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# Review of ultrasonic-based technology for oil film thickness measurement in lubrication

Pan Dou[a, b], Yaping Jia[a], Peng Zheng[a], Tonghai Wu[a*], Min Yu[c],

Tom Reddyhoff[c], Zhongxiao Peng[b]

[a] Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, P.R. China

[b] School of Mechanical and Manufacturing Engineering, The University of New South Wales, Sydney, 2052, Australia

[c] Department of Mechanical Engineering, Imperial College London, London, SW7 2AZ, United Kingdom

*Corresponding author: wt-h@163.com

**Abstract**

*Lubricant film thickness is the most informative variable that reflects lubrication conditions and transmission efficiency in the mechanical equipment, therefore its measurement is highly important. Despite a large number of theoretical models that have been developed to describe the lubricant film, complexities and uncertainties in a real tribo-pair contact still hinder the implementation of accurate and robust methods of in-situ film thickness measurements. Recently, ultrasonic-based measurement has been widely studied, showing promising potential owing to its non-destructive characteristics, high sensitivity, and limited physical modifications. This paper comprehensively reviews basic principles of ultrasonic-based oil film measurement; summarizes progress on calculation models and associated signal processing methods; exhibits in-lab demonstrations and in-situ applications; and discusses key technical issues and possible solutions.*

**Keywords:**

ultrasonic reflection, oil film thickness; calculation model; in-situ measurement



## 1. Introduction

Proper lubrication is critical to ensure that machines operate under desirable conditions with low friction and wear between contacting, moving components. To assess lubrication conditions and regimes (including full-film, mixed, and boundary lubrication), the thickness of a lubrication film is the most important and popularly used index to be evaluated.

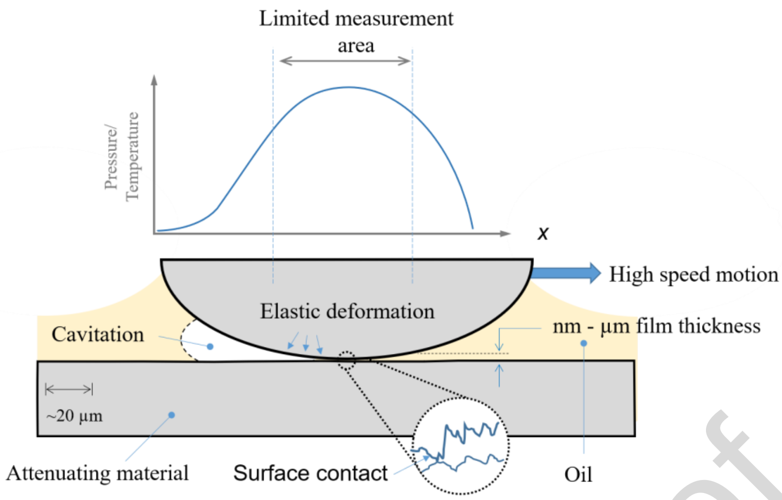



Figure 1 Schematic diagram of possible complicating factors associated with film thickness measurement in an engineering contact e.g. bearing, seal, piston-liner. A subset of these are likely to occur in a single component.

A lubricating oil film is often thin (in a micrometer or submicron scale) and affected by many variables including type of lubricant, operating condition (load and speed), stiffness, roughness, and texture of two contact surfaces, and temperature, etc as shown in Figure 1. Under certain conditions such as overloading or start-stops, the oil film thickness changes during operation and the film is likely to be ruptured by surface asperities. Therefore, measurement of the thickness of the lubricating film often requires high spatial resolution, fast repetition frequency, without disturbing the lubrication flow field.

There are a number of methods for the measurement of oil film thickness, for example: the optical interference method [1]-[4], the fiber-optic displacement method [5], and laser-induced fluorescence [6]-[11] can provide film thickness with a high resolution and accuracy. However, a transparent window is required on either side of the friction pairs, which is not always feasible practically. Electrical methods, including the resistance [12] and capacitance method [13][14], use an equivalent electrical circuit between two solid parts to measure the oil film thickness. Although a transparent window is not needed, the electrical-based measurement techniques often introduce considerable noise when the current passes the moving part(s). The eddy current method [15][16] has found its application in many industrial situations, for example, thrust bearings. However, a screw hole in the loading zone of the bush is necessary for holding the probe, making the method intrusive and limiting its application.

As a non-invasive technique in engineering applications, ultrasonic-based approaches [17][18] use sound pulses and their propagation into different media (solids and fluids) to perform oil film measurement. Figure 2 shows the essential components of an ultrasonic-based measurement system, which is composed of an ultrasonic sensor, an ultrasonic pulser-receiver (UPR), an oscilloscope/digitizer, and a computer. The working principle is briefly summarized as follows. With the instruction sent from the computer, a voltage pulse, generated by the UPR, excites the ultrasonic sensor. Consequently, a cluster of sound pulses in a suitable frequency band is emitted and transmit into a tribo-pair (e.g., solid-oil film-solid), which is typically composed of two solid surfaces and a lubricant that fully or partially separates them. These pulses travel in the tribo-pair and transmit partially at the interface between different media. Part of these reflected pulses (i.e., echo) return to the sensor and excite the electrical pulses of the sensor, which are received by the oscilloscope and computer. The return pulses can be treated as the modulated signal of the incident one once it passes through the oil film. Signal processing techniques or models are often required to calculate oil film thickness from the echo signal.

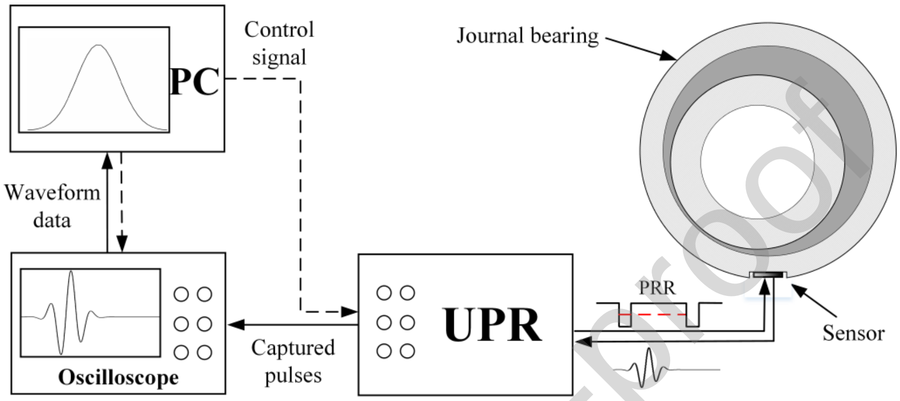



Figure 2 Four key components in an ultrasonic-based system for film thickness measurement: an ultrasonic pulser-receiver (UPR), an ultrasonic sensor, an oscilloscope, and a computer

In the past 20 years, ultrasonic-based techniques have progressed significantly in terms of the development and improvement of different models to estimate oil film thickness and applications of the models in lab-based and practical situations. However, there are still technical challenges when using the existing methods for practical application. This paper focuses on available ultrasonic-based techniques for oil film thickness measurement. The organization and the main content of this review include three main areas:(a) existing models (developments and applications), (b) typical application cases, and (c) technical challenges. Figure 3 summarizes the key points of the 3 areas, and detailed reviews are presented in the following sections.

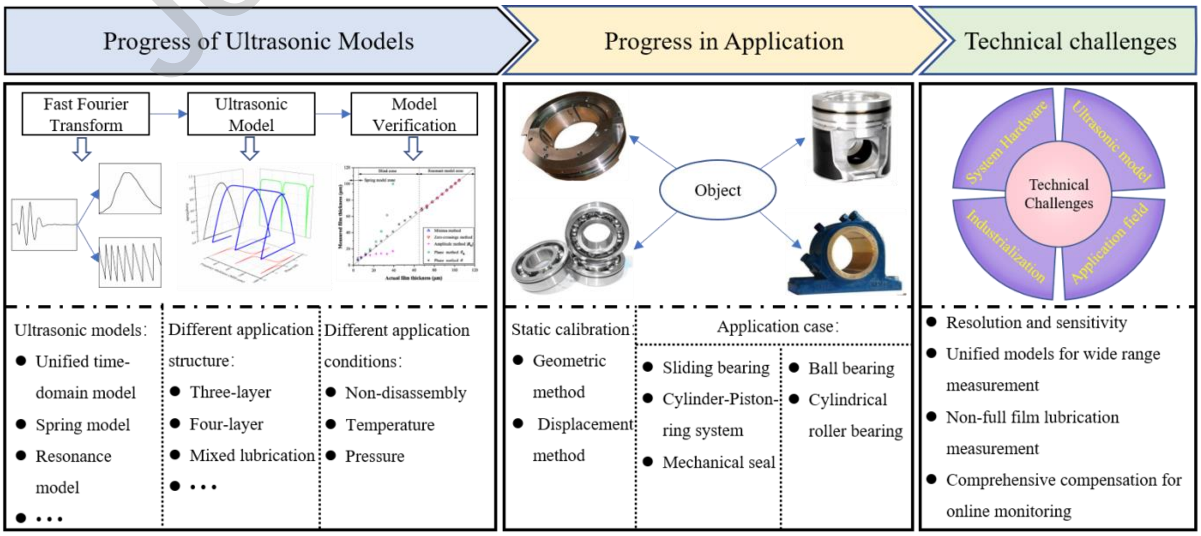


Figure 3 The main contents of this review including existing models, applications, and technical challenges

## 2. Ultrasonic models

Ultrasonic models are used to measure oil film thickness for lubrication evaluation based on various sonic propagation behaviors. According to the geometry of lubricated structures and the characteristic of sound pulse propagation, the calculation models can be categorized as parallel and non-parallel surfaces. Special efforts have also been made on the models for different application situations. This section focuses on the progress of the ultrasonic models from two perspectives: tribo-pair structures and application conditions. Figure 4 shows the progress (including the timeline) of the ultrasonic models.

