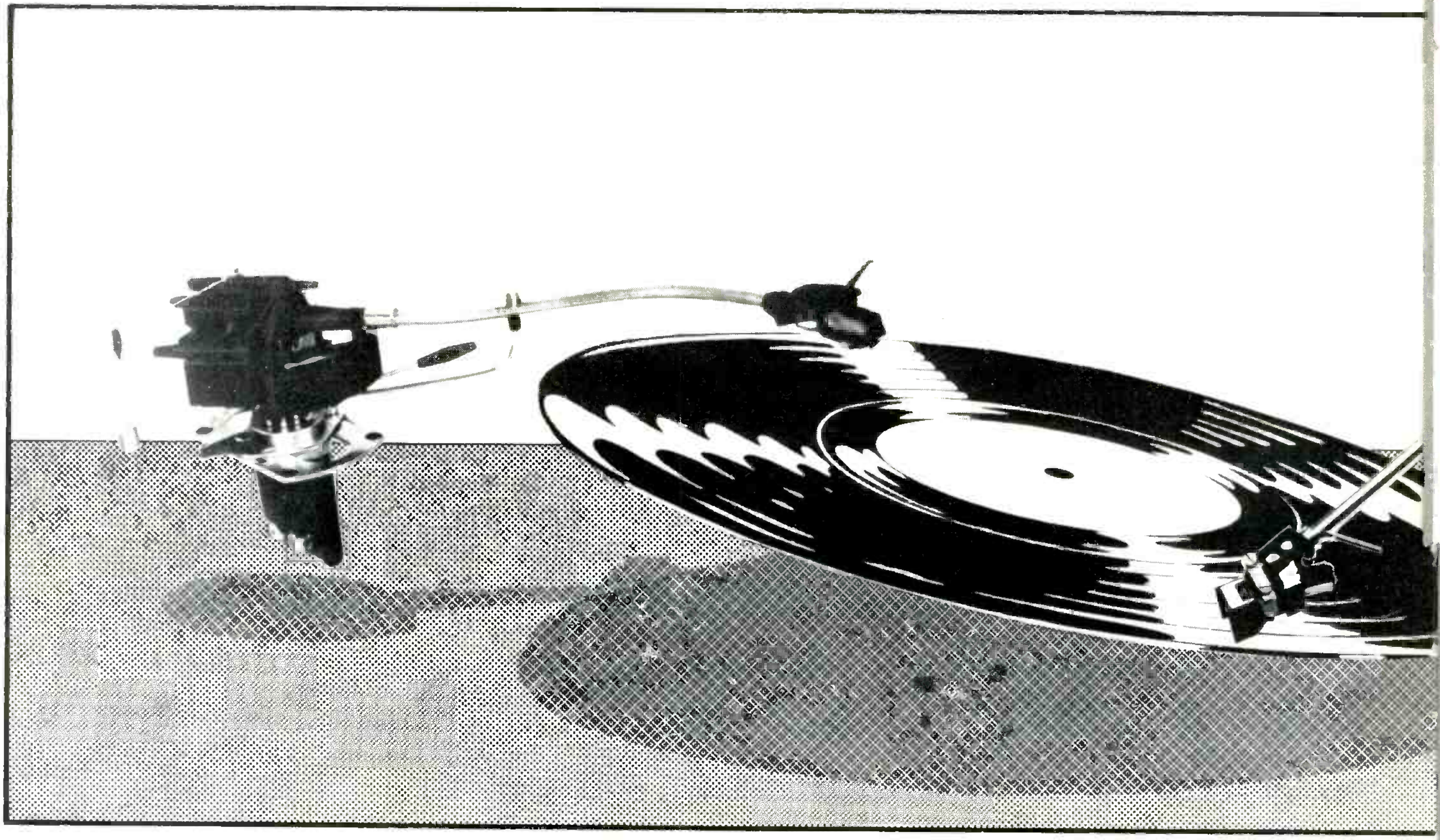
Understanding



The function of a phono cartridge was described in an earlier article (*Audio*, March, 1979) in which the tonearm was assumed to be virtually ideal. Its only influence on cartridge performance was taken to be the effect of a single parameter, the equivalent mass. We can perform a similar exercise with tonearms, this time assuming the cartridge to be virtually perfect.

To understand the function of a tonearm and its contribution to the overall quality of a hi-fi system, it is necessary to remember one basic fact. Electrical signals are generated in the cartridge when, and only when, a relative movement occurs between the record surface in contact with the stylus tip and the surface on which the cartridge is mounted at the end of the tonearm. Such signals will be generated regardless of the cause of the relative movement.

To be strictly accurate, signals are generated when there is relative movement between the vibrating section (the armature) and the static sections of the transducer elements within the cartridge. However, if the cartridge is perfect, the stylus tip will move in a manner identical to the record surface so that an identical movement is transferred to the armature. Also, the static section of the generating elements will be rigidly connected to the end of the tonearm. Thus, a relative movement between the stylus tip and the end of the tonearm will generate signals, whether audible or inaudible (except induced signals such as hum or r.f. breakthrough.)

To analyze the performance of the tonearm and its contribution to audio quality, it is necessary to examine the effect on the tonearm of the various sources causing movement in a record playing system, and thereby to deduce the movement of the tonearm relative to the record surface. This analysis concerns the dynamic properties and includes what may be called the performance of the tonearm. But unless the cartridge is correctly aligned relative to the record, relative movement of the transducer elements will not be the same as the recorded signal. The tonearm also has static properties which make a contribution, and these causes are cartridge mounting and tonearm geometry.

