NATIONAL UNIVERSITY OF SCIENCES & TECHNOLOGY
SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING

LOCALIZED CAPACITIVE TECHNIQUE FORTHE MEASUREMENT OF OIL-FILM THICKNESS IN A JOURNAL BEARING

(Patent Application Number: 188/2013)

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NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

BE Mechanical Project Report

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Titled: **Localized Capacitive Technique for the Measurement of Oil-Film Thickness in a Journal Bearing** be accepted in partial fulfillment of the requirements for the award of BE degree.

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DEDICATION

We would like to dedicate our work to our parents whose endless support throughout our academic career has been the most important factor in all our successes.

ACKNOWLEDGEMENTS

We would like to express our gratitude to our supervisors, Dr. Nabeel Anwar and Dr. Riaz Ahmed Mufti, whose guidance was essential in ensuring the success of this project. We would also like to thank Mr. Jawad Aslam and Mr. Rehan Zahid whose help was quite important in making sure we proceeded in the right direction.

It is also imperative for us to thank all the supporting technical staff at the SMME Labs particularly that at the Manufacturing Resource Centre, Electronics Laboratory, Measurements Laboratory and Engine Tribology Laboratory.

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SECTION 1

PROJECT SUMMARY

Vehicle emissions can affect the environment in several ways. Cars emit greenhouse gasses, such as carbon dioxide, which contribute to global warming. Some air pollutants and particulate matter from cars can be deposited on soil and surface waters where they enter the food chain; these substances can affect the reproductive, respiratory, immune and neurological systems of animals.

Despite vast research to formulate compatible fuels and engine oils to reduce emission and improved fuel efficiency, no such hardware has been developed to measure the viscosity of oil to reduce shear friction which exist almost in all parts. This directly affects the fuel consumption and thus emission. Experienced engineers and scientists tried to measure the film thickness using resistive and total capacitive technique but only with limited success.

Our research was aimed towards the development of a localized capacitive technique to measure the oil film thickness between journal and bearing. Circuits were developed and tested to ensure that the slightest change would register a notable change in the output voltage (the variation in capacitance was between 3 x 10^{-9} Farads and 18 x 10^{-9} Farads). The circuit was then implemented in an automotive engine, and the results were recorded to successfully calculate the eccentricity of the journal with respect to the bearing.

The process and results of our work are explained comprehensively in the report comprehensively. We have also filed a patent for the developed technique.

SECTION 2

LITERATURE REVIEW

SUB-SECTION 2.1

PAPERS REVIEWED

For the purpose of this project, 3 papers were taken into consideration. Details, along with the abstracts of these papers are mentioned below:

1. A comparison of the total Capacitance and Total Resistance Techniques for Measuring the Thickness of Journal Bearing Oil Films in an Operating Engine

   Bearing oil film thickness (BOFT) values were determined for the front main bearing of a four-cylinder engine at different engine speeds, loads and oil temperatures using two different measurement techniques. The total resistance technique assumes the oil film can be modelled as a simple ohmic resistor. The total capacitance technique assumes the oil film can be described as a simple capacitor. A comparison of results determined using both methods for a set of single-grade oils demonstrates that although the methods agree quantitatively for certain combinations of engine test conditions and oils, the level of precision with a total capacitance technique is greater than with the total resistance technique. This difference is attributed to the fact that the oil dielectric constant, which is needed for calculating BOFT values in the total capacitance method can be measured more precisely than the oil conductivity which is needed in the total resistance method. Of the two methods the total capacitance technique is superior for measuring bearing oil film thickness in an operating engine.

2. Oil Film Thickness in Engine Connecting Rod Bearing with consideration of Thermal Effects

The aim of this paper is to study the thermal effects on minimum oil film thickness in a connecting rod bearing. This method incorporated the total capacitive technique recorded in the previously mentioned paper. The results were analyzed with respect to changes in temperature, which is not covered in the scope of our project. The Minimum Oil Film Thickness (MOFT) over an engine cycle estimated with consideration of thermal effects is closer to that measures than that estimated by using the iso-viscous lubrication theory.

SUB-SECTION 2.2

COMMENTS

The circuits mentioned in both the papers above were first incorporated in our project. However, since our methodology incorporated a localized method, the readings of the voltages were too small for the circuit resulting in the capacitors getting saturated.

Subsequently, we had to develop a new circuit which enabled us to record capacitance from 3.5 to 20 Pico-farads. The development and implementation of this circuit is discussed later in this report.