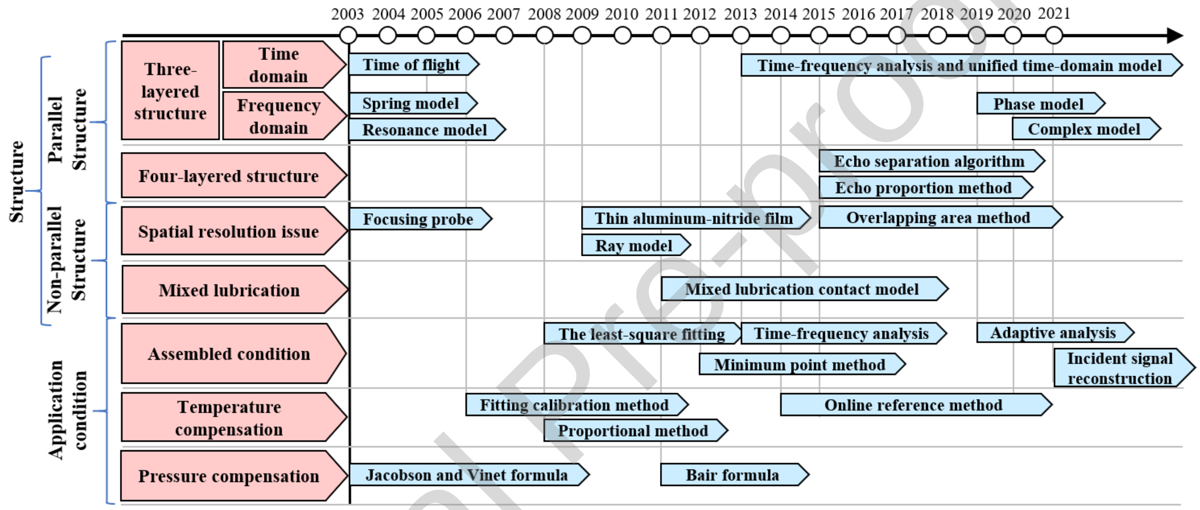



Figure 4 Overview of the progress of the existing ultrasonic models largely grouped based on tribo-pair structures and application conditions

### 2.1 Calculation models and lubrication structures

Considering the geometry of the lubricated interface in a tribo-pair, most surface contacts can be classified as either parallel or non-parallel structures. The differences of sound pulse propagation characteristics in these two structures lead to the necessity of different mathematical models, detailed as follows.

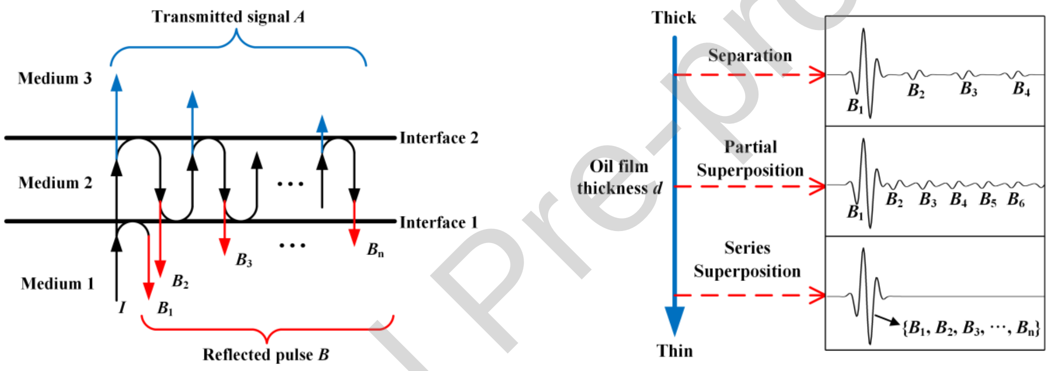
#### 2.1.1 Models for parallel structures

A parallel structure is an approximated abstraction that can be found in applications such as a thrust bearing, the port plate of a plunger pump, the end of a gear pump. In view of the propagation of sound pulses, an equivalent three-layered structure (e.g., steel-oil-steel) can be simplified to correlate the film thickness with the measured echo pulses. For bearings with soft coating, a four-layered structure of steel-coating-oil-steel has to be considered with some particular technical issues, which will be presented in the second half of this section.

##### 2.1.1.1 Three-layered structure

A schematic diagram of ultrasonic pulse propagation in the three-layered parallel structure of solid 1 (Medium 1)-oil (Medium 2)-solid2 (Medium 3) is shown in Figure 5. Once an incident pulse $I$ is transmitted to the structure, penetration and reflection occur on each interface due to the mismatch of the acoustic impedance of the two materials. After multiplying the above propagation, the pulses in Medium 2 (oil film) attenuate gradually due to the loss of energy. The echoes collected from the initial incident end are recorded as the reflected pulses $B\{B_1, B_2, \cdots, B_n\}$. A group of models have been applied to calculate the oil film thickness.

In this section, existing models are reviewed from two aspects: time domain and frequency domain. Models in the time domain use signal processing methods to obtain the time interval between echoes to determine oil film thickness. Popular models include the time-of-flight model, time-frequency analysis method, and unified time-domain model. In contrast, models in the frequency domain use the frequency response characteristics of the reflected and incident signals to determine the oil film thickness, including the spring model, resonance model, phase model, and complex model.




(a) (b)

Figure 5 The propagation of ultrasonic pulse in a three-layered structure: (a) propagation principle [19], and (b) time-domain signal diagram of different oil film thicknesses [20]. The incident pulse is denoted as $I$. The reflected pulses are denoted as $B\{B_1, B_2, \cdots, B_n\}$

1) Time-domain models

As illustrated in Figure 5(b), echo pulses present different time intervals as determined oil film thicknesses. The time interval is utilized to measure the thickness in most available models in the time domain. Among existing models for three-layered parallel structures, the mostly used one is the time-of-flight (TOF) method [17], which uses the travel time of the ultrasonic pulse in the oil layer to calculate oil film thickness. The accuracy depends on the sampling interval and can be improved by interpolation [21] and/or polynomial fitting [22].

For a thin oil film, partial overlap may occur between adjacent echoes, resulting in a poor measurement resolution. Therefore, isolation of the overlapped echoes is important for improving the measurement accuracy. Time-frequency analysis is performed to resolve the overlapping problem of echoes as mentioned above. Jiao et al. [23] have used wavelet analysis to determine the transient position of the first two echoes. This is effective for dealing with partially overlapping pulses by selecting suitable primary functions. However, this method is not effective for severely overlapping pulses.

A unified time-domain model has been proposed to determine the time interval from the overlapped echoes [24]. The reflected pulses are matched by superimposing many pre-constructed standard signals with different amplitude and phases. The largest correlation between the matched and the standard values is taken as the criterion for the final choice. Further, the method has been improved by signal interpolation to realize the continuous measurement of large-scale film thicknesses [20]. However, the matching computation may be excessively time-consuming for online monitoring.

2) Frequency-domain models

This group of models performs frequency domain analysis to extract internal features from complicated echo waves to calculate the oil film thickness. More specifically, the ratio of the reflected pulse to the incident pulse is adopted. The reflection coefficient, defined by $R$, is defined for this purpose [25].

The variation of the reflection coefficient ($R$) against the component index of "frequency · thickess (MHz · μm)" in the steel-oil-steel system is shown in Figure 6 [26]. The index of $|R|$ and $\Phi$ represent the amplitude and phase of $R$, respectively. Accordingly, the typical models including the spring model and resonance model can be mapped with their respective measurable zones, which are described in detail in [19]. By selecting a suitable model, most thicknesses can be calculated from a measured reflection coefficient. Exceptionally, a blind zone exists between the effect zones of the resonance and spring models, which are detailed below.

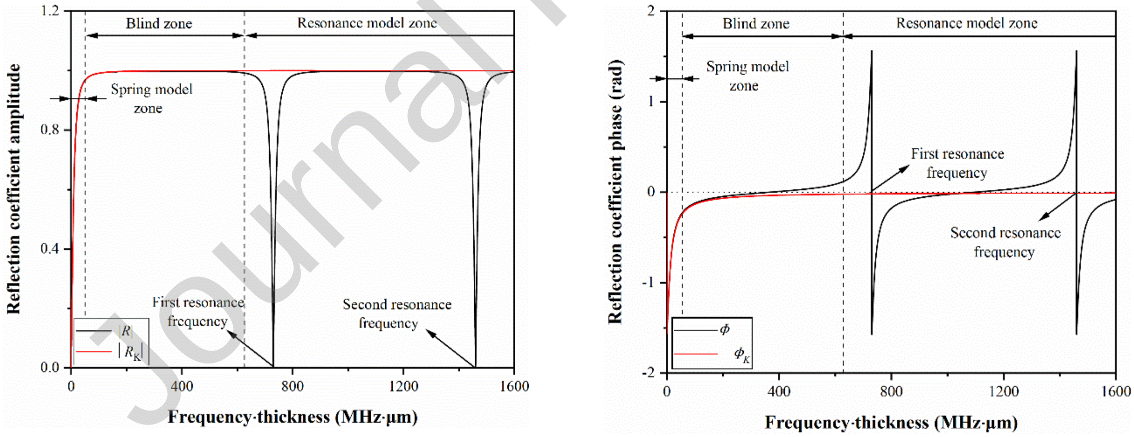



Figure 6 Reflection coefficient spectrum for a three-layer (steel-oil-steel) structure [26], (a) amplitude spectrum, and (b) phase spectrum

a) Resonance model

The principle of the resonance model can be explained with the continuum model that the reflected wave may resonate with the incident one when the film thickness is the integral multiples of the half wavelength of the ultrasonic wave [27][28]. The reflected wave then exhibits a minimum value of the amplitude spectrum at the resonance frequency, and with this, the oil film thickness can be calculated.

