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Oil Film Measurement in PTFE Faced Thrust Pad Bearings for Hydrogenerator Applications.

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Keywords

oil film measurement, thrust pad bearings, tilting pad bearings, PTFE faced bearings, fluid film bearings, ultrasound, lubrication, film thickness

Abstract

There is a growing trend in the replacement of the babbit facing in thrust pad bearings with a composite PTFE surface layer. The PTFE faced bearings have been shown to allow a greater specific pressure, reduce thermal crowning, and in some cases negate the need for an oil-lift (jacking) system. These designs of bearing require new methods for the measurement of oil film thickness both to assist in their development and for plant condition monitoring. In this work, an ultrasonic method of oil film measurement is evaluated for this purpose.

An ultrasonic transducer is mounted on the back face of the thrust pad. Pulses are generated and transmitted through the pad material, bonding interlayer, and PTFE surface layer. The proportion of the wave that reflects back from the oil film layer is determined. This is then related to the oil film thickness using a series of calibration experiments and a spring stiffness model. In practice the reflected signal is difficult to distinguish, in the time domain, from other internal reflections from the pad. Signals are compared with reflections when no oil film is present and processing is carried out in the frequency domain.

Experiments have been performed on a full size PTFE-faced thrust pad destined for a hydroelectric power station turbine. The instrumented pad was installed in a test facility and subjected to a range of loading conditions both with and without oil lift. Whilst there were some problems with the robustness of the experimental procedure, oil films were successfully measured and used to study the effect of the oil lift system on film formation.

Notation

c	speed of sound in the lubricant.
h	lubricant film thickness.
ω	angular frequency of the ultrasonic wave ($\omega=2\pi f$).
f	angular frequency of the ultrasonic wave.
R	reflection coefficient, the proportion of the amplitude wave reflected.

ρ density of the lubricant.

z acoustic impedance ($z=\rho c$)

1. Introduction

Engineers in the hydro-electric power industries of the former Soviet Union and China have pioneered the use of PTFE faced thrust pad bearings, replacing conventional tin based alloys, known as whitemetal or babbit. Installations in Canada, Japan, and the UK are following suit [1].

In these designs the PTFE layer is bonded onto the thrust pad by means of an intermediate layer of copper mesh. The PTFE sheet is first pressed onto the mesh and heated above its softening temperature. The PTFE is then partially extruded into the mesh, which is subsequently soldered onto the pad. (It should be noted that in the pads used in this study the mesh is fully filled with solder, the ultrasonic method would not work otherwise as reflections would occur from internal air gaps). Figure 1 shows a schematic of a section through the pad showing the layers and relationship to the oil film and thrust collar.

The use of PTFE faced thrust pads has a number of advantages. Testing has shown [2] that the pads can withstand a specific pressure (load divided by the surface area of the pads) up to 10 MPa, significantly higher than that which can be achieved with babbit. The PTFE thermally insulates the pad from the oil film so that there is less thermal crowing of the pad. Additionally, because the material is softer, there is both less likelihood of damage to the collar in the event of collapse of the oil film, and also a greater acceptance of pad surface tolerances or machining flaws. Further, because the sliding friction coefficient is low, there is the possibility that an oil lift system (also known as a jacking oil) is not required during start-up thus saving plant costs.

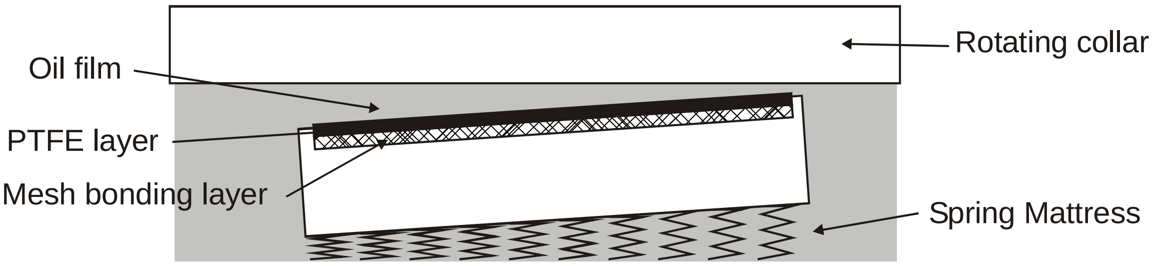


Figure 1. Schematic sectional view of a PTFE faced thrust pad showing pad construction and relationship to collar and oil film (not to scale: oil film, tilt, and layer thickness exaggerated).

However, PTFE has highly temperature sensitive mechanical properties. The modulus of elasticity decreases by a factor of ten with normal temperature rises within the bearing. The material is also subject to rate dependent creep. This means that the film shape will adjust as both the temperature and creep affect the surface geometry. Design methodologies based on conventional babbit materials, and especially the specification of the curvature of the pad surface, are no longer suitable. This is particularly important in pump-storage applications where the pad must be symmetrically pivoted and the formation of an appropriate convex surface is essential. As the pad heats up the surface curvature will change due to thermal distortion. If the pad is insulated from the oil film by a PTFE layer, the heat transfer will change and so the deflected surface shape will be different. This will alter the film forming behaviour, compared a conventional babbit faced pad.

There are now theoretical models for predicting oil film thickness under these new conditions [3]. The coupling of the oil film pressure to elastic deformation of the surface has shown interesting phenomena [2]; at higher specific pressures the film becomes almost parallel with a constriction at the outlet similar to that found in conventional elastohydrodynamic lubrication. The minimum film is therefore at this constriction around the pad sides and trailing edge. A method for the experimental verification of the film shapes in these kinds of thrust pads has yet to be achieved.

In operating plant, the temperature of the lubricating oil and the pad are used to monitor the condition of the bearing. A high pad temperature indicates the possibility of a film failure and is used as a trip. Unfortunately, the PTFE insulates the pad body from the likely source of failure, the surface, so pad condition monitoring is rendered ineffective. Instead, some form of heat conducting insert that breaks the surface, needs to be used to monitor surface temperature. This has the potential to disrupt the PTFE film formation mechanisms and negate some of the advantages described claimed above.

