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Evaluation of an Ultrasonic Method for Measurement of Oil Film Thickness in a Hydraulic Motor Piston Ring

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The efficiency of a hydraulic motor depends on the lubrication performance of the piston ring. If the film is too thin then wear occurs quickly, if it is too thick then oil is lost into the cylinder and efficiency is reduced. In this paper a technique for oil film measurement based on ultrasonic reflection is investigated. This has the potential to be used non-invasively on real components.

An ultrasonic pulse will reflect from a thin film interposed between two solids. The proportion of the pulse that is reflected depends on the stiffness of the intermediate layer. If the acoustic properties of the film material are known, then the stiffness can readily be used to determine the film thickness. This principle has been employed for the piston ring lubrication case. A piston/cylinder test bench has been used to evaluate the ultrasonic method. A focusing piezo-electric transducer is mounted outside the cylinder and ultrasonic pulses reflected back from the inner bore. The variation of these pulses as the piston ring passes underneath is investigated and used to determine oil film thickness. Films in the range 0.7 to 1.3 μm were measured; the thickness did not depend strongly on either ring speed or sealed pressure.

Several practical aspects were investigated such as, attenuation in the cylinder material, response time, and transducer resolution. Whilst this study demonstrated that film thickness measurement is feasible, there are a number of practical considerations that require further work, principally the focusing and coupling of the ultrasonic transducer and the response time.

1. INTRODUCTION

The radial piston hydraulic motor has radial pistons with constant displacement, (see fig. 1), and is used in low speed and high torque applications. It has an even number of pistons that operate in sequences of working pressure and charge pressure in a reciprocating motion. The hydrostatic pressure and oil flow corresponds to actual torque and speed respectively. When torque and rotational speed are produced, as in driving mode, the pistons move outwards under working pressure and inwards under charge pressure. The hydrostatic pressure is constant but differs in magnitude for inward and outward movements. The casing is stationary, which means that the cylinder block and piston assembly rotates. Between the end positions of a stroke, the piston tilts 2β due to the changed direction of the tangential force and clearance.

This kind of motor can provide very high torque in a relatively compact space. This makes them suitable for heavy-duty applications such as rock crushing, winches, and drilling equipment.

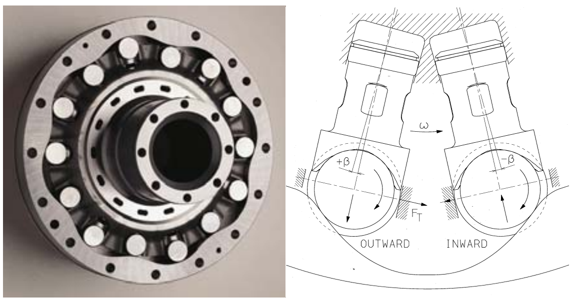

Figure 1. The Hägglunds radial piston hydraulic motor. Piston movement during the stroke in driving mode. Working pressure at outward movement and charge pressure at inward movement.

The efficiency of the motor depends on the piston ring–liner oil film since the function of the piston ring is to seal off the high hydrostatic pressure acting on the piston. If the film is too thick then oil flow is increased and hydraulic efficiency is reduced. If the oil film is too thin, then friction is increased, and piston ring failure is possible [1, 2]. A method for the measurement of oil films in-situ would prove useful in the design of piston ring components.

In the past capacitative methods [3] and resistive methods [4] have been used to measure piston ring oil films with some success; however this requires electrical isolation of the sliding components or the use of flush mounted probes. Laser induced fluorescence [5] has been used to measure the oil layer on a cylinder wall as the piston passes. A laser channelled through a fibre optic and a window in the cylinder is used to determine oil fluorescence. Films of the order of 3 to 6 μm were recorded in a fired engine as the rings passed the window location.

In this study an ultrasonic technique is evaluated with the help of a piston-liner bench test apparatus. This approach has the advantage that it does not require the use of windows or surface mounted probes. The reading can be taken non-invasively by passing the sound wave through the cylinder wall.

2. BACKGROUND

2.1. Reflection of Ultrasound from Interfaces and Films

When an incident wave of ultrasound strikes an interface between two materials, some of the sound wave will be reflected and some will be transmitted. The relative proportions are dependent on the acoustic properties of the materials either side of the interface and whether they are completely bonded. This phenomenon has been used to study aspects of the dry rough surface contact between two solid materials [6, 7, 8].

