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TIP-CLEARANCE MEASUREMENTS ON AN ENGINE HIGH PRESSURE TURBINE USING AN EDDY CURRENT SENSOR

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ABSTRACT

Gas turbine health monitoring is an important area of research. As the performance of aircraft and power plants increase, they will require better sensors in the health monitoring systems to prevent failures. Health monitoring systems also helps in preventive maintenance, unnecessary downtime and thus reducing the maintenance cost. Gas turbine blades are subjected to dynamic loads caused due to rotor imbalances, distortions in the intake flows etc. These loads cause low or high cycle fatigues and the blades can fail over time. Tip-timing and tip-clearance systems makes it possible to assess turbomachinery blade vibration by using non-contact measurement systems such as optical, eddy current, hall effect, capacitve etc. The most widely used systems in industry are optical. However, these systems are still largely prone to contamination problems from dust, dirt, oil, water etc. Further development of these systems for in-service use is problematic because of the difficulty of eliminating contamination of the optics. Other systems, although immune to contamination, may not be able to measure both tip-clearance and tip-timing at the same time due to their operating principle. These systems cannot be used in high temperature applications such as in a high pressure turbine where the temperatures can reach 1400 degree Celsius. Eddy current sensors are found to be quite robust and can measure both tip-timing and tip-clearance. They are currently being used for gas turbine health monitoring applications at low temperatures such as in the compressor stage and last stage of a turbine.

A new high temperature eddy current sensor has been developed in-house at the University of Oxford for application in gas turbine tip-timing and tip clearance measurements to assess blade vibrations. The current sensor is a modified version of the existing eddy current sensor that is able to operate at high temperatures of about 1400 degree Celsius. The paper presents the development of the sensor and experimental results of tip clearance measurements in the high pressure turbine stage of a jet engine. In the engine tests, two blades were reduced in height to increase the tip-clearance and the measurements were taken at both idle and max operating speeds. The sensor was found to work in these harsh environments and was sensitive enough to accurately determine the tip clearance at these elevated temperatures. The tests were carried out mainly to demonstrate the technique of obtaining good tip clearance measurements and the survivability of the sensors in the high temperature and pressure environment.

INTRODUCTION

Active health monitoring forms an important part of the aircraft systems. Health monitoring of gas turbine components ensures timely maintenance by detection of potential failures and thus reducing unnecessary down time.

Blades of a gas turbine engine 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). These can damage the blades and can lead to aerodynamic forcing causing high cycle fatigue. This 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.

Blade Tip-Timing (BTT) and tip-clearance measurements are routinely used to monitor engine blades for vibrations. Some of the methods used to for these measurements involve the use of optical probes, eddy current, capacitive, Hall effect sensors etc. [1], [2], [3], [4]. All these sensors measure the arrival time of the blades and some can measure the tip-clearance (eddy current and capacitance).

The eddy current sensor is the most robust and immune to contaminations when compared with industry standard optical probes. They are already being used in gas turbine power generation for in-service health monitoring on first stage compressor blades and on the last stage of steam turbine blades, whereas, the other type of sensors are still used on developmental engines due to their limitations.

The aim of this research is to show the performance and accuracy of a newly developed high temperature eddy current sensor and its application in measuring tip-clearances in the high pressure turbine stage of a small gas turbine engine.