Illustration: Sandy Young

Tonearms

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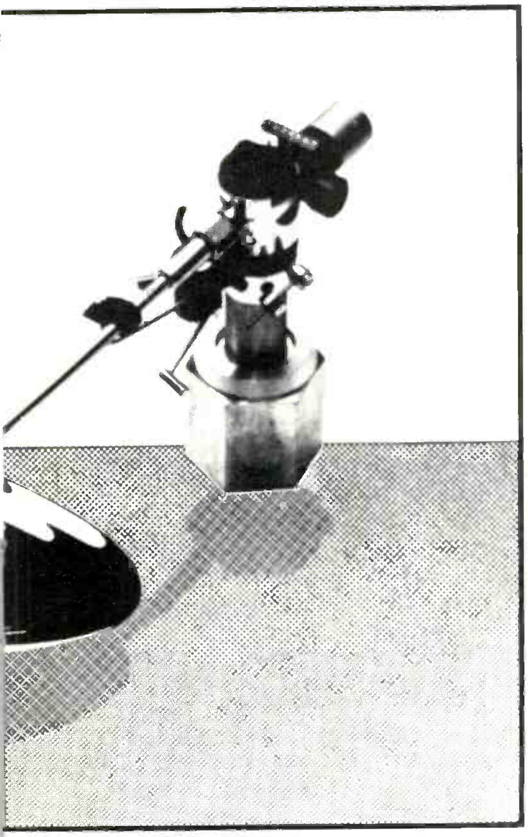


Cartridge Mounting

The cartridge is mounted on a tonearm in a fixture which in turn is mounted either permanently or so that it is removable at the end of the arm tube. Incorrect mounting can lead to two types of errors.

First, unless the cartridge stylus coincides with its designed position, the effective length of the arm is altered, leading to tracking error due to tonearm geometry.

The other error arises when the static transducer planes in the cartridge are not parallel to the planes of modulation on the record. This happens, for example, if the cartridge is mounted so that it is rotated on its horizontal axis. In this case, a small component of the signal from an undesired channel is picked up and mixed with the desired signal, as the relative movement of the generator elements is not identical to the signal engraved in the record grooves, as shown in Fig. 1. Since crosstalk is introduced, the stereo image suffers. The same result occurs if the transducer elements are rotated because the tonearm is incorrectly mounted; any other mounting error leads to the same result. In all cases the necessary correction may be applied at the cartridge.

For the best stereo image, the cartridge should be mounted to give equal separation in both channels. Rotating the cartridge on its horizontal axis will increase separation in one channel at the cost of separation in the other channel, but the rule about equal separation remains unaltered. Records themselves are often less than perfect, and the two channels may not be recorded at right angles or may be tilted with respect to the vertical. In such cases it is generally not possible to get the optimum degree of separation from the cartridge by conventional means.

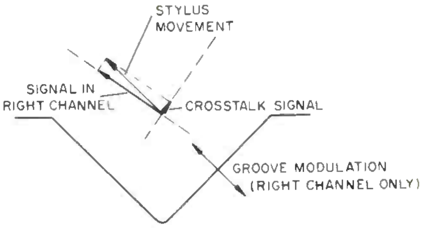


Fig. 1—Effect of crosstalk on stylus movement.

Tonearm Geometry

The mathematics of the geometry for conventional or radial tracking tonearms has been known for many years and is well documented, most recently in a comprehensive article by Kessler and Pisha (*Audio*, January, 1980). It is therefore sufficient to repeat a few of the most important points here.

Distortion due to tracking error, the angular error between the cantilever axis and a true tangent to the record groove, is not dependent on the error angle alone, but also on the speed of the record groove moving past the stylus.

Figure 2 shows an arm of effective length (l), mounted at a distance (d) from the turntable spindle. The arm length is the sum of the mounting distance and the effective overhang. At a radius (r) from the center, the angle between the line connecting the stylus and the tonearm bearing and the tangent to the groove is (x), and the angle with the radius is (90 - x). By the cosine law of triangles:

$$d^2 = l^2 + r^2 - 2\,lr\cos(90 - x)$$

$$\text{or, } x = \sin^{-1}\frac{(l^2 + r^2 - d^2)}{2lr}.$$

If the offset angle is (y), then the angular tracking error is (y - x). The distortion due to tracking error at radius (r) is proportional to (y - x)/r. Distortion due to tracking error is quoted in specifications as the error factor, which is the maximum angular error over the recorded surface divided by the radius at which this occurs (degrees/cm).

Unless qualified, this specification is misleading as it fails to specify the limits of groove radii for which the arm is designed. While the maximum radius is effectively fixed by the outside diameter of the record, and in any case is less critical, a small change in the minimum radius considered can alter the calculated error factor of a tonearm appreciably.

The minimum modulated groove diameter is not the same on all records, as it depends on the playing time, groove width, etc., and in practice can

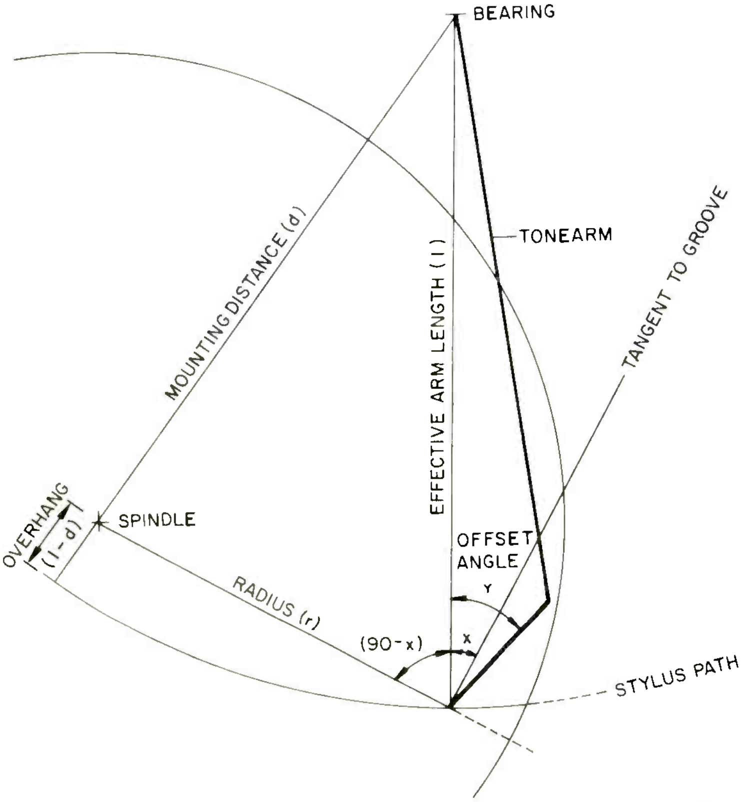


Fig. 2—Geometry of radial tonearm movement across a record.