However, by analyzing the time interval between two echoes, it is found that the minimum point phenomenon is caused by the definite time interval between two echoes instead of the resonance phenomenon [29]. Focusing on these two different explanations about the formation mechanism of the minimum point, the superposition principle of waves has been used to analyze the minimum point phenomenon. It is found that this phenomenon is caused by the mutual cancellation of the echoes and the incident waves. Further analysis has shown that the phase difference $\pi$ between the echo and the incident wave is the most essential reason for the formation of the minimum point phenomenon [30]. Furthermore, it is found that the resonance frequency can be obtained from the zero-crossings phenomenon in the phase spectrum as shown in Figure 6(b).

b) Spring model

The spring model is firstly proposed by Kendall and Tabor in 1971 by studying the contact area between two solid rough surfaces [31]. They prove that ultrasonic reflection is determined by the interface stiffness according to the quasi-static method. In 1973, Tattersall et al. report similar results when detecting the adhesive between two solid interfaces using ultrasonic [32]. In their work, the adhesive contact is equalized with a series of parallel springs. Correspondingly, the analytical expression of the reflection coefficient is constructed by the spring stiffness.

In the works by Dwyer-Joyce and Drinkwater et al., the oil film stiffness has been defined as the quotient of the bulk modulus and the thickness of oil film [33]. It is assumed that the reflectivity of the oil layer is dependent on the film stiffness and so the oil layer can be modeled with an elastic spring. Based on this, the oil film thickness can be calculated from the reflection coefficient directly. Primarily, the spring model can be derived from the theoretical reflection coefficient mathematically by omitting the higher-order terms [34]. Therefore, the spring model can be a linear expression of the oil film thickness when the value is less than the adopted ultrasonic wavelength. Figure 6(a) and (b) show the variation of the calculated reflection coefficient ($R_K$) by using the spring model against "frequency · thickess (MHz · μm)". $|R_K|$ and $\Phi_k$ represent the amplitude and phase of $R_K$.

c) Phase model

It can be found in Figure 6 that a blind zone exists between the resonance and spring models [26], where the amplitude is insensitive to the change in "frequency · thickess (MHz · μm)". In contrast, the phase angle still exhibits a modest change that is sufficient to calculate the oil film thickness (namely phase model) [26]. However, this method has no closed-form equation so an iterative solution is required. It means that the phase model has low computational efficiency.

d) Complex-model

To avoid the iterative solution of the phase model, an exact solution by simultaneously using both the amplitude and phase information has been proposed to calculate the oil film thickness directly [35]. Compared with the phase model, this model based on a closed-form equation [35] makes full use of the amplitude and the phase information of the complex ultrasonic reflection coefficient. This model enables direct calculation of the oil film thickness instead of iterative approximation. Meanwhile, this model does not require the acoustic impedance of medium 3 in Figure 5(a) when calculating the oil film thickness.

In summary, for a three-layered parallel structure, the existing models can cover a full range of the oil film thickness measurement both in the time domain and frequency domain. Pan Dou et al. have compared the measurement accuracy of the unified time-domain model and the frequency-domain models through the calibration experiment [24]. In the resonance model zone and the blind zone, the improved time-domain model shows similar measurement errors compared with the resonance model and the phase model. In the spring model zone, the error of the unified time-domain model is smaller than that of both the phase model and the spring model. Min Yu et al. have compared different frequency-domain models in terms of uncertainties and measurement accuracy [35]: 1) The uncertainty of the complex model is always greater than that of the phase model. 2) The uncertainty of the spring model is the smallest in its applicable range ($|R| < 0.95$).

#### 2.1.1.2 Four-layered structure

Alloy coating can be widely found in tribological components, e.g. the bush of a sliding bearing for anti-wear purposes. Therefore, a four-layer structure of substrate-coating-oil-steel has to be considered for ultrasonic models. For a thick coating, the echoes reflected from the interfaces of the substrate-coating and coating-oil can be separated from each other. And therefore a three-layered structure can be used for simplification. However, for a thin coating, the echoes from the interfaces of the substrate-coating and coating-oil overlap so that the echoes from the oil layer are difficult to be isolated.

To extract the reflection coefficient of the oil layer from the overlapping echoes in a thrust bearing with a thin coating, Geng et al. have referred to the reflected signal of the substrate-coating interface [36]. Zhang et al. have directly processed the overlapped signal with the superposition of some Gaussian echoes [37][38]. For the proposed methods, two issues exist and need to be solved. First is low efficiency when isolating severely overlapping pulses, in which only the first-order pulse can be treated with lower accuracy. The second is the limited effectiveness zone (< 10 μm) where the only amplitude is included in the separations. For the blind zone, these methods fail to work.

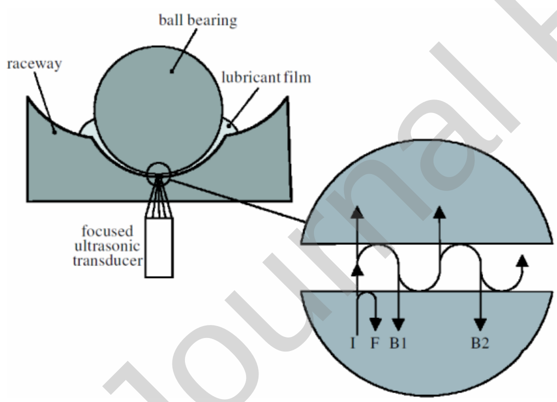
### 2.1.2 Models for non-parallel structures

It is a challenging task to measure the thickness of an oil film between two non-parallel surfaces such as in rolling bearings. Two main technical issues tackled by existing studies are the spatial resolution of oil film distribution and the film thickness characterization in a fluid-solid mixed contact. The following sub-sections review available approaches to address these two technical challenges associated with existing models for non-parallel structures.

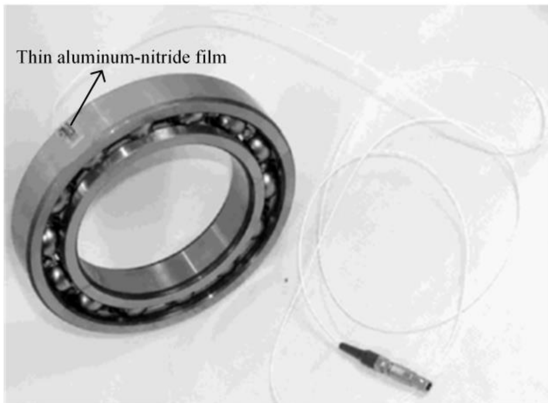
2.1.2.1 Spatial resolution issue and solutions

The contact between the ring and the roller in a rolling bearing can be treated as point or line contact between non-parallel surfaces. The oil film in the two surfaces is distributed with varied stress and thickness. The minimum thickness is in a microscale zone. Therefore, its identification is determined by the spatial resolution of the measurement. Due to the scatting effect of sound pulses, the spatial resolution of the ultrasonic method is poor for such cases. As summarized in Table 1, various attempts have been made to tackle this challenge over years. Developments can be categorized into two groups: one is to improve the concentration of the sensor, the other is focused on signal processing.

The sensor's concentration has been improved by employing the focusing lens and the liquid coupling media as shown in Figure 7(a) [39] [40]. A recent report by Zhang et al. has showed that an extremely thin aluminum-nitride film (less than 10 μm) can also improve the ultrasonic resolution with a high frequency of 200 MHz as shown in Figure 7(b) [42]. For easy operation, the piezoelectric elements have been cut into smaller pieces to improve spatial resolution [43][44]. The substance of all the above principles is to narrow the projected area to be less than the contact area. However, the real contact may be on a micro-scale and thereby limits the resolution of the conventional methods. Moreover, additional equipment is required for the focusing methods, limiting its application for industrial purposes.



