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Friction Dynamics of Lip Seals

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Abstract—Lip seals, important components in many hydraulic devices, dissipate energy through friction, resulting in power loss. This study contributes to an understanding of lip seal friction by further exploring the connections between friction behavior, viscoelastic properties of rubber and viscous properties of the lubricant. Experiments haven been conducted for short stroke oscillations, where these connections are quite strong. Sliding friction experiments at a variety of pressures, temperatures and oscillation rates (for different seal materials, surface roughnesses and lubricant viscosities) are examined. Speculative explanations are suggested for conditions under which friction maxima and frictional vibrations occur.

1. Introduction

Seals are necessary in hydraulic machine elements to prevent loss of fluid. The fluid used in a hydraulic machine element is often at elevated temperatures and under high pressures. The ideal seal should completely prevent leakage without dissipating any power from the machine. However, the dual goal of zero leakage and zero friction has not yet been attained because these two goals tend to be at odds with each other. For a seal to have low leakage, it must have extremely small separation from the surface against which it seals, which tends to create high friction. In many cases, the low-leakage ideal is more important, and the occurrence of moderate dissipative forces is reluctantly accepted. However, it is desirable to know what sort of pattern, if any, these dissipative forces follow. If friction forces are know, the seal and machine element may be designed to accommodate them in the best way.

While previous research has provided a basic understanding of seal friction as related to the rubber properties and the lubricant, the interaction of these two in friction behavior has not been closely examined. This experimental study of lip seal friction notes a few newly observed phenomena along with some previously observed ones and offers speculative explanations for them in terms of the interaction between lubricant and seal material behavior.

2. Previous work

While previous research has revealed some basic features of seal friction, some aspects have been throughly explored. In particular, information is lacking about the interaction between lubricant and seal mechanical properties in friction behavior.

In the case of unlubricated sliding, Grosch (1963) observed that friction increased toa maximum with increasing sliding speed and fell off again at higher speeds. For sliding on rougher surfaces, sometimes two maxima were apparent The observations that 1) the velocity at which friction is a maximum shifts to higher valus for higher temperatures, and 2) this velocity was different for various rubber materials led Grosch to assemble friction data for a given material into a "master curve" using a Williams-Landel-Ferry (WLF, 1995) transform. Both kinds of friction maxima were ascribed to damping loss in the rubber due to high frequency deformation. The first maximum was attributed to interfacial bond "jumping", while the second was related to defromations in the rubber caused by roughness on the opposing surface. (See Fig. 1.)

Nau (1971) has measured friction for lubricated sliding of rubber seals over a wide rage of speeds. The friction showed hydrodynamic lubrication behavior at hight speeds (μ proportional to $(\eta V)^{1/2}$). At lower speeds the friction rises with decreasing velocity as in other cases of boundary lubrication. (See

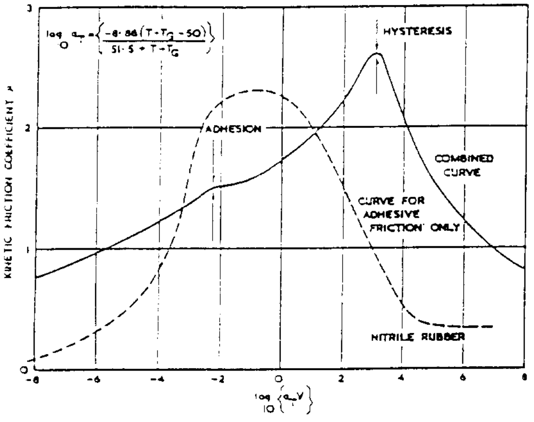

Fig. 1. Grosch's friction curves for dry sliding of nitrile rubber (Grosch, 1963 adapted by Nau, 1971).

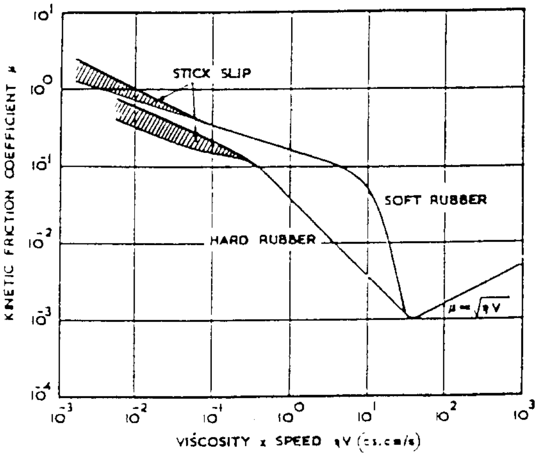

Fig. 2a. Cohen and Tabor's friction curves for steel on rubber with water or silicone lubricant (Cohen and Tabor, 1966).