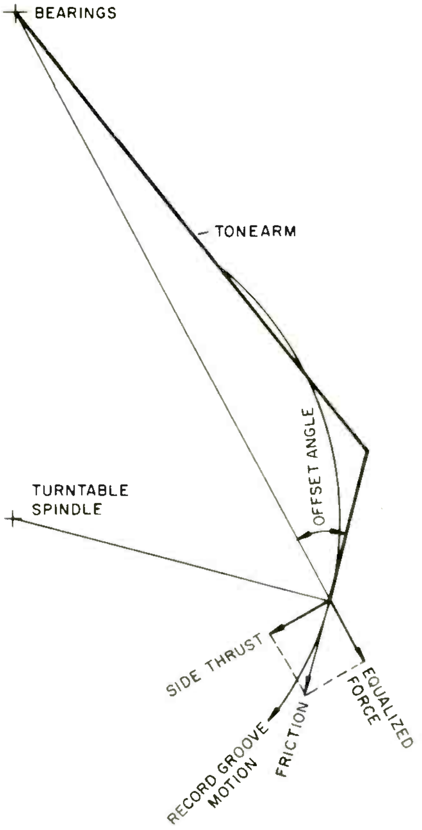


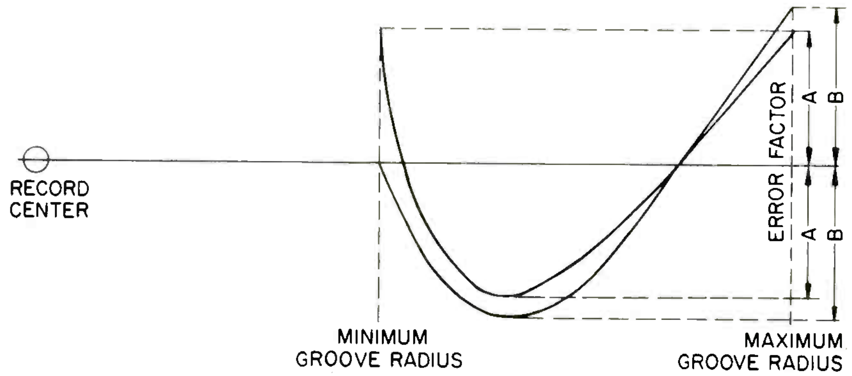
Fig. 4—Geometry of side thrust on the stylus tip.

vary by 2 cm or more on commercial records. Further, although national standards for the minimum permitted groove radius do exist, the various world standards do not specify the same radius. In other words, arms can differ slightly in their geometries simply because the designers have assumed different values for the maximum and minimum limits of groove radii.

Another source of small differences in tonearm geometry can occur because of different design philosophies. An arm can be designed so that the error factor is equal at the minimum and maximum record diameters, as well as at the point of maximum error somewhere in between, as shown in Fig. 3, Curve A. One could with justification say that since tracking distortion also rises with modulation level, and most recordings have high modulation levels at the end of the record, tracking error at minimum radius should be zero, as shown in Curve B.

Small errors in mounting distance from the center of the platter or in overhang adjustment can make comparatively large differences in angular errors, as well as the groove radii at which maximum and minimum errors occur. It is therefore important that the arm support is mounted correctly relative to the turntable spindle and that the effective arm length with the cartridge mounted is correct. This also means that where overhang is adjustable, an arm can be optimized to track any particular record. If the minimum and maximum radii of the modulated grooves on the record being played are measured, optimum overhang can be calculated for the offset angle of the arm, and the necessary adjustment in effective arm length made.

Fig. 3—Error factors for different tonearm layouts.



Note, however, that distortion generated by tracking error consists mainly of second and higher order even harmonics, which are the least objectionable of the various types of distortion. Also, tracking error distortion increases and decreases smoothly across the record surface, and no sudden changes occur to make the distortion more obvious. Thus, for any correctly mounted rational design of tonearm, small differences in geometry do not give rise to large audible differences.

Side Thrust or Skating Effect

The expression "skating effect" goes back to the days when a smooth disc was used to demonstrate this effect or to check the compensation applied. Since this method gives incorrect compensation, the term may also be said to be misleading.

Side thrust occurs due to the offset angle necessary for optimum angular tracking in radial arms. Friction between the stylus and the rotating record pulls the stylus in a direction tangential to the groove, as shown in Fig. 4. Since the force is not in line with the arm bearing, a rotating force is generated forcing the arm towards the center of the record. This force, called side thrust, depends on the instantaneous magnitude of the frictional force between the stylus and the groove walls.

In the absence of side thrust, pressure is equal on both walls of the groove at the points of contact due to the vertical tracking force (VTF), as shown in Fig. 5A. If side thrust acts in conjunction with the VTF, the two forces combine to give a result which is not vertical but is inclined towards the center of the record, as shown in Fig. 5B. The effect of this inclination is that there is more pressure on the inner groove wall (left channel) than on the outer, as shown in Fig. 5C. It is obvious that where this happens the cartridge cannot have ideal working conditions. The effect of side thrust can be compensated by applying a force at the tonearm bearing. If an otherwise correctly mounted and adjusted tonearm distorts due to mistracking on the right channel only on high-level signals, the cause can be inadequate side-thrust compensation; mistracking on the left channel only indicates overcompensation. Side-thrust compensation can be applied in many forms and ideally should give exactly the same force outwards that side thrust causes inwards. Various methods are used in commercial applications, such as a thread and weight, springs, opposing magnets, etc.