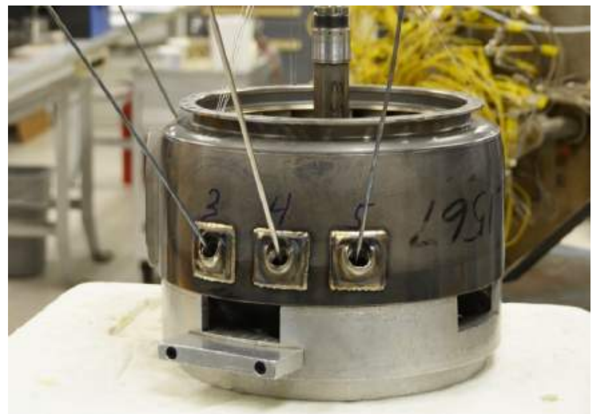
Experimental Setup

Figure 1a shows the high temperature eddy current probe developed at the University of Oxford. The sensor has a diameter of 10 mm and is enclosed by an Inconel 625 casing to withstand high temperatures ($> 1000°C$). The sensor has a coil with set number of turns and when a high frequency alternating current is sent to the coil, a magnetic field is induced. This field couples in to a conductive target and this coupled field generates reversed eddy currents. These eddy currents oppose the source magnetic field which changes the apparent inductance of the coil. An electronic circuit was built to generate the high frequency alternating current and to detect changes in the phase of the received signal against the source.

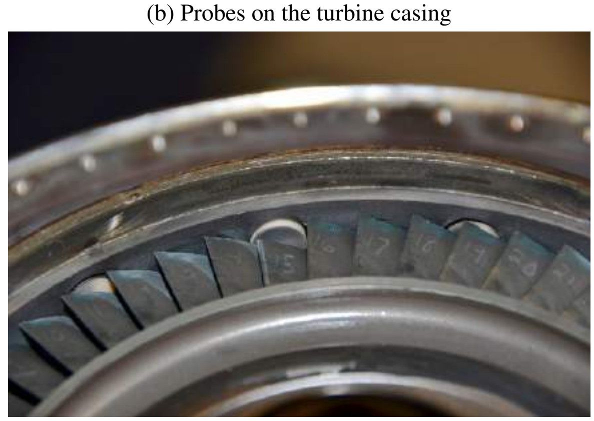
In a turbine configuration the coil is static and blade tips rotate past a radially positioned sensor. High frequency alternating current flows through the coil that run at many times the frequency of the machine's characteristic 1st mode. This high frequency is termed the "carrier" and is readily removed by filtering. However, remnant small amplitude evidence will remain superimposed on the response. The residual carrier and other unwanted electrical signal sources hereinafter are referred to as "noise".

The experimental setup consists of a small gas turbine engine with sensors placed in the first stage of the turbine as shown in Figs. 1b and 1c. Two blades were reduced in height for testing the sensor. The data acquisition system comprised of a Cleverscope® oscilloscope along with their proprietary data acquisition software. The data was acquired at 10 MS/s and the duration of acquisition was 2 s. The filtering and clearance measurements were done using MATLAB®.

(a) Eddy current sensor



(b) Probes on the turbine casing

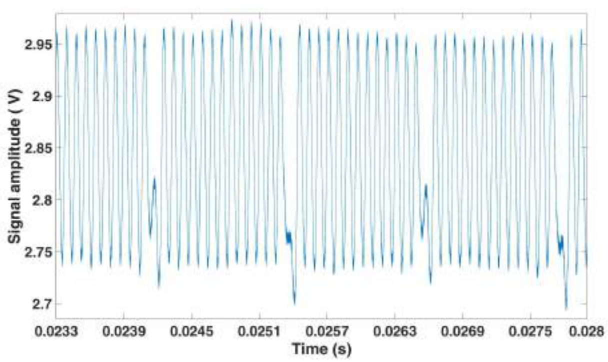


(c) Probes seen in the turbine casing

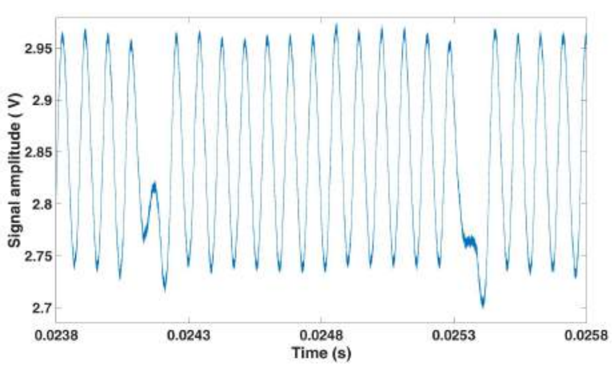
FIGURE 1: Hot eddy current sensor and mounting