SECTION 3

INTRODUCTION & THEORY

SUB-SECTION 3.1

COMPARISON BETWEEN CAPACITIVE AND RESISTIVE METHODS

Accurate measurements of the oil film thickness in a journal bearing of an operating engine have been the goal of bearing engineers for many years. Because of difficulty in measuring such small, rapidly changing dimensions, numerous different experimental techniques have been proposed to accomplish this objective. Many of these proposals have included the use of discrete probes or transducers located at various points around the circumference of the bearing. These probes have been designed to measure different physical quantities which change with the dimensions of the oil film, such as capacitance, magnetic fields, inductance and eddy currents. In the past two techniques were developed to measure oil film thickness.

Total Capacitive Method

Craig, King and Appeldoorn, and Girshick and Craig described the method which assumes the entire oil film as a capacitor. By properly insulating the bearing and assuming it to be circular, the minimum oil film thickness in the bearing at any point in time can be calculated from a capacitance measurement. This technique was referred as total capacitance technique.

Drawbacks:

- Measures only minimum oil film thickness (MOFT)
- Does not provide the variance
- Inaccurate readings

Total Resistive Technique

In an independent effort, Spearot, Murphy and Rosenberg measured the electrical resistance of the oil film to determine the minimum oil film thickness. This method was referred to as total resistive technique. This technique is a variation of the technique originally proposed by Bassoli et al. This method was used to determine those rheological properties of engine oils which effect bearing oil film thickness

Drawbacks:

- Higher reaction time
- Does not provide for the variance

In the above two methods for measuring oil film thickness in operating journal bearings, there is no requirement for placing any complex electrical transducers which are susceptible to failure within the engine. However, some of the old problems such as temperature effects on the electrical properties of the oils may still be significant. In addition, some new questions have to be addressed such as what happens to either the oil film capacitance or resistance signal when cavitations occur within a portion of the bearing film. Furthermore, there has never been an effort to determine whether any of these measurement techniques provide equivalent values for oil film thickness when used in the same engine bearing operating at fixed conditions on particular oil.

SUB-SECTION 3.2

THEORY BEHIND CAPACITIVE METHODS

In the capacitive methods, the shaft and the bearing are made to act as two ends of a capacitor. This capacitor is then incorporated in a circuit which then gives a variation in output voltage in response to a variation in capacitance.

The capacitance varies based on the two following governing formulae:

$$C \propto \frac{1}{d^2} \qquad \text{(Eq. 1)}$$

Where C is the Capacitance of the circuit and ‘d’ is the perpendicular distance between the two plates;

$$C \propto A^2 \qquad \text{(Eq. 2)}$$

Where ‘C’ is the Capacitance of the circuit and ‘A’ is the Area of a plate; in case of a difference in the areas of the two plates, the area of the smaller plate is to be considered.

SUB-SECTION 3.3

REASONING BEHIND LOCALIZED CAPACITIVE METHODS

Research till now has been conducted with Total Capacitive Methods. In such cases, the change in the total capacitance between the bearing and shaft is measured. This method however predicts only the variation in capacitance of the oil and fails to predict the behaviour of a shaft under varying conditions. Subsequently, the eccentricity cannot be simulated for detailed analysis of the lubricant.

In Localized Capacitive Methods, instead of the entire or half the bearing being charged, small points within the bearing are charged, at known angles to one another. These points are isolated from the rest of the bearing to prevent loss of charge to surroundings. The variation in capacitance at each point is recorded separately, giving multiple unique values of the capacitance at different points at the same time. Subsequent analysis of the data through data acquisition software and hardware can allow us to predict with reasonable accuracy the behaviour of the shaft in the bearing.

In our research, we incorporated 2 such points in the big end bearing of the connecting rod. Both these points were at 180 degrees to one another – this provided us a means to visually assess the accuracy of the data.

SUB-SECTION 3.4
THEORY BEHIND IMPLEMENTED CIRCUIT

The circuit can be split into 3 separate parts; a detailed discussion of each part is given below. The complete circuit is attached as Appendix A.

1. Capacitor

   This part of the circuit is linked to the external bearing, over which the variation of the oil film has to be measured.

2. Differentiator

   This part of the circuit converts the saw-tooth voltage into square-wave form. This subsequently allows us to digitize the data and hence increase the accuracy of the output.

