17th World Conference on Nondestructive Testing, 25-28 Oct 2008, Shanghai, China

Observation of Trapped Thin Oil Film Behavior between Ball and Disc with Using Ultrasonic Technique

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Abstract

Observation of the behavior of trapped oil film in Hertz contact region such as a ball and disc becomes an important theme even though the diameter of the trapped area is narrow with less than 0.5mm and the thickness is extremely thin with several hundred nanometers, because the contact between metals is avoided by this thin film and the safe driving can be secured. In this study, the measurement of oil film thickness and the observation of trapped oil film were carried out with using ultrasonic technique. The amplitude of the reflection wave from the boundary depends on the conditions of formation of trapped oil film as the ultrasonic wave emitted to the interface formed by a ball and a disc does multiple reflections in oil film. As a result of the measurement of oil film thickness with using an ultrasonic technique, it became clear that ultrasonic technique can measure the film thickness of about 50nm in the case of standstill surface with extremely small surface roughness. Furthermore, the potential that grasp the difference of the trapped conditions and the time change of formation conditions (oil film thickness) about some kinds of oil was able to clarify for bearing steel used in a normal ball bearing.

Keywords: Ultrasonic technique, Ball bearing, Bearing steel, Trapped oil film, Nanometers scale

1. Introduction

In recent years, oil film thickness of lubrication surface reaches nanometer scale as represented on elastohydrodynamic lubrication (EHL) film of a traction drive. It was reported that the solid contact in a Hertz contact region of two surfaces may be avoided by the oil which became high viscosity under the high pressure, when both rollers of traction drive became to stop. Meanwhile, when the wheels of a car run onto a rough road and are shocked, lubrication oil is also trapped between the ball and race of the bearing. The measurement of such a thin film has been conventionally performed by an optical method using transparence materials for one of frictional surface[1]. However, observation of trapped oil film between real lubrication surfaces such as combination surface of steel with roughness becomes important in particular for thin film lubrication.

In this study, the behavior of trapped thin oil film described above is evaluated with using ultrasonic technique. The ultrasonic waves emitted to the lubrication interface do a multiple reflection in the oil film, and the echo height of reflected waves from the boundary is dependent on trapped oil film thickness. Sound impedance, namely sound velocity and density of oil, increases with high pressure of oil in there, however, and sound impedance of oil becomes near to that of steel. Therefore it may become difficult even to detect the existence of oil film since the height of echo reflected from trapped region becomes extremely low.

For solving such a problem, highly precise ultrasonic flaw detector having resolving power of 0.1% in echo height is used to measure the minute echo height fluctuation. And the behavior of trapped oil when a steel ball impulsively came in contact with a steel disc on which the oil spread, is evaluated with observing a magnitude of reflection echo height and of a change of echo height during a load period. In this paper, those investigation results are described.

2. Measurement of Thin Oil Film Thickness in Nanometer Scale

As shown in Figure1, when an ultrasonic pulse is irradiated into an oil film and its thickness is less than the pulse width, multiple reflections will be occurred. Then the echo height h of the first reflected waves from the boundary (Second echo) changes in response to the oil film thickness. It will then be possible to estimate the film thickness L_m, which is a mean film thickness decided by $L_m=L_0+L=(R_{y1}+R_{y2})/2+L$, from observed h, where R_{y1} and R_{y2} are the surface roughness of the first material (Steel plate) and the second material (Steel ball) respectively[2-4]. In ideal situations, when the thickness of the first material is thick enough compared with a dead zone of ultrasonic flaw detector, oil film is in the atmospheric condition and both surfaces are completely parallel, film thickness L_m is able to calculate from the theoretical relation of the echo height and thickness[5]. In this study, echo height ratio, $H=h/h_0\times 100$ %, is defined for the evaluation of lubrication conditions, where h is the echo height observed in operation, and h_0 (Base echo height) is the echo height from the dry boundary.