For both applications of, bearing development, and condition monitoring, there is a requirement for a device to measure oil film thickness. However, practical realisation of such a device, especially outside of the laboratory, has proved difficult in the past. Measurements are complicated by the fact that the dimensions of the film are small compared with the size of the bearing components. In rotodynamic machinery eddy current sensors and proximity probes are usually used. The sensor is mounted outside of the lubricated region and so essentially measures the distance from one bearing shell to the other. In the case of a tilting pad bearing they can be fixed to the outside of the pad and record the distance to the collar [4,5]. Clearly this will not reflect a true picture of the film formed in a PTFE faced pad where the bearing materials themselves distort and deflect.

There are several methods that have been used to measure the oil film directly. Inductive position sensing transducers can be mounted on the side of a pad and used to determine the position of the pad from the rotating collar. This can give measurements of the pad tilt and position, but is not a direct measurement of the oil film. A conducting probe can be mounted on the bearing wetted contact surface to measure the capacitance of the oil film between the sensor and the opposing bearing surface [6]. Another approach is to use a fibre-optic system to reflect a light pulse from the bearing back face. The intensity of the reflected pulse is a measure of the lubricant film thickness through which it has travelled [7]. Both of these methods require intervention into the lubricant film; a hole must be drilled through the bearing surface and a sensor or window mounted adjacent to the oil film. This has the possibility of disrupting the formation of the film and weakening the bearing structure or surface. Whilst current methods of film measurement have proved successful in laboratory scaled down situations they have found few applications in commercial plant.

In this work, the use of a novel ultrasonic method for film thickness is investigated for the case of a PTFE faced thrust pad. The aim is to develop a sensor to assist both in thrust pad bearing development, and in condition monitoring. Ultrasound has the advantage that it can be propagated through the original bearing components non-invasively and with minimal modifications to the pad. The reflection of an ultrasonic pulse at the oil film is used to determine the oil film thickness. The method has been applied to study film formation in a development PTFE faced bearing under a range of operating conditions. The PTFE faced thrust pad raises a number of unique issues; primarily because of the large acoustic mismatch between the bearing and collar materials, and the fact that reflections also occur at intermediate layers within the pad.

2. Oil Film Measurement Approach

Ultrasonic Reflection at a Thin Oil Film

A short duration ultrasonic pulse can be transmitted through a bearing component. When the pulse reaches an oil film part of it will be transmitted through the film, and part will be reflected. The proportion of the wave amplitude reflected (known as the reflection coefficient) depends on the acoustic mismatch between the oil and the bearing materials and the thickness of the oil film. A thick oil film will reflect more sound than a thin film. Strictly, reflections occur at both the front and back faces of the oil film (and there are subsequent internal reflections) and all these reflected pulses are received. However, the oil films in most bearings are so thin that it is not possible to distinguish these reflections spatially. The thin layer behaves as a unique reflector. The layer can then be treated as a spring and it is the layer stiffness that determines the reflection coefficient.

The relationship between reflection coefficient, layer stiffness, and film thickness is developed in detail elsewhere [8]. For conditions where the oil film is thin compared with the ultrasonic wavelength, a simple relationship for the oil film thickness can be derived:

$$h = \frac{\rho c^2}{\omega z_1 z_2}\sqrt{\frac{R^2\left(z_1 + z_2\right)^2 - \left(z_1 - z_2\right)^2}{1 - R^2}} \qquad (1)$$

where R is the reflection coefficient, ρ and c are the density and speed of sound of the lubricant, ω is the angular frequency of the wave ($\omega=2\pi f$), and z_1 and z_2 are the acoustic impedances of the bearing materials either side of the layer of oil. The acoustic impedance is the product of the wave speed and the density of the material. Thus if the reflection coefficient can be measured, and the materials properties (both for the bearing shells and the lubricant) are known, then the film thickness can be determined. The reflection coefficient is a complex number, for this work the amplitude alone has been used. It is also possible to use the phase of the reflected wave. Under certain circumstances, this can have some advantages which are described in detail in [9].

For the present case the oil film is interposed between steel on one side and a composite structure of filled PTFE, copper mesh/solder, and steel. The acoustic properties of the latter are ill defined, oil films of known thickness have been measured in order to work back to the unknown acoustic impedance. In this way the reflection coefficient is calibrated to give measurements of the oil film thickness. Further, the density and speed of sound of the oil change with temperature. This is also must be considered in the measurements. The procedures for achieving this calibration are described later.

Ultrasonic Reflection Apparatus

An ultrasonic pulser/receiver is used to generate controlled voltage pulses. These pulses are used to excite a piezoelectric ultrasonic transducer. The front face of the transducer (the wear plate) is coupled directly onto the back face of the thrust pad. The transducer acts as both an emitter and receiver (pulse-echo mode). The reflected pulses are amplified, captured on the digital storage scope, and passed to a PC for signal processing. Figure 2 shows a schematic view of the apparatus layout.

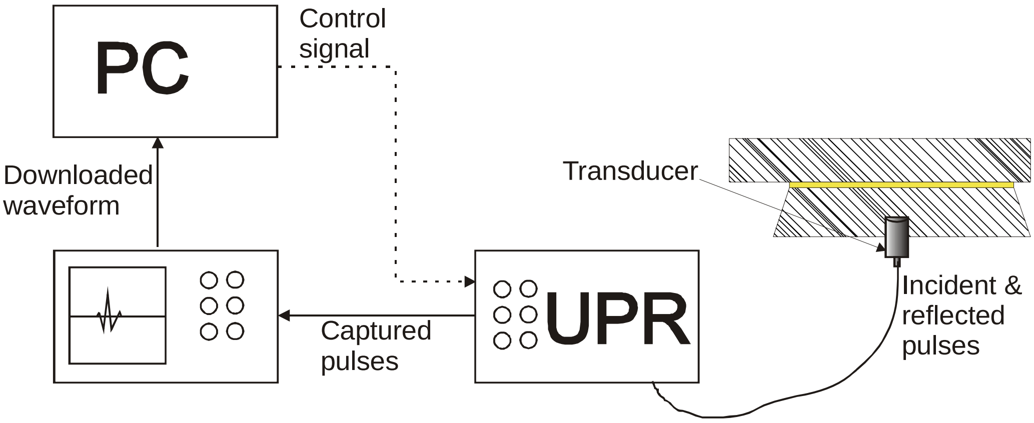


Figure 2. Schematic view of the ultrasonic pulsing, acquisition, and processing apparatus.

