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Film Continuity Problem on Journal Bearing Design

Tadataka Konishi* and Mitsuru Baba**

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SYNOPSIS

Pressure distribution has been measured and analyzed to clarify the fundamental characteristics of "continuous oil-film" formed in a transparent journal bearing, into which oil in general use is supplied. Measured pressure mostly shows quasi-Sommerfeld distribution, which is characterized by downstream shift of pressure profile and underdevelopment of pressure trough compared with Sommerfeld distribution for perfect oil-film. Sommerfeld distribution is approximately observed only under limited conditions : low eccentricity and low speed. Quasi-Sommerfeld state is rather common in "continuous oil-film", unruptured film formed by using practical lubricants, than Sommerfeld state. Continuous oil-film is accompanied by fine bubbles and is controlled by the growing up or down of the bubbles.

NOTATION

c radial clearance

c_p specific heat of lubricant

e journal eccentricity

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* Department of Information Technology

** Department of Mechanical Engineering

E modulus of elasticity
h film thickness
H nondimensional film thickness ($= h/c$)
L bearing length
N shaft rotational speed (revolutions per minute)
p film pressure
p_S supply pressure
R nominal radius of shaft and bush
ΔR radius increment of bush
t bush thickness
T lubricant temperature
T_1 lubricant feed temperature
T nondimensional temperature rise
W bearing load
β constant
ε eccentricity ratio
η lubricant viscosity
η_1 lubricant inlet viscosity
$\bar{\eta}$ nondimensional viscosity ($\bar{\eta} = \eta / \eta_1$)
θ angle, taken from the position of maximum clearance in the direction of rotation
ν Poisson's ratio
ρ lubricant density
ϕ attitude angle
ω angular velocity of journal

1. INTRODUCTION

Experimental observations of oil-film in ordinary journal bearings have always shown film rupture for usual operating conditions. Ordinary journal bearings are unsuited for the formation of 360 degree unruptured film, because of their difficulties in maintaining a flow continuity at their open ends. A few researchers managed to realize the unruptured film for limited conditions [(1)-(4)]. They measured pressure distributions and/or eccentricity loci, which approximated Sommerfeld solution. Some of them concluded that their empirical data agreed well with Sommerfeld solution. The remaining researchers noticed the subtle difference between the theory and their data but they had little interest in further investigations on the difference. Their valuable and poor follow-ups have resulted in a plausible support to a superficial interpretation of the unruptured film that it is an exceptional and simple phenomenon perfectly explained by Sommerfeld theory. Therefore, the unruptured film has been given an alias of perfect film. Their data however suggest an apparent distortion of pressure distributions and a minute sag of attitude angles from 90 degrees. Ruptured film has been a subject of abiding investigation for many lubrication researchers, while unruptured film has aroused in a few experimenters only a passing interest. Most researchers on film rupture have concentrated their perpetual efforts on cavities and film-cavity interfaces, but practically nothing due on the film region, the mother of rupture [(5)-(11)].

In our previous experiment [(12)], we skillfully controlled film rupture, by equipping a journal bearing with circumferential grooves at both ends of the bearing to supply pressurized oil. The device effectively precluded air invasion and maintained flow continuity around bearing ends. It easily regulated film rupture in an area between zero and a certain extent as well as the magnitude of negative pressure by controlled pressure of supply oil. Figs. 1 and 2 are the examples of the results obtained in the experiment by using an equivalent oil to ISO VG 10 and a cast iron bush : nominal bore is 50 mm, radial clearance is 0.280 mm, and bearing length is 70 mm plus two 15 mm-wide portions outside both grooves. In Fig. 1 showing attitude-eccentricity loci, white circles and black circles represent the results during reduction and increase, respectively, of the shaft speed between 1000 and 50 rpm.

With an increase in eccentricity, the journal center shifts almost horizontally but on the downward trend while the film is unrup-

