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**THE USE OF EDDY CURRENT SENSORS FOR THE MEASUREMENT OF ROTOR
BLADE TIP TIMING – SENSOR DEVELOPMENT AND ENGINE TESTING**

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ABSTRACT

The advent of tip-timing systems makes it possible to assess turbomachinery blade vibration using non-contact systems. Currently, the most widely used systems in industry are optical systems. However, these systems are still only used on development engines, largely because of 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. Hence, alternatives need to be developed that are immune to contamination but have equivalent resolution and bandwidth as the optical system.

Experimental measurements have been carried out using alternative sensors. An eddy current sensor has been developed in a series of laboratory and engine tests to measure rotor blade arrival times. Comparisons are made with an industry standard optical blade tip timing system. The results show that it is possible to acquire high quality blade tip timing data for use in engine condition monitoring using an eddy current sensor. This sensor allows measurements to be taken that do not suffer from flow contamination and allow deployment for hotter flow environments.

INTRODUCTION

There is a continuous drive for modern aircraft to fly further and faster, and have lower whole life cycle costs. Part of this process is set to be achieved through reduced maintenance activity by increasing monitoring of engine components during operation to detect potential failures and avoid unnecessary down time by allowing the prediction of maintenance requirements prior to potentially expensive failures.

Blade vibrations are caused by dynamic loads on the blade these can be generated by various mechanisms such as rotor imbalances, varying blade tip clearance, usually caused by non-concentric casings or orbiting of the main shaft, distortions in the inlet flow (caused by irregular intake geometries) and, stationary vanes or struts upstream or downstream of the rotor blade.

High cycle fatigue, often associated with increases in aerodynamic forcing resulting from blade damage, has a major impact on fleet availability, safety and whole life costs. However, there is currently no instrumentation available for the monitoring of blade vibration levels on in-service engines. 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.

The established method of assessing blade vibration in development testing of engines relies on the mounting of strain gauges onto blade surfaces and complicated telemetry or slip ring systems to transmit signals from the rotor. Alternative non-contacting measurement techniques have been developed to remove the interference caused by strain gauges. The most advanced and widely used technique is known as Non-contact Strain Measurement System (NSMS) or Blade Tip-Timing (BTT). These methods generally use optical probes mounted in the blade casing assembly. The principle on which the optical system operates involves the focusing of a narrow laser light beam onto the passing blade tip. As the blade tip enters the path of the light beam, light is reflected back to a photo sensor. The intensity of the reflected light rises very rapidly during blade passing. In the absence of any structural vibration, the time for the tip of a particular blade to reach the optical probe, called blade arrival time, would be dependant on the rotational speed alone. However, when the blade is vibrating, blade

arrival times will depend on both the amplitude and frequency of the vibration. Capture of a particular mode of vibration by a given optical probe depends on the location of the probe with reference to the vibration. Typically measurements are taken towards the leading edge of the blade tip to maintain near maximum sensitivity to the motion of the blade. The use of multiple optical probes for blade vibration analysis is becoming routine on development engines, however problems occur because the optics are vulnerable to contamination and a clear optical path is required from the casing to the blade tip. In practice optical systems require frequent cleaning, making them unsuitable for in-service use. Hence there exists motivation to find an alternative sensor to optical probes.

Non-contact blade tip timing measurements can be carried out using several different transducer systems, eddy current, capacitance, optical and microwave probes. Typical operating conditions inside the turbomachinery result in blade tip speeds of approximately 400ms⁻¹ and circumferential blade tip vibration amplitudes of order 0.3mm (within the compression system), which means that the time period over which the vibration is measured is 1 μ s. A measurement accuracy of at least an order of magnitude greater than this, i.e. 100ns is necessary to obtain valid vibration information. To achieve maximum probe sensitivity it becomes necessary to mount the detectors in close proximity to the blade tip. However to ensure that there is no fouling a clearance is required between the sensor and the casing inner wall. This does however affect the sensitivity of the eddy current and capacitance probes, as low amplitude output signals when amplified can contain relatively high levels of noise and, also, a reduction in bandwidth is observed. In addition consideration must also be given to the maximum allowable working temperature of the system, before it can be considered for use in hotter parts of the engine such as the high pressure compressor and turbine.

The aim of this research was to develop robust, easy to deploy blade tip-timing probes and associated electronics for use on in-service engines, to achieving improved probe life, higher temperature capability and better spatial resolution than is currently available. This will lead to a better measure of the variability within an engine set compared to conventional strain gauges and will aid extrapolation of the data to the fleet, and potential in engine systems on new products. Initially trials were carried out on the QinetiQ Turbine Test Facility using various sensor types against an optical sensor to down select a candidate sensor type to develop further. Three different types of sensor were trialed, eddy current, capacitive and high frequency pressure transducers, all were mounted in the casing above the rotor tip. The results of these trials indicated that the eddy current sensor showed the best promise for further development. These sensor types have been previously used or considered for tip timing or tip clearance measurements: by Flotow [1], Zielinski [2] and Belsterling [3] respectively.

This paper describes ongoing work to develop and evaluate tip-timing sensors using the eddy current principle for use in in-service engines. The evaluation of these sensors in recent gas turbine engine fan tests is described and the results are discussed.

EDDY CURRENT SENSORS IN TIP TIMING

Eddy current sensors are most commonly used for non contact proximity and displacement measurements. Their use in this application is well established and measurement accuracy is high. The sensors are rugged and are often used in contaminated environments.

A major advantage the eddy current sensor over the other probe types is that it offers the possibility of being able to take blade passing data through the casing, this has been demonstrated by Roeseler and Flotow [4] using a passive eddy current sensors. However, the presence of the casing is registered by the sensor, leading to significant attenuation of the target signal. Tests were carried out both with and without material between the sensor head and the target.

Two types of eddy current probes have been developed and used, passive and active [4,5], the passive probe deploys a permanent magnet to generate the magnetic flux and a coil to measure the voltage generated by the eddy currents in the target. Active probes can have one or multiple coils, in the simplest form a single coil is used to generate the magnetic flux and measure the voltage generated by the eddy currents induced in the target. Multiple coils are used to get differential measurements between the two coils. Eddy current probes are available off the shelf in various shapes and sizes for position measurements. Typical examples of the QinetiQ eddy current sensor are shown in Figure 1.

