2009 ME Graduate Student Conference
April 18, 2009

DYNAMIC FRICTION IN SLIDING LUBRICATED LINE CONTACT

Hossein Sojoudi
Ph.D. Candidate

Faculty Advisor: Prof. M. M. Khonsari

ABSTRACT

In the lubricated contact, operating under dynamic condition like variable speed, oscillating velocity, and oscillating load the behavior of friction coefficient is not only a function of velocity, but also a function of velocity history. A simple but realistic dynamic friction model is developed based on decoupling the steady and unsteady terms in Reynolds equation. Two different classes of simulations are performed to show the utility of the model: The so-called quasi-steady where the sliding velocity is varied very slowly and the other the oscillating sliding velocity where the friction coefficient exhibits a hysteresis type behavior. The results show the transition from boundary to mixed to full film regimes as the speed is increased. Both categories of the simulations are verified by comparing the results with published experimental data. The model captures the lag between a change in sliding velocity and the corresponding change in friction. The ability of the model to accurately predict dynamic friction behavior over the different regimes reveals that the squeeze-film effect plays an important role in a dynamic friction.

THEORETICAL DEVELOPMENT

Operating under dynamic condition, the instantaneous friction coefficient arises from two separate origins: asperities interaction and fluid traction. Squeezing effect is a key parameter influencing the fluid film thickness as the speed changes. Total applied load, F_T, is a combination of the asperity contact, F_C, hydrodynamic force, F_H, and squeeze force, F_{sq}:

$$F_T = F_H + F_C + F_{sq} \qquad (1)$$

To predict the behavior of friction coefficient, the transient Reynolds equation, the relevant deformation equation, and the rheology equation need to be solved simultaneously. Such a solution procedure is very time-consuming and often experience convergence issue. Using Johnson's [1] load sharing concept the problem of solving unsteady elastohydrodynamic contact can be simply replaced by the problem of dry line contact considering the relevant deformation, the problem of solving lubricated line contact without surface roughness considering its relevant deformation, and the problem of squeeze action of fluid film. Neglecting the surface deformation under light load, the squeeze pressure can be derived by solving transient Reynolds equation and pressure-viscosity relation. Having the squeeze pressure, the total load is obtained by the integration of the squeeze pressure over the Hertzian contact area.

$$F_{Sq} = \int_{-a}^{a} \frac{ln(1 - q(x)\alpha)}{-\alpha} \, l \, dx \qquad (2)$$

where

$$q(x) = \frac{1}{\alpha}\left\{1 - exp\left(-\alpha p_{sq}(x)\right)\right\} \qquad (3)$$

where p_{sq} is fluid squeeze pressure and α is pressure-viscosity coefficient.

Subtracting the damping load from the total applied load, the corresponding steady load is obtained as:

$$F_S = F_T - F_{sq} \qquad (4)$$

Applying Johnson [1] load sharing concept, the steady load can be rewritten as:

$$F_S = \frac{F_S}{\gamma_1} + \frac{F_S}{\gamma_2} \qquad (5)$$

Moes [2] obtained an expression for the film thickness in elastohydrodynamic lubrication through solving Reynolds, deformation, and rheology equation for smooth surfaces. Substituting E' by E'/γ_2 and F_S by F_S/γ_2 in the Moes relation for the central film thickness will result the film thickness relation for the mixed lubrication regime:

$$\bar{h}_c \bar{U}^{-0.5} = \left[(\gamma_2)^{s/2}\left(H_{RI}^{7/3} + (\gamma_2)^{-14/15} H_{EI}^{7/3}\right)^{(3/7)s} + (\gamma_2)^{-s/2}\left(H_{RP}^{-7/2} + H_{EP}^{-7/2}\right)^{-(2/7)s}\right]^{s^{-1}} (\gamma_2)^{1/2} \qquad (6)$$

where

$$s = \frac{1}{5}\left(7 + 8e^{\left[-2\gamma_2^{-2/5}(H_{EI}/H_{RI})\right]}\right) \qquad (7)$$

with the following dimensionless parameters:

$H_{RI} = 3M^{-1}$, $H_{EI} = 2.621M^{-1/5}$, $H_{RP} = 1.287L^{2/3}$, $H_{EP} = 1.311M^{-1/8}L^{3/4}$, $H_{RP} = 1.287L^{2/3}$, $\bar{h}_c = h_c/R'$
$\bar{U} = \frac{\mu_0 u}{E'R'}$, $M = W\bar{U}^{-1/2}$, $W = \frac{F_S}{E'R'l}$, $L = G\bar{U}^{1/4}$, $G = \alpha E'$

Greewwood and Williamson's [3] model is used for the surface asperity contact where the contact of two rough surfaces is replaced by the contact between the equivalent rough surface with a smooth flat plate. In this study, the equivalent surface roughness parameters such as average radius of asperities, β, standard deviation of asperity heights, σ_s, and density of asperities, n, is used. Using Nondimensionalizing we arrive at the following expression:

$$\frac{2}{3}\bar{n}\bar{\sigma}_s{}^{3/2}\bar{F}_S F_{3/2}\left(\frac{\bar{h}_c-\bar{d}_d}{\bar{\sigma}_s}\right) = [1+(a_1\bar{n}^{a_2}\bar{\sigma}_s{}^{a_3}W^{a_2-a_3}\gamma_2{}^{a_2})^{a_4}]^{1/a_4}\frac{1}{\gamma_1} \quad (8)$$

