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Tubomachinery Blade Vibration Amplitude Measurement Through Tip Timing With Capacitance Tip Clearance Probes

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Abstract

Turbomachinery blade vibrations can cause High Cycle Fatigue, which reduces blade life. In order to observe this vibration a non-intrusive monitoring system is sought. The vibration can be detected by measuring blade tip timing since in the presence of vibration the blade timing will differ slightly from the passing time calculated from rotor speed. Much research and development has gone into investigating the ability of optical probes to achieve this. However, this paper looks at the potential for a dual use capacitance probe sensor to measure both tip timing and tip clearance. This paper provides new insights into the ability of a commercially available capacitance probe tip clearance measurement system for application as a non-intrusive turbomachinery blade tip timing measurement device. This is done by correlating capacitance probe tip timing results with simultaneously measured blade-mounted strain gauge vibration results and precise rotational speeds. Blade tip vibration amplitudes are measured using capacitance probes and compared to strain derived vibration levels. Thus the characterisation and quantification of the performance of the capacitance probe system when measuring blade vibration on a full-sized low-speed research compressor is analysed and reported.

Keywords: Capacitance Probe; Tip Timing; Tip Clearance; Turbomachinery; Blade Vibration

1. Introduction

Capacitance probe based clearance measurement systems see widespread use in turbomachinery applications to establish rotor blade tip clearance. This paper reports investigations into an alternative and additional use in aero-engine rotor blade tip timing measurement for these commercially available systems. Tip clearance is of great importance in the gas turbine industry; this is clear from the fact that gas turbine efficiency has an inverse relationship with tip clearance [1] [2]. Large tip clearance leads to large leakage flows, hence low efficiency, thus the common use of the capacitance probe clearance measurement technique in monitoring turbomachinery.

The most suitable method of capacitance probe for turbomachine tip clearance measurement is the frequency modulated (FM) capacitance probe. This method was first developed by Chivers (1989) [3] [4]. The work suggests that it is superior to a DC system for on-engine applications as FM capacitance probes are unaffected by gas ionisation effects that are present in gas turbines. It is also the case that DC systems have relatively poor frequency response, making their calibrations highly RPM dependent [5].

The vibration of turbomachinery blades is an important event to understand, observe and predict and is the reason for developing a tip timing measurement system. Vibration leads to High Cycle Fatigue (HCF), which limits blade durability and life. HCF can result in blade failure, having expensive consequences for the engine involved. The traditional method for monitoring blade vibration under test conditions is to use blade-mounted strain gauges. However, strain gauges are costly and time consuming to install. They have a limited operating life as they are subjected to the harsh engine conditions. Only a limited number of blades can be monitored with strain gauges as the number that can be used is limited by the number of channels in the slip ring or telemetry unit. They can also interfere with the assembly aerodynamics. Consequently non-intrusive alternative techniques such as tip timing are sought.

A survey of the open literature in blade tip timing shows that measurement systems are dominated by optical techniques. The laser Doppler method for tip timing measurement was first proposed in the 1970s [6]. The optical technique is appealing as it meets the high bandwidth requirements of tip timing measurements.

Optical systems have been successfully used on test rigs with several optical probes mounted equally spaced around the turbomachine casing. These systems can be used to obtain vibration amplitude through curve fitting and vibration frequencies by using Fourier analysis. Alternatively, algorithms on the signals from a number of probes over a number of rotor revolutions may be used to determine vibration amplitude and frequency [7]. However, there are practical problems associated with mounting such monitoring systems on in-service jet engines. Optical probes require high maintenance to keep the lenses clean, probably incorporating a purge air system to keep the lenses from fouling. Such

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impracticalities and added weight make it unlikely that an optical probe based tip timing system will be fitted on an in-service engine in the foreseeable future.

As an alternative to optical probe tip timing, this programme of research set out to investigate the practicalities of developing a dual use capacitance probe based sensor that is capable of measuring both turbomachinery blade tip clearance and tip timing. The capacitance probe has greater potential than the optical probe as a dual use sensor as it is difficult to measure tip clearance on a turbomachine using an optical probe, particularly an in-service jet engine again due to fouling issues. This will be achieved by taking an existing commercially available FM capacitance probe based turbomachinery blade tip clearance measurement system and using it to measure blade tip timing. Thus, this programme of research embarks on an extensive body of practical experimental work in order to gain an understanding of the capacitance probe's application as a tip timing measurement device. This work culminates in blade tip vibration measurement through capacitance probe tip timing.

To date, there has been one published example where the performance of capacitance probes was compared to an optical system's performance in tip timing measurement [8]. That report found that the optical system showed superior amplitude resolution to the capacitance probe system. This suggests that optical tip timing systems can detect blade vibration amplitudes more accurately than the capacitance based system.

Work has also been reported on specially designed capacitance probe head geometry, with the aim of improving the capacitance tip timing measurement [9]. This design is based on a multi-element probe head to improve spatial resolution. However, this type of probe head geometry is likely to have the disadvantage that it produces signals with lower signal to noise ratios than the signals produced with traditional probe head geometry. This is a factor which is vital to optimise in order to maximise the accuracy in timing measurements. A lack of comparative measurement performance data prevents any meaningful conclusions from being drawn thus far from this work.

Since the capacitance probe system is already established as the on-test-rig tip clearance measurement system, if it can be shown (or developed) to have a dual use in also adequately measuring tip timing, then the need to also engine-mount an optical probe based system would be negated.

This paper goes on to report the measurement of blade vibration using a commercially available capacitance probe based tip clearance measurement system. Results are presented and measurements are assessed against an independent strain gauge based blade vibration measurement system.

2. On-Rotor Non-Vibrating Blade Tip Timing

A series of on-rotor capacitance probe tip timing experiments have been conducted prior to the commencement of the on-rotor blade vibration measurement test programme reported here. These tests established the capacitance probe system's ability to time blade arrival using non-vibrating blades. This work is reported in detail by Lawson and Ivey (2003), so will only be summarised here to provide background and context to the work presented in this paper [10].

Compressor rotor blade vibrations have been measured using blade mounted strain gauges in conjunction with energising signal amplification electronics on the rotor. Vibration levels were found to result in very small amplitudes of blade tip deflections of not more than 20 microns. Hence, these tip timing investigations are essentially performed on non-vibrating blades.

The resolution with which the time of arrival of the blade can be determined with the capacitance probe based tip clearance system has been evaluated. This was done by measuring the blade passing period over several consecutive revolutions. This period was compared to the period measured by the optical Once Per Revolution (OPR) sensor. The consistency of these measurements was assessed at the compressor's designed operating speed of 850 RPM.