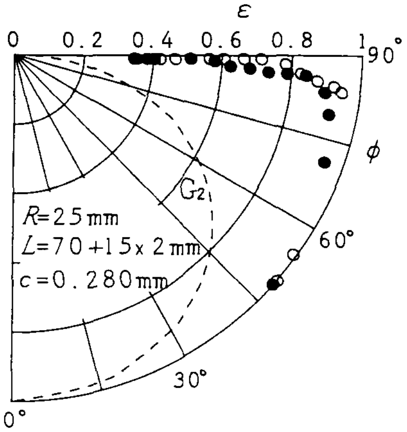

Fig.1 Attitude-eccentricity locus [(12)]

tured, and it falls remarkably when rupture occurs. Pressure distributions shown in Fig. 2 follows three different patterns depending on the pressure of supplied oil p_S. When p_S is high enough to keep the minimum pressure positive, the distributions profile agrees with Sommerfeld distribution shown by solid curves. When p_S is low and causes slightly negative pressure, the profile approximates the solid curve but shows an underdeveloped pressure trough. When p_S is very low, the trough disappears with the profile showing a flat bottom of almost zero pressure. Consequently, we innovated a classification of film state into three types: Sommerfeld type, quasi-Sommerfeld type, and ruptured film type. In fluid dynamics, the single-phase flow is the most fundamental state, and the two-phase flow is an important but derivative state. Therefore, the researchers of two-phase flow pay considerable attention to the original fluid. Their approach suggests a new viewpoint that the original flow in journal bearings is unruptured film rather than ruptured film.

A satisfactory solution of oil-film in journal bearings will not follow one-sided efforts biased to ruptured film, a secondary state. We consider that the surest approach is to investigate the transition process from unruptured film to ruptured film through intermediate states. However, the unruptured film, our starting point, remains virtually in the realm of the unknown, though it has been treated as already-known. The same remark may be nearly applicable to the film region of ruptured film. The present paper is concerned with pressure distributions of unruptured film formed in a transparent journal bearing equipped with circumferential input oil- grooves at both ends of the bearing.

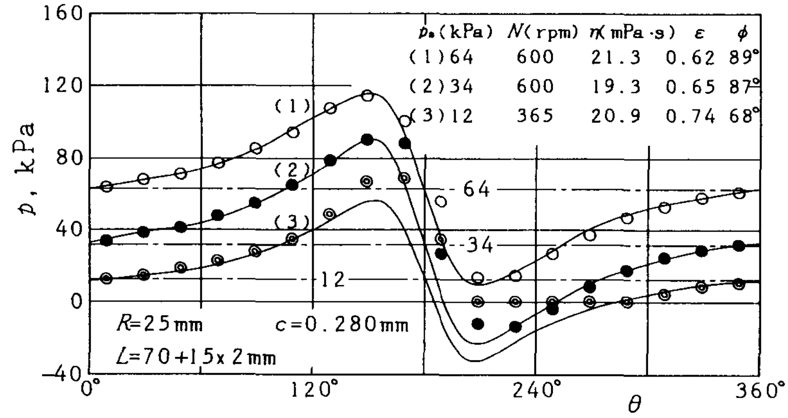

Fig.2 Pressure distribution(12)

2 EXPERIMENTAL EQUIPMENT

2.1 Equipment and procedure

Fig. 3 shows the equipment used which consisted of a revolving shaft assembly and a test section mounted with a transparent journal bearing. The horizontal steel shaft **1** was supported by two pairs of angular contact ball bearings **2** preloaded to remove bearing clearance and to increase rigidity. The shaft was driven by an infinitely variable speed oil-hydraulic motor **3**, which facilitated an arbitrary speed operation between 50 and 1500 rpm both in normal and reverse directions of rotation. The rotational frequency pulses were picked up by an electromagnetic transducer **9** and were input to a digital frequency counter.

A transparent bush **4** made of acryl resin was used to observe flow state during measurement of film pressure. The bush was inserted in a sleeve **5** which was finished to fit closely outside the bush and was bonded around the bush ends to ensure solid fitting as well as firm

