MEASUREMENT OF CLEARANCES USING CAPACITIVE PROXIMITY SENSORS IN TURBINE ROTOR STATOR CAVITIES

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ABSTRACT

Experimental displacement measurements are to be made using in-house designed and manufactured capacitive proximity sensors inside the Sussex Rim Seal, RiSe, Rig. Currently prototype sensors have been tested to understand the significance of measuring clearances when a sensor is responsive to both radial and axial movement of a component. The results presented here show how the signal from a sensor designed to measure displacement of a parallel target, changes as the orthogonal distance to the target is also altered. A two-sensor (orthogonal axis) approach has been adopted, calibrated and tested in a mock-up geometry. The measurement accuracy has been shown to have increased to within 0.05mm.

NOMENCLATURE

A – Sensing Area
C – Capacitance
d – Distance from sensor to target
x – Axial displacement
y – Radial displacement
ε_0 – Permittivity of air

1. INTRODUCTION

Measurements of seal clearances and gaps between rotating blade tips and their casings are highly important in gas turbines. This is because any contact between rotating and stationary surfaces could cause damage to the engine, or even cause it to stop. These distances can either be checked by the use of rub pins or monitored during operation by displacement sensors.

The RiSe Rig requires the location of the turbine disc to be monitored during operation in both axial and radial directions. This is to avoid contact and ensure safe working during testing. In the case of a successfully completed test the measured clearances could also be used to set-up geometry for computational analysis to improve the accuracy of results.

The previous build of the RiSe Rig was a 2-stage axial turbine and the axial and radial position of the rotor was measured using commercially available displacement sensors [1]. As can be seen in Figure 1, the axial sensor was located downstream of the second stage rotor and the radial sensor in the turbine stator well.

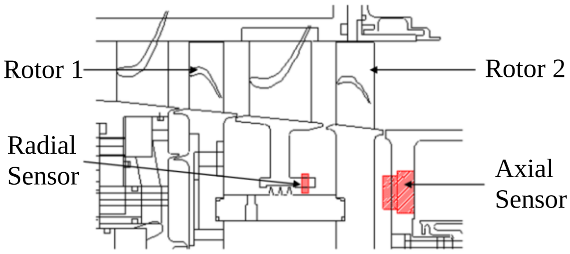

Figure 1 – Previous build of the RiSe Rig showing the locations of the Eddy Current sensors used. [1]

The main objective of the work described here in this paper is to develop a system that can accurately measure axial and radial positions of the disc at various circumferentially spaced locations, at a low cost. The system should also have an accuracy of 0.05mm or better.

2. DISPLACEMENT MEASUREMENT SENSORS

Two of the most common technologies that are used to measure displacement are either Capacitive or Eddy Current type systems. Both can be bought off the shelf by companies such as Micro-Epsilon or Lion Precision.

For the RiSe Rig, the sensors to measure these displacements could either be positioned in the rotor stator cavity, or the cavity that is downstream of the rotor. In the rotor stator cavity all measurement probes should not cause any obstructions to the flow as this will change the flow physics. However, for the downstream cavity it doesn't matter if the probes cause a disturbance to the flow, so they could be protruding from their mounting component.

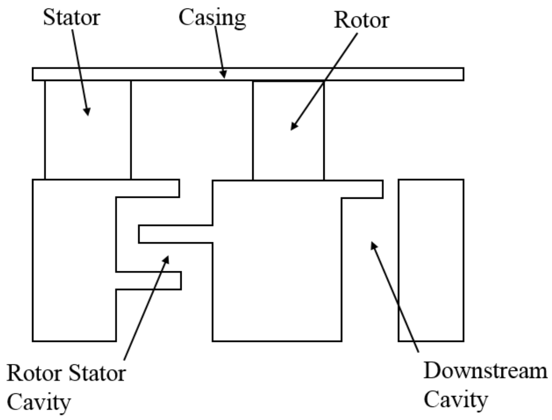

Figure 2 – Simplified cross-section of the RiSe test section, showing the location of the two potential instrumentation areas.

