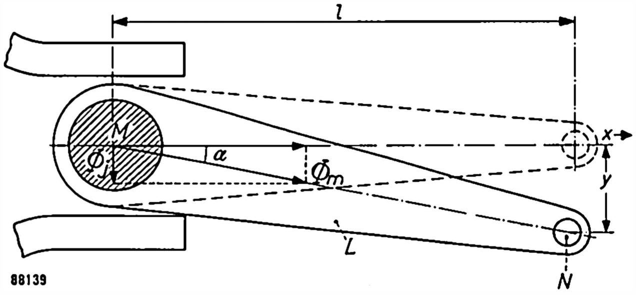

Fig. 3. The same situation as in fig. 2*b* with the main dimensions drawn to scale. Φ_m: the fraction of the total magnetic flux that reaches the yoke. Φ_j: the component of Φ_m that passes through the coils.

Construction of the pick-up

The various parts that go to make up the pick-up are shown in *fig. 4*. We shall now examine these components in some detail and consider the requirements they have to satisfy.

The magnet

It follows from equation (1) that, in order to obtain a high voltage from the pick-up (so as to get a high signal-to-noise ratio in the amplifier), the flux Φ_m of the magnet must be made as strong as possible. The magnet must further satisfy the following requirements:

1. Its moment of inertia about the axis should be as small as possible in view of the large accelerations occurring.
2. It should be proof against demagnetization by external magnetic fields. One reason for this is that the magnet together with the needle has to be replaced when the needle is worn out; it must not be possible for the loose magnets to become demagnetized by contact with iron parts or tools or by the action of stray fields from transformers, etc.

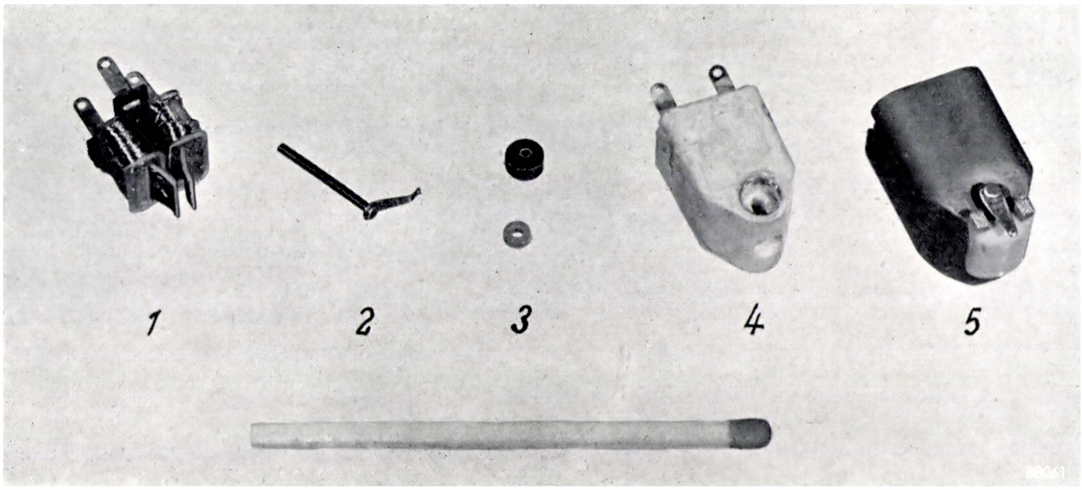

Fig. 4. Component parts of the magnetodynamic pick-up. *1* yoke with coils; *2* magnet with needle arm and needle; *3* rubber bush and p.v.c. bearing; *4* block of polyester resin which is cast around the yoke and coils, place being left for the insertion of magnet and bearings; *5* the block *4* complete with bush, bearing and magnet and shrouded in metal housing for magnetic and electrostatic screening; on either side of the needle arm are protective shoulders.

3. The magnet must be easy and cheap to manufacture.

In order to give the magnet a small moment of inertia an unusual design was adopted: a thin rod magnetized perpendicular to its axis. A "short" magnet such as this has a high demagnetization factor and this design was therefore made feasible only by using a material that has a high coercive force. Ferroxdure [3]) is such a material. Its coercive force is about 80 kA/m (about 1000 oersted), in comparison with about 50 kA/m for "Ticonal" steel [4]). Ferroxdure is suitable for the purpose in mind in other respects as well. Its density is about 4000 kg/m^3, as against about 7000 kg/m^3 for "Ticonal" (a low density is desirable from the point of view of a small moment of inertia). Thin rods of ferroxdure can be manufactured by extrusion, followed by sintering. These processes lend themselves better to mass production than the casting of rods from magnet steel. After sintering, the ferroxdure rods are ground in a centreless-grinder, since they inevitably become somewhat distorted in the course of the sintering operation. Accurately dimensioned rods are thus obtained which are easily interchangeable and have a restoring couple which is satisfactorily reproducible.

A compromise necessarily has to be made between giving the magnet small mass and making it supply a big flux. The best form has been found to be a rod 1 mm in diameter and 12 mm long, its effective length being 8 mm .The flux has the value derived above, namely 0.7 μVsec; the mass is about 40 mg, and the effective mass at the needle point, which determines the magnitude of the inertia forces set up, is only 3 mg. (The effective mass is the equivalent mass considered to be concentrated in the needle point and possessing a moment of inertia with respect to the magnet axis equal to that of the whole moving system.)

The attraction between an iron turntable and a magnet of this small size is quite negligible compared with the minimum force with which the needle must rest on the record in order not to jump the groove. This constitutes one of the great advantages of the magnetodynamic system over the electrodynamic system.

The needle arm and the needle

The function of the needle arm is to communicate to the magnet the movements of the needle point. There are two components of the latter: a lateral movement corresponding to the modulation of the groove, and a vertical movement resulting from the so-called "pinch-effect" (a sinusoidal groove, for example, is narrower in the flanks than at the peaks, with the result that the needle is borne up in the former and sinks down in the latter; see article cited in footnote [1])). Only the *lateral* movement of the needle has to be communicated (without distortion or loss) as an angular movement of the magnet; this implies that the needle arm must be so rigid in a lateral sense that resonance of the needle arm and magnet in the lateral direction occurs only at a frequency higher than the range that has to be

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[3]) J. J. Went, G. W. Rathenau, E. W. Gorter and G. W. van Oosterhout, Philips techn. Rev. **13**, 194-208, 1951/52.

[4]) B. Jonas and H. J. Meerkamp van Embden, Philips tech. Rev. **6**, 8-11, 1941.

reproduced, i.e. above 20 kc/s. At frequencies above resonance almost all the movement of the needle is absorbed by the flexion of the needle arm, resulting in a big drop in the output voltage. In the second part of this article, dealing with the frequency characteristic, it will be shown that the needle arm does in fact satisfy the above condition.

Since the needle extends below the needle arm, the lateral force on the needle point creates a couple that to some extent twists the needle arm. Like the frequency of lateral resonance, the resonant frequency of this torsional effect must lie above the range of frequencies to be reproduced. If the system is excited at the torsional resonance frequency, the magnet remains practically still and the output voltage drops to zero, while the needle makes a shrill sound and there is heavy wear of the record. The frequency at which torsional resonance occurs is decided by an effective mass (other than that for lateral movement) at the needle point and the torsional stiffness of the needle arm. The obvious way of raising the torsional resonance frequency above 20 kc/s is to make the needle arm thick enough. However, this would bring us into conflict with a third requirement that the needle arm has to satisfy: it must not transmit to the magnet the vertical movement of the needle resulting from pinch effect; this vertical movement occurs at a frequency double the modulation frequency and, if it contributed to the pick-up output, would introduce a second harmonic. In theory, of course, no movement of the magnet other than the turning movement induces a voltage in the coils; but the slight departures from symmetry that are inevitable in mass-production prevent this ideal from being completely realised. Hence the magnetodynamic pick-up, like the electrodynamic one, does have a certain response to vertical needle movement.

The "vertical response" can be reduced to a minimum by making the needle arm relatively flexible in the vertical direction, whereby the resonant frequency of magnet and arm for vertical movement is reduced to below the frequencies where pinch effect is considerable (roughly speaking above 1000 c/s); hence the vertical movement is absorbed by the needle arm and thus prevented from affecting the magnet. Flexibility of the needle arm in the vertical direction has two further advantages. Firstly, it means that the effective axis for movement in the vertical plane is closer to the needle, so that the effective mass for movement in this direction is virtually limited to the mass of the needle and its fixture to the arm. Secondly, if by mischange the pick-up should be dropped on to the disc, the needle arm can flex back such that the weight of head is taken on two shoulders fixed to the housing (visible in fig. 4, No. 5); this protects the brittle ferroxdure rod against breakage. On the other hand, however, the needle arm must be sufficiently stiff to support the weight which the pick-up exerts, via the needle, on the record (about 10 grams) without bending too far. By suitable choice of the material, shape and dimensions of the needle arm these requirements can be satisfied. The resulting torsional resonance frequency is in the region of 25 kc/s while the resonant frequency for lateral vibration is still higher.

