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THE USE OF EDDY CURRENT SENSOR BASED BLADE TIP TIMING FOR FOD DETECTION

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ABSTRACT

Deterioration of rotor blades due to foreign object damage (FOD), erosion by sand/water, low cycle fatigue (LCF) and high cycle fatigue (HCF) all limit blade life, but cannot always be detected before a failure. The advent of tip-timing systems makes it possible to assess turbomachinery blade vibration using non-contact systems. However, these systems are still largely optical based and therefore suffer from contamination problems, further development of these systems is difficult due to problems associated with keeping the sensors clean.

Experimental measurements have been carried out using an alternative eddy current sensor that has been validated in a series of laboratory and engine tests to measure rotor blade arrival times. A series of engine trials have been conducted to assess their capability for detection of pre-existing damage and the capture of dynamic foreign object damage (FOD) events. The results show that it is possible to acquire high quality blade timing data for use in engine condition monitoring. In addition for the detection of FOD created damage and FOD damage as it occurs.

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.

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 to optical probes. Other sensors have been tested for use as tip timing sensors in health monitoring systems as well as methods for damage detection, e.g. Von Flotow [1,2].

The aim of this research was to demonstrate robust, easy to deploy blade tip-timing probes that are immune to contamination and employ associated electronics for use on in-service engines, to achieve improved probe life, higher temperature capability and better spatial resolution than is currently available with non-optical probes. Results from earlier back-to-back eddy current and optical probe engine trials, reported in GT2008-50792 [3], indicate that the QinetiQ eddy current sensor is capable of providing results that are comparable to an optical tip timing probe and at the same time is immune to contamination. On the success of the early trials further trials to demonstrate the sensor capability to detect foreign object damaged (FOD) blades and dynamic FOD events. Details of the sensor and associated electronics are reported in ASME paper GT2008-50792.

Recent work to evaluate tip-timing sensors using the eddy current principle for use in in-service engines has been conducted at QinetiQ Shoeburyness on a Spey RB168-101 engine using QinetiQ eddy current sensors and industry standard optical probes for comparison purposes. Seven eddy current and four optical sensor locations were fitted over the first and second stage fan rotors. Data were recorded at a number of different configurations and engine speeds. Blade passing data (time of arrival) was obtained with and without damaged blades fitted to the engine. In addition tip timing data was obtained during a dynamic FOD event by releasing objects such as small stones at the inlet to the engine.

ENGINE TESTS

Foreign object trials were conducted on the QinetiQ engine test facility based at Shoeburyness ranges. This facility is remotely stationed such that higher risk trials, such as with damaged blades or with foreign objects released at inlet to the engine, can be carried out. The engine used for the trials is a Spey RB168-101, holes could be machined in to the upper half of the casing to locate the sensors.

Seven eddy current probe locations were machined in to the Spey fan casing above the first and second stage rotor rows as shown in figures 1 and 2. In addition 5 optical probe locations were machined; these were interleaved with the eddy current sensor positions. Six of the eddy current sensors and all optical sensors were fitted to measure on the blade leading edge on both stage rotors. One eddy current sensor on both rows was fitted to measure the trailing edge position; this sensor was positioned such that it could be used in conjunction with a leading edge sensor to measure the blade untwist. To reference blade position and obtain an accurate speed measurement a once per revolution signal was recorded from the engine.

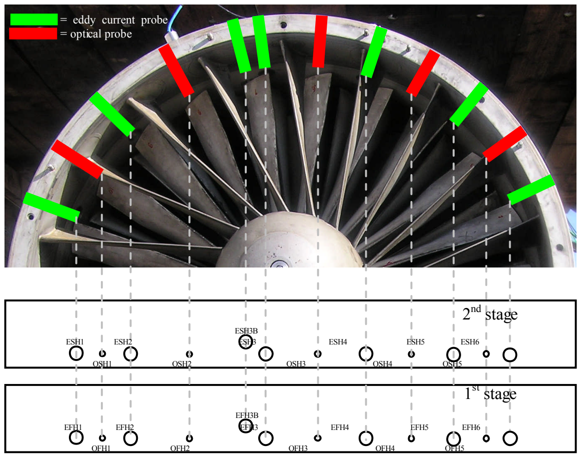

Figure 1: Position of eddy current and optical sensors

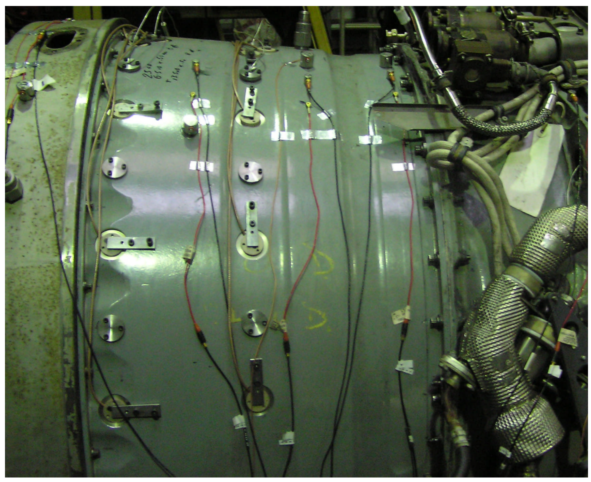

Figure 2: Eddy current and optical sensors fitted to the fan casing

Two types of eddy current sensors were deployed to detect FODed blades and dynamic FOD events, 13mm and 6mm. The 13mm sensors have a range up to 7mm whereas the 6mm sensors have a range of about 3mm. The sensors were flush mounted with the inner wall of the casing, the cold blade tip clearance was estimated to be approximately 3.5mm. The blade tip width at the measurement point near the leading edge is approximately 3mm. 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.

