

# HIGH TEMPERATURE EDDY CURRENT SENSOR SYSTEM FOR TURBINE BLADE TIP CLEARANCE MEASUREMENTS

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## ABSTRACT

A new high temperature eddy current sensor has been developed for application in turbomachinery tip-timing and tip clearance measurements to assess blade vibrations. Present industrial standard sensors used in tip timing systems such as optical, capacitance, Hall effect etc. are unable to operate at elevated temperatures  $> 400^{\circ}\text{C}$  for long durations without active cooling and these sensors are not sufficiently robust to withstand the harsh environment. Eddy current sensors are found to be a good alternative and are currently being used for gas turbine health monitoring applications at low temperatures, for example in the first stage of compressors and in the low pressure section of steam turbines. The newly developed sensor is a modified version of the eddy current sensor that is able to operate at high temperatures of about  $800^{\circ}\text{C}$ . The sensor can be used to measure stator-rotor clearances in shaft seal applications, or in a turbine stage of a gas turbine engine where the temperatures are significantly higher. This paper presents the characteristics of the high temperature eddy current sensor, driving electronics and various validation results. The experiments were carried out on a rotor with blades and flat sectors simulating a stator/rotor seal to measure tip clearances. The sensor system is demonstrated at varying temperature intervals starting from room temperature to over  $800^{\circ}\text{C}$ . Comparisons are made against an existing industrial standard capacitance sensor system up to  $250^{\circ}\text{C}$ . The results show good agreement between the eddy current and the capacitance probe for the flat sectors over the temperature range, giving credence to the eddy current probe data, but that the eddy current probe achieves a more accurate, repeatable and reliable measurement for the blades, as well as extending the temperature range. The eddy current sensor is immune to dust, dirt, oil and water contamination and therefore is considered a better solution than the capacitance sensor.

## INTRODUCTION

Tip-timing and tip clearance measurements are an important area of research in gas turbine health monitoring. These techniques help in the detection of failure and prevent unnecessary downtimes as well improve safety. This ensures timely maintenance and hence reduction in

costs to replace failed components. Gas turbine blades are subjected to vibrations caused by dynamic loads such as rotor imbalances, varying blade tip clearance due to non-concentric casings, distortions in the inlet flow (caused by irregular intake geometries). The damage on the blade can lead to aerodynamic forcing causing high cycle fatigue which has a major impact on safety and whole life costs. Detection of the changes in blade vibration modes and levels due to damage or deterioration would allow improvements to the inspection, repair and replacement process.

Currently there are various methods for tip-timing and tip clearance measurements that comprises, optical probes, eddy current, capacitive, Hall effect sensors etc. [Flotow et al., 2000, Lattime and Steinetz, 2009, Vakhtin et al., 2009, Hafner et al., 2011]. All these sensors measure the arrival time of the blades and some can measure the tip clearances (for example eddy current and capacitance). The arrival times and tip clearances can be explained as follows. In the absence of any form of vibrations, the time for the tip of a particular blade to reach the probe is dependent on the rotational speed alone. However, when the blade is vibrating, the blade arrival time will depend on both the amplitude and frequency of the vibration. The amplitude of the signal will provide the tip clearance which allows how close the blade is to the casing to be evaluated. Tip clearance measurements are quite important as there are tight tolerances between the blade and the casing which has to be maintained to achieve optimum efficiency.

Most of the sensors available in the market are mainly used for research and development purposes and have limitations of measuring only tip-timing, but not tip clearance (such as optical, reluctance etc.). The eddy current sensor however is able to measure both tip-timing and tip clearance and is found to be robust and immune to contaminations [Chana and Cardwell, 2008]. These sensors are already in use to monitor the health of gas turbine power plants on first stage compressor blades and on the last stage of steam turbine blades. The other limitation with the sensors available in the market are that they are not suited for high temperature applications as most of them can be used at a maximum temperature of about 300°C. Due to this limitation, they cannot be used in the turbine stage of a gas turbine engine where high temperatures are encountered. Cooling systems can be incorporated, however, they will add unnecessary weight and complexity to the system. This is not favourable in an aircraft as additional weight means added fuel consumption and increased cost of running.