2.1 EDDY CURRENT SENSORS

An Eddy Current sensor uses the principle of supplying a coil with an alternating current that causes a magnetic field to be formed around it. If this is placed close to an electrically conducting metallic object, then eddy currents will be induced and these will form an electromagnetic field. This field interacts with the magnetic field of the coil and causes a change of impedance in the coil [2]. The data acquisition system that is connected to the sensor will measure this change of impedance and convert it to the measured distance between the sensor and the target.

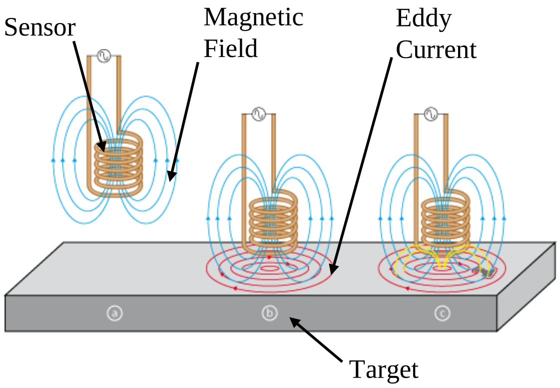

Figure 3 – Diagram showing the operating principle of a basic eddy current sensor. [3]

Due to the working principle, each sensor has to be paired with a data acquisition device which excites the sensor and records the measurement. The sensors available commercially have a very high accuracy and can measure to a precision of 0.025µm. A wide variety of different size and shape sensors are available on the market that can be used for ranges between 0.5mm up to 80mm. One aspect to consider is that the size of such sensors are inherently linked to the measurement range. One example is the Micro-Epsilon U15 which has a 15mm range. However this sensor has an outside diameter of 37mm so would not be usable within the rotor stator cavity. There is limited space available to install a sensor for radial displacement in the vane platform. The sensor needs to be smaller than 2mm thick and 5mm diameter. There is a commercially produced sensor that could be used to measure the radial height in the rotor stator cavity, however this only has a range of 0.5mm and also requires a target that is at least a diameter two times bigger than the diameter of the sensor [4]. There is a large selection of potential commercially produced sensors that are small enough to be used within the downstream cavity, but this is not the current intention.

2.2 CAPACITIVE SENSORS

A Capacitive sensor uses the principle that two conductive (metallic or non-metallic) surfaces within a close distance of one another will have a capacitance. As the two surfaces are moved closer or further apart this capacitance will change. This change of capacitance can be measured using a data acquisition device that can convert the resulting voltage output to a number.

The capacitance, C, between two surfaces can be calculated using the following formula:

$$C = \frac{\varepsilon_0 A}{d}$$

Where ε_0 is the permittivity of air, A is the sensing area of the sensor and d is the distance of the sensor to the target.

As with the Eddy Current sensors, Capacitive sensors could also be sourced commercially. Figure 4 below shows a typical capacitive sensor that can be used for a range up to 20mm. This sensor has a resolution of 7.5nm at 2 Hz up to 200nm at 8.5 kHz. The size of these sensors would mean that they would need to be located in the downstream cavity like with the eddy current sensor option that was mentioned earlier.

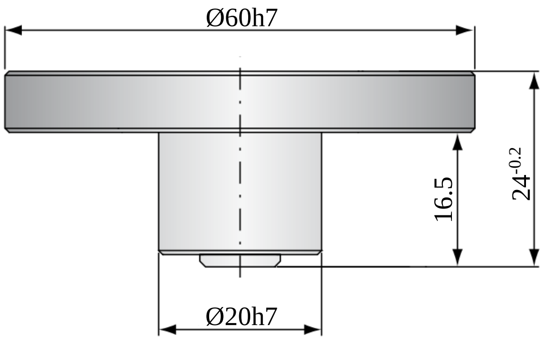

Figure 4 – Side view of an example commercially available Capacitive sensor. [5]

One of the main advantages of a Capacitive sensor is the simplicity of its design. As it only requires the sensor pad and guard to be manufactured from a conductive metal, then these can be of any shape or size required. If commercially available sensors were purchased, the shape would most likely be circular, however if they were manufactured in-house they could potentially be designed to fit the geometry of the rim seal. This would mean that the overall size of the sensor could be reduced as the distance to be measured is decreased.

The in-house manufactured Capacitive sensors would be used with custom designed signal conditioners that are locally made at lower costs but with reasonable accuracy.

