Pickup Tracking Error

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Misconceptions on the subject of tracking error are many, and recent articles have been sparse. The author presents a lucid analysis of tracking error and its effects upon distortion in phonograph reproduction.

THE PROBLEM of keeping a phonograph pickup tangent to the record grooves at different radii has been with us ever since manufacturers abandoned the cylinder player, a device in which the pivot of the overhead pickup was driven across the record by a feed screw. With disc records, tracking error constitutes a problem, and the reasons for it and the principles involved in its solution are here discussed.

Some years ago the most serious effect of tracking error was considered to be undue wear of the record. The tip of a steel needle loses its spherical shape after a few revolutions of the turntable and is ground to the form of a wedge, with its long axis lying along the groove. If the pickup then turns with respect to the groove due to change of tracking angle the needle tip is re-ground and abrasion of the groove walls is increased. There has been some disagreement as to the extent of this increase, but in any case a jewel stylus maintains its shape better, and turning the spherical tip in the groove does less harm. Record wear is therefore a minor matter in tracking considerations when jewel styli are used. Tone arm design even makes a degree of sacrifice in this direction (side thrust is allowed to increase) for the sake of other benefits.

The main result of tracking error in modern equipment is that the vibration axis of the pickup is turned from the groove, generating distortion. If the line from stylus to arm pivot is at an angle to the groove tangent, the stylus is also pressed against one groove wall more than the other. Extreme angles will cause an increase in record wear and in the chances of groove jumping. None of these effects was very noticeable on older phonographs because pickups were quite heavy and tracking distortion was relatively small compared to other types of distortion.

Side Thrust

Figure 1 shows the forces acting on the stylus under two conditions of tracking error. The stylus at rest is subject only to the weight of the pickup and support of the groove, and will always be seated correctly, no matter what the tracking angle. When the groove is moved past the stylus, however, the tip is subjected to two additional forces equal to each other in magnitude, the frictional force F_o of the groove which tries to drag the stylus with it in a tangential direction, and the force resisting F_o in a direction toward the pivot, shown as F_a. When the frictional pull of the groove and the resistance of the arm do not lie along the same line, a resultant side force is exerted on the stylus independent of groove modulation, either towards the center of the record, as at (A) in *Fig.* 1, or away from the center, as at (B). The slope of the groove walls directs some of this force upward, and so if pressure against the sidewall is great enough the stylus will climb towards and possibly over the top of the wall.

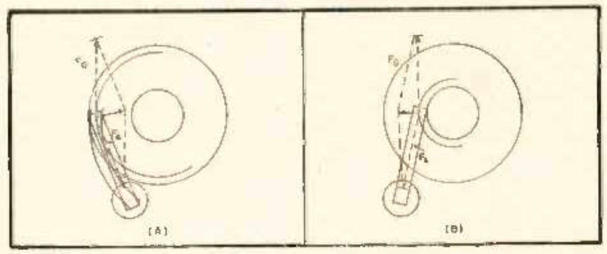

Fig. 1. Force components of side thrust on stylus.

The force resisting frictional drag of the groove is applied along the straight line from arm pivot to stylus, coupled from the pivot by means of the arm. Since the arm is rigid the direction of the line of force is formed by the stylus and pivot independent of the particular shape of the arm. The tendency of the stylus to ride up on the walls of the groove cannot, therefore, be made less by the use of a bent arm.

Contrary to occasional popular opinion this tendency is actually somewhat greater in offset arms, not because of their shape but because of the way in which they must be mounted. The imaginary line connecting the pivot and stylus of an offset arm makes a larger angle with the groove tangent than the corresponding line of a properly mounted straight arm. The greater the angle of offset the worse the offending nature of the pivot location in this respect, and the more the side thrust on the stylus. This is one of the reasons that studio-type offset arms are long, requiring only a small angle, even though an eight-inch arm with a larger angle may be designed to have almost negligible tracking error. The increased side thrust of bent arms is accepted as a far lesser evil than tracking error. Since the side thrust of bent arms is always directed toward the center of the record, a moderate amount serves to overcome frictional resistance of the arm pivot.