In this paper, we look at a new high temperature eddy current sensor developed at the University of Oxford for tip-clearance applications to be used in turbine stages of a gas turbine engine. The sensor is compared with an existing industrial capacitance probe to show its performance against an industrial standard sensor system.

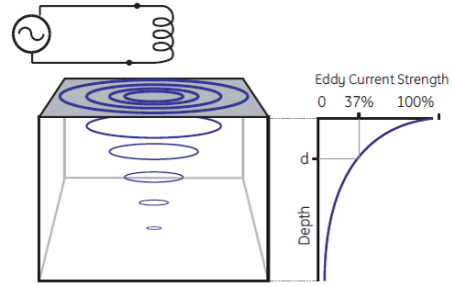
## **Experimental setup**

The experimental setup consists of a rotor and casing made with Inconel 625 as shown in Fig. 2a. All parts are sprayed with Boron Nitride ( $< 10\ \mu\text{m}$  thick) to reduce corrosion and fusion that can occur at high temperatures. The rotor had a nominal diameter of 100 mm. The rotor design incorporates 4 identical flat tipped blades whose tips are at a constant radius of 50 mm to help determine the spatial characteristics of the sensors. Six sectors of continuous radius at 50, 49.9, 49.8, 49.6, 49.0 and 48 mm are incorporated to test unmodulated rotating surfaces called “lands”. The “lands” simulate a stator/rotor seal in a gas turbine engine and are incorporated into a single rotor to minimize the experimental runs. Vertical axis is used to simplify motor drive to the rotor from outside of the furnace that has a PWM (pulse width modulation) DC drive motor and control. The drive shaft is a composite made of  $\text{Al}_2\text{O}_3$  ceramic

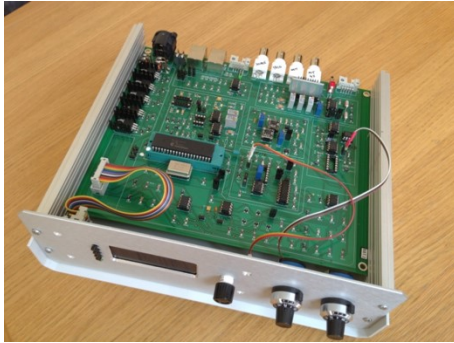
and Inconel 625 that is designed to be tolerant to high thermal differentials and high surface temperatures at rotating interfaces. The torque supplied to the rotor is controlled by the current and a slipping clutch. For smooth torque delivery, belt drive and a double bearing block mounts on the top and bottom are used. Compliant spline drive within the furnace allows for various modes of misalignment.