Four (XP84049) optical spot probes were fitted to the first and second stage fan rotors. On each stage the probes were arranged to be over the leading edge of the rotor, at the same axial position as the centre of the eddy current sensors, but separated by a circumferential distance. The probes were fitted equispaced between the eddy current probes. All the optical probes were routed to a nearby cabin where they were connected to a 'laser brick' for the laser transmission and receive signals.

The optical probe conditioning 'laser brick' provides illumination into one half of the bifurcated fiber optic, which is transmitted to, and emitted from the tip of the probe. As the blades on the rotor under test pass the probe, some light is reflected back into the probe, and is transmitted into the other half of the fiber bundle to a detector.

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 systems. The preferred option for correction of this problem was to develop an alternative triggering technique more suited to the eddy current sensor output signals. This was initially developed and validated in software and has since been implemented in analogue electronics. The analogue electronics allow the correction to be carried out in real time allowing the use of tip timing acquisition and analysis systems developed for optical systems.

Corrected signals are very similar to the optical probe output signals and is of a square wave form therefore, making it ideally suited for threshold triggering.

A dedicated data acquisition system, comprising a high performance industrial PC and high speed multichannel (10 channel) timer card, was used for both stages of the fan rotor. Blade time of arrival pulses are accurately timed in this system by the high speed timer cards at 50MHz. Time of arrival of each blade tip is stored by the data acquisition system. This method allows the rotors to be monitored for many hours without accumulating large amounts of data, since the raw data is not stored.

Some raw data were recoded at high bandwidth from eddy current and optical sensors to allow the raw data quality to be compared and to perform a direct comparison of the signals.

TEST CONDITIONS

A typical test cycle involved starting the engine and bringing it to idle, low pressure shaft speed approximately 2,300 rpm. After a few minutes to allow the oil system to warm runs could commence. For the runs, a series of gentle accelerations and decelerations of the engine were performed, with data being recorded throughout on the tip timing system and snap-shots of raw data taken on storage oscilloscopes. The runs started at the idle speed of 2,300 rpm and accelerated to 8,000 rpm and back down to 2,300 rpm before the next test.

The accelerations and decelerations were varied from a few seconds to approximately 4 or 5 minutes; in addition some runs were carried out with accelerations followed by a period of dwell at a certain speed and then further accelerations or decelerations.

DATUM TESTING

Tip timing measurements were initially taken on the first and second stage fan rotors, both of these have unshrouded tips and are without snubbers. The blade material is an aluminum alloy. The blades on these rows were not deliberately damaged. Some blades on the first stage rotor did show evidence of slight operational FOD damage, which was estimated to be less than 0.5mm in depth. The second stage rotor blades had significantly less damage which was of order 0.25mm. Once measurements had been taken with the datum set of blades three second stage rotor blades were removed and replaced with blades from a different set taken from a spare engine. Tip timing measurements were taken over a number of cycles as described on the stage two fan rotor.

All the eddy current sensors successfully survived the engine running throughout the tests showing the high mechanical integrity and immunity from contamination displayed by the sensors. This also indicates that for fan applications the sensors are sufficiently robust to be used without any form of metallic shielding.

A comparison of the blade deflections for the datum and added blades has been presented in figure 3 using eddy current sensor data. The three replaced blades are clearly evident and show a large change in position in comparison to the datum measurements. Deflection of three blades can be noted to have changed significantly in comparison to the other blades. Using the once per rev, these were confirmed to be the locations at which the different blades were fitted. The different blades appear to be arriving later than the other blades this translates to an aerofoil deflection towards the suction side of the blade of approximately 2.5mm.

This deflection is thought to be caused by the blades taking up a different position as the engine accelerates and the blades lock due to the centrifugal force. This is most likely caused by slight differences in the root fixing as a result of the manufacturing process as they are from a different batch.

Figure 4 gives comparable results for optical sensor data which shows the same result. Surprisingly the original blades do not all compare for the datum and changed blade results, blades 5, 8, 21 and 22 show a difference in both the eddy current and optical results. Further examination of other eddy current and optical sensor data shows that the difference is found with the same blades on each measurement. This behavior could be expected of blade 5 as it neighbors blade 4 and could have been disturbed aerodynamically however, blades 8, 21 and 22 are not neighboring blades. The effect that is most likely to have caused this change is an alteration of the mass balance of the rotor (blades plus disc), since the three different blades were not matched in weight to those removed, nor were they fitted with similar blades opposite. This is likely to have caused an out of balance of the rotor assembly.