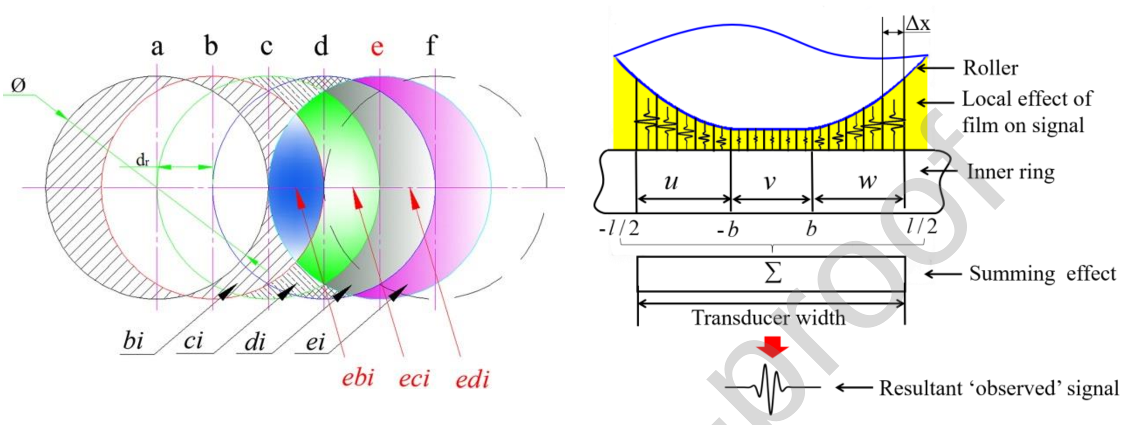

(a)




(b)

Figure 7 Different sensors are used to improve the spatial resolution: (a) focus probe [17], (b) deposited aluminum-nitride film [42]

Some researchers have focused on signal processing methods to improve spatial resolution. With a roller bearing of low speed, an overlapping area method of adjacent measuring points has been proposed [45]. When the roller passes the fixed sensor, the overlap of the adjacent focal zones of the contact is used to subdivide the contact zone as shown in Figure 8(a) [44]. However, this method is limited by the highest rotation speed of the bearing cage for identifying overlap zones. In another study, the ray model has been proposed with the practical application prospect. The sound field is equivalent to a cluster of rays and the oil film thickness can be calculated by each sonic ray. In principle, the measurement for the non-parallel surface can be with high resolution as shown in Figure 8(b). However, the method is highly influenced by the non-negligible pulse scattering by the profile and the roughness of the contact surfaces. Practically, the distribution of the reflection coefficient can be calculated by applying the ray model on the profile geometry of the solid surface which is derived from EHL theory or measured by stylus profilometry. By this, the average thickness in the lubrication contact zone or minimum film thickness can be obtained from the calculated distribution [43] [44].




(a) (b)

Figure 8 Different signal processing methods for improving spatial resolution: (a) overlapping area method of adjacent measuring points [45], (b) ray model

In summary, due to the low signal-to-noise ratio and complex process, the improvement of spatial resolution by sensors has been limited. New techniques such as local coating can be effective but may be costly for industry applications. Signal processing can be effective for the current sensors but requires a higher pulse emission frequency for high-speed bearings, which can be achieved with the enhancement in ultrasonic pulse emission technology.

#### 2.1.2.2 Mixed lubrication issue and solutions

In the mixed lubrication regime, the oil film is not continuously distributed and therefore it is difficult to be characterized. To address this issue, in 2011, Dwyer-Joyce et al. introduces a mixed lubrication contact model with equivalent parallel springs to determine the oil film thickness under mixed lubrication [46]. With the stiffnesses of solid contact and oil pressure, the load ratio of roughness peak and lubrication film is solved by combining the Hamrock and Dowson full film lubrication equation, Greenwood and Williamson rough contact equation, and force balance equation. By setting up a continuous process from static dry contact to static wet contact then to mixed lubrication between a flat steel disc and a sliding steel ball, the model is proved to be able to separate the stiffness contribution of rough contact and oil layer from experimental data.

However, the consistency between the total stiffness of the mixed lubrication model and the experimental stiffness decreases with the decrease of the film thickness, and there is a large error between model and experimental results in both static dry contact and wet lubrication [46]. Therefore, how to establish a coupled fluid-solid contact model to accurately obtain the stiffness of the rough surface interaction and fluid film, and to distinguish the lubrication state (full-film lubrication, mixed lubrication) remains a research challenge.

### 2.1.3 Summary of existing models

Establishing ultrasonic models for different structures and working conditions has remained an area of intense research for the last 20 years. A summary is given in Table 1 concerning not only the models but also their limitations and applications. It can be generalized that, despite a substantial accumulation of researches, current progress on engineering applications is limited.



Table 1 Ultrasonic-based oil film thickness measurement method

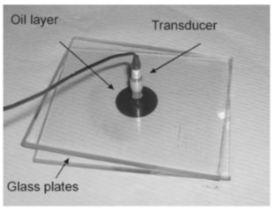
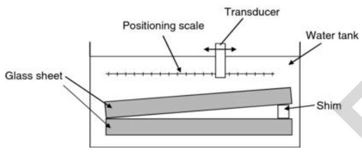
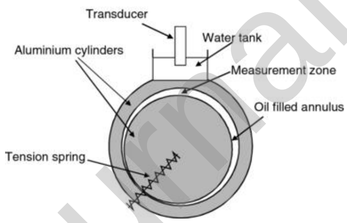
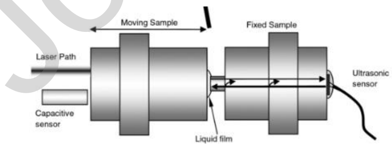
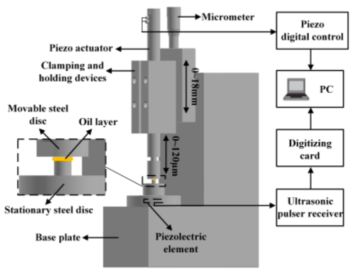
| | | | Model and characteristics | Time | Scope of application | Limitations | Application |
|---|---|---|---|---|---|---|---|
| Parallel structure | Three-layered structure | Time-domain model | Time-of-flight method | 1992 | Thick-film measurement when the echoes can be completely separated | Low computing speed | Piston ring |
| | | | Time-frequency analysis method | 2003 | Thick-film measurement when the echoes are partially overlapped or completely separated | | None |
| | | | Unified time-domain model | 2016 | Full scale | | Clearance between screw and barrel |
| | | | Resonance model | 2003 | Thick-film measurement when the echoes are partially overlapped or completely separated | | sliding bearing |
| | | Frequency-domain model | Spring model | 2003 | Thin-film measurement when the echoes overlap severely | Not applicable to blind area | Piston ring, sliding bearing, rolling bearing |
| | | | Phase model | 2019 | Thin-film measurement when the echoes overlap severely | | sliding bearing |
| | | | Complex model | 2020 | Thin-film measurement when the echoes overlap severely | | None |
| | Four-layered structure | | Spring model & proportion method | 2015 | Thin-film measurement when the echoes overlap severely | | None |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Spring model & echo separation algorithm | 2015 | Thin-film measurement when the echoes overlap severely | | None |
| | | Spring model & focusing probe | 2003 | Thin-film measurement when the echoes overlap severely and the oil layer has a curvature surface | Large volume, need to be punched, not suitable for industrial measurement | Rolling ball bearing, Cylindrical roller bearing |
| | | Spring model & thin aluminum-nitride film | 2009 | Thin-film measurement when the echoes overlap severely and the oil layer has a curvature surface | Complex manufacturing process, high cost | None |
| Non-parallel structure | Spatial resolution | Spring model & ray model | 2015 | Thin-film measurement when the echoes overlap severely and the oil layer has a curvature surface | Need to know the profile of the oil layer | Piston ring |
| | | Spring model & overlapping area method of adjacent measuring points | 2015 | Thin-film measurement when the echoes overlap severely and the oil layer has a curvature surface | High repetition rate, low speed | Cylindrical roller bearing |
| | Mixed lubrication | Spring model & mixed lubrication contact model | 2011 | Thin-film measurement when the echoes severely overlap in a mixed lubrication condition | The error increases with the decrease of film thickness ratio | None |

### 2.1.4 Experimental Validation

Using a known accurate measurement to compare with ultrasonic measured results is defined as the model validation. Model validation is an important part in model development. Available techniques and methods used for this purpose are presented in this section. To validate the ultrasonic models, static calibration has been widely adopted with the controllable thickness of oil film in a three-layered parallel structure. Two kinds of principles have been reported by controlling geometry or displacement. The details about principles and the results are summarized in Table 2.

Table 2 Calibration methods of the ultrasonic models

| Calibration method | | Device diagram | Results | Validated model | Characteristics |
|---|---|---|---|---|---|
| Geometric method | Oil drop method [47] |  | There is a good agreement with the diameter method | Spring model | ● Calibration range: 3-30 μm<br>● Be vulnerable to be affected by roughness and deformation |
| | Wedge method [33] |  | The agreement is good with the geometrical prediction | Spring model<br>Resonance model | ● Large scale range<br>● Be vulnerable to be affected by gasket deformation |
| | Annular oil film method [17][47] |  | The measured and geometry results have a strong correlation | Resonance model | ● Verify the influence of curvature through the circular oil film<br>● Thick film |
| Displacement method [26][35][47][48] | |  | The result shows a strong correlation with the calibrated displacement technique | Resonance model | ● Full-scale range<br>● The initial point needs to be defined<br>● Be vulnerable to be affected by initial point and displacement increment |
| | |  | There is a general agreement with calibrated displacement technique | Spring model<br>Phase model<br>Complex model | |

1) Geometric methods

To obtain the reference oil film, the closed geometry between static solid surfaces is often adopted as the initial validation, including the oil drop method, wedge method, and annular oil film method. Two parallel glass plates have been used with the oil drop method and the reference thickness could be determined from the area, mass, and density of the oil drops[47]. The calibration range can be 3~30μm due to the surface roughness and the plate drift. To achieve a wider range, a wedge has been adopted by the two oblique glass plates supported by different gaskets with known thickness [33]. Similarly, an annular oil film has been formed between the shaft and the ring to obtain films with a wide film thickness range. With this, the influence of curvature on the oil film measurement is investigated [17].

2) Displacement methods

Oil film can be also formed by precisely controlling the displacement between two solid surfaces [48]. The precision can be maintained by a high-precision piezoelectric displacement converter and a capacitive displacement sensor or a laser interferometer. A wide range of oil film thicknesses can be obtained to examine most ultrasonic models. It is worth noting that the absolute value of the oil film thickness is given by the ultrasonic method, while the displacement is the relative value, so the initial point of the film thickness should be defined to bridge these two values. However, the initial errors seem difficult to overcome due to surface roughness.