The total friction coefficient is the sum of the asperity contact friction and fluid traction effect:

$$f=\frac{F_{f,H}+F_{f,C}}{F_T} \quad (9)$$

The asperity contact friction is assumed to follow the Coulomb's law:

$$F_{f,C}=f_c F_c \quad (10)$$

Assuming the separation of two rough surfaces to be constant and equal to the central film thickness, h_c, the hydrodynamic friction force is represented as [6]:

$$F_{f,H}=\tau_L\left(1-e^{-\mu(u/h_c)/\tau_L}\right).2al \quad (11)$$

RESULTS AND DISCUSSIONS

The oscillation frequency plays an important role in this process. If this accelerating and decelerating process happens very slowly, then the mechanism of unsteady sliding contact at each instant can be approximated by an equivalent steady-state condition.

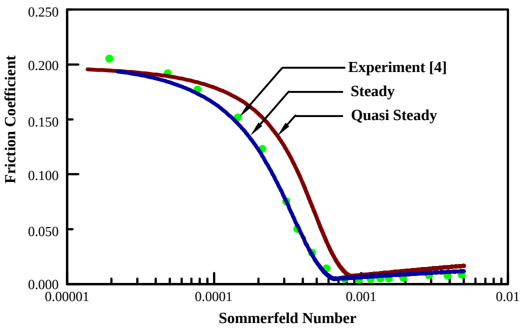

Fig. 1 Friction coefficient as a function of Sommerfeld

The simulation results show that the model captures the behavior of the Stribeck curve in boundary, mixed, and full lubrication regimes. The comparison of the results reveals significant insight into the squeeze phenomena in quasi-steady contact of lubricated surfaces. Figure 1 illustrates that as the sliding velocity is increased in the mixed regime, the deviation from experimental steady friction behavior becomes more pronounced. Movement of interacting bodies in the normal direction is the primary cause of this deviation; the difference between the quasi-steady simulation result and steady (simulation and/or experiments) is the squeeze effect.

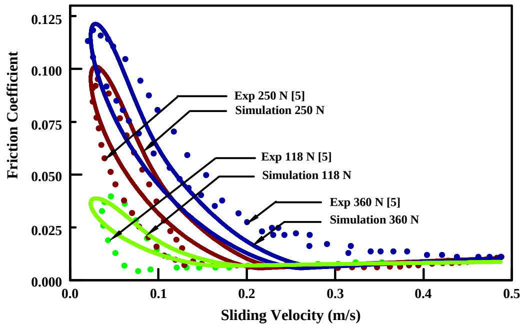

Fig. 2 Friction coefficient as a function of velocity

Another set of simulations illustrate how dynamic friction coefficient behave when oscillating frequencies in the motion are taken into account. Figure 2 shows the simulation results and the comparison with experiments reported in [5]. The predicted results closely capture the experimentally observed hysteresis effect in the mixed regime where there is high contribution of asperities that support the applied load. As the velocity increases, the film thickness increases. This implies a minus squeeze force; so the film thickness becomes less than its corresponding value of the steady-state case resulting in a higher friction coefficient. While during the decrease in the velocity the process in reverse, the squeeze is a positive force and it contributes in carrying the load. This result in a higher film thickness which translates to a lower friction coefficient compared to the corresponding value in the steady lubrication.

ACKNOWLEDGMENTS

I would like to thank my advisor, Professor Khonsari, for his constant guidance and all my colleagues at LSU Center for Rotating Machinery (CeROM).

REFERENCES

1. Johnson, K. L., Greenwood, J. A., and Poon, S. Y., 1972, "A Simple Theory of Asperity Contact In Elastohydrodynamic Lubrication," Wear, 19, pp. 91–108.
2. Moes, H., 1992, "Optimum Similarity Analysis With Application to Elastohydrodynamic Lubrication," Wear, 159, pp. 57–66.
3. Greenwood, J. A., and Williamson, J. B. P., 1966, "Contact of Nominally Flat Surfaces," Proc. R. Soc. London, Ser. A, 295, pp. 300–319.
4. Lu, X. B., Khonsari, M. M., and Gelinck, E. R. M., 2006, "The Stribeck Curve: Experimental Results and Theoretical Prediction," J. Tribol., 128(3), pp. 789–794.
5. Hess, D. P., and Soom, A., 1990, "Friction at a Lubricated Line Contact Operating at Oscillating Sliding Velocities," J. Tribol., 112(1), pp. 147–152.
6. Roelands, C.J.A., Correlational Aspects for the Viscosity–Temperature–Pressure Relationship of Lubricating Oils, Druck VRB, Groningen (1966).