**Article:**

Taghizadeh, S. orcid.org/0009-0001-0387-3304 and Ghadbeigi, H. orcid.org/0000-0001-6048-9408 (2025) A comparative study of in-situ wear characterisation in reciprocating tribological contact using ultrasound. Wear. 206033. ISSN 0043-1648

https://doi.org/10.1016/j.wear.2025.206033

# A Comparative Study of In-Situ Wear Characterisation in Reciprocating Tribological Contact using Ultrasound[⋆,⋆⋆]

Saeid Taghizadeh[a,1], Hassan Ghadbeigi[a]

[a] School of Mechanical, Aerospace and Civil Engineering, Sir Frederick Mappin Building, Mappin Street, University of Sheffield, Sheffield, S1 3JD, UK

ARTICLE INFO

*Keywords*:
ultrasound
wear
online monitoring
phase difference

ABSTRACT

Ultrasound detection techniques have been widely used as non-destructive methods to detect cracks and measure lubricant film thickness, as well as viscosity. When ultrasonic waves are incident on boundaries, they are partly reflected and transmitted. The reflected waves give information about the medium, contact, and boundaries. In previous studies, ultrasound has been used to measure the wear size of a workpiece or pin. The current study aims to use two well-known ultrasonic methods, time-of-flight (TOF) and phase difference, to measure the wear depth in real-time for both the pin and workpiece in a dry contact. The sensitivity and accuracy of these methods are then investigated. These methods can be used to determine the wear size of a tool and workpiece for future work. In this experiment, two longitudinal transducers were used in a pulse-echo mode mounted on a pin and workpiece. The pin and plate (workpiece) were made of stainless steel. A nominal contact pressure of 0.25MPa was applied to the pin while sliding at an oscillating speed of 50mm/s. The attached transducer to the workpiece captured the reflected signals from the plate boundaries. These reflected waves were used to measure the wear depth of the plate only. The transducer mounted on the pin measured the TOF and phase difference of reflected waves from the pin-workpiece contact, which contains the pin's wear. The monitoring and in-situ measurements were run for 200m. The worn pin and workpiece were scanned using a 3D optical profilometer to measure the wear depth and compare the results with ultrasound. The results showed that the phase difference gives more accurate results than the TOF (TOF) method. It was also observed that the transducer with a peak frequency of 7.25MHz measured the wear depth with 10 times accuracy compared to the transducer with a peak frequency of 2.1MHz.

## 1. Introduction

Wear is defined as the material loss of the contacting surfaces during the relative motions [1] and significantly influences the lifetime of the tools and machines [2, 3]. Several methods and techniques characterise wear, such as mass-loss and surface profilometer [4]. One of the disadvantages of these techniques is that they are lab-based and offline. In other words, the contacting parts or the worn surface must be detached from the running condition and examined to measure the wear. Alternatively, eddy current, linear potentiometers and laser displacement can be used to measure the displacement and position [4]. Although these techniques are online methods, they are sensitive to thermal expansion, wear debris, and migrated particles from one contacting surface to another surface [4].

Ultrasound has been used to measure the wear depth [4–6]. Birring et al., [5] used the time-of-flight (TOF) method to measure the wear depth, while Ahn et al., [6] employed wave speed. Brunski et al. [4] measured the wear depth using a reference signal near the interface and frequency resonant dip. The current study aims to use two well-known ultrasonic methods, TOF and phase difference, to measure the wear depth in real-time for both the pin and workpiece in a dry contact. The sensitivity and accuracy of these methods are then investigated. In this study, the reference signal is defined as the pin's and workplace's reflection pulse before sliding. These reference signals are used for the TOF and phase difference methods. The results are then compared with a 3D optical profilometer.

[⋆] This document is the results of the research project funded by the SENSYCUT EPSRC (EP/v055011/1) and EPSRC KE fund.