For a liquid/steel interface there is a complete coupling and the proportion of the sound wave reflected is dependent on the acoustic impedance of the materials either side of the interface (i.e. the product of the density and the speed of sound). Typically 95% of the wave amplitude is reflected.

Where there are two interfaces (e.g. steel/oil/steel) with a large separation perpendicular to the path of the approaching sound wave (as in the case of a thick layer) the sound wave will be reflected as two discrete waves; one from the front face of the oil layer and one from the back. The time between these is a function of the speed of sound of the centre layer and the thickness of that layer. If the layer is sufficiently thick and the measuring frequency high, then the two signals can be resolved spatially and the layer thickness determined. Unfortunately, practical limitations means this method will only work for films thicker than around 100μm; thicker than those found in most machine elements.

2.2. The Response of a Thin Imbedded Layer to Ultrasound

Where there are two interfaces in close proximity to each other (as in the case of a thin layer) this layer will act as a single reflector. The response can be modelled using a quasi-static spring model approach [9]. The proportion of the sound wave amplitude reflected, R then depends on the stiffness of the intermediate layer, K according to the equation:

$$R = \sqrt{\frac{(\omega z_1 z_2)^2 + K^2 (z_1 - z_2)^2}{(\omega z_1 z_2)^2 + K^2 (z_1 + z_2)^2}} \qquad (1)$$

where ω is the angular frequency of the wave ($=2\pi f$), and z_1 and z_2 are the acoustic impedances of the materials either side of the layer. If the materials either side of the interface are identical this reduces to:

$$R = \frac{1}{\sqrt{1 + \left(\frac{2K}{\omega z}\right)^2}} \qquad (2)$$

A discrete pulse of ultrasound contains a frequency spectrum that is a function of the actuator (in this case a piezo-electric element) and the driving electric pulse. Each of these frequencies will give a result in reflection coefficient, according to equation (2). But the stiffness should remain independent of the wave frequency. Dwyer-Joyce et al. [10] demonstrated that equation (2) could be used to determine the stiffness of oil films in both the elastohydrodynamic and hydrodynamic regimes, and that the deduced stiffness was indeed independent of measuring frequency.

The stiffness of an oil film can easily be related to its thickness, h and the bulk modulus, B (note the stiffness is expressed per unit area):

$$K = \frac{B}{h} \qquad (3)$$

Combining (2) and (3) and, noting that the speed of sound in the oil is given by; $c=\sqrt{(B/\rho)}$, gives a simple relationship between oil film thickness and reflection coefficient.

$$h = \frac{2\rho c^2}{\omega z}\sqrt{\frac{R^2}{1-R^2}} \qquad (4)$$

This approach has been used to determine the oil film thickness in journal bearings [11], and ball bearings [12]. In this study the apparatus has been used to evaluate the possibility of measuring the oil film formed between a piston ring and a cylinder. The films generated in the relatively slow pistons of a hydraulic motor make a suitable initial case for study, since the oil film thickness occurs over a large area and is thus an easier target to locate.

3. ULTRASONIC MEASUREMENT APPARATUS

3.1. Generation and Capture of Signals

An ultrasonic pulser/receiver (UPR) is used to send a high frequency pulse to the transducer. The pulser section of the UPR sends a high voltage (100 V) top hat signal to the transducer. The width of the pulse is tuned, in order to excite the transducer at its resonant frequency to give the maximum power output.

Typically the pulse rise time (the square-ness of the top-hat function) is less than 9 ns. The pulse width is typically 100 ns. In a pitch-catch arrangement (as used in these experiments) the pulse is transmitted to the probe along a cable that is also used to receive the reflected signal (the transducer acts as both and emitter and receiver). The receiver section of the UPR receives the reflected signal from the transducer, typically 30 mV. This signal is then amplified using a low noise amplifier and sent to the digitiser.

