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The Measurement of Turbomachinery Blade Vibration 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. Thus the characterisation of the performance of the capacitance probe system when measuring blade vibration on a full-sized low-speed research compressor is analysed and reported.

NOMENCLATURE

A	electrode area
C	capacitance
E_o	permittivity of free space
E_r	relative permittivity of dielectric between electrodes
ESPI	Electronic Speckle Pattern Interferometry
FEA	Finite Element Analysis
G	amplifier gain
GF	strain gauge factor
H-P	high-pass
HCF	High Cycle Fatigue
I	current
IGV	inlet guide vane
OPR	once-per-revolution
PSD	Power Spectral Density
R	resistance
RPM	Revolutions Per Minute
V	voltage
cal	calibration factor m/Pa
d	blade tip deflection
δ	electrode separation

Subscripts

out	amplifier output

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]. 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) [2]. The paper 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.

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 on-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 [3]. 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 [4]. 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 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 sets 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 [5]. 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 [6]. This design is based on a multi-element probe head to improve spatial resolution. 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.

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 [7].

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 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) [8].

TEST EQUIPMENT AND INSTRUMENTATION

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 [9]. 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.

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.

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 at as far out a position 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) [8].

The overall uncertainty of the OPR sensor timing is assessed in detail in Lawson (2003) [8]. 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.

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 [10]. 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 millimeters, made from Nickel-Chromium Alloy and of electrical resistance 350 Ohms. The gauge positions are shown in Fig. 1.

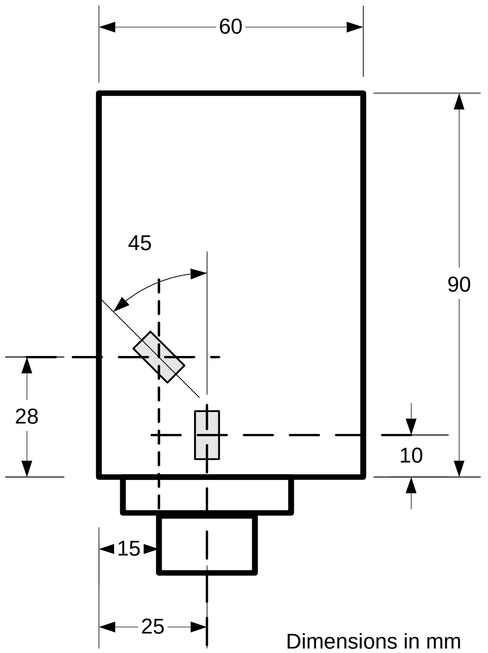

Figure 1. Blade-mounted Strain Gauges

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.

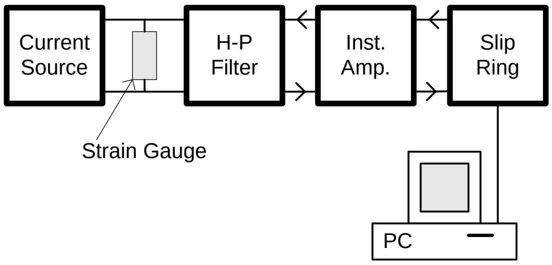

Figure 2. On-rotor Strain Gauge Energising and Amplification Circuit Block Diagram

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 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) [8].

Table 1: Measured & Simulated Blade Natural Frequencies

Mode	ESPI Measured Frequency	Simulation 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
Blade, Mode 1, Root Gauge	16.9 MPa/mm	29%
Blade, Mode 1, 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.

EXPERIMENT METHOD

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

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

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

The precise rotor speed is 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 can then be calculated by measuring tip timing. This distance is measured in the absence of blade vibration. This value is then compared to the distance measured when the blade is vibrating. The difference between these distances is the instantaneous blade tip vibration displacement level. The concept is illustrated in Fig. 4.

EXPERIMENT RESULTS AND ANALYSIS

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 PSD 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.

