UNDERSTANDING PHONO CARTRIDGES

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Any device that converts one form of energy to another is called a transducer. A phono cartridge is a transducer that converts the mechanical energy provided by a phonograph record to electrical energy delivered to an amplifier. Any transducer system can, in principle, be used as the generator of a cartridge, although in practice, there are certain constraints.

Two transducer systems dominate the cartridge market today; the ceramic or crystal-based transducer at the less expensive end of the market and variations of the magnetic transducer at the higher end. Other systems have been used, but have never really been commercially successful. This article deals with the operation of magnetic cartridges.

Interfaces

While in a theoretical discussion, it may be adequate to assume that external elements are perfect, when evaluating the ability of a cartridge to reproduce music from records, we must take into account the interaction with its interfaces. There are three important interfaces for a cartridge: The record which it is playing, the tonearm in which it is mounted, and the amplifier to which it delivers its output. Each of these interfaces sets limitations on final performance.

The record is a disc made of vinyl, with a spiral groove containing recorded information modulated into each side of the groove wall. As the record rotates, the cartridge stylus is vibrated by the groove. It is these vibrations which must be transmitted to the amplifier in the form of electrical energy.

The tonearm is expected to position the cartridge above the record to give it ideal working conditions at all times. Its ability to do this is partly determined by the cartridge itself. This will be illustrated in the section on compliance.

The modern amplifier receiving the cartridge output has a more or less standardized sensitivity. This means that for a given groove modulation, a minimum voltage must be supplied to the amplifier. Also, the cartridge load, a parameter that follows from design details of the amplifier together with the cables connecting the cartridge to the amplifier, can affect the electrical working conditions of the cartridge.

Recorded Information

The phonograph record master is cut on a mastering lathe, using a specially made disc. After various processes, the commercial record is stamped in vinyl plastic and *should* be an exact copy of the original master.

The input to the mastering lathe is an electrical copy of the sound received at the microphones. In stereo records, the groove walls are modulated so that the information from the two channels are at right angles to each other, as shown in Fig. 1. The left channel is on the inside wall, and the right on the outside.