Tip clearance measurements

The engine was air cranked to approximately 10,000 rpm to test the high temperature eddy current probes and instrumentation chain prior to the actual engine run. Figure 2a shows eddy current sensor data from the HP turbine during an air crank for just over one revolution of the HP turbine. The gaps between the peaks are blades that were reduced in height as mentioned earlier. These blades helped in providing a once per rev reference. Four blades were reduced in total, two by approximately 2 mm and two more by approximately 4 mm. An issue one might face was detecting two blades at once due to the physical size of the eddy current sensor relative to the blade spacing at the tip. By reducing the blade height, the probes would at least have detected some blades individually. However, the current measurements (Fig. 2a) clearly show that each individual blade is detectable with the eddy current sensor and furthermore we see good quality of signal from the zoomed in view in Fig. 2b. Now, the relative tip clearance between the blade tips can be measured with the height of the peaks of the signal.



(a) Signal from the sensor



(b) Zoomed in view of the signal

FIGURE 2: Tip clearance signal during air cranking

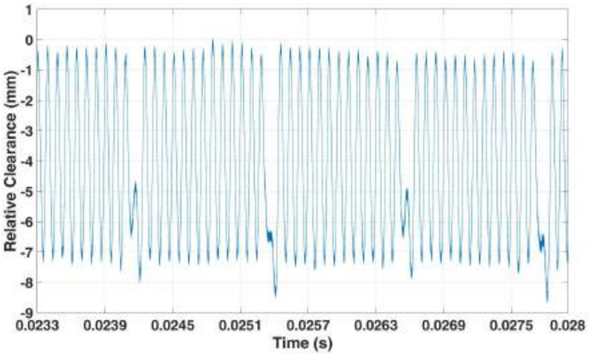
Since the sensor output is in volts, the signals have to be converted to "relative clearance (mm)" and "absolute clearance (mm)". In the present case, the difference of voltage from the reduced blades is known to be 2 mm and the conversion coefficient mm/V is obtained. The signal is then multiplied with the conversion coefficient to obtain the relative clearance values. The stand off distance from the normal blade is measured and then added to the relative clearance measurements to obtain absolute clearance values.

An important consideration while calculating absolute clearances was assuming that the sensor is flush with the casing and, the casing is set to the zero position on the vertical axis. However, the sensor is likely to have thermally grown as will have the casing and it is not known if the growth is differential and therefore the sensor may not be flush with the casing. This introduces an error on the absolute clearance with respect to the casing although this should be relatively small.

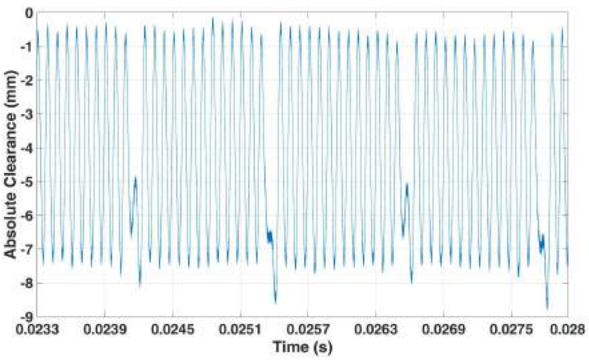
The engine was initially operated at idle for oil pressure, leaks and other checks for about 5 minutes each time after the air crank runs. Next two runs were performed for engine operation and oil consumption checks. The test run entails a stair step profile to max operating conditions over 25 minutes, 7 minutes dwell at the max conditions, rapid deceleration to idle, 5 minutes at idle, shutdown, restart, 5 minutes at idle, 10 min accelerate to max operating conditions, one minute dwell, decelerate over 10 minutes, idle for 5 minutes and shutdown.