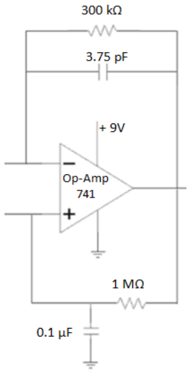

Fig 1 Differentiator Circuit

3. Filters

In our circuit, a Two-Pass filter has been incorporated. This allows us to remove the unnecessary noise in the circuit and hence smoothen the curve. This method has been suggested by for the same purpose Chao-Yu Chen et al. [1]allows us to achieve our requirement of removing the noise.

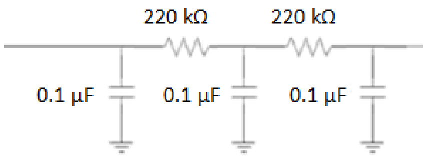

Fig 2 Filters

SUB-SECTION 3.5

ISSUES FACED

The project commenced in June 2012, with literature review throughout the summer break. Although we were largely able to meet our goals, we encountered problems at 2 points during the project:

1. During the proof of concept phase, we faced some difficulty in achieving the mirror finish essential to ensuring that the surfaces in consideration behaved like a capacitor. It must be kept in mind that since the variation in distance is only up to 40 Pico-meters, minor roughness can lead to a direct flow of charge between the two plates leading to the assembly failing to act like a capacitor.

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[1] Chen, Chao-Yu et al. (IEEE) (2009) *A Two-Pass Filter for Impulse Noise Reduction Based on Edge Characteristics.* Fifth International Conference on Intelligent Information Hiding and Multimedia Signal Processing

2. Due to the small magnitude of the changing variation, and the absence of any literature to record such small changes, we faced some problems. This was solved through the development of circuits with the help of Dr. Nabeel Anwar and the subsequent testing of those circuits to finally reach one which best suited our requirements.

However, for both these cases, we were able to solve the problems within the buffer time period we had kept for the project.

SECTION 4

METHODOLGY

The project was divided into two phases, both of which have been discussed individually below:

1. Phase I – Proof of Concept
2. Phase II – Implementation in Engine

These two phases have been discussed below individually:

SUB-SECTION 4.1

PHASE I – PROOF OF CONCEPT

This phase required us to prove the functionality of the system before installing it in an engine. For this purpose, we employed the following equipment

- Micrometer Screw Gauge
- Aluminium and Stainless Steel probes
- Stainless Steel and Aluminium wires (3 millimetres diameter)
- Acrylic (machined to specifications)
- Resistors, Capacitors, and ICs based on the circuit requirements

The process was carried out in the following manner:

1. Acrylic was machined to the dimensions specified in Appendix E. This machined product had one hole in which the aluminium probe was pressed-fit in. The other was supposed to be pressed fit on to the end of the spindle of the micrometer screw gauge.

2. Similarly, another acrylic was machined to the dimensions specified in Appendix E, and this machined product had one hole in which the stainless steel probe was pressed fit in. The other hole of the acrylic was supposed to be pressed fit on to the anvil of the micrometer screw gauge.
3. Holes of a diameter of 1 millimetre were drilled in to the sides of the acrylic towards the metal. Wires were then installed through these holes such that they could extract charge to and from the metal/acrylic surface.
4. The surfaces containing the probes were flushed to a surface finish in micro-meters. This gave us a mirror finish, allowing the acrylic and metals to have surfaces that were flat and level with one another.
5. These acrylics were then installed on to the micrometer.
6. The wires were then first connected to a LCR circuit to measure the capacitance between the two plates (and subsequently to a circuit to measure change in voltage, development of which is discussed later on in this section).
7. The distance between the two plates was then varied from a distance of 0 meters to 40 micro-meters and the changes in value in the capacitance (and voltage) were then recorded)

Simultaneously a circuit, to convert the capacitance into measurable voltage was developed. This circuit was developed after detailed literature review, which itself yielded in no suitable options to measure the variance in capacitance which was from 3.5 Pico-Farads to 19 Pico-Farads.

The detailed theory behind this circuit is discussed in Section 3, Sub-Section 3.3, while the circuit drawing is shown in Appendix A.

The same system detailed above was now connected to the circuit, which we had developed on a breadboard. Steps 1 through 5 remained the same, whereas in Step 6, the LCR meter was disconnected and the circuit developed was connected.

SUB-SECTION 4.2

PHASE II – INSTALLATION IN ENGINE COMPONENTS

For the second phase of the project, the system was tested through for its functionality on the components of an actual engine. Components of a *'Suzuki Mehran'* engine were procured – these components included a connecting rod, a crankshaft and suitable sets of bearings.