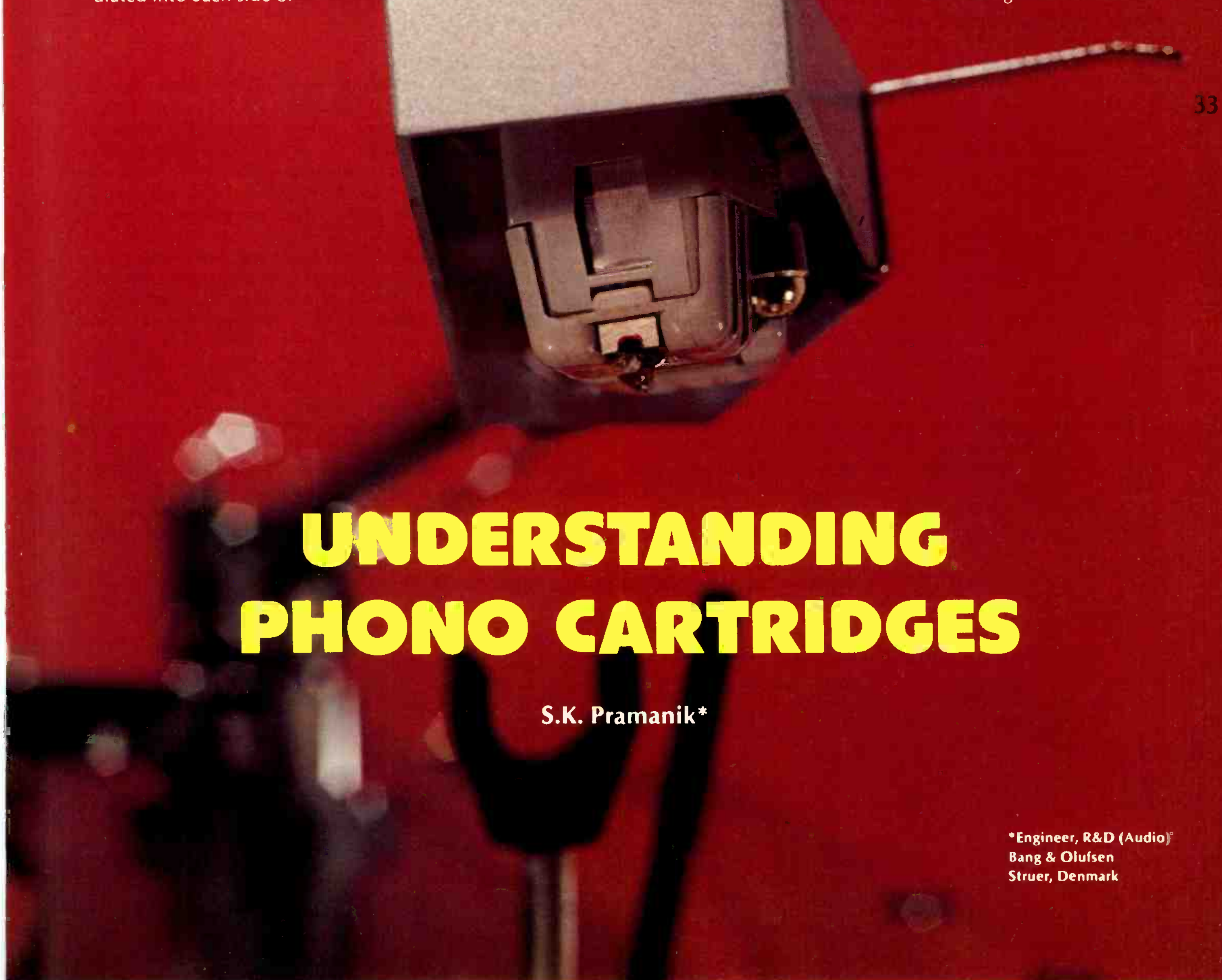

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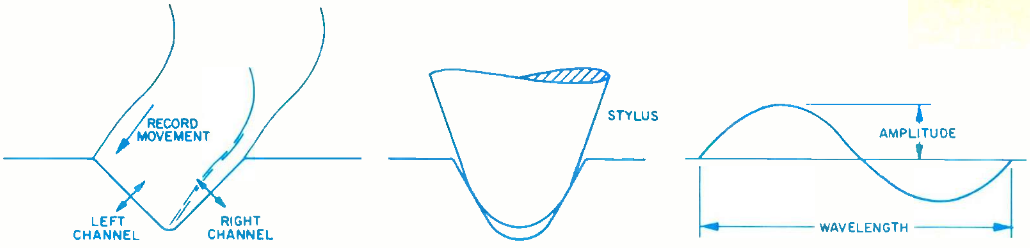
Fig. 1 — Stereo signal in record groove, fit of stylus in groove, and relation of amplitude and wavelength.



When a record is reproduced, the stylus makes contact with both walls, and as the record rotates, it follows the vibration as engraved in the groove. This vibration is then transferred to another part of the cartridge, where it is converted into electrical energy. The voltage of the electrical output of the cartridge is determined by the velocity the stylus attains at any point while tracking the groove modulation. This means that for an engraved sine wave, the pitch depends on the wave length, and the volume on the speed of the stylus perpendicular to the direction of record rotation. The actual wave length engraved on the record will decrease with the distance of the groove from the record center, as the groove speed relative to the stylus falls. The lateral velocity, which is directly related to the output voltage, remains the same at all groove diameters for the same signal.

For a given sound input at low frequencies, groove amplitude will be large compared to that for the same input at high frequencies. Acceleration of the stylus will be low, as there is a relatively long time available to reach maximum velocity. For high frequencies, modulation amplitude will be small, but because of the relatively short time available to reach maximum velocity, acceleration will be high. In order to limit the width of the groove, a standardized equalization curve is used to reduce levels at low frequencies. In addition, to reduce random noise which is most audible at high frequencies, the high end of the spectrum is amplified. The opposite curve is later used in the amplifier to recreate the original sound. In spite of this, low frequencies are characterized by large groove amplitude, and high frequencies by high levels of acceleration.

Magnetic Transducers

All magnetic cartridges are based on the same physical principle. If a magnet, some soft magnetic material (which will be referred to as iron), and a coil form a magnetic circuit, movement of any one of the elements with respect to the other two will induce a voltage in the coil. The element that moves is called the armature. In all three systems, movement of the armature induces a voltage in the coil by altering the magnetic flux through it. If the coil and the change in flux through the coil were the same, the electrical output would be identical, irrespective of which of the three elements move to cause the change in flux. The three principles are illustrated in Fig. 2.

The moving-coil transducer, also called dynamic, has a fixed magnet flux in the air gap. The flux relative to the coil changes, however, as the coil in the air gap connected to the stylus moves, inducing a voltage.

In the moving-magnet transducer, the magnet is connected to the stylus and located in the air gap. Flux in the magnetic circuit is changed directly as the distance of the magnet to the poles changes, inducing a voltage in the coils wound on the iron.