(a) Hot eddy current sensor



(b) Eddy current sensor working principle



(c) Eddy current sensor driver and measuring unit



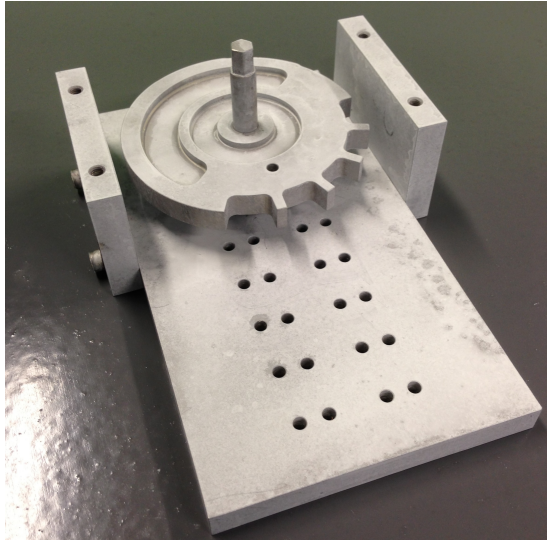
(d) Capacitance sensor

**Figure 1: Hot eddy current sensor and electronics**

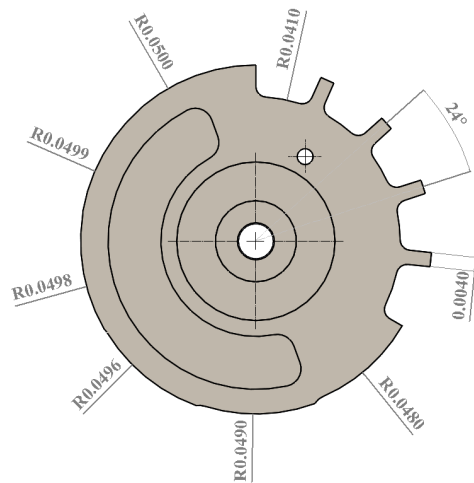
The eddy current sensor built at University of Oxford is as shown in Fig. 1a. The sensor has a diameter of 10 mm with a range of 5 mm. The sensor has a platinum coil with approximately 60 turns wound on a ceramic structure made of  $Al_2O_3$  and is encapsulated in Inconel 625. A sinusoidal alternating current of approximately 1-2 MHz is sent to the coil which induces a magnetic field. This field couples in to a conductive target and the coupled field generates reversed eddy currents (Fig. 1b). These eddy currents oppose the source magnetic field which changes the apparent inductance of the coil. An electronic circuit (Fig. 1c) with a standard micro-controller and instrumentation amplifier was built to generate the high frequency sinusoidal alternating current and detect changes in the phase of the received signal against the source. The electronics is capable of driving the sensor over a cable length of up to 10 m with a high temperature cable. The power requirement for the electronics is 18-36 V, 175 mA.

The capacitance probe (Fig. 1d) is an industry standard off the shelf type made by Thermo-coax<sup>®</sup>, used in combination with a Fylde<sup>®</sup>FE-419-CDT capacitance displacement amplifier unit. The probe has a tip diameter of 5 mm and a casing diameter of 15 mm, and an average accuracy of 1%.

Figures 2a and 2b show the rotor used in the experiments. As mentioned earlier, the rotor contains four flat tipped blades and six continuous sectors called “lands”. The sensors were placed next to each other at 10 and 30 degrees with fixed stand-off distances of 0.8 mm and



(a) Rotor with blades and lands



(b) Rotor sketch



(c) Hot eddy current and capacitance sensor



(d) Rotor in the oven at 800°C

Figure 2: **Experimental setup**



0.6 mm respectively from the surface of the rotor with maximum radius (Fig. 2c). The entire test rig as shown in Fig. 2d is placed inside an electric oven that can be heated up to 1400°C. It was ensured that the faces of the sensors were parallel to top surface of the blades. The rotor was spun at a constant 800 RPM for all cases. High frequency alternating current flows through the coil that run at many times the frequency of the machines characteristic 1st mode. This high frequency is termed the carrier and is readily removed by using a band pass filter.

The data acquisition system comprised of a Cleverscope® oscilloscope along with their proprietary data acquisition software. The data was acquired at 100 kS/s and the duration of acquisition was 2 s.

## Results and discussion

Two tests were conducted using the rig. The first test comprised of only the eddy current sensor with the temperature increased from room temperature all the way up to 800°C in steps of 100°C. The second test comprised of both the eddy current sensor and the capacitance probe. The capacitance probe had a manufacturer specified maximum temperature of 400 – 500°C, but the calibration data was limited to 250°C.

Since the rotor contains both blades and lands (flat sectors), the signal from the sensor for each revolution will have blades as peaks and lands as steps. For comparison purposes, the data was separated into blades and lands. This was achieved by finding the regions of lands in every revolution, removing them from the signal and then stitching them together using MATLAB® (see algorithm 1). The signal after separation are as shown in Fig. 3.

