

Ultrasonic measurement of oil film thickness using piezoelectric element

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Abstract Ultrasonic method is promising in oil film thickness measurement, while the commonly used commercial transducers are bulky and then sometimes hinder the application of this technology in field. Using the piezoelectric element is an alternative method and has the advantage of being convenient to be fixed. In this work, the key points of the use of the piezoelectric element are summarized. A calibration rig is set up to test the performance of oil film thickness measurement using piezoelectric element. The results show that using the piezoelectric element can measure the oil film thickness effectively and accurately.

Keywords Ultrasonic · Oil film thickness · Piezoelectric element · Calibration rig

1 Introduction

Oil film thickness is a key indicator of the lubrication state in machine components such as bearings, gears, and seals; the thickness of the oil film layers has a significant effect on their

performance, efficiency, and life. Measurement of this oil film thickness can provide a quantitative way to monitor the lubrication state and then can void the failure of the machine caused by poor lubrication timely. As the thickness of such films is usually at micron or sub-micron scales and the films are normally located at a closed space, accurate measurement is very difficult to achieve. Until now, there are several techniques available to do this measurement based on the electrical [1–3], optical [4, 5], or acoustic [6–8] characteristics of the oil film layer. The electrical methods obtain the oil film thickness via the resistance or capacitance of the oil film layer. When doing this measurement, the electrical methods require the sensors contact with the up and down interfaces of the oil layer thus will lead to a big damage on the equipment structure and also affect the formation of the oil film layer. This makes them difficult to apply in many industrial applications. Optical methods are the most accurate methods which can measure the oil film thickness of nanometer scale while they require a transparent window through which to make the measurement and so are rarely used outside the laboratory.

In comparison with the methods mentioned above, benefiting from the strong penetrability and linear propagation of the ultrasound, the ultrasonic method removes the requirement of sensors' contact with the oil layer or material transparency and is a very promising method. Among the ultrasonic methods, time of flight (TOF) is the first appeared method and has been used in many industrial occasions. For thick oil layer, the oil film thickness can be obtained by measuring the time difference between the reflected signals from the up and down interfaces of the layer. While when the oil film thickness falls below 100 μm , the decreasing time difference between the returning signals begins to overlap in the time domain, and an accurate measurement of the TOF between them cannot be made. As the oil films observed in tribological applications are typically in micron or sub-micron scale, TOF measurements

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are therefore unfeasible. To overcome this problem, two novel ultrasonic techniques have been developed which aim to accurately measure the thickness of films below 100 μm . One method uses the resonant frequency of the oil film and is known as the resonance frequency method. The other one is based on the reflection ratio of the ultrasound on the oil layer, known as the spring model approach [9]. The resonant frequency method [10] can measure the oil film thickness in the range of 10–100 μm , and the spring model [7] is powerful in measuring oil film thickness below 10 μm . Since the spring model was proposed by Drinkwater in 2003, the ultrasonic methods were then extensively used to measure oil film thickness in various tribological components such as ball bearings [11], roller bearings [12, 13], seals [14], journal bearings [15], and thrust bearings [16] in laboratory.

As a non-invasive method, the linear propagation of the ultrasound inherits the advantages of the optical methods, and the strong penetrability of the ultrasound overcomes the drawback of requirement on transparent window or transparent material in optical methods. When measuring the oil film thickness in tribological components by ultrasound, the use of commercial transducers is common. They come in different configurations and frequencies and are ready to use. The commonly used commercial transducers in ultrasonic oil film thickness measurement include commercial NDT contact transducer and commercial NDT immersion transducer. The setups of them are shown in Fig. 1a,

b, respectively. From Fig. 1, it can be seen that both the commercial NDT contact transducer and the commercial NDT immersion transducer are bulky and need a large space to be fixed. However, in some cases, it is not feasible to use a commercial transducer as the tight space. Using the bare piezoelectric element becomes an alternative method. Compared with the commercial transducers, the bare piezoelectric element has several advantages. Firstly, the bare piezoelectric element is very thin (e.g., a 10-MHz piezoelectric element made from PZT5A3 is only about 0.2 mm); it can nearly be set up in any occasion with little change on the structure of the machine. Secondly, the commercial transducers use the water or water-based gel as the coupling agent, so the measured signal is easy to be influenced by the machine vibration, while the bare piezoelectric is normally bonded on the back of the tribological components with adhesive which acts as both curing agent and coupling agent; the measured signal therefore is very stable. Furthermore, the bare piezoelectric element can be cut into nearly any figures and sizes as expected, and it can be used in the applications which require high space resolutions.