Transducer Selection

Inspection of equation (1) shows that it becomes unstable as R tends to unity. So that, when thin films are being measured a small amount of noise in the signal causes a large error in the measurement. The solution is to use a higher frequency transducer. However, higher frequency frequencies are more likely to be attenuated by the materials through which they pass. A compromise between frequency and bandwidth is needed. In this work a broadband longitudinal 1 MHz planar transducer was used. The transducer has energy in the range 0.4 to 1.2 MHz. These frequencies are all transmitted through the pad, copper mesh/solder, and PTFE layers with a manageable level of attenuation.

The piezo-electric sensor diameter is 19 mm; the emitted pulse will spread laterally as it travels through the pad material. The spatial resolution is thus somewhat greater than the crystal diameter (probably around 20-50 mm diameter). For a large size thrust pad this kind of resolution is probably acceptable. But for work on spatially smaller oil films it becomes necessary to focus the ultrasonic wave to improve spatial resolution [10].

The transducer is coupled to the back face of the pad using a water-based gel couplant. In practice the transducer needs to be held in position so that the coupling layer does not vary. This would change the amplitude of the pulse incident on the oil film. This is especially the case when, as in these thrust pad experiments, the bearing element is subject to loading and movement. A spring retaining assembly is used to keep the transducer consistently pressed against the back face of the pad (as shown in figure 3).

Signal Processing

The first step in the signal processing is the recording of a reference reflection. Initially a pulse is recorded from the back face of the bearing shell when the collar is lifted away from the pads and any residual oil wiped away. This received pulse has then been reflected from an interface between the pad surface and air. The acoustic impedance of air is very low so virtually all the ultrasonic wave is reflected. The reflected signal is thus essentially equal to the incident signal. All subsequent reflected signals can then divided by this reference to obtain the reflection coefficient.

The bearing faces are then reassembled. The bearing is set in motion and reflected pulses from an oil film are captured, digitised, and passed to the PC. A fast Fourier transform (FFT) is performed on the pulse to give an amplitude against frequency plot. This is divided by the FFT of the reference signal to give a reflection coefficient spectra (i.e. R vs f).

Equation (1) is then used to calculate the film thickness from the reflection coefficient. In principle it should not matter which frequency is chosen to make this calculation. The film thickness should be independent of the measurement frequency. Despite the fact that frequency appears in equation (1), its effect on h is cancelled by the counter-variation of R with frequency. In laboratory test oil films between homogeneous media, this is the case and the measured film thickness is independent of frequency [8]. In practice, the presence of intermediate layers, which might cause overlapping reflections, results in some slight variation with frequency. In these tests a calibration is performed at one frequency and the results measured at the same frequency.

3. Static Calibration Tests and Film Thickness Measurements

In initial studies a simple static oil film was created using shims to separate a ground flat steel surface from a sample section cut from a thrust pad (as shown in figure 3). Shims of various widths were used to simulate different oil film thicknesses.

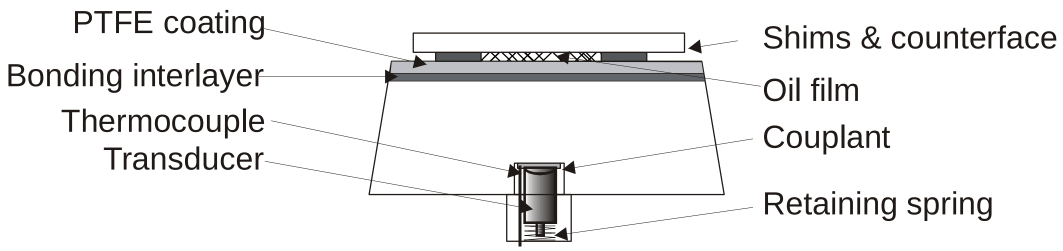


Figure 3. Schematic diagram of the apparatus used to simulate an oil film.

There are a series of reflections from the bearing and oil film (shown schematically in figure 4); the front face of the copper mesh/solder interlayer (A), the interface between the interlayer and the PTFE (B), and the oil film front and back (C & D).

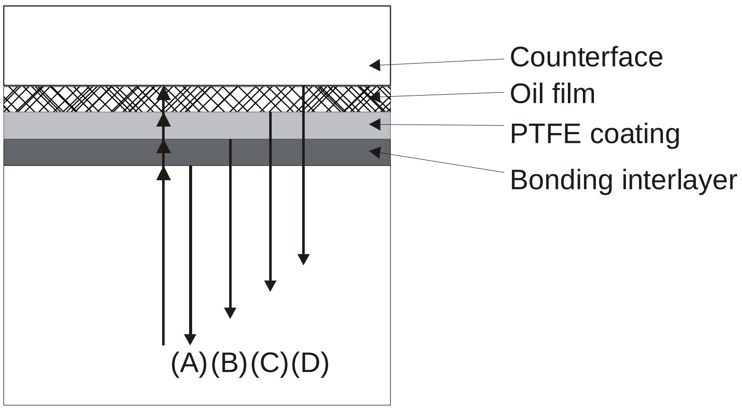


Figure 4. Schematic representation of the reflection from layers within the bearing pad.

The pulses reflected back from a pad/air interface and from a pad/oil film interface are recorded. Figure 5 shows the two such reflections superimposed on a single graph. The first two peaks, A and B are reflected from the copper mesh/solder layer front and back faces. The third peak is reflected from the oil film (the pad surface). The reflected pulses A and B show a trough and two peaks. These are discrete in the time domain. The oil layer is so thin that the reflections C and D are effectively superimposed. It is difficult to see the same pattern of peaks and troughs because of this superposition. This is further complicated by the fact that a phase shift also occurs between these two pulses as they are reflected from their respective interfaces.

From the amplitude plots (figure 5) it can be difficult to judge which of the peaks in the signal correspond to which reflection. This peak must then be the pad surface reflection, since all the internal reflections will be unaffected by a surface film being changed. It then becomes simple to extract only the parts of the waveform that change when the film thickness changes. Thus, the bold line on figure 5 coincides with the faint line at all locations except at the portion of the signal that corresponds to the oil film (peaks C & D). Figure 6 shows the extracted reflection peaks for a series of five different oil films.