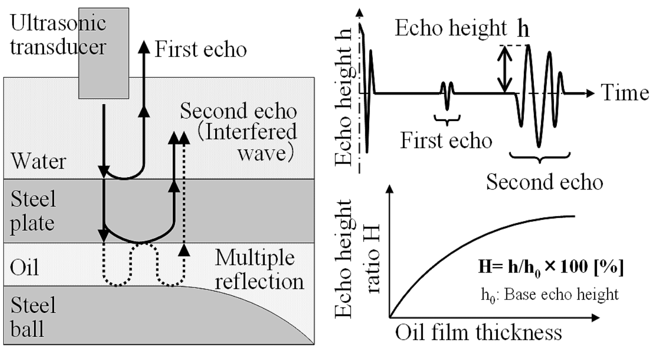


Figure 1. Measurement principle of oil film thickness

Figure 2 shows the schematic view of the experimental equipment. The potential of measurement of extremely thin oil film thickness formed between glass convex lens having 44m radius and flat glass plate, both surfaces are smooth (R_y is about 52nm), is investigated by using the ultrasonic probe which has 50MHz central frequency and 0.2mm focus diameter. And the film thickness estimated from the echo height ratio H is compared with a measurement result obtained by the optical interference method using the green light emitting diode which had resolving power of 86nm for the film thickness.

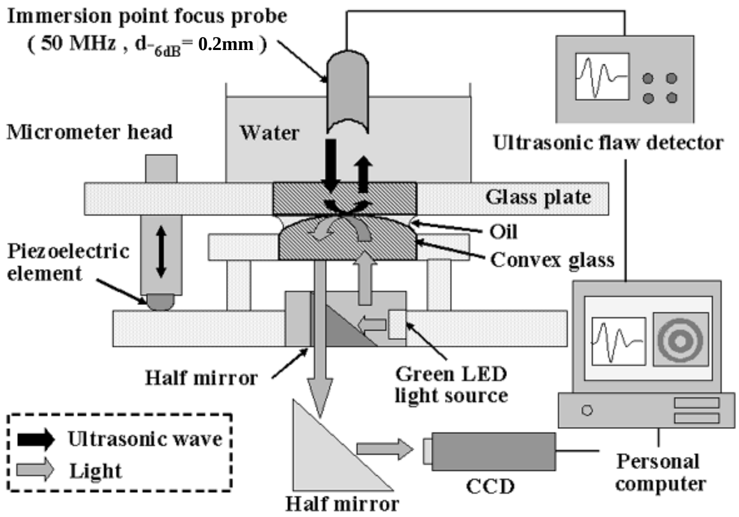


Figure 2. Schematic view of experimental equipment

An example of the result is shown in Figure 3. Oil film thickness estimated from the H agrees with the film thickness decided by the curvature of the lens or obtained by the optical interference method described above, even if it is about 50nm as shown in Figure 3. This result shows a potential which can estimate the film thickness in nanometer scale by an ultrasonic technique, if surface roughness is extremely small.

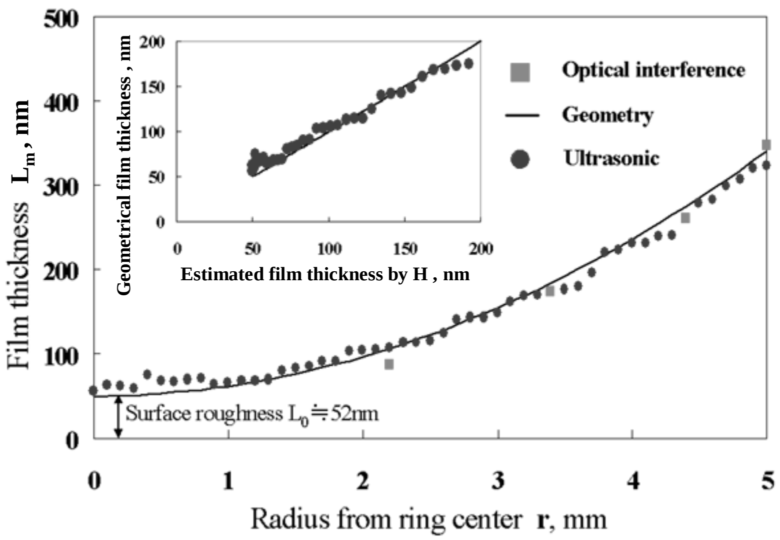


Figure 3. Film thickness measurement results by optical method and ultrasonic technique

3. Observation of Trapped Oil Film

Observation of the behavior of trapped oil film in Hertz contact region such as a ball and disc is important because the solid contact between metals is avoided by such a thin film and safe driving can be secured. A schematic view of experimental equipment for the observation of trapped oil film is shown in Figure 4. The behaviors of trapped oil film when a steel ball of 1 inch in diameter (R_a=0.01μm) came in contact impulsively with the steel disc (R_a=0.04μm) on which the oil spread were observed with using a immersion probe, which has a nominal center frequency of 50MHz and focal diameter of 0.2mm.