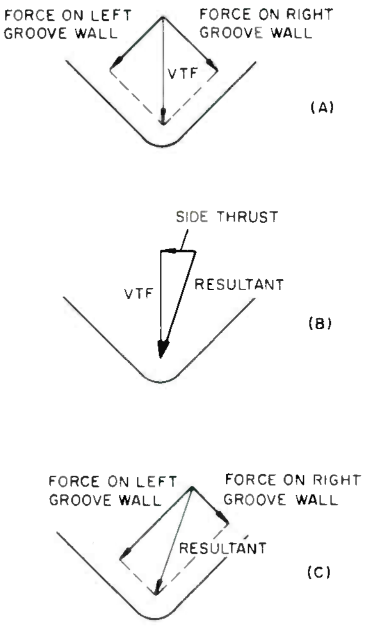


Fig. 5—Analysis of side thrust.

It should be remembered that side thrust is affected not only by relatively constant factors such as the shape and polish on the stylus and by vertical tracking force, but also by the material from which the record is made and by such varying conditions as groove radius and modulation. Since side thrust varies more or less at random over the surface of the record, it can never be compensated exactly. A good compromise is to adjust compensation to cope with the highest level of modulation likely to be met on records. Although overcompensated for all lower levels of modulation, no mistracking will occur at any modulation level because the pressure will always be higher than the minimum required for the stylus to maintain contact with the groove walls.

Tangential Tracking

The conventional tonearm is pivoted on fixed axes to allow movement in the vertical and horizontal planes. Another approach to the design of tonearms is the tangential tracking tonearm.

In the tangential arm the horizontal bearing (which allows tonearm movement in the vertical plane) is a conventional bearing, but the vertical bearing is replaced by a carriage which moves as required to keep the cartridge tangential to the groove, as shown in Fig. 6. Such tonearms are also called parallel or straight-line tracking arms.

The most obvious advantage is that tracking error can theoretically be zero, and the cartridge is allowed to track the record with geometry identical to that when it was cut. In practice this advantage is less important than it might seem, as the errors in correctly designed and mounted radial tonearms are so small that a tangential tonearm provides only minor audible improvement. Also, small tolerance errors in mounting a tangential tonearm can lead to a constant tracking angle error over the whole of the record surface, virtually negating its advantages (a 1-mm error in length gives approximately a 1-degree error at minimum radius).

Assuming that the moving carriage functions ideally, the tangential arm offers two major advantages. Since the minimum length required by radial arms for adequate tracking becomes unnecessary, the tangential arm can be short and straight. The short arm weighs very little and leads to a fairly large reduction in the effective mass of the tonearm. Further, since the bearings are always directly behind the stylus in line with the cantilever, the frictional force at the stylus is taken up by the bearing. Thus, there is no side thrust under any conditions, and no compensation is necessary. The contact force on both groove walls provided by the VTF is the same over the whole surface of the record, and it does not vary.

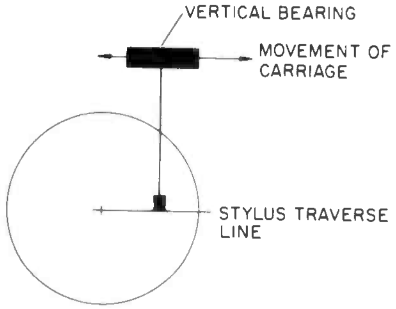


Fig. 6—Geometry of tangential tracking tonearm.

Many forms of tangential tracking can be devised, from the purely mechanical to contactless electronic servo systems. While the method used is a matter of engineering application, the requirement for the mechanism remains the same for all kinds of tonearm, i.e. that the mechanism should have no (or as little as possible) influence on the function of the cartridge.

Bearings

The primary requirement for the bearings is that they be free from friction, a force that always opposes motion. As the stylus tracks and the arm is moved inwards in a slow spiral by the groove acting on the stylus tip, friction in the vertical bearing (allowing horizontal tonearm movement) exerts a force attempting to stop the arm from moving. The outer wall of the groove must therefore exert a larger force to move the arm, resulting in a higher pressure on the outer groove wall (right channel) with a corre-

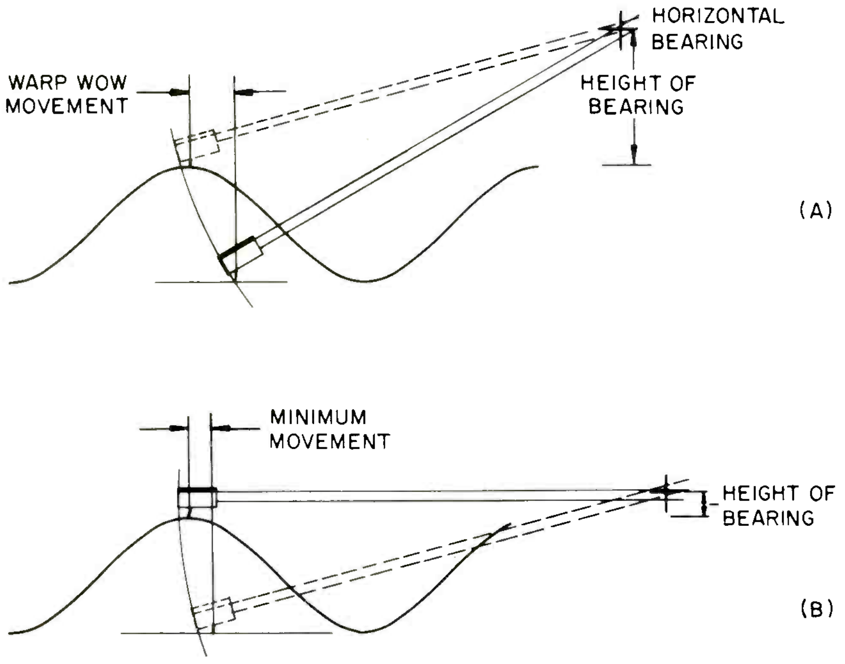


Fig. 7—Effect of different bearing heights on stylus movement with record warp.

sponding decrease on the inner wall. If a correctly mounted and adjusted tonearm mistracks on the left channel only on high-level signals, the cause can be friction in the vertical bearing.