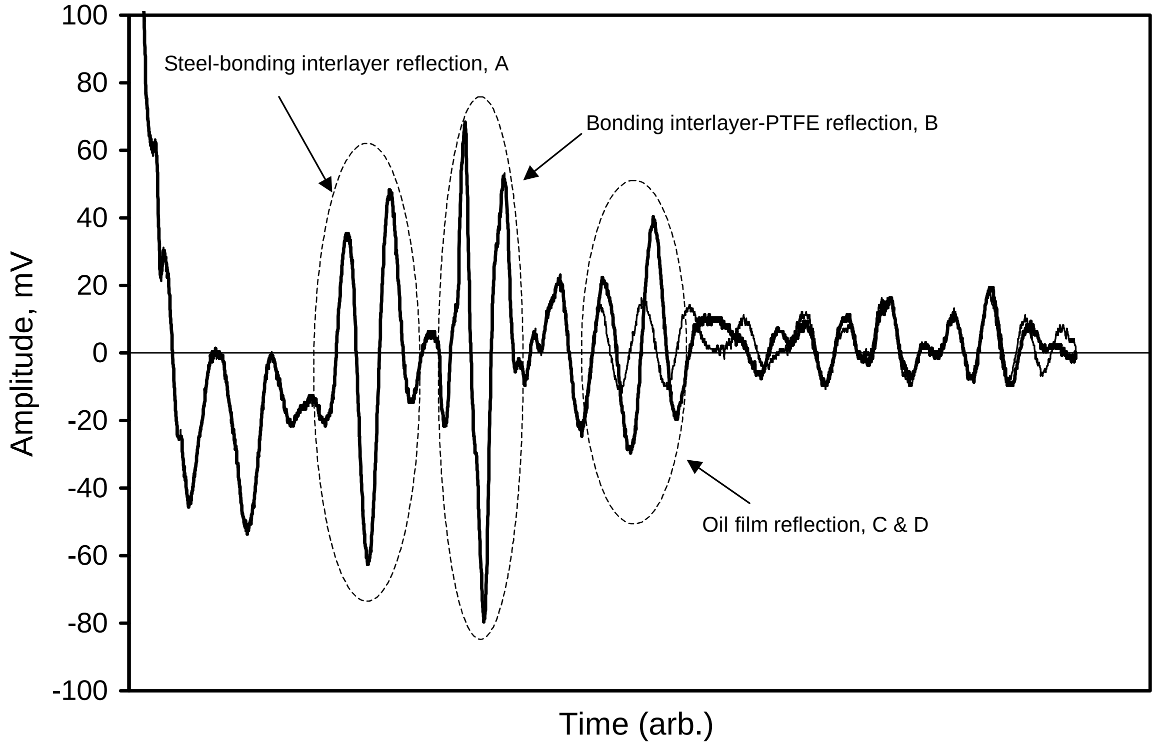


Figure 5. Pulses reflected back from a pad/air interface (bold line) and a pad/oil film interface (faint line). The internal and surface reflections are indicated.

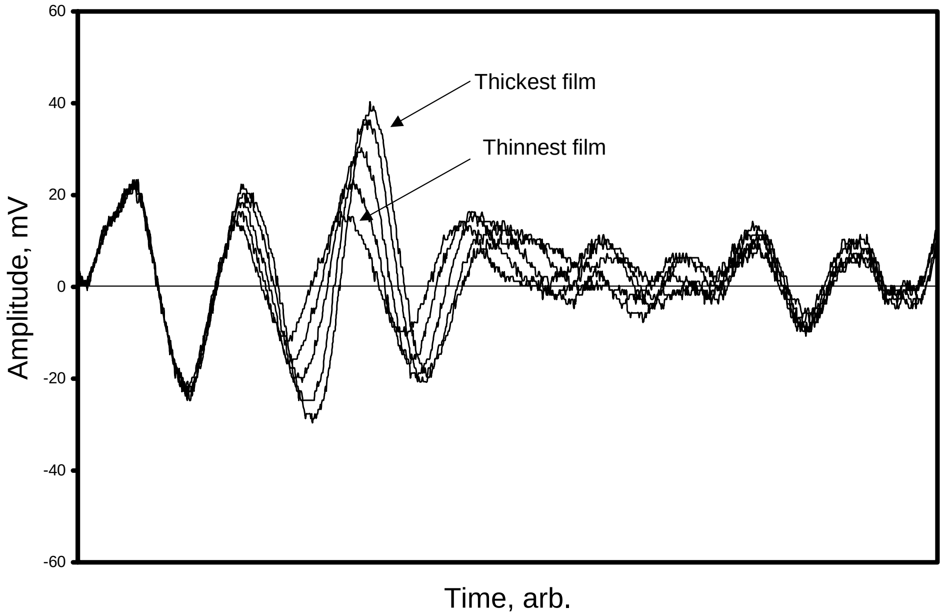
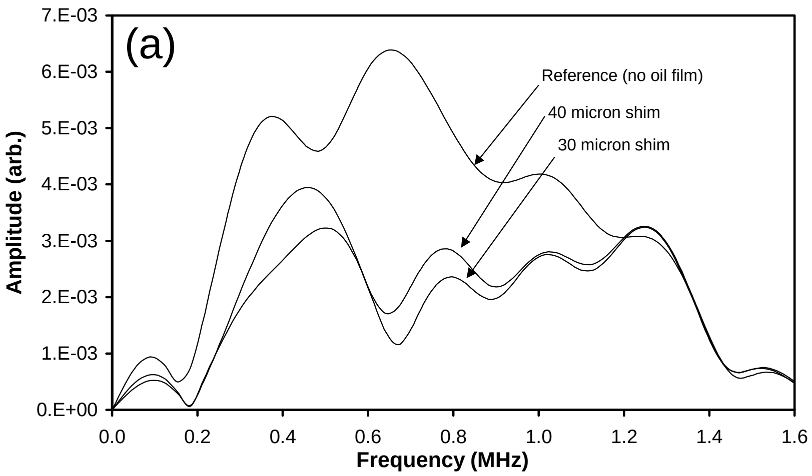
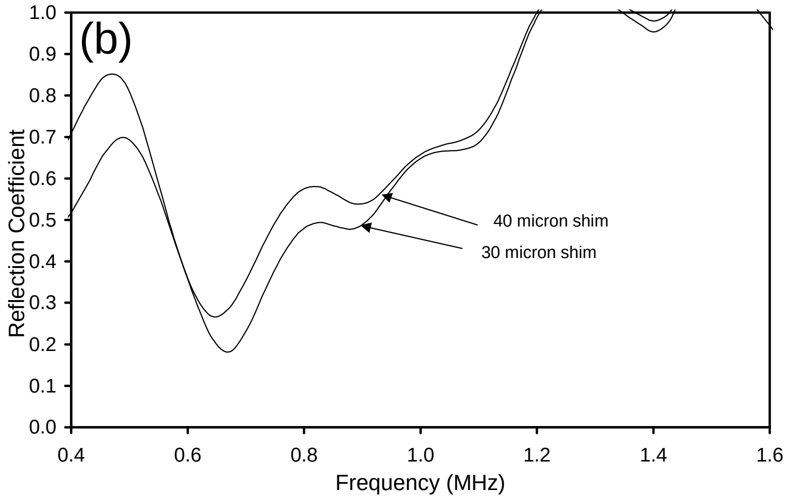


Figure 6. Reflected pulses from five different oil films; the peak corresponding to the oil film alone has been extracted from the whole reflected signal.