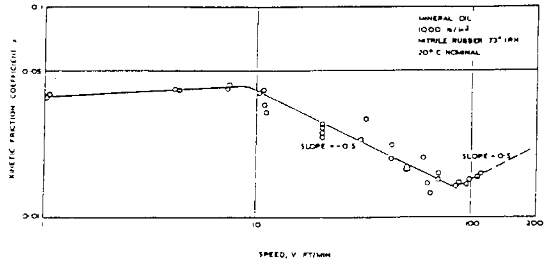

Fig. 2b. Nau's friction measurements for a rubber seal ring, mineral oil with EP additive (Nau, 1971).

Fig. 2.) Nau observed a maxiumum in oil-lubricated friction at low speed qualitatively similar to those found by Grosch for dry sliding. In addition, stick-slip vibration was observed in both of the lubricated sliding studies and found to have a maximum critical velocity, above which stick-slip did not occur. Nau found that the maximum critical velocity increased with temperatue.

All of these studies examined constant speed sliding with strokes significantly longer than the seal contact width. However in real hydraulic devices, sliding excursions tend to be more complex. They may start and stop in various places, slide with varying speeds, or oscillate. In addition, little is said about the interaction between the seal damping properties and the lubricant shear properties in explanations of friction behavior. In the following presentation, this interaction is explored in more detail for short stroke oscillations.

3. Experimental Conditions

Sliding friction of one elastomeric lip seal was measured with paraffin oil lubricant (no additives) under a variety of sealed pressures, oil temperatures and sliding rates. The tests were oscillatory, with short stroke shaft oscillations (5 mm, on order of

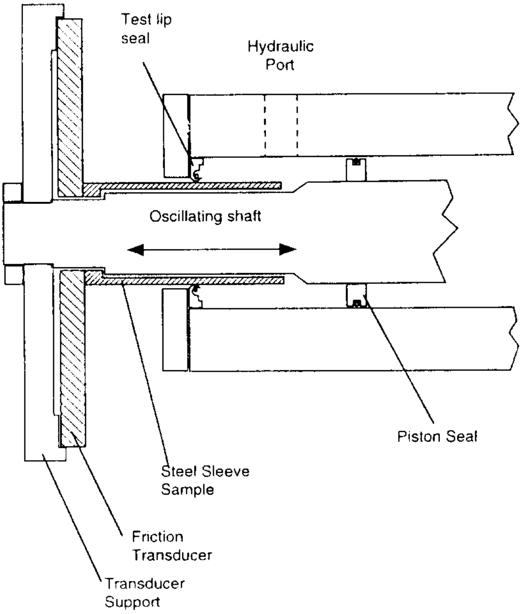

Fig. 3. Schematic device to measure lip seal friction.

two contact widths) provided by an eccentric motor drive. paraffin oil was chosen as a lubricant because it is relatively inert chemically, thus making the interactions at the lubricated surfaces as simple as possible. Pressure was maintained at constant values within 2 psi; oil temperature was maintained constant within +/-2°C for several settings.

Friction of single lip seal is measured through a sleeve free to slide on the oscillating shaft. This sleeve is attached to an axial force transducer which is in turn connected to the shaft. (See Fig. 3). For a typical friction measurement, data was collected over consecutive oscillations, resulting in a time trace such as the ont shown in Fig. 4. Peak values, most often occurring near the beginning of a sliding excursion, were compiled from the time traces. Peak to peak friction values are basis of the rest of the results reported here.

There are a total four seals in the sliding system, two lip seals and two piston seals. while the fiction behavior of the piston seals is not dealt with here, all four of the seals produce friction forces and thus influence the dynmic behavior of the sytem, i.e. vibration.