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### Algorithm 1 Separating blades and lands from the signal

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1. Find all the troughs/valleys in the signal using MATLAB® peakfinder
  2. Locate the troughs before and after lands in every revolution
  3. Stitch all the lands together and do the same for blades
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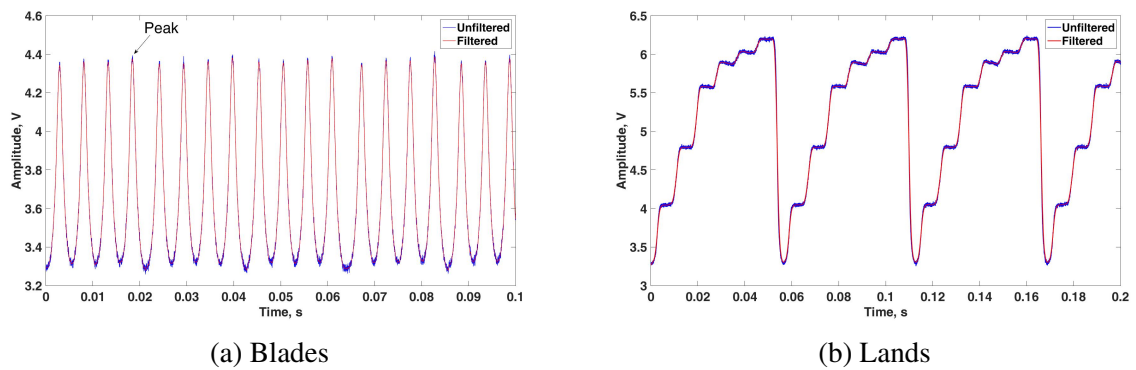


Figure 3: Segregated signal before and after filtering

The signal from the eddy current sensor contains noise and was filtered using a 1st order Savitzky-Golay filter in MATLAB® to remove all the high frequency noise. The signals before and after filtering are shown in Fig. 3. From Fig. 3, we note that we were able to remove the noise without losing significant information from the signal. The peaks shown in Fig. 3a corresponds to the mid portion of the blade's top surface and in Fig. 3b, the flat portions in the signal correspond to the lands on the rotor.

Since the sensor output is in volts, the signals have to be converted to “relative clearance (mm)”. For blades, the height of the blade in “mm” is divided by the height of the peak (i.e. from trough to peak of a particular curve) in volts (V) for each case to obtain the conversion coefficient (mm/V). The height of each peak corresponds to the relative blade height as the trough represents the absence of the blade tip and the physical distance represented by the signal is unknown. Since the rotor was machined from a single piece and the blades are slotted, the assumption can be made that there are no blade vibrations in any direction. The peak values were subtracted relative to each other to obtain relative clearance values. In the case of lands, a similar approach was used where the height was taken as the difference between the first (corresponding to the first land) and last flat section of the signal. The voltage values were then converted to “mm” at each temperature. It was assumed that the effects of thermal expansion were minimal as the entire rig was made of the same material and the relative expansion between the sensors and the rotor to be the same.

### Eddy current sensor only

As discussed in the previous section, the rotor was spun at a constant speed of 800 RPM and the measurements were taken from room temperature (referred to as “Cold”) to 800°C. Figure 4 shows the comparison of revolution averaged signals for the blades and lands (continuous sectors) at different temperatures. The revolution average is carried out for four revolutions only. The data is presented in steps of 200°C for clarity. Notably from Figs 4a and 4b, it is clear that the sensor is able to detect the blades and lands for about 800°C without the loss of sensitivity.