This peak (i.e. the pad surface reflection) is extracted from the signal to give an amplitude against time plot. This is passed through an FFT to obtain an amplitude against frequency spectrum. This spectrum is then divided by the equivalent spectrum for the reference case (i.e. reflected from an air interface and thus equal to the incident wave). This gives a plot of reflection coefficient against frequency. The reflection spectrum, R is then be used in equation (1) to calculate the film thickness, h at all frequencies. Figure 7 shows the FFT, the reflection spectrum, and the film thickness spectrum for a 30μm and 40μm oil film generated by the use of shims.





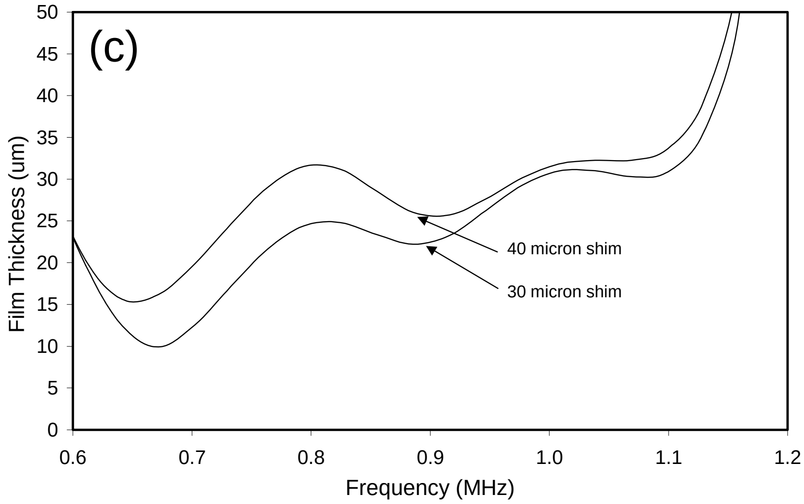


Figure 7. (a) Fourier transform of the pad surface reflection, (b) Reflection coefficient spectrum and (c) film thickness spectrum for 30 and 40µm oil films.

Figure 7a shows that, although the transducer is labelled as1 MHz, it has energy in the bandwidth $0.4 < f < 1.2$ MHz with a centre frequency of around 0.8 MHz. The reflection coefficient spectra shown in figure 7b are therefore only reliable in that bandwidth (and outside the range sometimes gives reflection coefficient greater than zero where the noise dominates the signal).

In theory any frequency can be used to determine the oil film thickness. Whilst the reflection is frequency dependent, the film thickness is not. However, in practice, the plot of film thickness against frequency (figure 7c) tends not to be constant. This is because in extracting the pad surface reflection peak some important parts of the signal have been lost. When an FFT is performed this manifests itself as a loss at some frequencies (and hence a non-constant film thickness).

Unfortunately this peak extraction is necessary to separate the required reflection from those at the intermediate layers. In other work on hydrodynamic films [11] where there is no intermediate layer, the surface reflection is discrete and in this instance a full frequency reflection spectrum can be obtained which leads to film thickness results at all frequencies. In practice, the best results are obtained by using the centre frequency of the transducer for the calculations. The shims used were 30 and 40 µm thick and the measured film at the centre frequency are 25 and 35 µm thick. Whilst the agreement is reasonable it is not excellent and only an accuracy of ~±20% is achievable at this stage.

The output of piezoelectric transducers are temperature dependent. Since temperature variation is expected in the application, this has to be incorporated into the measurements. A simple calibration exercise was carried out. The transducer, pad, and a captive oil film are placed in a temperature controlled oven and the reflected signal from the oil film is monitored. The oven temperature is ramped up very slowly (over the period of two days) to ensure the assembly reaches an equilibrium temperature. Over the temperature range 20 to 80°C, the transducer output increases by around 15%; the data is approximately linear and a correction factor was established.

The calibration described above incorporates two factors, firstly the temperature effects on the transducer output and secondly the effects on the oil itself. The acoustic properties (i.e. ρ and c) of the oil also change with temperature. This variation can readily be obtained by measuring the time of flight through a bath of oil as the temperature is varied. Strictly we should have two temperature sensors, one in the oil, and one at the transducer. The first should be used to determine the acoustic properties of the oil and the second the output characteristic of the transducer. However, the variation of the oil leads to a very small change in reflection (<5%) and the difference in temperature between the oil and the transducer is likely to be small in any event. All recorded reflection coefficients were adjusted according to the above calibration.

4. Measurements from an Operating Thrust Pad

Pad Instrumentation

The pad used for these trials was one from a pump-storage hydroelectric power station. The approximate dimensions of the pad were; length 400 mm, outer chordal diameter 440 mm, and thickness 80 mm. The pad was faced with a 3 mm thick layer of PTFE filled with graphite bonded using the copper mesh and solder method described above.

Before locating the transducer it was necessary to perform some propagation tests through the pad. It was necessary to position the transducer so that the emitted beam would not reflect from any internal cooling channels, thermocouple ports, or voids in the copper/solder interlayer. A position near the outer radius located at 80:20 (non-dimensional radial/circumferential position %:%) was selected. Although the pad operation is bi-directional, the results reported here are all for when the collar rotation was such that the transducer was closest to the leading edge.

The transducer was sprung loaded onto the back face and coupled with a standard ultrasonic gel (in the same manner as shown in figure 3). A thermocouple is placed alongside the transducer to record the local temperature. A protective case is bolted to the pad back face surrounding the transducer and wiring. A spring was removed from the supporting mattress to accommodate the transducer and casing.