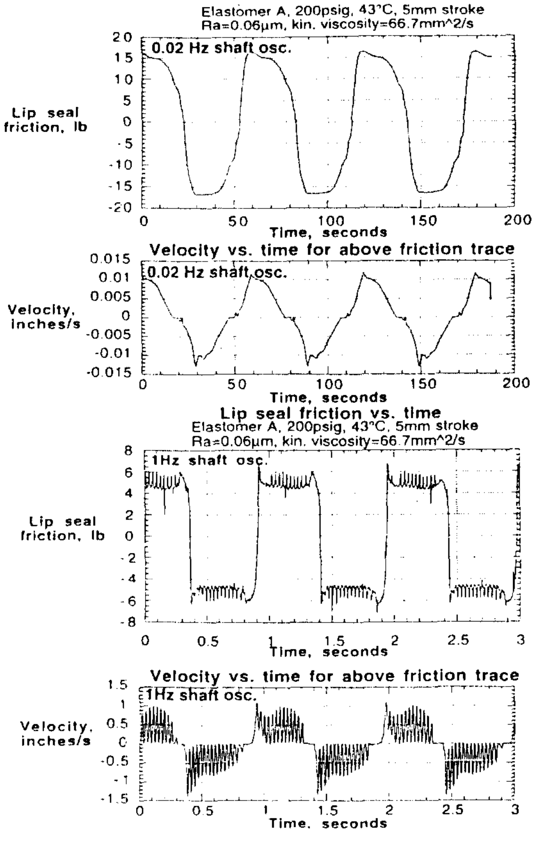

Fig. 4. Lip seal friction vs. time.

4. Lip Seal Friction Behavior

The effect of experimental parameters on two specific behaviors is the focus : maxima in peak to peak friction values (when taken as a function of oscillation rate) and frictional vibration. Friction data are shown and the osbserved behaviors are given a tentative, preliminary interpretation in terms of interactions between seal material damping and lubricant viscous shear.

4-1. Conditions affecting the speed at which a friction maximum occurs.

Several experimental parameters appeared to relate significantly to lip seal friction behavior, particularly to the oscillation rate at which maximum friction occurred It appears that the WLF transform is incapable of assembling data into a "master curve" when shaft roughness or lubricant viscosity are changed. This points to a strong interaction between lubricant, surface and seal viscoelastic properties.

4-1-1. Temperature

Fig. 5a shows peak to peak friction values for a sealed pressure of 200 psig and several values of temperature and shaft reciprocation rate (Elastomer A). While friction for all temperatures becoms quite small

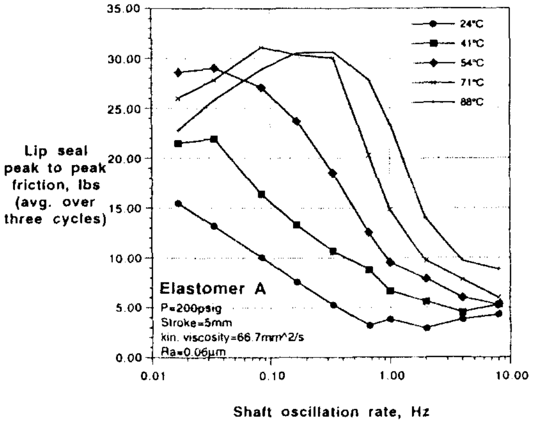

Fig. 5a. Lip seal friction vs. WLF transformed oscillation rate.

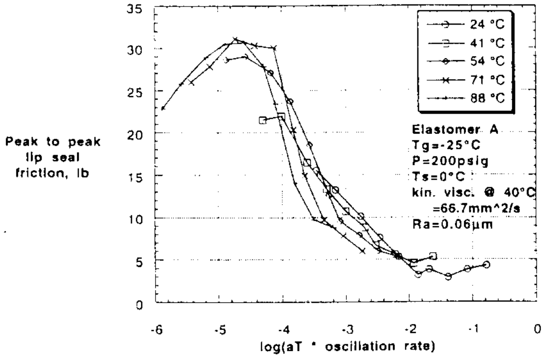

Fig. 5b. Lip seal friction vs. WLF transformed oscillation rate.

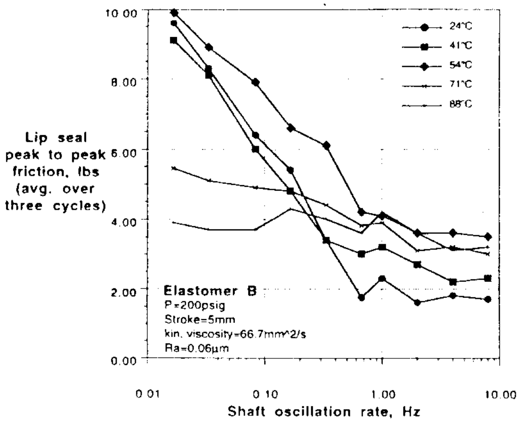

Fig. 6. Lip seal friction vs. shaft oscillation rate for five temperatures.