2.3 ALTERNATIVE TECHNIQUES

Other techniques to measure displacements include using Laser Transducers or Rub Pins.

The Turbine Test Rig reported by Sangan, et al. [6] used Laser Transducers to measure the deflection of their rotor disc. The air supply that they use is provided by an electronically driven compressor, so the temperatures within the rig are much lower than what will be seen in the RiSe Rig. Due to the issue of operating temperature, this technology was not considered for use within the RiSe Rig.

The other alternative to use is Rub Pins, these have the main advantage that cost will be negligible for installation and there is no requirement for any data acquisition. However, as there would be no measurements during operation of the RiSe Rig this technique was also not considered.

2.4 TECHNOLOGY COMPARISON

The RiSe Rig could use either Eddy Current or Capacitive sensors to monitor the position of the rotor disc.

If Eddy Current sensors were chosen, then they could only be mounted on the downstream face of the rotor disc, as it would not be possible to fit them in the rotor stator cavity due to the size of sensor required to measure the displacements. As each sensor is paired with a data acquisition box the cost of a system for six probes would be several thousand pounds.

If Capacitive sensors were sourced commercially, then they would have a similar performance and cost to the Eddy Current option. However, another option is that the sensors are manufactured in-house, and the electronics data acquisition equipment could be manufactured locally. This would mean that the sensors could be designed to fit in the geometry of the rim seal, so could be used in the rotor stator cavity. The cost to manufacture the sensors themselves will be negligible. This system would be able to measure 12 simultaneous capacitive sensors, and also includes the electronics to measure a high frequency blade tip probe, for a total of 13 sensors. The main issue with this system is that the sensors will need to be designed, tested and calibrated. Also, depending on the design of the data acquisition system, the accuracy of the measurement may not be as good as the off-shelf options, but could be within required limits.

Comparing the three different options the two commercial available alternatives would produce accurate results, however it would not be possible to instrument them in the rotor stator cavity and therefore the rim seal gaps would need to be estimated, hence possibly reducing the accuracy. The other main issue is the cost, as a system that has six sensors would cost up to a few tens of thousands of pounds. Therefore, it is decided that the best option is to manufacture the sensors in-house and locally produce the data acquisition system.

The Capacitive sensors when mounted in the rim-seal static wall will be close to wall-surfaces that are both parallel and orthogonal to it. This means that the measurement will be affected by both the axial and radial position of the seal. However, radially above the axial seal will be positioned the radial sensor, so by using both measurements it should be possible to calculate the displacements of both directions.

3. SENSOR DESIGN AND CONSTRUCTION

A mock rim seal was manufactured to test the sensors, it was decided that this should be made from laser cut MDF, due to the availability of material and ease of manufacture. The MDF that was used is 6mm thick, so a rectangular sensor was designed that would use the available space. Figure 5 shows the design of the sensor's sensor pad and guard. By calculating the area of the sensor pad it can be found that if this were a circular design it would have a diameter of 3mm. This would mean that if it was a commercial design the range would be set to under 1.5mm [7]. This is because the output of the sensor is linear when the distance to the target is in this range, however as this increases the output becomes non-linear. This won't be an issue as the data processing will be able to calibrate for any output.

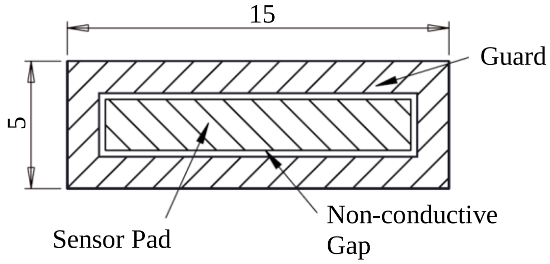

Figure 5 – Design of the sensor.

The sensors are manufactured from double-sided copper circuit board on a Roland MDX 540 3 axis CNC Milling Machine. The manufacturing process is very simple, with the first step to remove the copper between the sensor pad and guard using an engraving tool. A cylindrical cutter is then used to produce the gap around the edge of the guard and finally to cut the complete shape out of the stock material. Afterwards a pillar drill is used for the holes through the sensor. Figure 6 shows one of the sensors before it has been soldered to a cable.