From what has been said it will be evident that the needle arm, apparently so simple, is a component to which a great deal of attention has to be given.

The magnet and the needle are fixed to the needle arm by cleating them with small collars of aluminium. Needle, collar and needle arm are first positioned in the cleating jig. The unflanged end of the collar is then cleated by a suitably shaped tool (see *fig. 5*) The magnet is fixed to the needle arm by a similar method. Not only does this method give a reliable joint but all play is taken up by the aluminium cleating so that there is no need to demand extremely fine tolerances in the dimensions of the parts.

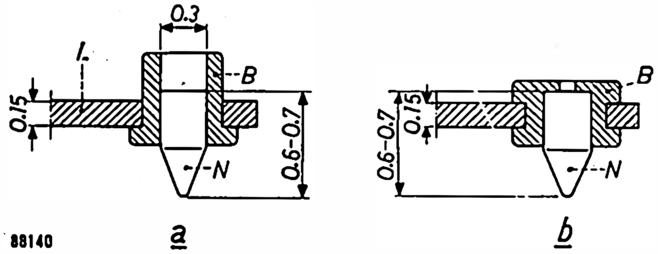

Fig. 5. Attachment of the needle *N* to the needle arm *L* by an aluminium cleat *B*. (*a*) Before cleating, and (*b*) after. Dimensions are in mm.

The magnetodynamic pick-up (*fig. 6*) is manufactured in two models, identified by a coloured mark, which differ only in the type of needle and which are easily interchangeable. Type AG 3020 (with a green spot) is for standard 78 r.p.m. records and has a sapphire needle; the radius of curvature of its tip is 75 microns, as is usual in needles for these records. Type AG 3021 (red spot) is for microgroove records; the tip of its diamond needle has a radius of curvature of 25 microns.

Diamond was chosen for the needle point of the second type for the following reasons. With the force of 10 g weight with which the point rests on the record and the smaller radius of curvature of the microgroove needle, the pressure is so high that a sapphire needle wears comparatively quickly. The wear of the needle results in distorted reproduction, particularly of high notes. If the pick-up is used with an amplifier and loudspeakers capable of reproducing very high audio frequencies [5]), the wearing of the sapphire point is perceptible as a troublesome distortion after comparatively few records have been played. The rate at which diamond wears is some tens of times slower. Added to this, less wear of the needle point means less wear in the records. One might expect that the harder and more resistant to wear the needle point, the greater the wear of the record but in fact the latter is mainly dependent on the shape of the needle point: the harder the needle, therefore, the longer it will retain its initial approximately hemispherical shape and hence the smaller the wear of the record.

Fig. 6. Philips record-changer, type AG 1003, equipped with the AG 3021 magnetodynamic pick-up.

The magnet bushes

The magnet bushes must allow the magnet to turn about its axis, but provision also has to be made for a restoring couple that tends to bring it back to a definite position of equilibrium. This is necessary to ensure that the needle arm lies parallel to the groove when the latter is unmodulated. If this condition is satisfied, tracing distortion is at a minimum [6]).

The restoring couple is obtained by clamping one end of the magnet into a rubber bush (*R* in fig. 1). The stiffness so obtained must have a certain minimum value for the reason given above, but it must not be greater than necessary; at low frequencies, the stiffness largely determines the force required to give the needle a certain lateral displacement, and this force in turn determines the minimum downward force of the needle required to prevent it jumping the groove. We shall return to this matter of choosing a value for the vertical force later.

A value of 200 N/m ($= 0.2 \times 10^6$ dyne/cm) has been chosen for the stiffness s. The maximum amplitude $\hat{y}_{\max}$ is 100 microns for a standard 78 r.p.m. record at low frequencies; at higher frequencies the maximum amplitude is less, being limited by other factors during the cutting of the record: see article quoted in footnote [2]). The lateral force necessary to give the needle point this maximum amplitude is therefore of the order of $s\hat{y}_{\max} = 200 \times 100 \times 10^{-6}\text{N} = 20$ mN.

Apart from the restoring couple, the moving system must have a definite amount of damping. This is a question not only of the resonance phenomena already mentioned but also of the resonance of the mass of the pick-up arm with the stiffness of the moving system. In Philips record-changers equipped with a magnetodynamic pick-up this latter resonance occurs at about 30 c/s. The damping action of the rubber bush is very slight; for this reason, at the lower end a polyvinyl chloride bush (*P* in fig. 1) is used in which the magnet can turn. The plastic gives considerable mechanical damping

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[5]) See for example J. J. Schurink, The twin-cone moving-coil loudspeaker, Philips tech. Rev. **16**, 241-249, 1954/55.

[6]) To discuss the reasons for this would be outside the scope of the present article. It may be mentioned here that the arm of the pick-up should ideally be designed so that the symmetry plane of the tracking system is always parallel the tangent to the unmodulated groove (see for example to B. B. Bauer, Tracking angle in phonograph pick-ups, Electronics **18**, 110-115, March 1954).

over an extensive range of frequency, but the restoring couple set up by the lower bush is very small. Together with the effective mass and the stiffness, the damping provided by the lower bush goes to make up the mechanical impedance; it must not be made excessive, because a damping force is also supplied by the needle point. This being so, the magnet is not clamped in the polyvinyl chloride bush but can rotate as in a bearing; in fact the bore of the bush is somewhat greater than the diameter of the magnet so that the latter is pulled to one side of the bearing wall by the frictional force between needle and record. This turns out to give a satisfactory degree of damping, the fact that the bush in question is lower down and very close to the needle also playing a part. Interchanging the two bushes has little effect on the restoring couple but causes a big decrease in damping.

The mounting of the magnet described above is not rigid in any direction and hence it allows of movements other than rotation. This is undesirable, as we have already seen, in view of the second harmonic that may arise from the pinch effect. On the other hand, mounting the magnet in bearings that permit a turning movement only appears to make reproduction "hoarse", particularly at high frequencies. There is a rule valid for all pick-up systems according to which the moving system of the pick-up must be given various degrees of freedom in the higher frequency range; the limited movements thereby permitted keep the mechanical impedance to a minimum. As far as rotational movements are concerned, the impedance is a minimum for rotation about that axis for which the moment of inertia is least. At high frequencies the horizontal and vertical movements of the needle point, and hence those of the whole moving system, are very complicated and very difficult to investigate; their amplitudes amount to a few microns at the most and their accelerations attain some hundreds of times g, as already stated. If the moving system is deprived of one degree of freedom, the mechanical impedance at the needle point may rise so high that the forces set up by the groove modulation acquire values at which a distortionless trace is no longer possible. In every pick-up, therefore, a favourable compromise must be sought between the number of degrees of freedom allowed to the moving system and the acceptance of voltages produced by undesired movements of that system. The quality of the pick-up depends considerably on how well this compromise is chosen. In this respect a system such as the magnetodynamic, in which in principle only one type of movement induces a voltage, has a great advantage over a system wherein voltages are induced by more than one type of movement.

The yoke

The yoke must have as small a reluctance as possible, and is therefore made of a material of high initial permeability. It consists of a strip of cross-section of $6 \times 0.35 = 2.1$ mm^2, bent into the required shape.

If the needle point has an amplitude $\hat{y}$ of 0.1 mm, the amplitude of the alternating flux through the yoke is:

$$\Phi_{\mathrm{j}} = \Phi_{\mathrm{m}} \frac{\hat{y}}{l} = 0.7\times10^{-6}\times\frac{0.1}{5} = 14\times10^{-9} \text{ volt.sec.}$$

Hence the magnetic induction in the yoke in the same circumstances is:

$$B_{\mathrm{j}} = \frac{14\times10^{-9}}{2.1\times10^{-6}} \approx 7\times10^{-3} \text{ volt.sec/m}^2 \ (= 70 \text{ gauss}).$$

This is a very low figure, and hence the possibility of distortion due to the saturation of the yoke is ruled out (the saturation induction for the material used is about 0.5 Vsec/m^2). Equally, there is little likelihood that magnetic asymmetry will produce too high an induction in the yoke, for even if the entire flux Φ passed through it, the static induction in the yoke would still only amount to 0.35 Vsec/m^2.

The low value of the alternating induction has an advantage over and above the elimination of distortion due to saturation. There is no danger of *noise* arising from the reorientation of Weiss domains (Barkhausen effect [7]). The absence of this kind of noise has been confirmed by an experiment in which the needle was made to move with a large amplitude at a low frequency; there was absolutely no indication of any noise associated with this movement.

Polyester resin is cast around the yoke carrying the coils. A sturdy block (fig. 4, No. 4) is thus formed, in which the positions for the bearings are accurately centred with respect to the yoke. The coils are completely enclosed, making the pick-up proof against tropical climates.