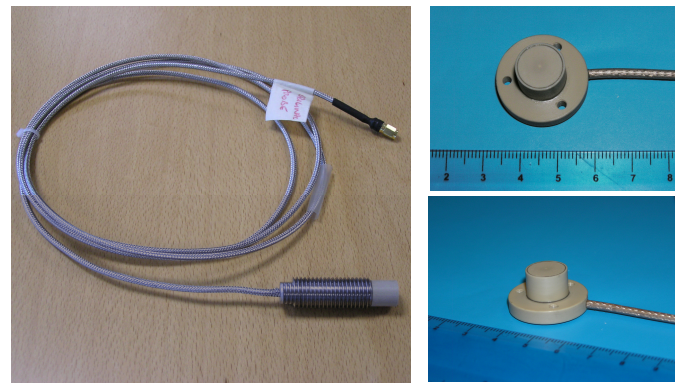


Figure 1: QinetiQ eddy current sensor developed for tip-timing

SENSOR DEVELOPMENT AND EVALUATION

Initially, bench tests were carried out on a standard off the shelf eddy current sensor. The sensor was chosen to have a reasonable range while having overall dimensions of an acceptable size, and particularly that the sensor head was not

so large as to cause mounting problems or that there would be a risk that the sensor would detect more than one blade simultaneously. Range of eddy current sensors is generally around half the diameter of the coil a range of approximately 5 to 7mm was required hence, a sensor of 13mm diameter was chosen.

Preliminary tests were carried out on a small rotating test rig. The sensor was mounted so that it could be traversed towards and away from the rotor. A simple shield was mounted between the sensor head and the rotor to act as a casing. The shield could be moved relative to the sensor head by means of a micrometer adjuster. This allowed the gaps between the rotor/shield and the shield/sensor to be accurately set to any required value. For these early tests, the material used for the shield was aluminium. Early trials showed that it was possible to detect blade passing events through casing materials up to 2mm thick.

After the success of the early trials it was thought that a more realistic evaluation of the sensors should be carried out by mounting the sensors in a pocket to simulate casing material around the sensor head. Initially an aluminium sensor pocket was manufactured with different thicknesses of shield that could be screwed to the end to act as the turbine casing. The left of figure 2 shows the housing and the removable shield plates. Tests showed that the pocket design and material were having a serious effect on the sensor performance and that it was not possible to get useable signals when a shield was fitted.

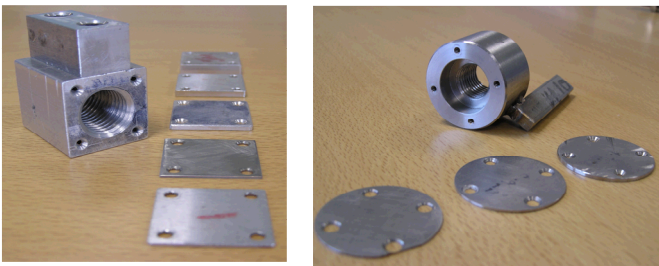


Figure 2: Aluminium and stainless steel sensor pockets with shield plates

In order to overcome these problems, the pocket was re-designed with an air cavity around the sensor head. The re-designed pocket and shields are shown on the right in figure 2. Tests were carried out using a 0.9mm shield and varying tip gaps from 0.5 to 2.0mm. Although the signal was small in amplitude, it was of reasonable quality, with very well defined peaks at the blade passings. Figure 3 gives the output amplitude against the tip gap.

Redesign of the sensor coil was carried out next to improve the signal output; the redesigned sensor was kept the same size and shape. Figure 3 shows the difference between the original and the mark 2 sensor for the case with a 0.5mm shield. Redesigning the coil improved the new sensor output

approximately 10 times that of the original and, although the noise level increased when the blade is not present this does not affect the blade arrival time accuracy

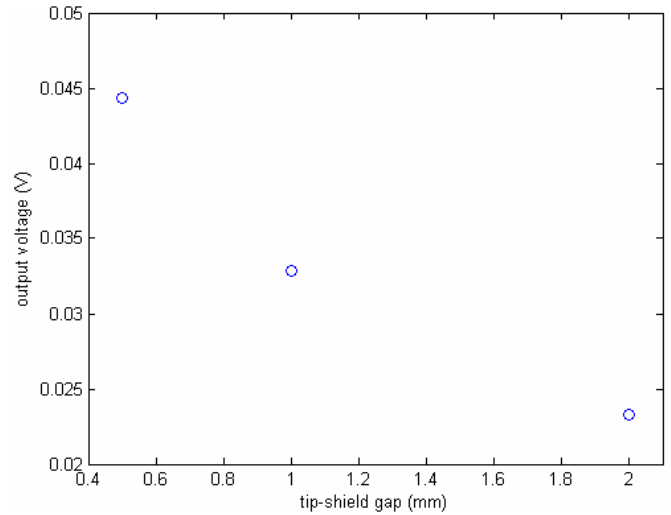


Figure 2: Original sensor output against tip gap using stainless pocket with 0.9mm shield

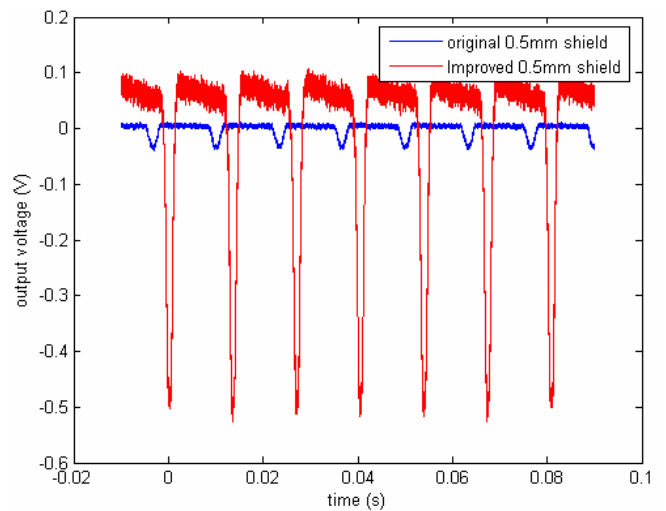


Figure 3: Original and improved) sensor performance using stainless pocket with 0.5mm shield

In view of the improvement in results stemming from the redesign it was decided to produce a new sensor which pushed the changes made to the mark 2 sensor even further. This sensor was again kept within the dimensions of the original sensor.

Figure 4 shows the fluctuation amplitude from the mark 3 sensor using a 0.9mm stainless shield at various tip gaps. At a 1.0mm tip gap the fluctuations are large and clearly detectable with amplitude approximately three times that of the mark 2 sensor. As the tip gap is increased, the size of the fluctuations

reduce, although even at 3mm gap the blade passing is still detected.