The pad was already installed with brass inserts set into the PTFE face to carry thermocouples. In addition inductive proximity probes were located at each of the test pad corners. The probes were calibrated to record the distance from the PTFE surface to the thrust collar (but were only used during static operation of the pad).

The instrumented thrust pad was then installed in the bearing test apparatus. The RF cable from the transducers was fed out to the digital scope and PC for analysis (as shown in figure

1). The thermocouple wire from transducer pocket was passed to a digitiser and the PC. A bespoke interface was written in the Lab View programming environment. The program was designed to; drive the pulser and scope, capture and record reflected signals, process waveforms to give film thickness, and calibrate for any temperature fluctuations.

Thrust Pad Test Apparatus

The thrust pad is located inside a purpose built test-rig (designed, constructed, and operated at the Michell Bearings Factory in Newcastle-on-Tyne, UK). The test rig uses a reduced number of thrust pads. Figure 8 shows a schematic diagram of the test apparatus. Pad number 2 is the test pad with the pads either side (1 and 3) to simulate oil carry over effects from pad to pad. A matching set of four pads is located above the thrust collar. Each pad is supported by a mattress of springs.

The drive shaft is driven by an electric motor through a drive belt. Load can be applied to the collar hydraulically through the upper set of thrust pads. The pads are lubricated by immersion in Shell Turbo T32. A facility exists to hydrostatically lubricate the thrust pads, either during start-up or normal operation. Jacking oil is supplied to the thrust pads from the back face of the pad through a duct to a port located centrally on the pad surface.

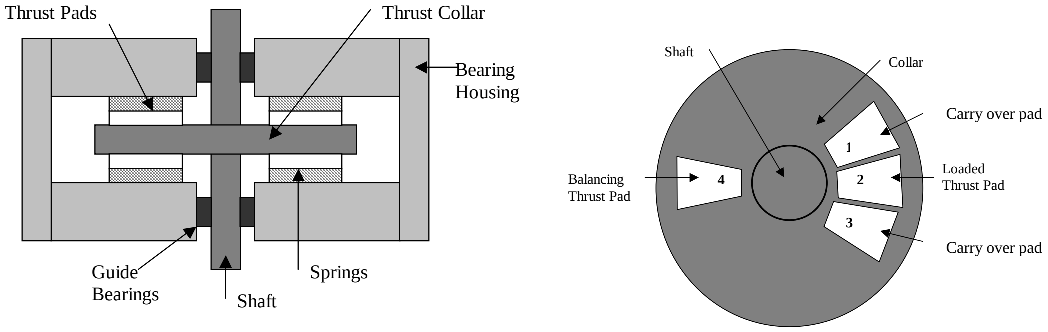


Figure 8. Elevation and plan schematic diagram of the thrust pad test apparatus.

Static Oil Lift Tests

In some preliminary experimentation the jacking oil was gradually increased under varying applied bearing loads. The aim was to compare the ultrasonic recorded film thickness with readings from proximity sensors at the leading and trailing edge of the pad. The jacking oil pressure was increased from zero to a maximum (20 MPa) against a range of bearing loads, in order to manually alter the oil film thickness. The range of oil films measured ultrasonically (18 to 90 μm) compared well with readings from the proximity probes when interpolated to the location of the transducer.

Variable Load and Speed Tests

Figures 9(a) and (b) show the variation in measured film thickness measured ultrasonically (at the leading edge outer pad radius 80:20 position) as the bearing load and operating speeds are varied. Note that here the bearing loads quoted here have been scaled as if the bearing were a true full compliment of thrust pads. The data has some degree of uncertainty since it is based on calibration (the data of figure 7c) which itself has an inherent error; ±10μm is the expected level of accuracy in this data. Much higher accuracy can be achieved when the intermediate layers can be separated out.

The temperature typically varied by 8°C over the duration of the speed variation tests (less for the load variation tests). The monitored temperatures were used to correct the measured reflection coefficients before the film thickness was determined.

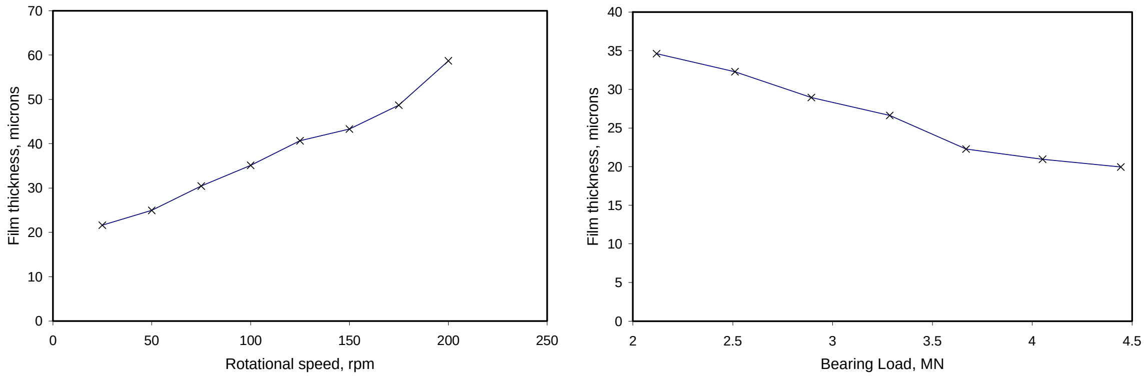


Figure 9. The variation of oil film thickness measured using an ultrasonic transducer at the 80:20 location as (a) the rotational speed is increased (bearing load 4.3 MN), and (b) bearing load is increased (bearing speed 25 rpm). No jacking oil supply.

The Effect of Jacking Oil

Hydroelectric power stations are frequently required to start-up at very short notice (especially when used for the supply of peak time electricity). The application of jacking oil during this run-up and its effectiveness was investigated. Figure 10 shows the refection coefficient recorded during a rapid start-up (0 to 500 rpm in 500 seconds) in the presence of jacking oil. This data is then processed using the calibration method described in section 3 above, to give the oil film thickness. This data is also shown on figure 10.

