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Determination of Sliding Friction Between Stylus and Record Groove*

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A method is presented for determining the coefficient of sliding friction between stylus and record groove. The method consists of measuring the time intervals required for a freely rotating record (on a turntable) to decelerate from one known speed to another, both with and without a stylus sliding in the record groove. The method has been used to evaluate the frictional characteristics of several brands of phonograph records in mint condition and after treatment with various preservatives, cleaners, and antistatic agents. Some test results are presented.

0 INTRODUCTION

The development and evaluation of preservative coatings for phonograph records required tests that would accurately indicate the condition of the record-groove surfaces with regard to wear susceptibility and frictional characteristics. The wear test consisted of simply 100 plays on a record, followed by visual examination for wear debris and audio evaluation or signal distortion testing for playback quality. For frictional characteristics a "spin-down" test was refined into a procedure which would permit the determination of the coefficient of sliding friction μ between stylus and groove.

Although the usefulness of a low rate of record-groove wear is obvious, the usefulness of low stylus/groove friction may not be. Intuitively one might guess that lower frictional drag would result in more accurate tracking by the stylus of the groove contour features and, therefore, would yield improved playback fidelity, especially at higher frequencies. Whyte [1] reported such an effect for an experimental lubricant without knowing the extent of friction reduction provided by the lubricant. Hunt [2], while estimating that the stylus/groove coefficient of friction would be 0.2–0.5, suggested that stick-slip-friction-induced noise would be reduced by lowering frictional drag through lubrication, choice of materials having lower interfacial adhesion, or reduction of stylus loading.

In addition to friction effects on noise and fidelity, its effect on the skating force has been considered by Bauer [3] who estimated that a μ value of 0.25 would be typical, and by Kogen [4] who evidently calculated stylus/groove friction forces from measured skating forces, although no μ values were presented.

The skating force is proportional to the friction force and is a function of the groove radius (the distance from record center to stylus position) and geometrical relationships peculiar to each turntable/tone-arm design [4]. The modern phonograph turntable provides an adjustable antiskating torque at the tone-arm pivot and requires only the stylus load as the torque determinant, since the friction force is proportional to the stylus load. This means that the antiskating compensator design must assume specific values of groove radius and stylus/groove coefficient of sliding friction. Presumably some intermediate groove radius would be assumed, but what level of friction coefficient? The assumed μ level would be of interest, for example, to someone who has treated records with an effective record preservative providing a low μ. If the assumed design μ level was 0.30 and the records show 0.15, half the recommended antiskate setting should be applied for more optimum stylus tracking.

Shiga [5] considered the effect of friction in a mathematical analysis of distortion due to groove-wall deformation; and Barlow and Garside [6] measured μ values of styli sliding on flat plastic surfaces in a very thorough investigation of factors affecting play-

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back distortion. Evidently using the floating tone-arm design of Rangabe [7], they measured μ values on flat nylon of 0.16–0.21 and on flat vinyl of 0.24–0.36. Rangabe [7] measured drag forces of a stylus sliding in the grooves of various records; and using his stylus force of 3 g, the drag forces yield μ values ranging from 0.18 to 0.30. These are evidently the only published experimental data for stylus/groove friction, and their measurement required the use of a special tone-arm apparatus not commonly available.

The present paper describes a straightforward method for determining stylus/groove μ values using a belt-driven turntable. The method could be useful for studying μ as a function of such parameters as stylus load, stylus-tip geometry, groove radius, modulation level, and record composition. It has been used to evaluate frictional characteristics of experimental and commercially available record treatments: preservatives, cleaners, and antistatic agents. Some illustrative results are presented.

