Ultrasonic monitoring of lubricating conditions of hydrodynamic bearing

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Abstract. The performance of a hydrodynamic bearing is illustrated by the lubricating conditions which transfer from one to another when working condition is changed. The thickness of lubricant film is the key parameter of lubricating conditions. The lubricating conditions of hydrodynamic bearing can be monitored by the measured film thickness and the relationship between them. For thin lubricant film layers less than ultrasonic wavelength, the spring model method is applied to measure the film thickness. The proportion of the ultrasound reflected from film layer, depended on the film stiffness, is determined and then can be readily converted to the film thickness. For the thicker films ranging from several microns to tens microns, ultrasonic resonance method was employed. An adaptive measurement algorithm is presented to automatically choice appropriate ultrasonic measurement method according to the different lubricating stage. All the range of lubricant film thickness of a hydrodynamic bearing can then be measured by the automatic selection of spring model and resonance methods. Simulation device of lubricant film layers with PZT positioning stage is designed to verify the accuracy of the adaptive measurement algorithm. Hydrodynamic bearing experimental setup is used to generate varies of lubricating condition by changing the shaft speed, radial direction loading force, and lubricant temperature. The lubricating condition of hydrodynamic bearing is then evaluated according to the measured lubricant film thickness and the working conditions.

1. Introduction

As tribological components and supporting parts, hydrodynamic bearings are core components of varies of high-speed and high-precision rotating equipments. Whither equipments can run steady or the running qualities of equipments are directly affected by the performances of hydrodynamic bearings. Breakdown and failure of lubricating film are all the inducements of equipment abnormal, industrial accident, wear and seizure of lubricating surfaces. Therefore, lubricating condition monitoring of hydrodynamic bearing is of great importance for the ensuring of safety and steady running of rotating equipments.

The thickness of the lubricating film is a key parameter for tribological components such as hydrodynamic bearings. If the film is too thin, then surface contact can occur resulting in high friction and wear. If the film is too thick, energy is expended needlessly in overcoming churning loses [1]. The thickness of a lubricating film depends on the lubricant properties, the geometry of the bearing

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surfaces and the operating conditions. Film thicknesses usually range from approximately 0.1 micron to tens of microns. The lubricating film is so thin that it is difficult to measure by general method.

Traditional techniques for lubricating film thickness measurement in bearings, by either electromagnetic or optical means, suffer from serious drawbacks. The sensor or probe located at the bearing contact face or penetrated through a transparent window may all structurally weaken the bearing component and or disrupt the formation of the lubricating film. Therefore, these methods are generally used to test of modified bearings and can rarely be used outside of the laboratory.

Ultrasonic methods for lubricating film thickness measurement are studied by scholars. Ultrasonic waves propagate through a bearing shell and reflect from a lubricating film. The thickness of the lubricating film is then be determined and measured by the proportion of the wave reflected. Ultrasonic measurement method has broad application prospects for which does not have these theoretical drawbacks.

In [2-3], ultrasonic measurement principles for lubricating film thickness are discussed and the measurement range of basic there methods are investigated. An ultrasonic time-domain measurement method for thin plate is discussed in [4]. Theoretical basis and application procedure of spring model method are studied in [5], and reflection coefficient solution and its application in journal bearing are explained. Liquid film is monitored by time-domain and frequency-domain approach in [6]. High frequency ultrasound is successfully used in the measurement of ball bear lubricating film thickness [7][8]. Auto-calibration ultrasonic measurement method presented in [1] improved the performances and extended the utilization of spring model method, which can obtain the reference reflection coefficient without separating the lubricating components and compensate the temperature effects of transducer.