Figure 3a gives the relative clearance values for the air crank test at 10000 rpm i.e. with respect to each blade and not the casing. The peaks of the signal represent the tip of the blade. The tallest blade is set to the zero position. This was done to show how the clearance of each blade varies with other blades and the shortened blades are clearly seen here and they are in good agreement with the measurements provided by the engine manufacturer of the amount the blades have been reduced by. Figure 3b gives the absolute clearance variation for each blade and figure 3c shows the peak clearance values of the blades for the run and we see some variation in the clearance values.

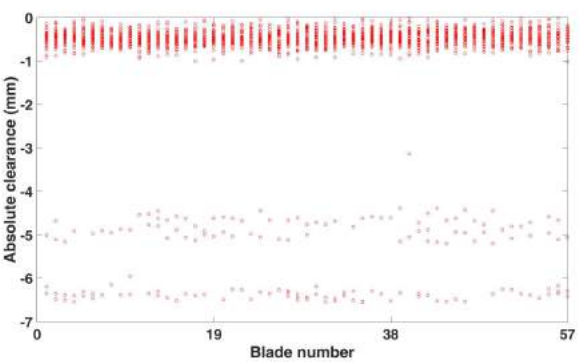
Once several air cranks had been completed the engine was fired and brought to idle speed of 23000 rpm which is around 43,000 rpm for the HP shaft. Figures 4a and 4b shows eddy current sensor measurements of relative and absolute clearances from a fired engine run. Notably the data the sensors to be operating and also shows some low frequency overlapping on the signal. Firstly, the variation in the peaks is greater than the air crank data and there seems to be a repeatable pattern to the variation. The repeatable pattern is caused by a whirling of the shaft with reference to the casing. However, the tip clearance between the different blades is easily detectable. We also note that the variation in absolute clearance values has increased quite a lot as shown in Fig. 4c, which is also indicative of increase in whirling of the shaft. Finally, figure 5a shows the measurements of relative clearance values at higher speeds. The data shows that the probe has measured very good quality signals at the higher operating conditions of speeds, temperatures and pressures as well as vibrations. The whirling is more apparent at higher engine speeds where a sinusoidal variation is clearly observed (Fig. 5b