1 TEST METHOD

The principle utilized in this test is that a freely rotating turntable with phonograph record will exhibit a uniform rate of deceleration when subjected to the frictional torque drag of either (1) the center spindle bearings, or (2) spindle bearings plus stylus sliding in the groove for a few revolutions. By measuring or calculating the moment of inertia of the total rotating system (turntable, mat, and record) and establishing several testing parameters, one can derive a formula for calculating the coefficient of sliding friction between stylus and record groove. The testing parameters are stylus load (grams), the initial and final turntable angular velocities (radians per second) as deceleration bases, and the mean radial distance from record center to groove where the stylus slides during the turntable's deceleration from initial to final selected base velocities. Two other constants required are the groove cross-section angle (current standard is 90°) and the acceleration due to gravity (981 cm/s^2) to convert grams of stylus load (mass unit) to a unit of force (g-cm/s^2).

The friction test is conducted in two parts: first, by removing the drive belt, mounting the test record on the turntable, spinning the turntable by hand to 45 r/min (1.5π rad/s), and measuring the time required for the speed to decelerate to 33½ r/min (1.11π rad/s) through drag action of the spindle bearings alone; and second, by hand-spinning the turntable again, engaging the stylus in the groove; and measuring the time required for the speed to decelerate from 45 to 33⅓ r/min through the combined frictional drag of bearings and sliding stylus.

The coefficient of friction is then calculated by entering parameters, constants, and measured deceleration times into the following general formula:

$$\mu = \frac{I(W_1 - W_2)\sin(\theta/2)}{gNR}\left(\frac{1}{t_T} - \frac{1}{t_B}\right) \tag{1}$$

where

- I = moment of inertia of total rotating system, g-cm^2
- W_1, W_2 = angular velocities (rad/s) of turntable at initial and final bases for deceleration time interval measurement
- θ = groove cross-section angle (standard angle = 90°)
- g = acceleration due to gravity (981 cm/s^2)
- N = stylus load, grams
- R = mean distance (cm) from record center to groove where stylus slides during record's deceleration from W_1 to W_2
- t_T = time (seconds) required for record to decelerate from W_1 to W_2 with stylus sliding in groove
- t_B = time (seconds) required for the W_1-to-W_2 deceleration without stylus in groove

The derivation of the friction formula (1) and the determination of the moment of inertia are presented in the Appendix. Since the quotient term is constant for friction tests at a given stylus load on any given groove section of a record, the calculation of the coefficient of friction becomes a matter of multiplying that constant by the difference in reciprocal deceleration times. Typically t_B is about 23–27 s for a Yamaha YP-450 turntable, depending on the degree of bearing warmup before testing, and t_T, 10–16 s. The total moment of inertia is approximately 186 000 g-cm^2 for the combination of a typical 12-in (0.3-m) LP vinyl record and the Yamaha YP-450 turntable platter. Both t_T and t_B are measured at least six times for each test, and average values are used to calculate μ. The sensitivity of the method has been found to yield values of $\mu \pm 0.01$.

The turntable speeds of 45 and 33⅓ r/min are convenient to use for deceleration bases since they are easily measured by stroboscopic marks on many turntables, utilizing the turntable's own strobe light or a fluorescent lamp for illumination. Where the turntable is not strobe marked, label-size strobe disks are available to slip on the spindle over the record. If significant, the moment of inertia of such a disk should be added to that of the turntable, mat, and record.

Usually the first groove section following lead-in is the easiest to use for stylus–groove friction testing. Coordinating initial turntable speed (45 r/min) with the stylus sliding near the start of that groove section—or at the start of any preselected groove section—requires a little technique which experience will bring.

2 RESULTS

Some friction test results obtained using the described method are presented in Tables 1 and 2.

The record preservatives in Table 1 are seen to vary widely in their friction-reducing properties. None of those tested caused the stylus/groove coefficient of friction to increase, but the commercial product E and the experimental product I produced no significant effects on friction. In contrast, commercial D and experimental G, H, and J produced substantial friction reductions, enough to warrant downward adjustments in the antiskate setting if the antiskate compensator were designed for μ values of 0.25–0.30.