The two coils together constitute an approximately astatic system and hence they are but little affected by stray magnetic fields arising from the gramophone motor and any transformers that may be in the vicinity. On account of the relatively high output voltage, the leads from the pick-up to the amplifier pick up little interference. In both these respects the magnetodynamic pick-up compares

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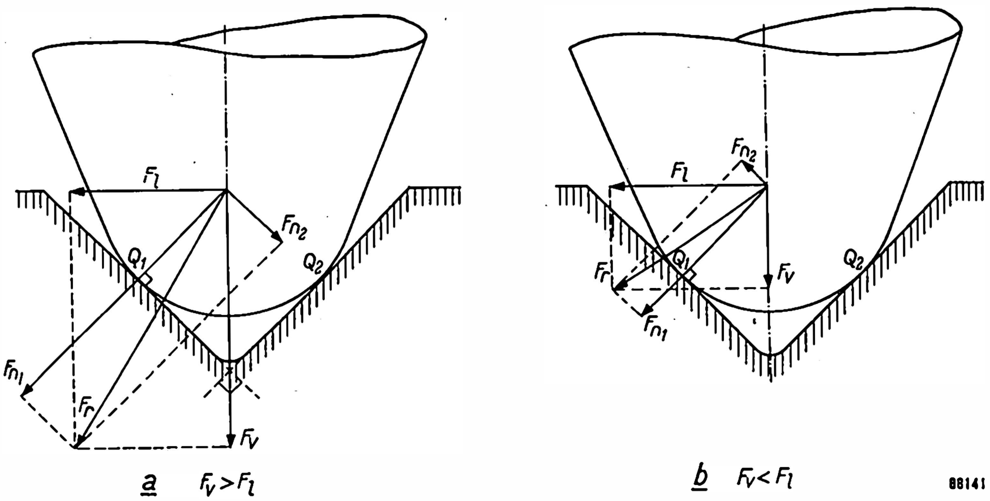
[7] H. Barkhausen, Phys. Z. **20**, 401-403, 1919; B. van der Pol, Versl. Kon. Akad. Wet. Amsterdam, **29-I**, 341-348, 1920.

favourably with electrodynamic and other magnetic types. Nevertheless, as a further measure against any residual fields, it is provided with magnetic screening. This consists of a soft iron casing (fig. 4, No. 5) into which the two bearings have been inserted in it.

Finally, the system thus screened is mounted in a "Philite"housing. The housing has a terminal by which the magnetic screening can be connected to the earth terminal of the amplifier, so that it serves as electrostatic screening at the same time. The yoke is also connected to earth, thus obviating undesirable phenomena due to static electricity generated by the friction between needle and record.

The optimum value for the vertical needle force

F_v, the vertical force with which the needle presses on the record, is an important quantity. In general, it is desirable to keep this force small to prevent excessive wear. If the pick-up is too light, on the other hand, there is a risk that the needle will jump the groove. The following considerations show us in what circumstances this risk is present.



a $F_v > F_l$ b $F_v < F_l$

Fig. 7. Forces on the needle point. F_v vertical force with which the needle rests on the disc. F_l total lateral force. In case (*a*) $F_v > F_l$, in case (*b*) $F_v < F_l$. F_r, the resultant of F_v and F_l, has components F_{n1} and F_{n2} perpendicular to the two walls of the groove. In case (*a*) F_{n2} is in a direction such that the needle maintains contact with the right-hand wall at point Q_2; in case (*b*) the direction of F_{n2} is such that this contact is not maintained and the needle rides up along the left-hand wall of the groove. (Friction, and the deformation of the walls under needle pressure, are neglected.)

Apart from the vertical force F_v, there is a lateral force F_l acting on the needle point, which is the resultant of several lateral forces. Diagrams illustrating two cases appear in *fig.* 7, (*a*) where $F_v > F_l$ and (*b*) where $F_v < F_l$. F_r, the resultant of F_v and F_l, can be resolved into two components, F_{n1} and F_{n2}, perpendicular to the walls of the groove, which are approximately at right angles to each other. In both cases F_{n1} is balanced by a reaction from the left-hand wall on the needle point at Q_1, their point of contact. In fig. 7*a* the direction of F_{n2} is towards the other wall and it is balanced by the reaction at point Q_2, the needle thus being kept in contact with the wall at this point. However, in fig. 7*b* the direction of F_{n2} is away from Q_2; the needle will therefore tend to lose contact with the right-hand wall and, if F_{n2} is sufficient to overcome the frictional force due to movement against the left-hand wall, the needle will ride up the latter. This results in distortion or, at worst, de-tracking of the needle. Hence the highest value of F_l that occurs determines the lowest permissible value of F_v if this danger be avoided.

As already stated, F_l is the resultant of a number of lateral forces. Of these, the inertial force of the moving system (its magnitude is the product of the effective mass at the needle point and its acceleration) is the largest at high frequencies. In order to minimise this force the moving system is designed to have as small an effective mass as possible; the value of the latter is in fact 3 mg.

The maximum permissible acceleration is found by considering the smallest radius of curvature that may occur in the groove without distortion arising; if the radius of curvature ϱ of the modulation peaks were smaller than R, the radius of curvature of the needle point, the needle would be in contact with the groove at three points instead of two, and distortion known as over-modulation would arise. Taking $\varrho = R$ as a rough basis, a peak acceleration of the order of 300 g is found for the fundamentals of the higher frequencies (see article cited in footnote [2])). However a third harmonic of about 40% is then present in the velocity [8]), and consequently one of $3 \times 40 = 120\%$ in the acceleration. Taking this into consideration, we arrive at a maximum value of the total acceleration of $(100 + 120)\%$ of 300 g, that is, of $660\ g \approx 6600$ m/sec^2. This, with the effective mass of 3 mg, produces a maximum lateral force of inertia of $3 \times 10^{-6} \times 6600$ N ≈ 20 mN (≈ 2 g weight).

Oscillograph measurements of the voltage delivered by the pick-up shows that accelerations even greater than 6600 m/sec^2 — and hence correspondingly greater forces of inertia — sometimes occur at the needle point. The higher accelerations may be caused by higher modulation velocities (where $\varrho < R$), giving overmodulation, which brings about a big increase in distortion; this in its turn again increases the acceleration owing to the harmonics involved. A further cause of the increased accelerations may be the building up of high amplitude needle vibrations due to groove-needle resonance [9]).

There are two other lateral forces besides the force of inertia just stated. Firstly, owing to the frictional drag of the needle on the record and the geometry of the pick-up arm, there is a constant inward force on the pick-up across the record; in Philips gramophones this is about 15 mN. Secondly there is the stiffness force which was shown earlier to have a maximum value of 20 mN at the lower frequencies for normal 78 r.p.m. records, this being the product of the stiffness s = 200 N/m and maximum needle displacement $\hat{y}_{\max} = 100$ microns. Such large displacements occur only at low frequencies, but the higher frequencies *and* their harmonics can also be present in the groove at the same time. These three forces can therefore be additive and in this way we arrive at a maximum of $20 + 15 + 20 = 55$ mN for the lateral force F_l; this, then, is the lowest value permissible for F_v. There is still a further point to be considered, however: the pinch effect causes a periodic variation in the magnitude of F_v. The amplitude of the alternating component may amount to about 10 mN so that a *static* value of at least $55 + 10 = 65$ mN is required for F_v.

This calculation is by its very nature only an approximation to the real state of affairs. However, bearing in mind that all the unfavourable circumstances are rarely present in combination, the minimum value of 65 mN, as calculated, agrees well with the value found by experiment. In fact a force of from 60 to 70 mN appears to be just sufficient for records with large modulation amplitudes to be faultlessly played, provided that the greatest attention is paid to the bearings and the balancing of the pick-up arm. Extreme care in production is not an insuperable objection in the making of professional equipment but, in the case of gramophones for domestic use, it is required that efficient tracing of the groove be obtained with pick-up arm that is simple and inexpensive. For these reasons F_v is given a somewhat higher value, viz. 100 mN (about 10 g weight). This value not only guarantees stable operation but also minimum wear, for it has been shown experimentally that with a weaker force there is again an increase in wear.

Part II of this article will deal with some properties of the magnetodynamic pick-up, including its frequency characteristic.

Summary. The new magnetodynamic pick-up type AG 3020/21 has a small rod-shaped magnet as its moving system; the rod is magnetized perpendicularly to its axis, about which it can turn, and is mounted between the ends of a yoke of magnetically soft material. A needle arm is fixed to the rod magnet whereby the lateral movement of the needle as it follows the groove in the record is converted into an angular movement of the magnet. An alternating flux is thus produced in the yoke, giving rise to a signal voltage in the coils wound on it. The angular movement of the magnet is provided for by an upper flexible bush of rubber and a bearing at the lower end of polyvinyl chloride. The rubber bush gives the magnet a restoring couple and the p.v.c. bearing provides the necessary damping against undesired resonances. The pick-up is manufactured in two models, type AG 3020 with a sapphire needle fitting the groove in standard 78 r.p.m. discs, and type AG 3021 with a diamond needle for microgroove discs. The departure from linearity between the angular movement of the magnet and the induced signal voltage is extremely slight. The sensitivity of the pick-up (ratio of r.m.s. voltage to peak needle velocity) is about 4 mV per cm/sec. A study of F_v, the force with which the needle presses on the disc, yields an optimum value of F_v of 100 mN ($\approx$ 10 g weight) in gramophones for domestic use, this value being sufficient to prevent de-tracking and giving minimum wear. The pick-up is proof against tropical climatic conditions.