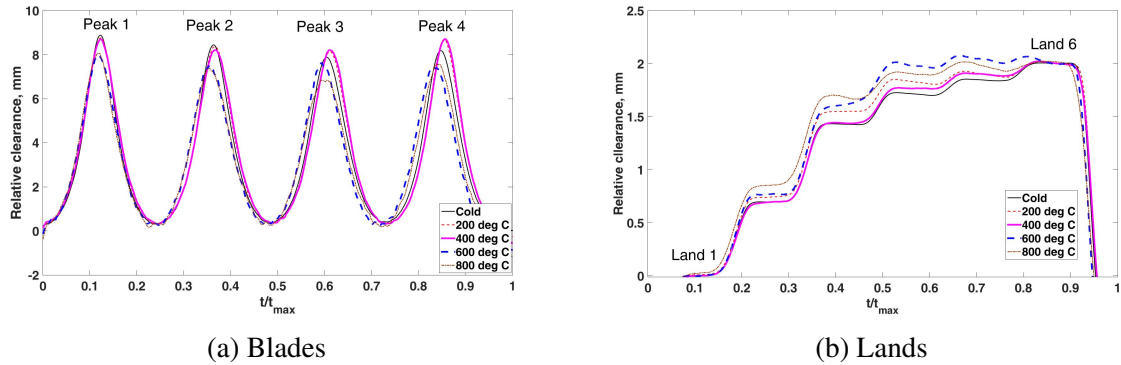
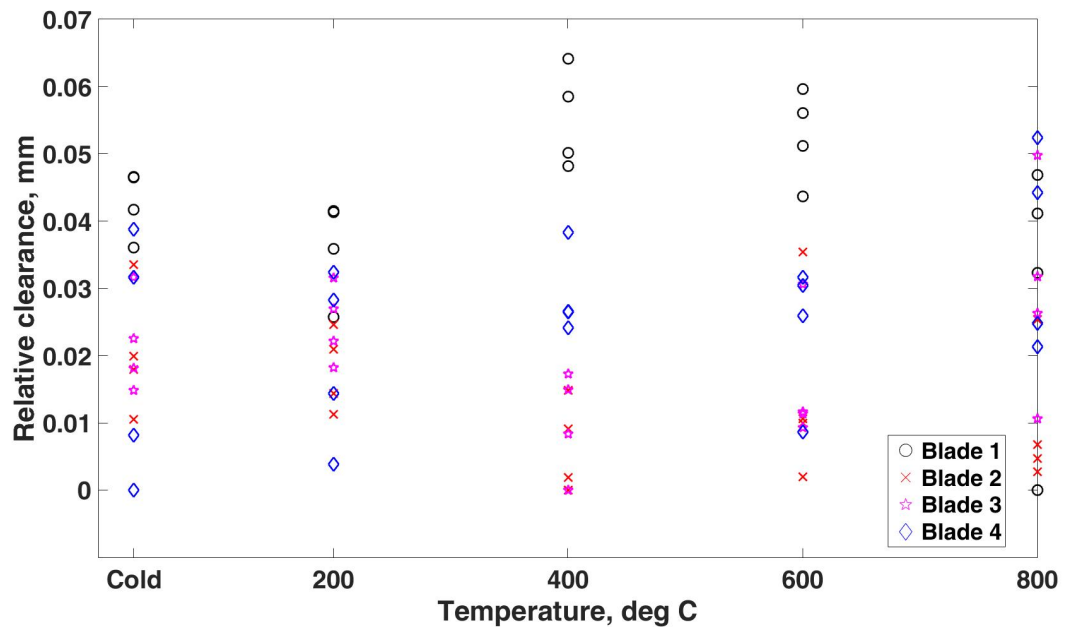


Figure 4: **Comparison of revolution averaged relative clearance at various temperatures**

