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A THEORY OF CAVITATION IN AN OSCILLATORY OIL SQUEEZE FILM

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INTRODUCTION

The cavitation of oil films in bearings subjected to dynamic loads is not well understood. In order to compute reliably the performance of dynamically loaded bearings, it is important to know the underlying mechanisms of the cavitation phenomenon and be able to predict its occurrence and subsequent development. From previous studies (Sun and Brewe, 1992; Sun, Brewe and Abel, 1993) the following features of cavitation in submerged bearings (i.e. with no air entrainment) are known: (1) Cavitation is confined to one region, which contains residual oil filaments of the fractured film. (2) The pressure in the cavitation region is the vapor pressure of oil. (3) Tensile stress is present in the oil film outside the cavitation region. (4) The occurrence of cavitation requires not only a low pressure level but also some other condition. In this paper a **new** cavitation model is proposed, that incorporates the above features, considers the effect of surface tension, and preserves mass conservation in the cavitation region. The model is applied to an oscillatory oil squeeze film bounded between two parallel circular plates, a problem that has been extensively studied in the past (Hayes and Feiten, 1964; Rodrigues, 1970; Parkins and May-Miller, 1984; Boedo and Booker, 1995; Optasanu and Bonneau, 2000). New results derived from the model are presented and compared with those of previous studies.

CAVITATION MODEL AND PROBLEM FORMULATION

Consider a squeeze film bearing submerged in an oil pool, Fig. 1. The bearing consists of a lower fixed plate and an upper plate (circular, with radius a) oscillating with frequency ω and amplitude ε. The gap h between the plates may be described as:

$$h = h_o - \varepsilon \sin \omega t \qquad \text{for} \qquad t \geq 0 \qquad (1)$$

where h_o is the mean gap during the oscillations, and t is time. The fluctuation of oil film pressure p at the center ($r = 0$) is the largest if the oil film does not cavitate. Let it be assumed that a cavitation nucleus exists at $r = 0$. When the center pressure decreases to the oil vapor pressure p_v, cavitation begins here. A circular cavitation region, of radius $R(t)$, at the uniform pressure p_v and containing broken oil filaments inside, grows from an assumed nucleus size R_o outward to a peak value, then the refilling oil from the surrounding pool forces the cavitation region to shrink and eventually vanish at $r = 0$. Outside the cavitation region the oil film is continuous, even if its pressure falls below p_v. In other words, once cavitation commences the oil film outside the cavitation region becomes stronger in keeping itself intact, the low pressure there then tends to "pull" the nearby existing cavitation boundary to spread. As the cavitation region grows, the radial velocity of the oil film flow at and near the cavitation boundary is unlikely to be uniform across the oil film. The largest radial velocity is recognized as the velocity of the cavitation boundary, because only in this way no cavity can be entrained into the full-film region. Thus, the slower-moving part of the oil film is "overtaken" by the fast-moving boundary and left in the cavitation region, which forms the observed residual oil filaments. These filaments are left stationary on the bearing surfaces since there is no pressure gradient inside the cavitation region. When the cavitation region shrinks, these oil filaments join the refilling oil to become a part of the continuous film again.

At the interface between the cavitation and full-film regions stress is continuous. This brings about a pressure boundary condition:

$$p_{r=R} = p_v - \sigma\left(\frac{1}{R} + \frac{2\cos\overline{\alpha}}{h}\right) \qquad (2)$$

where σ is surface tension of oil, and $\overline{\alpha}$ is (dynamic) contact angle the meniscus makes with the solid plates. This angle depends on the velocity of the cavitation boundary, $\dot{R}$, and their relation is obtained from an empirical correlation (Jiang, Oh and Slattery, 1979).

During the expansion of the cavitation region, the postulated flow continuity condition is:

$$Q_{r=R} = 2\pi R\left(1 - \overline{\beta}\right)h\dot{R} \qquad \text{for } \dot{R} > 0 \qquad (3)$$

where Q is the volume flow rate of oil, and $\overline{\beta}$ is a numerical factor between 0 and 1. As said above, $\dot{R}$ is taken to be the largest radial flow velocity of oil. Hence, the volume expansion rate of the cavitation region is more than Q at the cavitation boundary, and the former should be reduced by the factor (1-$\overline{\beta}$). If the radial flow velocity has a parabolic distribution at and near the cavitation boundary, the value of $\overline{\beta}$ is 1/3. Equation (3) also shows that the oil left behind the cavitation boundary has an equivalent film thickness $\overline{\beta}h$.

When the cavitation region recedes, because the residual oil filaments in the cavitation region joins the inward flowing continuous film, Q at the cavitation boundary need only match a reduced volume reduction rate of the cavitation region. The corresponding flow continuity condition, therefore, takes the form:

$$Q_{r=R} = 2\pi R(h - \overline{\beta}h_{past})\dot{R} \qquad \text{for} \qquad \dot{R} < 0 \qquad (4)$$

where h_{past} denotes the previous gap thickness at $r = R$ when $\dot{R} > 0$.

SOLUTION AND RESULTS

By using the standard lubrication theory and boundary condition (2), the pressure in the full-film region is obtained. The development of the cavitation region is obtained by numerically integrating equations (3) and (4) with the use of a MATLAB function "ode23". Sample results for the case $R_o/a = 0.004$, $p_v/p_a = 0.0003$, $h_o/a = 0.01$, $\eta\omega a/\sigma = 10.77$, $(\eta\omega/p_a)(a/h_o)^2 = 1.489$, $\varepsilon/h_o = 0.5$ are shown in Figs. 2 and 3. In the above parameters, η denotes viscosity of oil and p_a denotes ambient pressure in the oil pool. Figures 2 show the controlled variation of bearing gap and the corresponding variations of center pressure and cavitation size. Figure 3 shows several pressure traces at different radial locations: with "a" very close to the center, "b" within the maximum radius of the cavitation region, and "c" outside the cavitation region. These computed pressure traces compare favorably with the measured ones reported in the literature.