S.Taghizadeh@sheffield.ac.uk (S. Taghizadeh)
ORCID(s): https://orcid.org/0009-0001-0387-3304 (S. Taghizadeh)

## 2. Theoretical Approach

Ultrasound has been used as a non-destructive method to measure oil film thickness, viscosity, contact stiffness, and crack detection. Ultrasonic waves are generated by a piezoelectric transducer. These waves are propagated in a medium and partly reflected from the boundaries where there is an acoustic mismatch. The reflected waves contain information about the interface and medium. One of the methods that is used to generate and receive the ultrasonic waves is the pulse-echo method. In this technique, the emitted ultrasonic waves generated by the transducer are received by the same transducer. The time that these pulses are travelled from the transducer until the transducer receives them is called the TOF. This method has been used to measure the thickness of the wall and parts.

The TOF has also been used to measure the wear depth. Despite its advantages, extracting the correct time from the reflected waves can be challenging and lead to inaccurate wear depth measurement. For example, when the reflected pulses are noisy, the truncated point of the waves affects the results. The other ultrasonic property is the phase angle, which measures the lubricant film thickness. To do this, the angle of the Fast Fourier transform (FFT) of the reflections is determined, and the difference is given as the phase difference angle. Unlike TOF, the phase difference is less sensitive to the truncated window when both of the reference and reflected waves are truncated at the same point on the waves.

## 3. Experimental Approach

In this experiment, the pulse-echo mode was used to capture the reflection coefficient from the pin-workpiece interface. As the workpiece oscillated at a constant speed, the pin was loaded, and the reflections from the interface were recorded. Figure 1 shows a schematic diagram of the bespoke designed to capture the reflected ultrasonic signals from the interface. The pin was loaded against the workpiece in a Bruker UMT-3 tribometer. A stainless steel pin (tool) was made as a stepped cylinder of a smaller diameter of 5mm at the bottom and a larger diameter of 10mm at the top. The upper part of the pin was made with a larger diameter to have sufficient space for the transducer, and the contact area was made with a smaller diameter to create higher contact pressure at a lower applied load. The workpiece was made of stainless steel with dimensions of 70mm by 70mm and a thickness of 22mm. The contact faces of the pin and workpiece were ground with silicon carbide papers of 1200 grit size to achieve a surface roughness (centre-line average $R_a$) of $0.793\mu m$ and $0.623\mu m$ for the pin and workpiece, respectively. The surface roughness was measured using an optical 3D profilometer (Alicona Infinite Focus SL) according to standard ISO 4287. A nominal contact pressure of 0.25MPa was applied to the pin while the workpiece oscillated at the constant speed of $50mm/s$ a stroke length of 50mm for 2000 cycles (total distance of 200m). The contact pressure was sat relatively small to generate less wear in the pin and workpiece to investigate the sensitivity of the ultrasound in detecting the wear depth.

A piezoelectric transducer with a peak frequency of 7.25MHz was attached to the upper face of the pin using a coupling gel. This transducer emitted 3-tone burst cycles at a peak-to-peak incident voltage of 90V, amplified with a high-power amplifier (RITEC RAM-5000). A second transducer with a peak frequency of 2.1MHz was placed at the back face of the workpiece with the 3-tone burst cycles. A PC equipped with LabVIEW was used to emit the pulses and capture the digitised reflections from the interfaces.

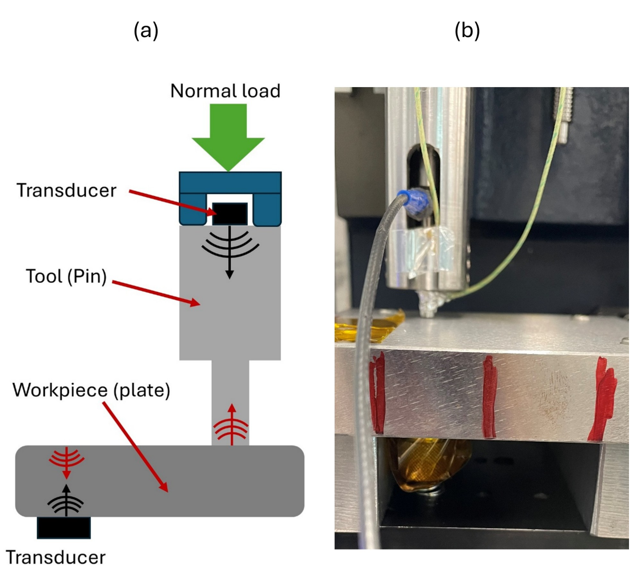


**Figure 1:** Experimental set-up: (a) schematic diagram; (b) experimental apparatus.

Figures 2 and 3 show the reflected pulses from the interface received by the transducers attached to the pin and workpiece.