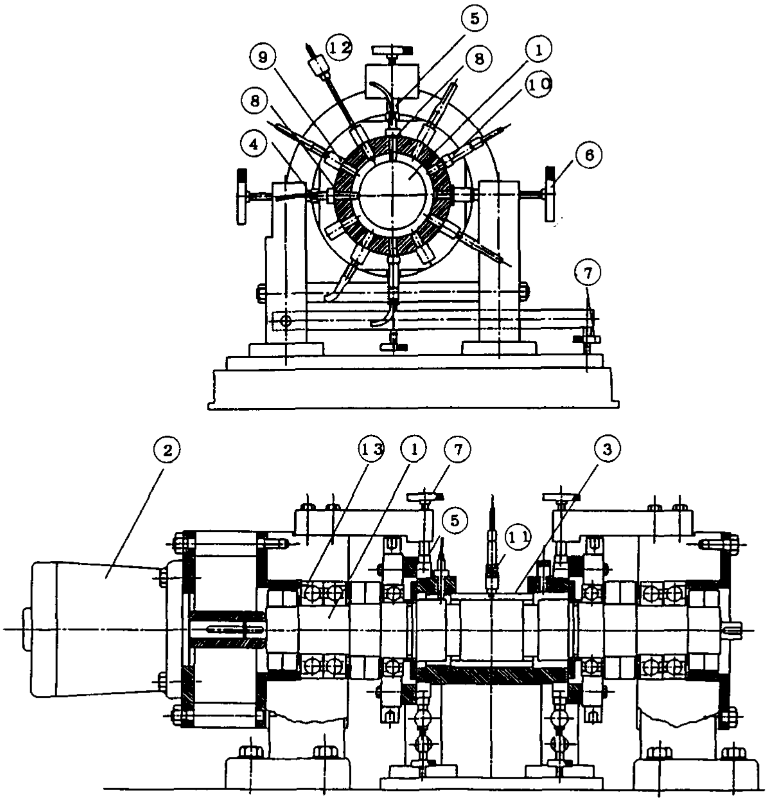

Fig.3 Experimental equipment

sealing of the test section. For extensive observation of film, the sleeve was widely windowed at the middle of it to form shoulders on the both sides. The bearing eccentricity and the position of maximum clearance were controlled by two positioning devices, one for each shoulder of the sleeve. Each device was comprised of a clearance adjuster and a supporting disc **7** which was mounted on the revolving shaft with a ball bearing between. The adjuster was equipped with four adjusting screws **8** and two eddy current displacement sensors **10**, two screws and one sensor for horizontal and other two and one for vertical. The sleeve having been adjusted to a preselected position was secured to the supporting discs with clamping bolts. During pressure measurement the provided position was always observed and was readjusted if necessary.

Two seal discs **6** were mounted on the revolving shaft to restrict oil discharge from the sleeve ends and to form annular grooves for oil supply between the bush ends and the discs. The lubricant oil was fed into each groove through quadruple holes spaced at 90 degrees intervals around the sleeve shoulders. The oil temperature was measured by two thermistor thermometers **11** built in the sleeve, one for each groove. The temperature was satisfactorily maintained within ± 0.1 K of specified temperatures by the use of a temperature controller.

Three miniature transducers **12** operating on the principle of semiconductor strain gauges were used for pressure measurement. Two for pressure of supplied oil were installed to the sleeve in a similar manner as the thermometers. The film pressure was applied to the remaining one through a transducer mounting adapter and a 0.5 mm diameter hole located on the widthwise middle position of the transparent bush.

All the instruments and a microcomputer supplemented with peripheral devices comprised a data acquisition and processing system. Pressure measurement was executed at a specified journal velocity and pressure of supplied oil after removal of visible bubbles from oil. Main dimensions of the journal bearing used were as follows:

Nominal radius	$R = 25$ mm
Bearing length	$L = 50$ mm
Radial clearance	$c = 0.305$ mm
Bush thickness	$t = 5$ mm

2.2 Accuracy of experiment

Internal radius of the acryl resin bush used varies within ±1.2μm about the average radius at a cross section and it varies within ±2μm widthwise. The journal runout is about 5μm at a maximum. Errors of bearing gap measured in operation, however, is kept remarkably below the journal runout by means of the sleeve supporting mechanism mounted on the shaft with ball bearings between; it is within ±1.5μm even at a large eccentricity ratio of 0.7 which accompanies a minimum clearance of about 100μm. In addition, normal and reverse directions of journal rotation produced no discriminating difference between pressure distribution data. Therefore, the roundness error of bush and the runout of journal exerted insignificant influences on the experiment.

The temperature rise of the lubricant is a subject of importance to journal bearings. Assuming that the journal and bearing surface are adiabatic, the energy equation around the widthwise mid circumference is simplified as follows (13):

$$\frac{\partial \overline{T}}{\partial \theta} = \frac{2\overline{\eta}}{H^2} \qquad (1)$$

where

$$\overline{T} = c_p \rho \frac{T - T_1}{\eta_1 \omega} \left(\frac{C}{R}\right)^2 \qquad \overline{\eta} = \frac{\eta}{\eta_1} = \exp\left(-\beta\,(T - T_1)\right)$$

The temperature rise overestimated from Eq.(1) due to the adiabatic assumption is 0.3 K at the highest under a following operating condition.