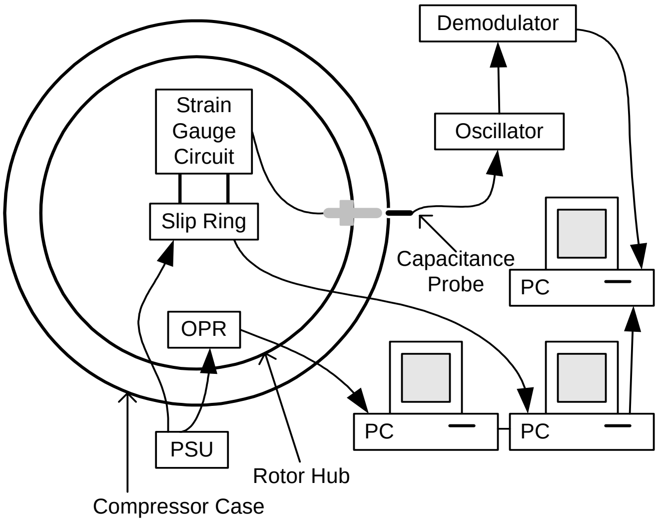

Figure 3. On-Rotor Experiment Set-Up

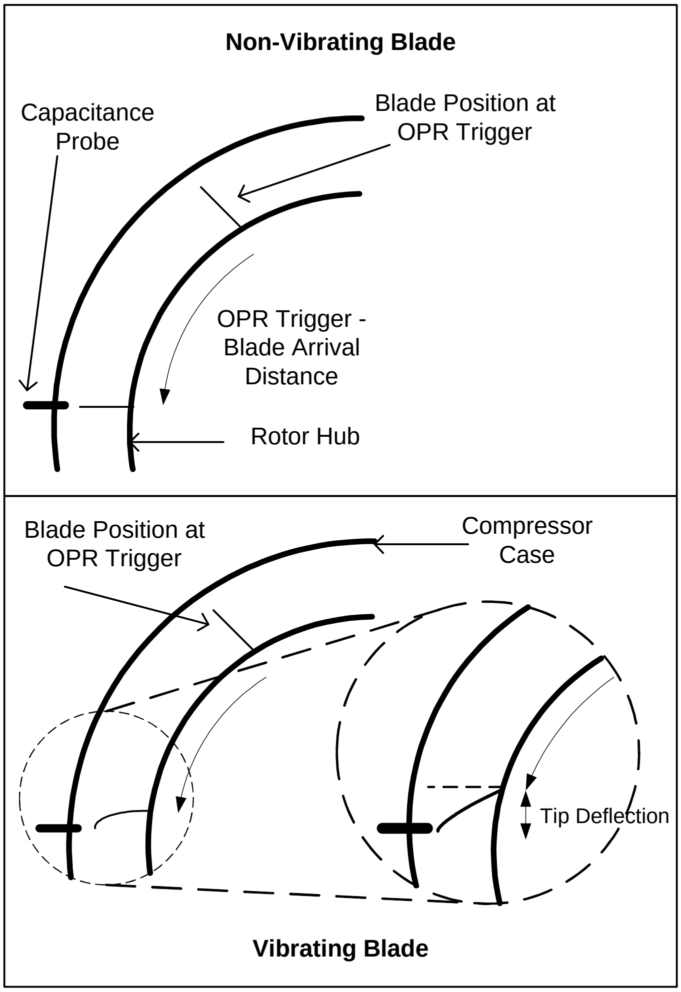

Figure 4. Blade's Travelled Distance

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 Equation (1). A full derivation of Equation (1) is given in Lawson and Ivey (2003) [7].

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

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.

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 [7].

Blade Vibration Measurement Through Single Probe Tip Timing

The ability of a single capacitance probe to measure blade vibration has been investigated. This has been done with the instrumented blade vibrating in mode one.

The distance that the instrumented blade travels through from the moment that the OPR sensor is triggered until the tip arrives at the capacitance probe has been measured. This has been done by timing the interval between the OPR sensor triggering and the blade’s arrival at the 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 the capacitance probe.