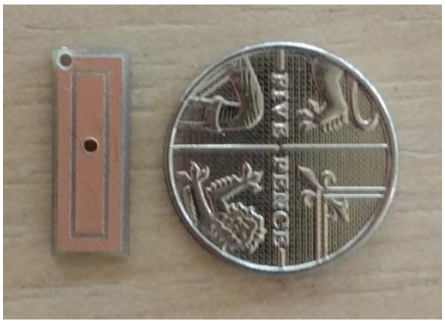

Figure 6 – Sensor after CNC manufacture.

A co-axial cable is used to connect the sensors to the data acquisition electronics. The core of the cable is soldered to the sensor pad, and the earth is connected to the guard. Figure 7 shows a cross-section of the sensor. Two holes are drilled through each sensor; one goes through the sensor pad and the other goes through the guard. A small wire is fed through the hole in the guard to connect the two layers of copper together. This helps to shield the sensor pad.

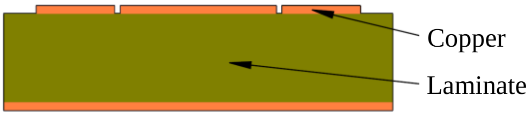

Figure 7 – Cross-section along the length of the sensor design.

4. EXPERIMENTAL SETUP

To accurately calibrate both sensors it is essential that their position relative to the target can be set and controlled. Since accurate positioning is easily possible with the CNC machine's XYZ control pad, it can also be used to calibrate the sensors. Figure 8 shows the position of the two sensors and their relation to the target. Both of the sensors are instrumented into the laser cut MDF similarly to how they will be mounted in the rig component with the surface flush with the wood. The radial movement of the sensor to the target is controlled using the X-Axis of the CNC and the axial movement is controlled using the Z-Axis. The CNC mill allows for movement of 1μm in all directions and has a repeat accuracy of ±0.05mm when under no load conditions.

The target is an aluminium bar that is stuck to the bed of the CNC mill and the mock stationary part of the rim seal is connected to the spindle.

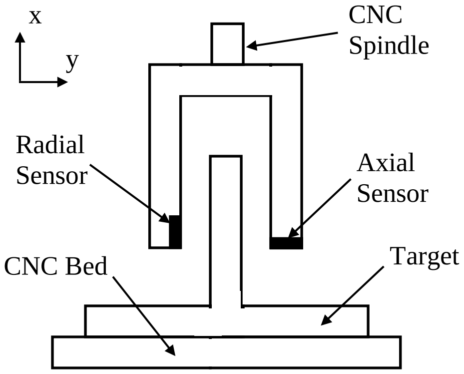

Figure 8 – Diagram showing a cross-section of the setup.

The sensors are both connected to a data acquisition system that converts the measurement of capacitance to a 12-bit resolution decimal count. A computer is used to monitor and record the data from the calibrations by using National Instruments LabVIEW code. This can record the data at a frequency of up to 10 Hz, which is exported to MATLAB for analysis.

5. RESULTS

Single or dual axis calibration of the sensor is possible. As the measurements from both the axial and radial sensors will be affected by component surfaces that are parallel and perpendicular to them, a calibration using both axis must be completed. To understand how this calibration will improve the measured result, it is compared against a single axis calibration.

5.1 TWO AXIS CALIBRATION

The two sensors are calibrated together by altering the axial and radial position of the target. The target and the sensor are separated by between 1mm and 5mm along both the axes, and the target is moved in increments of 0.2mm. From this a contour map can be created, as seen in Figures 9 and 10. For both sensors the axial and radial displacement refer to the same position of the target. Therefore, for the axial sensor, the radial displacement refers to the distance of the radial sensor to the target, and the opposite is true for the radial sensor.

Figure 9 shows the response of the axial sensor to variation in axial distance from the target. It is seen that when the axial sensor is close to the target in the axial direction, there is little effect of the proximity of the radial target to it. However, when the axial displacement increases, the proximity of a surface in the radial direction has a greater effect on the measured value. A similar response is also on plotting the response of the radial sensor, however it is the axial proximity that affects the measurement of the radial displacement.

