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DEVELOPMENT OF A LIGHT LOAD FRICTION TESTER

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FOREWORD

This new tribometer measures friction characteristics of bonded dry film lubricants under light to moderate loads. Although this tester was designed specifically for loads of approximately 5 grams to several 100 grams, it operates satisfactorily at loads approaching 5 pounds. This apparatus, used as a friction coefficient measuring device, will yield performance data useful in comparing bonded lubricant formulas. As a research tool, it evaluates friction's variation with change in contact stress, contact load, and contact geometry. The authors believe that controlled experiments using this apparatus might reveal information needed to understand the true nature of bonded film lubrication.

DISCUSSION OF THE APPARATUS

The tribometer developed used J. Den Hartog's oscillating bar concept, modified to yield different methods of friction coefficient determination. Basically, the tribometer (Figure 1) consists of two rollers mounted on shafts driven by a motor in the same direction or in opposite directions according to the gear arrangement. Many possible operational modes exist.

DYNAMIC FRICTION, OSCILLATION MODE

With the rollers rotating in opposite directions, a lubricant-coated bar is placed off center on the rollers and released. If the roller speed is always sufficient to maintain slip the bar will oscillate in a harmonic motion until damped out. The dynamic friction coefficient is calculated as

$$\mu = \frac{H}{\left[\frac{gT^2}{4\pi^2} + h \right]} \quad (1)$$

Derivation of Equation (1)

$$\Sigma F = m\ddot{x} \quad (2)$$

$$\mu_l F_l - \mu_r F_r = \frac{W}{g} \ddot{x} \quad \text{if } u_l = u_r \quad (3)$$

$$F_r = \frac{W}{2} \frac{(H + x - \mu h)}{-(H - \mu h)} \quad (4)$$

Figure 1. Tribometer

Figure 2. Schematic of Tribometer During Oscillation Mode

$$F_1 = \frac{W}{2} \frac{(H - x - \mu h)}{(H - \mu h)} \quad (5)$$

Substitution of Equations 4 and 5 into Equation 3 gives

$$\ddot{x} + \frac{\mu g}{H - \mu h} x = 0 \quad (6)$$

Recognizing that the constant term of x in equation (6) is

$$w = \sqrt{\frac{\mu g}{H - \mu h}} \quad (7)$$

Where w is the natural frequency of this system

From Equation (7)

$$\mu = \frac{H}{\frac{gT^2}{4\pi^2} + h} \quad \text{and} \quad w = 2\pi/T \quad (8)$$

No damping term appears and its effect has been assumed to be negligible.

The error associated with neglect of damping may be evaluated as follows.

Using elementary vibration theory for systems with linear damping leads to

$$\mu_{\text{correct}} = \left[1 + \left(\frac{\ln \frac{x_1}{x_n}}{2n} \right) \right] \quad (9)$$

From experience with this apparatus $x_1 = 1.0$ inch, $x_n = .05$, and $n = 4$; thus the damping error is less than 2 percent if only four oscillations are observed.

To obtain an accurate friction coefficient value as determined by Equation (1) the proper time period T must be used. Since successive cycles may have different time periods, an averaging of several cycles might not reflect the true friction coefficient being sought. For example, such a case would arise if,

Figure 3. Plot of Equation 1

as bonded lubricant wore, the friction coefficient increased. To adequately compare films such as this, a time period measuring device must be used that records the time for each cycle and not the average time. This technique would permit comparison of films at equal wear conditions.

BEARING DYNAMIC FRICTION, OSCILLATION MODE

With test bearings installed in the rollers, the resulting bar motion will again be oscillatory. However, constant sliding occurs at the bearing radius, with constant rolling contact between bar and rollers. If the bearing friction coefficient is defined as the ratio of the tangential force at the shaft surface resisting rotation divided by the radial load applied to the bearing, the friction coefficient f is calculated as

$$f = \frac{2H_p}{r} \left[\frac{1 + \frac{2gJ}{W_p^2}}{\frac{gT^2}{2\pi^2} + 2h} \right] \quad (10)$$

