

Ultrasonic Imaging of the Piston Ring Oil Film During Operation in a Motored Engine - Towards Oil Film Thickness Measurement

2010-01-2179

Published
10/25/2010

Emin Yusuf Avan, Robin Mills and Rob Dwyer-Joyce
The University of Sheffield

Copyright © 2010 SAE International

ABSTRACT

The oil film that forms between piston rings and cylinder liners is an essential parameter which influences parasitic loss and emission rates in an internal combustion (IC) engine. Several methods have been used to analyse these thin oil films in the past, however, all these methods have required invasive access to the contact area via a window or a surface mounted sensor in the cylinder wall or liner. This paper introduces a novel approach for the imaging of the piston ring - cylinder contact, non-invasively.

A straight beam ultrasonic contact transducer was coupled to the wet-side of the cylinder wall of a motored diesel engine. Ultrasonic waves were propagated through the cylinder wall and reflections from the ring-liner contact were recorded as the piston rings passed over the sensing area. The proportion of an ultrasonic pulse that is reflected from the layer, known as reflection coefficient, varies with the stiffness of the layer and the acoustic properties of the matching materials and lubricant. The transducer has successfully detected the rings and the reflection coefficient has been generated using the recorded reflection from the contact. Future evaluation of the oil film thickness (OFT) at the ring contact has been proposed using various ultrasonic transducers.

INTRODUCTION

Power loss in the ring-liner contact is one of the most critical issues in an internal combustion engine affecting operation and efficiency. The formation of an oil film in this contact is an essential parameter for analyzing oil availability and its distribution over the contact area. Proper control of the film allows; a decrease in fuel and oil consumption, reduction in ring and liner wear, increase in engine power output and a reduction in harmful exhaust emission.

Several methods have been applied to enable ring-liner film thickness measurements. Capacitance [1,2,3,4] and laser induced fluorescence (LIF) techniques [5,6,7] have successfully been applied for piston ring lubrication. However, both of these methods require the need to penetrate the cylinder wall or liner in order to access the piston ring-wall contact area. Table 1 shows OFT range and methods in selected literature.

Table 1. Measured ring film thicknesses in literature.
(Eddy C.: Eddy Current, Cap: Capacitance, F:Fired, M:Motored) * Approximate range deduced from the graphs

Ref. Num.	Method	Engine	OFT range (µm)	Engine Speed (rpm)
[10]	Eddy C.	F	1.0 – 19	900
[6]	LIF	F	0.4 – 4.0	1500–2000
[7]	LIF	F	1.0 – 4.5	1000
[8]	LIF	F	0.6 – 3.5	2000
[9]	LIF	M	*5.0 – 18	300-1200
[1]	Cap.	F	1.0 – 10	1000-1900
[2]	Cap.	F	4.0 – 23	2000
[4]	Cap.	M	0.2 – 8.0	1300-1400

In this paper, we explore the process of imaging the piston rings using reflected ultrasound and then show how oil film thickness measurements can be made using this reflection data. This approach involves continually passing pulses of ultrasound through the cylinder wall. When no ring is present, the ultrasonic pulse will be completely reflected, but when there is a ring present, some of the ultrasound is transmitted through the interface into the ring. This method is non-invasive and does not require penetration of the cylinder

wall. However high speed ultrasound pulsing and data acquisition is required to capture the passage of the rings.

The proportion of the incident wave amplitude that is reflected is expressed by the reflection coefficient using,

$$R = \frac{A_r}{A_i} \quad (1)$$

where A_i is the incident wave amplitude and A_r is the reflected wave amplitude. Figure 1 shows five cases; (a) an ideal interface between two identical materials, (b) an ideal interface between two dissimilar materials, (c) an interface between a solid and air, (d) an interface between dissimilar materials with an intermediate layer, (e) an interface between a solid and air, with a thin layer of oil on the surface.