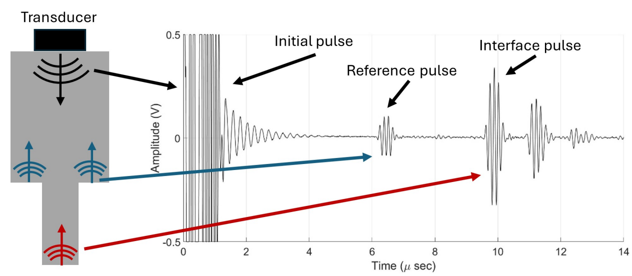


**Figure 2:** Initial pulse and reflected ultrasonic waves from the boundaries of the pin.

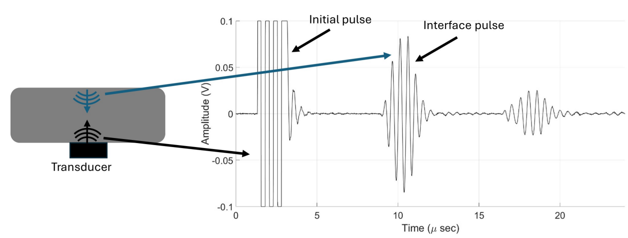


**Figure 3:** Initial pulse and reflected ultrasonic waves from the boundaries of the workpiece.

## 4. Results and Discussion

Figure 4 shows the surface of the pin and workpiece before and after sliding scanned with a 3D optical profilometer (Alicona Infinite Focus SL). The heat generated during the sliding increases the pin's length and varies the media's acoustic velocity [4]. Therefore, the reflected ultrasonic waves from the interface were influenced by the temperature and wear of the contact. Brunskill et al., [4] used a notch, so the reflected signal from this point was considered as a reference signal to reduce the effect of heat generated during sliding. However, in the current study, the reflection from the interface before the first run was considered a reference pulse with no effect on temperature and wear. These reflections were also used to measure the speed of sound in the pin and workpiece (pin: 5990m/s; workpiece: 6004m/s). Figures 5 and 6 show the reflections from the interface for the pin and workpiece after a distance of 5m and 200m. It is seen from Figures 5 and 6 that there is no time shift between the reference signal (before sliding) and the reflection after 5m

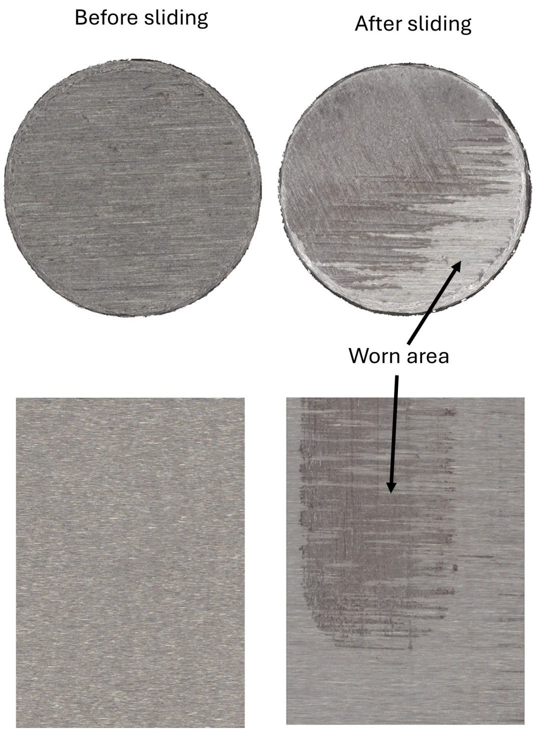


**Figure 4:** Fresh and worn pin and workpiece scanned by a 3D optical profilometer (Alicona Infinite Focus SL).

sliding for both the pin and workpiece. However, the time shift is more visible for the reflection after 200m. The wear depth is determined using the TOF, which is given by:

$$d = \frac{c\Delta t}{2} \tag{1}$$

where $c$ is the speed of sound, and $\Delta t$ is the time shift (the time difference between the reference pulse and the signals at any sliding distance) of the corresponding point on the pulses. It should be noted that Eq. 1 is used for the pulse-echo and pitch-catch through reflection modes. The value of $\Delta t$ of the reflections and the reference signals for the pin at the sliding distance of 5m is zero, while at 200m, it is $8\mu sec$. The mean value of the $\Delta t$ of the reflections and the reference signals for the plate at the sliding distance of 5m is zero, and for 200m, it varies between $8\mu sec$ and $16\mu sec$. The value of $\Delta t$ was substituted into Eq. 1 (and Eq. 2 in the phase difference equation) to determine the depth of wear, as shown in Figure 8. One of the challenges of using the TOF is taking a point on the reflection to determine the wear depth. For example, when there is noise in the reflection, the TOF cannot be measured accurately. However, using the reflection pulse before the sliding as a reference overtakes this disadvantage. Using the TOF, the pin's and workpiece's wear depth cannot be determined after 5m sliding.

Figure 7 shows the phase difference of the pin's and workpiece's reflections. These are determined by the difference of the phase angles of the reflections at any sliding distance and the reference.

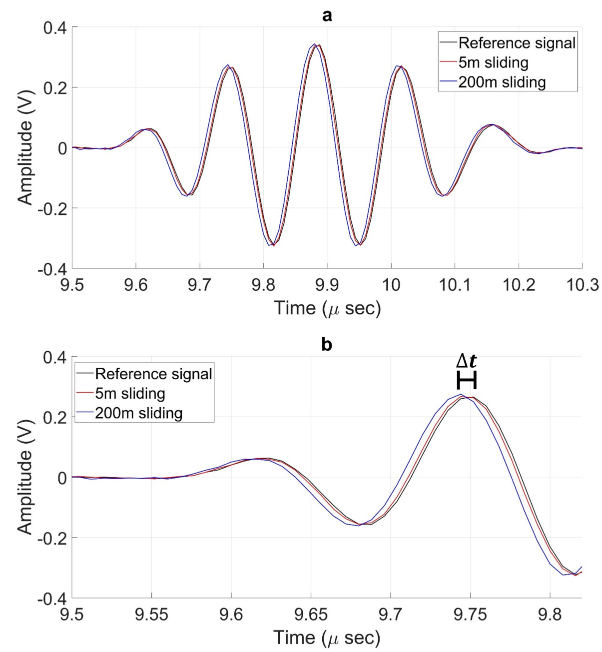


**Figure 5:** A comparison of the time domain reflected waves before sliding, after 5m and 200m sliding of the pin: (a) full reflection (b) zoomed in.

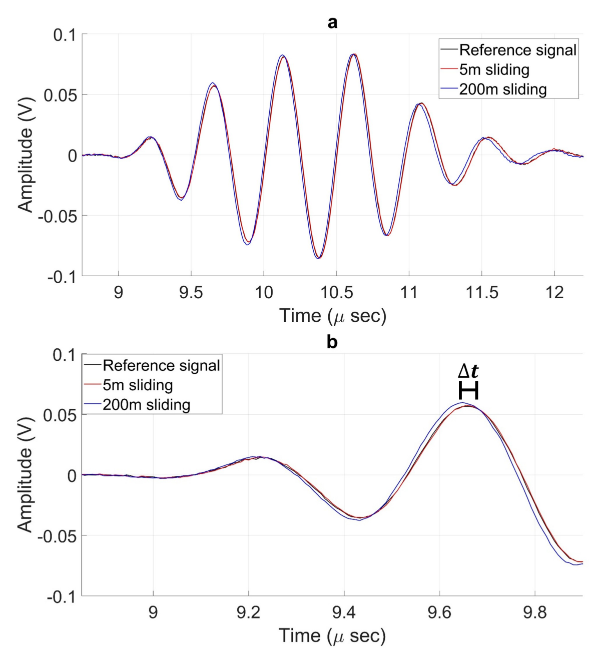


**Figure 6:** A comparison of the time domain reflected waves before sliding, after 5m and 200m sliding of the workpiece: (a) full reflection; (b) zoomed in.