η_1 = 40 mPas, N = 1500 rpm, ε = 0.7

C_p = 2.1 kJ/(kgK), ρ = 850 kg/m^3, β = 0.045 k^{-1}

The temperature rise of 0.3 K is small enough to neglect oil viscosity change. Thermal expansion coefficient of acryl resin is about $7\times10^{-5}K^{-1}$ and a 0.5μm increase in bush radius due to a 0.3 K rise is insignificant.

The bush may elastically deform due to an action of oil film pressure which is composed of the static pressure and the dynamic pressure. The uniform pressure of supplied oil acts statically on the internal wall of the bush. An action of uniform internal pressure changes the radius of a thin walled cylinder as follows:

$$\Delta R = \frac{R^2}{E\,t}\left(1 - \frac{\nu}{2}\right) p \qquad (2)$$

Modulus of elasticity of acryl resin is about 3 GPa and Poisson's ratio is about 0.3. Nearly all the data in our present experiment were measured at a supply pressure of 25 kPa, which might produce a radius increment of about 0.9μm. The dynamic pressure of continuous film is dominant in a limited region and it has a peak and a trough astride the position of the minimum film thickness. The peak has an increasing effect on the bush radius and the trough has an opposite effect. Their effects nearly cancel out each other because of their adjacent locations. Accordingly,the influence of the dynamic pressure on bush deformation is relatively insignificant. This inference is satisfactorily supported by the fact that the acryl resin bush produced almost the same empirical results with the aforementioned data obtained from the cast iron bush. Cast iron has a modulus of elasticity nearly 50 times larger than that of acryl resin and its deformation is small enough to neglect.

Consequently, at an eccentricity ratio of 0.7 and a supply pressure of 25 kPa the worst situation gives overall errors as follows: error for eccentricity ratio smaller than 0.014 and error for angular position of pressure measuring hole smaller than 1.1 degrees.

3 DISCUSSION OF RESULTS

3.1 Results

Figs. 4 to 8 show the results of pressure distribution in unruptured film obtained by the use of ISO VG 22 bearing oil. Small circles and solid curves represent measured pressures and theoretical Sommerfeld distributions, respectively.

Figs. 4 to 6 summarize the pressure profile transition depending on eccentricity ratio ε. When ε is 0.5 or less, measured pressures agree with Sommerfeld distribution as seen in Fig.4. When ε increases to 0.6 or 0.65 as shown in Fig. 5, there appears a discriminating difference between the data and the theory. Over a wide range of θ astride the position of minimum clearance, the data show a trend behind the theory in their change and the empirical profile lies a little backward. This trend is more remarkable in Fig. 6 which shows the results at ε of 0.7 and 0.75. In addition, the pressure data in

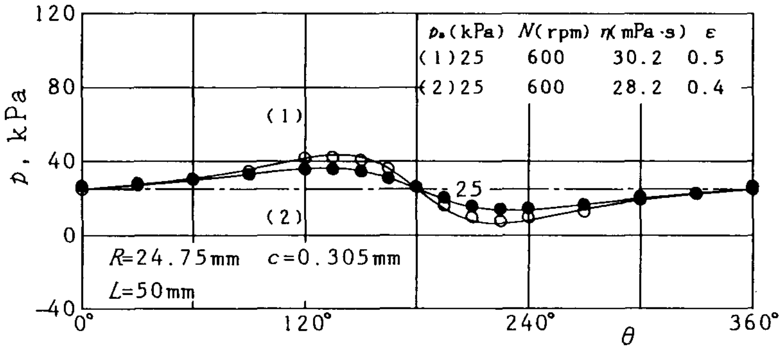

Fig.4 Pressure distribution(1)

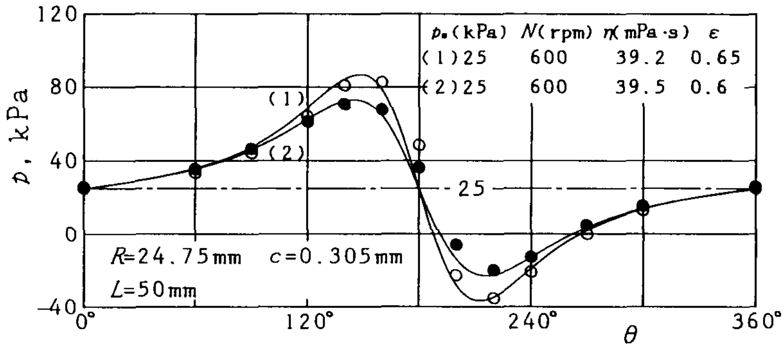

Fig.5 Pressure distribution(2)