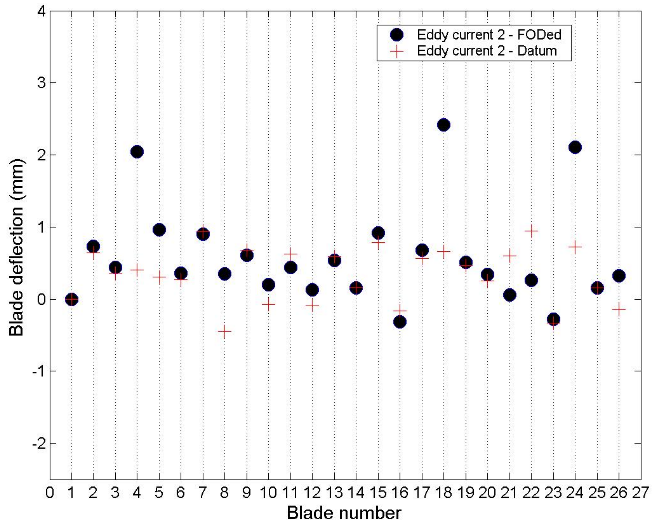

Figure 3: Blade deflection with datum and added blades – eddy current sensor

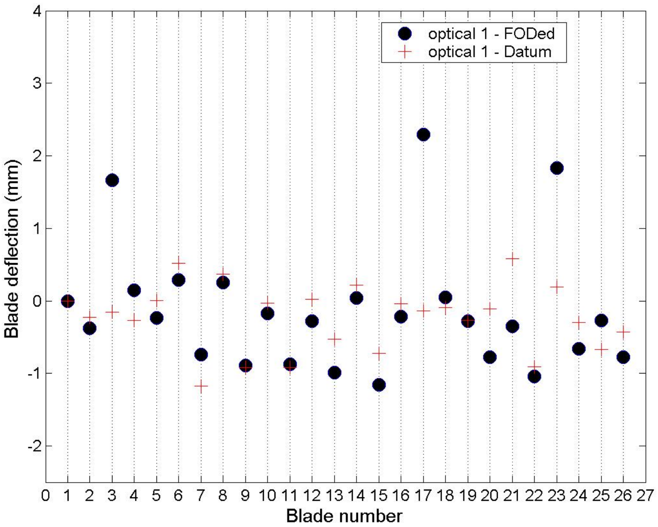

Figure 4: Blade deflection with datum and FODed blades – optical sensor

Figure 5 gives a comparison of an eddy current sensor and two optical sensors; optical sensor 1 is close to eddy current sensor 2 (see figure 2) whereas, optical sensor 4 is almost 90° from eddy current sensor 2. The comparison between the optical and eddy current is reasonable given that the sensors are in different circumferential positions and would therefore measure the blade during different parts of the vibration cycle. Notably blade 9 shows the largest difference between sensor 4 and the other two sensors.

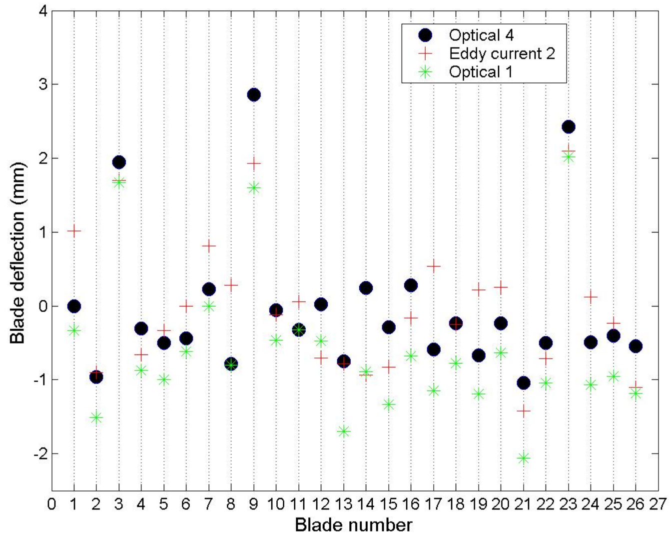

Figure 5: Blade deflection with added blades – Optical sensors 1 and 4 and eddy current sensor 2

SIMULATED FOD

Tip timing measurements were carried out on the second stage fan rotor to assess the ability of the system to detect simulated FOD, which was done by deliberately damaging some of the rotor blades.

Three second stage rotor blades (numbers 1, 7 and 15) were removed and artificially damaged in a similar manner to that expected in service, simulating FOD damage at three different span-wise locations. Figure 6 shows the three damaged blades. The damage was kept to the leading edge with blade one damaged in the top one third of the span by removing a wedge section of approximately 6mm width and depth. Blade two was damaged in a similar manner but near the mid-span. The third blade was damaged within the lower third of the blade and was kept to about 3mm. Tip timing measurements were taken over a number of cycles as described above on the stage two fan rotor with the damaged blades fitted.

Although some datum runs were carried out prior to damaging the blades, subsequently it became apparent that these were insufficient to carry out averaging between runs. Further in to testing it became apparent that more datum runs were required to obtain a better average, hence two more blades were damaged (numbers 2 and 20). Blade 20 was damaged at mid height on the leading edge with a 'V' cut to simulate FOD, and blade 2 at mid height on the trailing edge with a small slit, to simulate a crack. Following this the blades were re-fitted and more tests carried out. Figures 7 and 8 show the simulated FOD on these blades.