If a record is eccentric, there will also be an outward motion of the tonearm for every half-rotation (if the eccentricity is very small, it may just compensate for the inward motion of the groove at that point with no net outward movement). On the other half-rotation the inward motion will be larger by the amount of eccentricity. Bearing friction will have the same effect, but the increase and decrease in contact pressure will alternate between groove walls.

Friction in the horizontal bearing (vertical movements) has a similar effect when tracking a warped record. In this case, however, the arm is stopped from moving with the warp, resulting in an increase or decrease in the effective VTF on both groove walls simultaneously, depending on whether the stylus is being forced up or down by the warp. The effect will also occur when the stylus is lowered onto the surface to play a record, with a consequent decrease in the effective VTF.

Undesirable effects also occur if there is play in the bearings. Such effects do not lend themselves to easy mathematical analysis, because they depend on the complex interplay between the design of the remainder of the tonearm and the amount and type of play. It can be seen that under the influence of external forces (such as friction) between the stylus and the groove, the whole arm will move. If the movement is in the line of the arm tube, it will result in wow, similar to warp wow explained below. But movement can also be sideways or up and down, with results which will depend on a combination of many factors. All that can be said in general is that the result will not be an accurate reproduction of the recorded signal, and the effect is likely to be unpleasant.

Two bearing types require a little elaboration. The first of these is called a knife edge, sometimes used for the horizontal bearing. The entire weight of the tonearm rests on the bearing "edge," which is supported in a suitably shaped slot. In bearings of this type, there is theoretically no friction; vertical movement of the tonearm results in one of the surfaces rolling on the other, rather than sliding. The rolling action will alter the effective length by a small amount as the end of the tonearm rises, but this can be used to advantage to compensate for warp wow. The other type of bearing is the unipivot, in which a single point, on which the arm rests, is used for both vertical and horizontal movements. While the complexities of the design are a subject in itself and cannot be discussed here, a correctly designed unipivot can provide extremely low friction with minimal side effects.

Finally, an important aspect of bearing design is a consideration of the lead wires from the cartridge. These have to pass through or around the vertical bearing, and they are attached to a point below the surface of the turntable base. As the tonearm moves horizontally, the lead wires twist and may generate torque to move the tonearm either inwards or outwards. Both the leads and their layout can therefore play an important part in overall performance and may even be a determining factor in the choice of the type of bearing used.

Warp Wow

The height of the horizontal bearing above the record surface is important for reproduction quality. As the tonearm moves up and down under the influence of record warps, the stylus moves in an arc with the axis of the horizontal bearing as its center. If the bearing is well above the record surface, as in the exaggerated sketch of Fig. 7A, the stylus will move forward simultaneously with its upward movement, and the speed of the record groove relative to the stylus will decrease. The effect is identical to a decrease in turntable speed, and it lowers the pitch of the reproduced signal. The reverse occurs as the stylus moves down the warp and the pitch returns to its nominal value. This variation in pitch due to the combination of bearing height and warped records is known as warp wow.

The ideal bearing position is at a height above the record surface equal to the height of warps, which results in minimum changes in relative speed, as shown in Fig. 7B.

The axis of the horizontal bearing can lead to another undesired effect unless it is perpendicular to the axis of the cartridge cantilever. As the tonearm moves up under the action of warps, the arm "twists" simultaneously with respect to the record surface, as shown in Fig. 8A. The result is a changing crosstalk pattern as the arm moves up and down, depending on the angle

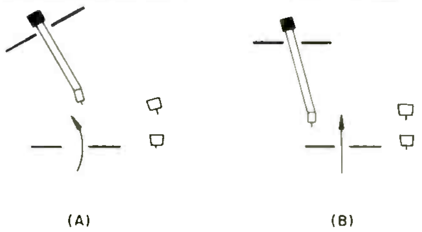


Fig. 8—Effect of undesired axis in the horizontal bearing on tonearm movement with warps.

between the transducer elements and the record surface, and this leads to an unsteady or unstable stereo image. In an ideal case the horizontal bearing will be perpendicular to the axis of the cantilever so that the cartridge does not twist, as shown in Fig. 8B.

Equivalent Mass

For static balance, the mass of the arm tube, the headshell and mounting accessories, and the cartridge itself, which lie on one side of the horizontal bearing, must be balanced by a counterweight on the opposite side. The counterweight can usually be moved to first achieve perfect balance and to another position to supply VTF. In some designs, additional weights or springs are used to provide vertical tracking force, but these are ignored for the sake of simplicity in the analysis below.

Consider the arm of Fig. 9, consisting of a weightless tube and a cartridge of mass M including the headshell, etc., counterbalanced by a counterweight 10 times the mass of the cartridge, or 10 M. Then, if the distance of the cartridge from the bearing is 10 x units, the distance of the counterweight for perfect balance is x, or one-tenth of the distance of the cartridge. This arm has an inertia given by the various masses times the square of their distances from the bearing. Thus, the respective contributions will be:

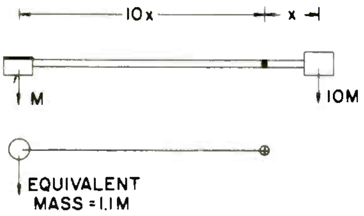


Fig. 9—Analysis of equivalent tonearm mass considers the length from stylus to pivot point (10 x) and length from counterweight to pivot (x).

Cartridge inertia
$= M\,(10\,x)^2 = 100\,M\,x^2$;
Counterweight inertia
$= 10\,M\,(x)^2 = 10\,M\,x^2$.
Therefore, total arm inertia
$= 100\,M\,x^2 + 10\,M\,x^2 = 110\,M\,x^2$.