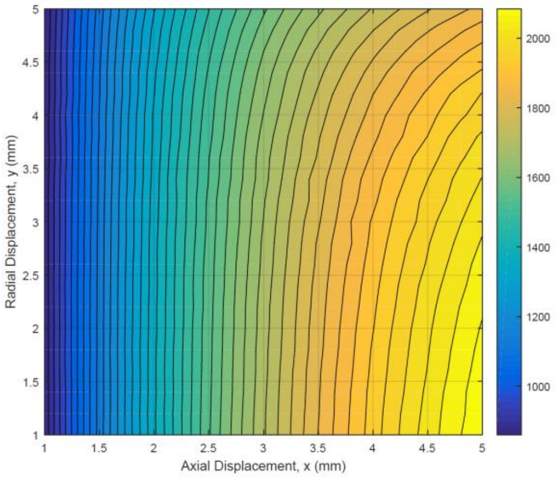

Figure 9 – Contour map of the axial sensor for digital count against radial and axial displacement.

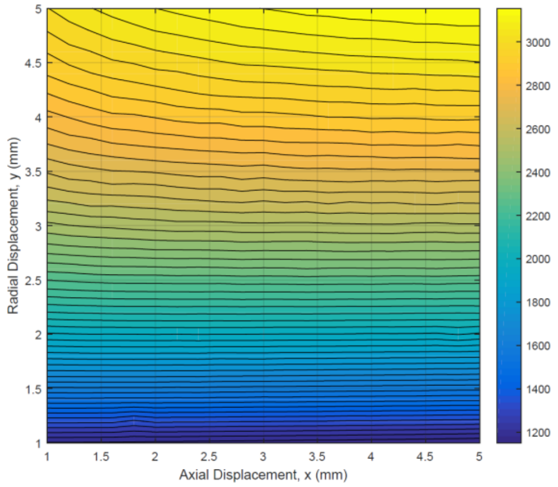

Figure 10 – Contour map of the radial sensor for digital count against radial and axial displacement.

5.2 DATA CONVERSION

The two contour maps can be used together to calculate the positions of the two sensors from their measured values. If only one sensor is used then it would not be possible to accurately calculate the position of the target that is orthogonal to it especially when the distance of the target surface in the primary sensing direction is large. When the target is positioned in the confines of the two contour maps, the locations of the two sensors should be unique.

Figure 11 shows a number of measured points and the axial and radial positions from the two sensors. This graph is produced by comparing the two outputs of the sensors, and finding a measurement that matches the output using the calibration plots shown in figures 9 and 10.

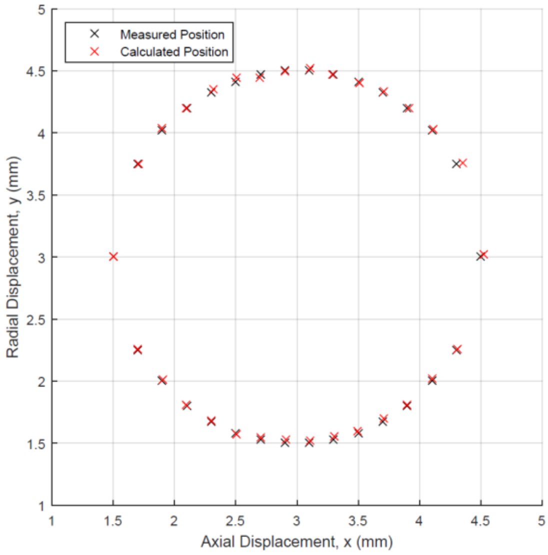

Figure 11 – Comparison between measured and calculated locations of axial and radial displacement.

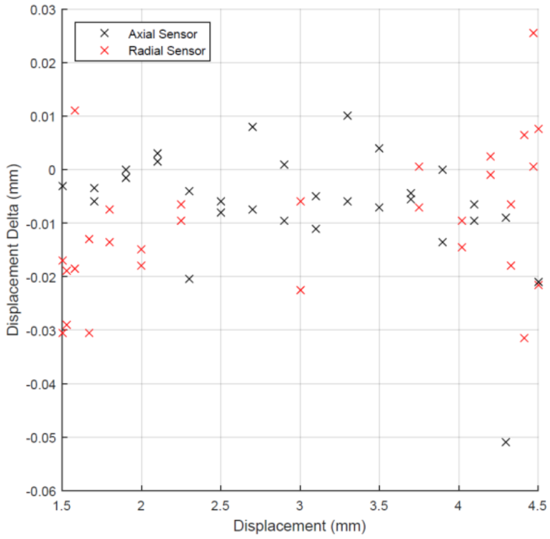

Figure 12 – Delta between measured and calculated displacement.