Figure 6: Damaged blades (Numbers 1, 7, 15) fitted to engine

Figure 7: Damaged blade (Number 2) fitted to engine

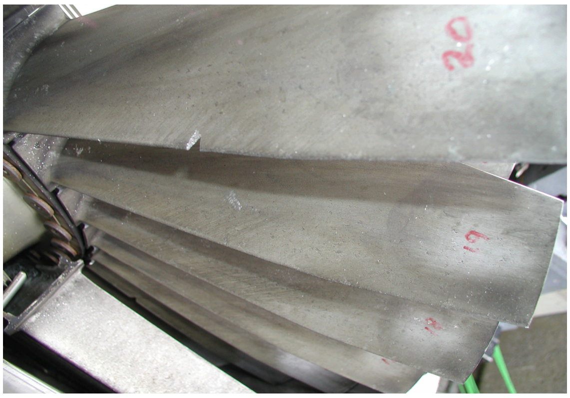

Figure 8: Damaged blade (Number 20) fitted to engine

The engine was then run over a number of test cycles and tip timing measurements obtained. Figure 9 shows a comparison of averaged rev to rev blade deflections at full speed over about 1000 revolutions. Each trace represents a different cycle and the plot contains data from both datum and simulated FOD runs. These data were taken from eddy current sensor 2. The maximum average deflection is approximately ± 1mm notably the results in this figure do not particularly identify the damaged blades however, there is a separation in the data on blades 4 and 24. These represent blades 7 and 1 respectively on the engine and are two of the three damaged blades. The third damaged blade, blade 15 appears on the plot as blade 12, although in this case there appears to be little effect on the blade position. In addition there is some separation on blades 17 – 21 (on the plot) but it is not evident on every cycle. Clearly the results from damaged and undamaged runs show that a change in the blades has occurred. Figure 10 shows the average of the traces in figure 9. This more clearly shows the separation on blades 4 and 24.

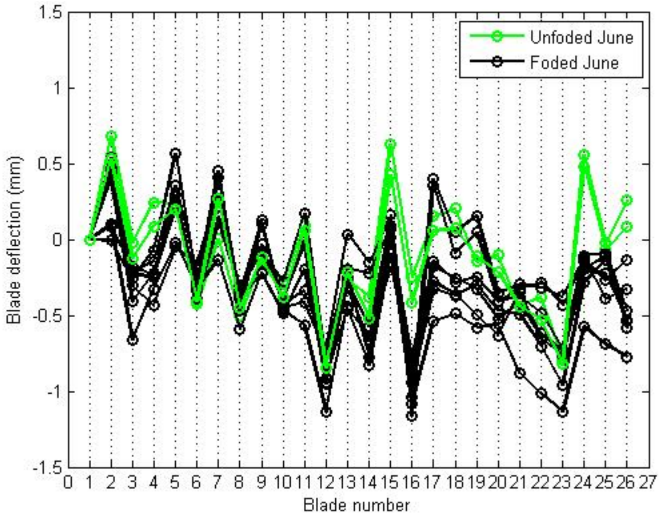

Figure 9: Average rev to rev deflection FODed and unFODed blades

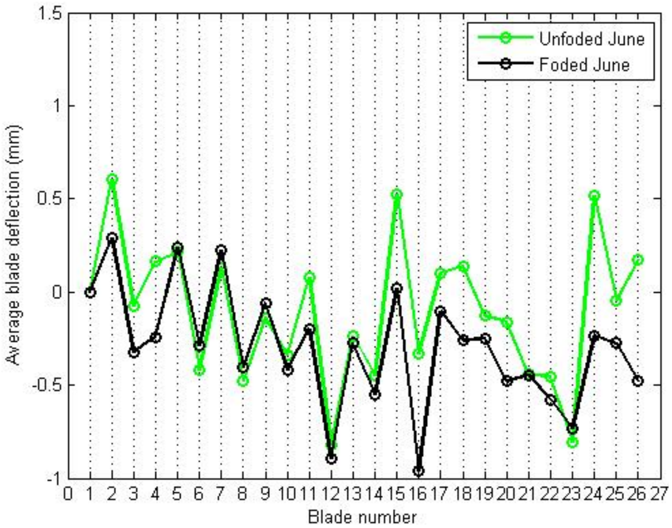

Figure 10: Average rev to rev deflection FODed and unFODed blades

As the datum dataset was small, more blades were damaged in an attempt to produce larger datasets for comparison. This further damage was applied to blades 20 and 2 (on the engine). Figures 11 and 12 show this data averaged as in figures 9 and 10 for the original and additional simulated FOD data. The additional damage to blades 20 and 2 appears in the figures as blades 17 and 25 respectively. As in the datum comparison there is very little to mark out the damaged blades, although some changes have occurred between the datum and FOD results. Identification of the damaged blades is not obvious however a change in the blades is easily identified. Examination of the data in this form does not show conclusive results, however there may be other methods available for processing this data which will allow identification of the damaged blades. Analysis of the blade movement using multiple sensors may reveal changes in the unsteady behavior of the blades before and after being damaged. Further processing of the data are being carried out to try and identify the damaged blades however, this may not be necessary in-service as detecting a change in the blades should be sufficient to indicate damage. There are a number of reasons why the damaged blades are not clearly seen, the first is that the mass balance of the rotor blades will have changed causing the behavior of some blades to change, secondly the blades have a pin fixing at the root and this may not be taking the identical position on every run-up of the rotor assembly. In fact each time the rotor is spun it is unlikely that all blades will take the same position when they lock as this will depend on when the blade locked i.e. was it in the vertical, horizontal or inverted position relative to the rotor rotation. The locking position could be examined by carrying out where the engine fan was brought to rest on every spin-up and with some runs performed where the engine brought to idle and re-accelerated.