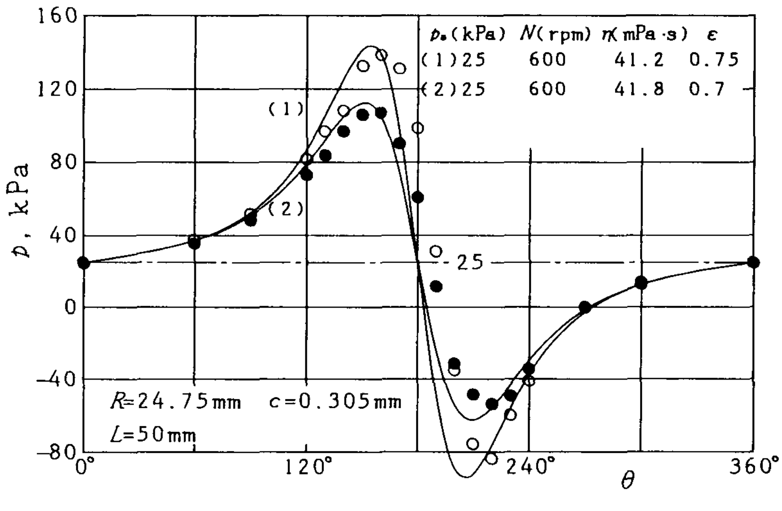

Fig.6 Pressure distribution(3)

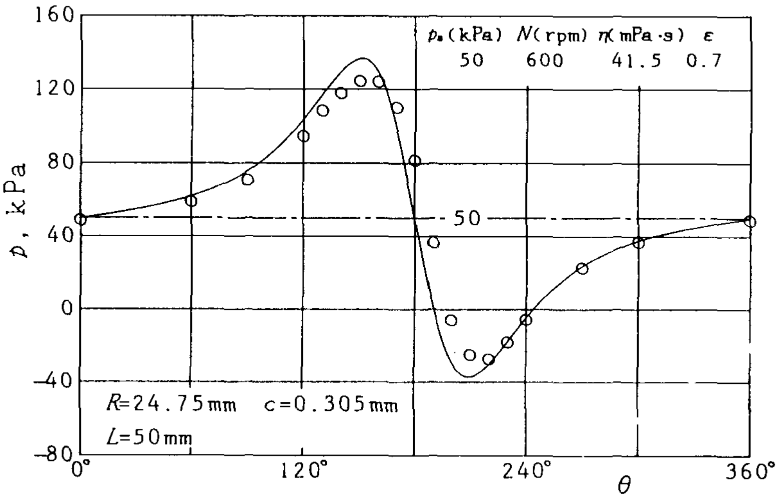

Fig.7 Pressure distribution(4)

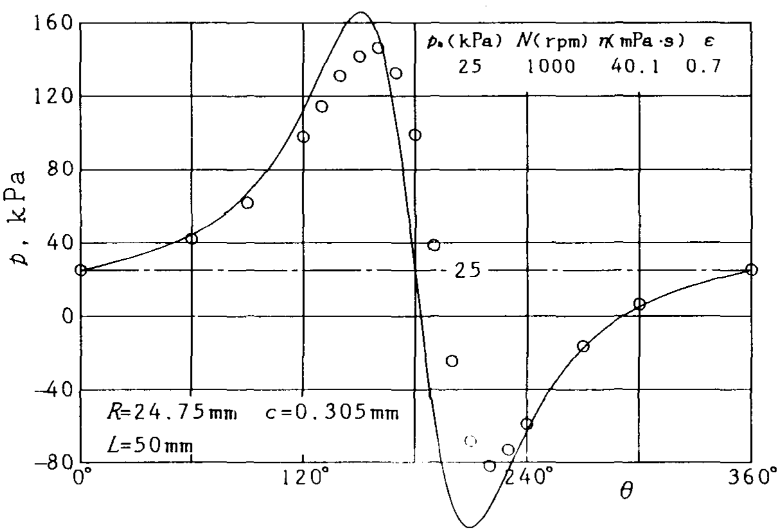

Fig.8 Pressure distribution(5)

the figure are characterized by underdeveloped peaks and troughs. The film state shown in Figs. 5 and 6 corresponds to the pressure distribution which we named quasi-Sommerfeld state in our previous paper (12). Figs. 4 to 6 show that the film state removes from Sommerfeld type to quasi-Sommerfeld type with an increase in ε which is accompanied by an expansion of pressure fluctuation.