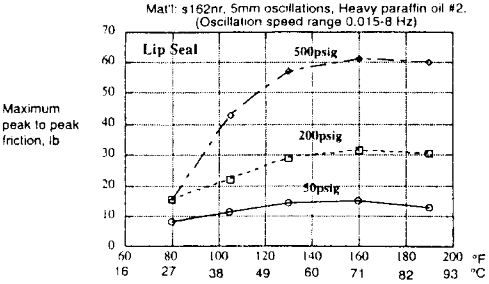

Fig. 7. Maximum lip seal friction vs. temperature.

at the highest speeds tested, a large range of friction values appears at lower speeds. The general decreasing trend is consistent with observations by Nau, Cohen and Tabor where lubricated elastomer friction showed a negative friction-velocity slope for low to moderate speeds. This may be due to the increasing influence of the lubricant on friction with increasing speed and the decreasing contribution of elastomer deformation. At lower speeds, however, the seal friction exhibits maxima which are consistent with the trend observed by Grosch for dry rubber friction and by Nau for rubber seal friction. The oscillation rate at which this maximum occurs shifts toward higher values as the temperature goes up.

These data are plotted in WLF transform space in Fig. 5b, where the transform is given by -8.86(T-Ts)/(101.6+(T-Ts)). The Tg value of minus 25°C was obtained for cyclic strain at 1.6 Hz based on the damping maximum, and the reference temperature of cyclic strain at 1.6 Hz based on the damping maximum, and the reference temperature of Ts=Tg+25°C was found to give good overlap of the data from different temperatures.

4-1-2. Seal material

Friction results for another lip seal composition (Elastomer B) is shown in Fig. 6. Here too there appears to be a trend in behavior with temperatue, though no maxima are apparent. Since the Tg of Elastomer B is minus 39°C, fourteen degrees lower than that of Elastomer A, it is expected that the maximum occurs at lower sliding speeds than were tested here.

A WLF transform of this data does not compress it into a single curve, because the behavior at the highest two temperatures is quite different from that at lower temperatures. Since the drastic change in behavior appears about at the (Tg+100) limit of the WLF transfrom, it is likely that material-specific properties become dominant for the higher temperatures.

4-1-3. Sealed pressure

Friction of the lip seals increases with sealed pressure. (See Fig. 7.) This is expected because the geometry of the seals allows the pressure to squeeze the lip against the shaft more tightly with increasing pressure. This in turn would lead to a thinner lubricating film and apparently more damping loss in the seal material. Fig. 8 shows an additional effect of interest: the friction maximum tends to shift toward higher oscillation rates with increasing sealed pressure. This shift could be caused by a rise in local seal temperature caused by additional frictional heating at higher pressures.

4-1-4. Lubricant viscosity

When the original mineral oil of kinematic viscos-

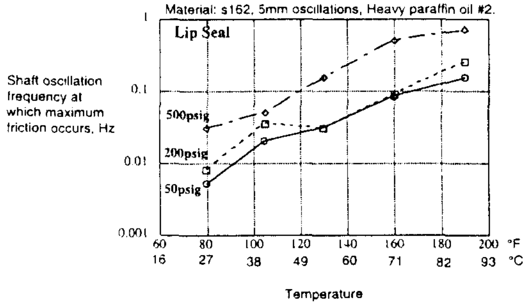

Fig. 8. Estimated speed at which peak in lip seal friction occurs as a function of temperature.

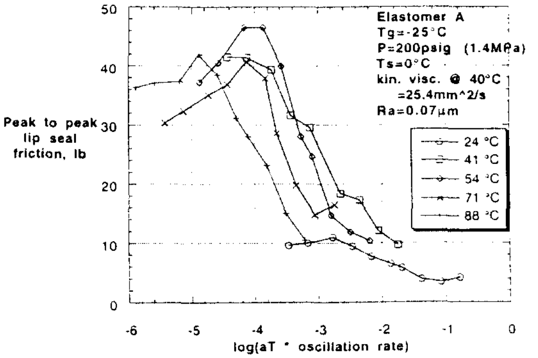

Fig. 9. Lip seal friction vs. WLF transformed oscillation rate.

ity 66.7 mm^2/s is replaced by one of 25.4 mm^2/s, the friction for similar conditions tends. on average to be slightly higher. When data for five temperatures is plotted in WLF transform space using the same values of Tg and Ts (Fig. 9). it is can be seen that the curves do not compress so nicely into a "master curve" as was the case for the more viscous oil. Here, the WLF transfrom appears to shift higher temperature data too fat. It seems that at higher temperatures, the seal material experiences higher frequencies for the same oscillation rate.