The interested frequency domain is in -6dB bandwidth of the amplitude of the peak frequency. This bandwidth (corresponding to 6dB reduction in amplitude) was considered in the frequency domain of the reflected waves to evaluate the lower and upper cut-off frequencies and is recommended by the transducer manufacturer, where the amplitude of the

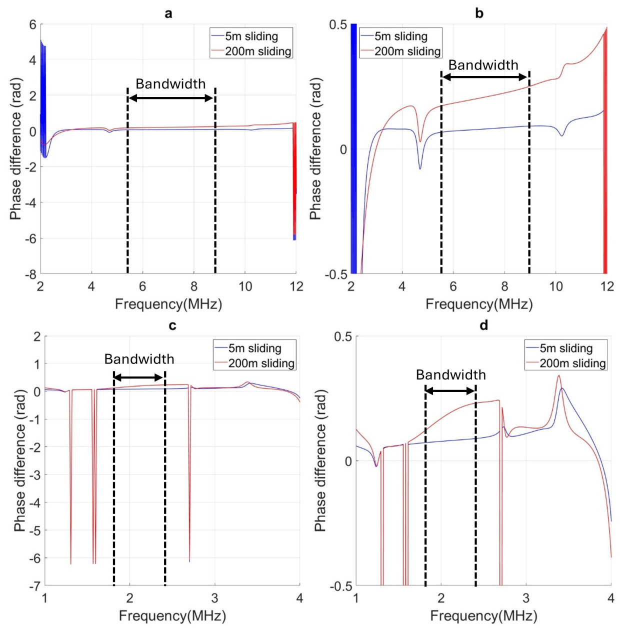


**Figure 7:** The phase difference of FFT transforms of reflected ultrasonic waves at the 5m and 200m sliding: (a) pin; (b) y-axis zoomed-in of the pin; (c) workpiece; (d) y-axis zoomed-in of the workpiece.

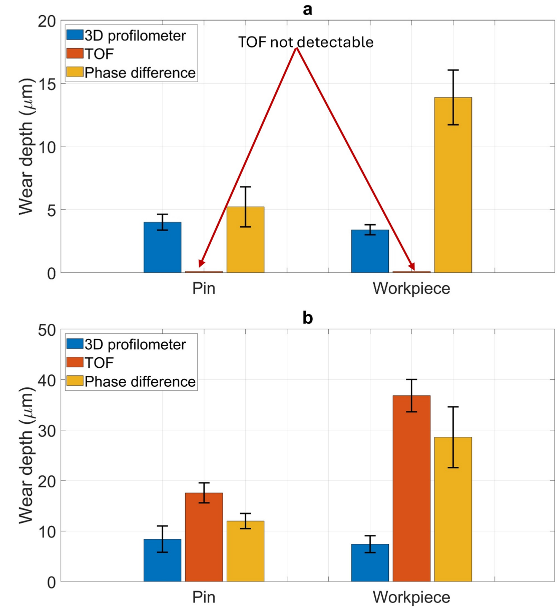


**Figure 8:** Wear depth measured with a 3D optical profilometer, TOF and phase difference of the pin and workpiece after: (a) 5m; (b) 200m sliding.

FFT of reflected waves is 50% of the peak. Unlike the TOF method, the phase difference is visible for the 5m sliding. The wear depth for the pin and workpiece is determined by [7]:

$$d = \frac{c\phi}{4f\pi} \tag{2}$$

where $\phi$ is the phase difference (rad) and $f$ is the peak frequency (Hz). The wear depth of the pin and workpiece at the sliding distance of 5m and 200m are shown in Figures 8a and 8b, respectively. Although the experiment was run once, the wear depth of the workpiece and pin was measured at five different regions. The wear depth was measured with the TOF, and the phase difference between the pin and workpiece was considered over five reflections. Figure 8a shows that the TOF cannot determine the wear depth in the pin and workpiece after 5m sliding. However, the phase difference can measure the wear depth after this sliding distance. However, the wear depth determined with the TOF and phased difference for the pin and workpiece after 200m sliding is higher than that measured with the 3D profilometer; the phase difference shows a more accurate value than the TOF.