(a) Relative clearance at 10000 RPM

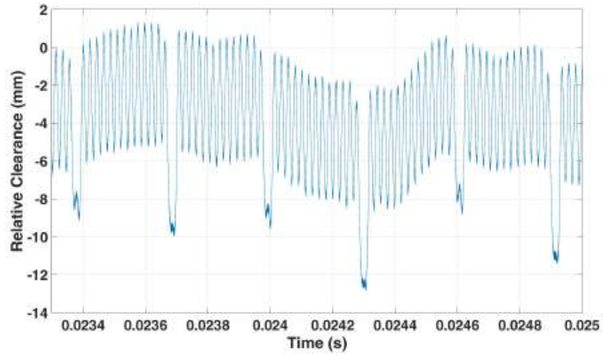


(b) Absolute clearance values at 10000 RPM

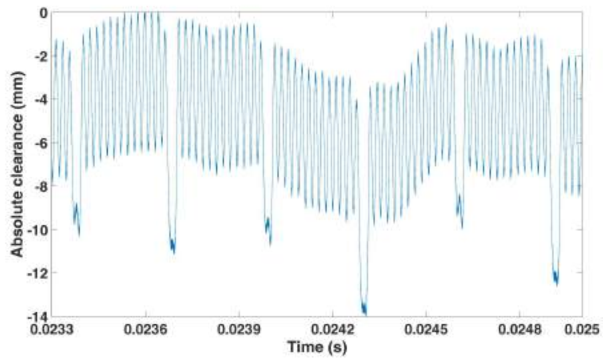


(c) Zoomed in view of the peak

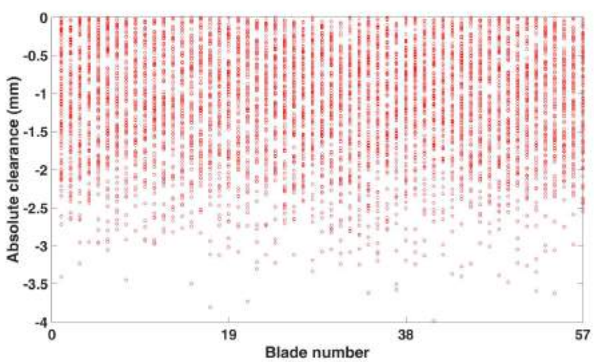
FIGURE 3: Clearance values at 10000 RPM



(a) Relative clearance at 43000 RPM



(b) Absolute clearance values at 43000 RPM



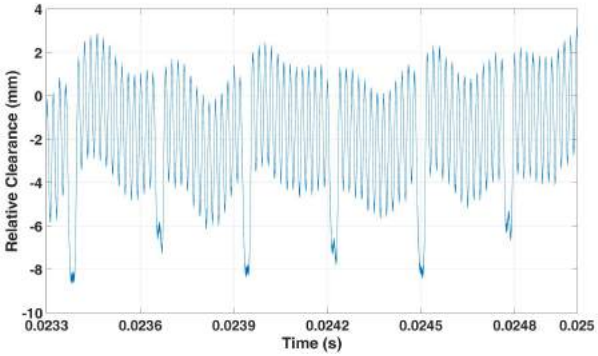
(c) Absolute clearance values at 43000 RPM

FIGURE 4: Clearance values at 43000 rpm

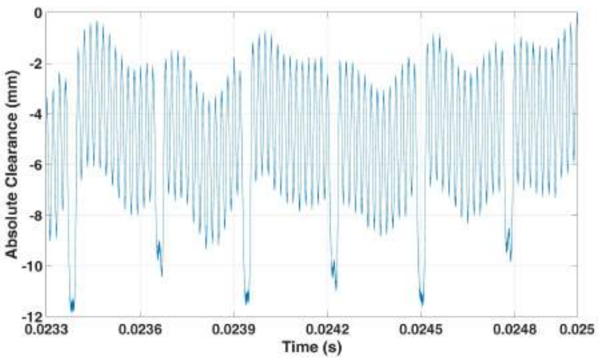
and 5c), which is not unusual for rotating turbomachinery. The statistical analysis of the absolute clearance values with respect to blade numbers show that as the speed increases, the variation in clearances increases from 1.097 mm to 1.32 mm.

A post-test analysis was carried out on the high temperature probes once the trials were completed and the probes recovered after the engine was dismantled. Surprisingly the eddy current sensor probes were found to have been damaged during the test. Figure 6 shows the damage to the various probes. During fitting the probes were slightly angled and the forward part of the face was slightly closer to the casing on the gas path side than the rear of the sensor, towards the cable exit. Figure 6a shows the damage to one of the eddy current sensor probes inside the turbine. In general the probe body and cable is in very good condition, however the 3 eddy current sensor probes have cracked ends with small parts missing.

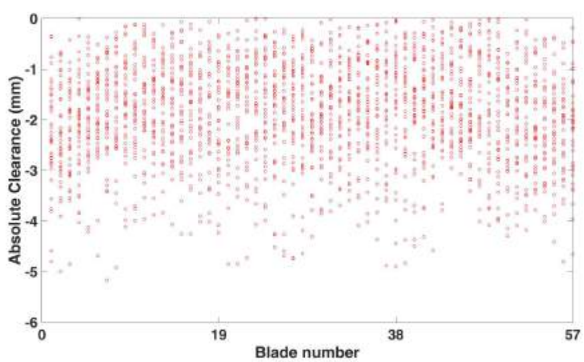
On closer inspection of the probes it was found that all 3 of the eddy current probes had suffered a rotor blade tip rub. Fig-