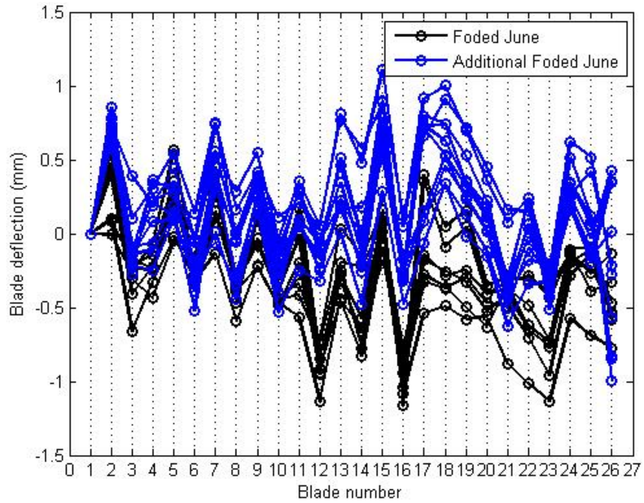

Figure 11: Average rev to rev deflection original and additional simulated FOD

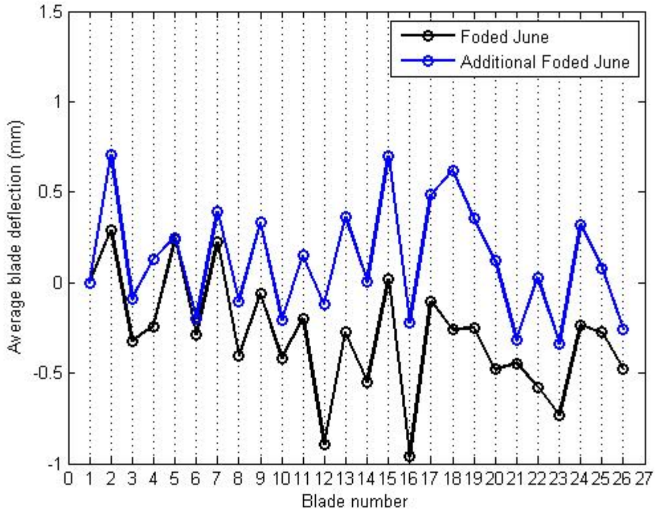

Figure 12: Average rev to rev deflection original and additional simulated FOD

It became apparent quite quickly that after shut down blades take up slightly different positions when the engine is next run but if the engine is only brought back to idle between acceleration cycles, the blades maintain their average position. Figure 13 shows a series of ten traces of average blade deflection at full speed over four engine start ups. Within each start up the engine was brought back to idle and back up to full speed before the next set of data was recorded. Although there is variation between all the traces, there is a definite grouping by start up cycle.

What is not known is if a more modern blade fixing such a dovetail or furtree root would exhibit the same behavior and if this particular result is as a result of the pin fixing.

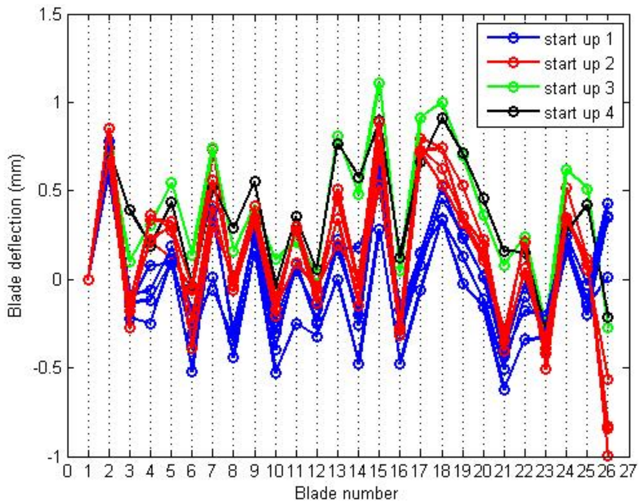

Figure 13: Average rev to rev deflection grouped by start up

DYNAMIC FOD

The dynamic FOD events were carried out on the engine by introducing foreign objects into the inlet duct of the engine. Release of the foreign objects was achieved by removing the standard inlet duct and replacing it with a longer duct with a hole approximately half way along the top. The foreign objects were remotely released from the grip of a QinetiQ robot with the engine running at 80% speed, 8,000rpm on the low pressure shaft.

Foreign objects chosen were of three types, pencil erasers, crayons and small pebbles of various sizes. Although it was known from previous tests that damage would be sustained on the blades when stones are used, it was necessary to impact the blades sufficiently to produce an excitation that could be measured. A selection of the foreign objects used is shown in figure 14.

A major part of the trial was to conduct a series of dynamic FOD tests while monitoring the first stage rotor. In these tests BTT, oscilloscope and vibration transducer data were obtained. Due to the limitations on the number of eddy current sensor signal conditioning channels, monitoring of both the first and second stage fan rotors was not possible.

Figure 14: Foreign objects used for dynamic FOD

Detection of the eraser being ingested into the engine was not possible and is therefore not included here. Figures 15 to 19 cover the data from a FOD test using crayons. Figure 15 shows an LP shaft speed trace together with a plot of blade arrival time interval from an eddy current sensor. The speed trace shows the run over which data were recorded. The engine starts at idle, then accelerates to approximately 4000 rpm before accelerating again to 8000 rpm and then decelerating back to idle. The FOD event occurs during the period at full speed. A disturbance is visible on the arrival time interval trace during this period which is caused by the FOD event at approximately 540 seconds. Figure 16 shows a casing vibration trace taken at the time of the FOD event and triggered by the event. These vibration traces are a good indicator of the timing of FOD events, but give no indication of which blades have been affected and the likely level of damage sustained. The vibration transducer was fitted directly above the first stator on the casing. Figure 17 shows a waterfall plot for the same sensor for the period of the run at full speed. It can be seen that just before rev number 28000 on blade 4 that there is a disturbance which causes the deflection to shift dramatically for one rev and subsequently leaves the blade in a different average position. The initial disturbance marks the point and, the blade which took the main FOD impact. There are also smaller disturbances on most of the other blades at the same time. They may also be smaller pieces of the FOD (as it shatters) item as it is broken up and impacts other blades. It could also be, however, a slight disturbance on the once per rev signal, which is used as a reference. A closer inspection of the once per rev signal shows no evidence of any disturbance at this point in the run. Figure 18 shows the average and rev to rev blade deflection for the same period as covered by the waterfall plot (approximately 10000 revs) at full speed. The largest instantaneous deflections can be seen on blades 4 and 5. The deflections are calculated using a tip radius of 400mm, which is close to the actual value, although at 10mm this seems quite large, although it may be that the FOD impacted as the blade approached the sensor. The immediate effect of the strike lasts only three revolutions of the rotor furthermore, as noted in the waterfall plot, the blade takes up a slightly different average position after the strike. In addition many of the other blades show small deflections (much smaller) for a single rev, these out lying deflections as mentioned previously may be caused by a slight disturbance on the once per rev, which should affect all the blades equally, or because the FOD is broken into multiple pieces creating small impacts on other blades. Once again no noticeable disturbance can be identified on the once per rev signal.