It can be seen that the contribution of the cartridge, although only one-tenth the weight, is much larger than that of the counterweight, because the cartridge is further from the bearing. Also, if a longer arm tube is used, the inertia of the arm increases as the square of the tube length (x), given the same cartridge and counterweight. Arm inertia can be lowered by reducing either mass or the length of the arm.

We can now introduce the concept of the equivalent mass of the tonearm. By Newton's second law of motion, force equals mass multiplied by acceleration, or acceleration equals force divided by mass. If we can find a mass which, when substituted for all the arm masses and placed at the stylus, will accelerate at the same rate as our arm when subjected to the same force applied at the stylus, this will be its equivalent mass. The equivalent mass can be calculated by the reverse process used for calculating inertia, since the distance of the cartridge was 10 x and inertia was $110\,M\,x^2$.

Equivalent mass
$= 110\,M\,x^2 / (10\,x)^2 = 1.1\,M$.

Note that the mass of the cartridge alone was M and that the calculated equivalent mass, 1.1 M, includes the contribution of the cartridge and the counterweight, but not of the rest of the arm. In a real case, similar contributions will be made by every component in the arm according to its mass and to its distance from the bearing. While the calculation will be more complex, it is based on the same principle.

It can also be shown that if a lighter counterweight is used, the equivalent mass of the arm increases. If the counterweight is used, the equivalent mass of the arm increases. If the counterweight mass is halved to 5 M for static balance, it will have to be placed at twice the distance from the bearing, or at 2 x. Then,

Equivalent mass
$= 100\,M\,x^2 + 5\,M\,(2\,x)^2 / (10\,x)^2$
$= 1.2\,M\,x^2$.

Thus, the equivalent mass increases to 1.2 M by halving the weight of the counterweight.

The equivalent mass plays its primary role as a part of the vibrating system (as explained under tonearm resonance), but it also has a secondary role. For slow movements of the record surface, such as with track warps, the force required to move the arm depends on its inertia or equivalent mass. The higher the equivalent mass of the arm, the larger the force required from the record to push the arm up. Conversely, the larger the inertia, the larger the VTF required to pull the arm down to maintain contact between the stylus and the record.

Resonance

If a mass is suspended at one end of a spring (Fig. 10), 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 of rest. If the mass is displaced from its position of rest and released, it will oscillate at a frequency called its natural, fundamental, or resonant frequency. The resonant frequency (f), a function of the stiffness of the spring (k) and the suspended mass (m), is given by the equation:

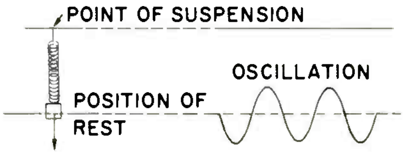


Fig. 10—Basic analysis of oscillation.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}.$$

The equation shows that resonant frequency rises for stiffer (or lower compliance) springs and for lower masses. If the point of suspension vibrates, the mass will also move, but the movement will depend on the oscillating frequency. The mathematical analysis of the phenomenon is known as the theory of forced vibration.

Below the resonant frequency, the end being oscillated and the mass move virtually together as if they were rigidly connected, and relative movement between the mass and the point of suspension is virtually zero, as shown in Fig. 11A.

With increasing frequency, amplitude of the mass increases but the movement of the mass follows a short time after the movement of the other end. The resonant condition occurs at the same frequency as for free oscillation, where the mass and the point of suspension move "out of phase." When the point of suspension moves down, the mass moves up, and vice versa. Relative movement between the mass and the point of suspension will be largest at this frequency and equal to the sum of the amplitudes of the forcing vibration and the resonance movement, as shown in Fig. 11B.

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 remains completely still, even though the point of

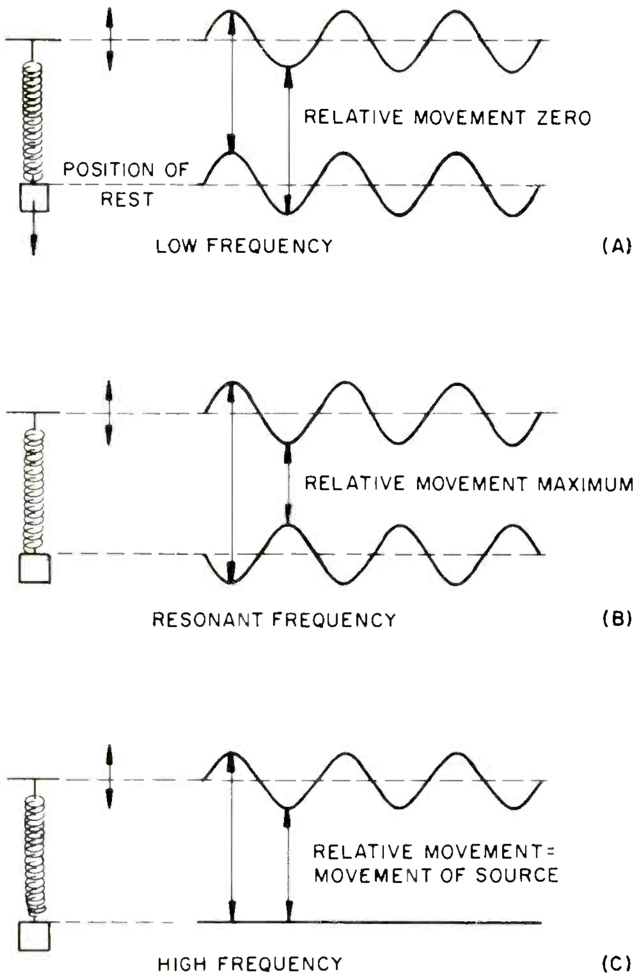


Fig. 11—Relative movement of the weight depends on the oscillation frequency.

suspension moves as vigorously as ever, as shown in Fig. 11C.