## 2.2 Different application conditions of existing models

Regarding practical applications of the models presented in section 2.1, there are two main concerns to be considered. First, the reference signal cannot be obtained directly without disassembling object parts. Second, the operating temperature and pressure of the oil film affect the accuracy of the ultrasonic parameters. The main progress on these problems is analyzed in this section.

### 2.2.1 Oil film thickness measurement under the assembled condition

The reflection coefficient is fundamentally important for most frequency-domain models. In order to calculate the reflection coefficient, the reference signal from the metal-air interface should be involved, which often impossible in an assembled machine. Therefore, some investigations have focused on the oil film thickness measurement in an assembling tribo-pair.

As given in Table 4, different solutions have been put forward regarding two principles [23][24][47][49][50]. One is to directly extract the thickness from the echo signal from the oil film without the reference signal. The other is to obtain the reference signal indirectly from the echo signals from the oil layer under different film thicknesses.

Table 3 The measurement method of film thickness under the assembled condition

| Method | Applicable range | limitations |
|---|---|---|
| Minimum point method [47] | Resonance model zone | When the echo number is less, the film thickness error is larger |
| Time-frequency analysis [23] | Resonance model zone | Complex calculations |
| The least-square fitting [49] | Spring model zone | The film thickness needs to be within a certain range |
| Adaptive algorithm [50] | Spring model zone<br>Blind zone | The film thickness needs to be within a certain range |
| Incident signal reconstruction [19] | Full scale | The film thickness should be largely ranged to cover both the resonance model zone and the blind zone in advance |

Hunter et al. have found a resonance phenomenon, where a local minimum point appears in the amplitude spectrum of the echo signal from an oil layer [47]. Therefore, the minimum point frequency is directly extracted to calculate the oil film thickness. However, the measurement error increases with the fewer echoes used [36]. The time-frequency method proposed by Jiao et al. is also able to achieve the measurement of thick oil film without a reference signal [23].

Some researchers have established the mathematical relationship between the incident signal and the echo signal from the oil layer by extracting the incident signal from the continuously changing echo signals. In 2005, Reddyhoff et al. use the spring model to establish the regression relationships of the amplitude and phase between the incident wave and the echo from the oil layer, respectively [49]. By collecting the echo signals under different film thicknesses, the amplitude and phase of the incident signals can be obtained from this regression model with acceptable errors. However, only the spring model is analyzed in this research.

In 2019, a new regression model to calculate the incident signal indirectly based on the continuum model is proposed by Kaeseler et al [50]. Compared with the previous regression model, this newly developed model is able to deal with both the spring and blind zones. Then, the algorithm of extended Kalman filter (EKF) is proposed to estimate the incident signal from the new regression model [50]. Compared with the previous method of the least-square fitting to obtain the incident signal, this method can adaptively estimate the incident signal according to the collected lubricating film reflection signal and has real-time and fast performance.

In 2021, Pan et al. propose an incident signal reconstruction method from the echo signals by using the equivalence condition between the incident signal and echo signal [19]. This method requires the oil film thickness to be largely ranged to cover both the resonance model zone and blind zone in advance.

In summary, non-dismantling measurement has been demonstrated. However, the accuracy and the scope of the methods require further attention. The latter is particularly important for the applications under the large-scale variation during the starting and stopping operations.

### 2.2.2 Real-time compensation of temperature and pressure

During the operation of a machine, the friction pair structure experiences changes in temperature and pressure. The temperature alternation will change the sound speed and density of oil, as well as the waveform of the reference signal. The pressure change will lead to a change in the oil sound speed and density. Thus, temperature and/or pressure variation will finally affect the accuracy of the measurement model, and therefore temperature compensation and pressure compensation are vitally important for the accuracy of the measurements.

#### 2.2.2.1 Temperature compensation

Temperature compensation aims to cancel out the influence of sound velocity, oil density, and reference signal waveform on ultrasonic measurement results. For example, the sound velocity at a specific temperature is usually calibrated by the time difference between the two adjacent echoes from an oil film with known thickness [51]. The variation of oil density with respect to the temperature can be compensated through the density formula proposed by Dowson and Higginson, where the thermal effect is taken into account [51]. The difficulty of temperature compensation mainly lies in the compensation of the reference signal in its waveform. Different methods have been proposed for the reference signal compensation, as shown in Table 4.

Table 4 Reference signal compensation methods

| Method | Scope of application | Characteristics |
|---|---|---|
| Fitting calibration method [52] | Spring model, Resonance model Phase model, Compound model | ● Pre-calibration is needed<br>● Suitable for detachable parts and difficult to be used in engineering |
| Proportional method [53] | Spring model | ● Self-compensation of amplitude<br>● A sensor with the delay line is needed or the structure geometry has to be modified |
| Online reference method [54][55][56] | Spring model, Resonance model Phase model, Compound model | ● No disassembly required<br>● Great significance in engineering application<br>● Many uncertain factors |

For the fitting calibration method, a series of reference signals within a certain temperature range are collected to obtain the mathematical equation for signal amplitude compensation [52]. To compensate for the signal amplitude and the signal phase simultaneously, a time-domain reference signal compensation model has been proposed [51]. Three factors including signal waveform expansion, signal amplitude attenuation, and signal time shift are considered to compensate for the variation of the reference signal by temperature. The time-domain signal can be compensated by calibrating these three factors under different temperatures. However, components must be dismantled for thermal calibration which limiting the application in the industry.

A proportional method has been proposed to avoid thermal calibration [53]. The "intermediate echo" such as the echo from the end of the delay line of the sensor is monitored under different temperatures, and the amplitude of the reference signal can be compensated by using the variation of the "intermediate echo". However, to enable the desirable “intermediate echo” in a typical three-layered structure, a sensor with the delay line has to be used or the structure geometry has to be modified.

The above methods typically require a static air reference taken before testing, which increases the difficulty in industrial application. Subsequently, the online reference method has been proposed [54][55][56]. Another signal such as the echo signal in the cavitation area of the journal bearing is selected as a near-simultaneous reference. The new reference is collected and updated in real-time for each test case and the effect of temperature can be eliminated.

Currently, some limitations still exist about the temperature compensation. Firstly, the temperature of components and lubricating oil has to be measured in real-time to compensate for sound speed, oil density, and the reference signal waveform. In the static test with uniform temperature distribution, the temperature can be accurately measured. However, temperature gradients usually exist in continuously running machines, resulting in compensation errors. Second, although the online reference method has a potential application prospect, the actual compensation effect has not been verified, and the influence of various factors, such as the residual lubricating oil on the reference interface, Therefore, the temperature compensation of ultrasonic film thickness technology is still the bottleneck in engineering applications.

#### 2.2.2.1 Pressure compensation

Pressure compensation is mainly concentrated in the point and line friction pairs. When the lubrication film is in the elastohydrodynamic lubrication state, the oil film pressure changes greatly compared with the hydrodynamic lubrication state, resulting in significant changes in the density and bulk modulus of the lubrication film. According to the spring model, the bulk modulus needs to be compensated to obtain accurate film thickness. There are two compensation methods. One has been proposed by Jacobson and Vinet [46]. The other is the empirical formula proposed by Bair which is usually considered to be the most accurate and can be extrapolated to the case of high pressure [40]. Cook [57] has successfully applied the formula proposed by Bair in the volume-pressure-viscosity correlation.

In the case of high pressure, existing studies have considered the effect of pressure on bulk modulus. In reality, the velocity and density are also affected by the temperature, thus affecting the solution of the bulk modulus. Therefore, the combined effect of temperature and pressure needs to be further analyzed. Secondly, in the actual point and line contact friction pairs, the pressure is not uniformly distributed, so the bulk modulus at different positions is not uniformly distributed. Methods to accurately calculate the film thickness need to be further developed. More information about future work can be found in section 4.

# 3. Practical applications

There are various liquid-lubricated mechanical components, and by inspecting the loading ability, these can be categorized into two types: low-stress and high-stress contact parts. The former is characterized by thick lubricant film represented by sliding bearings, while the latter is characterized as a thin lubricant film represented by rolling bearings. Ultrasonic-based measurements have been applied to probe the oil film thickness in both occasions. Figure 9 shows the progress timeline of the models and their applications. The remainder of this section reports various applications of the models.

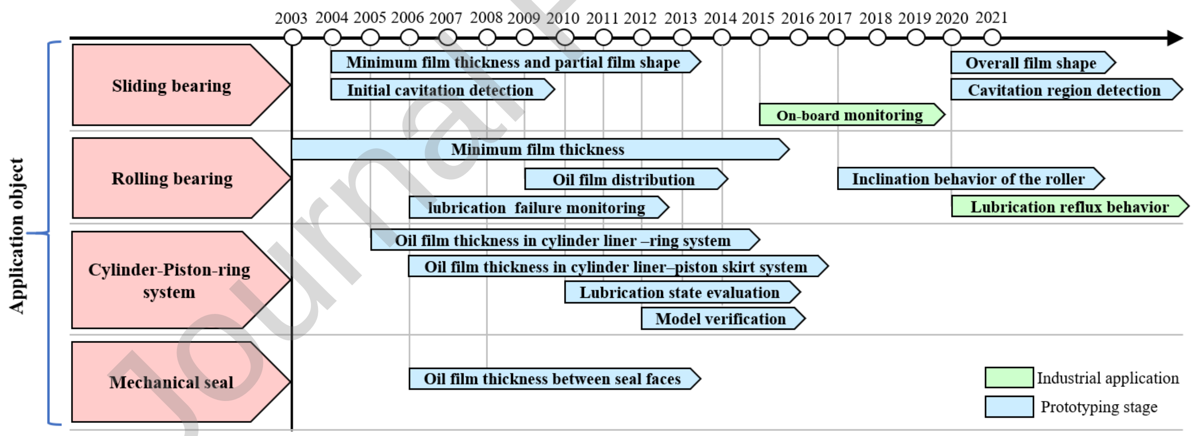



Figure 9 Progress timeline of the models and their applications

## 3.1 Sliding bearings

Hydrodynamic sliding bearings are key components in mechanical equipment, which are widely used as support in hydropower and thermal power generating units, rocket engines, high-speed precision machine tools. Therefore, the measurement of oil film thickness has attracted great attention, in particular, to identify the parameters of lubricating film from ultrasonic signals. Lubricating performances in relation to the loading ability, cavitation, and bush deformation are also studied.