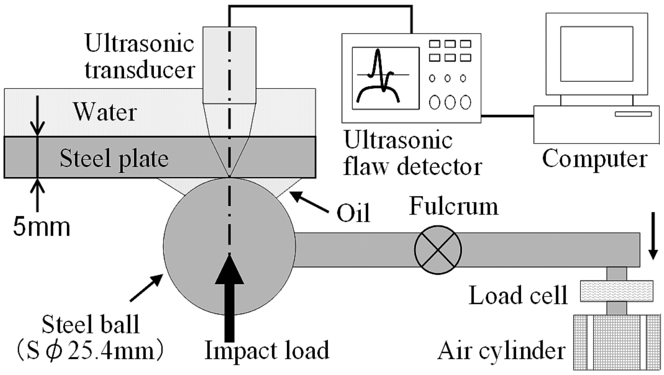


Figure 4. Schematic view of experimental equipment

Figure 5 shows a variation of load between contacting surfaces measured by a load cell set to an air cylinder. In this study, following experimental data are arranged with loading speed at initial stage of loading, which affects degree of the occurrence of trap. Dafney turbine oil (DN100) and Santotrac basis oil (ST) of a property shown in table 1 were used as sample oil. Santotrac basis oil (ST) is commonly used as a traction oil, and the pressure-viscosity coefficient α which shows the degree of increase of viscosity with a pressure is larger than that of Dafney turbine oil (DN100). Therefore ST is solidified under the high pressure and becomes difficult to leak from trapped region.

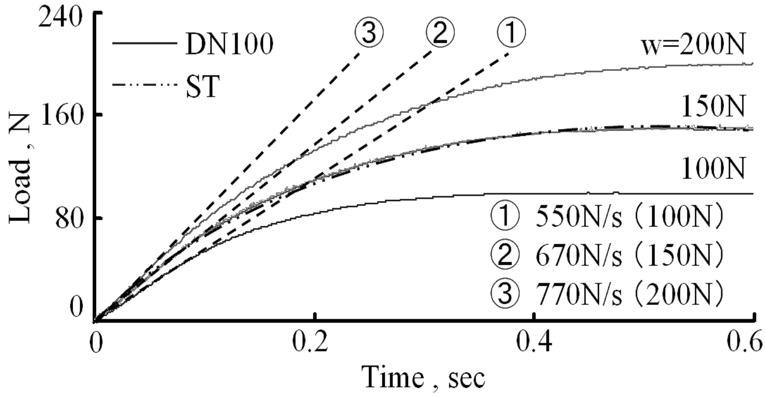


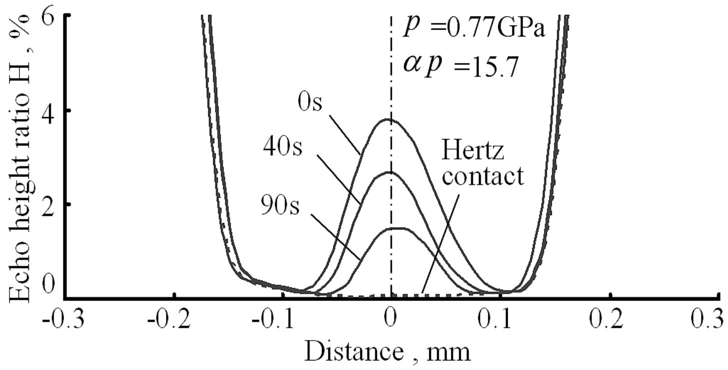
Figure 5. Loading curve and loading speed