Though the bare piezoelectric element is promising in field application, it is not easy to use. The performance of the piezoelectric element is a function of bonding, soldering, and pulse conditions. In this paper, some key points on the use of piezoelectric element are summarized, and a calibration rig was set up to verify the accuracy of oil film thickness measurement using the piezoelectric element.

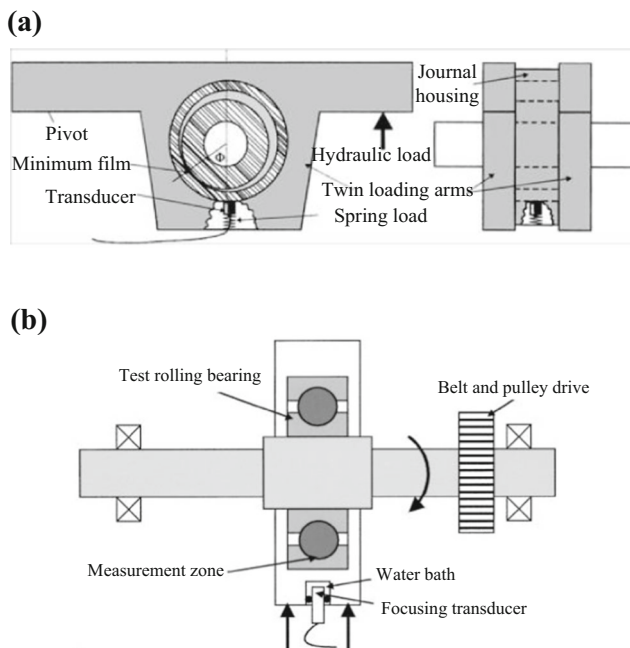


Fig. 1 The schematics of the setup of the commercial NDT transducers (a) commercial NDT contact transducer (b) commercial NDT immersion transducer

2 Background

It is well known that when ultrasound reaches an interface between two acoustically dissimilar materials, some of the wave will be reflected while the others will be transmitted. The proportion of a wave reflected by an interface can be quantified in the form of reflection coefficient. The reflection coefficient is related to the acoustic dissimilarity of the interface materials by the relationship shown in Eq. (1) [17]:

$$R = \frac{z_1 - z_2}{z_1 + z_2} \quad (1)$$

where R is the reflection coefficient and Z_1 and Z_2 are the acoustic impedance of the materials either side of the interface.

When a sound wave reaches two-parallel but closely offset interfaces, the reflections from each interface will superimpose. In this case, the reflection coefficient cannot simply be calculated from Eq. (1). The reflections from the up and down

interfaces of the layer then can be regarded as one reflection. Assuming the material either side of the layer is the same, the reflection from a thin embedded layer can be expressed as the following [9]:

$$R(f) = \frac{\frac{1}{4} \left(\frac{Z}{Z_0} - \frac{Z_0}{Z} \right)^2 \sin^2 \left(\frac{2\pi h}{\lambda} \right)}{\sqrt{1 + \frac{1}{4} \left(\frac{Z}{Z_0} - \frac{Z_0}{Z} \right)^2 \sin^2 \left(\frac{2\pi h}{\lambda} \right)}} \quad (2)$$

where Z_0 ($Z_0 = \rho c$) is the acoustic impedance of the oil film, h is the thickness of the oil film layer, λ ($\lambda = \frac{c}{f}$) is the wavelength of the ultrasound in oil layer, Z is the acoustic impedance of the material on either side of the oil layer, R is the reflection coefficient, ρ is the density of the oil, c is the ultrasound speed in oil layer, and f is the ultrasonic frequency. The reflection coefficient is the amplitude ratio of the reflected signal comparing with the incident signal in frequency domain. As the incident signal is normally difficult to obtain, the reflection coefficient is often obtained by comparing the signal reflected from the oil layer to that from a known interference interface:

$$R(f) = \frac{A_m(f)}{A_{\text{ref}}(f)} R_{\text{ref}} \quad (3)$$

where $A_m(f)$ is the amplitude of ultrasonic waves reflected from the oil film layer, $A_{\text{ref}}(f)$ is the amplitude of ultrasonic waves reflected from the reference interface, and R_{ref} is the reflection coefficient of the reference interface. Typically, $A_m(t)$ would be measured by first isolating in time the signal reflected from the oil film from any other signals and converting this to frequency domain via fast Fourier transform (FFT) to obtain $A_m(f)$; the reference measurement is taken in a similar way, using the signal reflected from the reference interface. In this work, the reference signal was taken from a steel-air interface and the reference reflection coefficient, R_{ref} , was found nearly 1.

From Eq. (2), it can be seen that when the sine function $\sin(\frac{2\pi h}{\lambda}) = 0$, the reflection coefficient R reaches the minimal value; at this moment, $h = \frac{m\lambda}{2} = \frac{mc}{2f}$. Therefore, when there is minimal value in the effective bandwidth, we can obtain the oil film thickness via the frequency at where the minimal value happens. This is just the principle of the resonant frequency method.

Furthermore, when the thickness of the oil layer is much thinner than the wavelength of the ultrasound in the oil layer

($h \ll \lambda$), the approximation $\sin(\frac{2\pi h}{\lambda}) \approx \frac{2\pi h}{\lambda}$ is established. Then Eq. (2) can be simplified as follows:

$$h = \frac{\rho c^2}{\pi f Z} \sqrt{\frac{|R(f)|^2}{1 - |R(f)|^2}} \quad (4)$$

From Eq. (4), it can be seen that the oil film thickness can be obtained via the reflection coefficient, assuming that all the parameters of the material are known. The parameters of the oil and the material used in this paper are shown in Table 1. This is the principle of the ultrasonic spring model for oil film thickness measurement.

The resonant frequency method and the spring model method are the two major methods for the oil film thickness measurement using ultrasound in tribological components. Generally, the resonant frequency method is suitable for the thicker oil film thickness measurement, and the spring model is suitable for the thin film thickness measurement. The detailed ranges of the two methods are determined by the following procedures.

According to Eq. (2), we can obtain the relationship of the oil layer reflection coefficient against the product of film thickness and the frequency (as shown in Fig. 2). From Fig. 2, it can be seen that reflection coefficient reaches minimal value when the product of the film thickness and the frequency is 645 $\mu\text{m MHz}$. The center frequency of the piezoelectric element used in this paper is 10 MHz with a bandwidth of 5–13 MHz (−3 dB). Therefore, the measured range of the resonant frequency method is 49.6–107.5 μm , and the measured range of the spring model is 0.11–6.9 μm under condition $0.1 < R < 0.95$.

3 Experiment

3.1 Apparatus

Figure 3 shows the apparatus used in this paper. The apparatus has two parts: ultrasonic oil film thickness

Table 1 Acoustic properties of oil and bearing steel

	Oil L-TSA 68 at ambient pressure	Bearing steel
Density ρ (kg/m ³)	850	7600
Ultrasonic wave velocity c (m/s)	1300	6000
Acoustic impedance z (10 ⁶ kg m ^{−2} s ^{−1})	1.105	45.6
Bulk modulus B (GPa)	1.44	273.6