Detailed sequence regarding the execution of this phase is as mentioned below:

1. Two probes were installed in the big end of the connecting rod of the bearing (diagram attached). Both of these were installed at 180 degrees to one another – this allowed us to identify, with respect to one another, whether the output results are realistic or not. The aluminium probes of diameter 3 millimetres, were drilled into the bearing, and later flushed with the surface for a smooth finish. The Aluminium was electrically isolated from the rest of the bearing and attached to the circuit. Aluminium surface acted as one end of the capacitor, whereas the (charged) surface of the shaft acted as the other end.

2. The shaft and the aluminium, was connected to a Printed Circuit Board (PCB), made along the same lines as the circuit we had earlier developed.

3. A saw-tooth wave is given as input to the circuit. The differentiating part of the circuit converts the saw-tooth wave into a square wave. Further filters are employed to remove

ripples from the output (shown in Appendix A). The capacitance is therefore quantified as an analogue voltage signal.

4. This output is then entered into the National Instruments' USB 6009 (other data acquisition hardware may also be used), and subsequently fed into National Instruments' LabVIEW software (alternatives may also be used). The software then takes the data, and averages it out so as to give proper variation in voltage based on the variation in capacitance, which is in result to the change in distance between the bearing and the shaft.

5. The addition of more probes is employed for increased accuracy, but also to find out eccentricity of the shaft from the bearing. For said purpose, the outputs from all the probes are fed into the same software. After separately averaging each other out, the results are fed into an equation which calculates the eccentricity based on the angles between the probes.

SECTION 5

EXPERIMENTS UNDERTAKEN

Four experiments were undertaken in the following order

Phase I

1. In order to identify the relationship between the capacitance and the distance between two parallel plates (Aluminium and Stainless Steel), machined acrylic was installed on the micrometer and connected to a LCR Meter (as described in Section 4 – Phase I), and the distance were adjusted from zero to 40 micro-meters. The subsequent capacitance was then recorded. (Results in Section 6.1)

2. In order to indentify the relationship between the capacitance and the output voltage, the machined acrylic was then connected to the circuit (Appendix A). The changes in the output voltage were then recorded via a digital oscilloscope. (Results in Section 6.2)

3. In order to indentify the relationship between the distance and the output voltage, the machined acrylic was then connected to the circuit (Appendix A). The changes in the output voltage were then recorded via a digital oscilloscope. (Results in Section 6.3). this served as the standard calibration based on which future results were to be examined.

Phase II

4. In order to test the functionality of the system, the system was installed on a connecting rod and the crankshaft. Subsequently, the system was subjected to dynamic conditions and the output was analyzed. The circuit was connected to DAQ hardware (National Instruments' USB 6009 in this case) and after processing the output via a software (National Instruments' LabVIEW Software in this

case), the results were exported to a Microsoft Office Excel Sheet and analyzed. (Results in 6.4)

The experiments mentioned were carried out at different times and under different conditions to check reproducibility and reversibility.

SECTION 6

RESULTS

SUB-SECTION 6.1

In line with the experiment highlighted in 5.2, the results are as follows:

Distance (Micrometers)	Minimum Capacitance (pF)	Maximum Capacitance (pF)	Average Capacitance (pF)
0	Over	Over	Over
5	17.5	19.1	18.3
10	10.9	12.2	11.55
15	7.2	8.4	7.8
20	5.5	6.7	6.1
25	4.8	5.1	4.95
30	3.7	5	4.35
35	3.4	4.4	3.9
40	3.3	4	3.65

