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The real-time measurement of wear using ultrasonic reflectometry

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ABSTRACT

Ultrasonic reflectometry is commonly used in the fields of non-destructive testing (NDT) for crack detection, wall thickness monitoring and medical imaging. A sound wave is emitted through the material using a piezoelectric transducer. This waveform travels through the host medium at a constant speed and is either partially or fully reflected at an interface. The reflected wave is picked up by the same sensor; the signal is then amplified and digitised. If the speed that sound travels through a host medium is known as well as the time this takes, the thickness of the material can be established using the speed, distance and time relationship.

Previous work has concluded that the ultrasonic method is too inaccurate to measure wear due to the errors caused by temperature, vibration and the experimental arrangement. This body of work looks at methods to minimise these errors, particularly the inaccuracies introduced from the change in temperature caused by change of acoustic velocity and the thermal expansion of the material, which can be significant in many applications. Numerous case studies are presented using the technique in both laboratory and industrial environments using low cost retro-fittable sensors and small form electronics.

1. Introduction

The understanding of wear behaviour is paramount to material selection and machine element design. It is difficult to predict in-situ wear behaviour due to the large number of influential parameters. A common method to build up an understanding of wear behaviour is to conduct laboratory based experiments with similar materials and representative contact conditions. Analysis of wear then takes place post-experiment. The traditional method of quantifying wear is the mass-loss measurement, the procedure of measuring the mass before and after the test and reporting the overall mass removed. This method has been successfully used for many applications, although not always feasible when material transfer takes place or when testing porous materials in lubricated environments.

Another post-test measurement method is surface profilometry. This is the procedure of 'measuring the surface of a material', usually using an optical or stylus based method. These tools are very useful to characterise surface detail and deep grooves, but cannot measure wear of some geometries such as a cylindrical pin, as the entire contacting face will wear down with no datum point for reference. In some cases, i.e., wear on a ball; it is possible to estimate wear from geometrical wear scars. The drawback is that none of these methods actually give a value for wear rate, only absolute wear post-test. It is possible to intermittently halt the test, remove specimen and take measurements, but this can interfere with the experiment.

Eddy current, linear potentiometers and laser displacement sensors are all devices that are used to measure position and displacement. By mounting a sensor on a fixed position measuring the displacement of the moving wearing component, it is possible measure a change in component thickness and thus infer a measurement of wear. Some tribometers have this feature fitted as standard or as an optional extra, for example the Plint TE99 Universal Wear Testing machine has the option of having a transducer to measure the vertical movement of the pin relative to the fixed datum during the test. In the product literature, this is described as 'giving an indication of wear', but factors such as to thermal expansion, wear debris and the transfer of material can also result in some displacement. These displacement systems measure the position of the specimens and from which infer the net wear of both components.

Ultrasound has been trialled as a tool for measuring thickness change to understand wear evolution. However, as noted by Birring and Kwun, the method is possibly too inaccurate because of errors caused by temperature, vibration and the experimental arrangement [3].

The aim of this work was to investigate ultrasonic measurement of wear in order to develop a methodology able to overcome the previous issues, as potentially ultrasound can provide improvements over other available techniques if these can be remedied.

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2. Theory

Ultrasonic reflectometry is commonly used in the fields of NDT for crack detection, wall thickness monitoring and medical imaging. A sound wave is emitted through the material using a piezoelectric transducer. This waveform travels through the host medium at a constant speed and is either partially or fully reflected at an interface. The reflected wave is sensed by the same piezo sensor which generates a low voltage electrical signal proportional to the magnitude of the pressure wave. The signal is then amplified and digitised. A typical time domain plot, known as an A-scan, can be seen in Fig. 1.

The first feature on the time-domain plot is known as the 'initial bang'. This is the digital signature of the excitation pulse picked up by the receiver. The sound wave then travels through a solid medium at a constant velocity. If it reaches an area of differing density (such as a solid-air interface), the wave is partially reflected and partially transferred according to the acoustic impedance of the material. With a solid-air interface, it can be assumed that 100% of the pressure wave is reflected. The reflected wave is then detected by the same sensor. A result of this is an electrical pulse that can be seen in the time-domain A-scan. If the speed that sound travels through a host medium is known (a material property) as well as the time taken (or time-of-flight), the thickness of the material can be established using the speed, distance and time relationship. This method is commonly used in ultrasonic thickness gauging. Wear is defined as the removal or deformation of a material on a surface from a mechanical action of the opposite surface [1]. Therefore that by accurately measuring the change in thickness of a material, a measurement of wear can be directly inferred. This work investigates the use of ultrasound as a measurement tool to achieve this.