In this study, ultrasonic resonance method and spring model method are combined to measure the all range of lubricating film thickness of the hydrodynamic bearing. An adaptive measurement algorithm is discussed, which can automatically choice appropriate ultrasonic measurement method according to different lubricating stage. Simulation device of lubricating film layers with PZT positioning stage is designed to verify the accuracy of the adaptive measurement algorithm. Hydrodynamic bearing experimental setup is designed to generate varies of lubricating condition by changing the shaft speed, radial direction loading force, and lubricant temperature. The lubricating condition of hydrodynamic bearing is then evaluated according to the measured lubricating film thickness, these running parameters, and the Streibech experimental curve.

2. Background

2.1. lubricating conditions of hydrodynamic bearing
According to classical lubrication state diagram shown in Streibech experimental curve, lubrication state is divided into hydrodynamic lubrication, mixed lubrication, and boundary lubrication three regimes. Dowson increases the fourth lubrication state of elasto-hydrodynamic lubrication (EHL) to the classical lubrication state diagram.

Lubricating film thickness is 3 to 5 times the value of composite surface roughness of lubrication surface in hydrodynamic lubrication regime according to classical lubrication theory. In mixed lubrication regime, lubricating film thickness is about 3 times the value of composite surface roughness. In boundary lubrication regime, lubricating film thickness is more small and close to zero. EHL film thickness is between hydrodynamic lubrication film thickness and mixed lubrication film thickness.

Hydrodynamic lubrication is often the key technology to ensure high-tech equipment and ultra-precision machine work. And according to classical lubrication theory, lubrication state changes one state to another with the changing of speed, load and lubricant viscosity. Therefore, lubrication condition monitoring of hydrodynamic bearings plays important role to ensure equipment safe and reliable.

2.2. Ultrasonic lubrication film thickness measurement
2.2.1. Ultrasonic reflection at an interface

When an ultrasonic wave strikes an interface between two perfectly bonded media (see Figure 1), some proportion of the wave amplitude will be transmitted, whilst some is reflected [1]. The proportion of the wave reflected, known as the reflection coefficient, \( R \) depends on the acoustic impedance of these two materials. Typically for a wave passing through steel and striking an water interface, approximately 93.5% of the wave amplitude is reflected (\( R = 0.935 \)).

![Figure 1. Some cases of liquid film interface between two perfectly bonded media](image)

If ultrasound is incident on a layered system then some of the wave will be reflected at the front face of the layer and some at the back face. For thick layers, the reflected pulses separated and it is possible to distinguish the discrete reflections in the time domain. From the time between the reflected pulses and the acoustic velocity, the lubricating film thickness is readily obtained. But the lubricating film thickness of hydrodynamic bearings is usually too thin to use this simple method.

2.2.2. Resonance method

When an ultrasonic wave excited from a frequency adjustable transducer is normally incident on a specimen, resonance occurs in the thickness direction of specimen if the specimen thickness equal to an integral multiple of ultrasonic half-wavelength. Adjusting ultrasound incident frequency from low to high, a series of resonance frequencies can be captured from response ultrasonic wave.

In reflection coefficient spectrum, resonance frequencies show as a series of minima. If, in this way, layer resonant frequencies are measured, film thickness can be obtained with the sound speed.

The thickness of a lubricating film is given by

\[
h = \frac{cm}{2f_m}
\]

(1)

Where, \( c \) is the speed of sound in the lubricant layer, \( h \) is the thickness of lubricating film, \( m \) is the mode number of the resonant frequency and \( f_m \) is the resonant frequency (in Hz) of the \( m \)th mode.

In order to improve the measurement accuracy of film thickness, nonadjacent resonant frequencies are used to calculate the film thickness by take their average, instead of using one frequency or two adjacent resonant frequencies. The film thickness calculated by this method is given by

\[
h = \frac{(n - m)c}{2(f_n - f_m)}
\]

(2)

where, \( n \) greater than \( m \) is also the mode number of the resonant frequency. Obviously, film thickness can be calculated of higher precision by take some nonadjacent resonant frequencies and get their average.