The capacitance probe period was found to be consistent within two microseconds over the entire sample of data collected. This represents approximately 0.1 mm tip displacement in the aforementioned test conditions. This is within the expected error bands, as assessed by Lawson (2003) [11].

3. Test Equipment and Instrumentation

3.1. Compressor Test Facility

A full-sized, low-speed compressor test facility was commissioned at Cranfield University's Gas Turbine Engineering Laboratories to provide a vehicle for the experiment programme reported here. The facility is a one and a half stage compressor comprising Inlet Guide Vane (IGV), rotor and stator stages. A 60 kW electric motor drives the compressor. The facility is classified as 'low speed' as its 850 RPM designed operating speed and 1200 RPM maximum speed are approximately 10% of the speed of a typical modern industrial turbomachine.

The diameter of the machine's hub at the rotor is approximately one meter. The diameter of the flow passage is 1.2 meters. The flow passage is approximately five meters long. The exhaust outlet area is controlled by a back pressure valve, which is operated using a small electric motor.

The compressor's rotor is fitted with three times oversized blades. This results in an operating airflow more representative of the airflows found in high-speed engines [12]. The blades have thus been designed with future machine airflow research in mind, rather than the blade tip timing measurement system being researched in this project. The rotor is comprised of 79 blades, each measuring 90 mm in the radial direction and a 59 mm chord from leading edge to trailing edge. They are cast in LM24 aluminium alloy. The stator and IGV stages each contain 72 blades.

3.2. Capacitance Probe Based Tip Clearance Measurement System

The capacitance probe based system being used in this investigation to measure tip timing is commercially available as a turbomachinery tip clearance measurement system.

The RotaCap system supplied by Rotadata Ltd., Derby, UK is an FM capacitance probe based tip clearance measurement system. The system includes a mineral insulated capacitance probe connected to an oscillator module by a semi-rigid stainless-steel sheathed tri-axial cable which is filled with powdered mineral insulation. The oscillator module provides a 10 MHz frequency throughout the probe assembly. This connects via an interconnecting cable to a demodulator unit. The demodulator optimum operating bandwidth is 100 Hz to 70 kHz. The system electronics are calibrated by tuning the Phase Locked Loop to the same frequency as the oscillator. This is achieved by turning a screw on the demodulator unit.

4. Once Per Revolution Sensor

An essential factor in using tip timing to measure blade vibration is knowing the precise rotational speed of the compressor's rotor. This is achieved through the design of an optical once per revolution sensor. In order to make this sensor as accurate as possible three areas must be considered, namely; mechanical issues, optics and electronics.

Physically, the system used consists of a statically mounted laser and receiver arrangement and a fin mounted on the rotor. The fin cuts the laser beam once per rotor revolution; hence with the use of some electronic circuitry a precise RPM is obtained.

To maximise the accuracy of the system it is desirable to cut the laser beam as quickly as possible at any given rotor RPM speed. This will maximise the resolution with which the arrival time of the fin at the laser beam can be determined. To this end, the fin is mounted radially as far out as possible, just below one of the blade roots. Thus, the tangential fin velocity for any given angular velocity is maximised.

Analogue receiver and Schmitt trigger based digitiser circuits were designed and used to provide a digital OPR passing signal. The optics and electronics used are described in detail in Lawson (2003) [11].

The overall uncertainty of the OPR sensor timing is assessed in detail in Lawson (2003) [11]. It was found to be of the order of, and no worse than 0.1 microseconds. This represents approximately 5 microns tip deflection at a rotor speed of 850 RPM. This error level is expected to be at least an order of magnitude lower than that of the timing measurements taken from the capacitance probe system, thus a more precise definition of the OPR error is unnecessary for this application.

It should be noted that the precision optical OPR sensor used on the test rig here is unlikely to be practically applicable in a development engine. It was used here in these tests as the most accurate means by which to determine RPM, thus maximising the accuracy by which the performance of the capacitance probes tip timing measurements could be assessed. However, in moving the proposed capacitance probe tip clearance and tip timing system to application on a development engine, an alternative method of determining RPM is likely to be required. One method which could be successful is to use the capacitance probes themselves to also determine RPM, in a potential tri-use arrangement. By using a standard development engine non-precision OPR sensor to trigger each revolution event, all the blade passing signals from the capacitance probes could be used to calculate the RPM.

5. Strain Gauge Blade Vibration Measurement System

To provide an independent blade vibration measurement for comparison with the proposed vibration measurement through capacitance probe tip timing, blade mounted strain gauges are used to derive blade tip deflections. These instrumented blades, when calibrated can provide a separate system to compare the capacitance probe tip timing against.

In Lawson and Ivey (2002) it was identified that two strain gauges per blade should be mounted to allow detection of the first four modes of the blade's vibration [13]. The locations and orientations of the two gauges on the blade's surface were also determined through finite element stress analysis. Robust, high performance strain gauges were chosen for the task. The gauges are encapsulated in glass-fibre reinforced epoxy-phenolic resin to protect them. The foil is 1.57 square millimetres, made from Nickel-Chromium Alloy and of electrical resistance 350 Ohms. The gauge positions are shown in Fig. 1.

6. Strain Gauge Energising and Signal Amplification Circuits

An electronic circuit was developed from first principles to energise the blade mounted strain gauges and amplify the resulting signal. The circuit was designed with on-rotor operation in mind although it was initially used in static off-rotor tests.

On-rotor operation of the blade mounted strain gauges necessitates that the strain gauges' signals be passed through a slip ring to route the signals to the data acquisition PC. The slip ring introduces significant noise to the strain gauge signals. In order to greatly increase the strain gauge signal to system noise ratio, pre-slip ring (on-rotor) amplification of the strain signals is used. Fig. 2 shows a block diagram of the circuit concept.