4-1-5. Shaft roughness

When average shaft roughness height is increased from 0.07 µm to 0.25 µm, friction values about double, on average. The friction maximum for a given temperature occurs at higher shaft oscillation rate for the rougher shaft than for the smoother one. Both of these trends are consistent with the observations made by Grosch for dry sliding.

However, when the data are plotted in the same WLF transform space as was used for Fig. 5b and 9,

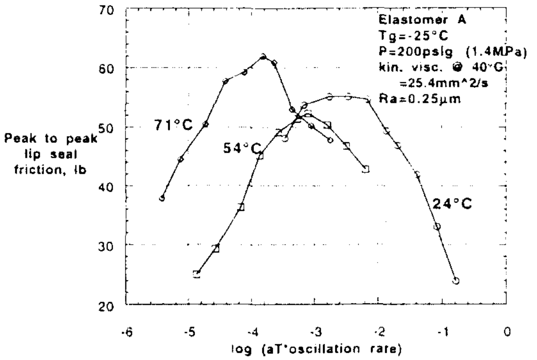

Fig. 10. Lip seal friction vs. WLF transformed oscillation rate.

it can be seen that the friction data for different temperatures are widely separated along the WLF axis. (See Fig. 10) The treand is the same as for Fig. 9 but stronger, with the higher temperature data being grossly over-shifted. It appears as though when the contact is more severe, the seal material experiences progressively higher frequencies at higher temperature for a given oscillation rate.

4-2. Conditions for frictional vibration

Frictional vibrations (fluctuations in shaft velocity) were observed under some of the sliding conditions tested. In some cases, the vibrations were so strong that the minimum velocity approached zero : stick-slips. In Fig. 11, which is similar to Fig. 5a, conditions of frictional vibration and stick-slip are marked.

Note that in all cases of frictional vibration, the slope of the friction-rate curve is negative. This is a necessary but not sufficient condition for frictiional vibration; there are several conditions in Fig. 11 were the slop is negative, but no frictional vibration occurs.

Note also that the there do exist oscillation rates below which frictional vibration (including stick-slip) does not occur. This is a first glance somewhat surprising, since most research on stick-slip speaks only of a miximum critical velocity, not a minimum critical velocity. One might raise an objections to introduction the notion of a minimum critical velocity for stick-slip: how can velocity during a frictional vibration can reach zero if there are speeds below which such vibration will not occure? Once the vibrational velocity reaches a value where the firction-

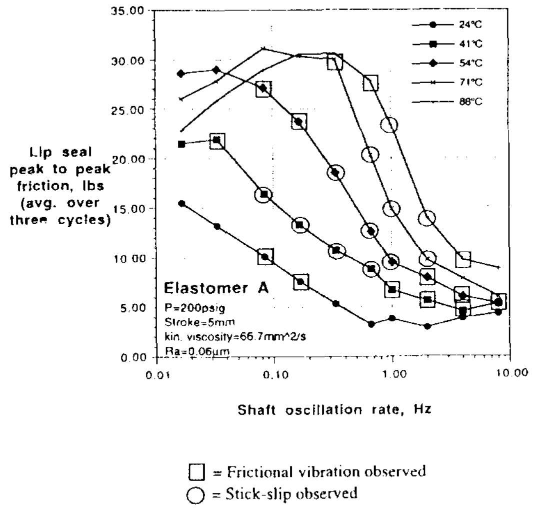

Fig. 11. Lip seal friction vs. shaft oscillation rate for five temperatures.

velocity slope is positive, the vibration should stop.

One plausible explanation for this behavior can be given considering how lip seal friction changes dynamically as sliding velocity changes. Since oil is present in the seal system, some amount of fluid is interposed between sliding surfaces. The faster the surfaces slide relative to each other, the greater will be the thickness of that fluid layer, However, if the velocity decreases suddenly, some time will be requried to squeeze oil out of the sliding interface to reach a new equilibrium. Thus, the, friction value will lag behind the speed. If the frictional vibrations occur rapidly enough that the actual friction never falls with decreasing speed, it is possible for the vibration to continue all the way the zero velocity.

5. Conclusions

Lip seal friction behavior appears to relate to the viscoelastic properties of the seal, particularly at low speeds, and to the viscous properties of the lubricant. Friction peaks are observed to change speed markedly with temperature, sealed pressure, lubricant and surface roughness, such that the WLF transform cannot fully account for friction behavior. The fact that lubricated friction changes tend to lag behind velocity changes can explain the observation of a "minimum critical velocity" for stick-slip. Because of the wide range of friction values observed and their implications for power loss in hydraulic machines, it is important that these behaviors be understood in greater detail.

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