The moving-iron transducer, also called variable reluctance or induced magnet, changes flux by altering the magnetic path in the air gap, as the iron armature moves. The coils are wound on iron poles which form part of the magnetic circuit.

In order to get sufficient output, the size, materials, and layout of the elements in the three cases will not be the same. But none of the principles, in themselves, have any performance advantage over the others. Performance will depend on how accurately the stylus can be made to follow groove modulation, how accurately stylus movement can be transferred to the armature, and how accurately armature movement can be converted to a change in flux.

The sections that follow illustrate some of the important design and performance parameters; some aspects of a major problem in record reproduction, record and stylus wear, will also be covered.

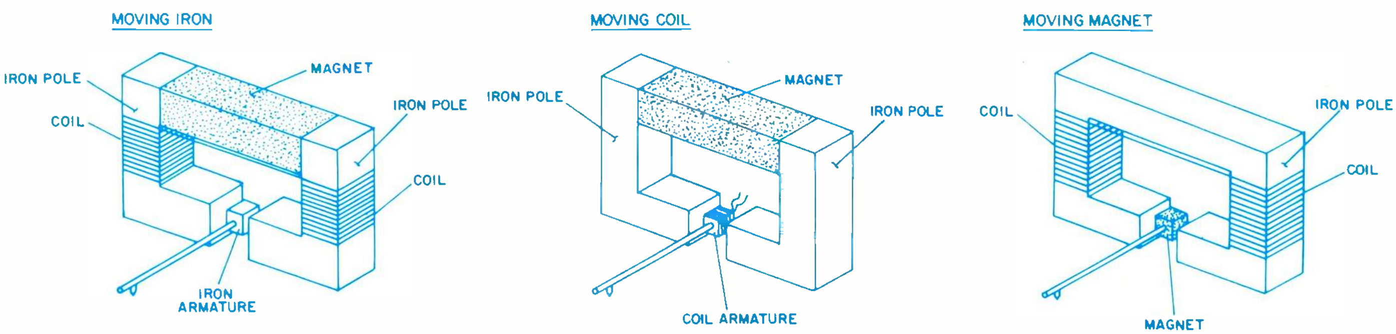
Vertical Tracking Force

Terms such as stylus pressure, tracking weight, etc., are also used to denote the Vertical Tracking Force (VTF). This force is set on the tonearm to ensure contact between the stylus and the groove. The stylus makes contact with the groove wall in two small areas, the size of which depends on the shape of the diamond, as shown in the diagram. Force per unit of contact area is pressure, and in this case will be called the stylus pressure generated by the VTF.

Vinyl plastic, of which modern records are made, is not completely rigid and deforms under pressure. Like other plastics, it has two main zones of deformation, although there is no sharp transition between them. At low pressure, up to point A in Fig. 4, deformation is said to be elastic, and the vinyl returns to its original shape when the pressure is removed. For higher pressures, such as at B, C, and D, the material is deformed progressively deeper into the plastic region, so that it only partially returns to its original shape when pressure is removed.

Thus, for any reasonable VTF, stylus pressure is comparatively low, and while the groove deforms under the stylus, it returns to its original shape after the stylus has passed. But for VTF above a certain level, stylus pressure is so high that

Fig. 2 — The three basic types of magnetic transducers.



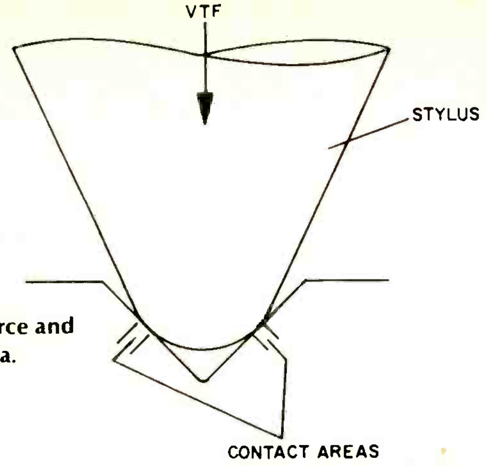


Fig. 3 — Vertical tracking force and contact area.