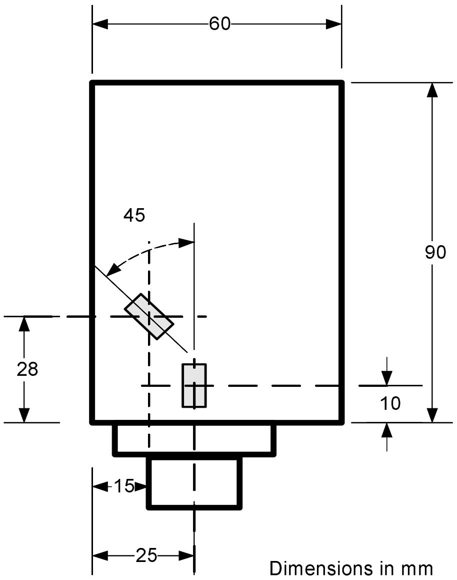

Fig. 1. Blade-mounted Strain Gauges

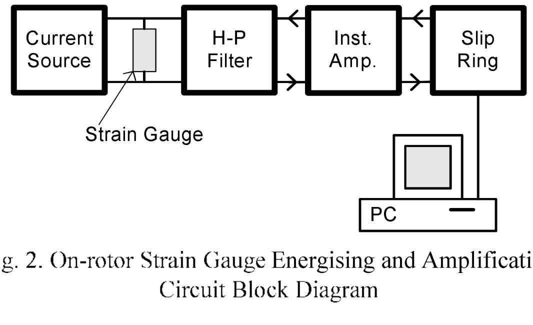

Fig. 2. On-rotor Strain Gauge Energising and Amplification Circuit Block Diagram

7. Strain Gauge Signal to Tip Deflection Calibration

In order to relate the changes in resistance of the blade mounted strain gauges to blade tip deflections, calibration tests were carried out at Rolls-Royce plc. During these tests the first four modes of vibration of the compressor rotor blades and quasi blades were investigated by measuring the natural frequencies of vibration and capturing the mode shapes. The quasi blade is a flat plate of 2 mm thickness with the same length and breadth as the original compressor blade.

The blades were mounted on a V-block and excited on a crystal exciter vibration table. The natural frequencies were measured using Electronic Speckle Pattern Interferometry (ESPI) and the results are shown in Table 1. Here the results are also compared to the frequencies obtained through FEA results reported in Lawson (2003) [11].

Table 1
Measured and Simulated Blade Natural Frequencies

Mode	ESPI Measured Frequency	Simulated Frequency	Discrepancy
1	244 Hz	243 Hz	0.4%
2	736 Hz	740 Hz	0.5%
3	1471 Hz	1486 Hz	1.0%

Holography was used to capture the mode shapes of the blades. Blade tip deflections were measured using an optical system, while strain gauge signals were simultaneously captured. Deflections were measured at three points on the blade tip; at the leading edge, mid chord and at the trailing edge. This was done while exciting each blade and quasi blade at each of the first four natural frequencies of vibration in turn. Calibration factors were thus established in terms of MPa/mm. Chosen example calibration factors for the compressor rotor blades and quasi blades are presented in Table 2.

Table 2
Strain Gauge to Blade Tip Mid Chord Deflection Calibration Factors

Case	Calibration Factor	Error
Vibration Mode 1:		
Root Gauge	16.9 MPa/mm	29%
Leading Edge Gauge	5.1 MPa/mm	33%

The errors in the calibration factors arise from the signal to noise ratio of the strain signal generated during calibration and the number of fringes visible in the ESPI images. For the blade the errors are high at around 30%. This is due to the small strain level present during calibration (24 microstrain) and the sparsity of the fringes generated using ESPI. The low number of fringes limits the accuracy with which the tip deflections can be determined to during calibration. The low strain level results in a low signal to noise ratio obtained during the calibration process. Both of these effects contribute to produce the large error bands associated with the blade calibration factors.

8. Experiment Method

A strain gauge instrumented quasi blade was mounted on the compressor's rotor and its vibration was measured using the electronics and equipment previously described. A low stiffness blade was used to ensure sufficiently high levels of vibration during testing. Blade vibration measurement was also performed through tip timing using two capacitance probes. These probes were mounted on the compressor's rotor ring at two of the five circumferential positions available. The rotor ring comprised a ring surrounding the rotor, forming part of the compressor's case. The probes were positioned to study blades passing fixed circumferential positions on the rotor casing. The capacitance probes were positioned over the paths where the mid-chord of the blade tips pass. The set-up is illustrated in Fig. 3.

Compressor rotor speed was measured using the optical OPR sensor. The capacitance probe, OPR and strain gauge signals were captured using data acquisition hardware and software. Three PC's were used running three different hardware and software combinations. Acquisition was synchronised using the OPR sensors signal.

The time of OPR signal's arrival was measured by digital timer acquisition hardware and was taken as when the OPR digitiser output crosses the +2V level (goes digital high). This was clocked by the timer hardware at 80 MHz.

The precise rotor speed was measured using the optical OPR sensor. The distance that the instrumented blade travels from the triggering of the OPR sensor until detection of the blade by the capacitance probe could then be calculated by measuring tip timing. These distances were measured in the absence of blade vibration. This value was then compared to the distance measured when the blade was vibrating. The difference between these distances is the instantaneous blade tip vibration displacement level. The concept is illustrated in Fig. 4.