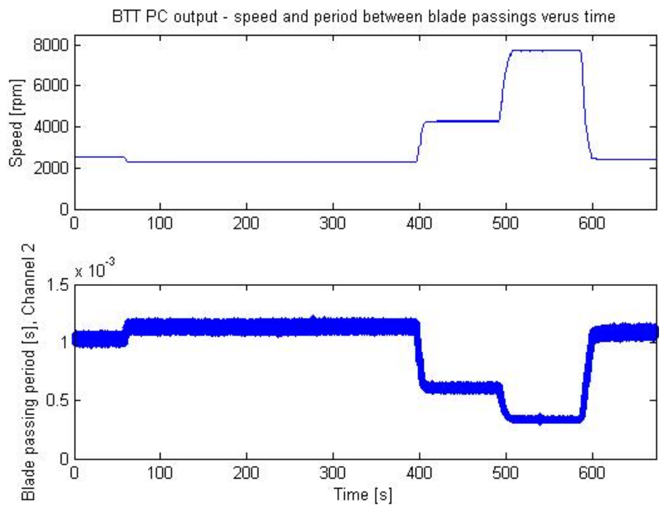

Figure 15: Speed plot and Eddy current sensor blade arrival time plot

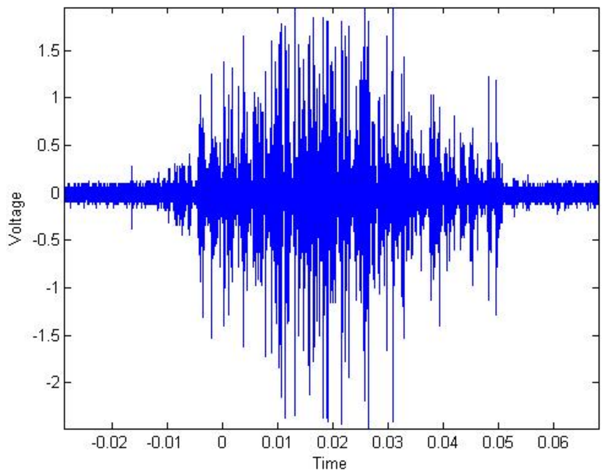

Figure 16: Vibration plot during FOD event from casing mounted vibration sensor

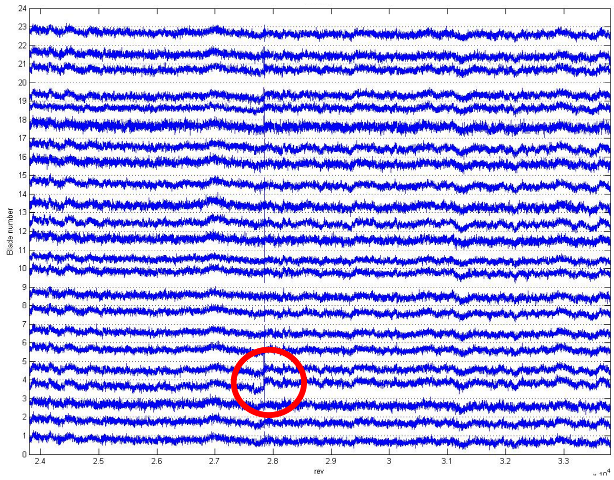

Figure 17 Waterfall plot showing FOD strike

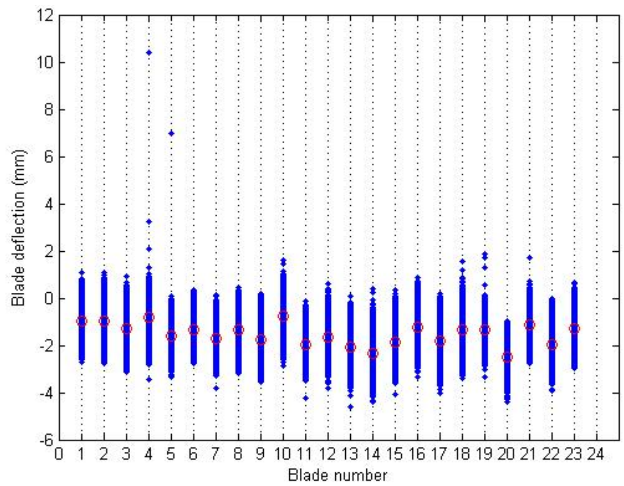

Figure 18: Average (red) and rev to rev (blue) blade deflections showing FOD strike

Figure 19 shows average (at least 1000 revs) and instantaneous blade deflections at the point of the FOD strike. Notably the deflected blades (4 & 5) can be clearly identified.