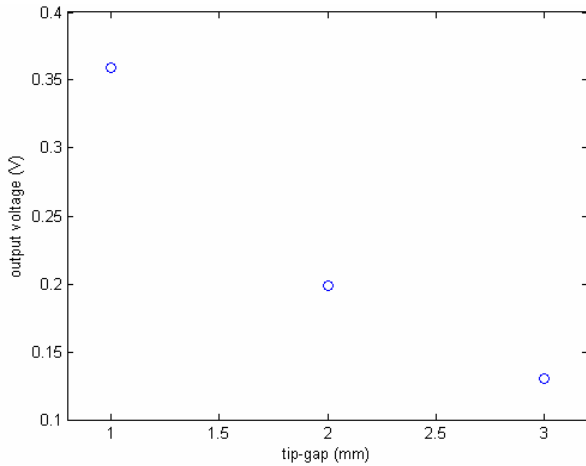


Figure 4: Mark 3 improved sensor output against tip/shield gap using stainless pocket with 0.9mm shield

Figure 5 shows the mark 3 sensor output with changing shield thickness at both 1.0mm and 2mm tip gaps. The increase in shield thickness has a large effect on the size of the fluctuations, though in all cases the peaks were identifiable. In the plot the blue markers showing the 1.0mm tip gap and the red, the 2.0mm tip gap. It can be seen that for the thin shield, the reduction in amplitude is large as the tip gap is increased. As the shield thickness increases, the output falls, but so does the reduction with increased tip gap, such that with a 1.5mm shield, there is virtually no difference in the amplitude of the fluctuations as the tip gap is increased from 1.0 to 2.0mm.

ENGINE TRIALS

Armed with a greatly improved bench tested sensor gave confidence to move to an engine trial [6] of the probes. The opportunity to ‘piggy back’ trial the sensors arose via Rolls-Royce, an AE3007 engine on test at Rolls-Royce Indianapolis. A number of tests, including blade tip timing trials, were to be carried out on the first stage fan rotor. The engine runs at 8700 rpm and the first stage fan rotor has 24 blades. The tests were to be carried out with a shield in the form of a blind pocketed holder between the sensor head and the fan blade tips.

Figure 6 shows a schematic of the test cell and the instrumentation configuration. Four sensors were mounted in the fan casing. Figure 7 shows a front view of the engine in the test cell looking face on to the fan and casing. The sensor pockets were mounted into holes drilled into the fan casing

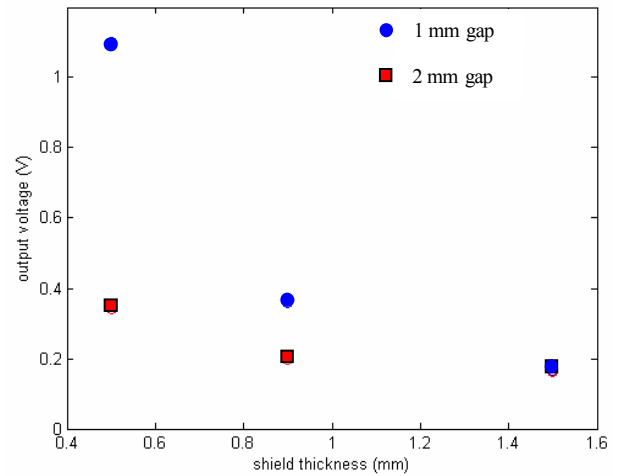


Figure 5: Mark 3 improved sensor output against shield thickness using stainless pocket and both 1mm and 2mm tip gaps

Figure 8 shows one of these mounting holes from the underside with the sensor pocket fitted. The outside of the casing was spot-faced to allow the pocket to sit squarely on the casing and the sensor was positioned with its centerline at approximately 0.3 axial chord. While this will tend to reduce the signal strength, placing the sensor head nearer the leading or trailing edge increases the amplitude of blade vibrations. Figure 9 shows the approximate location of the sensors in the fan casing, with the thickness of the pocket base in inches.

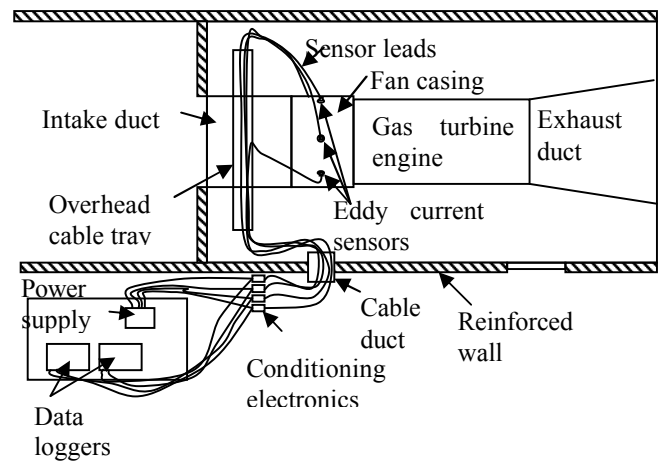


Figure 6: Schematic of the set up for the fan tests

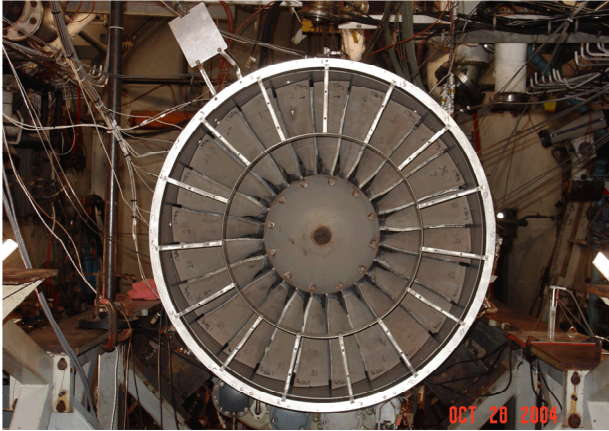
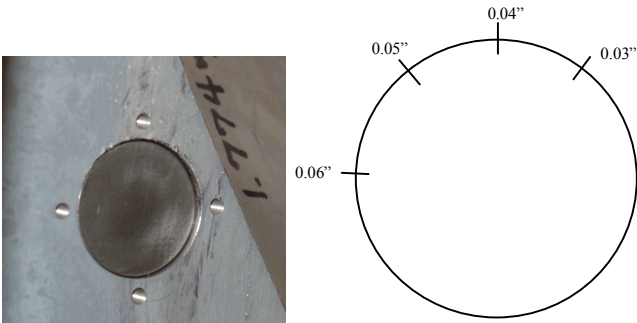


Figure 7: Test engine showing the fan



Figures 8 and 9: Sensor pocket fitted in the fan casing and sensor positions in the casing with casing thickness indicated

The pockets were manufactured in stainless steel with different base thicknesses in order to test the sensors ability to measure blade passing data through thicker shields and to allow comparison of the different results. Although manufactured using US measurement units, the metric equivalents are: 0.75mm, 1.0mm, 1.25mm and 1.5mm.