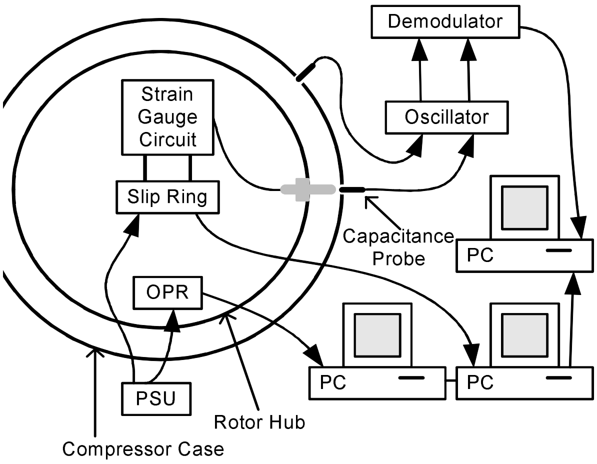

Fig. 3. On-Rotor Experiment Set-Up

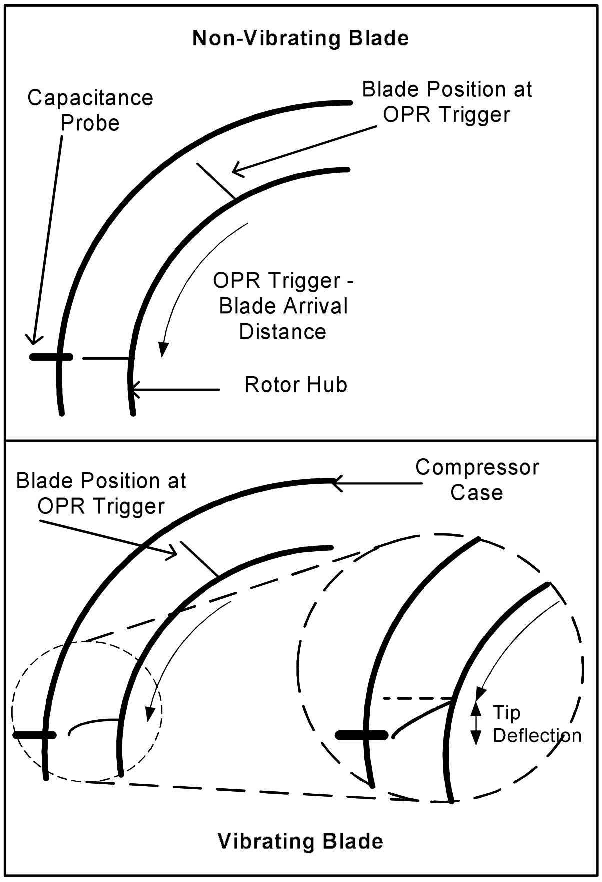

Fig. 4. Blade's Travelled Distance

9. Experiment Results and Analysis

9.1. Strain Gauge Derived Blade Vibration Measurement

At the rotor speed of 938 RPM the instrumented blade was observed to resonate in the first mode of vibration. This is the expected result since the 16 engine order frequency at this rotor speed coincides with the first natural frequency of the blade. The source of the 16 engine order is the 16 compressor intake struts.

The Power Spectral Density (PSD) plot of the root strain gauge signal shows that the frequency of vibration is 253 Hz as illustrated in Fig. 5. This is in accountable agreement (within 4%) with the frequency of the first mode of vibration reported from simulations and from ESPI tests in Table 1. The discrepancy is due to on-rotor centrifugal stiffening effect. Spectrally, this is also true for the voltage trace from the leading edge mounted strain gauge.

Given this single frequency of vibration content of the voltage signal, the tip displacements may be directly calculated from both strain signals. This is done by using the appropriate strain level to tip deflection calibration values (see Table 2) and electronic circuit properties in conjunction with Eqn. (1). A full derivation of Eqn. (1) is given in Lawson and Ivey (2003) [10].

$$d = \frac{E \cdot \Delta V_{out}}{cal \cdot GF \cdot R \cdot G \cdot I} \qquad (1)$$

Tip displacement vibration level traces have been derived from the root strain gauge and leading edge strain gauge respectively by using the method described in the preceding paragraph. The amplitudes of tip deflection derived from the two strain gauges are not in good agreement, being 1.5 mm and 0.9 mm respectively for the typical sample data presented here. However, this is consistent with the large errors associated with the strain to tip deflection calibration values as explained in Section 7.

The root mounted gauge consistently measures higher tip deflections than the leading edge mounted gauge. To mitigate the large errors, the average of the two tip deflections derived is taken as the definitive strain derived tip deflection. Therefore, this results in a tip deflection amplitude of 1.2 mm for the example data presented here. This is some 100 times the vibration levels of the compressor rotor blades used for the 'non-vibrating' tip timing tests reported in the previous findings in Lawson and Ivey (2003) and suggests that the capacitance probe based tip clearance measurement system will be able to detect vibrations of this amplitude [10].

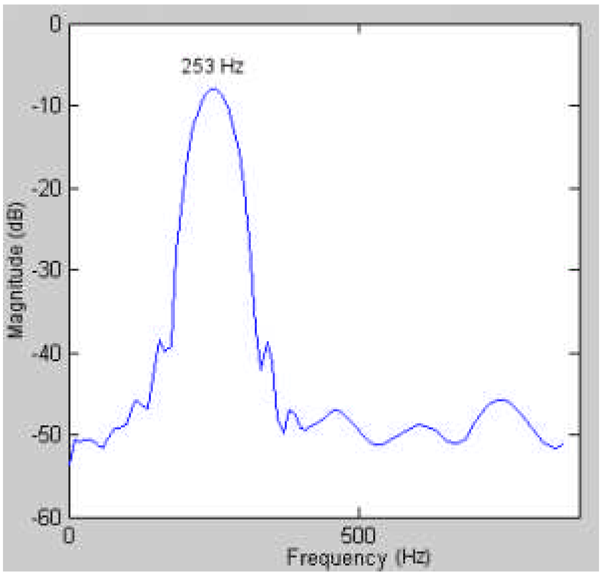

Fig. 5. Root Strain Gauge Blade Vibration Signal PSD

9.2. Blade Vibration Measurement Through Dual Capacitance Probe Tip Timing

The commercially available capacitance probe based tip clearance measurement system's ability to measure blade vibration amplitude through tip timing has been assessed. This has been achieved by using two capacitance probes and associated oscillator and demodulator electronics.

Two capacitance probes were positioned on the compressor case at different circumferential positions. Both were positioned protruding into the flow over the path at which the mid chord positions on the blade's tips pass.

The distance that the instrumented blade travels through from the moment that the OPR sensor is triggered until the tip arrives at each capacitance probe has been measured. This has been done by timing the interval between the OPR sensor triggering and the blade's arrival at each capacitance probe. This timing, in conjunction with the precise rotor RPM speed measured using the OPR sensor, allows the distance travelled by the blade tip to be calculated. Clearly, in the absence of blade vibration, this distance is constant. However, with blade vibration present, this distance will differ from the expected distance due to the blade tip displacement caused by blade vibration. The concept is depicted graphically in Fig. 4.

Before the tip deflection detected through tip timing can be established, it is first necessary to measure, in the absence of vibration, the distance that the blade travels between the OPR sensor triggering and the moment it is detected passing each capacitance probe.

This was achieved by using the blade mounted strain gauges and associated electronics to monitor blade vibration levels, and consequently derive blade tip deflections using the method described in the previous section. The blade's distance travelled is then measured using the capacitance probe at several different RPM speeds where the blade vibration levels are very small.

The blade's time of arrival at the capacitance probe is established using the constant voltage threshold method described in Lawson and Ivey (2003) [10]. This method involves timing the blade arrival by establishing the time index when a threshold value on the leading edge of the signal is crossed. Therefore, this method is only valid for a single blade over a small RPM range, as is the case with the measurements presented here. The instrumented blade was mounted such that it was fractionally longer than the other blades. This simplified post processing of the capacitance probe signals since the instrumented blade then produced a higher signal level when passing the capacitance probe than the other blades. This made it easy to distinguish from the other 78 blades when processing the data gathered from the capacitance probe signals. In real engine testing this method would not be possible since all the blades are more or less the same length. Consequently, more sophisticated post processing would be required.