The comparisons in Table 2 show that thoroughly cleaning a record with detergent solution will, in most cases, cause an increase in friction, sometimes a large increase. And the cleaning effect appears to vary from one brand of record to another. For example, cleaning had essentially no effect on μ of brands B and E; caused a slight μ increase on brands F and G; and caused rather large μ increases on brand C. Brands A and D exhibited mixed effects, with their μ values tending to increase as a result of cleaning. However, one brand-A record showed an increased μ on one side and a decreased μ on the other. Although no investigation was made of the effects of modulation frequency or amplitude on frictional drag, the possibility that such effects might be involved in the frictional difference between sides 1 and 2 of the one record A was considered. This difference did not appear after cleaning; hence modulation was probably not a factor. Nevertheless the matter deserves to be studied.

Table 1. Effect of various record preservatives on stylus/groove friction (Shibata stylus at 1.5-g load).

Record Preservative	Coefficient of Friction: Record in Mint Condition	Coefficient of Friction: Treated Record
Commercial		
A	0.33	0.23
B	0.30	0.23
	0.31	0.25
	0.34	0.27
C	0.31	0.29
D	0.29	0.14
	0.28	0.17
	0.30	0.18
E	0.29	0.29
F	0.30	0.21
Experimental		
G	0.33	0.11
H	0.35	0.18
I	0.34	0.34
J	0.30	0.15

Table 2. Effect of record cleaning on stylus/groove friction (Shibata stylus at 1.5-g load).*

Record Manufacturer	Side	Coefficient of Friction: Mint Condition	Coefficient of Friction: After Cleaning
A	1	0.27	0.29
	2	0.26	0.29
A	1	0.38	0.40
	2	0.43	0.39
B	1	0.34	0.34
C	1	0.24	0.34
C	1	0.28	0.64
D	1	0.29	0.30
D	1	0.28	0.36
	2	0.28	0.37
E	1	0.27	0.27
F	1	0.26	0.29
F (white record)	1	0.22	0.23
G [7 in (178 mm) /45 r/min]	1	0.15	0.19

* Cleaning procedure: Using washable velvet, wiped playing surface with groove-tracking arcs while surface was flooded with phosphate detergent solution (designed for lab glassware). Rinsed with tap water. Quickly blew dry with dry nitrogen gas.

The μ variation from one mint record to another reflects differences in composition, mold release (if any), and condensable vapors in the atmospheres of the various manufacturing facilities. The removal of lubricative record-surface deposits by cleaning is believed to cause the observed increases in stylus/groove friction. Lower-than-average friction values were exhibited by the white-pigmented record of brand F and the polystyrene injection-molded record of brand G.

3 CONCLUSION

A simple method for determining the coefficient of sliding friction between stylus and record groove has been devised and is suitable for studying the friction effects of various playback parameters. The method can utilize any belt-driven turntable/tone-arm assembly from which the turntable platter can be removed in order to measure its moment of inertia.

4 REFERENCES

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APPENDIX A

A.1 Derivation of the Stylus/Groove Friction Formula

1) The total torque T_T acting to slow a freely rotating turntable involves (a) the sliding-friction torque of

the stylus sliding in the record groove T_S plus (b) the rolling/sliding-friction torque of the spindle bearings T_B,

$$T_T = T_S + T_B . \tag{2}$$

2) The total torque acting to slow the turntable is the product of the moment of inertia I of the total rotating system and its deceleration rate α_T,

$$T_T = I\alpha_T . \tag{3}$$

Without the stylus sliding in the groove, the turntable will decelerate at a slower rate α_B due to the drag torque bearings alone T_B,

$$T_B = I\alpha_B . \tag{4}$$

Substituting Eqs. (3) and (4) in Eq. (2),

$$I\alpha_T = T_S + I\alpha_B . \tag{5}$$

The deceleration rate due to the stylus/groove friction cannot be measured independently of deceleration due to the spindle bearings. Therefore T_S must be determined by difference,

$$T_S = I\alpha_T - I\alpha_B = I(\alpha_T - \alpha_B) . \tag{6}$$

3) In terms of the stylus–groove friction force f or the coefficient of friction μ,

$$T_S = fR = \mu nR \tag{7}$$

where n and R are the stylus force normal to the groove walls and the torque radius, respectively.