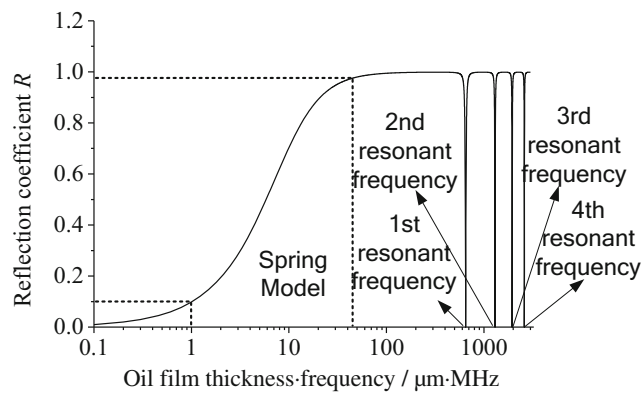


Fig. 2 The reflection coefficient of the oil layer against the product of film thickness and the frequency

measurement system and a rig for accurately control of the oil film thickness. The rig is mainly consisted of a micrometer-driven translation stage, a clamp, a piezo actuator, and a piezo digital controller. The maximum travel range and the resolution of the micrometer-driven translation stage are 18 and 10 μm , respectively. The piezo actuator was used to adjust the oil film in fine step size. In detail, the known lubricant film was set using the following procedure: firstly, a thick lubricant film was formed and the oil film thickness was

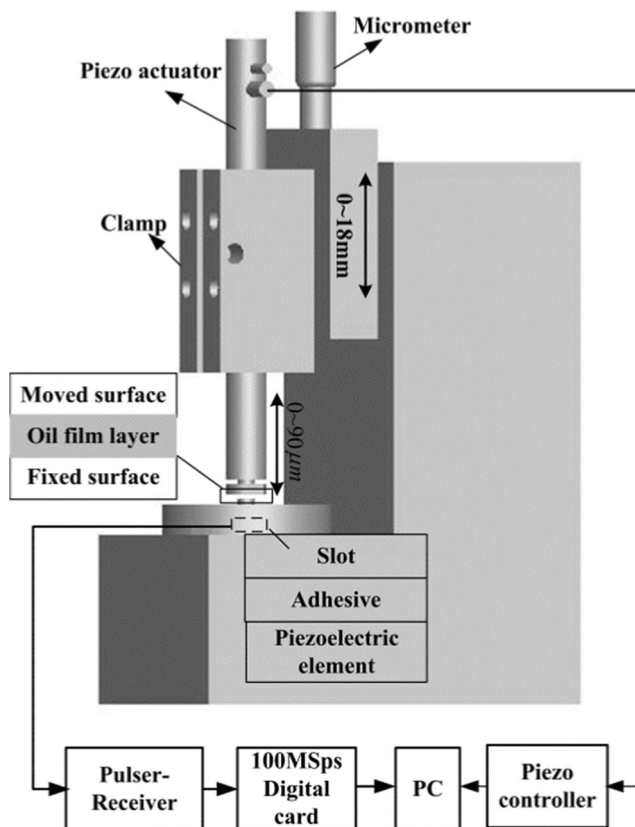


Fig. 3 The schematic of the apparatus

measured by the resonant frequency method which is proven to be accurate. The obtained thick film thickness was treated as the starting number. Then, the lubricant film was reduced by the piezo actuator in closed loop to form a set of known oil films.

3.2 Set up of the piezoelectric element

Figure 4 shows the figure of the piezoelectric element and its setup on the back of the circular base. The diameter of the piezoelectric element is $\Phi 7$ mm and the thickness is about 0.2 mm. During the setup, a slot with 3 mm depth was firstly made on the back of the circular base, and then the piezoelectric element was bonded using the adhesive.

The method of bonding is very important when considering the frequency response of the piezoelectric element. When bonding the piezoelectric element, there are two points that need to be noted: firstly, the expected bonding location should be flat and smooth as much as possible, and secondly, the bond line should be thin and uniform. Figures 5 and 6, respectively, show the wave in time domain when a small dent is in the location and when the bond line is too thick. From Fig. 5, it can be seen that when the setup surface is uneven, some noise will be introduced. From Fig. 6, it can be seen that when the bond line is too thick, the damping will be small which will lead to poor transmission of sound energy into the component.