FORTRAN programs were used to establish the blade passing times by retrieving the time index when the chosen constant voltage threshold is crossed. This threshold voltage was chosen on the rising edge of the blade passing signal, where there is a high rate of voltage change. This is the method of determining time of arrival of the blade at the capacitance probe found to be most accurate from the investigations in Lawson and Ivey (2003) [10].

In these vibrating blade tests the additional threshold criteria was used to ensure that only the instrumented blade passing signal peaks above this threshold voltage value. In this way the time of arrival determination of the blade of interest was easily automated, thus greatly speeding up the data analysis process.

Fig. 6 illustrates the OPR triggering to capacitance probe blade detection distances calculated by averaging measurements over several revolutions at several different rotor RPM speeds. The distance is not constant over the speed range, even at blade non-vibrating conditions. There is a clear trend of decreasing distance measured with increasing rotor RPM speed. This is to be expected and is due to the use of the constant voltage threshold method used to determine time of arrival. Since signal strength increases with frequency, then as rotor RPM increases the blade passing signal peaks get higher. Thus the measured distance becomes shorter as RPM increases. The measured distance can be seen to decrease by 0.15 mm over the speed range 775 RPM to 1050 RPM. The error bars on the trace in Fig. 6 represent the uncertainty in the distance measured. This error is dominated by the small vibration levels actually present when calculating the distance in the 'non-vibrating' condition.

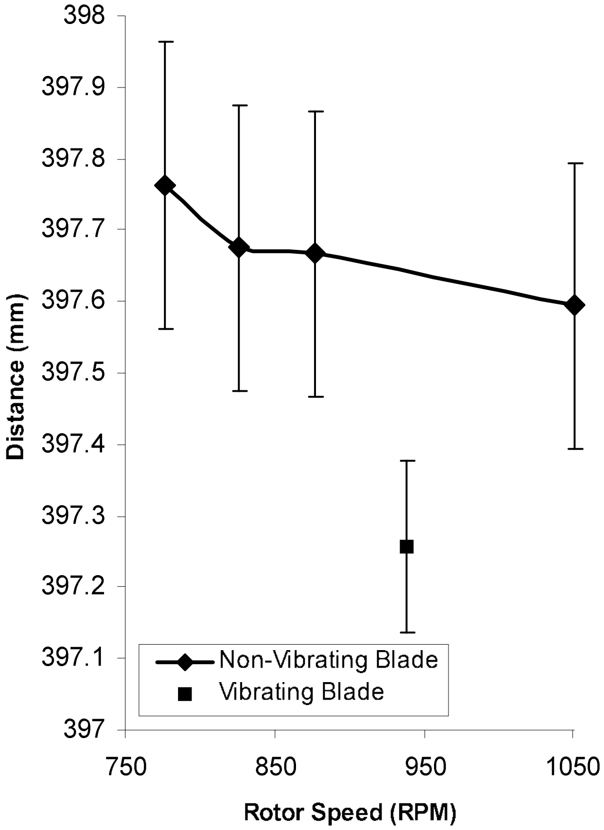

Fig. 6. Blade's Distance Travelled from OPR Trigger to Capacitance Probe 1 Detection

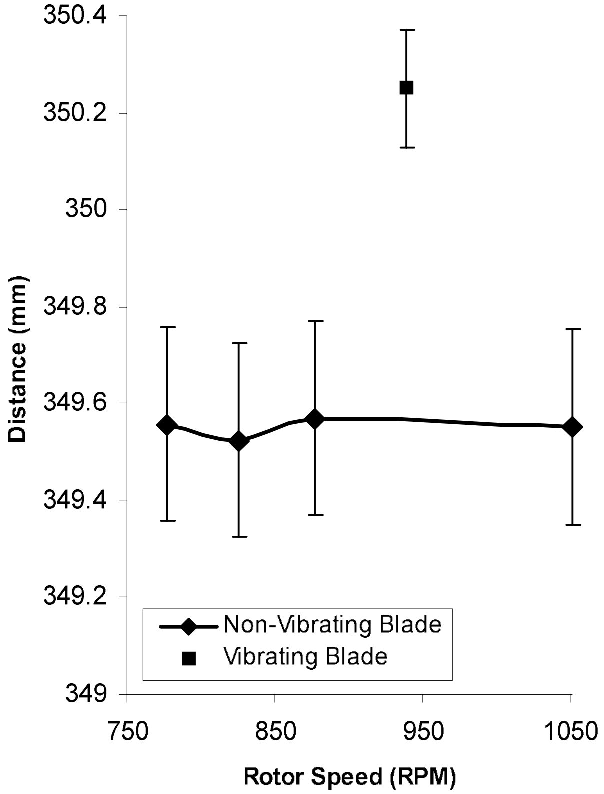

Fig. 7. Blade's Distance Travelled from OPR Trigger to Capacitance Probe 2 Detection

With these distances plotted, the expected distance at the blade resonant condition rotor speed of 938 RPM can be interpolated. This non-vibrating distance must be interpolated since it cannot be measured directly at 938 RPM due to the large vibration amplitudes present. In the test case shown in Fig. 6 this corresponds to 397.65 mm. The actual measured distance at 938 RPM, in the presence of blade vibration is 397.25 mm. This is also illustrated in Fig. 6. Thus, a blade tip deflection of -0.4 mm is inferred.

Fig. 6 and Fig. 7 show these distances as measured through tip timing at capacitance probes one and two respectively. Both of these figures show the distances measured in cases where the blade is not vibrating. The measured distance in the presence of blade vibration is also shown. The difference between these two values represents the blade tip deflection measured through tip timing. In the example data illustrated in Fig. 6 and Fig. 7 this can be seen to be -0.4 mm at capacitance probe number one and +0.6 mm at capacitance probe number two.

The distance between the two capacitance probes has also been measured using tip timing in conjunction with the precise rotor RPM speed measured by the optical OPR sensor. Fig. 8 shows the expected non-vibrating blade condition distance to be 48.1 mm at 938 RPM. The actual physical separation between the capacitance probe mountings is 48.0 mm. As well as the machining tolerances, discrepancies between the distance measured using tip timing and the actual distance stem from capacitance probe clearance setting differences. Small differences in the clearance setting between each probe mean that different peak voltages will be produced when the instrumented blade passes. This fact, in conjunction with the same constant arbitrary threshold voltage value being used to determine blade time of arrival at both of the probes, causes an absolute distance error. Therefore, this distance measurement is most useful as a relative one, used to compare with the distance measurement in the presence of blade vibration. This does not have a detrimental effect on the tip timing measurements, since measurements are relative ones, and as such consistency is the important factor.