Tab 1 Relationship between Distance & Capacitance

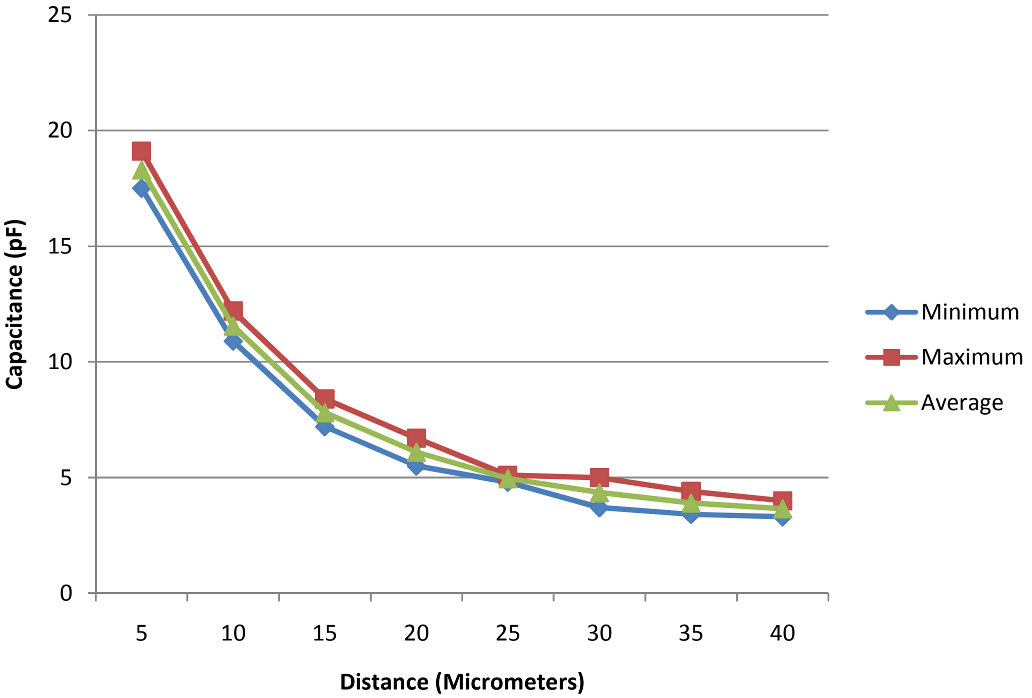


Fig 3 Relationship between Distance & Capacitance

SUB-SECTION 6.2

In line with the experiment highlighted in 5.1, the results are as follows:

Inputs	f = 10 kHz V_{in} = 5.45 V V_{CC} = 15.5 V $-V_{CC}$ = -15.5V

Capacitance (pF)	Minimum V_{out} (V)	Maximum V_{out} (V)	Average V_{out} (V)
4.27	7.56	7.62	7.59
4.70	7.44	7.52	7.48
5.22	7.32	7.41	7.365
5.88	7.25	7.31	7.28
6.71	7.05	7.19	7.12
7.83	6.93	7.04	6.985
9.40	6.77	6.92	6.845
11.75	6.53	6.83	6.68

Tab 2 Relationship between Capacitance & Voltage

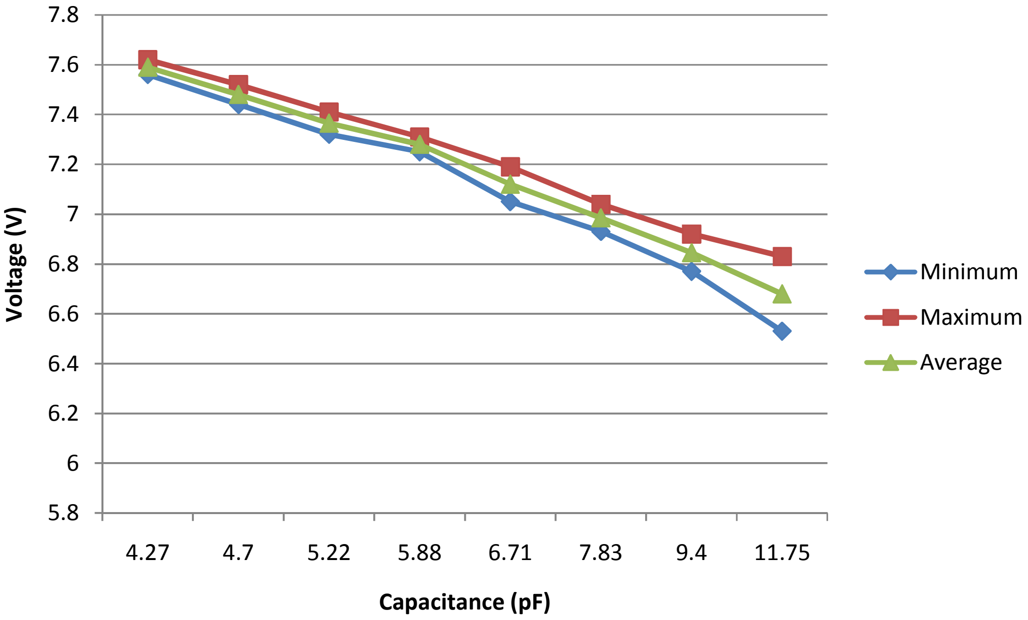


Fig 4 Relationship between Capacitance & Voltage

SUB-SECTION 6.3

In line with the experiment highlighted in 5.3, the logged data gave the following results:

Distance (micrometers)	V_{out} Reading 1	V_{out} Reading 2	V_{out} Reading 3
10	3.1	3.09	3.09
20	1.75	1.748	1.75
30	1.697	1.70	1.698
40	1.68	1.67	1.67

Tab 3 Relationship between Distance & Voltage

Fig 5 Relationship between Distance & Voltage

SUB-SECTION 6.4

In line with the experiment highlighted in 5.4, the connecting was rotated over 360 degrees, and the results recorded were as under:

Angle	Probe 1	Probe 2
0	1.868	3.12
13.33	1.873	3.12
26.66	1.885	3.12
39.99	1.933	3.065
53.32	1.967	3.101
66.65	1.99	3.083
79.98	2.014	3.076
93.31	2	3.117
106.64	2.042	3.076
119.97	2.072	3.058
133.3	2.079	3.005
146.63	2.135	2.857
159.96	2.194	2.786
173.29	2.234	2.783

186.62	2.255	2.85
199.95	2.278	2.873
213.28	2.305	2.877
226.61	2.325	2.896
239.94	2.317	2.9
253.27	2.309	2.899
266.6	2.31	2.893
279.93	2.333	2.883
293.26	2.356	2.873
306.59	2.368	2.838
319.92	2.38	2.805
333.25	2.402	2.749
346.58	2.421	2.802
359.91	2.407	3.12