After being bonded well, the cable was soldered firmly on the positive and negative electrodes of the piezoelectric element. The other end of the cable was connected to the ultrasonic oil film thickness measurement by a SMB connector. The ultrasonic oil film thickness measurement system includes the ultrasonic pulser-receiver card, the digital card, and the piezoelectric element. In practice, the pulser-receiver card generates and sends a configurable pulse to the

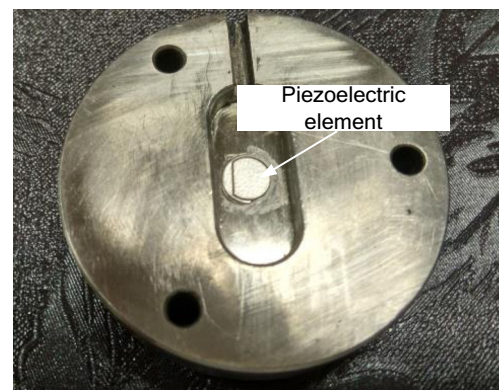


Fig. 4 The figure of the piezoelectric element and its setup

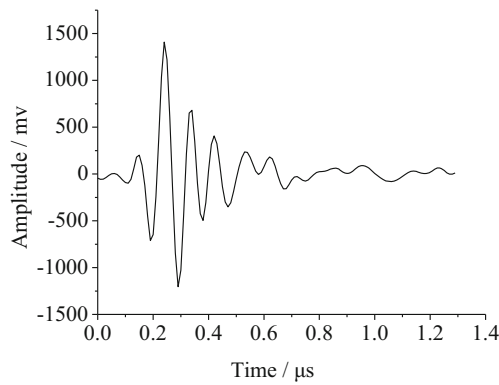


Fig. 5 The wave in time domain when a small dent is in the location

piezoelectric element. Being excited by the pulse outputted by the ultrasonic pulser-receiver (UPR), the piezoelectric element began to vibrate and outputted ultrasound. The outputted ultrasound penetrated the circular base and reached the oil film layer where some of the ultrasound was reflected and the other part was transmitted. The reflected signal was then sampled by a 12-bit, 100-MSps PCI digester card and were sent into computer memory for post-processing. Usually the pulse is configurable in the following ways:

- Pulse amplitude, i.e., the voltage that is sent to the piezoelectric element. This controls the amplitude of the signal that will get sent from the piezoelectric element and hence the amplitude of the signal that is received by the piezoelectric element.
- Pulse width, i.e., the length of the pulse that is sent to the piezoelectric element. This controls the frequency of excitation of the piezoelectric element.
- Pulse shape. Common pulse shapes are a spike, a negative square wave function, and a sine wave.
- Pulse rise time. This is the time taken for the pulser to go from 0 V to the specified voltage.

In this work, a negative square wave function was chosen as the pulse shape, the pulse rise time is about 10 ns, and the

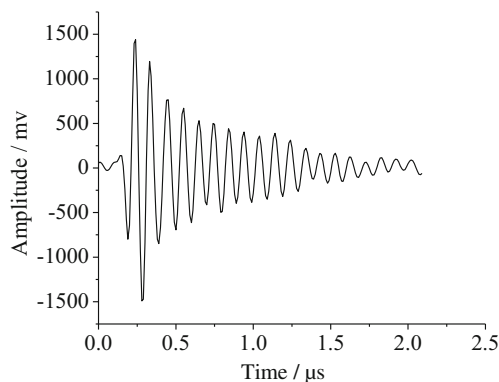


Fig. 6 The wave in time domain when the bond line is too thick

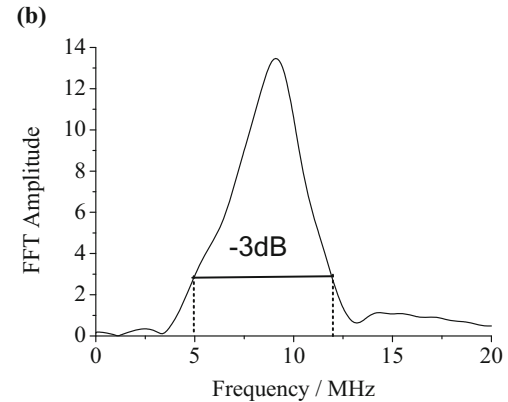
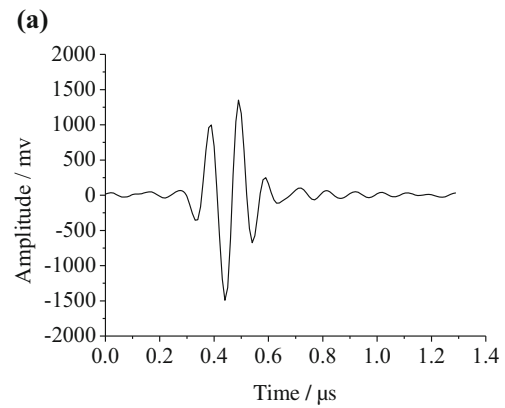