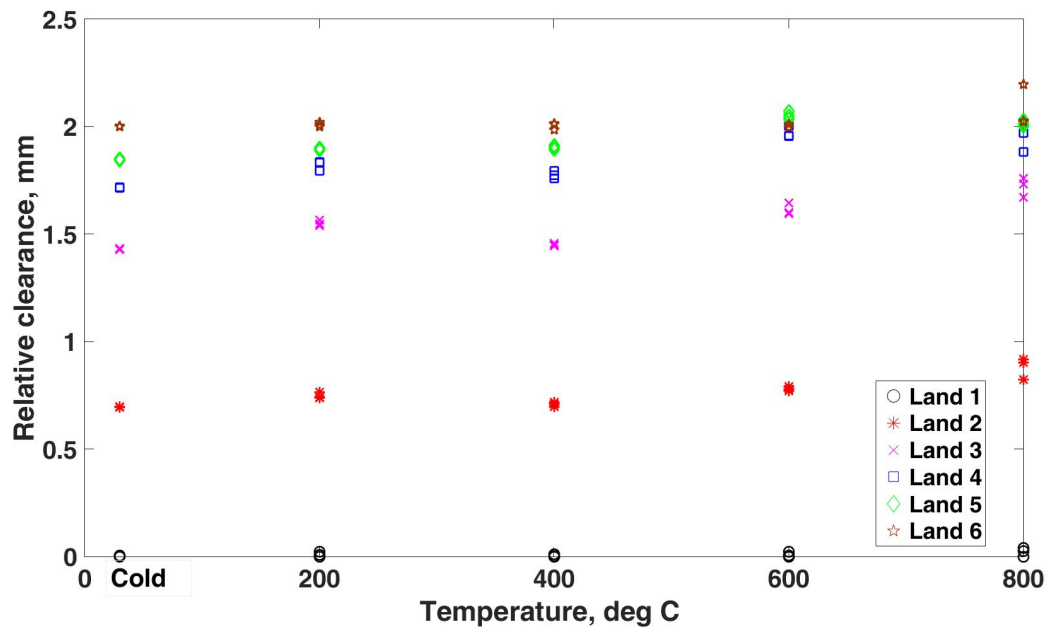
The clearance value comparison at different temperatures for the blades and lands for four revolutions are shown in Fig. 5. Notably, as the temperature increases, the clearance variations calculated by taking the standard deviation for blades (Fig. 5a) changes by a maximum of 0.022 mm at room temperature and 0.026 mm at 800°C. In the case of lands (Fig. 5b), the variations were approximately 0.003 mm and 0.01 mm at room temperature and 800°C respectively.

### Comparison with capacitance probe

In this set of experiments, both the eddy current sensor and capacitance probe were tested at temperatures up to 250°C. Figure 6 shows the revolution averaged signal comparison between the two sensors at room temperature and at 250°C. It should be noted that there was a phase shift between the signals in time due to the location of the two sensors. The offset was removed