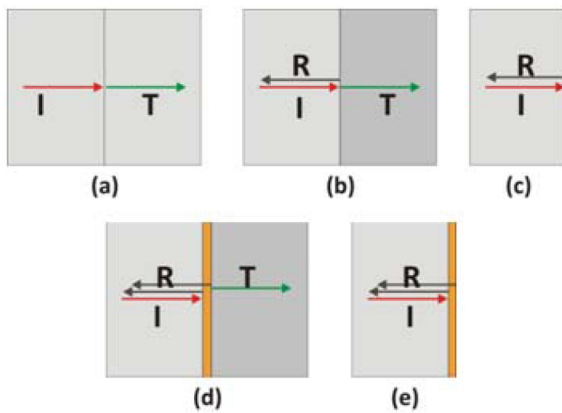


Figure 1. Reflections from ideal interface configurations

For case (a) the incident wave is completely transmitted to the matching material and $R=0$, if the matching materials are different, which is depicted in case (b), then the proportion that is reflected from the interface is given by;

$$R = \frac{z_1 - z_2}{z_1 + z_2} \quad (2)$$

where, z , is the acoustic impedance of the interface materials and the subscripts denote the position of the materials either side of the interface. It is difficult to measure the incident signal, but if the matching material is air, case (c), most of the incident wave is reflected due to a high acoustic mismatch between the materials. Hence, in practice, the incident signal can be recorded using this reflection. However, if the incident wave strikes a layer rather than an interface, case (d), then the wave is reflected back from the front and back face of the layer. If the layer is very thin then the two reflections are close together. This situation can be modeled by using a quasistatic spring model. Tattersall [11] demonstrated that the reflection coefficient for a thin layer is defined by,

$$R = \frac{(z_1 - z_2) + i\omega / K(z_1 z_2)}{(z_1 + z_2) + i\omega / K(z_1 z_2)} \quad (3)$$

where, ω , is the angular frequency of the ultrasonic wave ($2\pi f$) and, K , is the stiffness of the interfacial layer. For the same reason as described in case (c), the incident signal for the layer can be recorded using the reflection in case (e).

TEST APPARATUS

THE MOTORED ENGINE

A Perkins Engine 1100 Series was modified to be driven by an external electric motor. The engine's valve train and head were removed. The lubricant and water systems were modified to lubricate and cool just the cylinder block. There are a number of access points on the engine to mount the transducer on the outside surface of the cylinder walls. The block, made from cast iron, had 4 cylinders with a displacement of 4.4litres, a bore of 105mm and a stroke of 127mm. A shaft encoder was connected to the crankshaft in order to gain a feedback of both engine speed and timing pulse for triggering the transducer. The oil used in the measurement was 15W-40 multi grade oil.

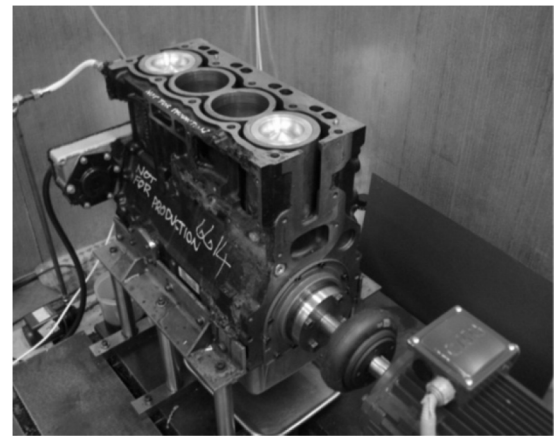


Figure 2. Motored Engine used in the tests

ULTRASOUND INSTRUMENTATION

The ultrasonic equipment consisted of an ultrasonic pulser-receiver (UPR), a 5 MHz straight beam ultrasonic contact transducer, an oscilloscope and a dedicated PC. A schematic view of the test equipment and their connections is shown in Figure 3. A LeCroy LT342 oscilloscope was used in this study, which allowed signal voltages to be viewed additionally to be digitized before downloading the data into the PC for signal processing. The scope samples at a bandwidth of 500 MHz and the sampling rate is 500 Msamples/second. It has 250 kB internal memory capacity.