During the initial running, very poor signals were obtained until the engine was at full speed. Figure 10 shows an example of the sensor outputs at full speed, the blue trace shows the output through the 0.03" shield and the green trace the signal through the 0.04" shield. The red trace is a once per rev signal from the engine. Through the 0.03" shield, the sensor is clearly able to pick up the blade passing, with 24 clearly defined peaks per revolution. The peaks are not all the same height indicating the variation in blade tip clearance with the casing. For the 0.04" shield, though the sensor captured some blade data, not all of the blade passing can be seen and the peaks are not sufficiently distinct to be of use as tip timing data. The same is true for the outputs through the 0.05" and the 0.06" shields.

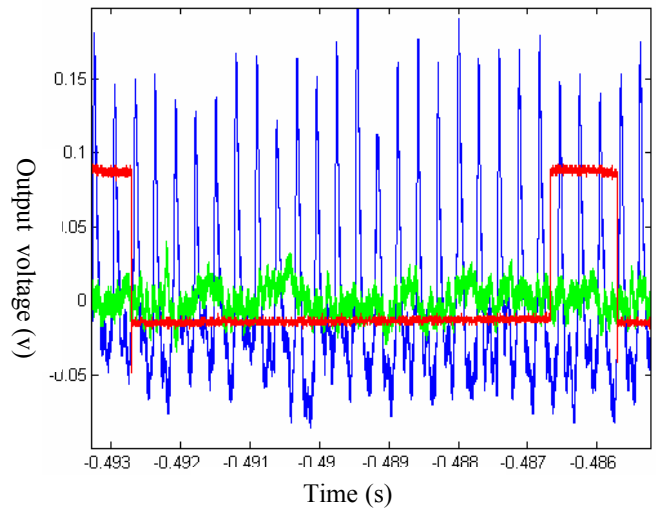


Figure 10: Initial sensor output through 0.030" (blue) and 0.040" (green) thickness casings

On inspection it was found that the static clearance between the blade tips and the casing was larger than the sensors had been configured for and was a significant contributory factor towards the poor quality of the signals. In addition to this, the shield of the sensor pockets was sitting below the surface of the casing. This meant that the sensors had to pick up the blade passing across a large tip gap, as well as the shield thickness operating at the extreme of its range. During the bench tests, this had only been possible through very thin shields. The blades used in these tests were also wider than the fan tips and so presented a better target. During the engine tests, as the engine speed increased the fan tip clearance reduced as the blades untwisted and stretched under the centrifugal loading, enabling some measurements to be made at full speed.

In order to get useable measurements, it was decided to machine back the shoulders of the pockets so that the end of the pocket would sit flush with the inner surface of the casing. Unfortunately, during machining the thinnest shield was damaged and it was not considered safe to remount it on the engine. The other pockets were successfully machined and were remounted on the engine.

Figure 11 shows the output through the 0.04" shield. Taken at full speed, these data show all 24 blades. There is, however, a large variation in the peak height and in particular, two of the blades have very low peaks. The result from the 0.05" and 0.06" shields are very similar to that for the 0.04" shield except that the peaks are slightly lower. It was still possible to count all the blade passings, despite the extra thickness of shield, indicating that the interaction between the sensor, shield and target is not simple.

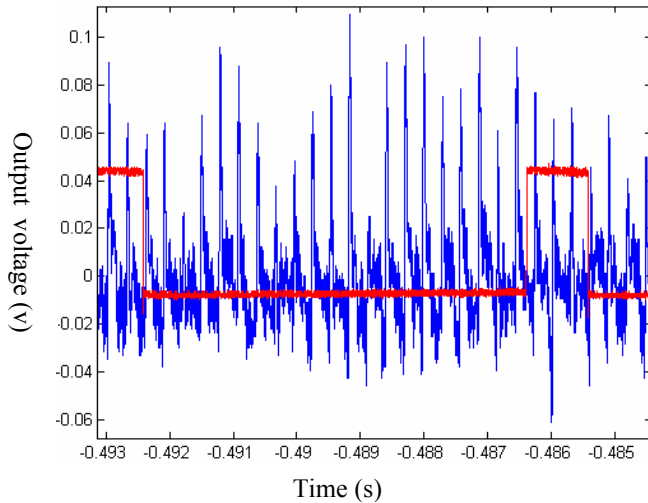


Figure 11: Sensor output through 0.040" thickness casings after tip clearance reduction

After the acquisition of blade passing data through a shield, the ends of the pockets were machined off to allow blade passing data to be taken without any intervening material between the sensor head and the blade tips. Figure 12 shows one of the modified pockets prior to being fitted back on to the engine. In the pocket design, a space was left around the sensor head to eliminate influence from the pocket on the sensor. As it was not considered desirable to leave this space empty after the sensor had been set flush with the end, the space was filled with an RTV compound.

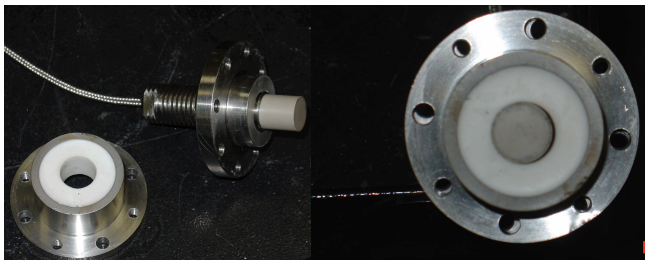


Figure 12: Sensor pocket machined to allow direct line of sight from sensor to blade tip

Figure 13 shows data from one sensor taken at full speed and is typical of the data taken during this phase of the testing. The output is much larger than when a shield is present and in all cases the blade passing is clearly visible. In addition the base noise level is much reduced in comparison to the through case data. In order to be of use in a blade tip timing system, data from sensors must be adequately monitored and conditioned so that the outputs to the engine health monitoring system are both reliable and repeatable.

Although four sensors were fitted into the engine fan casing, each was tested in a slightly different configuration.

The sensors were mounted in blind pockets, the base of which was a different thickness in each case. This was done in order to test the ability of the sensor to operate through casing material and detect blade arrival. The varying signal strength and quality of these data necessarily limit its use in terms of vibration analysis; the prime purpose of these tests being to detect blade passing in the presence of an intervening casing on an engine. Later in the test programme data was taken with the end of the pocket removed in order to maximise the signal strength and improve the raw data quality.