4) Combining Eqs. (6) and (7),

$$\mu nR = I(\alpha_T - \alpha_B)$$

$$\mu = \frac{I}{nR}(\alpha_T - \alpha_B) . \tag{8}$$

5) Resolving the forces between stylus tip and groove walls having an included angle of ϕ,

$$\text{stylus force (vertical)} = n \sin\frac{\phi}{2} .$$

Converting from force to mass, that is, stylus weight or load as measured N,

$$gN = n \sin\frac{\phi}{2}$$

or

$$n = \frac{gN}{\sin(\phi/2)} \tag{9}$$

where g is the acceleration due to gravity (981 cm/s^2).

6) Deceleration rates can be determined by measuring the time t required for the turntable to slow from one speed W_1 to another, W_2. Without stylus sliding,

$$\alpha_B = \frac{W_1 - W_2}{t_B}$$

and with stylus sliding,

$$\alpha_T = \frac{W_1 - W_2}{t_T} .$$

The difference term in Eq. (8) then becomes

$$\alpha_T - \alpha_B = \frac{W_1 - W_2}{t_T} - \frac{W_1 - W_2}{t_B}$$

$$= (W_1 - W_2)\left(\frac{1}{t_T} - \frac{1}{t_B}\right) . \tag{10}$$

Substituting Eqs. (9) and (10) into Eq. (8) yields Eq. (1):

$$\mu = \frac{I(W_1 - W_2)\sin(\phi/2)}{gNR}\left(\frac{1}{t_T} - \frac{1}{t_B}\right) .$$

A.2 Determination of Moment of Inertia

Few turntable geometries lend themselves to a mathematical calculation of the moment of inertia, as do records, turntable mats, and strobe disks. For disks, cylinders, and other uniform bodies of rotation, the moment of inertia can be calculated from the formula

$$I = mr^2 \tag{11}$$

where

I = moment of inertia, g-cm^2
m = mass of the body, grams
r = radius, centimeters

If the disk or cylinder has a hole in its center (axis of rotation) having a significant radius, the formula becomes

$$I = m(r_1^2 + r_2^2) \tag{12}$$

where r_1 and r_2 are the inner and outer radii of the body. Standard 12-inch phonograph records, turntables, and mats do not have a hole of significant radius.

Unless the moment of inertia of the turntable can be obtained from the manufacturer or calculated (possibly by considering the turntable as an assembly of two or more geometrically ideal disks and cylinders whose radii can be measured and masses calculated), the moment of inertia of the turntable must be determined experimentally. This is most easily carried out by measuring its period of oscillation while suspended by its center hole with a torsion spring. A straight piece of high-tensile-strength wire, such as piano wire, will serve as a torsion spring. For the test 1–2 m of wire will be needed, depending on its diameter (stiffness).

A metal disk with a small hole in its center can be used to calibrate the torsion spring. The disk should have a uniform geometrical shape so that its moment of inertia can be accurately calculated from either Eq. (11)

or (12). For best calibration, its moment of inertia should be in the same order of magnitude as that of the turntable.

A pin vise may be used to clamp the lower end of the wire. It should be large enough to support the metal calibration disk and small enough in relation to the disk's hole so that the nose of the pin vise will wedge into the disk's hole for a snug, nonslip fit. A more secure method is to use a bolt (or threaded rod) with a hole through its center for the wire. The disk with the bolt-sized hole could then be secured between the nut and bolt head (or between two nuts). The end of the wire should be doubled back into the hole (and around a short rod or pin) to support the load on the bolt.

A vise or similar secure means may be used to clamp the upper end of the wire. It is essential that the upper end of the wire be firmly fixed in place without slippage in its holder and without movement of the holder.