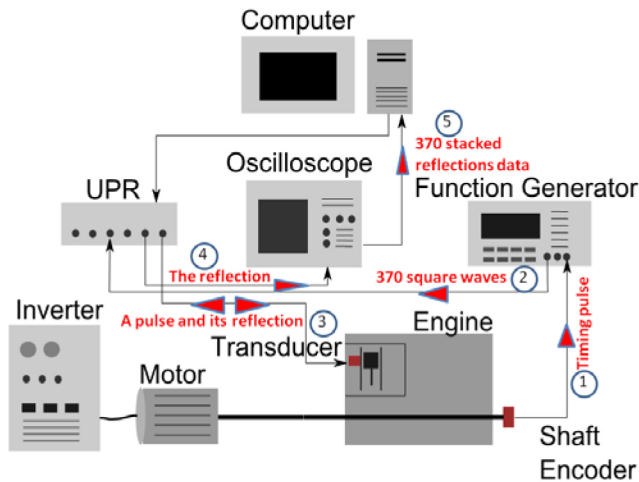


Figure 3. Schematic diagram of the test equipments and their connections

The 5MHz contact transducer, shown in Figure 4, was coupled to the wet-side of the cylinder wall using a magnetic clamp. Liquid coupling was applied on the interface between the transducer and outside surface of the cylinder wall to prevent air going into the interface. This liquid coupling allows transmitting of ultrasound from the transducer to the medium due to higher acoustic impedance and lower attenuation compared with air.

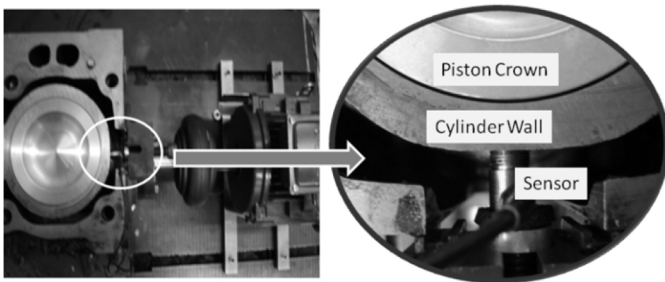


Figure 4. A top view of the engine showing the transducer location

TEST PROCEDURE

The contact transducer was coupled to the wet-side of the cylinder wall of the motored diesel engine. The ultrasonic reflection measurements start with a timing pulse from the shaft encoder (see Figure 3). The timing of this pulse can be adjusted according to the desired piston position inside the cylinder (e.g. TDC), which is namely called the triggering point. When the piston is on the triggering point, the shaft encoder sends the timing pulse to the function generator, which generates a defined number of square waves (e.g. 370 square waves). These square waves are used as an external triggering source for the UPR, which produces and sends an equivalent number of short duration high voltage signals to

the transducer. A piezo element inside the transducer is excited by these voltage signals and generates ultrasound waves which propagate through the cylinder wall. The transducer operates in a pulse-echo mode, therefore, it captures the reflections from the cylinder as the piston rings pass over the transducer area. These reflected signals are amplified and sent through the oscilloscope. The pulse of interest (b in Figure 5) is selected for each of the reflected signals. These selected segments (they constitute a pulse sequence) are digitised and stored by the oscilloscope and then the data is downloaded to the computer.

SIGNAL PROCESSING

Once the data is passed to the computer, the reference signal is created by averaging the initial reflections in the pulse sequence because the triggering system allows a reflected signal to be recorded at a time before the rings reach the transducer location. Hence, initial reflections in the pulse sequence are from the reference interface (case (e) in Figure 1) and the remainder from the layer (ring-oil-wall, case(d) in Figure 1). A fast Fourier transform (FFT) is performed on both the reference signal and each reflected signal, giving the amplitude variation in the frequency domain. The next step is to calculate the reflection coefficient, which is obtained by dividing the FFT of reflected signal by the FFT of reference signal.

In the experimental stage, the average of the FFT's for the first 5 pulses in the pulse sequence were used to generate the reference signal. TDC, BDC and the middle section of the cylinder (MID) were separately used to specify when the system should be triggered. A square wave with 370 cycles was produced by the function generator for each shaft encoder timing pulse. The number of cycles was determined by the storage limitation of the oscilloscope. To obtain an optimum number of data points, the scope was set to acquire 370 segments of which each contained 500 sample points sampled at 500 MS/s (2 ns/pt). The frequency of the triggering square waves was selected according to the piston speed to ensure that the entire ring pack was captured.

RESULTS

Figure 5 shows a sample time domain plot of the reflected signal from the cylinder wall. The peak (a) is a combination of sensor initiation and reflection from the wet-side of the cylinder, while the peak (b) is the reflection from the inner cylinder wall and is changing as the piston rings pass over the transducer location.