Fig. 7 The wave of the reference signal (a) time domain (b) frequency domain

pulse width is set according to the center frequency of the piezoelectric element as the following:

$$PW = \frac{1}{2f} \quad (5)$$

where PW is the pulse width and f is the center frequency of the piezoelectric element.

3.3 Process of the experiment

During the experiment, we firstly measure the reflected signal from the circular base-air interface and save it as the reference

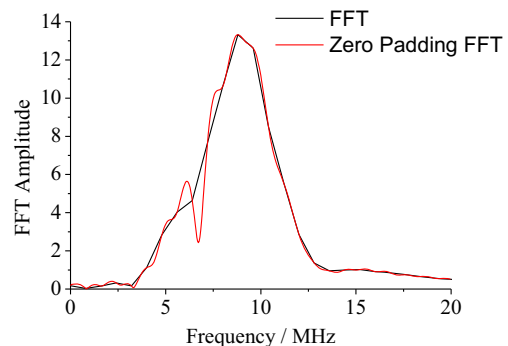
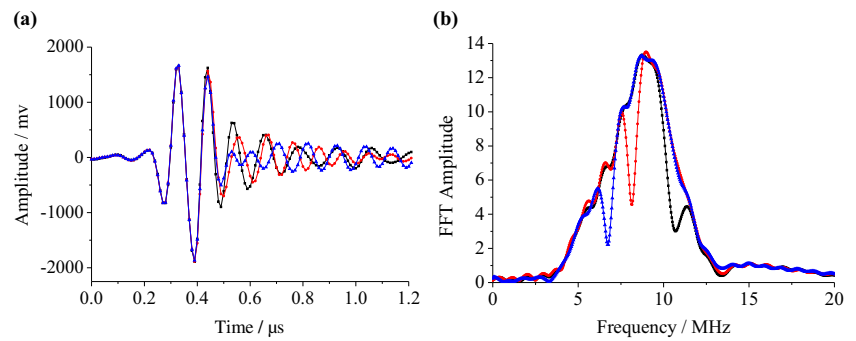


Fig. 8 Comparison effects of the FFT and zero padding FFT

Fig. 9 The reflected signal when the oil film layers are in the measured range of the resonant frequency method (a) time domain (b) frequency domain



signal. Figure 7 shows the waves of the reference signal in time domain and frequency domain. Then, drop the oil on the surface of the circular base, adjust the micrometer-driven translation stage to form a thick oil film layer with certain thickness, and measure the oil film thickness using the resonant frequency method. Set this oil film thickness as the base point, and then adjust the oil film thickness using the piezo actuator to form a series of known oil film layers.

When using the resonant frequency method to obtain the oil film thickness, the accuracy of the frequency where the minimal value happen determines the accuracy of the result. In this paper, zero padding FFT is used to increase the frequency resolution. Figure 8 shows the comparison effect of the FFT and zero padding FFT. From Fig. 8, it can be seen that zero padding FFT can increase the frequency resolution and

hence increase the accuracy of the results by resonant frequency method.

