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Ultrasound-based measurement of liquid-layer thickness: A novel time-domain approach

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ABSTRACT

Measuring the thickness of a thin liquid layer between two solid materials is important when the adequate separation of metallic parts by a lubricant film (e.g., in bearings or mechanical seals) is to be assessed. The challenge in using ultrasound-based systems for such measurements is that the signal from the liquid layer is a superposition of multiple reflections. We have developed an algorithm for reconstructing this superimposed signal in the time domain. By comparing simulated and measured signals, the time-of-flight of the ultrasonic pulse in a layer can be estimated. With the longitudinal sound velocity known, the layer thickness can then be calculated. In laboratory measurements, we validate successfully (maximum relative error 4.9%) our algorithm for layer thicknesses ranging from 30 μm to 200 μm. Furthermore, we tested our method in the high-temperature environment of polymer processing by measuring the clearance between screw and barrel in the plasticisation unit of an injection moulding machine. The results of such measurements can indicate (i) the wear status of the tribo-mechanical screw-barrel system and (ii) unsuitable process conditions.

1. Introduction

Non-invasive ultrasound-based determination of liquid layer thickness is essential to evaluating the separation of metallic parts by a lubricant film. Insufficient film thickness is an important indicator of possible surface contact, which causes high friction and wear in machine elements such as bearings, mechanical seals, hydrostatic slideways and the tribo-mechanical screw-barrel system used as a plasticizing unit in polymer injection moulding and extrusion. Existing techniques for liquid layer thickness measurement are electrical (electrical resistance, layer capacitance, eddy current) or optical (optical interferometry, fluorescence of liquid layer) methods. Nevertheless, there are several disadvantages using these methods: Electrical methods require electrical isolation of the machine elements separated by the liquid layer and/or surface mounted sensors. For optical methods an optical access to the liquid layer must be provided. Ultrasound-based lubricant film thickness estimation is usually based on reflection measurements using a transducer that transmits and receives ultrasonic pulses. The film thickness can be estimated either from the resonant frequency or the layer stiffness. These methods have been used successfully to monitor the thickness of lubricant films in seals [1] and ball bearings [2]. However, measuring the thickness of lubricant films in the range of 1–100 μm requires broad-band transducers with high centre frequencies.

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Another application of ultrasound is measuring the clearance between plasticizing screw and barrel at high temperatures (> 200 °C) and high pressures (> 1000 bar) during polymer processing [3,4]. Here, the lubricant film is formed by the molten polymer granules. From such measurements, the radial displacement of the screw (and thus possible unwanted points of contact between screw and barrel surface) and the level of wear of the screw flight can be determined by analysing the time-of-flight (TOF) difference between the reflections from the inner radius of the barrel and from the screw flight. Possible reasons for a radial displacement are inappropriate process conditions and misalignment of system screw and barrel. The screw and the barrel are subjected to adhesive, abrasive and corrosive wear. While adhesive wear is caused by unavoidable contacts between screw and barrel during the plasticisation process, abrasive and corrosive wear depend on the type of polymer being processed. Ultrasound-based measurement of the screw/barrel clearance could reduce inspection time compared to conventional methods. Furthermore, the received signal is the sum of multiple reflections of the ultrasound pulse in the thin layer requiring signal processing methods that are able to distinguish between the reflections. Various deconvolution techniques [5–11] using the wavelet, frequency or time domains have been proposed to resolve this issue.

In this paper, we propose a novel approach to measuring the thickness of a liquid layer using low-cost components. We have developed an algorithm that temporally resolves multiple overlapping pulses reflected in the liquid layer between two steel surfaces. An assessment of the system's accuracy in laboratory experiments showed that the smallest detected film thickness is 30 μm. Furthermore, the system was tested and successfully deployed in the harsh industrial environment of polymer processing.

2. System model

A schematic of a thin liquid layer between two steel surfaces is shown in Fig. 1. The incident ultrasonic pulse S_{in} is transmitted into the steel layer, and the main part of sound energy (assuming that $l_{steel} \gg l_{layer}$ and $z_{steel} > z_{layer}$, the acoustic impedances z_s and z_l of steel and the liquid layer are products of the densities and sound velocities in the respective materials) is reflected by the steel/liquid interface denoted as $S_{m,ref}$. This reflection is overlaid with subsequent multiple reflection signals $S_{1,layer}$, $S_{2,layer} \ldots S_{n,layer}$ from the thin liquid layer [12]. The lost signal parts $S_{1,loss}$, $S_{2,loss} \ldots S_{n,loss}$ (i.e., those not received at the ultrasound transducer) are transmitted into the steel layer below the liquid film. The received signal is given by

$$S_{ref}(t) = S_{m,ref}(t) + S_{1,layer}(t) + S_{2,layer}(t) + \ldots + S_{n,layer}(t) \tag{1}$$

Due to the discrete data acquisition (assuming that $T_s = 1/f_s$, where f_s is the sampling frequency), the received discrete-time signal is

$$S_{ref}[k] = S_{ref}(t)|_{t=kT_s}. \tag{2}$$

Assuming that the main reflection signal $S_{m,ref}$ is known (from a calibration measurement or at positions where the liquid layer is so thick that the reflected signals do not overlap), the superimposed reflection signals from the thin liquid layer can calculated by

$$S_{layer}[k] = S_{ref}[k] - S_{m,ref}[k]. \tag{3}$$

2.1. Proposed algorithm

Fig. 2 shows amplitude weighting factors for the multiple reflections from the thin layer.

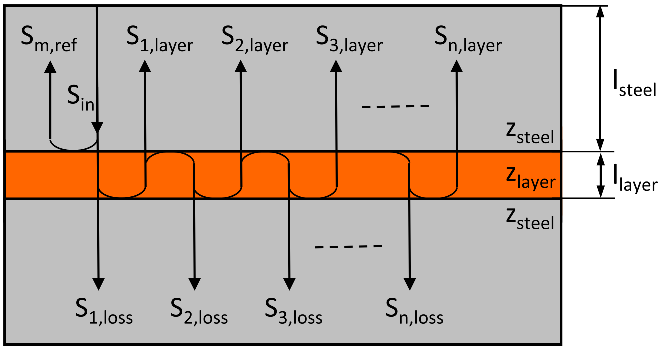

Fig. 1. Schematic diagram of the reflection of an ultrasound pulse in a liquid layer between two metal surfaces.

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