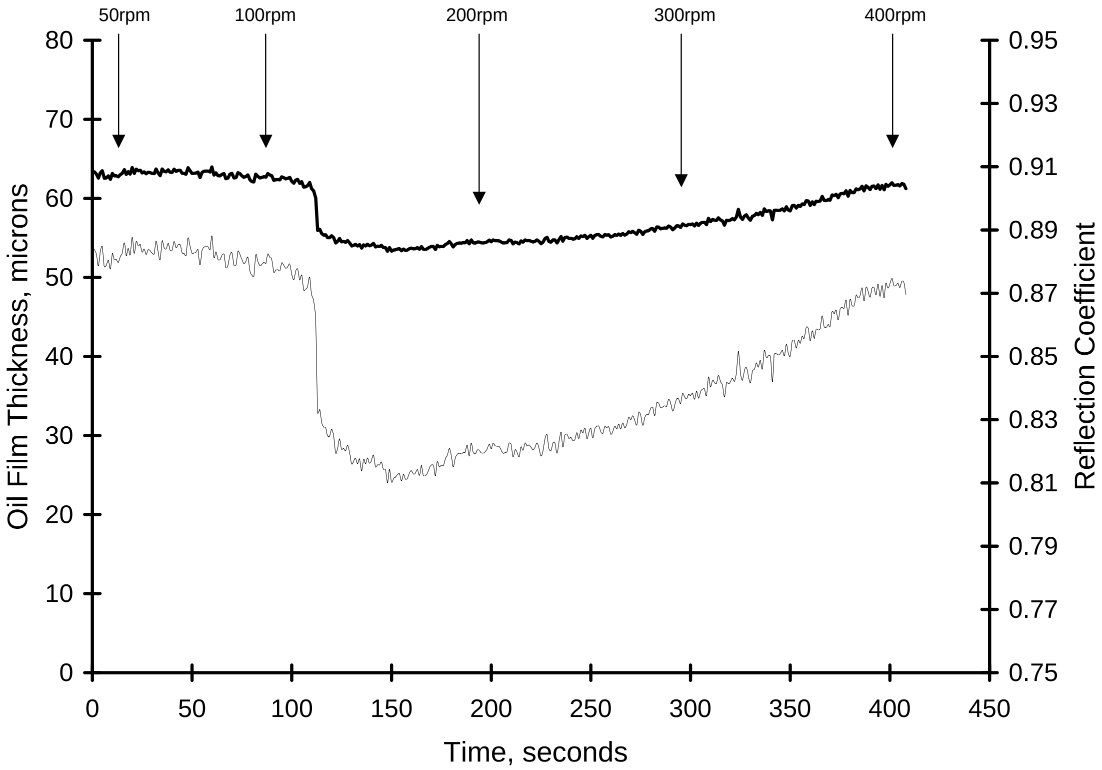


Figure 10. Reflection coefficient (bold line) and calculated oil film thickness (faint line) variation during a rapid start-up.

A collapse in the oil film occurs at around 100 seconds when the speed has reached around 140 rpm. Figure 11 shows the measured film thickness re-plotted against speed. For comparison further operating cases are shown; a lower jacking oil pressure, a rapid start-up and a slow start (0 to 500 rpm in 5 minutes) without jacking oil. Again, all measurements are recorded at the 80:20 location close to the leading edge and outer radius.

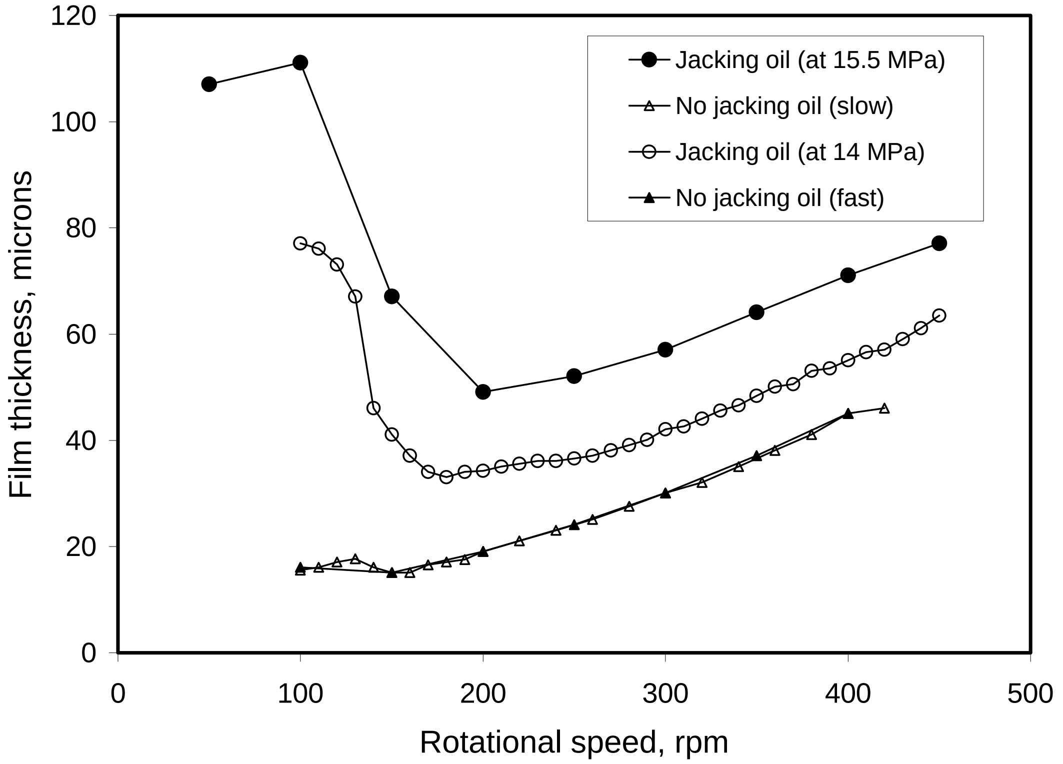


Figure 11. The variation of oil film thickness during a rapid start-up (solid data point markers) and during a slow start up (hollow data point markers) both with and without the application of jacking oil.

The results without the action of jacking oil show the build-up of a hydrodynamic film as expected. The film thickness increases monotonically with speed as more oil is drawn into the contact. The rate of speed increase (the slow and fast ramping up tests) has made no difference to the film formation (certainly when there is no jacking oil present). At these accelerations the inertia effects on film formation are negligible.

When the jacking oil is used the film starts off thicker but falls away rapidly between 100 and 200 rpm. This rapid drop in the oil film thickness is caused by the oil being swept out of the contact at elevated rotational speeds. The volume of oil being pumped into the bearing is insufficient to balance the Couette flow out of the bearing. At higher speeds the flow is augmented by the hydrodynamic entrainment of more oil and the film thickness starts to increase again. The slightly lower jacking oil pressure makes a significant difference to the overall oil film thickness.