1) Oil film shape

The oil film shape is a critical concern for high-speed sliding bearings. The prospect of the ultrasonic technique has been demonstrated by measuring the film thickness at the maximum load point using the amplitude and phase respectively[58]. Good consistency between the measurement results and the numerical solution of Raimondi and Boyd is obtained except for some absolute errors indued by friction temperature and misalignment of the axle [59].

Subsequently, to examine the oil film shape in a running journal bearing, Dwyer-Joyce and coworkers [60] have measured the partial distribution of film thickness around the circumference. The minimum film thickness is derived from the geometry shape of the gap and the attitude angle is obtained through the position of the minimum film thickness and the oil inlet. Again, the measured results agree well with the hydrodynamic theory. However, this measurement will be interfered under the high-load condition where the bush is likely to be deformed elastically [60]. Due to this consideration, the experiment has been improved by Kasolang [61][62] by placing the sensor in a hollow shaft and transmitting the high-frequency ultrasonic signal through the slip ring.

The main problem with these measurements is the limitation of the single ultrasonic models whose effective ranges could not cover the variation range of film thickness. Thereby, Beamish [55] has applied the spring model and the resonance model simultaneously to cope with different film thicknesses. Through the tests of centering, misalignment, and shutdown, the formation and the overall nonlinearity of circumferential oil film thickness are explored under different conditions.

2) Cavitation detection

For bearings with high accuracy and high load, cavitation caused by the pressure drop in the divergent region of bearings occurs and can erode the bush surface. However, cavitation is difficult to be detected due to its complicated causes. In 2004, Dwyer-Joyce reports the influence of cavitation on ultrasonic measurement [60]. However, the exact position of the cavitation front varies with eccentricity, the supply pressure, and the lubricant, which is difficult to determine. By measuring the circumferential full film thickness profile under different loads, the information of cavitation initiation and film reconstruction in the cavitation region is revealed [61].

3) On-board monitoring

Real-time monitoring of oil film in sliding bearings has been performed in machines under actual operating conditions, e.g., the bearings in an automobile power train by Suzuki et al. [63] and the bearing of an air conditioning compressor by Oyamada et al.[64]. It is found that unlike in component testing, the temperature, pressure, and oil mixture all have certain influences on the measurement in running machines.

4) Limitations

Despite the above progress and the potential prospects for ultrasonic-based film monitoring, this endeavor faces significant challenges summarised as follows:

- Regarding the oil quality, bubbles are common in the lubrication of sliding bearings. The air-oil mixture changes the sonic velocity of the pure oil and ultrasonic measurement fails when encountering extensive cavitation. For elastic deformation of sliding bearing, it remains difficult to isolate the contribution of the cavitation from the overall reflected signals.
- In the measurement of oil film thickness, Beamish et al. reported a small but sharp decrease in oil film thickness at TDC caused by bearing deformation in bearing bush[55]. This deformation cannot be predicted by the Raimondi Boyd model based on the complete rigidity of components. Further, the local deformation of the soft bush surface is widely found in heavy load bearings. Although reports on this topic are scarce, it presents a problem for ultrasonic measurement.
- The influence of temperature is no doubt fundamental for most measurements. It affects the density, sonic velocity, and deformation. So far, compensation is mainly relayed on the temperature measurement of the oil inlet and outlet. Further compensation with exact temperature in oil film needs to be studied.
- Regarding the thin-liner bearing, the influence of the ultrasonic reflection signal at the substrate-liner interface cannot be removed accurately and large-scale oil film thickness calculation cannot be realized.

### 3.2 Rolling bearings

Oil film in rolling bearings, for both ball and cylinder bearings, is characterized in micro- or nano-scale size in both depth and plane dimensions. In addition, these ultra-thin films appear and disappear instantaneously under complicated phenomena including local elastic deformation, solid asperity contact, and transient temperature, etc. In this regard, researchers have analyzed the problems related to the film thickness measurement, including measurement limit, and minimum oil film thickness. Based on the film thickness measurement, the distribution of film thickness is further investigated. The reflection coefficient is also studied to directly reflect the lubrication failure behavior.

1) Film thickness measurement

Many efforts have been made to improve spatial resolution and the pulse repetition rate (PRF). Solutions include applying a focused sensor and developing new sensors, details of which are presented below.

To improve the spatial resolution, a water focusing sensor is initially introduced in 2003 to measure the oil film thickness in ball-bearing tribo-pairs [17]. Moreover, significant limitations are also encountered including the extraction of actual film thickness within rough surface contacts, the acoustic attenuation by a thick ring, the spatial resolution of the sensor, the rotational speed suitable for repeating frequency, and the effect of temperature on the sensor.

With a high-frequency focusing sensor, Zhang et al. has used the angular spectrum method to study the interaction between the sound field and the thin oil film based on the spring model [65]. The ultrasonic field is decomposed into component plane waves via spatial Fourier transform and then the component plane waves with different angles are recombined into an ultrasonic field via the inverse angular spectrum. An upper limit of the reflection coefficient is found. Correspondingly, a calibration method is studied based on the difference between the weighted reflection coefficient and the normal one, and a minimum thickness of 0.2 μm is obtained. In another study, Zhang et al are able to measure a central film as thin as 0.3-1.0μm [39].

A new type of ultrasonic pulser-receiver with a maximum pulse repetition rate of 100 kHz has been developed, and the speed of bearing that can be measured has been increased to 2000 rpm and the measurable working range has been greatly expanded [66]. The simulation analysis shows that the roller vibration is the cause of the fluctuation of lubrication film thickness. Furthermore, the PRF is shown to be limited by the requirement that the pulse transmitting interval is sufficiently long to ensure the echo separation.

2) Oil film distribution

To measure the oil film distribution, the reflection coefficient should be corrected for the uneven sound pressure and bulk modulus in the focus area of the sensor [39]. Based on the ray-tracing theory and the angular correlation spectrum distortion theory, the influence of the tilt angle between the incident pulse and the received echo pulse has been analyzed. The analysis shows that the measurement error decreases with the increase of central frequency, focal length, and the decrease of sensor aperture. Therefore, an ideal sensor should have a higher central frequency, a smaller aperture, and a longer focal length.

In 2009 Drinkwater et al. make an AIN piezoelectric thin-film sensor with a central frequency of up to 200 MHz [42]. They investigate the influence of geometric deformation of the raceway on the obtained reflection signal with a ray model, to revise the measured reflection coefficient. A slight improvement is obtained compared with the water-focusing measurement. Besides, the highlight of this work is the advantage of the thin-film sensor over the extra-equipped sensors, such as miniature, reliable connection with objects and high spatial resolution, etc.

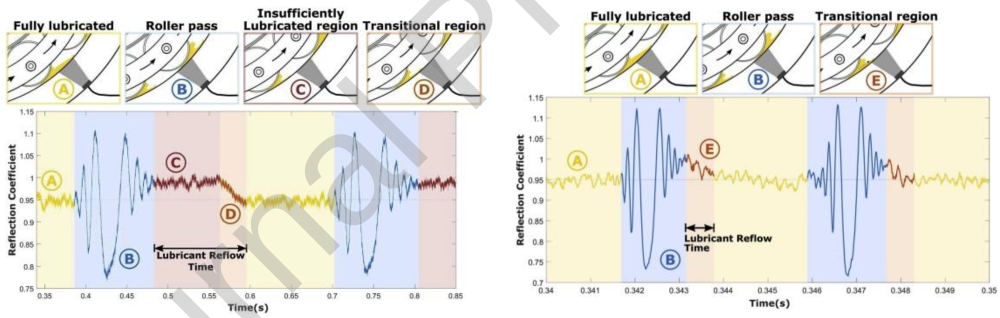
In 2012, Ibrahim and Dwyer-Joyce use a 25 MHz water focusing transducer to analyze the oil film thickness distribution of ball bearing [67]. This study shows that, considering the resolution limitation, a more accurate oil film profile can be obtained by using a high pulse repetition frequency to match the instantaneous appearance of the contact zone. This means that the measurement technology would be challenged to measure high-speed rolling bearings.

To detect the inclination behavior of the roller bearing, the axial distribution of oil film thickness of lubrication film has been measured by two sensors arranged in parallel in the axial direction of cylindrical roller bearing [68].

3) Lubrication failure monitoring

Zhang et al have studied failure detection in rolling bearing with ultrasonic-based film monitoring. With the help of a light-reflective position method, the contact area of the ball-ring can be matched with the film detection point exactly[69]. The bearing failure in an accelerated experiment is detected from the response law of reflection coefficient and co-operated with the temperature and vibration information. This study initializes online failure monitoring of rolling bearings as another application for ultrasonic technology.