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[8]) J. A. Pierce and F. V. Hunt, On distortion of sound reproduction from phonograph records, J. Acoust. Soc. Amer. **10**, 14-28, 1938/39; W. D. Lewis and F. V. Hunt, A theory of tracing in sound reproduction from phonograph records, J. Acoust. Soc. Amer. **12**, 348-365, 1940/41.

[9]) J. B. S. M. Kerstens, Mechanical phenomena in high-note reproduction by gramophone pick-ups, Philips tech. Rev. **18**, 89-97, 1956/57, in particular pp. 000. See also Part II of present article.

A MAGNETODYNAMIC GRAMOPHONE PICK-UP

II. FREQUENCY CHARACTERISTICS

by N. WITTENBERG.

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The frequency response is all-important in gramophone reproduction, as in all fields of sound reproduction. It is not possible however, to consider the frequency characteristic of a pick-up as such, because the frequency response depends not only on the pick-up but also on the properties of the gramophone record. A further complication is that, for high frequencies, the response is dependant on the position of the pick-up on the record. These and other questions are discussed here with reference to the magnetodynamic pick-up described in Part I of the article.

The new pick-up working on the magnetodynamic principle, type AG 3020/21 (fixed coil, moving magnet), has properties that make it well-suited to both professional and non-professional use. Its design was the subject of Part I of this article [1]). In the present part of the article we shall go more closely into some properties of the pick-up.

The frequency characteristic

The frequency characteristic of the system pick-up - gramophone record is defined, for this type of pick-up (signal proportional to needle velocity), as the signal voltage induced (r.m.s. value E) as a function of the frequency f, when the sinusoidal recording of the test record is such that its generating point has constant peak velocity $\hat{v}$. From this characteristic we may deduce the required frequency response of the associated amplifier in order that the loudspeaker shall give as faithful a reproduction as possible of the original recorded sound.

Most record manufacturers work with the characteristic marked B in *fig. 1* in the making of long-playing records. The curve gives the relationship between frequency and the recording velocity to be recorded on the disc (i.e. constant input voltage on the first amplifier). Since the voltage from a magnetodynamic pick-up is proportional to needle velocity, for a record cut in this manner the characteristic of the reproducing channel must be the reciprocal of B; this is the curve marked A in fig. 1 [2]).

Using a test record [3]) with stepwise frequency bands and recording velocities in accordance with B [4]) — it is possible to determine the frequency characteristic of a pick-up in combination with this record by measuring the voltage produced at each of the recorded frequencies, which are known.

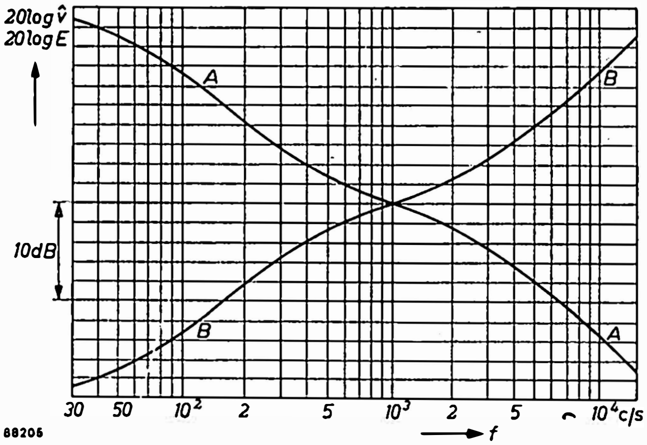

Fig. 1. A: frequency characteristic of a reproduction channel for gramophone records, largely accepted as standard.
B: the reciprocal of A; this curve shows how the modulation velocity of gramophone records should vary with f, the recorded frequency.

Reasons why the response should extend to very high frequencies

In designing the magnetodynamic pick-up the aim was to extend the frequency response to the highest possible frequencies. One may well ask what purpose is served in trying to reproduce frequencies over 15 kc/s, since few persons apart from children can hear these frequencies, and in any case they occur only very rarely in the average recording. The reasons are the following.

In an earlier article [5]) in this Review it was

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[1]) N. Wittenberg, A magnetodynamic gramophone pick-up, I. Construction. Philips tech. Rev. **18**, 113-122, 1956/57.

[2]) A is the proposed "standard reproduction channel"; see Philips techn. Rev. **17**, 104, 1955/56, or G. Slot, "Microphone to ear", Philips technical Library, Popular Series, 1956, pp. 46-49.

[3]) Test records of various types are available; the sound is recorded with a known modulation velocity, and the pitch may change continuously or in steps.

[4]) The Decca test record LXT 2695 meets this requirement satisfactorily.

[5]) J. B. S. M. Kerstens, Mechanical phenomena in gramophone pick-ups at high audio frequencies, Philips tech. Rev. **18**, 89-97, 1956/57 (No. 3)

demonstrated that the frequency spectrum of the output voltage of a pick-up has an upper limit fixed by one of two mechanical phenomena. One of them is connected with the fact that the needle point causes elastic deformation of both groove walls (also some plastic deformation, but this is neglected here), the deformation being deeper in the convex wall (for frequencies below the needle free resonant frequency). One consequence of this is that the amplitude of the needle point is less than the amplitude of the groove, i.e. there is a *static tracing loss*. The loss is greater the shorter the wavelength λ recorded on the disc; at a certain wavelength λ_{co}, the cut-off wavelength, the loss is so great that the output voltage drops to zero. The other phenomenon that may impose an upper limit on the frequency spectrum is *resonance*. This can be either a resonance of the pick-up assembly itself [6]) or it may be the groove/needle resonance (stiffness of the groove wall/effective mass at needle point) dealt with in the article cited in footnote [5]).

In many pick-up designs the frequency spectrum is limited by one of the resonances of the pick-up assembly, but in the magnetodynamic pick-up these appear only at frequencies higher than that of groove/needle resonance. It is therefore the groove/needle resonance that imposes the upper limit on the spectrum of the magnetodynamic pick-up. In the article [5]) its effect is referred to as *dynamic tracing loss*.

Now, to answer the question as to the purpose of reproducing frequencies above 15 kc/s, let us assume that it is a resonance frequency f_{res} that forms the upper limit to the spectrum, which therefore does not go up to frequencies where static tracing loss is dominant. If f_{res} falls within the audible range the result is that reproduction is "coloured", that is, a sound with the frequency of the resonance is heard continuously in the background, the sound being stronger the less the damping. This "colouring" is due to sounds at this particular frequency being emphasized by resonance. It is equally due to ringing effects each time the resonant system is excited. Not only music and speech are subject to "colouring" but also the *noise*, however faint, that is always present to some extent in the record. Accordingly, the noise heard in reproduction will be less *troublesome*, if not less strong, *the higher the limiting resonance frequency is made.*

A second argument for raising f_{res} above the audible range is that large phase shifts occur in the neighbourhood of that frequency. These affect the reproduction of the sudden bursts of sound that frequently occur in music; phase shifts cause these transients to be lost to a great extent in reproduction.

As the spectrum is broadened out, the easier it becomes to pick out individual instruments. To some extent the effect is analogous to the better and better impression of reality given by looking at a series of half-tone photographs of the same scene but printed from blocks of increasingly finer screens. This is a third reason for putting f_{res} above the audible range.

But even if the lowest resonant frequency lies at, say, 20 kc/s, there is still no guarantee that the needle will faithfully follow the groove at very high audio frequencies, should these be present in the recording. Static loss has the consequence that, with increasing frequency, reproduction gradually falls off; at f_{co} and beyond, it inevitably drops to zero, f_{co} being the frequency corresponding to the cut-off wavelength λ_{co}. In general, the frequency f and the wavelength λ are connected by the formula $f = V_g/\lambda$. V_g is the velocity with which the groove passes under the needle, and it is proportional to the diameter of the circle formed by the groove being traced. Hence, as the pick-up moves inwards towards the centre of the disc, f_{co} gradually becomes lower. If f_{co} falls below the resonant frequency that has previously imposed an upper limit to the spectrum, from that moment onwards it is f_{co} that imposes the limit.

We shall now investigate these phenomena as they affect our pick-up, in the light of measurements carried out upon it.

Measurements on the magnetodynamic pick-up at high audio frequencies

Fig. 2 gives the frequency characteristic of the AG 3020 pick-up as obtained by measurement with the aid of two test records [7]); on these records frequency bands of 20 kc/s, 18 kc/s, 16 kc/s, etc. are recorded with wavelengths such that there is no noticeable tracing loss, and with constant recording velocity (except for the 20 kc/s band where, according to the manufacturer, the recording velocity was 11 dB too low; it was indeed found that at 20 kc/s the voltage given was about 11 dB too low). It will be seen from the diagram that no limiting resonance occurs below 20 kc/s; that groove/needle resonance does not occur below that frequency is to be

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[6]) See under the heading "*The needle arm and the needle*" in Part I of this article [1]) (p. 117), where lateral resonance and torsional resonance are discussed.