Fig. 8 shows a measured distance of 47.0 mm in the presence of blade vibration. Thus indicating that the blade has travelled 1.1 mm in its vibration cycle between detections by the two capacitance probes (for example from -0.5 mm to +0.6 mm). This measurement, in conjunction with the times of arrival at both capacitance probes can then be used to calculate the blade tip vibration amplitude.

This amplitude is calculated by curve-fitting the two instantaneous blade vibration magnitudes measured through tip timing to the vibration cycle sine wave. The frequency of vibration is obtained from spectral analysis of the strain gauge derived signals. Hence, the amplitude of vibration can be calculated through tip timing.

Example data for the vibration measured through tip timing are shown in Table 3 for six consecutive revolutions with the compressor running at 938 RPM. The tip deflection measured at each probe can be seen to change with each revolution. This indicates that the phase of the blade vibration sine wave is not locked with rotor revolution.

Table 3
Dual Capacitance Probe Blade Tip Timing Vibration Measurements

	Distances in Millimetres Measured Through Tip Timing		
Revolution	Tip Deflection at Cap. Probe 1	Tip Deflection at Cap. Probe 2	Vibration Amplitude
1	0.55	-0.55	0.94
2	0.58	-0.52	0.94
3	0.40	-0.69	0.94
4	0.29	-0.81	0.99
5	0.19	-0.85	0.97
6	0.04	-1.07	1.14

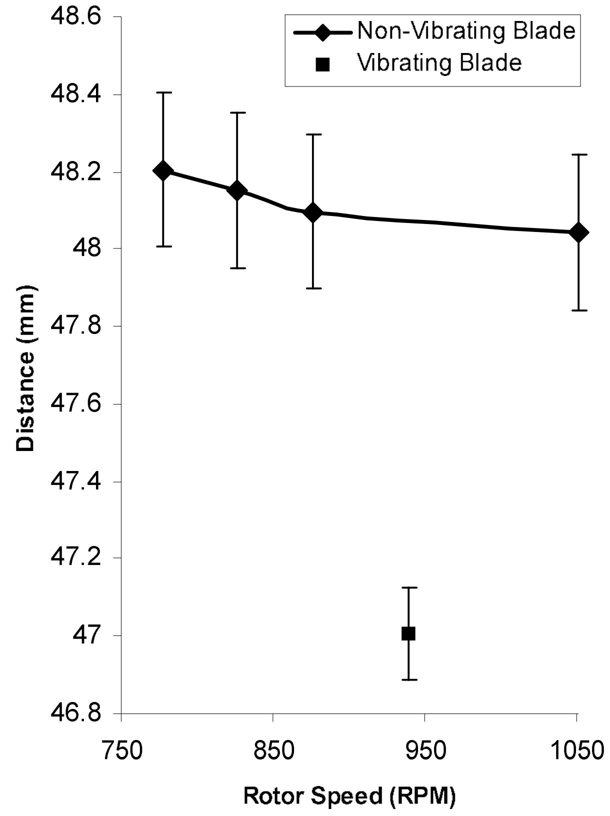

Fig. 8. Blade Distance Travelled from Capacitance Probe 2 to Capacitance Probe 1

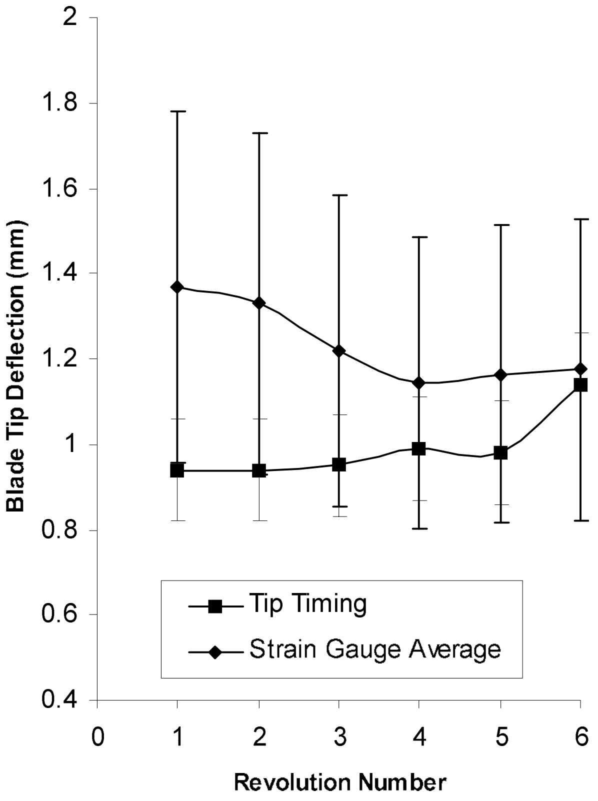

Fig. 9. Blade Tip Vibration Amplitudes

The overall vibration amplitude can be seen to be relatively constant (within 15%). This is expected from experience gained with the strain gauge derived blade tip deflections [11]. Small drifts in rotor RPM speed that are present from one revolution to the next, even when the rotor speed is set 'constant' by the controller, result in changes in vibration amplitudes over time.

The blade tip vibration amplitudes measured through dual capacitance probe tip timing can be compared with those determined from the blade mounted strain gauge signals. Fig. 9 shows the tip deflection amplitudes calculated from tip timing and those calculated from the blade mounted strain gauges. The error bars in Fig. 9 show that the deflection measurement by tip timing is more accurate than the strain derived measurement. The strain derived amplitude is the average value calculated from the two amplitudes derived from the two gauges. The amplitudes of blade tip deflection are plotted from the same data set presented in Table 3. The results can be seen to agree within the calculated error bands, as illustrated in Fig. 9.

The discrepancy between the strain derived and tip timing calculated amplitudes can be seen to decrease as the strain derived amplitude decreases. In general, the amplitude calculated from tip timing is lower than that derived from the strain gauges. The discrepancy reduces as the phase position on the vibration cycle that is detected by the tip timing approaches a peak or trough. This is apparent from the example data presented in Table 3, and was also present in other data sets collected during the experimental programme. Thus, it can be seen to be desirable to calculate vibration amplitudes from tip timing over several rotor revolutions when using this timing and amplitude calculation method. The highest of the calculated amplitudes from the data set will then be closest to the strain derived amplitude measurement.

9.3. Vibrating Blade Tip Timing Results Error Analysis

Several factors contribute to the error in determining the time of arrival of the single instrumented compressor rotor blade. There is a digitising error associated with the acquisition of the capacitance probe and OPR signals. The noise level present in the capacitance probe signal is also a source of error. There is a small error in the timing of the 'non-vibrating' condition blade events. This error is associated with the small vibration levels actually present at rotor speeds away from the resonant speed of 938 RPM.