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REFERENCES

Boedo, S., and Booker, J. F., 1995, "Cavitation in Normal Separation of Square and Circular Plates", ASME J. of Tribology, Vol. 117, pp. 403-410.

Hays, D. F., and Feiten, J. B., 1964, "Cavitaties between Moving Parallel Plates", in Cavitation in Real Liquids (Edited by Davies, R.), Elsevier, pp. 122-137.

Jiang, T. S., Oh, S. G., and Slattery, J. C., 1979, "Correlation for Dynamic Contact Angel", J. of Colloid and Interface Sci., Vol. 69, p. 74.

Optasanu, V, and Bonneau, D, 2000, "Finite Element Mass-Conserving Cavitation Algorithm in Pure Squeeze Motion. Validation/Application to a Connecting-Rod Small End Bearing", ASME J. of Tribology, Vol. 122, pp. 162-169.

Parkins, D. W., and May-Miller, R., 1984, "Cavitation in an Oscillatory Oil Squeeze Film", ASME J. of Tribology, Vol. 106, pp. 360-367.

Rodrigues, A. N., 1970, "An Analysis of Cavitation in a Circular Squeeze Film and Correlation with Experimental Results", PhD Thesis, Cornall University, Ithaca, NY.

Sun, D. C., and Brewe, D. E., 1992, "Two Reference Time Scales for Studying the Dynamic Cavitation of Liquid Films", ASME J. of Tribology, Vol. 114, pp. 612-615.

Sun, D. C., Brewe, D. E., and Abel, P. B., 1993, "Simultaneous Pressure Measurement and High- Speed Photography Study of Cavitation in a Dynamically Loaded Journal Bearing", ASME J. of Tribology, Vol. 115, pp. 88-95.

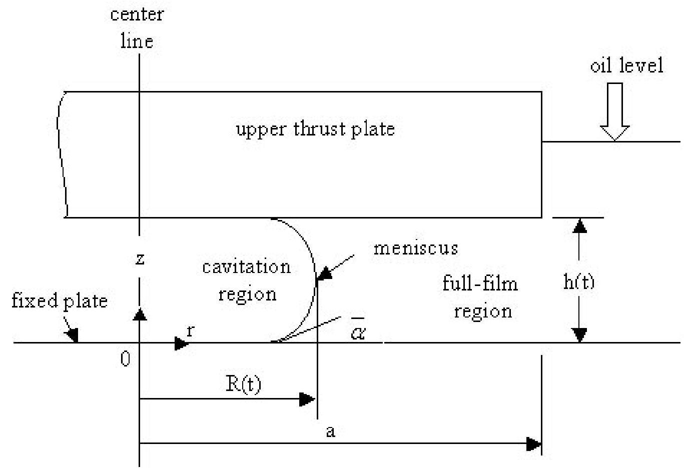

Figure 1. Schematic of a cavitated oil squeeze film

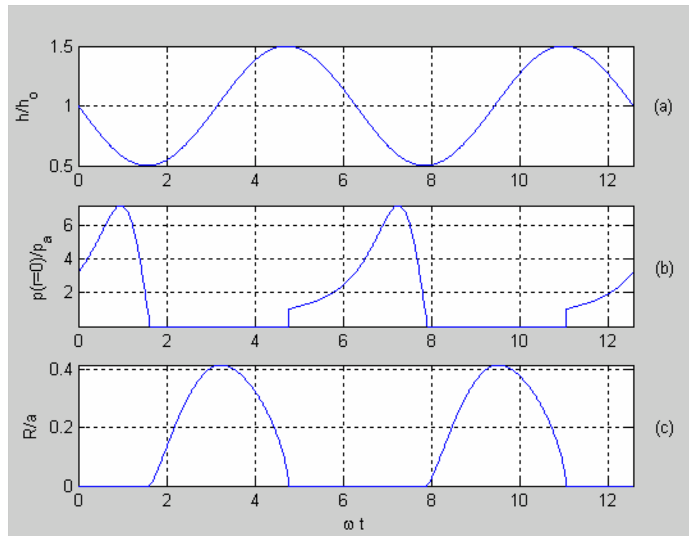

Figure 2. Variation of (a) film thickness, (b) pressure at center, and (c) cavitation boundary with time

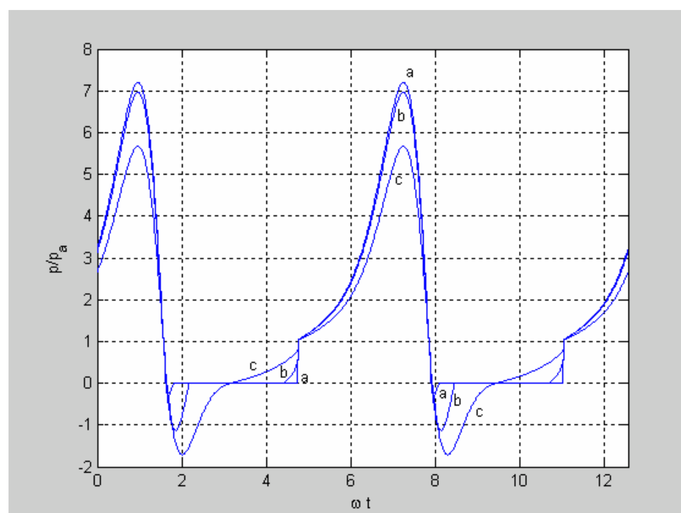

Figure 3. Variation of pressure with time, a: $r/a = 0.05$; b: $r/a = 0.2$; c: $r/a = 0.5$