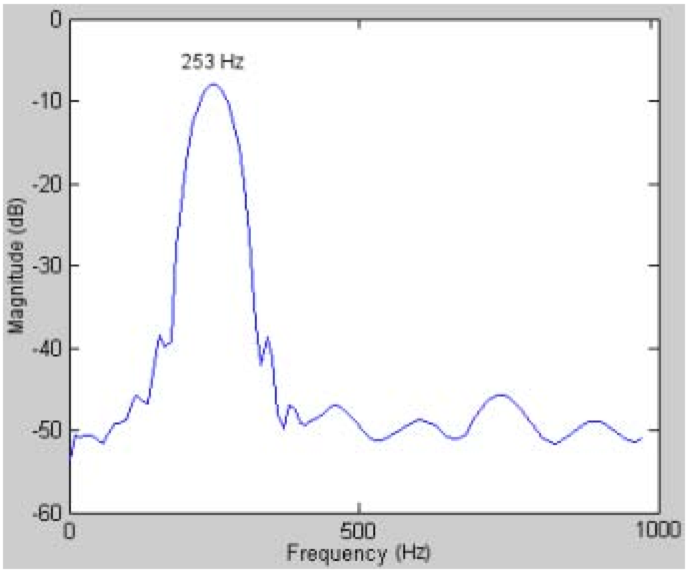

Figure 5. Root Strain Gauge Blade Vibration Signal PSD

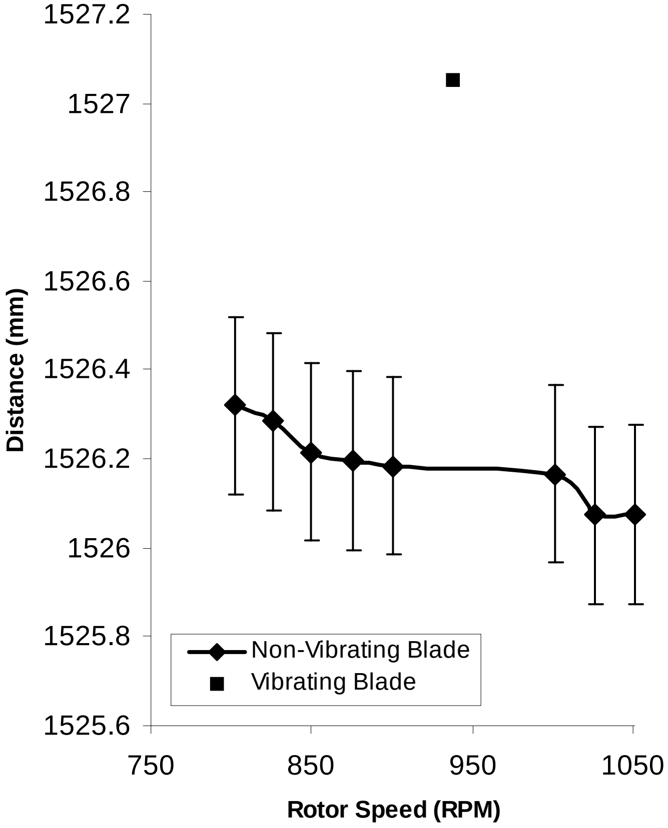

Figure 6. Blade’s Distance Travelled from OPR Trigger to Capacitance Probe Detection

This is 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) [7]. 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 programmes are used to establish the blade passing times by retrieving the time index when the chosen constant voltage threshold is crossed. This threshold voltage is 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) [7].

In these vibrating blade tests the additional threshold criteria is 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 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 0.2 mm over the speed range 800 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.

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 1526.2 mm. The actual measured distance at 938 RPM is 1527.1 mm. This is also illustrated in Fig. 6. Thus, a blade tip deflection of 0.9 mm is inferred. This is consistent with the levels of tip deflection calculated from the independent vibration measurement system using blade mounted strain gauges. From the results reported in 'Strain Gauge Derived Blade Vibration Measurement', tip deflections of between -1.2 mm and +1.2 mm are expected. Therefore, the 0.9 mm deflection measured through single capacitance probe tip timing is consistent with some point on the 1.2 mm amplitude sine wave.

Investigation of Blade Vibration Across Resonance

The ability of a single capacitance probe based tip clearance measurement system to measure vibration across blade vibration mode one resonance through tip timing has been investigated. Tip timing was performed over various different rotor RPM speeds. The constant voltage threshold method for determining blade time of arrival is used [7] [8]. Tip timing was measured at various speeds above and below resonance, in the absence of vibration. This was done to establish the distance that the instrumented blade travels from the moment the OPR sensor is triggered until its arrival is detected by the capacitance probe. The concept is illustrated in Fig. 4.

Several tip timing tests were carried out at speeds close to and across the rotor speed that causes mode one resonant vibration in the instrumented quasi blade. Fig. 7 represents a test case carried out with the capacitance probe mounted over the path at which the mid chord positions of the blade tips pass.

From the non-vibrating blade timing data illustrated in Fig. 7 the expected distance at and around the 938 RPM blade resonance speed can be seen to be 349.6 mm, in the absence of blade vibration. Fig. 7 also illustrates the marked change in measured distances as the rotor speed moves across the blade's mode one resonance speed.

Fig. 8 shows the tip deflections calculated from the tip timing results presented in Fig. 7. A tip deflection phase change is clear from Fig. 8. The level of blade tip deflection detected varies from -0.5 mm to +0.5 mm as the rotor speed traverses the resonance speed of 938 RPM. This is the expected result from theory of forced harmonic vibration of a single degree of freedom, lightly damped system, of which the blade can be considered [11].