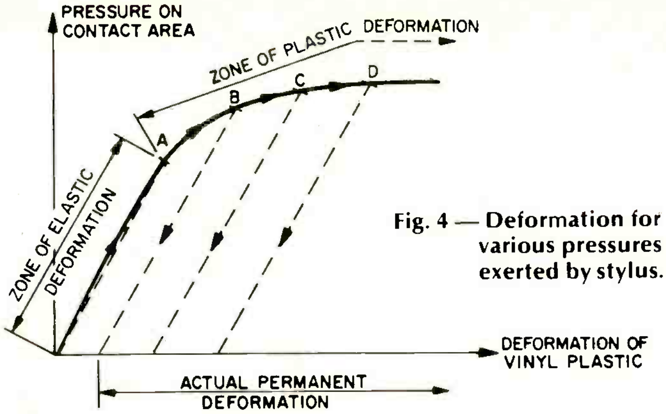


Fig. 4 — Deformation for various pressures exerted by stylus.

plastic deformation occurs and the vinyl suffers permanent damage. For unmodulated grooves, this point is not reached until the VTF is well above 30 mN (approx. 3 grams).

But when grooves are modulated the picture changes. It will be shown that the stylus pressure on the record changes with modulation, giving wear depending on whether the vinyl remains within the elastic region or if it is deformed into the plastic region.

A misconception about VTF is that the wear is sometimes directly attributed to this VTF factor, but wear which can only be caused by friction between the stylus and the groove walls. If the stylus is correctly shaped and well polished, wear is negligible. However, if the stylus is badly polished, worn, or damaged, wear can increase dramatically.

Effective Tip Mass

The moving parts of any cartridge have an equivalent mass associated with them. Called the Effective Tip Mass (ETM), it is a mathematical concept, but has a very real effect and practical value. The main elements contributing to the ETM are the armature, the cantilever which connects the stylus to the armature, and the stylus itself, which together form the stylus assembly. The weight of the individual elements alone should not be confused with their contribution to the ETM, as their relative positions play an equally important part.

The stylus assembly is usually suspended so that it rotates about a point. While in practice this is not strictly true, it is assumed for the sake of simplicity.

Given a generator system design including an armature, we can reduce the contribution of the armature to the ETM by increasing the length of the cantilever connecting it to the stylus. A longer cantilever is heavier than a short one, giving a larger contribution to the ETM. The contribution of the stylus does not change with the length of the cantilever.

The interplay between these factors is illustrated in Fig. 5. It can be seen that as cantilever length increases, the contribution of the armature decreases. At the same time the contribution of the cantilever increases, while that of the stylus remains constant. The sum of the factors shows a minimum value at a particular cantilever length, which is optimum for that armature and that kind of cantilever. If we wish to alter the ETM or if the cantilever length found is unsuitable, the design must be changed and a new optimum for the combination found.

At the same time mimimum voltage output must be provided, and this is also related to the size of the armature and the movement transferred from the stylus to the armature. In addition, the cantilever length must be adequate for clearance between the cartridge and the record. Because these factors conflict with low cartridge ETM, this is a very fundamental and difficult parameter for the designer, one that sets its mark on the rest of the design and on overall performance.

The need for low ETM follows from Newton's first law of motion, which says F = M x A, where F is force, M is mass, and A is acceleration. If we find a mass, M, which for a given force, F, accelerates at the same rate, A, as the moving parts of our cartridge, then this mass is the ETM of the cartridge. The ETM can be thought of as being concentrated at the stylus tip, and as the exact equivalent of all masses of the individual moving parts for forces applied at the stylus tip.

Newton's law now tells us that for any given acceleration on the record, the force between the record and the stylus is proportional to the ETM. Of course, acceleration on the record is not constant, and we also know that for the ETM of a given cartridge, that force is proportional to the acceleration.

Consider the stylus at the bottom of the groove modulation. A force is provided by the record to move the stylus, defined by the ETM and the acceleration at that point. When the stylus reaches the top of the modulated groove and attempts to go down, there is no force available in the record to maintain contact. This is provided externally by the VTF, which must be at least as large as the force defined by the ETM and the largest acceleration on the record. If this VTF is not provided or it is too low, the stylus will momentarily loose contact with the record, but will return further down the groove causing severe damage at the point of contact (see Figs. 6 A and B).

Even when VTF is adequate, the pressure at the bottom of the groove is now due to the sum of the force required to accelerate the ETM and the VTF, which is constant. The larger the ETM, the larger the combined force, and the resultant pressure can easily be sufficiently high to cause plastic deformation and permanent damage.

Since high acceleration occurs only with relatively high frequencies, low ETM is important only at the high end of the recorded spectrum. Wear caused by high ETM will occur on a record with a large high frequency content, where distortion due to wear is most audible.