4 Results and analysis

Fig. 9 shows the reflected signals in time domain and frequency domain for different oil film thicknesses when their thicknesses are in the range of the resonant frequency method. From the time domain wave, it can be seen that the information of the oil film thickness contains in the tail of the wave. In the frequency domain, different thickness oil film layers have different resonant frequencies where the minimal values happen. Figure 10 shows the wave in the time domain and also the frequency domain for different oil film thicknesses when their

Fig. 10 The reflected signal when the oil film layers are in the measured range of the spring model method (a) time domain (b) frequency domain

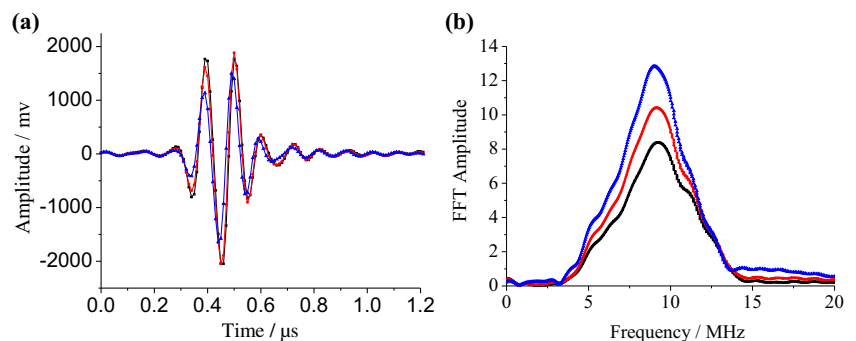
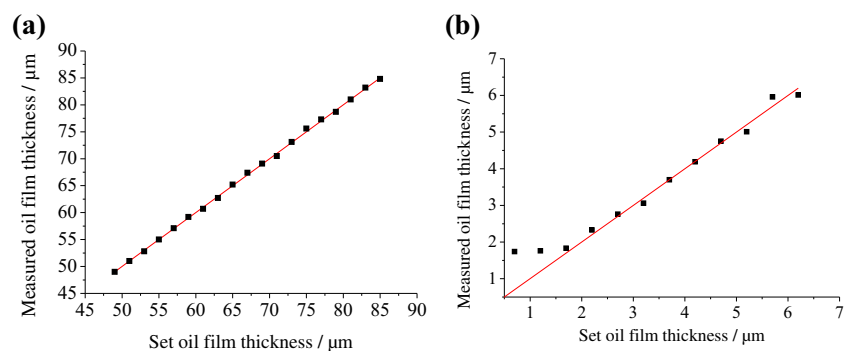


Fig. 11 The comparison of the measured results with the piezo actuator displacement (a) the resonant frequency method (b) the spring model



thicknesses are in the range of the spring model approach. From Fig. 10, it can be seen that the information of the oil film thickness performance on the amplitude both in the time domain and the frequency domain. The oil film thickness can be obtained by the reflection coefficient at any specified frequency via Eq. (4).

In this paper, an oil film layer with 85 μm thickness is set as the base point. When the thickness of the oil film layer is in the measured range of the resonant frequency method, the piezo actuator is set to reduce the oil film layer every 2 μm , and when the thickness of the oil film layer reaches the measured range of the spring model, the piezo actuator is set to reduce the oil film layer every 0.5 μm . Figure 11 shows the measured thickness against the set oil film thickness. From Fig. 11, it can be seen that both the resonant frequency method and the spring model approach can measure the oil film thickness very accurately. However, from Fig. 11b, it can be seen that when the oil film layers are below 1.7 μm , there is a big error. There are major two reasons which may cause this error. Firstly, limited by the machining accuracy, the piezo actuator is impossible to be completely perpendicular to the circular base. Secondly, when the distance of the two surfaces is below 1.7 μm , there will be many asperities contact and hence very difficult to reduce the distance of the two surfaces closer.

5 Conclusions

As a non-invasive method, ultrasonic oil film thickness measurement method has many advantages and is very promising. However, the commonly used commercial transducers are bulky and these sometimes hinder the use of the ultrasonic methods in situ in the real machine. Using the piezoelectric element is an alternative way and is expected to break the bottleneck. This paper did some researches on the oil film thickness measurement using the piezoelectric element. As the performance of the piezoelectric element is a function of the bonding, soldering, and the pulse conditions, some key points on the use of the piezoelectric element are summarized. Then, a calibration rig which can set a series of known thickness oil films is set up and the accuracy of the oil film thickness measurement using piezoelectric element is tested. The results show that using the piezoelectric element can measure the oil film thickness effectively and accurately.

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