Tracking Error Distortion

It is evident that an arm which maintains tangency well due to its offset design may actually produce more side thrust than an arm with greater tracking error, and distortion generated by non-tangency cannot be laid primarily at the door of improper seating of the stylus in the groove. Even if the arm holds the pickup at an angle to the groove tangent, the stylus may follow the groove convolutions without error. Stylus motion in an oblique, pickup however, will not be perpendicular to the groove, and instantaneous stylus displacement relative to the longitudinal axis of the pickup will not correspond to the recorded signal. *Figure* 2 shows consecutive positions of styli in two identically modulated grooves. In (A) there is no tracking error. Displacement of the stylus relative to the pickup, plotted against time, is a copy of the groove's wave form. In (B), with the stylus tip still following the groove, a tracking error of α results in a distorted shape of the same graph. As can be seen, maximum stylus displacement relative to the center line of the pickup occurs first too soon and then too late within the recorded period. Maximum stylus displacement across the pickup is also greater in amplitude than maximum displacement relative to the center line of the groove.

This effect is aggravated when groove modulations are heavier or closer together. The distortion generated is therefore inversely proportional to groove radius and turntable r.p.m., and directly proportional to the amplitude and frequency of the recorded sound.

Another source of possible tracking

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distortion is the offset angle of the cartridge in bent arms[1]. The force trying to carry the stylus away from the arm pivot tends to turn a swivel-type stylus assembly to face the pivot. But the cartridge held by a bent arm cannot, by the nature of its mounting, ever face the pivot. Thus the lateral position of the stylus following an unmodulated groove is not along the center line of the cartridge, and the stylus at lateral rest is not at the center of its normal play. *Figure* 3 illustrates this angular bias in a pickup and in an analogous system made up of two linked rods.

The amount of bias is directly proportional to the compliance of the coupling between stylus and pickup and to the angle of offset of the cartridge. It will become significant only if the moving element of the cartridge is driven into a non-linear region of operation, in which case asymmetrical or even-harmonic distortion is generated. It is far less consequence than the first type of tracking distortion, or offset arm design would offer no advantage, but it constitutes a second reason for making offset arms as long as possible and with a small angle.

Arm Design and Mounting

The approximate solution to the tracking problem is to use a tone arm as long as can be afforded, to locate the pivot in that position which produces the least variation of angle between arm and groove (ignoring the absolute values of the angles) and to then offset the pickup from the arm to bring the center line of the cartridge or element to tangency with the grooves at selected radii. The most popular misconception about the offset arm is the belief that it is the bend in the arm which produces the reduction in tracking angle variation, due to a "virtual pivot" or other fancied cause. The variation in groove-pickup angle for any arm of given length, mounted at a specified point, must be the same whether the arm is straight, bent, or shaped like one of the snakes of an ancient Egyptian head-dress. This becomes clear if we think of a bent arm forming a rigid triangle with the line from pivot to stylus. The angle between this line and grooves of different radii, representing the tracking of a straight arm, must vary exactly the same amount as the angle between the grooves and the offset pickup. Improvement in tracking can only result from the shift in pivot mounting which the offset allows us to make.

It is possible to choose a mounting point for a given arm such that the arc swept across the record intersects the grooves with minimum variation of angle. *Figure* 4 shows the arcs produced by the same arm from different pivots. Considering only the variation in angle at which the arc encounters each groove it will be seen that arc 3 has the best tracking. The graph of tracking angle versus radius indicates that arcs 1 and 2 decrease their angles of intersection with each groove as they approach the center, while arc 3, representing a position of the pivot which "overhangs" the stylus past the turntable spindle, decreases its intersecting angle only up to a minimum point and then increases the angle again as further progress toward the center is made. The fact that the intersecting angle goes through a minimum point means that for some angle values before the minimum there will be an equal value after the minimum.

It would not be feasible to mount a straight arm to sweep arc 3, because although the variation in angle is small the actual angle at which the pickup would be held is far from the tangent. A positional bias is therefore applied to the pickup element by offsetting it β. We have already seen that the variation in intersecting angle is independent of arm shape, and so we will not lose the advantage of minimum variation by this offset, while we gain correction by this method for the absolute value about which the tracking angle varies.

Zero tracking error may be achieved at two points: at the groove for which the offset makes a perfect correction, and at its mate on the other side of minimum. The points of zero tracking error (determined by the angle of offset) and the groove radius at which the minimum intersection angle occurs (determined by the pivot mounting) are adjusted for optimum performance. These adjustments are concerned with keeping $\frac{\alpha}{r}$ rather than α alone as small as possible.

Tracking Equations

The tracking equations of most interest are those which furnish information on optimum offset angle, correct pivot mounting for a given arm, and the tracking error and distortion of a given system. B. B. Bauer[2] has derived general forms of some of the foregoing equations in a clear and interesting article to which the reader is referred. The equations below apply only to twelve-inch records, and have had small decimals of no significance dropped.