Compliance

To generate signals, the armature must be able to move under the action of forces at the stylus tip. To allow this, the entire stylus assembly is suspended so that it can rotate about a point, generally on an elastomer at the armature. The distance the stylus moves for a given force is quoted as compliance and is determined by the stiffness of the elastomer and the length of the cantilever. Inversely, for a given stylus movement due to record modulation, the suspension exerts a force attempting to restore the stylus assembly to its mean position of rest. The stiffer the suspension, the larger is this force. Elastomer stiffness is not constant, however, but varies with frequency. Thus, if frequency increases, compliance decreases (becomes stiffer). That is, for the same vibration at a higher frequency, the restoring force is larger.

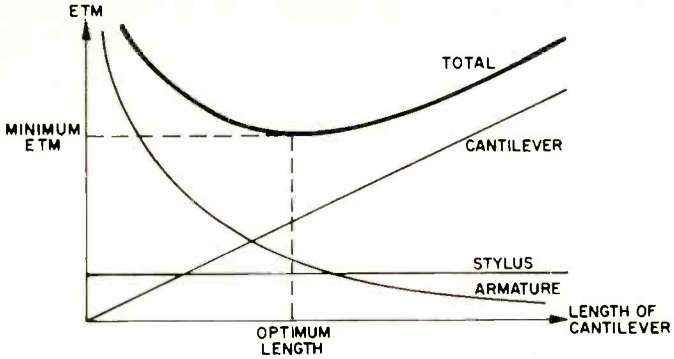


Fig. 5 — Effect on effective tip mass of increasing various cartridge parameters.

The static compliance generally quoted by manufacturers is therefore of little value in estimating the performance of a cartridge. More important is a frequency-related *dynamic* compliance, which is not quoted by manufacturers due to the lack of an accepted standard method of measurement.

The static compliance does, however, have some importance, in that it sets an upper limit on the VTF that can be applied. The cartridge needs a minimum clearance from the record, and this height is reduced with increasing VTF. The height without VTF is determined by the designed cartridge geometry, and the recommended VTF quoted by the manufacturer normally gives a mean position so that the armature is in its optimum working position. Too much variation from this recommended VTF value can alter the working position, leading to distortion.

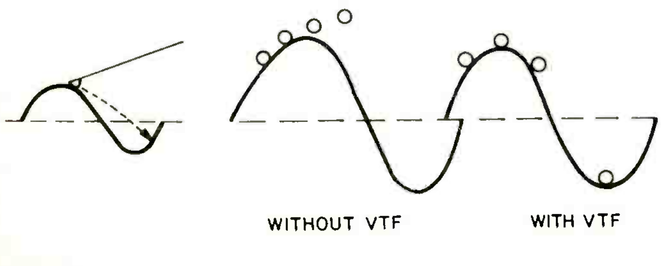
As record modulation vibrates the stylus and the stylus attempts to move below its mean position, there will be no force on the stylus enabling it to maintain contact with the groove, unless a force us supplied externally. This force is the VTF; it acts through the suspension and must be at least as large as the restoring force to maintain contact with the record.

If VTF is too low or smaller than the restoring force, the stylus will lose contact with the groove, and severe damage will occur where the stylus again contacts the groove.

It is evident that when the stylus is moved above its mean position, the total force on the record is the sum of the restoring force and the VTF. If cartridge compliance is low and sufficient VTF is applied to maintain contact with the grooves for the largest amplitude found on records, the sum of the VTF and the restoring force can be so large as to result in stylus pressure that deforms the groove into the plastic region, causing permanent damage.

Large forces due to compliance occur only for large stylus movements, that is, at large groove amplitudes, which occur only at the lower end of the recorded spectrum. Thus, compliance is a parameter that affects only the low frequency tracking ability of a cartridge, and wear can occur in passages with a large low frequency content if compliance is too low.

Fig. 6 — Motion of stylus tip with and without vertical tracking force.



Resonance

If a mass is suspended at one end of a spring, the other end of which is fixed, the spring will extend, depending on its stiffness and the size of the mass, to attain a fixed "mean" position. If the fixed end is now oscillated the mass will also move, but its movement will depend on the oscillation frequency. At a very low frequency, the end being oscillated and the mass will virtually move together, and relative movement between the free end and the mass will be virtually zero.

With increasing frequency, amplitude of the mass movement increases, but the movement of the mass follows a short time after the movement of the other end. At a certain frequency, dependent on the mass and spring stiffness, a resonant condition is reached, where the mass and the opposite end move "out of phase." When the opposite end moves down, the mass moves up, and vice versa. Relative movement between the mass and the free end will be largest at this frequency.

As frequency increases again, this out-of-phase movement decreases and the movement of the mass progressively decreases. Relative movement will also decrease. At a very high frequency, the mass will be completely still, even though the opposite end moves more vigorously than ever. The relative amplitude is plotted as a graph against frequency in Fig. 8B. The amplitude of movement at the opposite end is held constant.