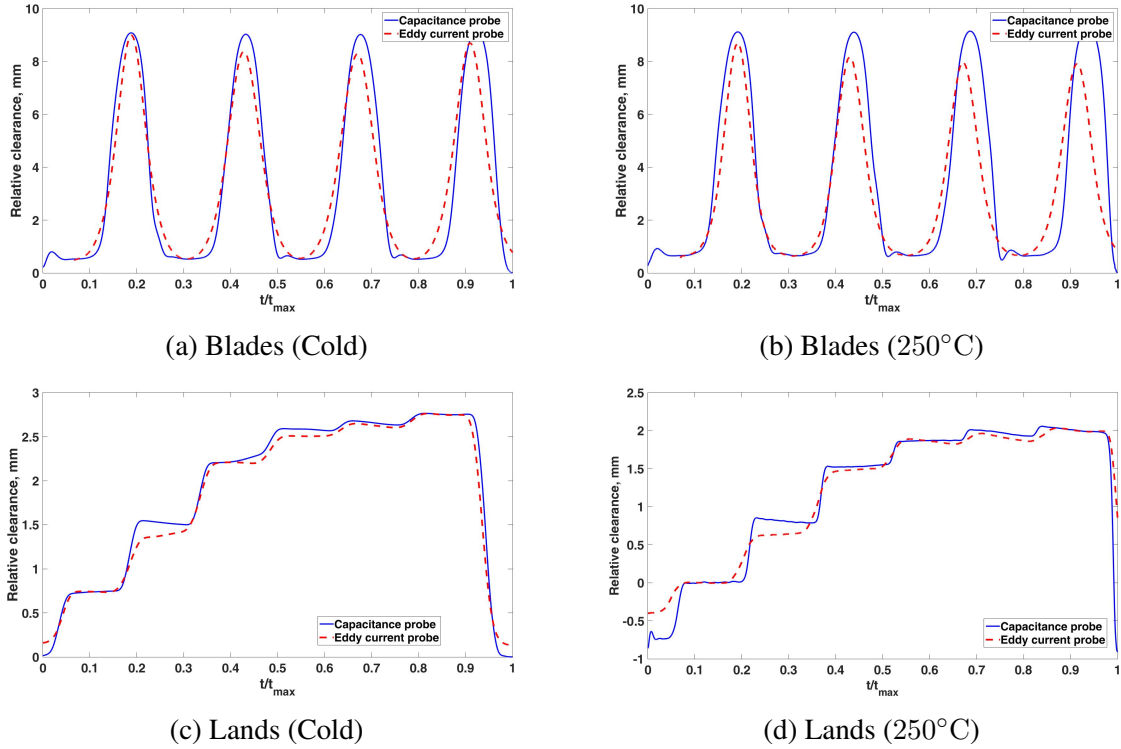
(a) Blades



(b) Lands

Figure 5: Comparison of tip clearances at different temperatures

while post-processing for better comparison. At both temperatures, the agreement between the sensors for both blades (Fig. 6a and 6b) and lands (Fig. 6c and 6d) is reasonably good. The clearances were obtained by the same procedure outlined earlier.