[7]) Deutsche Grammophon-Gesellschaft Nos. 68421 and 68439. These are 12" shellac records playing at 78 r.p.m., which together cover the range of frequencies from 20 kc/s down to 30 c/s.

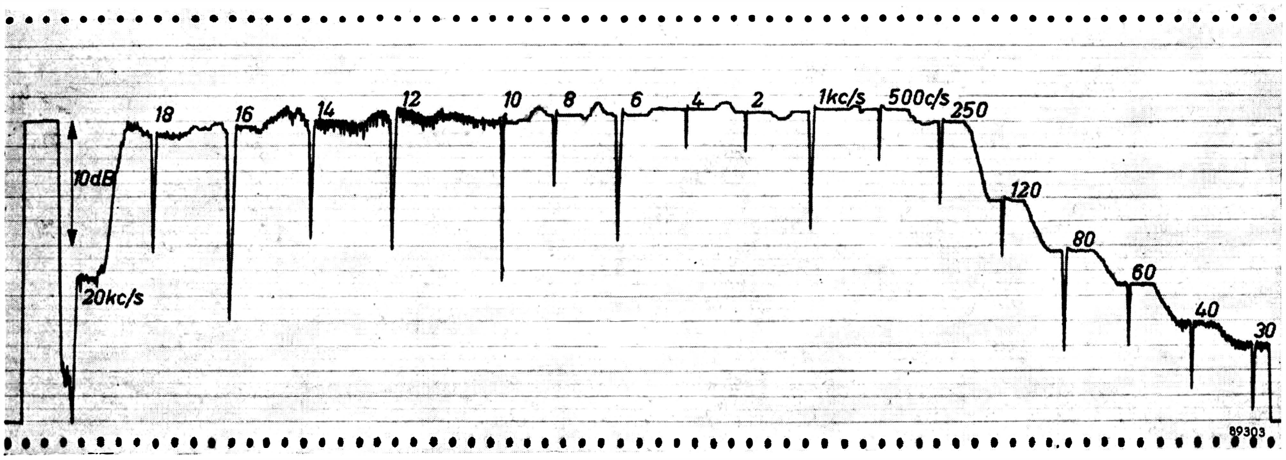

Fig. 2. Trace (on logarithmic scale) of voltage delivered at different audio frequencies by a non-loaded AG 3020 pick-up during the playing of shellac test records DGG 68 421 and DGG 68 439 [7]). The wavelengths cut in these discs are everywhere greater than the cut-off wavelength. The vertical force F_v was 0.1 newton.
On the extreme left is the 1000 c/s voltage reference level. The measurements proper begin at f = 20 kc/s (where, according to the manufacturer of the records, the modulation velocity during recording was 11 dB too low). The inverse peaks in the trace are frequency markers; only to the immediate right of each mark have the frequency and modulation velocity the right values. Modulation velocity is constant from 18 kc/s to 250 c/s and decreases at lower frequencies.

attributed, for one thing, to the high elastic modulus of the shellac material of which the test records are made.

The microgroove pick-up, AG 3021, — the same pick-up system apart from the needle — can be examined using another test record; this too has frequencies of up to 20 kc/s recorded, but with shorter wavelengths [8]). The curve *a* in *fig. 3* is that supplied by the manufacturer of the record and gives the recording velocity $\hat{v}$ as a function of frequency, as determined by optical methods; also indicated in the diagram is the wavelength λ for each of the seven bands from 20 to 8 kc/s. An ideal pick-up would have an output voltage curve with the same shape as curve *a*. Instead, we find the characteristic marked *b*; it seems that about 18 kc/s a small resonance occurs which causes the characteristic to rise by a few decibels, after which it falls rapidly. It is not permissible to attribute the difference between *b* and *a* entirely to resonance, however, for a certain amount of static tracing loss may be involved. To separate this latter from resonance effects (dynamic tracing loss) we make use of the following artifice.

Referring to the wavelength scale (top right, fig. 3), *b* gives the voltage as a function of λ. In order to eliminate resonance phenomena we shall associate the same wavelengths with frequencies at which no resonance occurs by making the disc turning more slowly. If we make the speed 10 r.p.m. (instead of $33\frac{1}{3}$ r.p.m., the speed at which curve *b* was obtained), the highest frequency reproduced becomes 6 kc/s; the form of *b* makes it unlikely that any resonance will occur below that frequency.

The voltages measured at 10 r.p.m. are given in curve *c* as a function of wavelength (*not* of frequency); the ordinates have been corrected for the lower voltages measured resulting from the lower speed. Hence *c* gives, as a function of λ, the *needle*

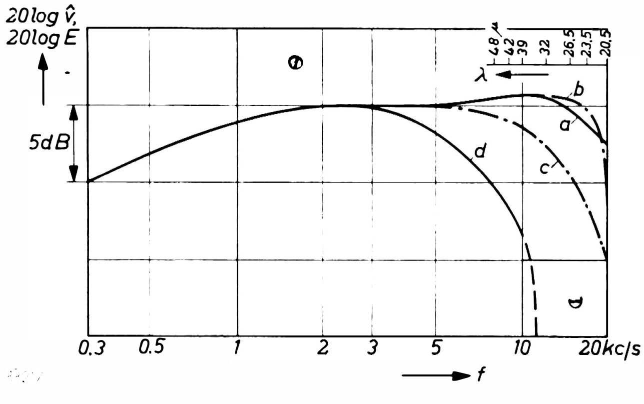

Fig. 3. *a*) Modulation velocity $\hat{v}$ as function of frequency f for the Cook 10A synthetic resin test record (curve supplied by the manufacturer) [8]). *b*) Voltage E delivered by non-loaded AG 3021 pick-up during playing of Cook 10A record at $33\frac{1}{3}$ r.p.m.; wavelength scale appears at top right. *c*) E as function of λ, for the same record turning at 10 r.p.m.; ordinates have been corrected to allow for the low rate of rotation. The range of wavelengths from 20.5 to 48 microns is recorded in grooves of diameters from 24 to 22 cm. *d*) curve of E as function of f, as reconstructed for the innermost groove, which has a diameter of 12.5 cm. The vertical force used in obtaining curves *b*, *c* and *d* was 0.1 newton.

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[8]) Test record Cook 10A (made by Cook Laboratories), a 10″ synthetic resin microgroove disc playing at $33^1/_3$ r.p.m.

point velocities occurring at the recording velocities of *a* but without interfering resonances. The difference between *a* and *c* is therefore the static tracing loss. In the particular conditions in which the measurements were carried out (radius of curvature of the diamond needle point 25 μ; vertical needle force $F_v = 0.1$ N; record of synthetic resin) static tracing loss becomes perceptible at wavelengths shorter than about 50 μ.

The full curve in *fig. 4* is the static tracing loss plotted as function of λ. The function is expressed by equation (10) of article [5]):

$$\hat{y}_s = \hat{y}_{co} \left\{ 1 - \left(\frac{\lambda_{co}}{\lambda} \right)^2 \right\}$$

where $\hat{y}_s$ is the amplitude of the needle point in the absence of resonance, and y and λ are the amplitude and wavelength of the groove cut in the record. By inserting various values of λ and the corresponding values of $\hat{y}_s/\hat{y}$ given in fig. 4 we can determine λ_{co}, the wavelength at which the velocity of the needle point is zero and at which therefore the pick-up ceases to deliver a voltage. In this way we find that $\lambda_{co} = 16$ μ.

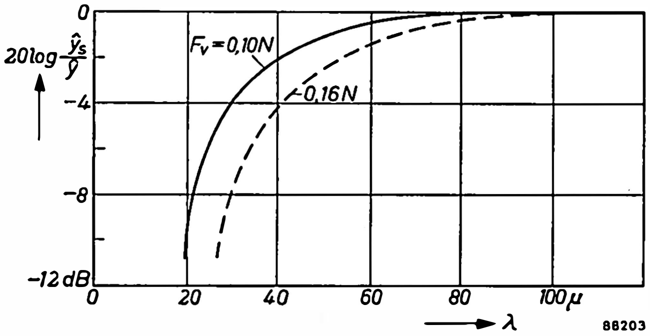

Fig. 4. The static tracing loss 20 log $\hat{y}_s/\hat{y}$, as derived from curves *a* and *c* in fig. 3, plotted against the groove wavelength λ for vertical forces F_v of 0.10 and 0.16 N. The cut-off wavelength becomes longer as F_v is increased.

For a given set of conditions (radius of curvature of needle point 25 μ; $F_v = 0.1$ N; record of synthetic resin having an elastic modulus 3.3×10^9 N/m²), equation (11) of article [5]) gives the following relation between cut-off frequency f_{co} and groove velocity V_g in m/sec:

$$f_{co} = 55\,000\ V_g \text{ c/s}.$$

Hence $\lambda_{co} = V_g/f_{co} = (1/55\,000)$ metres = 18 microns. Considering the errors involved the measurements described, the fact that extrapolation has to be used, and the uncertainty in the value of the modulus of elasticity, which is considerably dependent on temperature, the agreement between calculation (18 μ) and measurement (16 μ) is satisfactory.