Tonearm

The cartridge makes certain demands on the tonearm if it is to provide optimum performance. The most fundamental is on friction in the tonearm bearings. The tonearm must hold the cartridge firmly in the correct position above the modulated groove at all times and must remain completely steady at all frequencies that are modulated in the record. However, the record groove is a spiral, and the force to move the arm is provided by the record, through the stylus. If the bearing friction is sufficiently high, a force similar to the VTF, but acting sideways, will be applied at the stylus assembly suspension, pulling the armature out of its central position.

Similarly, if the arm is subjected to vertical movements, such as may be caused by a warped record, bearing friction will add to or subtract from the VTF depending on the arm movement, and stylus pressure will vary. If the bearing friction is small compared to the VTF both in the vertical and horizontal directions, distortion due to armature displacement is minimal.

Tonearm resonance also affects stylus pressure, with similar results. As the cartridge body is rigidly connected to the arm, it may be regarded as being a part of the arm itself. The arm has an equivalent mass, which depends on the weight and distribution of the various sections of the tonearm, together with the weight of the cartridge. This equivalent mass and the stylus assembly compliance form a resonant system when the stylus assembly is vibrated by the record. Therefore, there will be a resonant frequency which, with arms and cartridges available today, lies between 5 and 25 Hz.

Using the information on resonances, it is seen that at frequencies much below the resonant frequency, such as caused by warps and similar faults in the record, the tonearm will faithfully follow the stylus movement. There will thus be no relative movement of the armature, and the electrical output will be zero. The suspension will act as a rigid connecting member, and the only force exerted on the record is that required to move the equivalent mass of the arm. It is thus an advantage to have a low arm mass, and this includes low weight of the cartridge.

Again, at frequencies much above resonance, the tonearm will not move, and stylus movement is transferred directly to the armature without any influence from the tonearm.

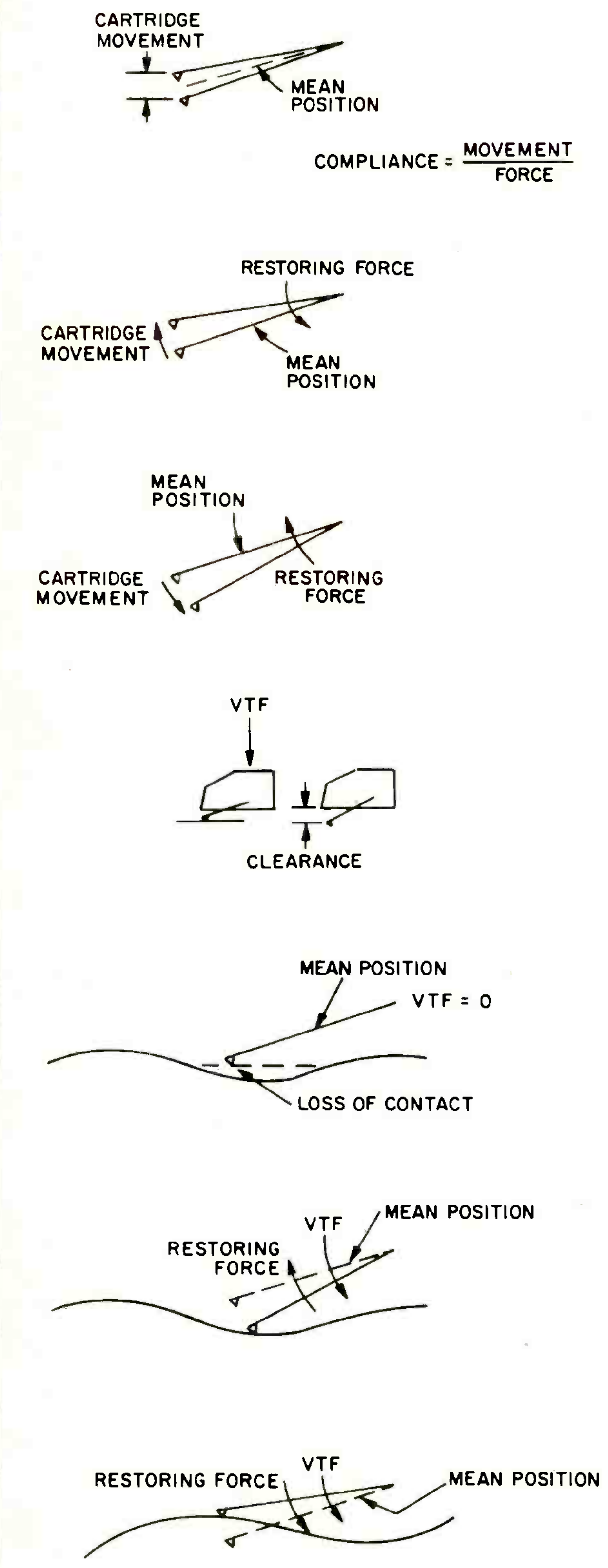


Fig. 7 — Illustrations of the effects of compliance on stylus motion.