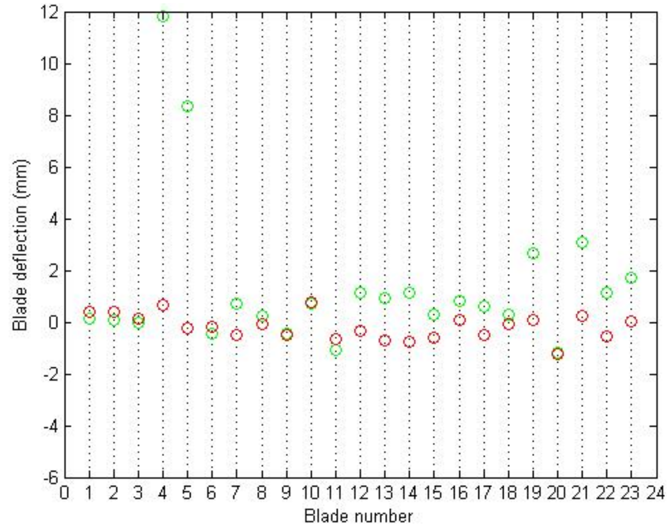

Figure 19: Average (red) and single rev (green) blade deflection

Figures 20 to 24 show a similar set of plots for a test using a stone as the FOD item. Figure 20 shows the speed plot and blade passing interval. The lower plot contains blade passing information for all blades from sensor 2 and has no influence in this plot from the once per rev signal. The FOD event is apparent as a disturbance in the plot just after 150 seconds into the run.

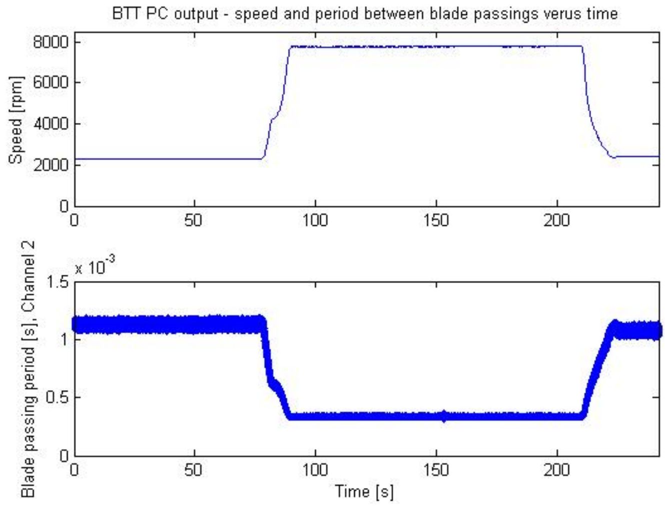

Figure 20: Speed plot and Eddy current sensor blade arrival time plot

Figure 21 shows the waterfall plot for the portion of the run at full speed. The FOD impact is apparent on blade 9 at around rev number 12000. As in the previous example there is a sharp spike in the deflection of the blade after which its position and general level of deflection are altered. In this case however, there appears to be very little effect on the other blades. This is further evidenced in figure 22 where there is only a single outlier which, appears on blade 9, the blade that was struck with the foreign object. The strike is again clearly evident in figure 23 which again shows the average and instantaneous deflection at the point of impact.

Figure 24 shows a photograph taken after the completion of the FOD tests which clearly shows evidence of FOD sustained during the trial.

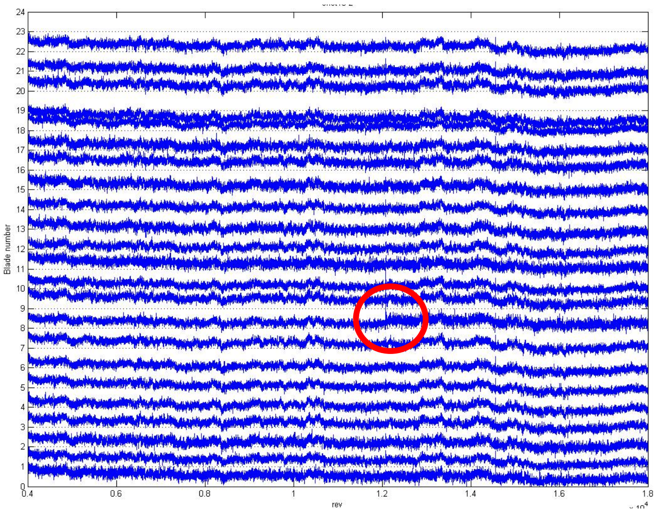

Figure 21 Waterfall plot showing FOD strike

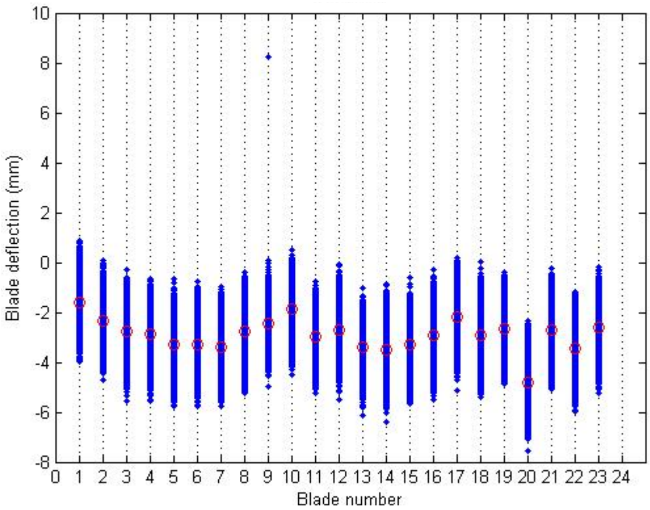

Figure 22 Average (red) and rev to rev (blue) blade deflections showing FOD strike