Equation (17) of article [5]) states that λ_{co} is proportional to the cube root of the vertical needle force F_v. We can verify this relation by repeating the measurements with another value of F_v, say 0.16 N. The cut-off wavelength to be expected would then be $(0.16/0.10)^{\frac{1}{3}}$ times 16 or 18 μ; that is, say 20 μ. The broken-line curve in fig. 4 is drawn for an F_v of 0.16 N and from this we find a λ_{co} of 22 μ. Here too, therefore, there is satisfactory agreement.

Let us return to fig. 3 and compare curves *b* and *c*. The difference between them is the dynamic tracing loss, which arises on account of a resonance phenomenon at about 18 kc/s, where the difference is at its greatest. The assumption that this resonance is that of the groove/needle system (stiffness of groove wall and effective mass at needle point) can be justified as follows.

The resonant frequency of a damped vibration is given by:

$$f_{res} = f_0 \sqrt{1 - \frac{1}{2Q^2}} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which f_0 is the natural frequency of the system and Q is the quality factor. A good approximation for f_0 is $\sqrt{S/m}/2\pi$. In accordance with equation (15) of article [5]), the stiffness of the groove wall is:

$$S = \frac{3}{2} \frac{F_v}{a_0 \sqrt{2}}.$$

Taking $F_v = 0.1$ N and a_0 (depth of penetration in the unmodulated groove wall) $= 2 \times 10^{-6}$ metre we find that $S = 53\,000$ newtons/metre, and taking $m = 3 \times 10^{-6}$ kg we obtain $f_0 = 21.2$ kc/s. From fig. 3 we see that the greatest difference between *b* and *c* is 6 dB, which corresponds to a Q of 2. These values of f_0 and Q, inserted in equation (1), produce a f_{res} value of 19.8 kc/s, which is near enough to the resonance observed at 18 kc/s to make it probable that this resonance is that of the groove/needle.

We see from fig. 3 that the resonance effect is stronger than might be mistakenly supposed from curves *a* and *b*, and that over a big range of frequency it compensates the static tracing loss. The question might be posed as to whether the straightness of the characteristic in fig. 2 is also due to compensation of this kind. This does not seem to be the case: if we give a slower turning speed to the shellac record with which this characteristic was obtained, we get the same line as that given at the normal speed of 78 r.p.m. The shortest wavelength on this record is 60 μ, this producing the 20 kc/s tone; this frequency is cut in a groove of about 30 cm diameter. Fig. 4, which was obtained with a synthetic resin record, shows that the tracing of this wavelength involves a loss smaller than 1 dB, so that for the shellac record, with its higher elastic modulus, it is certain that no perceptible tracing loss will arise at $\lambda = 60\ \mu$. We may therefore conclude from the straightness of the characteristic that the system is free of resonance below 20 kc/s.

Comparison of curves *a* and *b* in fig. 3 may perhaps lead to the question: what is the significance in practice of the static tracing loss? The loss is, after all, largely compensated by dynamic tracing loss (groove/needle resonance), which is determined by the material of the record, the radius of curvature of the needle, the vertical force F_v and the effective mass — that is to say by factors that are always the same for a given gramophone and type of record. Apart from this, it would be an easy matter to correct insufficient or excessive compensation in the amplifier. But what has to be borne in mind is that static tracing loss is a *direct* function of wavelength, and only an *indirect* function of frequency, via the relation $\lambda = V_\mathrm{g}/f$. Consequently the frequency at which a given combination of record and pick-up will exhibit a certain static loss is dependent on the groove velocity V_g and thus on the diameter of the groove.

On the record used for the measurements of fig. 3, the range of frequencies from 20 kc/s to 10 kc/s is registered in grooves having a diameter of from 24 cm to 22 cm; consequently, curve *b* in fig. 3 is valid only for that portion of the disc. Further towards the edge of the record the same wavelengths produce higher frequencies; here, therefore, there is stronger reproduction of high frequencies than from grooves nearer the centre. It would be possible to obtain the characteristic for the innermost grooves by using a test record on which wavelengths of from 20 to 50 μ were cut in grooves having a small diameter. Such a disc is not available, but we can reconstruct the characteristic in question from curves *a* and *c* by taking into account that the frequency at which static tracing loss has a given value is proportional to the diameter of the groove. Characteristic *d* in fig. 3 has been constructed in this manner; it applies to the innermost groove of a long-playing record, which has a diameter of 12.5 cm. The cut-off frequency, which is 23-26 kc/s for curve *b* ($\lambda = 18$ or $16\ \mu$), is only 12-13.5 kc/s for curve *d*. These frequencies are below the resonant frequency and hence there can be no compensation due to resonance (negative dynamic tracing loss) above 12-13.5 kc/s in the innermost grooves.

The foregoing has attempted to show that there is no point in supplying a frequency characteristic with a pick-up without at the same time specifying the test record used and the value of F_v the vertical force during the measurements. Even then, the characteristic gives no more than an overall impression of what may be expected from the playing of a normal record; it must be remembered that static tracing loss is dependent on the groove velocity, that is, on the diameter of the groove being traced. Fig. 3 shows that this effect becomes perceptible at a frequency as low as 3 kc/s.

Reproduction of very low frequencies

In the foregoing attention has only been given to the upper register. We shall now say a word about the reproduction of very low frequencies. In the magnetodynamic pick-up, unlike the electrodynamic there is no objection to the use of a coil with a large number of turns. An input transformer — essential for the electrodynamic pick-up — is thereby rendered superfluous. The transformer is an expensive item if good reproduction of low audio frequencies is required for its primary then has to have a high self-inductance. The fact that there is nothing to set a lower limit to the frequency spectrum of the magnetodynamic pick-up is, of course, favourable for the reproduction of musical sounds of the lowest pitch, but at the same time it leaves the way open for undesired low frequencies. Vibrations of very low frequency arise through mechanical shock or vibration; they may arise in the gramophone itself or in the recording equipment (in the latter case they form part of the recording). Although these frequencies are often below the limit of audibility (in the region of 10 c/s, say), they can be very troublesome in that the unwanted voltage they cause may take up a large part of the grid swing in the output stage; when this happens even a weak signal, in combination with the unwanted voltage, may overload the amplifier. The difficulty is removed by suitable design of the amplifier, but to go into details would be to depart from the framework of the present article.

Effect of the electrical load on the frequency characteristic of the pick-up

The load across the pick-up during the above determinations of the characteristics was very small. In normal use, however, there is a greater load on the pick-up — not only that of the amplifier input impedance, but also that of a capacitance of about 250 pF, consisting mainly of the capacitance of the connecting lead between pick-up and amplifier. Since the internal impedance of the pick-up is partly due to a self-inductance of 0.6 H, a tuned circuit is formed; the resonant frequency of which is in the vicinity of 13 kc/s; this resonance, being inside the audible range, is undesirable. By making the right choice of load impedance, however, this resonance can be damped to a point where it practically ceases to be effective. Two frequency response curves appear in *fig.* 5: the first is curve *b* from fig. 3, as obtained with a parallel capacitance of some tens of pico-farads and a load impedance of 0.5 MΩ; curve *e*, the second characteristic, was obtained by using the same test record with a parallel capacitance of 250 pF and a load impedance of 68 kΩ. The difference between the two curves becomes greater than 2 dB only above 14 kc/s. With the majority of records the difference is scarcely audible; for this reason a value of 68 kΩ is recommended for the terminating resistance.

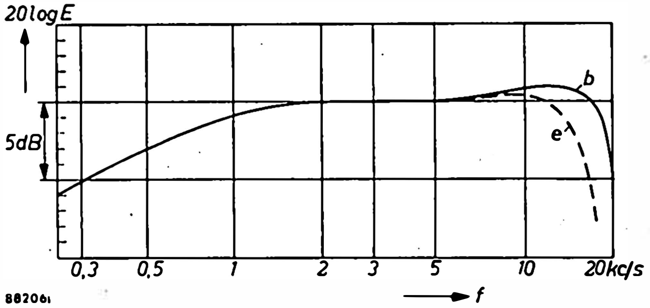

Fig. 5. The effect of the pick-up's electrical load on its frequency characteristic. Curve *b* was obtained with a pick-up type AG 3021 subject to practically no load; for curve *e* the pick-up had a load consisting of 68 kΩ in parallel with 250 pF, the circumstances otherwise being the same. Curve *b* here is identical to curve *b* in fig. 3.

Non-linear effects

When short wavelengths — that is, high frequencies cut in small-diameter grooves — are traced, effects become perceptible which, for the sake of simplicity, were not taken into consideration in the article referred to under [5]). Thus strong non-linear tracing distortion may arise [9]) because, for example, the peaks of a sinusoidal groove are so sharp that the needle point no longer fits into them. The main consequence is that third harmonics are set up. Even if their frequencies are above the cut-off frequency, it is still possible for these harmonics to be reproduced, for the cut-off frequency is determined by the static tracing loss which itself depends only on the actual pattern cut in the disc: hence any frequencies due to distortion in the playback process are not effected by the cut-off frequency. This non-linear effect may partially compensate harmonics recorded on the record but lost on account of static tracing loss, and in this way it may give rise to an impression of better reproduction of the upper register. However, these phenomena have been so little investigated that it is not possible to go into them here.