At the resonant frequency and near it, the tonearm moves in a direction opposite to the direction of stylus movement. This is an out-of-phase condition, and the tonearm can move many times more than the stylus. The large relative movement between the cartridge and the stylus produces a peak in the frequency response curve. The movement can be so large that contact between the record and stylus is lost.

Tonearm damping at the bearing can reduce this problem, but cannot solve it. The out-of-phase movement at resonance is reduced, at the cost of an extension of response below resonance. This means that the tonearm with damping is more difficult to move below the resonant frequency than one without damping. A better solution is to place the resonant frequency of the tonearm and cartridge at a point where warp frequencies are seldom small; that is, as close as possible to 15 Hz and certainly above 10 Hz. This demands not only a light tonearm and cartridge, but a compliance that is not too high and matched to the tonearm mass.

Frequency Response and Damping

The ETM of a cartridge supplies the mass for another resonance system. Together with the elasticity of the record material, which acts as a spring, there is a resonance which in most modern cartridges lies between 15 and 50 kHz. This may be called the high frequency resonance of the cartridge. Since the elasticity (or compliance) of the record is essentially constant, the resonant frequency depends on cartridge ETM alone. The lower the ETM, the higher the resonant frequency.

The reasoning applied to any resonance is also valid here. At and around the resonant frequency, there will be out-of-phase effects which leads to increased relative vibration of the armature compared to the amplitude of the groove modulation. This gives a peak in the frequency response curve.

Further, due to the out-of-phase movement, stylus pressure acting on the record will vary, and at points where pressure is maximum and minimum, the stylus may cause plastic deformation or loss of contact with the groove leading to damage on making contact again. This is the most prevalent form of wear and distortion for cartridges in general. In cartridges with high ETM, it is possible to measure the effect as a "footprint" in a frequency response curve due to wear at the resonant frequency after a single playing of a record. The high frequency resonance results in a peak at the upper end of the frequency response curve of the cartridge, after which response falls sharply. A square wave test shows ringing on the horizontal sections of the curve.

To avoid these effects, the resonance is usually damped, using the suspension elastomer as the damping medium. Careful choice of the material, size, shape, and position of the elastomer is required to match the damping properties to the high frequency resonance, to give the necessary compliance, and the optimum frequency response characteristics.

Distortion

Differences between the recorded signal and the electrical output from the cartridge can be due to mechanical, magnetic, or electrical causes. Specific forms of distortion will not be discussed, but the most important causes will be detailed.

Mechanical causes are those where armature vibration is not identical to that of the stylus. Some of these are the many resonances described earlier in the tonearm, the stylus assembly, or the record. Particularly those factors which move the armature away from the designed working position lead to effects which are audibly unpleasant.

A resonance that has not been mentioned earlier is that of the cantilever itself, which can add both harmonic and intermodulation products to the armature vibration. Another

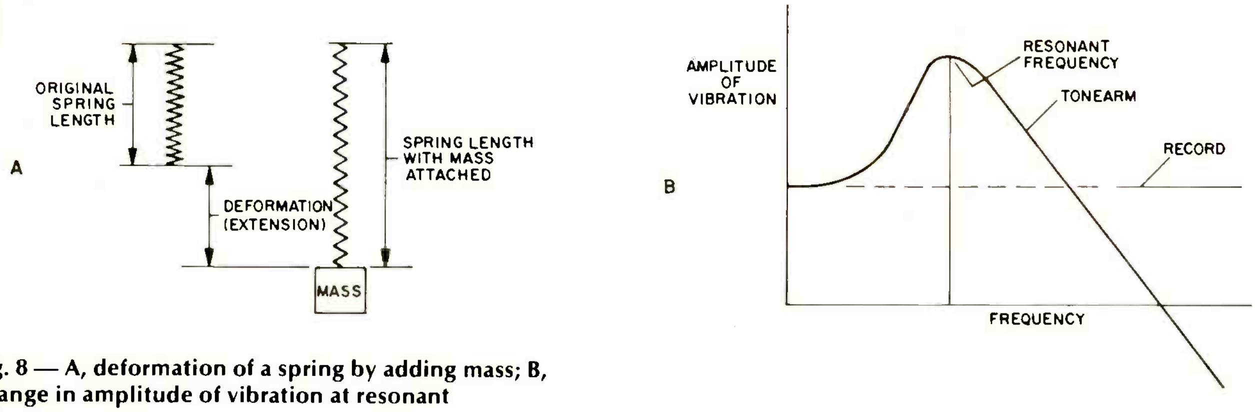


Fig. 8 — A, deformation of a spring by adding mass; B, change in amplitude of vibration at resonant frequency.