The error associated with the OPR signal is very small, as reported in Section 4. Therefore, this does not contribute significantly to the overall error in determining blade time of arrival.

9.3.1. Discretisation Error

As with all analogue to digital (A/D) conversion processes, discretisation errors arise in the acquisition of the capacitance probe and OPR sensor signals. The A/D converters used in these investigations are of 8-bit word length type. Therefore, this corresponds to 256 discrete levels to which the voltage signal is discretised. Analogue inputs are possible over the range $\pm 5V$; the voltage resolution is thus 40 mV per digital level.

The time resolution is of course dependent on the sampling frequency. The data acquisition hardware is limited by the number of sample points it can hold in the on-board memory. The sampling rate is also limited by the maximum clock speed of the data acquisition hardware; namely 20 MHz.

During this set of tests, sampling was carried out for one second at a sampling rate of one million samples per second. This duration allowed several consecutive revolutions to be captured at the running speeds at which the tests were carried out. The resolution in time due to discretisation is therefore one microsecond.

The rotor speeds of interest for the tip timing tests are those at and around the rig's designed operating speed of 850 RPM. At these speeds the rising edge of the capacitance probe's voltage signal has a relatively high rate of change, as shown in Fig. 10. As a result the signal moves through several 40 mV discrete voltage levels from one sample to the next. Thus, the voltage level discretisation is not the critical source of uncertainty caused by signal digitisation. Therefore, the critical discretisation effect in terms of error in time of arrival is that determined by the sampling rate. In these tests this results in an uncertainty in time of arrival of not more than one microsecond per signal.

9.3.2. Error Due to Signal Noise

Significant levels of system noise are present in the commercially available capacitance probe based tip clearance measurement equipment. The noise signal present when the compressor is running at 850 RPM is illustrated in Fig. 11, where noise spikes of as high as $\pm 0.25V$ are observed. This signal has shown higher voltage noise spikes than the noise trace when the compressor is at rest, where the noise spikes are $\pm 0.15V$ in magnitude.

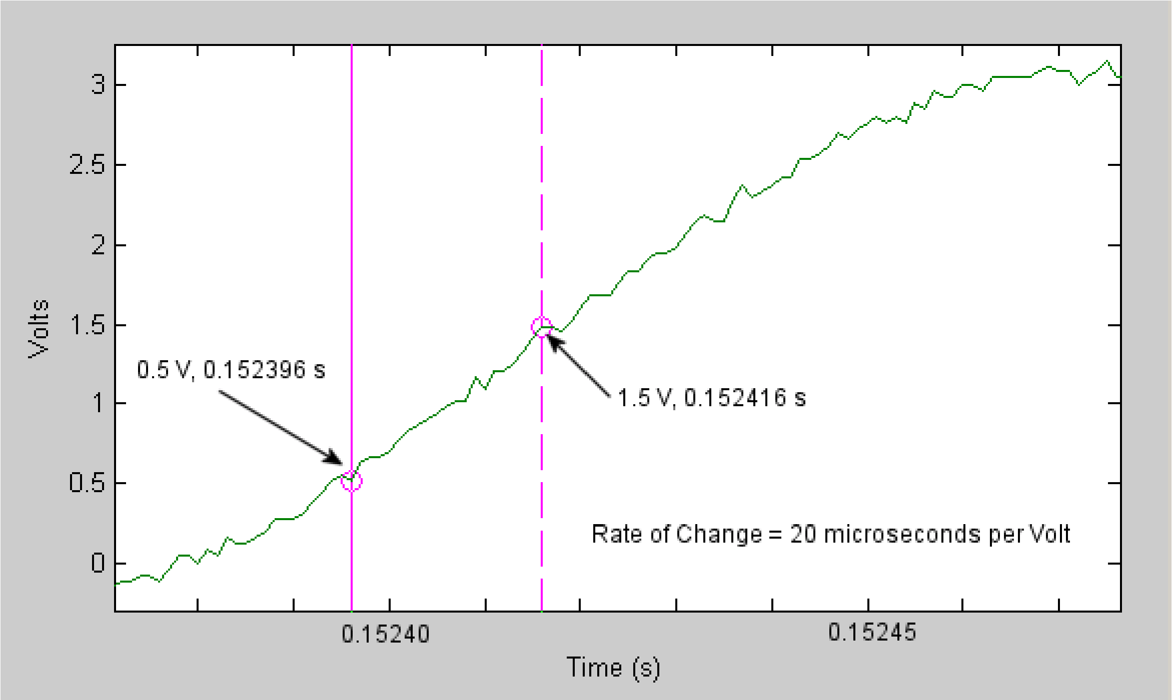

Fig. 10. Capacitance Probe Signal Blade Passing Total Rising Edge at 850 RPM

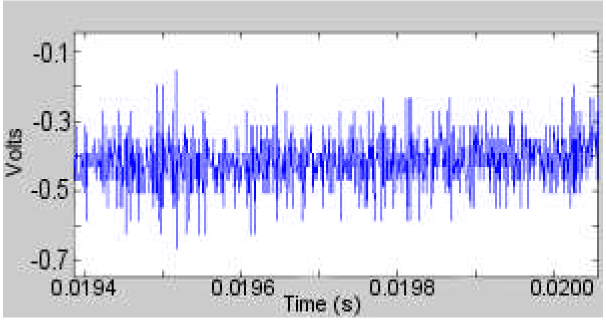

Fig. 11. Capacitance Probe Signal Noise at 850 RPM

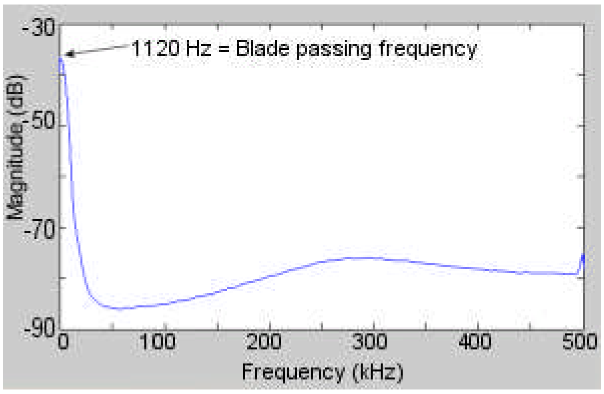

Fig. 12. PSD of Capacitance Probe Blades Passing Signal

The signal peaks during testing were 5 V. Therefore, this represents a signal to noise ratio of 20:1 inherent with the capacitance probe system.