Figure 12 shows that as the displacement increases there is apreciable difference between the measured and calculated displacements. The average errors are 0.008mm and 0.014mm for the axial and radial sensors, respectively. Note that the accuracy is dependant upon the position during calibration. The calibration derived numbers suggest that the CNC machine's positioning accuracy is much better than 0.05mm as mentioned earlier.

5.3 SINGLE AXIS CALIBRATION

To understand how the double axis calibration improves the measurement of the axial sensor, a comparison is done against a calibration of a single axis.

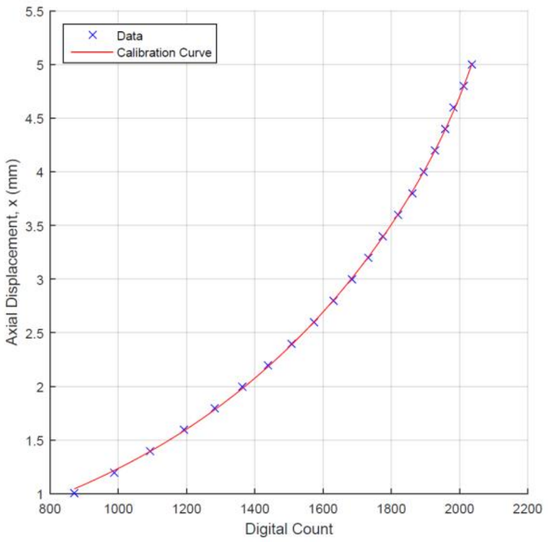

Figure 13 – Single axis calibration of the axial sensor.

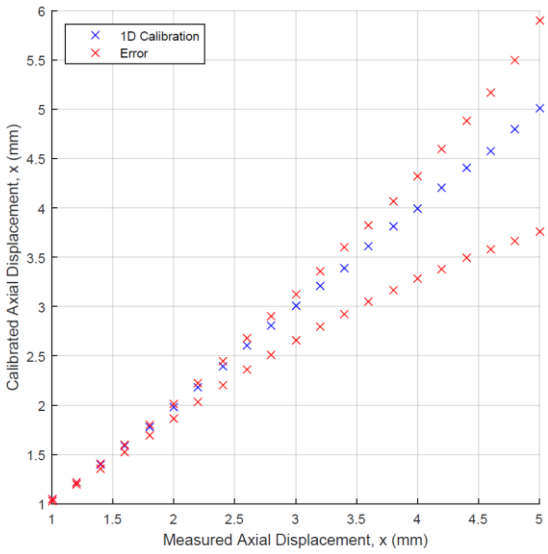

Figure 15 – Error between the single axis calibration and maximum and minimum measurements of the double axis calibration.

Figure 13 shows a single axis calibration with z-axis data extracted from Figure 9. The radial position of the target to the sensor is approximately mid-way between the upper and lower bounds. At this location, the output of the sensor gives an average resolution of 0.003mm.

The calibration curve that is produced can be used with the complete dataset of the double axis calibration to see how the calculated displacement changes for different radial positions.

From Figure 15 it can clearly be seen that the error increases as the axial displacement increases. At a measured displacement of 2mm there is an error of approximately 0.25mm with a worst error of just over 1.5mm at 4.4mm. This clearly shows that a single axis calibration should only be used for the first 1mm of displacement.

The worst error of the dual axis calibration is 0.05mm at a distance of 4.3mm from the target, which shows that it is a far more accurate technique than using a single axis calibration. This error can be improved by using a higher fidelity approach to the data conversion which should reduce it to within the resolution.

6. CONCLUSION

This paper has described the development of a system that can measure displacements using capacitive proximity sensors where a sensor is sensitive to displacement of a target in two planes.

The developed system meets the set objective of being low cost and also providing an accuracy of 0.05mm or better.

The results presented show how the position of a sensor designed to measure a displacement of a target in the parallel plane, is affected by the proximity of the target in the orthogonal plane. An improvement in error of 1.45mm was found for using a dual axis calibration compared with a single axis.

ACKNOWLEDGMENTS

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