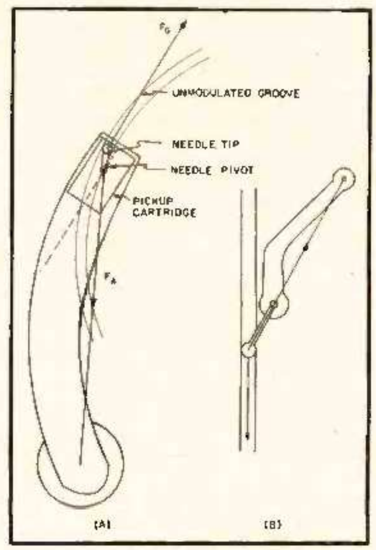

Fig. 3. (A) Pickup bias due to cartridge offset, and (B) analogous mechanical system illustrating pickup bias.

Optimum offset angle β for an arm of length l inches (pivot to stylus tip) is:

$$\beta = \frac{179}{l} \text{ degrees}$$

The overhang D (the distance from spindle to stylus) of such an arm, or of an arm with a larger angle of offset (some designs have considered minimum tracking error without reference

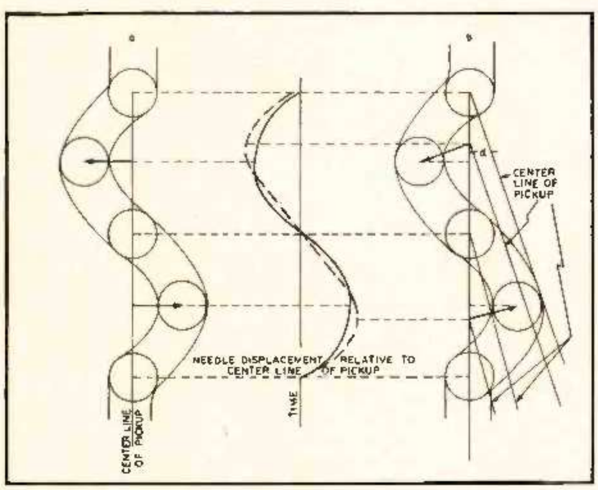

Fig. 2. Distortion caused by tracking error arrows indicate maximum stylus displacement relative to pickup.

[1] G. A. Briggs, *Sound Reproduction*, 2nd ed., Wharfedale Wireless Works, Bradford, Yorks. Quote on page 206 from a paper by W. J. Lloyd.

[2] B. B. Bauer, "Tracking angle in phonograph pickups," *Electronics*, March 1945, p. 110.

to the need for better tracking at the inner grooves) should be:

$$D = .9\left[\frac{\beta}{57.3} - \frac{1.8}{l}\right]\left[\sqrt{1 + \frac{(\beta/57.3)^2}{(\beta/57.3 - 1.8/l)^2}} + 1\right] \text{ inches}$$

and when β is equal to the optimum $\left[\frac{179}{l}\right]$ deg., the expression simplifies to:

$$D = 4.2/l$$

The equations for D are inaccurate for arms whose angle of offset is less than the optimum β. For arms in which β is between 2/3 of optimum and optimum we must change the expression to:

$$D = 2.9\left[\frac{5.8}{l} - \frac{\beta}{57.3}\right]\left[\sqrt{1 + \frac{(\beta/57.3)^2}{(5.8/l - \beta/57.3)^2}} - 1\right]$$

And for arms whose offset angle is less than 2/3 of optimum we use:

$$D = \frac{.013\beta - \frac{1}{l}}{.36}$$

The equation for a straight arm, with β equal to zero, becomes:

$$D = -\frac{1}{.36\,l}$$

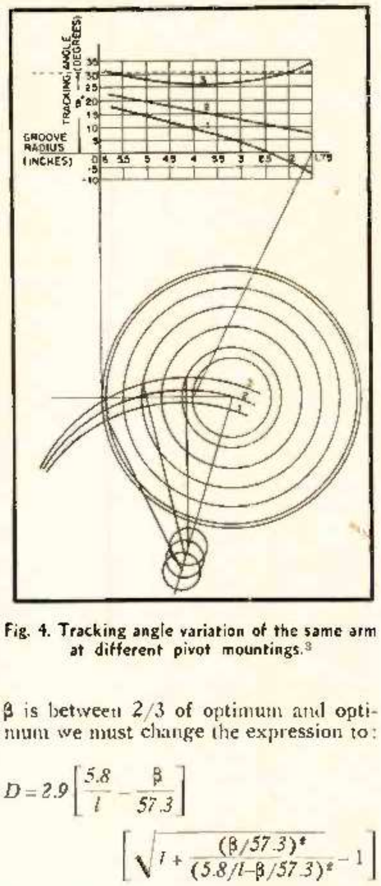

Fig. 4. Tracking angle variation of the same arm at different pivot mountings.[3]

[3] Values from Ralph P. Glover, "A record saving pickup," *Electronics* Feb. 1937, p. 31.