The procedure for experimental determination of the turntable's moment of inertia is then carried out by the following steps:

1) Set the calibration disk in oscillatory motion and, with a stopwatch, measure the time required for ten or more cycles. Calculate the average period (time for one cycle).

2) Mark the wire at its upper end where it is clamped by the vise jaws. Then remove the wire's upper end from the vise and thread it through the turntable hole, lowering the turntable to rest concentrically on the calibration disk. To provide the maximum rotational friction between the two, the turntable should rest upside down on the disk. Now reclamp the wire's upper end in the vise at the same place as before. This is to ensure that the wire's torsional length is the same in both oscillatory tests.

3) Set the combined mass (calibration disk plus turntable) in oscillatory motion, again measure the time for ten or more cycles, and calculate the average period.

4) Calculate the turntable's moment of inertia as follows:

$$I_T = \frac{I_D (P_C^2 - P_D^2)}{P_D^2} \qquad (13)$$

where

I_T = turntable's moment of inertia, g-cm^2
I_D = calibration disk's moment of inertia, g-cm^2 (calculated)
P_C = period of oscillation for the combined mass of turntable and calibration disk, seconds
P_D = period of oscillation for the calibration disk alone, seconds

The turntable should be the belt-driven type. By disengaging the belt from the drive spindle, the turntable will turn freely without the slowing effects of electromagnetic field interactions associated with a direct-drive turntable. Also, the method of calculating the coefficient of friction in Eq. (1) assumes that the turntable spindle's moment of inertia is negligible or is included in the total. The assumption of negligibility would introduce an error of unmeasurable magnitude in the case of a direct-drive turntable. However, even if the moment of inertia of the drive-motor rotor could be measured or supplied by the manufacturer, the electromagnetic slowing effects would reduce t_B and t_T and thereby reduce precision of the computed coefficient of friction when compared with friction determined on a freely rotating turntable of equal moment of inertia.

THE AUTHOR

Robert P. Pardee was born in Atlanta, Georgia, in 1923. He studied at the Georgia Institute of Technology, earning a B.S. degree in chemical engineering in 1943. His graduate work was done at the University of Colorado where he received an M.S. in chemical engineering. His work experience began with Texaco Research Labs in lubricant and additive development. He later worked for the Jet Propulsion Laboratories in Pasadena and, subsequently, for Sandia Corporation in the area of lubrication engineering. In 1970 he joined Ball Aerospace Systems where he concentrates on materials engineering and development of phonograph record-care products.

Mr. Pardee has 11 U.S. patents in the fields of metal-working lubricants, glass-mold release agents and protective coatings for movie film and phonograph records. The author of articles published in technical journals, he is a member of the American Society of Lubrication Engineers, the American Association for the Advancement of Science, the Institute of Environmental Sciences and Tau Beta Pi Honorary Engineering Society.

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LETTERS TO THE EDITOR

COMMENTS ON "DETERMINATION OF SLIDING FRICTION BETWEEN STYLUS AND RECORD GROOVE"

The author of the above Engineering Report[1] has developed a simple method of measuring the mean frictional drag over a number of record grooves without the need for special equipment. In contrast, Rangabe and Snell[2] used a modified floating arm to measure instantaneous values of drag. Two points are worth noting. First, the frictional drag may vary by as much as 3:1 in an irregular manner over a given record (Table 1). Second, on modulated grooves, the drag depends on the cartridge used (Fig. 1). This is mainly due to the mechanical damping in the pickup suspension.