DYNAMIC FRICTION, STATIONARY MODE

With both rollers rotating in the same direction, the friction forces will drive the bar toward one end. If the bar is restrained by a force measuring device the friction forces are directly determined. The dynamic coefficient of friction is calculated as

$$\mu_d = \frac{P}{W} \quad (11)$$

Figure 4. Plot of Equation 10

DYNAMIC FRICTION, TILT METHOD

The rollers turn in the same direction forcing the bar against a restraint. If the plate of the apparatus is tilted from a level position, the principle of the elementary inclined plane is used to evaluate the friction coefficient. The coefficient is calculated as

$$\mu_d = \tan \phi \quad (12)$$

Figure 5. Free-Body Diagram of Left Roller During Dynamic Tilt Method

BEARING DYNAMIC FRICTION, STATIONARY MODE

With the rollers rotating in the same direction, the force exerted against the bar is measured. The bearing friction is calculated as

$$f = \sqrt{\frac{1}{\frac{r_o^2}{2} \left[\left(1 + \frac{2wH}{WH-PZ} \right)^2 \frac{W^2}{P^2} + 1 \right]} - 1} \quad (13)$$

A bar-roller combination of high static friction coefficient must be used in this mode to avoid slip at the bar-roller interface.

BEARING STATIC FRICTION, STATIONARY MODE

Both shafts are prevented from rotating and a force measurement device is used to apply force to one end of the bar until the bar moves. The static friction coefficient is calculated by the same relationship as for the corresponding dynamic case.

BEARING FRICTION MEASUREMENT, TILT METHOD

The rollers are turned in the same direction to drive the bar against a restraint at one end and the tester platform is slowly tilted until the bar moves away from the restraint.

The rotating friction coefficient of the bearings may be calculated from

$$f = \sqrt{\frac{1}{r^2 \left(w + \frac{W}{2} + \frac{Wh}{2H} \cdot \tan^2 \phi \right) + \frac{2 \tan^2 \phi \left(\frac{W}{2} \cos \phi + \frac{Wh}{2H} \sin \phi \right)}}} \quad (14)$$

STATIC FRICTION, RATIO METHOD

The limiting value of the static coefficient of friction may be found by disconnecting one of the driving rollers, and slowly rotating the disconnected roller in opposition to the other (rotating) roller so as to determine the extreme position of the bar, the point at which the static and dynamic friction forces are equal. The motion of the bar should be at a constant velocity so the acceleration force is zero.

Consider the left roller to be in static contact, and the right roller sliding,

$$\mu_{SL} = \mu_{dR} \frac{H + x}{H - x} \quad (15)$$

The above equation may be used to calculate the ratio of static to dynamic friction coefficients, and the value of the static coefficient found in the dynamic value is known.

STATIC FRICTION, STATIONARY MODE

With both rollers fixed to prevent rotation, a force measuring device is pressed against one end of the bar until it breaks away. The static friction coefficient is calculated from

$$u_s = \frac{P}{W} \quad (16)$$

SUMMARY OF FRICTION FORMULAS

	Bar Against Rollers	Bearing Inside Rollers
A. Dynamic Oscillation	$u_d = \frac{H}{\frac{gT^2}{4\pi} + h}$	$f_d = \frac{2\rho H}{r} \left[\frac{1 + \frac{2gJ}{W\rho^2}}{\frac{gT^2}{2\pi} + 2h} \right]$
B. Force Measurement	$u = \frac{P}{W}$	$f = \frac{1}{\left[\frac{r^2}{\rho^2} \left(1 + \frac{2wH}{WH-PZ} \right)^2 \frac{W^2}{P^2} + 1 \right]} - 1$
C. Tilted Position	$u = \tan\phi$	$f = \frac{1}{\frac{r^2 \left(w + \frac{W}{2} + \frac{Wh}{2} \tan^2\phi \right)}{\rho^2 \tan^2\phi \left(\frac{W}{2} \cos\phi + \frac{Wh}{2H} \sin\phi \right)}} - 1$

NOMENCLATURE

F = Radial contact force, bar against roller (lbs)

f = Bearing friction coefficient

g = Gravitational acceleration (386 in/sec^2)

h = Height of bar center of gravity above roller surface (in.)

H = Half of center distance between rollers (in.)

J = Mass moment of inertia of one roller with bearing installed (lb/in/sec^2)

K = A constant

n = Number of oscillations

P = Friction force (lb)

r = Bearing bore radius (in)

T = Time period of one oscillation (sec)

t = Time (sec)

W = Weight of bar (lb)

w = Weight of one roller with bearing installed (lb)

X = Coordinate location of bar center of gravity in direction of travel

y = Coordinate normal to x axis

Z = Distance from contact surface to line of action of force measuring device

μ = Coefficient of friction, bar against roller

ϕ = Circular frequency of oscillation

Ω = Angular velocity of roller (radians/sec)

ρ = Roller radius (in)

Subscripts

s = Static condition

d = Dynamic condition

l = Left roller

r = Right roller

n = Undamped valve

d = Damped valve