This body of work looks at methods to minimise the error in the measurement, particularly the inaccuracies introduced from the change in temperature of the material, which can be significant in many applications. This is more of an issue when continuous measurements are being taken with fluctuating temperature and less of an issue for a single measurement such as those taken using traditional ultrasonic thickness gauges.

A solution is proposed to account for thermal expansion using a reference measurement that changes with temperature. This allows a comparison to be drawn resulting in a more accurate absolute wear measurement. Furthermore, a frequency based method is introduced that allows for the errors from temperatures to be reduced further.

There are numerous ways to extract time information from an A-scan. The analogue sing-around and pulse-overlap methods have been traditionally used with varying degrees of success; more information can be found in Mason and Thurston [2]. With digitised waveforms, a number of options are available to calculate the time-of-flight. The zero-crossing time-of-flight cross correlation measurement is evaluated as the distance between the zero crossing points of two successive echoes. A few data points either side of the zero crossing point are fitted by a linear function, then the zero crossing point is calculated as the intersection of the linear function and the horizontal zero line. This increases measurement accuracy as it is not as dependent on the digitising clock speed.

With this method, it is important to capture at least two consecutive reflections in the waveform and use the distance (in terms of time) between the two reflections to calculate the time-of-flight. It is important to use the same zero crossing point in each reflection. It is not suitable to use the excitation pulse or 'initial bang' because the waveform is not of similar shape. In many ultrasonic applications, the same transducer that generates the sound-wave also receives the signal after it is reflected from an interface, this is known as pulse-echo mode. If this is the case, it is vital to remember that the time-of-flight refers to the path of material in which the ultrasound travels which is twice the thickness of the material so the sound has to travel there and back.

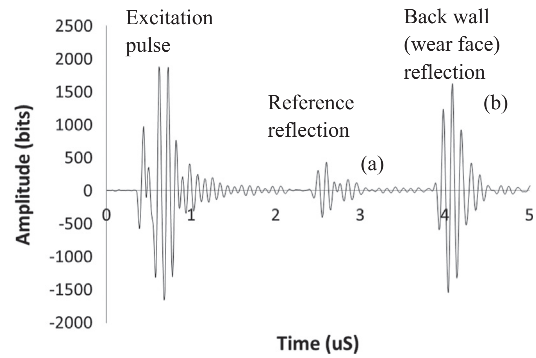

Fig. 1. A-scan from the instrumented aluminium pin.

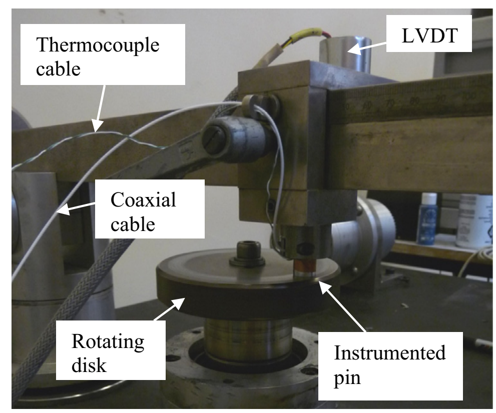

Fig. 2. GE99 pin-on-disk wear tester.

3. Experimental details

It was necessary to create a situation where a component experiences wear in a controlled manner in order to compare the ultrasonic method to other wear measurement methods. In doing so, attempts were made to validate the method and develop an understanding of the strengths, weaknesses, accuracies and errors involved.

A simple sliding configuration was used as it is a common dynamic wearing tribosystem. It is one of the most common tribometers used due to its simple geometry and the large amount of control over the testing parameters. The Eyre/BICERI universal wear testing machine, now known as the Cameron Plint GE99, was employed for this series of tests in the pin-on-disk configuration. A photograph of the equipment can be seen in Fig. 2.

The pin specimen was made from 10.8 mm diameter 1050A aluminium. This material was chosen as it is particularly effective in transmitting sound waves without creating internal reflections from grain boundaries and voids. A slot was cut in the top of the pins and a 2 mm × 7 mm 10 MHz ultrasonic sensor and thermocouple were bonded to the surface. This was then back filled with a high temperature potting compound to dampen the signal and protect the sensors. A diagram showing the dimensions of the pin specimen and the path of the sound wave can be seen in Fig. 3. A notch was cut in the side of the pin that partially covered the path of the ultrasonic wave to introduce a reference reflection into the