The through-thickness resonance method is a particularly robust approach, for ultrasonic film thickness measurement, which requires only the amplitude spectrum of the reflected wave. Meanwhile,
the higher resonant frequencies correspond to thinner lubricant films. In practice the frequency is limited by the attenuation of the ultrasonic pulse in the bearing materials. Typically, ultrasonic testing above 60 MHz becomes difficult due to attenuation in the bearing materials. So, resonances are only likely to be observed for the thicker films at higher frequencies. This means that if the lubricant layer is below about 10 µm, the resonant frequency will be above the measurable range [2].

2.2.3. Spring model method
Resonance method can be used to measure thick film which is greater than ultrasonic wavelength. If the lubricant film thickness is very thin with respect to the ultrasonic wavelength, then the system can be treated quasi-statically and the layer behaves like a spring. By considering the interaction of ultrasound with the lubricant layer and compatibility at the boundaries of the layer during the wave passage, a spring model approach is used to measure thin film and the reflection coefficient depends on the spring stiffness of the layer, $K$ according to [9]

$$
R = \frac{z_1 - z_2 + i\omega(z_1 z_2 / K)}{z_1 + z_2 + i\omega(z_1 z_2 / K)}
$$

(3)

In the case of the materials either side of the interface are identical $z_1=z_2=z$, this reduces to

$$
|R| = \frac{1}{\sqrt{1 + (2K / \rho c)^2}}
$$

(4)

The normal stiffness of a fluid layer, $K$ in terms of its acoustic properties is given by

$$
K = \frac{\rho c^2}{h}
$$

(5)

where $\rho$ is the fluid density, $c$ is the longitudinal wave speed of the fluid, and $h$ is the lubricant film thickness.

Finally, combining equation (4) and (5) and rearranging, gives the film thickness in terms of the reflection coefficient and properties of fluid layer.

$$
h = \frac{\rho c^2}{\pi f z} \sqrt{\frac{R(f)^2}{1 - R(f)^2}}
$$

(6)

Where $z$ is the acoustic impedance of the media surrounding the lubricant film, $R(f)$ is the amplitude of the measured reflection coefficient, which is a function of the ultrasonic frequency $f$. In general, the reflection coefficient is measured by comparing the signal reflected from the interface of interest to that from a known reference interface:

$$
R(f) = \frac{A(f)}{A_{ref}(f)} R_{ref}
$$

(7)

where $A(f)$ is the amplitude of the signal reflected from the lubricant-film layer, $A_{ref}(f)$ is the amplitude of the reference signal, and $R_{ref}$ is the reflection coefficient of the reference interface. The reflection coefficient calculated from equation (7) can then be used in equation (6) to extract the lubricant film thickness.

Figure 2 shows the expected reflection coefficient variation against frequency for a series of oil films between steel bodies (according to equation (6)). The figure shows that it is possible to use nondestructive testing frequencies range of 0.5~50 MHz to measure the thickness of lubricating films in common hydrodynamic bearing.
Figure 2. Reflection coefficient spectra for a range of water film thickness between steel bodies according to the spring model.

A reference reflection coefficient $R_{ref}$ is often acquired from steel-air interface by separating the lubricating components. This restricts the actual application of spring model method. Reference 1 introduced a new reference-free approach. A reference reflection coefficient is constructed by the relationship between the amplitude and phase of reflected wave. The further valuable aspect of this approach is its ability to be used as a self-calibrating routine to inherently compensating for temperature effects.

$$A = A_0 \cos(\phi - \phi_0)$$  \hspace{1cm} (8)

This relationship is the basis of the auto-calibration technique [1]. In practical terms the reflected amplitude and phase ($A$ and $\phi$) are measured simultaneously. $A_0$ and $\phi_0$ are the reference amplitude and phase, and they are found by fitting the equation (8) to the set of measured data using a least mean squared (LMS) algorithm. This is feasible because the reference amplitude and phase remain constant. Then $R_{ref}$ can be obtain form the relationship between the reference amplitude and phase.