Figure 9 shows the percentage error of the TOF and phase difference with respect to the 3D profilometer. Both the TOF and phase difference give a higher wear depth compared to the 3D profilometer. This can be due to the rise in temperature during sliding. where the length of the point and workpiece increase. It can be due to the TOF, phase difference methods and the frequency of the transducers as they are discussed here. It is seen that the percentage error in the wear depth of the pin and workpiece measured with the phase difference after the sliding distance of 200m was almost half of the wear depth measured with the TOF. The wear depth of the pin and workpiece was determined with transducers with a peak frequency of 7.25MHz and 2.1MHz, respectively. It is seen that the wear depth of the pin after the 5m and 200m were 30% and 42%, respectively. While the corresponding error for the workpiece was 109% and 297%. This indicates that by increasing the peak frequency of the transducers from 2.1MHz to 7.25MHz, the error of the wear depth measurement with ultrasound (phase difference) reduces by 6 to 10 times. This difference can be due to the relationship between the wear depth size and the wavelength of the ultrasonic waves. The wavelength of the ultrasonic waves in the pin (with a peak frequency of 7.25MHz) and workpiece (with a peak frequency of 2.1MHz) are 0.826mm and 2.86mm, respectively. The wavelength in the pin is almost 3.5 times smaller than that in the workpiece. However, more study is required to investigate the effect of higher frequency and wavelength on the accuracy of the wear depth measured with ultrasound.

## 5. Conclusion

In this study, the two well-known ultrasonic methods, the TOF and phase difference, were used for online wear depth measurement of a pin and workpiece. Proper reference pulses are crucial for measuring wear depth using the TOF. It was seen that the TOF cannot measure the wear depth of the pin and workpiece after 5m sliding distance as the were depth is small and cannot be detected by the TOF. However, the phase difference determined the wear depth at this distance. After the longer sliding distance (200m), the TOF could determine the wear depth. However, the phase

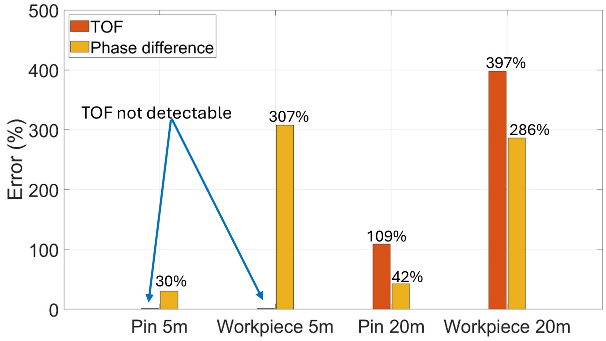


**Figure 9:** Percentage error of the TOF and phase difference of the wear depth in the pin and workpiece.

difference determined the wear depth by 50% more accuracy. In addition, the phase difference showed the wear depth measured in the pin (with a transducer with a peak frequency of 7.25MHz) was between 6 and 10 times more accurate than the wear depth in the workpiece (with a transducer with a peak frequency of 2.1MHz). This can be due to the smaller wavelength in the pin (0.826mm) than the workpiece (2.86mm).

## References


[1] J. Williams, *Engineering tribology*. Cambridge university press, 2005.

[2] H.-J. Kim, S.-S. Yoo, and D.-E. Kim, "Nano-scale wear: a review," *International Journal of Precision Engineering and Manufacturing*, vol. 13, pp. 1709–1718, 2012.

[3] J. Furustig, I. Dobryden, A. Almqvist, N. Almqvist, and R. Larsson, "The measurement of wear using afm and wear interpretation using a contact mechanics coupled wear model," *Wear*, vol. 350, pp. 74–81, 2016.

[4] H. Brunskill, P. Harper, and R. Lewis, "The real-time measurement of wear using ultrasonic reflectometry," *Wear*, vol. 332, pp. 1129–1133, 2015.

[5] A. S. Birring and H. Kwun, "Ultrasonic measurement of wear," *Tribology international*, vol. 22, pp. 33–37, 1989.

[6] H.-S. Ahn and D.-I. Kim, "In situ evaluation of wear surface by ultrasound," *Wear*, vol. 251, pp. 1193–1201, 2001.

[7] B. Béchadergue, L. Chassagne, and H. Guan, "Visible light phase-shift rangefinder for platooning applications," pp. 2462–2468, IEEE, 2016.