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[9]) J. A. Pierce and F. V. Hunt, On distortion of sound reproduction from phonograph records, J. Acoust. Soc. America **10**, 14-28, 1938/39. W. D. Lewis and F. V. Hunt, A theory of tracing in sound reproduction from phonograph records, ibid. **12**, 348-365, 1940/41.

Summary. Part I of this article dealt with the design of the magnetodynamic pick-up, types AG 3020/21. In Part II above the author puts forward a number of arguments for extending the frequency response to above 15 kc/s, as has been done in the magnetodynamic pick-up. In the course of the discussion on the frequency characteristic for the upper register, a method is described of separating static and dynamic tracing losses, these being a wavelength and a frequency effect respectively. With records of synthetic resin, static tracing loss exhibits a cut-off frequency of about 24 kc/s where the groove has a diameter of 24 cm, and of about 12 kc/s for the innermost groove; dynamic tracing loss, on the other hand, is connected with a groove/needle resonance at about 18 kc/s. A word is also devoted to reproduction at very low frequencies, to the effect of the electrical load on the pick-up and to non-linear effects.

Determining the Tracking Capabilities of a Pickup

H. E. ROYS*

Measurement of intermodulation distortion is shown to be a reliable method for evaluating pickups as to one important characteristic which is not readily measureable otherwise.

A PICKUP that is used for the purpose of reproducing disk records relies upon the mechanical contact between groove and stylus tip for actuation of the stylus. For in order to obtain faithful reproduction, it is necessary that the stylus "track" or maintain good mechanical contact with, and exactly follow, the undulations of the recorded groove. Where we are dealing with lateral recordings—and these form the bulk of the records in use today—we are primarily concerned with the contact between stylus and groove side walls as illustrated at (A) in *Fig.* 1. When the groove changes laterally from a mean position, due to the modulation, it is the side walls of the groove that exert a side thrust upon the stylus to make it follow. If the vertical force is low, the stylus will climb the side wall, as illustrated at (B), and then the effectiveness of the pinch of the "V" shaped record groove is lost, and poor tracking and distortion result.

Tracking has been a problem from the beginning of disk recording, even when the vertical force was half a pound instead of half an ounce. It is only by using adequate vertical force that the stylus can be held in the groove and so maintain good mechanical contact with the side walls. The tracking problem still exists today, even though vast strides have been made in the reduction of pickup mechanical impedance with a resulting improvement in tracking. Fine groove reproduction with a small stylus tip requires low vertical force if a minimum of record and stylus wear is wanted.

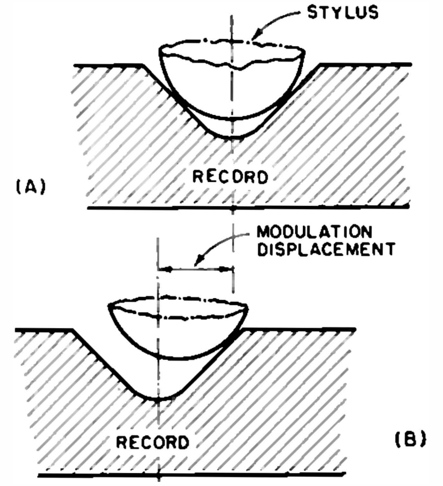

Fig. 1, (A) An ideal "fit" between stylus and groove side walls. (B) When the groove is displaced laterally from the mean position due to modulation, the tip will climb the side wall of the groove if the mechanical impedance of the pickup is high.

Method of Measurement

Since the tracking capabilities of a pickup depend upon its mechanical impedance, a measure of the mechanical impedance is also a measure of its ability to follow the recorded groove.

Determining the mechanical impedance is not a simple measurement, nor is it completely adequate. For example, practically all of the pickup and tone arm combinations tend to climb the groove side walls, rattle, and even skip out of the groove at tone arm resonance, and although skipping is not common at the high-frequency resonance, changes in response at resonance can be noted unless sufficient vertical force is used, as shown in *Fig.* 2. The mechanical impedance is high at the two resonant points, and usually the vertical force has to be increased several times over its normal value in order to keep the pickup stylus firmly in the groove. Yet listening tests indicate that the quality of re-

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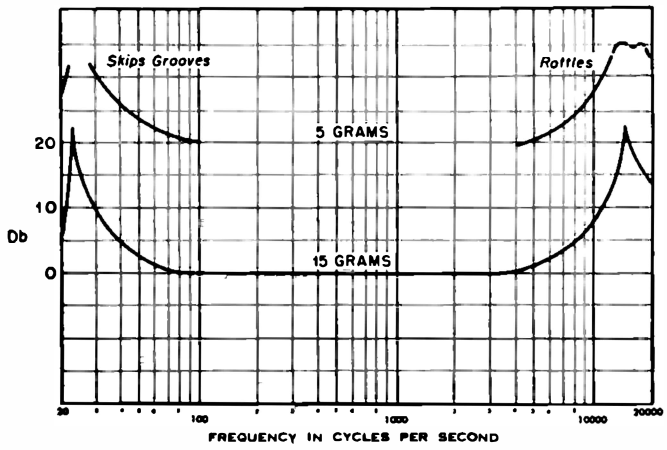
Engineering Products Department, RCA Victor Division, Camden, N. J.



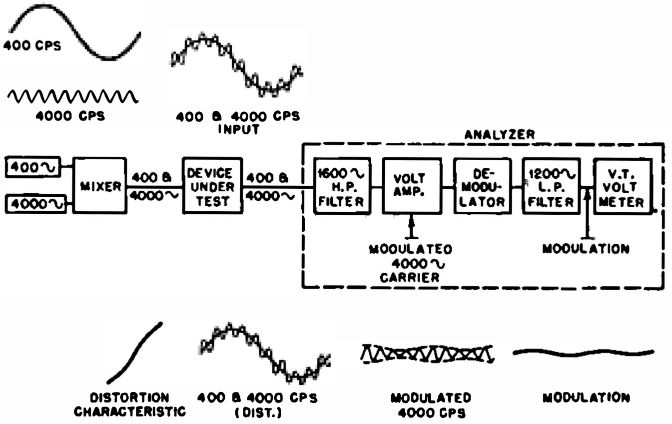


Fig. 2, left. This is a frequency response characteristic taken by the variable speed method. The peak at the low-frequency end is due to tone arm resonance, and the one at the high-frequency end is due to pickup resonance. The mechanical impedance characteristic is similar to this in shape. If the vertical force is too low, the pickup will skip grooves. Fig. 3, right, Block diagram showing the function of the components of the equipment. The sine-wave figures illustrate the appearance of the test signal, and how distortion shows up as amplitude modulation of the 4000-cps test tone.

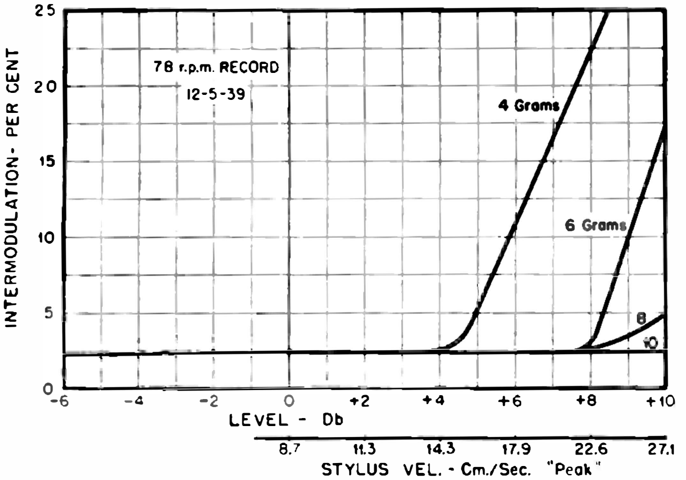


Fig. 4. Distortion curves obtained with experimental RCA magnetic pickup, illustrating its tracking capabilities and the improvement obtained as the vertical force is increased.

production is acceptable with the lighter force. This may be due to the fact that the mechanical impedance between the resonance frequencies is low, and it is throughout this region that the peak energies of speech and music are encountered so that, although the tracking requirements may be severe, the vertical force requirement is not great.

The intermodulation method of distortion analysis appears to be a good method of studying the tracking capabilities of a pickup, especially when using frequencies of 400 and 4000 cps. These frequencies lie between the two resonant frequencies of the pickup system and are located in the region where high peak energies of speech and music are normally encountered. The method is sensitive, and yet the measurements are simple and easy to make. In addition, measurement equipment is not absolutely necessary, as a great deal of useful information can be obtained by simply listening to the reproduction of the test record. In fact, the test record is probably the most valuable item of the test.