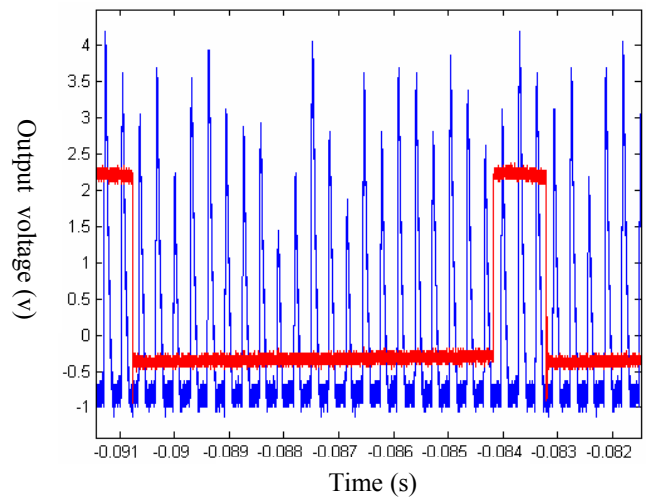


Figure 13: Output from casing sensor during engine operation at full speed

All the sensors successfully survived the engine running throughout the testing with no degradation of the signals becoming apparent. This shows evidence of the high mechanical integrity and immunity from contamination displayed by the sensors. It also indicates that for fan applications the sensors are sufficiently robust to be used without any form of metallic shielding.

The eddy current sensors used in the tests are sensitive to the tip clearance; however the pulse shape generated by each blade is not significantly altered, suggesting that a repeatable amplitude independent triggering technique is possible.

Figure 14 plots data rev on rev from a single data file containing 26 revolutions. Three blade passings are plotted with the ensemble averaged data over plotted. The plot demonstrates that the sensor output is repeatable where the tip clearance is maintained at a near constant value.

Although the sensitivity to clearance of the eddy current sensor offers useful additional information that is not provided by optical probes, amplitude variations lead to increased uncertainty in the determination of blade arrival times when using simple threshold triggering. The amplitude of the output signals from optical probes are not clearance dependant and generally have a very sharp rising edge, with the result that

threshold triggering systems work well with these probes. This can be seen in figure 15 which show data from optical and eddy current probes which were input to a current technology tip timing probe acquisition and analysis system [7].

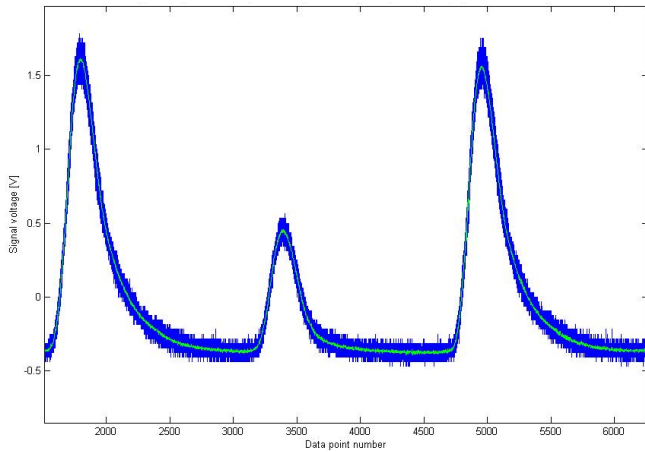


Figure 14: Sensor output data rev to rev and averaged data

For the optical probe data on the left, the arrival time essentially remains flat, except for the fluctuations caused by the blade flutter. On the right, the eddy current sensor data shows that as the engine speed increases, the signal amplitude increases, causing a shift in the triggering position which shows up as a change in arrival time. This results in the output for some blades shifting in relation to the adjacent blades. In both plots, a large blade vibration is detected during the engine acceleration at around 6200 RPM.

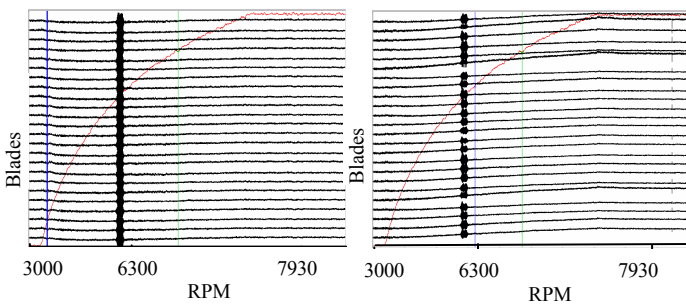


Figure 15: Individual blade waterfall plot, leading edge optical probe (left) and QinetiQ eddy current sensor (right)

The preferred option for correction of this problem would be to develop an alternative triggering technique more suited to the eddy current sensor output signal. However, it may be desirable to input signals into existing acquisition systems that use a threshold triggering system. In order to overcome the uncertainties which occur due to amplitude variations, the

signal would need to be conditioned to remove these variations.

FURTHER SENSOR AND SIGNAL CONDITIONING DEVELOPMENT

Blade arrival times calculated from an amplitude-corrected signal showed promise and it was decided to implement the correction into the signal-conditioning hardware so as to be performed in real time. The signal-conditioning system outputs a square wave that can be fed into existing acquisition systems that use a threshold triggering system. The system also outputs the raw analogue signal. Figure 16 shows the raw and output signals from a prototype signal conditioning system, which clearly shows the output pulse on the falling edge of the raw signal. The conditioning is performed using analogue electronics; however, it is intended to develop a digital signal processing system that allows triggering to occur on the rising edge of the raw signal. It is hoped that this will improve the accuracy of the timing pulse as in some cases the rising edge is considerably steeper than the falling edge.