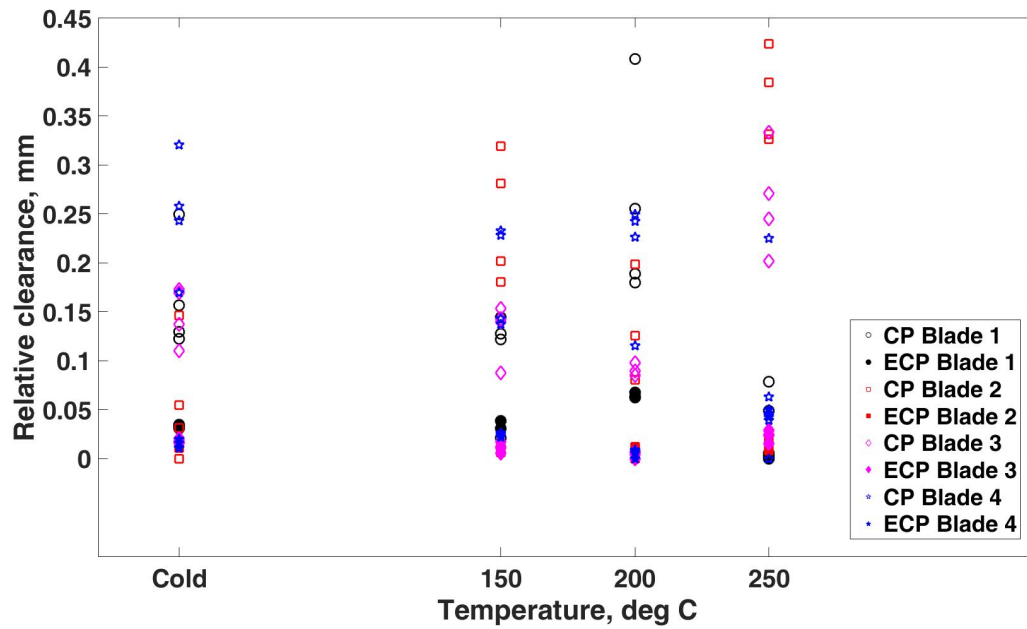


**Figure 6: Comparison of revolution averaged relative clearance at different temperatures**

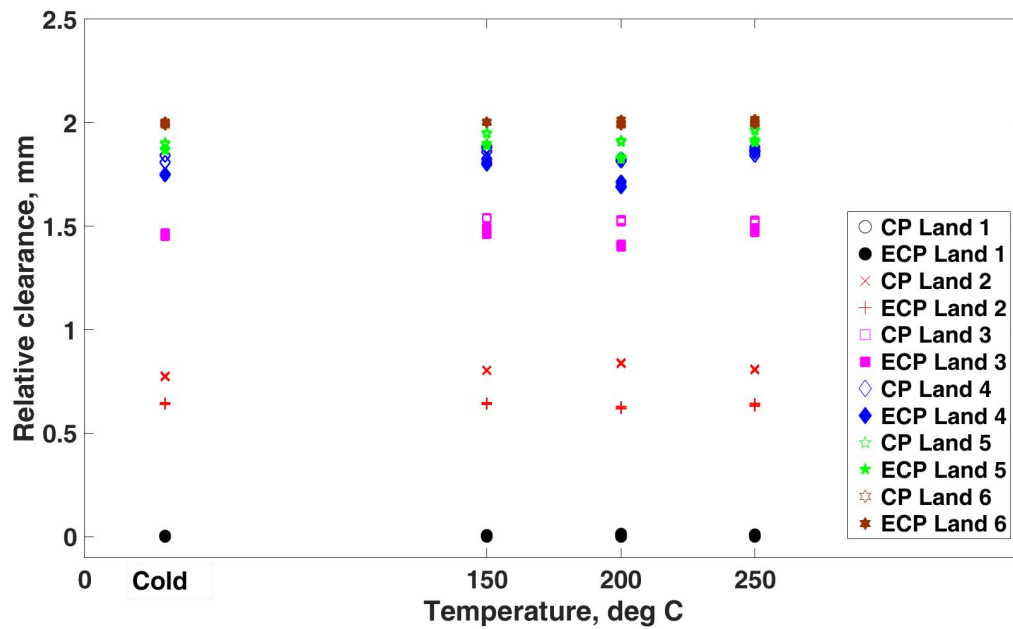
Figure 7 shows the comparison of clearance values at various temperatures between the sensors. The agreement between the eddy current sensor and the capacitance probe is good. The variations between the eddy current sensor and the capacitance sensor were calculated by taking the standard deviation of the tip clearance values at each temperature and for the capacitance probe (standard deviation variation) it was found to vary from 0.11 mm to 0.21 mm for blades (Fig. 7a) and 0.031 mm to 0.011 mm for lands (Fig. 7b) compared to the values of 0.027 mm to 0.043 mm for blades and 0.005 mm to 0.012 mm for lands for the eddy current probe, indicating that the latter has better repeatability and reliability of measurement. This demonstrates that the eddy current sensor can potentially perform better than the capacitance probe for both blades and lands. The eddy current probe also has added advantages of being robust, tolerant to oil and other contaminations, use in both low and high temperature applications and also on smooth continuous surfaces, whereas the capacitance probe always requires an interruption and cannot be used at high temperatures.

## CONCLUSIONS

A new high temperature eddy current sensor for tip-timing and tip-clearance measurements has been developed and tested at various temperatures and rotor surfaces. The data shows that the newly developed hot eddy current sensor shows good agreement when compared with the capacitance probe for the lands over the temperature range, giving credence to the eddy current probe data, but that the eddy current probe achieves a more accurate, repeatable and



(a) Blades



(b) Lands

Figure 7: Tip clearance comparison between capacitance (CP) and hot eddy current sensor (ECP)



reliable measurement for the blades, as well as extending the temperature range. The eddy current sensor is found to be operational showing all the features and clearances at 800°C and is accurate to within 6% at this temperature thus justifying its use in high temperature tip-clearance measurements. The data demonstrates that the eddy current sensor may be used in lower temperature applications (up to 500°C), such as for clearance measurement at shaft seal locations in gas and steam turbines with an extended life.

## ACKNOWLEDGEMENTS

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