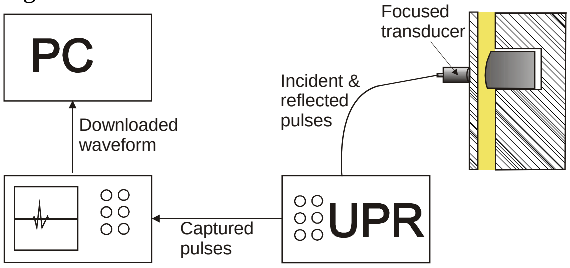

Figure 2. Schematic diagram of the equipment used for generating, capturing, and storing ultrasonic

A schematic of the apparatus is shown in figure 2. The digitiser used was a LeCroy® Waverunner® 342 Oscilloscope. The signal from the UPR is digitised at 500MHz. The signal is then downloaded to a computer via a GPIB cable. The GPIB connection is controlled using Labview® software. Once the data is downloaded to the computer it can be saved either for post processing, or processing in real time using Labview®.

3.2. Ultrasonic Transducers and Focusing

The transducer consists of a piezo-electric element in a waterproof housing. The transducer was a nominal 10 MHz, focused (the centre frequency was at 8.8 MHz), and 90% bandwidth. In this work it is necessary to focus the wave onto the oil film (normal contact transducers would result in spreading of the beam and reflection from regions surrounding the film). Focusing is achieved by means of a concave lens bonded to the piezo-element. The transducer has a focal distance of 75 mm in water and a corresponding focal area of diameter ~520µm. The piston ring has a thickness of 2 mm with a slight crowning. The ultrasonic spot size falls within a region of the ring face that is virtually flat. Reference [12] describes in more detail the focusing of ultrasonic waves and the resulting spatial resolution.

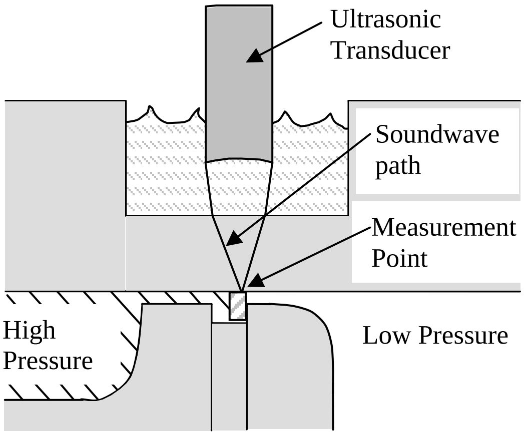

Figure 3. Schematic diagram of the transducer location and focusing through a water bath and the cylinder wall

Figure 3 shows a schematic of the transducer location and focusing system. The transducer was mounted in a small water bath above the piston ring rig. A positioning fixture allows the accurate location of the transducer over the piston ring contact.

3.3. Signal Processing

Initially a pulse is reflected back from the liner inside wall when there is no piston ring positioned underneath. The pulse is thus reflecting from a steel-air contact and we expect complete reflection (i.e. the reflected pulse equals the incident pulse). The time domain pulse (amplitude vs. time) is passed through an FFT to give the amplitude spectrum (amplitude vs. frequency). This is used as a reference signal. Successive reflection spectra from measured oil films are then divided by this reference signal to give the reflection coefficient spectra. This is then put into equation (4) to produce the thickness of the oil film. The output is then the oil film thickness measured at all the frequencies present in the ultrasonic pulse. The film thickness should be independent of frequency; in practice beyond the limits of the pulse bandwidth (where the energy of the emitted frequencies is low) the measurement becomes erratic and unreliable. Only data from the centre of the pulse bandwidth (with 6 dB) is used.

During experimental set up it was discovered that the time taken to capture the full waveform, digitise, download to the PC, FFT and save was greater than the time taken for the piston ring to pass across the measurement point. This problem was resolved by downloading the waveform to the PC and saving it for post processing. The data capture speed had to be fast enough to guarantee capture of a reflected signal from the oil film alone. To do this the speed was limited to 12mm/s to ensure a minimum of two measurement points on the piston ring. Post processing allowed a maximum capture speed of 8 Hz.

4. PISTON RING AND CYLINDER APPARATUS

4.1. Test Bench

The bench test apparatus used was originally developed to study the performance of different piston ring and cylinder bore designs [1, 2] during sliding motion. In this work a transducer was mounted on one of a pair of test cylinders.

Figure 4 shows a schematic of the test bench. Two cylinders are mounted on the bench as shown. Both pistons are driven by means of a connecting rod attached to a crank on a motor. Each piston has two piston rings; one at each end. High pressure oil (Shell Tellus T32) is fed into the cavity between the two rings (as shown in figure 5) and passes over the piston rings to the low pressure oil outlets. During the tests the pressure was varied from 10 to 30 MPa.