Tab 4 Results from Engine Components

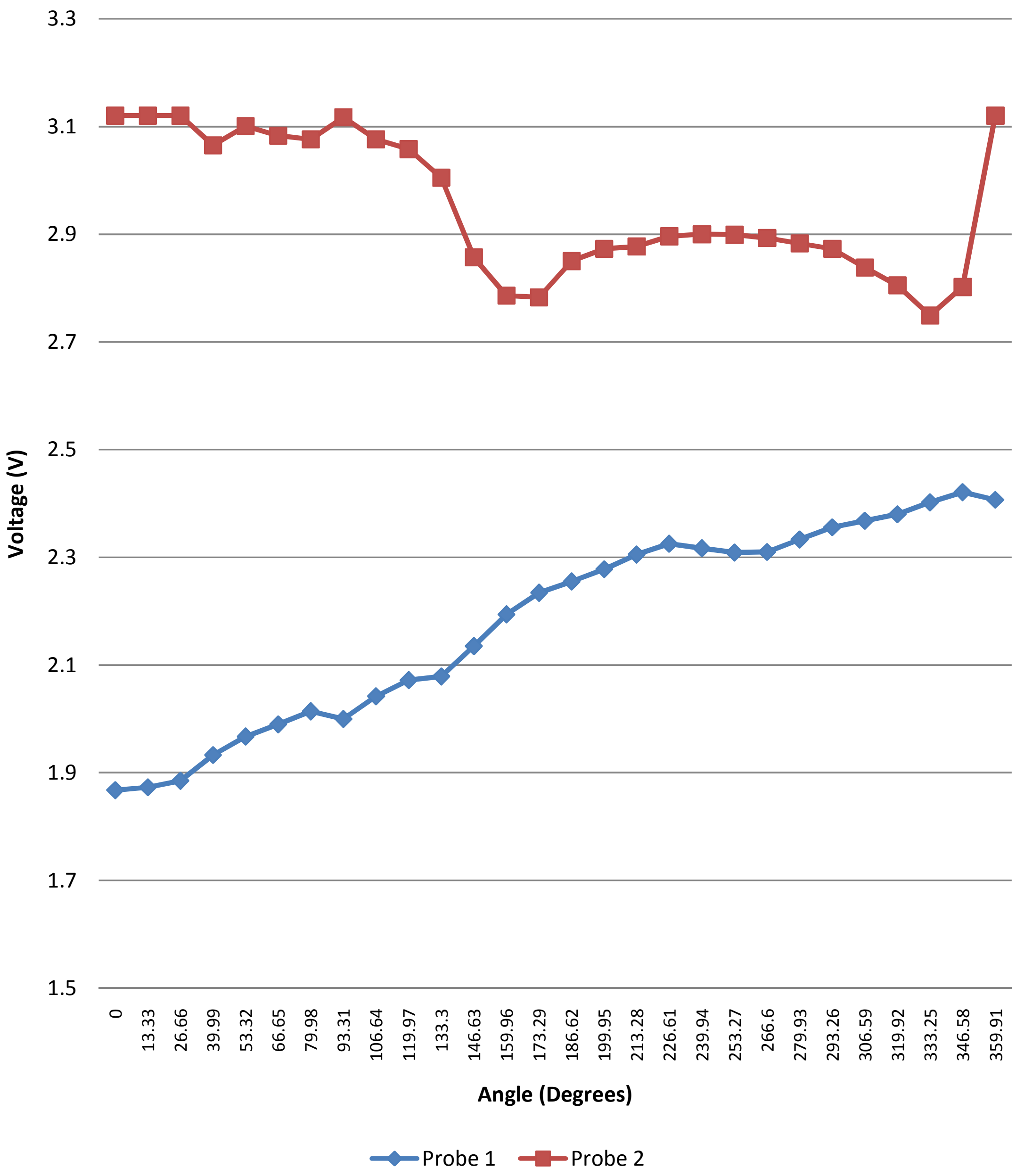


Fig 6 Results from Engine Components

SECTION 7

ANALYSIS

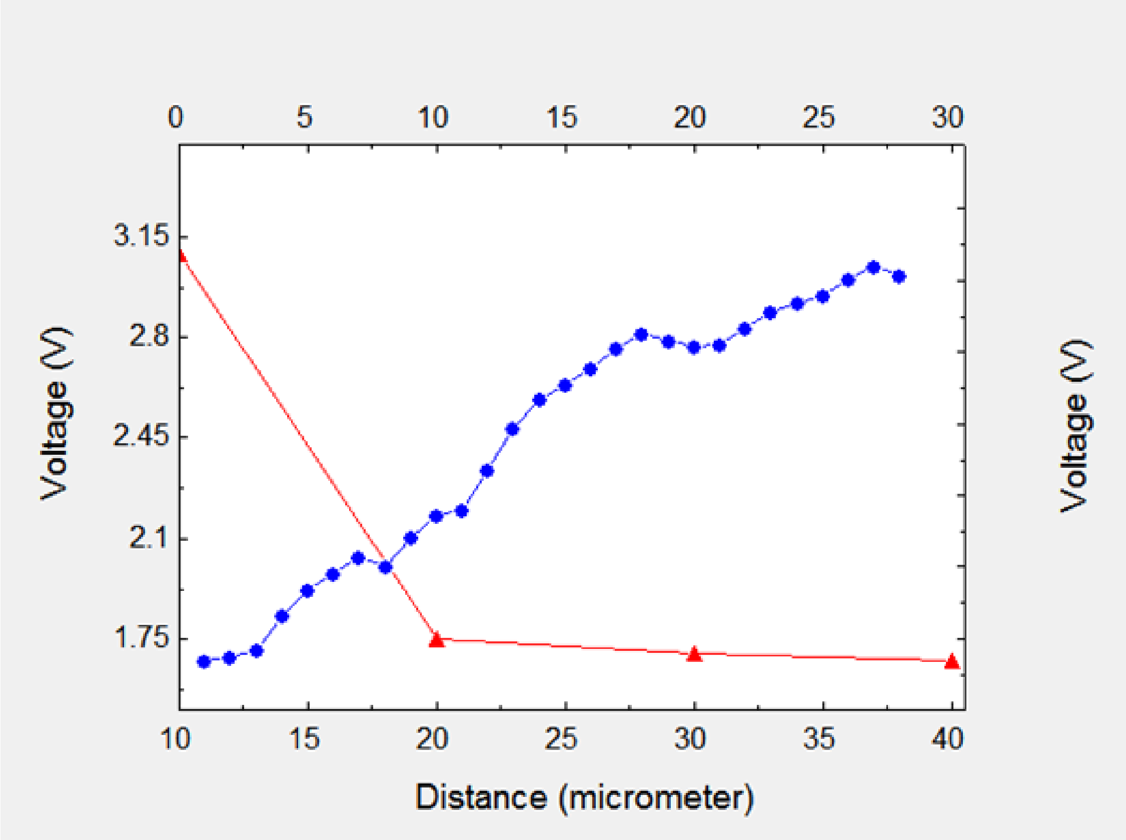
SUB-SECTION 7.1

RESULT ANALYSIS

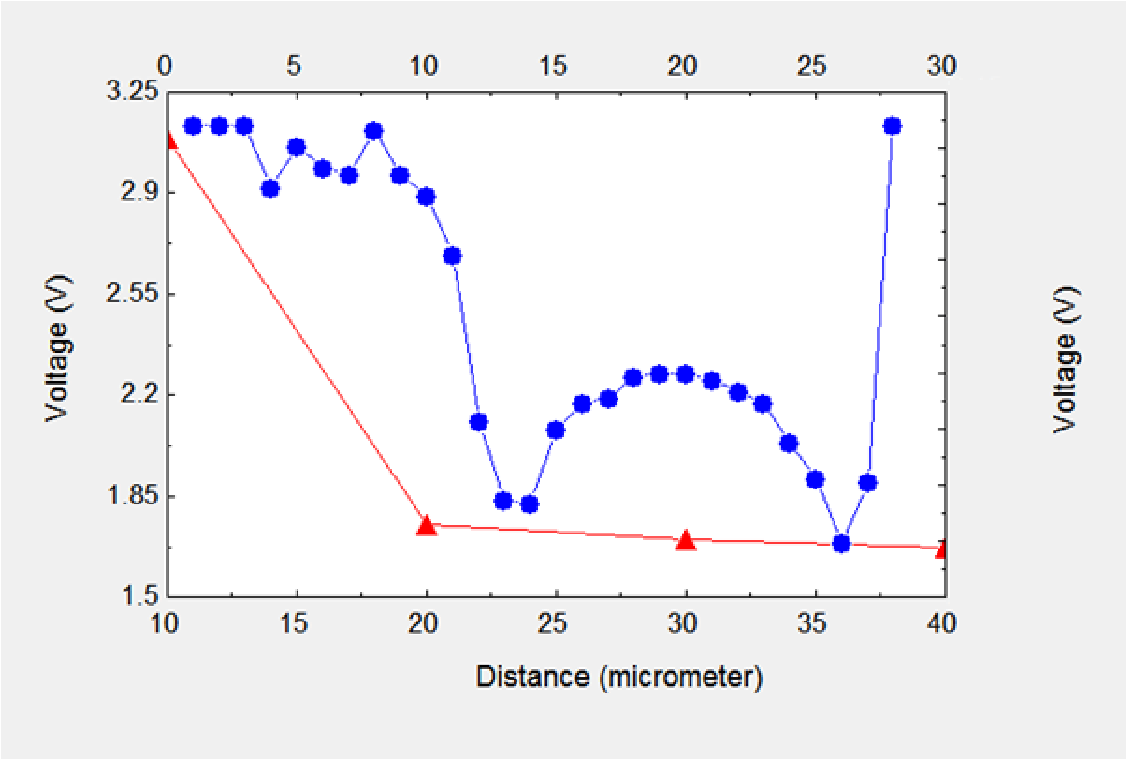
In line with The data obtained can now be converted to predict the behaviour of the shaft with respect to its distance from the journal bearing.

Using our previously established relationships, the variation in the results can now be mapped together with the calibrated results to find out the clearance at particular instances of time. These results are shown below:

For Probe 1:



For Probe 2



SUB-SECTION 7.2

COMMENTS

Both probes were installed at 180 degrees to one another (opposite sides on a bearing), and the inverse relationship of the results of these two, reinforces the accuracy of our results. Probe 2, however exhibits some fluctuations to the trend. These can be attributed to two factors:

- Low pressure of oil, as the oil was fed manually
- Probe 2 was vertically above Probe 1 and so the effect of gravity was much more significant

SECTION 7

CONCLUSION

The technique developed above is an innovative method of calculating the oil film thickness. The results from the probes, installed at 180 degrees to one another, show that the results from one probe compliment the results from the other. This can be easily derived from the fact that the relationship between the two results is inverse – as one increases the other decreases. This testifies the accuracy developed in our method.

This system developed has set the basis for detailed research, with increased accuracy to understand the behaviour of journal bearings by scientists & engineers.

Future Recommendations

The Localized Capacitive System can be used by the Lubrication Industry to predict the oil film behaviour in engines under dynamic conditions. This will facilitate the industry in the development of low viscosity lubricants for engines to reduce shear friction which exists in almost all parts of the engine. This will have a direct effect on fuel consumption and thus emissions.

The Localized Capacitive System is an important general purpose film thickness measuring system for research and industrial point of view. Some future areas are:

- Measuring the Eccentricity of Shaft
- Mapping the film thickness for different lubricants
- Predicting the viscosity of lubricants from film thickness

We would also like to highlight that a patent has been filed for the method mentioned above **(*“Oil film thickness measurement system for engine journal bearings using localized capacitive technique”* Patent Application Number: 188/2013).**

SECTION 9

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