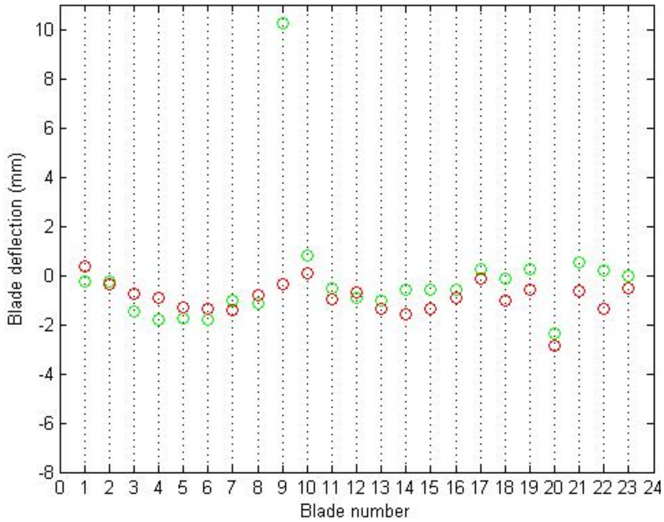

Figure 23 Average (red) and single rev (green) blade deflection

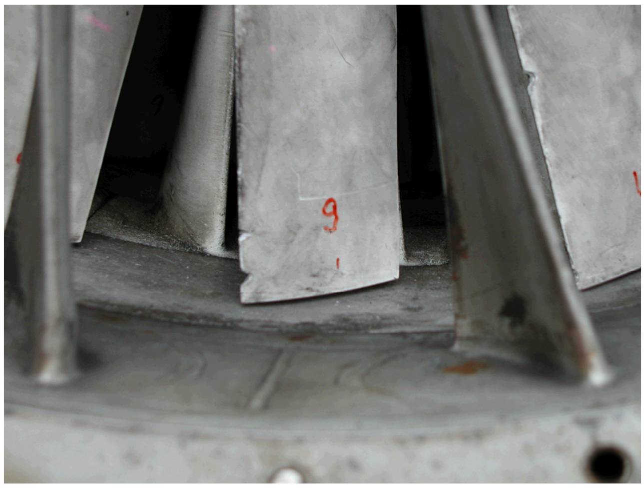

Figure 24 Dynamic FOD damage on first stage rotor

SUMMARY AND CONCLUSIONS

The use of tip-timing systems allows turbomachinery blade vibrations to be assessed using non-contact systems. The only useable system in industry is currently optical based. However, these systems are still only used on development engines, largely because of contamination issues which cannot be readily eliminated

Alternative sensors, which are immune to contamination, based on the eddy current principle have been developed by QinetiQ for tip-timing measurement that have the potential for in-service use. The sensors have been demonstrated on both the AE3007 engine fan and on the JSF LiftFan®. The eddy current tip timing system has now been used on a Spey engine to carry out further validation and to assess their capability for FOD detection.

A series of tests have been successfully completed in which QinetiQ eddy current sensors were mounted on the first and second stage fan rotors of a Spey RB168-101 engine in an open-air test facility based at QinetiQ Shoeburyness. These tests were used to demonstrate the ability of the eddy current sensor to measure the blade deflection and vibration. In addition the tip timing system was used to investigate the possible use of eddy current sensors for the detection of existing FOD and dynamic FOD events. The ability of the eddy current sensors to detect simulated FOD was investigated by fitting the Spey engine with five blades from the original second stage rotor set deliberately damaged to simulate FOD. Analysis of averaged blade passing data was not entirely conclusive in identifying the exact blades damaged on every occasion however, there was some effect on the blade position after the blades were damaged indicating that, even using averaged data the sensors were capable of detecting changes in blade position. Although examination of averaged data did not identify all damaged blades, analysis of the blade movement using multiple sensors may reveal changes in the unsteady behavior of the blades before and after being damaged. Measurements during the simulated FOD tests revealed that the average blade position varies slightly each time the engine is started, but remains relatively stable throughout engine cycles where the engine is not stopped. This is likely to complicate identification of damaged blades using average blade position

A series of dynamic FOD tests have been carried out with eddy current sensors monitoring the first stage rotor. In these tests a large high quality blade tip timing dataset was obtained. Dynamic FOD events have successfully been captured using the tip timing system with both soft and hard FOD impact events. Preliminary single sensor analysis of the data revealed both the impact and subsequent behavior of the affected blades. It was revealed that the initial dramatic effect of the impact lasts for only a very few revolutions, in some cases only one. Subsequently the blade is left in a different average position and its response to forcing and flutter may also be affected. This aspect has yet to be investigated. A comparison of optical probe and eddy current sensor BTT data analysed at Rolls-Royce [3] showed the data to be almost identical in quality even into the high frequency regions where previously poor frequency response compared to optical probes was thought to be one of the limiting factors in the use of eddy current sensors in tip timing measurements.

High bandwidth acoustic emissions vibration sensors were fitted to the exterior of the fan casing and measurements successfully captured using a high speed oscilloscope.

Further analysis of the tip timing data is needed to fully understand the potential for detecting simulated FOD and dynamic FOD events and to assist in the development of an off line or real time vibration or tip timing analysis system.

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