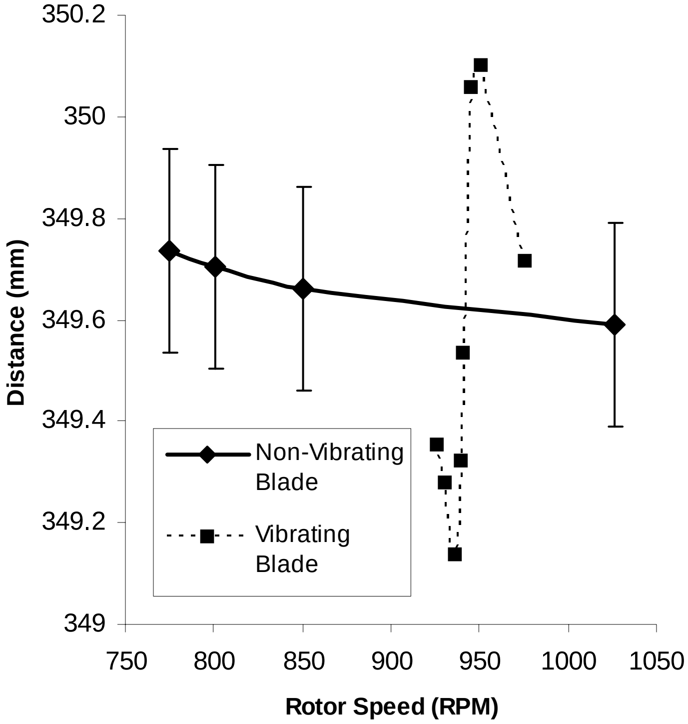

Figure 7. Blade's Distance Travelled from OPR Trigger to Capacitance Probe Detection v. RPM Speed Across Resonance

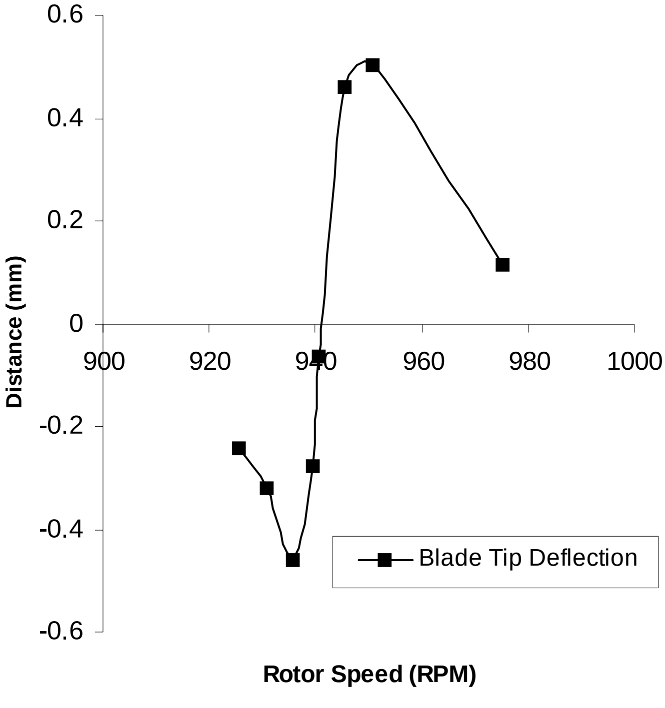

Figure 8. Blade Tip Deflection Measured Across Resonance by Capacitance Probe Tip Timing

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 in two ways. Single capacitance probe tip timing has been performed to measure instantaneous tip deflection. This was followed by an investigation into measuring blade vibration across resonance using single capacitance probe tip timing.

Blade vibration was investigated using blade mounted strain gauges. A low stiffness 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.

This vibration was successfully detected through single capacitance probe tip timing over several rotor revolutions. The method used to achieve this was to measure the distance that the instrumented blade travels through from the moment that the OPR sensor is triggered until the tip arrives at the capacitance probe. This has been done by timing the interval between the OPR sensor triggering and the blade's arrival at the 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 ability of capacitance probe tip timing to detect blade vibration across resonance was then investigated. The compressor was accelerated through the instrumented blade's mode one resonance speed of 938 RPM. During this, tip timing was performed using a capacitance probe. The blade vibration phase change over resonance expected from theory was detected by the capacitance probe tip timing.

The relatively low rates of change of capacitance probe blade passing signals compared to optical probe signals point to the conclusion that the vibration resolution of the capacitance probe will be lower.

This should be quantified through investigation of vibration amplitude and frequency measurement using capacitance probes, possibly in a comparative study with optical probes. Further work using multiple capacitance probes could enable this.

FURTHER WORK

The next step is to measure vibration amplitude. This will be performed by simultaneously using two capacitance probes to capture two instantaneous points on the vibration cycle. With the frequency of vibration obtained from the strain gauge signals, these two data points can then be fitted to a sine wave to establish vibration amplitude.

Further to this, three or more probes can be used to establish vibration amplitude and frequency, again using curve fitting. The use of additional probes (at least four) also opens the possibility to use more sophisticated data processing techniques, such as autoregressive methods.

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