The relative amplitude of the mass is plotted in Fig. 12 against frequency, the amplitude of the point of suspension which forces vibrations being assumed to be constant. This is a very important phenomenon and can be used to explain many facets of performance in cartridges, tonearms, and turntables. Resonance phenomena occur wherever masses are connected by springs (all materials have some flexibility and mass); the only differences are the amplitudes and frequencies of the resonant modes.

Tonearm Resonance

All tonearms form a resonant system, with the equivalent mass of the tonearm acting together with cartridge compliance as the spring. This resonance may be called its primary resonance (also called bass, fundamental, or simply tonearm resonance), and in commercial systems available today, the resonant frequency generally lies between 5 and 25 Hz.

Applying forced-vibration theory to tonearms, it is seen that if the oscillating frequency is far below the resonant frequency, such as is caused by low-frequency warps and similar faults in the record, both the stylus of the perfect cartridge and its tonearm faithfully follow the record warps. There is no relative movement between the record and the tonearm so that the electrical output is zero. The cartridge suspension acts as if it were a rigid connecting member, and the only force exerted by the record is that required to move the equivalent mass of the arm. This is one of the advantages of a tonearm with a low equivalent mass.

At frequencies far above the resonant frequency, such as at the audio frequencies of the signal on the record, the tonearm does not move. Stylus movement is transferred directly to the armature and converted to an electrical signal. The primary resonance of the tonearm has no influence on cartridge performance.

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 tonearm movement can be many times larger than the stylus movement. The large relative movement between the tonearm and the stylus produces a peak in the frequency-response curve at the resonant frequency. Response on either side of this peak will fall at 12 dB/octave below the resonant frequency. A typical response curve is shown in Fig. 13.

The movement in a direction opposite to that of the record can be so large that the cantilever cannot move the required distance, and contact between the record and stylus is lost. In less violent cases, tonearm vibration results in changing VTF at a rate corresponding to the resonant frequency, with unpredictable effects on cartridge tracking.

Another undesirable effect is the accentuation of rumble. Signals generated in the cartridge at low frequencies are boosted by up to 20 dB in the phono preamplifier because of the replay equalization necessary to compensate for recording characteristics. Any rumble present in the turntable or on the record will first be amplified by the tonearm resonance and then boosted by the record equalization. Also, the presence of a large subsonic signal induced in the cartridge by the movement of the tonearm at its resonant frequency can modulate the audio signal and create intermodulation products. These distortion products cannot be removed by any later process once they are generated.

The effects of the primary tonearm resonance are minimized if its frequency is at a point where warp frequencies seldom occur and amplitudes are small. Studies made of the distribution of warps in phonograph records show that the majority of warps lie at frequencies below 10 Hz. It is therefore logical to design the tonearm resonance to lie well above this frequency.

However, if the resonant frequency is too high, the electrical output of the cartridge will be influenced by audio frequencies, resulting in a boost at the lower end of the audio spectrum. A tonearm resonance well above 10 Hz, but below the recorded audio signal frequencies, demands not only a light tonearm and cartridge, but a cartridge compliance that is closely matched to the equivalent mass of the tonearm.

Two methods are commonly used to reduce the effects of tonearm resonance, respecially when it lies in the danger region below 10 Hz: The use of

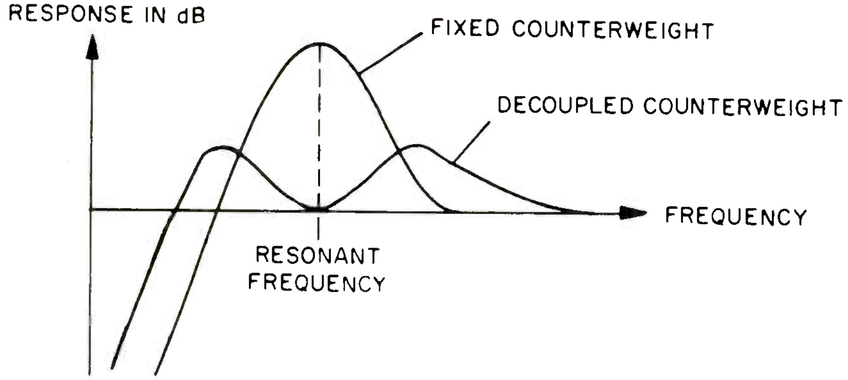


Fig. 15—Typical tonearm-cartridge resonance curve when the tonearm has a decoupled counterweight.

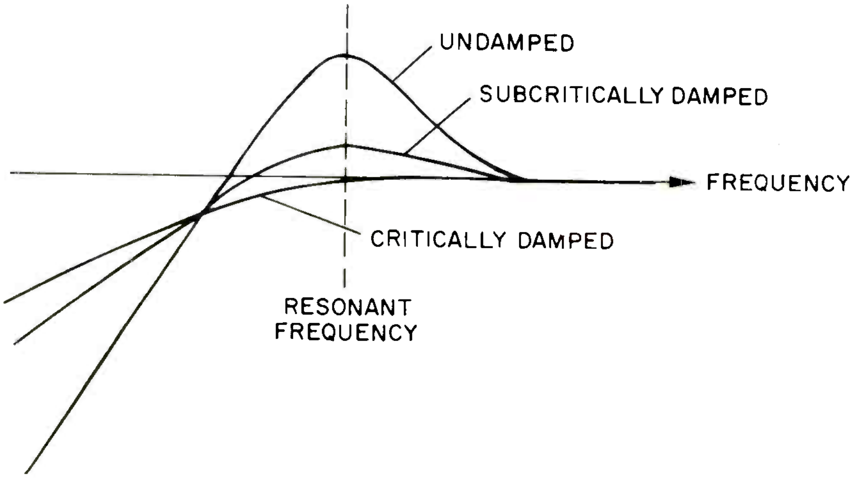


Fig. 16—Effect of bearing damping on tonearm-cartridge resonance.