Figs. 7 and 8 are compared with Fig. 5. A difference of the supply pressure between 25 kPa in Fig. 5 and 50 kPa in Fig. 7 is small enough to have an effect on the pressure profile. In Fig. 8 where the shaft speed is raised from 600 rpm in Fig. 5 to 1000 rpm, a widely expanded fluctuation of pressure is well characterized by quasi-

Sommerfeld type. In the figure the trough of calculated Sommerfeld pressure falls below absolute 0 atm(=-101.325kPa), while the measured one drops no further than about -85 kPa which is nearly the same trough pressure in Fig. 6.

Another experiment by the use of ISO VG 10 oil gave almost the same trends with those by VG 22 oil. Consequently,all the empirical data shows that quasi-Sommerfeld state is rather common in unruptured film formed by using mineral oils than Sommerfeld state which can be seen only in small fluctuation of pressure.

3.2 Continuous film and perfect film

Unruptured oil-film hardly occurs in ordinary full journal bearings and has been left in an unsatisfactory experimental study. A limited number of empirical data on the film have agreed nearly with Sommerfeld solution. Consequently, many lubrication researchers have took it for granted that the unruptured film in full journal bearings exhibits pressure profile of Sommerfeld type and they have often called the film perfect film.

However, our present experiments clarified that Sommerfeld theory does not always explicate unruptured film but quasi-Sommerfeld state is rather common in the film formed by using practical lubricants. This fact suggests that the pressure data of apparent Sommerfeld type really belong to quasi-Sommerfeld type and we only can not discriminate the subtle difference between the data and the theory. Perfect film which throughly satisfies Sommerfeld solution can be formed only by using ideal but inexisting lubricant. Unruptured film formed by oils in general use exhibits pressure profile of quasi-Sommerfeld type. Now, we use the term "continuous oil-film" to specify the practical unruptured film. Continuous oil-film is not a single state; it approaches perfect film on one side and the state just before film rupture on the other. At in-betweens, it exhibits the typical quasi-Sommerfeld state.

3.3 Fine bubbles in oil

Continuous oil-film just before rupture is attended by an intermittent flow of visible fine bubbles. The fine bubbles control the continuous film and produce the pressure distribution of quasi-Sommerfeld type. The pressure distribution varies its profile depending on the number and magnitude of bubbles, their flow state and so on.

A slight disturbance is effective enough to cause rupture to continuous film accompanied by a deep and negative pressure trough. Just before film rupture, the 'to and fro' motion of part of bubbles against the flow of oil is observed astride the position of minimum clearance. One of bubbles, once being caught at a little downstream of minimum clearance,rapidly grows up to cavities to make film rupture. At the outlet boundaries of cavities, foaming takes place with the resultant fine bubbles flowing downstream in a row.

In addition to visible bubbles, invisible more minute bubbles may flow in oil-film (14)-(15). Fine bubbles produce three different profiles of pressure distribution depending on the magnitude of their effect on the mother lubricant. Too small effect of fine bubbles to recognize produces the profile of Sommerfeld type and a moderate effect produces that of quasi-Sommerfeld type. Too large effect to keep continuous film causes film rupture. We have to pay more attention to fine bubbles flowing in the film region of ruptured film.

The growing up or down of bubbles or cavities depends on the flow of the gas into and out of the bubbles or cavities. The mechanism whereby bubbles or cavities in liquid grow up or down relates to diffusion phenomena and is a complicated problem, especially that of bubbles in oil. The flow of bubbles in oil constitutes a series of film rupture phenomena and preceding one, and also remains to be studied.

4 CONCLUSIONS

The results of the present research on continuous oil-film formed in a full journal bearing equipped with circumferential oil grooves at both ends of the bearing may be summarized as follows:

(1) Quasi-Sommerfeld state is rather common in unruptured film formed by using practical mineral oils than Sommerfeld state.

(2) Pressure data of quasi-Sommerfeld type are characterized by downstream shift of pressure profile and underdevelopment of pressure trough compared with Sommerfeld distribution.

(3) Sommerfeld distribution for perfect film is approximately observed only under limited operating conditions.

(4) The term "continuous oil-film" is used in order to specify the practical unruptured film and to discriminate it from perfect

film.

(5) Continuous oil-film approaches perfect film on one side and the state just before film rupture on the other. At in-betweens it exhibits the typical quasi-Sommerfeld state.

(6) Continuous oil-film is accompanied by fine bubbles, visible and/or invisible, and is controlled by the growing up or down of the bubbles.

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