3. Adaptive measurement algorithm

Lubricant film thickness measurement can be carried out in two methods as mentioned above. If the film is sufficiently thick, a high frequency transducer can be used to measure the thickness of lubricating film by the resonance method. For thin film less than ultrasonic wavelength, the spring model method can be used to measure the film thickness. In this case, the amplitude of the reflected wave is needed. Using auto-calibration technique, reference reflection coefficient can be obtained by LMS curve fitting and the relationship between amplitude and phase. Then the film thickness can be calculated according to equation (6) and (7).

In the actual measurement of lubricating film thickness, the lubricating film thickness of hydrodynamic bearings changes with the changing of load and speed and other factors. At the same time, lubrication condition may transition in the three lubrication states. For some hydrodynamic bearings of large equipments, lubricating film thickness ranged from 20µm to 80µm in range under normal operation, and which ranged from about 0 to 20µm in the process of machine startup or stopping when mixed lubrication and boundary lubrication may occurs.
Therefore, every one of this two measurement methods can not monitor all distribution range of the lubricating film thickness. In the lubrication conditions monitoring of this kind bearings, an adaptive algorithm for measurement methods selection is discussed, which can choose automatically appropriate measurement method according to different film thickness ranging. Adaptive algorithm adopts different measurement methods in accordance with the following rules. The speed of rotor is measured by the velocity sensor real-time. Equipment operation stages of either normal running or startup and stopping are judged by the program according the measured speed and basic equipment running information stored in advance. Therefore, the basic equipment running information such as speed range, rated speed and others should be reset and stored again in program if test object changes. In default, spring model method is firstly applied in the transitional stages, and in the normal operation stage resonances method is firstly applied.

Meanwhile, at any operation stage, lubricating film thickness ranging may change as working conditions change such as load, temperature, etc. Thus, two measurement methods should be changed freely and quickly in any one operation stage. Firstly, pulse frequency of transducer is adjusted through upper computer. If the ultrasonic reflection coefficient remains close to 1 at the low frequency band, the lubricant film thickness is too thick to be measured with the spring model method. Program automatically switches to the resonance method immediately. On the contrary, if the distinct minima in reflection-coefficient spectra do not appear in the whole frequency range while adjusting the transducer frequency, the lubricant film is too thin to be measured with the resonance method and program automatically switches to spring model method.

4. Experimental Apparatus

Figure 3 shows schematic of the measurement apparatus and lubricating film simulation device. An ultrasonic pulser-receiver (UPR) with ultrasonic transducer is used to generate and receive required ultrasonic wave. The pulser produces an electrical pulse exciting a transducer, creating an ultrasonic wave. A longitudinal wave ultrasonic transducer with a centre frequency of 10 MHz and a bandwidth of 7.5~13 MHZ (defined at the −6 dB points) was located to the test steel block or bearing such that it would send and receive pulses perpendicular to the lubricating film. The transducer was driven by UPR and operated in a pulse-echo mode. The transducer then receives reflected pulses back from the lubricating film. The reflected pulses are amplified, captured and digitized (at 200 MS/s) on the digitizing card, and stored on the PC for post-processing and analysis. The PC controls the UPR via the RS232 port, setting the pulsing frequency, pulsing rate and the amplification of the received signal. The PC also controls the oscilloscope for the capture of reflected signals. And big role of the PC is to switch measurement methods and select appropriate method according to different film thickness range.
A fluid film layer was produced by sandwiching the water or oil between upper and lower block of PZT positioning stage. PZT positioning stage has maximum displacement of 80μm and positioning resolution of 0.1μm. Displacement of positioning stage is controlled by the digital high-resolution DC power supply. Changing the displacement of positioning stage, water in tank of the middle stage can form fluid film layer of different thickness. Fluid film layers simulating all range of the lubricating film are used to verify the adaptive measurement algorithm and measurement methods. Model diagram and cross-section diagram of the PZT positioning stage used is shown in figure 4.