In 2020, Nicholas et al. arrange two piezoelectric ultrasonic sensors at the maximum load point and 40° position of the outer raceway of the high-speed shaft bearing in the wind turbine gearbox as shown in Figure 10 [56]. By recording the reflection coefficient, the situation that the roller outlet area is completely submerged or partially starved is displayed, and the random behavior of bearing lubrication is captured. The results show that different lubrication reflux behaviors are observed at low speed and high speed. At low speeds, the lubricant has sufficient time to return to the area previously cleaned by the roller. At high speeds, the lubricant is pressed into the area by the incoming roller. In some occasions, the entrance of some rollers is not completely submerged, while the nearby rollers are completely submerged. This proves the randomness of bearing lubrication.




(a) (b)

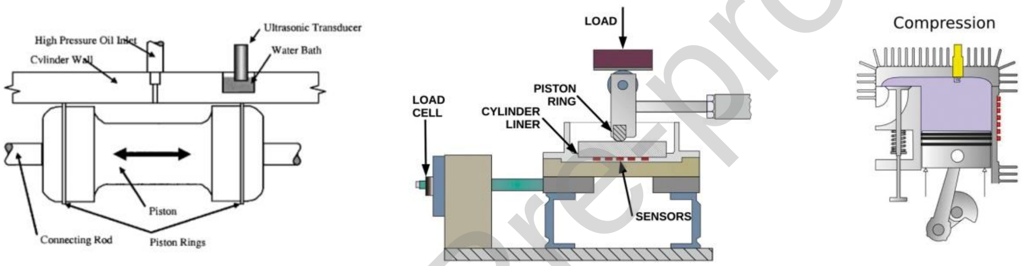
Figure 10 Monitoring of bearing lubrication behavior at (a) low speed and (b) high speed [56]

To sum up, with regard to oil film thickness measurement, a low-cost sensor suitable for industrial measurement needs to be developed, and the pulse repetition rate needs to be improved to meet the needs of accurate measurement of oil film distribution in high-speed rolling bearing film thickness measurement. The ultrasonic reflection coefficient has been proved to be sensitive to the oil film thickness and oil film bulk modulus, so the reflection coefficient can directly characterize the characteristics of lubricating film and lubricating failure behavior. This provides the potential to diagnose fault mechanisms, thereby improving the ability to predict the remaining life of bearings.

### 3.3 Cylinder-piston-ring system

Cylinder-piston-ring system is commonly used in reciprocating machines, such as engines and plunger pumps. The friction loss, which is closely linked to the lubrication condition, is an important indicator of the condition and performance of these efficiency-seeking machines. Due to the high pressure, the tribo-system requires ultra-thin oil film for sealing. Attempts to measure oil film thickness in such cylinder-piston-ring systems have been performed via a test rig and bench tester as shown in Figure 11 [70][71][72].

In the cylinder-piston-ring system, most of the contact friction occurs between the piston ring and cylinder liner, and between the piston skirt and cylinder liner. Among them, the oil film thickness is thinnest in the piston ring-cylinder liner contact, which is most prone to wear. Therefore, researchers have firstly studied the film thickness measurement and contact imaging between the piston ring and cylinder liner, and then analyzed the film thickness measurement and contact imaging between piston skirt and cylinder liner. The resulting film thickness measurements are further used to analyze the lubrication state and verify the numerical simulation model of lubrication contact.




(a) (b) (c)

Figure 11 Schematic diagram of oil film thickness measurement with test rigs of (a) hydraulic motor piston ring [70], (b) ring-cylinder liner [71], (c) single-cylinder engine piston [72]

1) Oil film thickness measurement in the cylinder liner–ring system

The friction between the piston ring and cylinder liner contributes significantly to the overall energy loss of machines including the internal combustion engines and hydraulic motors. The oil film thickness measurement within such a tribo-pair has been first conducted in a hydraulic motor piston ring test rig. A water focusing sensor and the spring model are adopted and film thicknesses in the range of 0.7~1.3 μm are successfully measured. However, the water focusing sensor is fixed on the outside cylinder and is difficult to position [70].

Subsequently, to track the variation of the lubricating film during the reciprocating motion, Avan et al. have measured the oil film thicknesses at the top dead center (TDC), bottom dead center (BDC), and the mid-stroke position of the cylinder (MID) [73]. Moreover, miniature sensors are adopted to improve spatial resolution[74][75]. With this, they find different lubrication conditions and cavitation degrees during the up-stroke and down-stroke. And large fluctuation has been observed in the up-stroke [71]. In addition, it is proved that the minimum film thickness has positive correspondence with reciprocating speed and negative correspondence with a normal load.

More comprehensively, the contact of the piston ring of a fired engine is imaged through a sensor array, including the compression ring and twin rails of the oil scraper ring. The minimum oil film thickness has a good consistency in the four strokes of induction, compression, power, and exhaust under the loaded condition. However, under the c idling condition, due to the piston swing and the inherent rotation instability of the single-cylinder engine, there is a great difference in film thickness in the four strokes.

This technique is only able to provide an average value of film thickness within the width of the sensor. Even when a small sensor is adopted, it could not provide the contour of the piston ring. However, the minimum thickness can be obtained by deconvolution calculation [43].

2) Oil film thickness measurement in the cylinder liner–piston skirt system

In 2006, Dwyer-Joyce et al measure the oil film thickness between the piston skirt and cylinder liner in a single-cylinder four-stroke engine. A wide variation range of oil film thickness 2~21 μm has been reported [76]. However, due to the absence of the relative position between the sensor and the piston, the measured film thickness cannot be matched with the geometry of the piston skirt accurately.

When the piston passes through the position of the sensor, the time history of the oil film thickness can be provided using a single sensor, while the obtained oil film profile does not represent the given instantaneous oil film shape, and the wrong prediction of the oil film shape may be caused by the piston's secondary motion. This problem is solved by Mills et al. in 2013 using a high-resolution sensor array [72]. With the correlation algorithms, the motion cycle is determined. The phenomenon of "piston slap" is captured in the piston skirt during the expansion stroke, which highlights the potential of the ultrasonic method to indirectly measure the piston secondary dynamics.

The simultaneous measurement of oil film thickness for the thrust and anti-thrust surfaces provides a method to infer piston direction in the cylinder. In 2014, a series of tests are carried out in both motored and fired conditions, and the obtained film profile is used to establish the image of the piston secondary motion [54]. The results show that a "double minimum" is observed on the anti-thrust surface due to the small rotation of the piston during the upward translation along the bore during the combustion stroke, and the phenomenon of "piston slap" appears due to the coupling of clearance and combustion pressure during the expansion stroke.

3) Lubrication state evaluation

In 2010, Avan et al study the lubrication state of the ring-cylinder liner tribo-system ring-cylinder liner reciprocating test rig with different lubricants [74]. The boundary and mixed lubrication of low viscosity oil and the fluid lubrication state of high viscosity oil are found from the oil film monitoring. The change of lubrication states and the influence of viscosity and additive composition are explored by inspecting the relationship between friction coefficient and oil film thickness [75].

The boundary and mixed lubrication of piston ring-cylinder tribo-pair are greatly influenced by surface morphology [77]. Oil film thickness is also adopted to explore the influence of surface roughness and surface morphology on the lubrication of ring-cylinder liner interface to optimize the material selection.

4) Model validation

Numerical modeling for lubrication design is difficult to be validated before oil film thickness could be measured. In 2012, a numerical model for ring-liner contact under full film lubrication is verified by the ultrasonic method [71]. In 2014, the transient friction dynamics of thermoelastic flexible piston skirt is verified by measuring the oil film thickness through the array of ultrasonic sensors on the thrust side of the piston skirt, to assist in the study of transient friction in the engine cycle [78]. Subsequently, a semi-automatic method has been proposed to predict the thermomechanical deformation of the piston skirt with the oil film numerically solved by the Reynolds equation and the accuracy of the proposed method is verified by ultrasonic film thickness measurement results [79].

5) Limitations

In conclusion, the ultrasonic method achieves the oil film thickness measurement in piston assembly, provides the basis for the optimization of piston structure, and shows potential in the research of piston lubrication state, cavitation phenomenon, secondary movement, and so on. However, it also has some limitations in the application. First, the accurate contour of the piston ring cannot be obtained due to the influence of spatial resolution. Second, the influences of oil contamination such as air bubbles need to be further studied. Finally, the precise compensation considering the temperature and pressure of the oil film should be included to improve the measurement accuracy.

### 3.4 Mechanical seals

Mechanical seals are commonly used in pumps, turbines, and compressors, etc. A thin oil film between seals can cause friction and wear, while a thick oil film may cause excessive leakage. Oil film thickness measurement is important for monitoring the condition and predicting seal failure. However, most of the new generation seals are made of silicon carbide rather than steel - the traditional material. Compared with steel, silicon carbide has different acoustic impedance and attenuation characteristics, which could lead to the failure of ultrasonic measurement.

To address this issue, Reddyhoff et al. [53] have analyzed the feasibility of the ultrasonic measurement technology in the measurement of oil film thickness between the seal faces through comparing with the method of optical and capacitance. The potential of the ultrasonic technique in measuring film thickness is verified. But there are still several limitations and challenges：

1 ) Because the sealing material can exhibit high ultrasonic attenuation, this can restrict measurements. In addition, due to the large impedance difference between the two sides of the oil film, the amplitude of the reflection coefficient is not sensitive to the change of film thickness, which reduces the measurement accuracy.

2 ) The non-uniform distribution and real-time change of the temperature in the sealing structure require real-time, accurate compensation for the ultrasonic measurement, which puts forward stricter requirements for the temperature compensation technology.