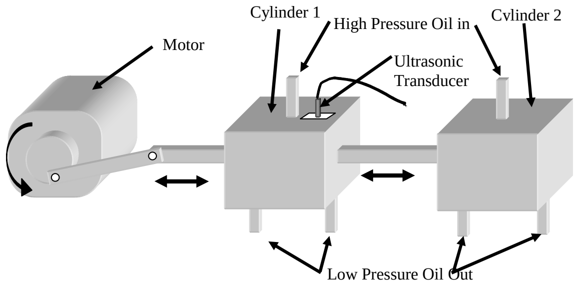

Figure 4. Schematic representation of the hydraulic motor piston ring test bench.

4.2. Piston Ring and Cylinder

A variety of piston-ring designs are possible. In this study a split ring type with asymmetric outer crowning were used. The piston rings were of diameter 75mm, thickness 2mm and made of hardened bearing steel, while the piston and cylinder bore were made of grey cast iron and nodular cast iron respectively. The material was found to attenuate ultrasound to such an extent that the signal could not be adequately propagated through the full cylinder thickness. Some of the thickness was machined away to provide a shorter path for the ultrasound (and also to act as a water bath).

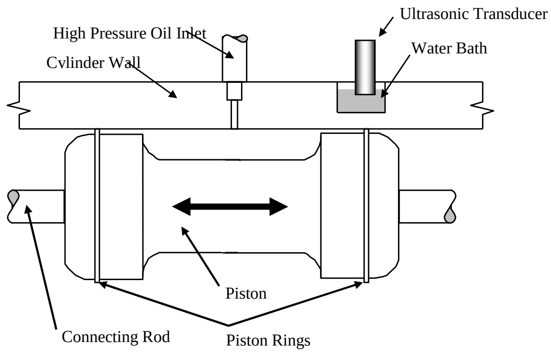

Figure 5. Schematic section showing the piston, rings, cylinder, high pressure oil inlet and transducer position.

The ultrasonic measurement system was turned on and then the piston rig was started. The ultrasonic measurement system continuously measured the reflected signal while the piston oscillated past the measurement point. The reflected signal was recorded for post processing to maximise the capture speed.

5. RESULTS

5.1. Reflected Pulses

The transducer was set to pulse continuously at a repetition rate of 0.1 kHz. The data capture rate was 0.125 s; this proved to be a factor limiting the speed of operation of the piston. Reflected signals were recorded for all positions of the piston with respect to the transducer. The reflected pulse was divided by the reference pulse. Figure 6 shows the reflection coefficient variation as the piston ring passes under the transducer on both its forward and backward stroke.

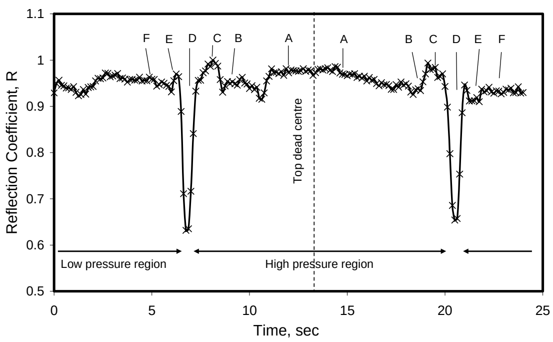

Figure 6. Plot of the recorded reflection coefficient as the piston moves from bottom dead centre (BDC) to dead centre (TDC) and back. Also shown are measurement points A, B, C, D, E, F.

Two troughs are clearly seen when the piston passes beneath the measurement location. When an oil film is present more of the sound wave is transmitted and so the reflected amplitude drops. Ideally the reflection coefficient when recording away from this location should be unity. There is some variation as can be seen; however the observed peaks and troughs are symmetrical suggesting that it is a geometry effect. Figure 7 shows a close-up of the piston ring and surrounding land. The measurement locations are approximately correlated with the features on the amplitude plot. The additional peaks are thought to be caused by either some residual oil left on the inside of the liner (in the low pressure region only), or the extra thick 'film' between the piston profile and the cylinder wall. However, at location D there are two distinct measurement points which give the same reading. These were taken as the minimum amplitude signal and were recorded for each passage of the piston.