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**Figure 3.** Schematic of the measurement apparatus and lubricating film simulation device.

**Figure 4.** Model diagram and cross-section diagram of PZT positioning stage for lubricating film thickness simulation.

Experimental setup for lubricating condition monitoring of hydrodynamic bearing is shown in figure 5. Experimental setup consists of hydrodynamic journal bearing, water supply systems, non-
contacting electromagnetic loading device, speed motor, lubrication water heating systems and various sensors. Lubricating condition of bearing changes when the rotor speed, loading force of shaft radial direction, and lubricant temperature are changed. All these working parameters are measured by varies of sensors in real time. Then, the lubricating condition of hydrodynamic bearing is evaluated by measured lubricating film thickness and these working parameters according to Streibeck experimental curve.

![Figure 5. Experimental setup for lubricating condition monitoring of hydrodynamic bearing.](image)

5. Results and Discussion

Controlling liquid film thickness of lubricating film simulation device by programmable DC power supply, a series of thickness values from 0.1µm to 2µm paced of 0.1µm are produced. Subsequently, 2µm to 75µm thickness paced of 1µm are produced. Adaptive measurement program is used to measure these series of film thickness, to verify the accuracy of the measurement algorithm. Reflected pulses recorded for a series of water films of thicknesses from 11µm to 15µm in measuring process is shown in figure 6. Measured fluid film thickness compared to that preset by PZT positioning stage is shown in figure 7.

It is seen in figure 7 that the adaptive measurement algorithm has the different accuracy in the different film thickness range. Higher accuracy can be achieved in thickness range of approximately from 0.1µm to 40µm and the range of from 62µm to 75µm. This measurement accuracy can meet the general measurement requirements. But, in range of approximately from 40µm to 62µm, the measurement results deviate from the preset thickness values considerably. The measurement accuracy in this range is comparatively low.

Changing the rotation speed of the experimental setup, adaptive measurement program is used to measure the film thickness under the same loading force. Variation of measured film thickness is not obvious. And the measurement results are dispersed much that may be due to the vibration of experimental setup. In addition, changing the size of the loading force of the experimental setup, adaptive measurement program is used to measure the film thickness under the same rotation speed.
The measured film thickness varied obviously. But the results remain dispersion, and the accuracy of measured results is still not very well.

![Figure 6](image1.png)

**Figure 6.** Pulses recorded for a series of water films of thicknesses from 11µm to 15µm.

![Figure 7](image2.png)

**Figure 7.** Measured fluid film thickness compared to that preset by PZT positioning stage.

### 6. Conclusions

An adaptive ultrasonic measurement program is developed to measure the lubricant film thickness of hydrodynamic bearings. The program measured all distribution range of the lubricant film thickness through chooses automatically appropriate measurement methods. And every one of present methods is suited to measure a specifically range of lubricant film thickness. The film layer simulation device is designed to generate all range of lubricant film thickness. The adaptive measurement program is used
to measure the liquid film thickness changed in simulation device, and the adaptive algorithm is verified by the measured results. Results show that the adaptive measurement algorithm has high measurement accuracy, and the film layer simulation device has the ability to generate all general ranges of film thickness.

Measurement accuracy is not high in the film thickness range approximately from 40µm to 62µm if using transducer of 10MHz center frequency and the lubricant is water. This is mainly due to the less sensitive of spring-film thickness method to the variation of film thickness in this range while the resonance occurs rarely of resonance method in this rage. The accuracy of measurement in this range can be improved by using a wider frequency band transducer and adjusting the frequency of the transducer.

Lubricant film thickness of experimental setup under different working conditions is measured by the adaptive measurement program. And the lubricating condition of hydrodynamic bearing is evaluated according to the measured results and the working conditions. The measurement accuracy in experimental setup is affected by the vibration of equipments, the processing speed of the measurement program, and the varying speed of film thickness. Lubricating condition under high rotating speed can be monitored by improving the processing speed of measurement program.

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