Table 1. Property of sample oil

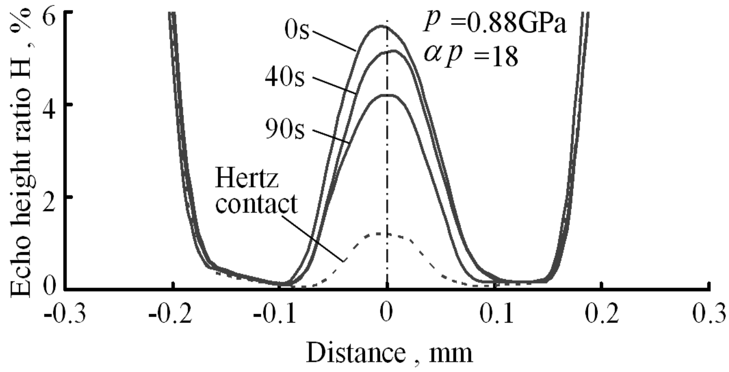
	ST	DN100
ρ	0.88	0.87
m/s	1435	1326
ν	20.4 (40deg.)	98.6 (40deg.)
α	30	20.9

P: Density, c: Sound velocity, ν: Kinetic viscosity
α: Pressure-viscosity coefficient

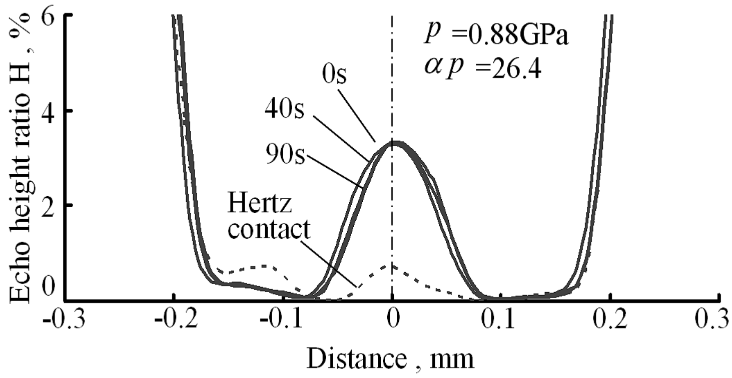
Distribution of echo height ratio H in a direction of diameter of a Hertz contact circle formed by a contact between steel disc and steel ball is shown in Figure 6. In the same Figure, measurement result of echo height H under extremely slow loading speed in which there is little potential to trap the oil is shown by a dashed line (Hertz contact).



(a) DN100_550N/s(w=100N)



(b) DN100_670N/s(w=150N)



(c) ST_670N/s(w=150N)

Figure 6. Distribution of echo height ratio H

For example, echo height ratio H when a steel ball impulsively came in contact with the steel disc is high at the center of trapped region (0mm) and low in outside as shown in Figure 6. And distribution shape of measured H agrees with that of trapped oil film thickness generally observed by light interference method[6]. Because the echo height ratio H lowers with the time (0sec,40sec,90sec), it can be judged that trapped oil in case of DN100 oil had been leaked gradually as shown in Figure 6(a)(b). On the contrary, a variation of H in a range of measurement time of 0-90 seconds is not recognized in case of ST oil that pressure viscosity coefficient α is large. This result shows solidification of ST oil trapped by high pressure.

4. Conclusions

An ultrasonic technique was applied for the purpose of the evaluation of thin oil film formation between contacting surfaces such as a ball/disc. In this technique, pulse ultrasonic wave was emitted from the back side of the first object to boundary surface, and then the state of oil film formation was estimated by the echo height reflected from there. As the result, the followings became clear.

(1) Mean film thickness of the oil film is able to calculate from the theoretical relation of the echo height and thickness in ideal situations.
(2) Oil film thickness of about 50nm is able to measure in the case of standstill surface with extremely small surface roughness.
(3) Observation of the film formation of trapped oil between ball and disc with roughness is possible even in the condition at which the height of echo reflected from trapped region becomes extremely low by the influence of the high pressure in trapped region.
(4) No-leakage of trapped oil in 90 second is achieved in case of a Santotrac basis oil (ST) of which the pressure-viscosity coefficient α is large and solidification is relatively easy.

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