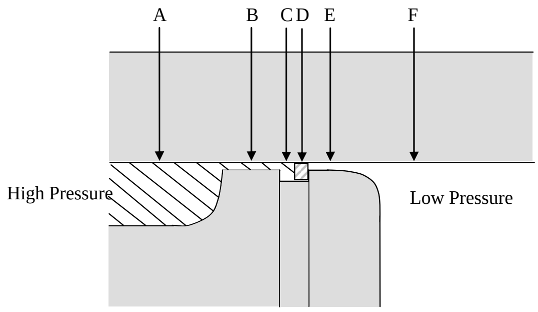

Figure 7. Close-up view of the piston profile either side of the piston-ring showing six measurement points, A, B, C, D, E, and F.

Figure 8 shows a series of pulses recorded as the film reduces in size as the piston measurement location moves from C to D.

The Fourier transform of a series of pulses (cropped using a Hanning window) is shown in figure 9; the reference pulse is marked. Each of the reflected pulses is divided by the reference pulse to give the reflection coefficient (shown in figure 10).

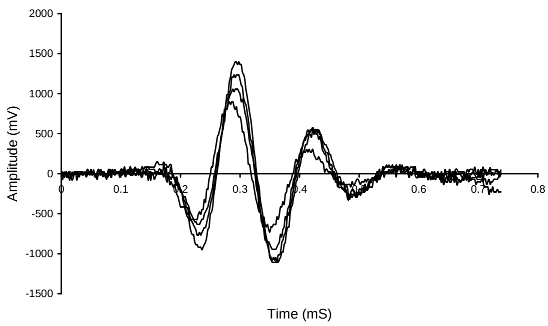

Figure 8. Pulses reflected from four oil films recorded as the ring moves from C to D (as the oil film reduces in thickness the amplitude decreases). 10 MPa, 9 mm/s

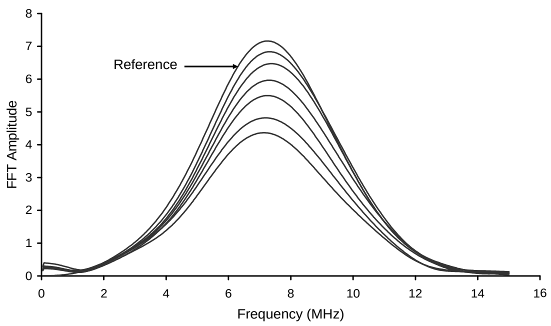

Figure 9. Fourier transform of the pulses shown in figure 8 (with two additional measurements added) recorded as the ring moves from C to D. The reference pulse is also shown.

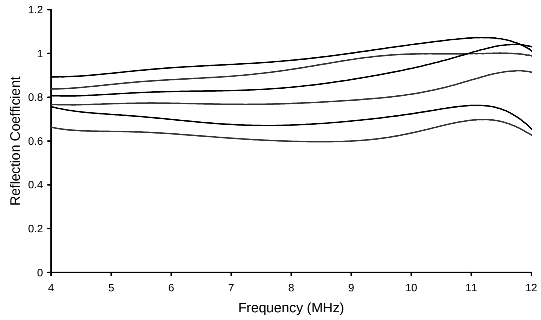

Figure 10. Reflection coefficient spectra obtained for the pulses of figure 8 recorded as the ring moves from C to D.

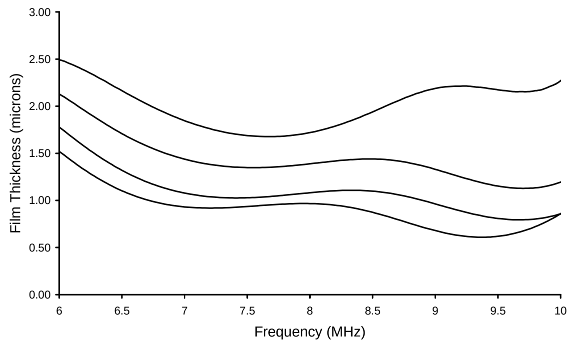

Figure 11. Film thickness determined for each frequency from the pulses of figure 7 recorded at the ring moves from C to D.