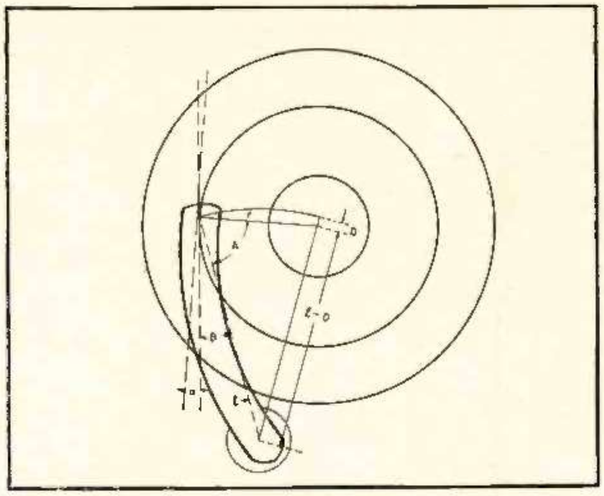

Fig. 5. Basic oblique triangle used in determining tracking characteristics.

As would be expected from the tracking curves of *Fig.* 4 optimum mounting of the straight arm requires that the needle be underhung by an amount which places the point of perfect tracking at the inner grooves.

The tracking error α of a given system at a groove of radius r is equal to:

$$\alpha = \sin^{-1}\left[\frac{r^2 + 2\,l\,D - D}{2lr}\right] - \beta$$

The derivation is simple and interesting enough to be included in the appendix. Maximum α over the record may be found by checking at the three radius values at which maximum error could occur: the inner groove, the outer groove, and the groove at which the angle of intersection with the arc of the tone arm reaches a minimum and begins to increase again. Tracking error at the first two points is found by using 1.75 inches and 5.75 inches, respectively, for the value of r. The radius at the third point can be solved for after setting the partial derivative $\frac{\partial\alpha}{\partial r}$ equal to zero, and is equal to:

$$r_3 = \sqrt{D(2l - D)}$$

The main tracking distortion is second harmonic. On a basis of stylus velocity change, the per cent distortion is:

$$H = \left[\frac{1.05\,fA\alpha}{Vr} \times 100\right] \text{ per cent}$$

where f = frequency of the signal in cps
A = amplitude of maximum groove modulation in inches (.004 inches at 250 cps would be typical of 78 r.p.m. commercial records containing loud passages.)
α = tracking error in degrees
V = r.p.m. of turntable
r = radius of groove

The tracking distortion produced in a standard commercial pressing by a properly mounted 8-inch straight arm (17-deg. maximum error at the outer grooves, 8-deg. maximum at the inner) may be expected to be of the order of 6 per cent on loud passages. A correctly designed offset tone arm of the same length will reduce the tracking error and the distortion by a factor of six.

APPENDIX

From the trigonometric formula for oblique triangles (see *Fig.* 5):

$$(l - D)^2 = l^2 + r^2 - 2\,l\,r\cos A$$

$$\angle A = \cos^{-1}\left[\frac{r^2 + 2\,l\,D - D^2}{2\,l\,r}\right]$$

$$\angle A + \angle\beta \pm \angle\alpha = 90°$$

$$\alpha = (90° - A) - \beta$$

$$\alpha = \sin^{-1}\left[\frac{r^2 + 2\,l\,D - D^2}{2\,l\,r}\right] - \beta$$

The ability of a pickup and tone arm to maintain good stylus-groove contact is often referred to as tracking capability, and the weight required to keep the stylus properly seated is called tracking pressure. These expressions would seem to have something to do with pickup tangency, but they do not. Stylus seating at normal tracking errors is almost independent of tangency. The term "tracking" is used in two different ways in relation to tone arms: it has a literal meaning which relates to seating of the stylus in the track of the groove; and a technical or mathematical one, which refers to maintenance of a constant tangency relationship between two variables, the pickup axis and the groove at the point of stylus contact. In the latter application the word is used in the same way as when it describes the behavior of one section of a variable capacitor, which "tracks" or keeps a constant capacitance relationship to another section with which it is ganged.