cause of false vibration is a longitudinal oscillation of the stylus assembly, often called precession. This oscillation, besides moving the armature out of its designed working position, can generate a signal of its own. Precession is also a resonant mode and can add harmonic products of its resonant frequency, as well as intermodulation distortion.

Compliance that is unnecessarily high can also lead to similar effects, especially in cartridge designs where the accuracy of lateral location of the armature is inadequate. The stylus assembly will then rotate about a point which itself moves sideways, leading to inaccurate movements of the armature.

Finally, among the mechanical causes, are the differences in shape between the cartridge stylus and the stylus that cut the record. This distortion is almost pure second harmonic and less audible than the types mentioned above.

Distortion due to magnetic causes may be defined as those where the change in flux is not identical to the armature vibration. The reasons can be non-linear armature induction or non-linear function of the iron.

The armature can give rise to distortion if the flux change due to movements of the armature is dependent on armature position. This can occur if the armature is not centered in the gap because of manufacturing tolerances, because of dynamic factors while playing a record for any of the reasons stated earlier, and also because a design has fundamentally non-linear armature induction.

Non-linear function of the iron is due to a property called hysteresis. Hysteresis is inherent in all magnetic materials, so that change of flux in the material is not identical to the change in magnetic field induced by armature movement.

The non-linearities due to problems of armature induction, as well as those due to hysteresis are minor, not only due to refinements in the design of all types of modern cartridges, but basically because the amplitude of armature vibration is small. Whatever transducer system is used, distortion due to these causes is small compared to those due to other causes.

When the flux through the coil changes, a voltage is induced in the coil. How accurately this voltage is transferred to the amplifier depends on the impedance of the coils in the cartridge and on the amplifier load. The impedance of the coils depends on the number of turns of wire on the coil and the magnetic characteristics of the iron on which the coil is wound. If the impedance is high, the electrical output will be sensitive to amplifier load.

The amplifier load consists not only of the resistance and capacitance designed into the amplifier input stage, and, as far as the cartridge is concerned, also those of the cables connecting the cartridge to the amplifier. The total capacitance together with the inductance of the cartridge coils form an electrical resonance, which can have an audible effect on sound quality. In many cases the cartridge must be specifically matched to the amplifier for best performance.

A special case is the moving-coil cartridge, which generally has very low coil impedances, as well as low electrical output. These require special output transformers or extra preamplifiers to give the necessary matching and the required output level. Inevitably the extra components add some noise and distortion, although modern, high-priced products have performances which are close to perfection.

Crosstalk

If the signal from one of the channels of a stereo pair breaks through into the other, the phenomenon is called crosstalk. The main cause is that the axes of the generating system are not parallel to the axes of the signal recorded in the grooves. This can be due to manufacturing tolerances or can be inherent in the transducer design, which may be sensitive to vibrations in the opposite channel. A small amount of crosstalk will not normally be audibly unpleasant, as it will only result in a minor reduction in stereo separation.

It becomes unpleasant if distortion products are present in the crosstalk signal. This can occur for any of the reasons given for distortion especially cantilever resonance, non-centered armature, lateral movement of the point of rotation due to excessive compliance, or a precession. Other causes of crosstalk are incorrect mounting of the cartridge in the tonearm relative to the record and resonances in the tonearm itself.

Conclusion

The objective for a cartridge designer is to balance a large number of factors, each of them requiring solutions that may be contradictory. The final result depends as much on decisions about the relative stress to be given to the various parameters, as on the skill in engineering design, and on precision in manufacture.

Very often stress on a single parameter has led to exceptional performance in one area. High compliance can give excellent tracking at the low end of the spectrum, undamped high frequency resonance to clear, sharp treble with a transparent or open sound. In the long run however, it is just as important that the cartridge treats records gently as the sound it produces. And if the listener has a wide range of musical interests, the cartridge must have above average performance in all aspects of sound reproduction, and not excel in only a few.