Finally equation (4) is used to obtain film thickness. This is plotted as figure 11. The measured film thickness data is, as expected, largely independent of frequency. The film thickness will be an aggregate of that which occurs over the spatial resolution of the transducer (520 μm) thus the crowning of the piston ring will tend to increase the measured thickness value. However, the level of crowning on the piston ring is small (over the distance of the spot size) that the effect on the film thickness measured is likely to be small.

5.2. Measured Oil Film Thickness

Measurements were taken for three ring sliding speeds, 6mm/s, 9mm/s and 12mm/s and a range of contact pressures (from 10 to 30 MPa). The sliding speed of the piston was limited to 12 mm/s due to the maximum capture speed of the equipment.

The film thickness remained at similar levels throughout most of the testing. Both increasing speed and reducing pressure caused a thicker oil film; but a great deal of scatter is observed. Figure 12 shows a series of film thickness measurements with changing speed and pressure.

It was believed that the spring loading caused by the piston ring was a more significant parameter than sliding speed or applied pressure. It should be noted that these tests were not intended as a comprehensive study of film thickness effects, but rather as an indication of the possibility of obtaining measurements.

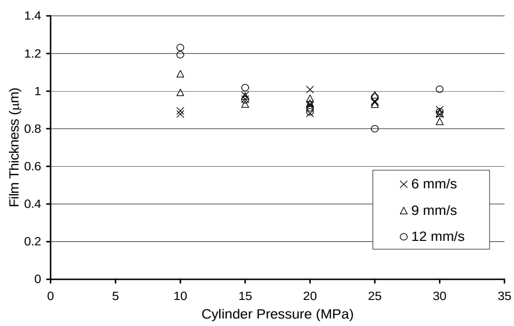

Figure 12. Oil film thickness between the piston ring and cylinder versus pressure for three different speeds.

6. DISCUSSION

In this bench test it has been possible to measure oil film thickness with an acceptable accuracy. It is difficult at this stage to determine how much of the scatter in results is due to the actual film varying and how much to measurement inaccuracies. In static tests [10] measurements are repeatable to less than a few percent. Certainly spring model assumptions hold, but there are inaccuracies associated with signal noise and interference from the reflections from the piston land.

The moving piston ring represents a reasonably large target. So positioning of the transducer laterally did not prove a problem. However a focusing transducer is still required. Coupling this to the cylinder with a water bath is somewhat awkward and improvements could be made by focusing through a solid material. The spatial resolution of the measurement can be improved by using higher frequency transducers but this leads to increased attenuation loses (up to around 50 MHz is feasible for a 4mm wall, giving a resolution of ~100 μm).

The speed of the data capture system was relatively slow (since a complete spectrum is digitised and downloaded for each measurement interval). This has limited the measurements to a relatively low sped. In principle it would be possible to speed up the signal processing by storing the data and downloading in batches or using a triggering system.

Ultimately, it would be desirable to use this approach on a working hydraulic motor (or indeed internal combustion engine). There are several experimental aspects that would need to be resolved. Primarily the positioning and coupling of the transducer needs to be refined, but also the high temperatures and temperature gradients may require more robust transducers. The method requires that the speed of sound in the oil is known (equation 4). In the hydraulic motor case, the oil in the contact is likely to have similar properties to that in the bulk. This may not be true in a fired engine and some independent calibration would be needed to convert reflection to film thickness. Another advantage of this design is that there is no cylinder liner present. An ultrasonic pulse will reflect from the cylinder bore-liner interface. This additional reflection could interfere with the oil film reflection. The thinner the liner more likely this is to happen; the issue needs to be addressed on a case by case basis.

7. CONCULSIONS

1. An ultrasonic technique has been used with some success to measure the oil film thickness in a piston ring cylinder contact. Piston sliding speeds were varied from 6 to 12 mm/s, and sealed pressures from 100 to 300 bar.
2. Films in this particular apparatus, and under the conditions tested, varied from 0.7 to 1.3 μm. The films did not reveal a strong dependence on either speed or pressure and the data showed some scatter.
3. All tests were performed on a bench test apparatus designed to simulate the pistons in a hydraulic motor. This allowed some experimental simplifications to be implemented.
4. For the method to be used on-site in a piston, or even on a fired engine, then some experimental improvements would be necessary. Principally the focusing system needs refinement, the temperature stability of the transducers needs consideration, and the data capture speed should be increased.

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