The data of figure 11 would indicate that in all cases a thick film is formed. However, it should be noted that the measurement sensor is located at leading edge. The trailing edge will be thinner. Importantly, the jacking oil can have the effect of causing a concave deflection of the pad. So whilst the central part of the pad is separated by a thick film of oil, the pad edges may be running close to the collar. Thus the sudden drop in oil film thickness during this run-up can be of concern. During a speed ramp, if a thick hydrodynamic oil film has not formed across the whole pad surface by the time the hydrostatic action falls away, then a pad wipe could ensue.

5. Discussion

Experimental Improvements

This work has shown the application of a new ultrasonic film measurement technique to a power station thrust bearing. Whilst film thickness readings were obtained there were a number of experimental issues that complicated and reduced the accuracy of the measurement process. The internal layers (copper mesh/solder and PTFE coating) within the pad caused reflections of the ultrasonic pulse. These reflections were partially superimposed on the required surface/oil layer reflection. This meant that the selected section of the pulse was missing some of the signal. The processed signals were thus not as clean as can be achieved when testing conventional white metal faced surface. An extra calibration process is also required, because the acoustic impedance of the pad surface is not defined by a single material.

The nature of the bearing meant that access to the transducer during operation was limited (without major overhaul of the test assembly). This meant that the transducers, once assembled, could not be adjusted. More work needs to be done to ensure the integrity of the coupling between the transducer and the pad back face. In subsequent work high temperature adhesives have been used for coupling with greater success. The transducers used were standard off the shelf designs. This means that they were fairly bulky and required the construction of a protective casing and the removal of a pad support spring. It would be feasible to purpose build smaller profile transducers that required less modification to the pad and support structure.

The reflected signals are recorded over a relatively large area of the oil film (over a diameter of ~20-50 mm). This low spatial resolution is adequate for studies of pad tilt but would not reveal detailed information about how the PTFE deforms. For this is would be necessary to use focusing immersion transducers where spatial resolutions down to around ~100 μm can be achieved [10]. This requires the coupling of the transducer at a fixed focal length in a water bath, which would be difficult to set-up in anything other than a laboratory environment.

Advantages of the Technique

The measurement of the oil film in a hydrodynamic bearing is practicable by two means. Firstly inductive probes can be mounted at the pad edges and used to sense the distance from the pad to the collar. This can provide useful data on pad tile and position. However, it is not possible to get measurements from within the film itself and certainly distortion of the PTFE surface within the pad would not be recorded. Secondly, capacitive sensors are also used. However, these have to be recessed into the pad and in contact with the oil film. This means some invasive machining required and the possibility of modification to the oil film by the presence of a surface mounted component.

The ultrasonic approach detailed here has two distinct advantages. Firstly, the sensors do not have to be in contact with the oil film. The wave is transmitted through the bearing surface, however, the sensor must be mounted normally to the film and have direct line of sight access. These leads to the second advantage that localised measurements can be taken from with the film. The deflection of the surface can thus be recorded. In principal it would be possible to install an array of piezo-elements and record a map of the film shape and hence surface deflection.

Limitations of the Technique

The main limitation of the approach is the transmission of the required ultrasonic frequency through the pad material. Fortunately the films generated are thick enough such that only relatively low frequencies are required. These lower frequencies are attenuated less in the pad material. Propagation through the 80 mm thick steel pad proved to be possible. However, any ducts, ports, or air pockets in the copper mesh would reflect sound and render the method inoperable. The PTFE bonding must therefore be of the type where the copper mesh is fully filled with solder. Alternatively, it would be feasible to install an insert through the pad and coupled to the PTFE back face. The ultrasonic signal would then be propagated through the insert rather than the pad and mesh.

The piezoelectric crystals used in this work are both sensitive to temperature and have a maximum operating temperature above which irreversible signal loss occurs. With the conventional transducers used in this work the temperature is limited to around 80°C when the adhesives used in their manufacture disbond. The use of more costly high temperature transducers would be required when above this value.

Future Prospects

The method as it stands has proved useful in understanding the film formation with respect to the timing of jacking oil during start-up. Addition of further sensors (and a multiplexing arrangement) would give information about the film distribution and pad tilt. Currently thrust bearing developers rely on proximity probes and thermocouples to deduce the film formation mechanism. An ultrasonic based film thickness sensor would compliment this instrumentation. However, to fully compare the results with computational codes it would be important to have spatial measurements of the oil film. This can only be achieved by the use of multiple sensors. Alternatively, the location of a sensor behind the rotating collar would allow a two dimensional scan of the film using a single transducer. This would require the implementation of a slip ring system suitable for high frequency signal transmission.

In addition to using the approach as a means to understand film formation, there is also the potential to use the sensor as a condition monitoring device. It would be preferable to monitor oil film thickness directly rather than to set high temperature alarms that trip when an oil film gets thin and heat is already generated. In principle this would be possible using such an ultrasonic method. However, it would certainly require the development of robust transducers and coupling systems.

One further useful piece of information that can be obtained is the thickness of the PTFE layer. The time between the reflections B and C on figures 3 and 4 can easily be converted to the layer thickness (by multiplying by the speed of sound in the filled PTFE). This can be continuously monitored during pad operation to record wear of the PTFE layer.

6. Conclusions

The thickness of the oil film generated by a PTFE faced thrust pad has been measured using an ultrasonic method. Transducers were coupled with the back face of the pad and the signals reflected at the front face were recorded. The PTFE and bonding interlayer cause internal reflections and so had to be carefully extracted from the signal in the time domain.

Calibration oil films were generated on the surface of the pad using shims. The measured results agreed well with the shim thickness. The thrust pad was installed in a purpose built test apparatus. Oil films were measured for a range of load and speed cases. For normal bearing operation films in the region of 15 to 100 μm were recorded.

With the application of jacking oil the oil film thickness is greatly increased. At a critical speed the jacking oil is swept out of the contact and film formation relies solely on the hydrodynamic action of the bearing, resulting in a sudden drop in oil film thickness. The magnitude of the jacking oil pressure has a significant effect on the film thickness but not on the speed at which the film collapses.

The tests have shown that the method can successfully measure oil films in this application and produce useful information about film forming mechanisms. However, there are a number of experimental issues that require further attention. Principally, these are concerned with transducer and coupling robustness, and the processing of multiple reflection signals.

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