(a) Relative clearance at 49000 RPM



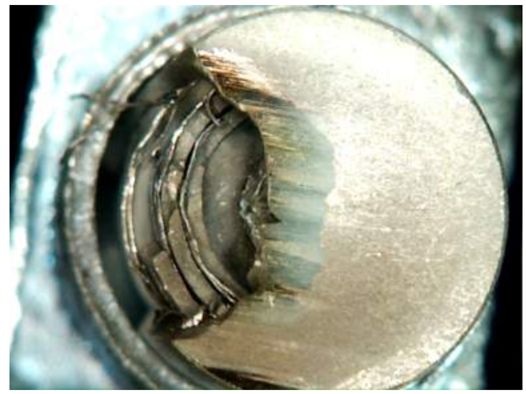
(b) Absolute clearance values at 49000 RPM



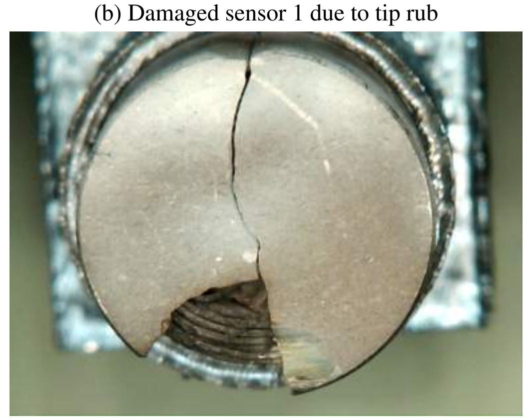
(c) Zoomed in view of the peak

FIGURE 5: Clearance values at 49000 RPM

(a) Damaged sensor in the engine



(b) Damaged sensor 1 due to tip rub



(c) Damaged sensor 2 due to tip rub

FIGURE 6: Tip rub of the sensor

ures 6b and 6c show the close-up photographs of the probe tips. The pictures show evidence that the probe tips suffered a rotor blade tip rub, the area where the blade came into contact with the probe can be clearly seen. The most likely cause of the tip rub was following a shut down the probes had thermally grown and the casing had cooled sufficiently that the probes were protruding through the casing. When the engine was restarted, the rotor expanded thermally and due to the rotation and centrifugal force a rub was experienced on the casing and the probe tips on the leading side. Evidence of the casing rub can be seen on the casing abradable. The manner in which the probes were mounted on the upper part of the probe body, differential thermal growth of the probes along the axis between the casing would have caused them to grow towards the turbine.

Conclusions

A new high temperature eddy current sensor developed for tip-timing and tip clearance applications has been used on a gas turbine engine to obtain tip clearance values in the high pressure turbine stage. The results show that the sensor was able to perform at these extreme environments without losing accuracy. The sensor did suffer some damage to its outer shell due to a tip rub caused due to thermal differentials but was still found to be operational.

Acknowledgement

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REFERENCES

[1] Flotow, A. V., Mercadal, M., and Tappert, P., 2000. "Health monitoring and prognostics of blades and disks with blade tip sensors". In Proceedings of IEEE Aerospace Conference, Vol. 6, pp. 433–440.

[2] Lattime, S. B., and Steinetz, B. M., 2009. "Turbine engine clearance control systems: Current practices and future directions". In 38th Joint Propulsion Conference and Exhibit cosponsored by AIAA, ASME, SAE, and 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, no. NASA NASA/TM–2002-211794 AIAA-2002-3790.

[3] Vakhtin, A. B., Chen, S., and Massick, S. M., 2009. "Optical probe for monitoring blade tip clearance". In 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, no. 2009-507.

[4] Hafner, M., Holst, T., and Billington, S., 2011. "Blade tip measurement advanced visualization using a three dimensional representation". In ASME 2011 Turbo Expo: Turbine Technical Conference and Exposition, no. GT2011-46523, pp. 419–425.