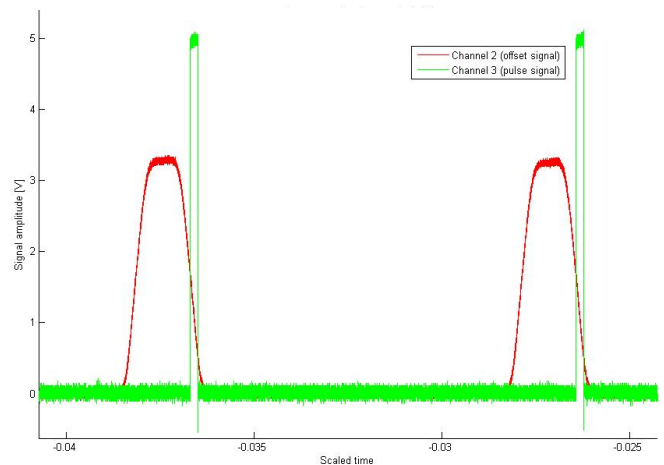


Figure 16: Falling edge triggering technique giving square wave output

After the testing of the Mark 3 eddy current sensors on the AE3007 engine, additional sensor developments were carried out to further improve the sensor performance. Two new sensors were produced that contained modifications to both the sensor coil and driving electronics, to improve sensitivity and range of the sensor. These sensors were then tested against a Mark 3 sensor in a series of bench tests. Figure 17 shows the output from all three sensors at the same tip gap setting. The figure shows that development sensor 1 (red trace) performed better than the Mark 3 sensor (blue trace), but development sensor 2 (green trace) performed worse. This result was repeated over a range of tip gap and speed settings. It was also repeated for a number of different sensor mounting holders,

used to simulate the presence of a casing around the sensor head.

Results of these tests led to the selection of development sensor 1 for use in testing. This sensor has been optimised to give a better resolution and sharper signal, however, it is sensitive to orientation. To assess the performance of the sensor in different orientations further bench tests were carried out over a simulated axial flow fan blade with the camber line of the blade at approximately 45 degrees to the axial direction. The sensor was mounted over the rotor tip and oriented axially, circumferentially and along the blade camber line. The results show that when axially aligned the sensor output was reduced in comparison to the other two orientations. The camber line orientation signal has a sharper peak, with peak amplitude 30% higher than the axially oriented probe, and a higher percentage signal rise per mm. However, all three signals exhibited a very similar shape.

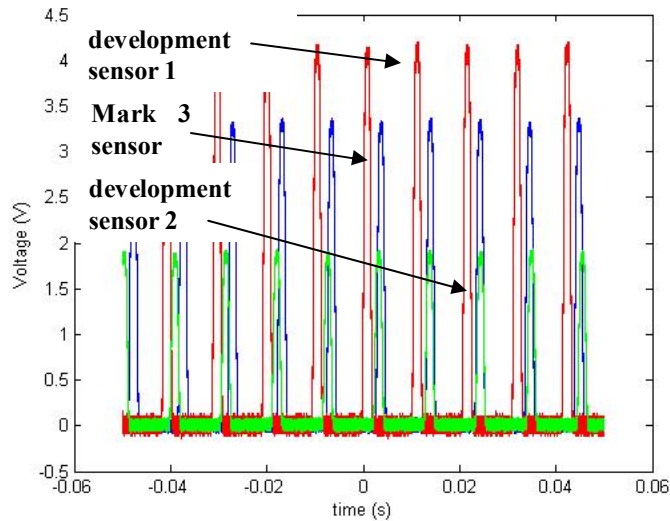


Figure 17: Variation in output from further development sensors

Prior to the use of these sensors in the engine tests it was necessary to carry out a test under representative conditions. These tests were carried out on a spin facility at Rolls-Royce Derby (see Figure 18). The sensor was mounted over the tip of a model fan stage in the facility and the rotor spun to simulate engine conditions in terms of tip speed and blade passing frequency (however, the spin rig blades are made of a single solid material, so did not simulate normal fan blades and unlike an engine there is no casing), an optical probe was also mounted in the facility. The sensors were mounted on a traverse table and data were taken for a range of tip clearances. Figure 19 shows the various outputs from the sensors. The red trace shows the raw analogue signal from the eddy current sensor, the magenta trace shows the output from the optical probe and the green trace shows the trigger pulse produced by the eddy current sensor analogue electronics. This trace is

similar in form to the optical sensor output and can be fed directly into the BTT system, for blade arrival times and vibration to be calculated using the standard threshold triggering technique within the BTT system. This has the advantage that the existing BTT system, which has had over a decade of development, can be deployed for blade vibration analysis using the signal from the new eddy current based tip-timing probe.

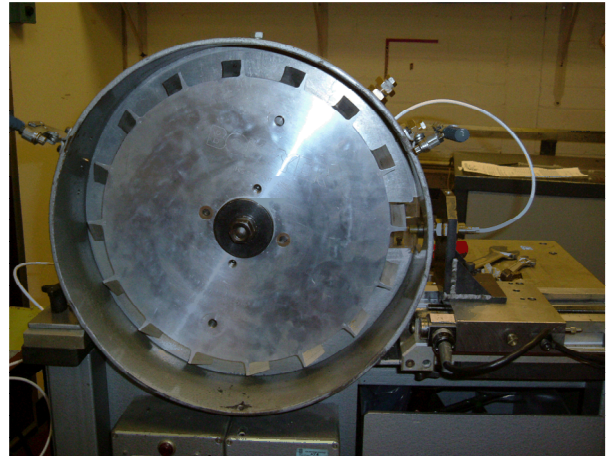


Figure 18: Simple spin facility, Rolls-Royce Derby

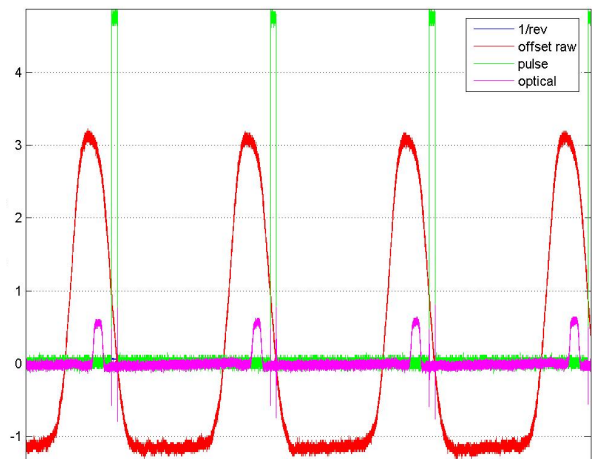
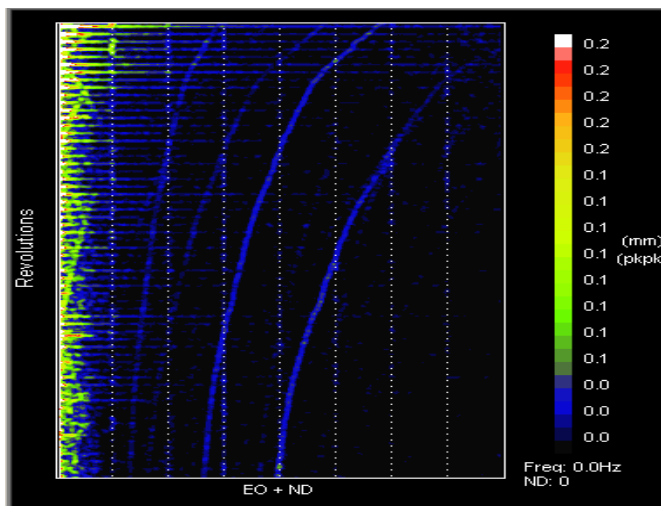