3 ) The bubbles in oils will deteriorate the measurement accuracy of this echo-based method. Part of the ultrasonic pulses could be reflected at the oil-air interface of bubbles, and further, interfere with the echo signal from the oil layer.

## 4. Key technical issues and possible solutions

Despite numerous fundamental advances over the past 20 years, ultrasonic-based oil film thickness measurement has had limited uptake in industrial applications. The section discusses key technical issues and possible solutions prospects for future breakthroughs.

1) Resolution and sensitivity

a) Spatial resolution

To measure the oil film thickness in point and line contact friction pairs with narrow contact areas in the industry, the sensor is required to have high spatial resolution and the modification to the bearing structure needs to be as small as possible. On one hand, the piezoelectric aluminum-nitride film has been proved to be a possible solution. The width of this state-of-the-art ultrasonic sensor has reached 0.3 mm [42]. However, with the decrease in the sensor width, the process complexity of the piezoelectric aluminum-nitride film increases, and the manufacturing difficulty becomes greater. At the same time, the energy of the ultrasonic signal decreases, and the thickness of the steel that can be penetrated decreases. Therefore, it is necessary to further analyze the limited minimum width of the piezoelectric aluminum-nitride film through experiments. On the other hand, the overlapping area method of adjacent measuring points has been proved effective in improving spatial resolution [45]. However, this method is limited by high bearing speed, where the maximum pulse repetition frequency of the ultrasonic pulser-receiver needs to be improved.

b) Sensitivity in the blind zone

In the three-layered structure, the measurement error in the blind zone, is non-negligible (up to $\pm 7\ \mu m$) [26] despite the phase model, complex model, and unified time-domain model are applicable. The main difficulty is that both the waveform amplitude and phase of the echo are insensitive to the change of the film thickness in the blind zone. In the future, the measurement accuracy in the blind zone may be improved by signal processing methods (such as repetitive measurements) and high-stability pulser-receivers.

2) Unified models for wide-range measurement

For the three-layered structure, the models (resonance model, complex model, etc) in the frequency domain can effectively cover the measurement range of the variation of oil film thickness in a wide range. However, it is necessary to switch between the models to cover the full range. The time-domain model, the unified time-domain model, is a unified solution of the film thickness model, but the algorithm needs to be improved to reduce the calculation time [20]. For some special multi-layer friction pairs, such as thin liner sliding bearing, the high-order reflected signals of multi-reflection should be considered to improve the calculation accuracy of the ultrasonic model [36]. Besides, the measurement range covering the blind zone should be considered by exploring more information from the spectrum of phase and amplitude [35].

3) Non-full film lubrication measurement

At present, ultrasonic technology has been proven to be applicable for full-film lubrication, however, not fully investigated in the case of mixed lubrication, where the contact stiffness is more complex and is determined jointly by (i) solid-to-solid contact in the areas where the surface asperity penetrate the ultra-thin oil film and (ii) the fluid film in the other regions where the surfaces are separated by the oil film. Therefore, reliably and accurately identifying the proportion of these two is important for mixed lubrication detection. A solution for measuring the average oil film thicknesses under the mixed lubrication conditions is to introduce the proportion factor using theoretical approximation [46]. The deviation caused by this approximation is, however, difficult to estimate, and the existing approach needs to be further studied and developed.

It is worth noting that recent research has broadened the initial spring model with the stiffness terms only to a stiffness-mass-damping model [34][80][81]. It is a new method to detect the state of mixed lubrication. However, using stiffness and damping to characterize the ultrasonic response of the lubricating interface requires a precise physical explanation [34], which is yet to be achieved. Furthermore, existing research shows that for dry friction and rough surface contact detection, damping has a great influence on the measurement results [81], while for fluid lubrication detection, it has almost no effect [34]. It is expected that future studies can provide an answer to the question, that is, can this phenomenon be the criterion for identifying the state of mixed lubrication.

4) Comprehensive compensation for online monitoring

In the actual operation of industrial machines, the changes of temperature and pressure will lead to the changes of the waveform of the ultrasonic pulse, the density, and the sound speed of the transmission medium, thus affecting the accuracy of film thickness measurement. At present, the research is mostly directed at a single working condition, without considering the complexity of actual working conditions. For the actual working conditions, the distribution of temperature and pressure in the medium is non-uniform and changes with time. Meanwhile, both of these parameters affect the waveform of the ultrasonic pulse, the density, and the sound speed of the transmission medium [39][51]. Therefore, it is difficult to compensate for the temperature and pressure variations comprehensively. In addition, lubricant degradation, surface roughness, debris interference, fluid cavitation, and so on will also affect the ultrasonic reflection signal and film thickness measurement results.

To accurately compensate for the influence of pressure and temperature, a multi-factor compensation model is necessary. First, the influence mechanism of temperature and pressure needs to be further studied to determine the coupling relationship between pressure and temperature. Second, the real-time pressure and temperature need to be measured using the temperature and pressure sensors. Third, the distribution of pressure and temperature with the position needs to be obtained, which may be achieved with help of the simulation technique of temperature field and pressure field. Fourth, the acoustic simulation technology can be used to analyze the influence of lubricant degradation, surface roughness, debris interference, fluid cavitation on the echo signal, such that corresponding compensation strategies can be established.

## 5. Conclusions

The current developments of ultrasonic film thickness measurement technology are comprehensively reviewed in terms of theoretical models, provisional practices, and technical issues. It can be concluded that ultrasonic models have been thoroughly developed for both parallel and non-parallel structures; the temperature and pressure effect on measurement results have been taken into account and further compensated in practice. Moreover, the accuracy and applicability of these models have been examined with various concerns on minimum film thickness, film distribution, cavitation, and other phenomena in friction pairs. Some initial applications, such as in sliding and rolling bearings, have been attempted. Before being promoted to industrial use, the following key issues need to be addressed i) insufficient resolution and poor sensitivity in the blind zone, ii) unification of wide range measurement models, iii) Non-full film lubrication measurement and iv) comprehensive compensation for online monitoring. Possible solutions to these have been proposed and should be the focus of future studies.

## Acknowledgments

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# Appendix

The reflection coefficient with a three-layered structure of "solid 1-oil-solid 3", $R(f)$, is defined as the ratio of the echo to the incident wave [25]:

$$R(f) = \frac{V_{12} + V_{23}\exp(\frac{4i\pi f d}{c_2})}{1 + V_{12}V_{23}\exp(\frac{4i\pi f d}{c_2})} \quad (1)$$

where $d$ is the oil film thickness; $f$ is the wave frequency; $c_2$ is the sound velocity in the oil ; $V_{12}$ and $V_{23}$ are the reflection coefficients at the interfaces of "solid 1/oil" and "oil/solid 3" respectively, calculated by

$$V_{12} = \frac{z_1 - z_2}{z_1 + z_2}, V_{23} = \frac{z_2 - z_3}{z_2 + z_3} \quad (2)$$

where $z_1$, $z_2$ and $z_3$ are the acoustic impedances of solid 1, oil, and solid 3 respectively.

Table 5 summarizes the calculation formulas of the most commonly used ultrasonic models. $|R(f)|$ and $\Phi_R(f)$ are the amplitude and phase of the reflection coefficient respectively. $\rho_2$ is the density of the oil. $f_m$ is the resonance frequency. $m$ is the resonance mode.

Table 5 Calculation formulas of the most commonly used ultrasonic models

| Ultrasonic model | Calculation formula ($z_1 \neq z_3$) | Calculation formula ($z_1 = z_3 = z$) |
|---|---|---|
| Spring model | $d = \frac{\rho_2 c_2^2}{2\pi f z_1 z_3} \sqrt{\frac{\vert R(f)\vert^2 (z_1 + z_3)^2 - (z_1 - z_3)^2}{1 - \vert R(f)\vert^2}}$ | $d = \frac{\rho_2 c_2^2}{2\pi f z} \sqrt{\frac{\vert R(f)\vert^2}{1 - \vert R(f)\vert^2}}$ |
| | $d = \frac{\rho_2 c_2^2 (\tan \Phi_R(f))(z_1 - z_3)}{2\pi f z_1 z_3^2 - \sqrt{(2\pi f z_1 z_3^2)^2 - (\tan \Phi_R(f))^2 (z_1^2 - z_3^2)(2\pi f z_1 z_3}}$ | $d = \frac{\rho_2 c_2^2}{\pi f z \tan \Phi_R(f)}$ |
| Resonance model | $d = \frac{m c_2}{2 f_m}$ | |
| Phase model | $\Phi_R(f) = atan\left[\frac{V_{23}(1 - V_{12}^2)\sin(\frac{4\pi f d}{c_2})}{V_{12}(1 + V_{23}^2) + V_{23}(1 + V_{12}^2)\cos(\frac{4\pi f d}{c_2})}\right]$ | $\Phi_R(f) = \text{atan}\left[\frac{(1 - {V_{12}}^2)\sin\left(\frac{4\pi f h}{c_0}\right)}{(1 + {V_{12}}^2)\left(1 - \cos\left(\frac{4\pi f h}{c_0}\right)\right)}\right]$ |
| Complex model | $d = \frac{c_0}{4\pi f} \text{atan}\left(\frac{\vert R(f)\vert \cdot \sin(\Phi_R(f)) \cdot (1 - V_{12}^2)}{\vert R(f)\vert \cdot \cos(\Phi_R(f)) + \vert R(f)\vert \cdot \cos(\Phi_R(f)) \cdot V_{12}^2 - \vert R(f)\vert^2 \cdot V_{12} - V_{12}}\right)$ | |

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**Declaration of Competing Interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.