The Test Records

For tracking studies, 78 and 45 r.p.m. records cut by Mr. R. C. Moyer of the Indianapolis plant are used. These were cut at different levels up to 10 db above an assumed normal recording value. Levels as low as a −6 db were also recorded so that an over-all range in 2-db steps from −6 to +10 db is available when using the 78-r.p.m. record and from −4 to +10 db with the 45-r.p.m. record.

The two frequencies were combined in the normal manner for the intermodulation signal, 400 cps for the low frequency and 4000 cps for the high with the 4000-cps tone 12 db below the 400-cps signal in level. The 0 db or normal level for the 45-r.p.m. record was made approximately 3 db lower than the 78-r.p.m. value in accordance with the general practice of cutting fine groove records at a reduced level in order to avoid cutting into adjacent grooves and also to minimize tracing distortion. The peak value of the 0 db or normal levels as measured by the optical pattern method while the pressings were being rotated (a necessity where two frequencies are combined in order to obtain an accurate evaluation of the pattern width) was measured to be 6 cm./sec. for the 45-r.p.m. record and 8.7 cm./sec. for the 78. The maximum peak recorded levels attained is about 27 and 18 cm./sec. for the 78 and 45 r.p.m. records respectively. It is difficult to determine just what peak levels are encountered in phonograph records, but it is believed that the levels on the test records are adequate for pickup tracking studies. The RCA 45-r.p.m. record system design is based upon a maximum recording level of approximately 14 cm./sec.

Both records were cut with a stylus having a tip radius of less than 0.0005 inch, so a fine groove pickup having a tip radius of 0.001 inch can be used with either record. The 78-r.p.m., record 12-5-39, has a groove wide and deep enough to accommodate pickups that have a tip radius of 0.003 inch, such as normally used with 78's. The 45-r.p.m. record, 12-5-37, has a narrow groove suitable only for reproduction with a pickup having a 0.001 inch tip radius.[1]

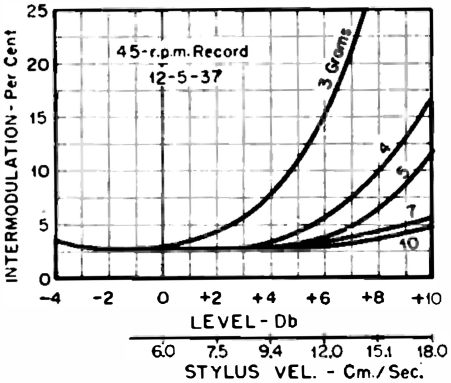


Fig. 5. Characteristic obtained with the pickup of Fig. 4 when using the 45-r.p.m. test record.

Test Procedure

Intermodulation test frequencies of 400 and 4000 cps have been found to be particularly useful for studies of distortion in disk recording and reproducing systems.[2, 3] *Figure* 3 shows a block diagram of the equipment used and also illustrates what the test signal, a combination of two frequencies, looks like on an oscilloscope and also how the distortion appears as modulation of the 4000-cps carrier.

In determining the tracking capabilities of a pickup, either of the intermodulation records is played while using various vertical forces, and the distortion is measured for each different recorded level. The results when plotted give a set of curves such as illustrated in *Fig.* 4. In general, the distortion is low for the low values of recorded signal, but at some higher level an abrupt change is encountered, and the distortion increases rapidly as the recorded level is raised. Increasing the vertical force shifts the breaking point to a higher recorded level, and by using sufficient vertical force, good tracking can be obtained at the highest levels available on the record.

Where the distortion appears abruptly and increases so rapidly with recorded level, it appears permissible to define good tracking in terms of vertical force and the recorded level where the break occurs.

Figure 5, however, gives the results obtained with the 45-r.p.m. record and shows the breaking point with resulting rise in distortion to be less abrupt than obtained with the 78. This makes it difficult to determine good tracking as defined above, and it may be necessary to establish some value of intermodulation, such as 10 per cent, for example, as the limiting value. Then for the pickup illustrated in *Fig.* 5 with a vertical force of 5 grams, good tracking can be expected for recorded levels up to about 17 cm./sec.

Ten per cent intermodulation when using test frequencies of 400 and 4000

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[1] Both of these records can be obtained from the Custom Record Sales Section, RCA Victor Division, 155 E. 24th St., New York 10, New York.

[2] H. E. Roys, "Intermodulation Distortion Analysis as Applied to Disk Recording and Reproducing Equipment," *Proc. I.R.E.*, October, 1947.

[3] H. E. Roys, "Analysis by the Two-Frequency Intermodulation Method of Tracing Distortion Encountered in Phonograph Reproduction," *RCA Review*, June, 1949.

cps, is a figure that has been arrived at after many careful listening tests over a wide-range system as the value at which tracing distortion becomes perceptible. It is the value that has been used to establish the inner recorded diameter of RCA's 45-r.p.m. records. Good correlation has been obtained between measurements and listening tests, and more recent tests indicate that the intermodulation method is equally useful in determining the tracking capabilities of pickups.

When making tracking measurements, it is often advisable to listen to the output of the test record in order to detect any irregularities that may occur due to record eccentricity or wobble causing a once-around variation in distortion at turntable speed (due perhaps to excessive friction in the tone arm bearings). Such variation may be so slight that it does not register on the meter, especially if the meter is sluggish in action, and therefore may be overlooked unless listening tests are made.

When making comparison tests with records containing music, the pickup will usually appear to track better than indicated by the intermodulation test records. In such cases, it is possible that the peak velocity on the music record is not as high as expected, or that its duration is so short that tracking distortion is not readily apparent. If several tests are made, especially while using a wide-range system so that tracking distortion can be more readily detected, it is believed that on the average, the agreement will be found to be good between measurements and listening tests.

Effect of Damping

It is the usual practice in pickup design to incorporate some mechanical resistance to smooth out the resonant peak of the pickup. The effect of the damper is usually judged by frequency-response measurements. During tracking studies it was noted that the damping material can have a detrimental effect on tracking. A sliver of viscoloid between the stylus and case of the pickup, used for the tracking tests of *Fig.* 4, gave the results shown in *Fig.* 6. The sliver was small and had little effect upon the response characteristic, but the effect on the tracking capabilities was such that the intermodulation increased from about 6 to 16 per cent at a recorded level of 27 cm./sec.

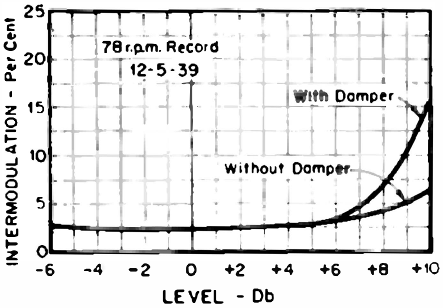

Fig. 6. A small piece of viscoloid applied for mechanical damping caused this change in tracking capabilities.

A large stiff block of viscoloid was tried in the same location with another pickup, and the results with and without the damper are shown in *Fig. 7*. In this case, the damper block was so stiff that it affected the tracking capabilities even at the lowest recorded levels. This is an unusual example, but it serves to illustrate that the damper block should be added with care, and the effect upon tracking as well as frequency response should be investigated.

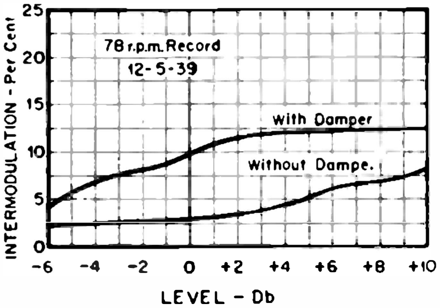

Fig. 7. A larger piece of viscoloid had a detrimental effect on tracking throughout the entire recorded range.

Several pickups of different design were investigated for tracking capabilities. The same vertical force was used, and the results are shown in *Fig.* 8. Two of the pickups were of the same type with minor changes in construction but considerable difference in the amount of damping material used. One pickup used no damping material, and another used a moderate amount. The pickup that used the greatest amount of damping material exhibited the poorest tracking capabilities, confirming the results of our tests as given above.

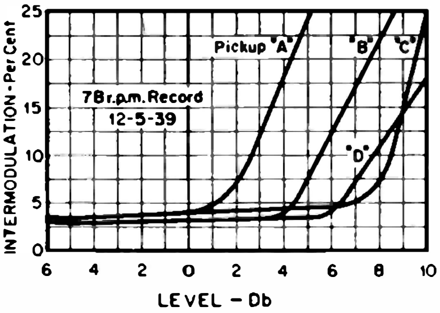

Fig. 8. Comparison of pickups of different types and construction.

Conclusions

The intermodulation method of distortion analysis appears to be valuable in determining the tracking capabilities of a pickup. By reproducing intermodulation frequencies that have been recorded at different levels, the necessary value of vertical force needed to insure proper tracking can be determined easily.

Measurement equivalent, although needed for a careful analysis, is not essential, as much useful information can be obtained by listening to the output of the test record.

Damping material so commonly used in pickup construction to obtain smooth response characteristics may adversely affect the tracking capabilities of the pickup and therefore should be investigated carefully and used judiciously.