Figure 19: Sensor outputs from spin tests carried out at Rolls-Royce

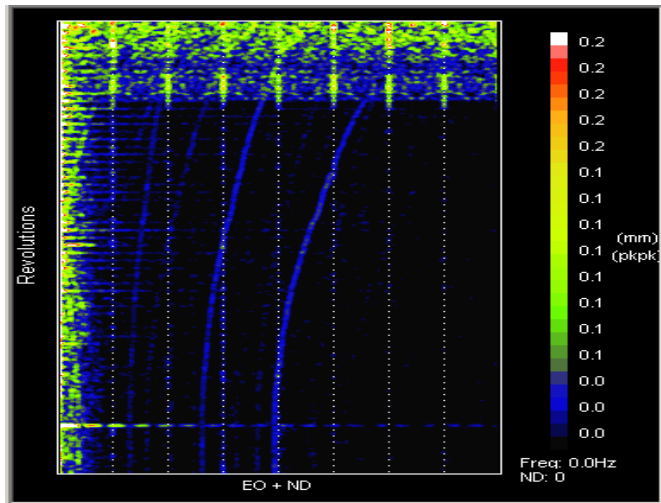
Figure 20 shows a comparison of the tip-timing results from the eddy current sensor and optical probe. The output from the eddy current sensor, on the left clearly show frequency components and vibration data and is comparable to the output from the optical probe. In these tests, the eddy current sensors were validated to perform as well for blade tip clearances up to 2.5mm and for blade deflections down to 0.1mm [2].

SPEY ENGINE TRIALS

Further validation tip timing trials were also conducted on the QinetiQ Spey engine test facility, an open air test facility based at the Shoeburyness ranges. A Spey RB168-101 engine was selected for the trial. Holes were machined in the upper half of the casing to locate the sensors. Seven eddy current probe locations were machined in to the fan casing on both the first and second stage rotor rows and in addition 5 optical probe locations were machined which were interleaved with the eddy current sensor positions. Six eddy current sensors and five optical sensors were fitted to measure on the blade leading edge on both stage rotors.



Eddy current system



Optical system

Figure 20: Tip-timing results showing frequency components from eddy current and optical probes

One eddy current sensor on both rows was fitted to measure the trailing edge position; these sensors were

positioned such that they could measure the blade twist in conjunction with one of the leading edge sensors. The sensors can be seen fitted to the fan casing in figure 21. To reference blade position a once per revolution signal was recorded from the engine.

Two types of eddy current sensors were deployed to detect blade vibrations, 13mm and 6mm. The 13mm sensors have a range up to 7mm and the 6mm sensors have a range of about 3mm. The sensors were flush mounted with the inner wall of the casing and the cold blade tip clearance was measured at approximately 3.5mm. The blade tip width at the measurement point near the leading edge was approximately 3mm. The tip geometry for the second stage is similar in profile to the first stage rotor but with a reduced chord length. At the trailing edge sensor location the trailing edge thickness is ~2mm.



Figure 21: Eddy current sensors mounted in the fan casing

Each eddy current sensor was fitted with a 10m cable that was taken to a near by cabin which had the driver circuitry to power and condition the sensors. In addition QinetiQ electronics were deployed to remove the tip clearance effect; these were located in a different cabin where the data acquisition was positioned.

A dedicated data acquisition system, comprising a high performance industrial PC and high speed multichannel timer card, was used for both stages of the fan rotor.

The blade time of arrival pulses are accurately timed by the high speed timer cards at 50MHz and the time of arrival of each blade tip stored by the data acquisition system. The time of arrival data are stored to the PC hard drive. This method allows the rotors to be monitored for long periods without accumulating excessively large amounts of data. Some raw data were recorded from eddy current and optical sensors with the once per rev signal on high speed oscilloscopes to allow raw data quality checks and to allow direct comparison of the signals.

A typical test cycle involved starting the engine and bringing it to idle, low pressure shaft speed approximately 2,300 rpm. The runs consisted of a series of accelerations and decelerations of the engine with data being recorded throughout on the tip timing system and snap-shots of raw data

taken on the oscilloscopes. The accelerations and decelerations were varied from a few seconds to approximately 4 or 5 minutes.

COMPARISON OF EDDY CURRENT AND OPTICAL DATA

Early in the testing inclement weather conditions persisted with almost continuous rain, this caused the optical sensors to suffer severe contamination from the water droplets. However, good quality blade passing data were captured with the optical probes on dry days where they remained clean enough to generate high quality pulses during the test programme. Figures 22 and 23 give typical engine speed traces with blade arrival time for eddy current and optical sensors respectively.