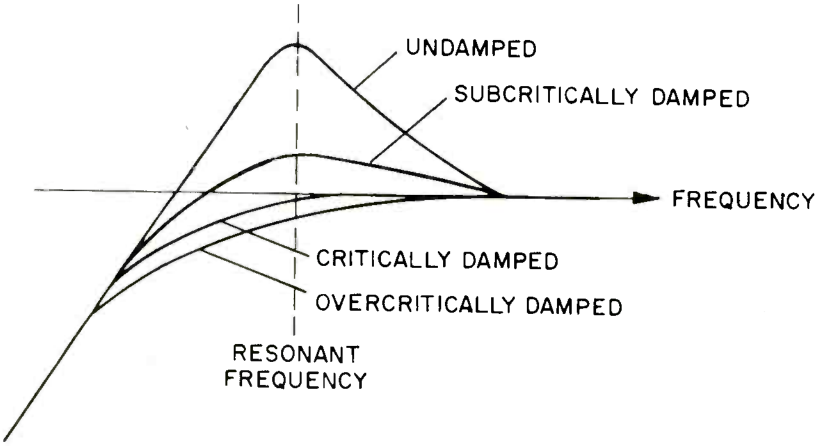


Fig. 17—Effect of damping which "tracks" the record on tonearm-cartridge resonance.

suspension tuned to the tonearm resonance, is shown in Fig. 15. There is a major advantage in that the peaks have smaller amplitudes, and at least the higher of the two resonances can be placed at a safe frequency near 15 Hz. The disadvantage is that the lower resonance extends the system response below that of the conventional arm, although damping can be added to prevent this. It can be seen, however, that critical matching between the tonearm, the counterweight, and the cartridge is required for the system to function correctly.

The case where the resonant frequency of the absorber is well below that of the main mass is unlikely to occur, because it implies a counterweight suspended more flexibly than can be tolerated in a practical tonearm.

If the resonant frequency of the absorber is well above that of the mass, the mass will begin to oscillate in the frequency region where the absorber is rigidly connected to the mass. Main resonance effects are therefore unaltered. At the higher absorber resonant frequency, the mass remains still so that no forces exist to move the absorber. The net result is a system identical to the single mass system.

Many tonearms with decoupled counterweights have a stiff rubber suspension, providing a resonant frequency appreciably higher than the tonearm resonance. Such arms are obviously not helped by counterweight decoupling but, in fact, may add to unpredictable and undesired resonances in the audio bandwidth. This is always a danger with any flexible member in a tonearm.

Tonearm Damping

Damping in a tonearm is usually applied at the bearing in the form of a piston moving in a viscous fluid. This form of damping applies a force proportional to the velocity of tonearm movement and opposes the movement. The out-of-phase movement at resonance is reduced at the cost of an extension of response below resonance. This means that the damped tonearm is more difficult to move below the resonant frequency, as shown in the response curves of damped and undamped tonearms of Fig. 16.

Another method is to apply damping between the tonearm and the record. A pad or brush which tracks the record is connected to the rest of the tonearm through a viscous link. If this method is used with a "critical" amount of damping, the tonearm resonance peak is removed without any extension of response below resonance. Critical damping is the amount that is just sufficient to flatten the resonant peak, but not so much as to cause a fall in response curve above the resonant frequency. Response curves for various amounts of damping are shown in Fig. 17.

Theoretically this is the ideal condition, but in practice it may function less than perfectly. This method is dependent on the tracking of the member resting on the record surface, which can add its tracking forces to those of the stylus and effectively change the tracking conditions for the

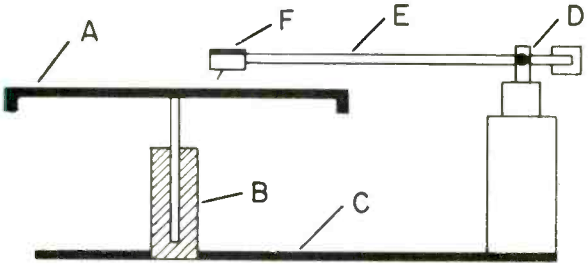


Fig. 18—Possible points of resonance (see text).

cartridge. It can also add resonances of its own or alter the frequencies and amplitudes of other resonances, which can be even less desirable.

Other Resonances

In discussing other resonances, it is insufficient to analyze the tonearm in isolation. Extending the argument stated in the introduction, it can be seen that undesirable signals can be generated due to any relative movement between the turntable platter and the tip of the tonearm (the cartridge is still assumed to be perfect). For example if the turntable platter does not run true, it will move up and down for every half-rotation. The effect is the same as a warped record.

Less obvious sources of relative movement are resonances, shown in Fig. 18, in the chain from the platter (A), the spindle and its bearing (B), the bearing support and its connection to the tonearm support (C), the tonearm bearings (D), the tonearm tube (E), and finally the mounting surface at the end of the tonearm (F).

No known material, either metal or plastic, is completely rigid, and therefore in physical terms every material always acts like a spring. Rigidity of any component can be increased by increasing the thickness of material used or by using suitable shapes with the same amount of material. Increasing stiffness without altering the distribution or size of the masses raises the resonant frequency but does not affect the amplitude. Each component in the chain has mass, and increasing the amount of material used increases its mass. Increasing mass without altering the stiffness of the components lowers the resonant frequency, but at the same time decreases the amplitude for the same external oscillation force. Each mass together with the elasticity of the materials in the chain form a resonant system, and, together with other resonances in the system, a complex series of dynamic absorbers, or to use the correct expression, a vibrating system with multiple degrees of freedom.

Conclusion

Provided all the masses and coefficients of elasticity are known (they can be measured or calculated), the resonant system can be analyzed. It should be remembered that the only point of interest is the relative movement between the turntable platter (hence the stylus tip) and the end of the tonearm. Such an analysis is only the starting point in a tonearm design.

Resonances and other factors can be traded off against each other, and the best design will be the best set of compromises for a particular application. In the final analysis, the matching of the tonearm to the cartridge and to the rest of the system will play an equally important part in the overall system performance, as will the design of the tonearm itself. A