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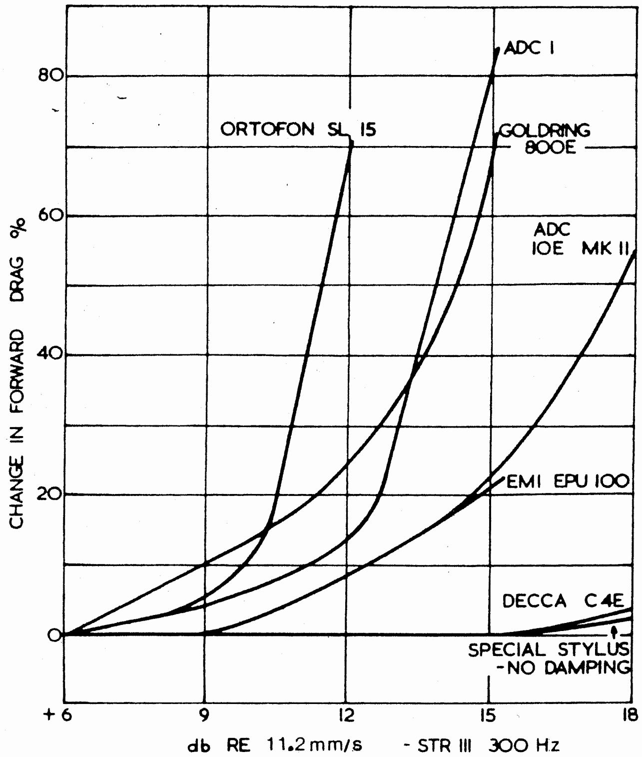

Fig. 1. Change in drag versus modulation velocity.

Table 1

Record	Effective Drag Coefficient* Minimum	Maximum	Estimated Average
Decca SXL 2193	0.35	0.75	0.40
Decca SXL 2261	0.35	0.60	0.40
Decca SXL 2154	0.30	0.42	0.35
Decca SXL 6202	0.45	0.55	0.45
Decca SXL 6379	0.40	0.50	0.42
Decca SET 323	0.35	0.50	0.35
Decca SXL 6215	0.35	0.90	0.40
Decca SET 311	0.35	0.50	0.45
DGG SLPM 138025	0.27	0.45	0.30
DGG LPM 18857	0.35	0.45	0.40
DGG SLPM 138645	0.35	0.45	0.35
EMI ASDF 217	0.30	0.32	0.30
SUPRAPHON PLP (s) 132	0.30	0.90	0.35
SUPRAPHON SUAST 50486	0.23	0.275	0.27
SUPRAPHON SUAST 50519	0.30	0.40	0.35
Record Society RS32	0.35	0.65	0.40
SAGA STXID 5248	0.27	0.35	0.30
SAGA STXID 5079	0.35	0.55	0.40
AMADEO AVRS 5034	0.30	0.55	0.35
URANIA US5702	0.33	0.40	0.35
EVEREST SDBR	0.43	0.65	0.47
PHILIPS 835-507AY	0.43	0.90	0.50

* Forward drag/playing weight. Special stylus without damping.

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AUTHOR'S REPLY

I am indebted to Dr. Barlow for bringing to my attention the work of Rangabe and Snell concerning the measurement of instantaneous stylus/groove frictional drag on a variety of phonograph records and the evaluation of mechanical damping properties of several cartridges.

All of the stylus/groove friction data presented in my paper were obtained with the use of a Bang & Olufsen model MMC 5000 cartridge having an integral Shibata stylus. Its mechanical damping properties were not evaluated. However, comparison of the friction data in my Tables 1 and 2 (after converting to the drag coefficient by the factor $\sin^{-1} 45°$) with the friction data quoted in Dr. Barlow's Table 1 permits a qualitative estimation. The two friction data sets compare as follows:

	Drag Coefficient	
	Rangabe and Snell	Pardee
Range of average values	0.27–0.50	0.31–0.61
Overall average	0.38	0.43

Assuming that the surface conditions and modulation velocities of the two groups of records are roughly equivalent, observed differences in frictional drag must be ascribed to differences in the damping properties of the two cartridges used in the tests. On this basis, the Bang and Olufsen cartridge appears to have some degree of mechanical damping since it yields average drag coefficients about 13% higher than those obtained by a cartridge exhibiting essentially zero mechanical damping, when each is subjected to a wide spectrum of modulation velocities.

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