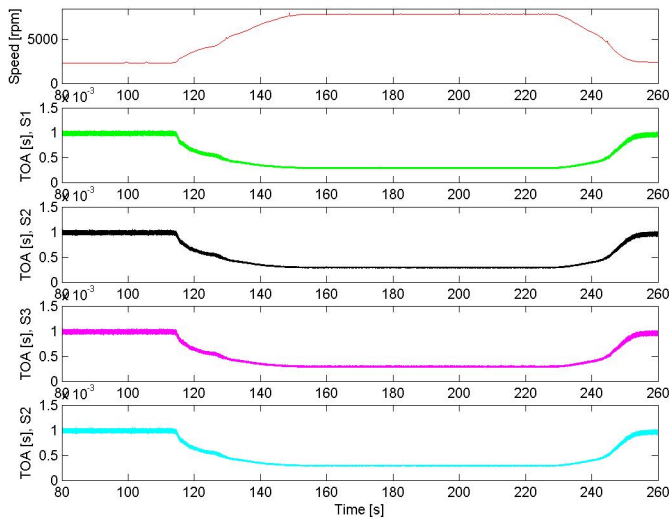


Figure 22: Speed and eddy current sensor time of arrival (TOA) data

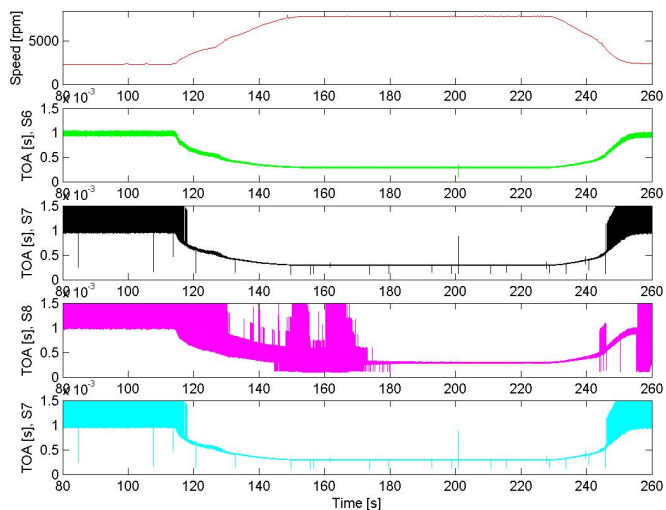


Figure 23: Speed and optical sensor time of arrival (TOA) data

Figure 24 shows a plot of blade deflection against engine speed for eddy current and optical probes on the second stage rotor. The top figure shows eddy current sensor data, which has a trace for each blade over the complete engine acceleration/deceleration. Each horizontal line tracks the blade deflection as the engine accelerates from idle (2,300rpm) to 80% speed (7,900rpm). The result clearly show the blade natural resonances as the engine is accelerated, which start at about 4,000rpm and end around 5,000rpm. Notably the blade

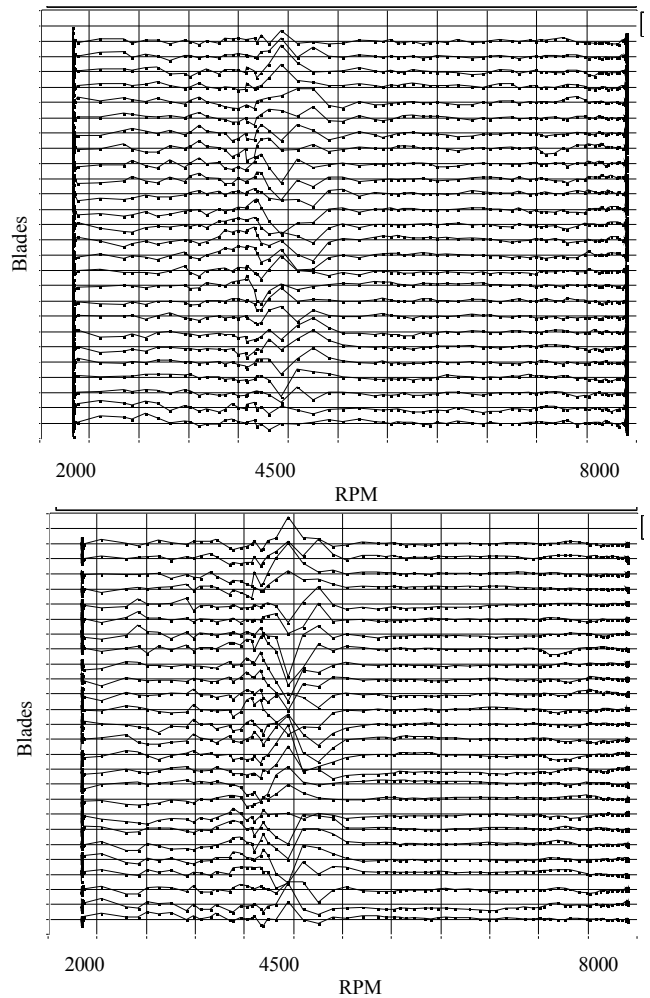


Figure 24: Waterfall plot - blade resonance with speed – eddy current sensor data (top), optical data (bottom)

deflections are relatively larger at idle than at full speed. The largest resonance was detected at 4,300rpm and was most likely associated with the natural resonance of the blade coinciding with the wake shedding frequency of the upstream stator. The lower plot gives a waterfall plot for optical sensor data. Overall the eddy current and optical sensor data show

very similar results, the eddy current and optical sensors are approximately 15° apart.

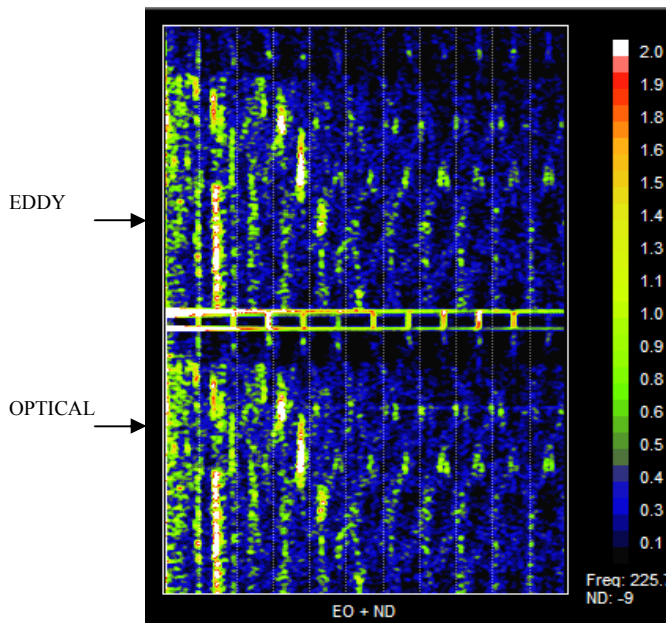


Figure 25: Comparison of optical and eddy current vibration data

Figure 25 shows a plot of optical and eddy current sensor BTT data from the Rolls-Royce tip timing analysis program. Each plot shows a deceleration. The time or revolutions on the Y axis and a frequency measure along the X axis. The contours indicate the magnitude of the deflections. The agreement between the plots is excellent even into the high frequency regions towards the right hand side of the plot. Previously, comparisons of the optical and eddy current sensors showed significant differences at high frequency. This has been overcome by the use of directional eddy current sensors and improved conditioning electronics.

SUMMARY AND CONCLUSIONS

Eddy current sensors, which are immune to contamination, have been developed by QinetiQ for tip-timing measurement that has potential for in-service use. The sensors have demonstrated their effectiveness on engine fan trials and shown themselves to be extremely robust.

The QinetiQ eddy current sensor has been optimized to make tip timing measurements through casing material and engine tests showed blade passing data could be acquired through casing material up to 1.5mm thickness. The demonstration shows that eddy current sensors have great potential for use in a through the casing tip timing system.

Signal conditioning electronics have been developed using an alternative triggering technique more suited to the eddy

current sensor output signals. The system has been validated in a series of engine tests. The electronics allow the triggering correction to be carried out in real time which allows the use of tip timing acquisition and analysis systems developed for optical systems.

The output from the eddy current blade tip timing system has provided measurements equivalent to the optically derived data even at high frequencies.

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