The PSD of the capacitance probe signal shown in Fig. 12 illustrates that the noise is fairly evenly distributed over the spectrum. The blade passing frequency is a clear peak in the PSD, while the rest of the signal power is small and evenly spread across the spectrum. Therefore, the filtering out of this noise is impractical. Treatment could be investigated using more complex signal processing techniques, such as autocorrelation. However, this is beyond the scope of this investigation, which aims to characterise the capacitance probes response in terms of tip timing.

Clearly this system noise has detrimental implications for consistently determining the time of arrival of the blade at the capacitance probe's fixed position on the compressor case. A higher signal to noise ratio would result in lower uncertainty in the determination of the blade's time of arrival, and consequently more accurate tip timing measurements.

An example of the entire rising edge of the blade passing signal at 850 RPM is shown in Fig. 10. This shows that small localised peaks can be present on the rising edge due to signal noise. This is clearly a potential source of error in determining the moment that the blade passes the capacitance probe by using the fixed threshold voltage method.

The typical blade passing signal rising edge illustrated in Fig. 10 shows that the rising edge has a rate of change of 20 microseconds per Volt. The typical noise level present in the capacitance probe signal is $\pm 0.1\,\mathrm{V}$. Typical error due to this noise level, based on capacitance probe signal rate of change is thus two microseconds. The error associated with the optical OPR sensor signal was very small, as described in Section 4. Therefore, this does not make a significant contribution to the overall error in determining blade time of arrival.

The comparison between the tip deflections determined through capacitance probe tip timing and the strain gauge derived tip deflections have significant errors associated with them. The errors in tip timing are illustrated by error bars in Fig. 9. The errors associated with the strain derived tip vibration amplitudes are also represented by error bars in the data set shown in Fig. 9.

10. Conclusions

The work reported in this paper provides new insights into the potential for a commercially available capacitance displacement transducer based turbomachinery blade tip clearance measurement system's use as a tip timing measurement system. This has been done by investigating the ability of the clearance measurement system with the alternative aero-engine tip timing application in mind for the equipment.

Preliminary on-rotor testing to establish the capacitance probe tip clearance measurement system's ability to time blade arrival using a non-vibrating blade has been briefly reported.

Blade vibration measurement through capacitance probe tip timing with a tip clearance measurement system has been investigated using dual capacitance probe tip timing. This was carried out to measure blade vibration amplitude with the use of curve fitting.

Blade vibration was investigated using blade mounted strain gauges. A low stiffness quasi blade was mounted on the compressor rotor. It was found that this blade could be resonated in vibration mode one at a rotor speed of 938 RPM. This is due to the 16 engine order coinciding with the blade's first natural frequency of vibration. Blade tip vibration amplitudes of up to 1.2 mm were measured.

The vibration was successfully detected through dual capacitance probe tip timing, which was used to measure blade vibration amplitude. This was done with the instrumented blade vibrating in mode one. Two capacitance probes were mounted over the blade tip mid chord paths at different circumferential positions. Capacitance probe tip timing was used to measure instantaneous tip deflections at both capacitance probes. The frequency of blade vibration was obtained from spectral analysis of the blade mounted strain gauges' signals. This frequency information was used in conjunction with the measured capacitance probe separation to curve fit a sine wave to the two tip timing measured tip deflections. In this way the blade tip deflection amplitude was calculated. This amplitude was compared to the tip vibration amplitude calculated from the blade mounted strain gauge signals.

The vibration amplitudes measured through capacitance probe tip timing agreed with those derived from the blade mounted strain gauges within the associated error bands. The amplitude derived from tip timing was consistently lower than that derived from the blade mounted strain gauges. The discrepancy between the two derived amplitudes was found to decrease as the strain derived amplitude decreased. This was because the rate of change of the vibration magnitude was lowest at the maxima and minima. Hence, errors in the timing measurement resulted in smaller differences in amplitudes calculated at the vibration cycle's maxima and minima than at high rates of change points on the vibration cycle. The discrepancy was also found to fall as the point in the vibration cycle detected by tip timing neared a signal maximum or a minimum. This can be attributed to the fact that the error in the strain derived deflection was directly proportional to the vibration amplitude. This was due to the error in the strain to tip deflection calibration factor.

The error in the amplitudes derived from the independent tip deflection measurement system using blade mounted strain gauges was assessed. The errors associated with the strain to tip deflection calibration factors dominate this, and are reported in Section 7. In order to mitigate this error the average of the tip deflections derived from the two blade mounted strain gauges was taken as the definitive strain derived tip deflection.

The uncertainty in determining blade vibration levels through tip timing was also assessed, and found to be around two microseconds in the non-vibrating blade tip timing tests reported in Section 9.3. This translates to a tip deflection uncertainty of approximately 0.12 mm for the vibrating blade tests conducted at 938 RPM.

Leading optical tip timing systems claim they can measure blade vibrations down to amplitudes of the order of 0.05 mm. These systems can be considered usefully applicable on development engines. Therefore, the uncertainty shown in the capacitance probe tip timing results presented here should be sought to be reduced before application of this system is considered on a development engine.

Further useful work could involve comparative tests in vibration measurements through tip timing using both an optical system and the capacitance probe based system used here. Further to this, the performance in tip timing of a capacitance probe based system with superior signal to noise ratio could be investigated.

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Biographies

Craig Lawson. Following the completion of a BEng (Hons.) in Electrical and Mechanical Engineering at the University of Edinburgh, he came to Cranfield University in 1999 to research a Ph.D. in Gas Turbine Instrumentation. On completion of the Ph.D. in 2003 he then joined the Aerospace Engineering Group at Cranfield University to work in Airframe Systems. His research background includes tip timing techniques in aero-engines, where he has experience developing instrumentation and electronics for application on turbomachinery. His current research interests include turbomachinery tip timing techniques, technology integration for the More Electric Aircraft and airframe systems technologies for Unmanned Air Vehicles.

Paul Ivey graduated from the University of Sussex with an honours degree in Engineering and Applied Science in 1983. He was appointed Research Officer and Undergraduate Tutor to the EPSRC/Industry funded Thermo-Fluid Mechanics Research Centre at Sussex. He was awarded D.Phil. in 1988 for his experimental and numerical work on the anti-icing systems of the RB199 aero-engine. Paul heads the Turbomachinery, Icing and Gas Turbine Instrumentation Group at Cranfield University. This group generates one of the largest portfolios of sponsored research in the School of Engineering by Research, Design and Development.