TIP TIMING TECHNIQUES FOR TURBOMACHINERY HCF CONDITION MONITORING

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ABSTRACT

High Cycle Fatigue (HCF) has been established as the major common failure mode in the US Air Force large fleet of aero-engines. Corrective measures for this failure mode in themselves deliver additional technical, managerial and cost pressures. Two responses are in place to address this problem; risk mitigation through accelerated engine development fixes and technology transition through targeted and focussed R&D studies. It is the latter that is of interests and is discussed in this paper. Aero-engine blade vibrations of sufficient amplitude 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. Work done to investigate the suitability of a commercially available capacitance probe tip clearance measurement system for application as a non-intrusive turbomachinery blade tip timing measurement device is reported. Capacitance probe results are correlated with simultaneously measured strain gauge results and the performance of the capacitance system in measuring blade vibration is analysed. The growing interest in blade high cycle fatigue within the aerospace industry, and an approach to monitoring their condition are discussed as an extension to the above study. The suggested approach is based upon the tip-timing method, using non-contact optical probes located around the engine's casing. Two current tip-timing techniques are suggested for the purpose. The techniques are summarised, the experimental validation of both methods outlined, and the approach taken to investigate the potential use as a condition monitoring tool described. The paper is concluded with a discussion of the future use of tip-timing as a condition monitoring tool.

INTRODUCTION

The US Air Force (USAF) owns some 25,000 engines with an asset value of some £32 billion (including spares and consumables). With new acquisitions such as the F22 this asset base is set to double in value to some $70 billion by 2015, see Friend (1999). Given this USAF engine asset base any analysis of fault data trending is most instructive. Sieg (2000) demonstrated the implications of High Cycle Fatigue for the readiness of the war fighter (data trending for common failure mode and business advantage). Using 'Mission Capable Rates' (MCR) as a top level management tool, the reduction in operational fighter readiness over the past ten years from a historical high of some 88% to a year 2000 figure of 74% saw the significant gains made in MCR since the early 1980s significantly eroded.

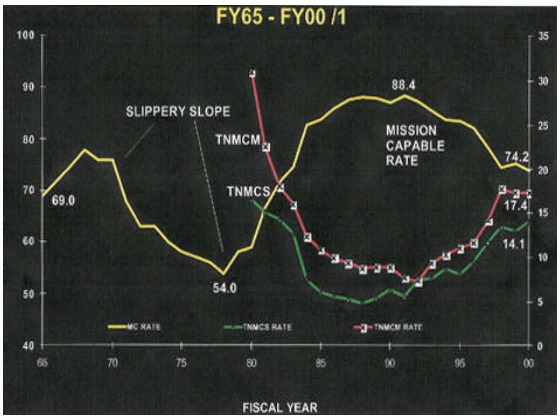

Fig 1 Mission Capable Rates

Capacitance probes.

Capacitance probe based clearance measurement systems see widespread use in turbomachinery applications to establish rotor blade tip clearance. 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) and is superior to a DC system for on-engine applications as FM capacitance probes are unaffected by gas ionisation effects that will be present in gas turbines. The capacitance tip clearance system measures the capacitance between the probe and the blade tip. This is then related to tip clearance using a pre-determined calibration factor in conjunction with the fundamental relationship for capacitance, *C*:

$$C = \frac{E_r E_o A}{d}$$

Where E_r is the relative permittivity of the dielectric between the electrodes, E_o is the permittivity of free space, *A* is the electrode area and *d* is the electrode separation. In this case one electrode is the blade tip, the other is a probe mounted on the engine casing. 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. They can also interfere slightly with the assembly aerodynamics. Consequently non-intrusive alternative techniques to strain gauges are sought and 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 and frequency by using Fourier analysis on the signals from a number of rotor revolutions. There has been one published example where the performance of capacitance probes was compared to an optical system's performance in tip timing measurement. That report found the optical system showed superior amplitude resolution to the capacitance probe system. Work has also been reported on specially designed capacitance probe head geometry, with the aim of improving capacitance tip timing measurement. The design is based on a multi-element probe head to improve spatial resolution. However, 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 would be negated.

The Tip timing Algorithms.

The Two Parameter Plot (2PP) method, developed by Heath (1999), is an indirect method using two probes located around the engine's casing to measure blade deflection. The deflection measured at each of the probes is plotted against one another as the blade's resonant frequency is traversed. Heath showed that these types of plots from either a circular or an ellipse shape, depending on the probe's spacing on the blade's resonance. Empirical relationships were derived relating the elliptical plot characteristics to the probe spacing on the blade's resonance. From this, the engine order, and hence the blade excitation frequency could be obtained. The Autoregressive (AR) method, developed by Carrington et al. (2001), is a direct method based on the equation of motion, shown by equation 1. The blade deflection, derived from the equation of motion is shown in equation 2, whereby x represents the sampled blade deflection at each probe, ω_n is the resonant frequency, A_n is the response amplitude, and D is the DC offset.

$$\ddot{x} + w_n{}^2 x = 0 \tag{1}$$

$$x = A_n \cos(w_n t + f_n) + D \tag{2}$$

Using second order Taylor expansions and some algebraic manipulation, the equation of motion is written in terms of the sampled deflections, as shown by equations 3 and 4. A minimum of four revolutions and four probes are required to establish the autoregressive parameters a_1 and D. With knowledge of these parameters, the resonant frequency and the amplitude of response can be obtained using equations 2 and 4.

$$x_j + a_1 x_{j-1} + x_{j-2} = D(2 + a_1) \tag{3}$$

$$a_1 = -2\cos(w_n \Delta t) \tag{4}$$

According to the literature, both methods provide frequency and amplitude of vibration as output parameters. From these parameters, modal damping and mode localisation are obtainable. However, validation of the algorithms thus far has been mainly numerically based, indicating a strong requirement for experimental testing prior to crack detection work.

Experimental Testing.

The experimental aim will be to establish the characteristics of a commercially available capacitance probe tip clearance measurement system and to verify the algorithms as tip-timing applications, and then to investigate their potential as HCF monitoring tools. Testing will be based on both finite element analysis and experimental work using the one and a half compressor test rig based at Cranfield University. The test rig is a one and a half stage compressor, with a maximum rotational speed of 1200RPM, 1m hub diameter, 1.2m flow passage diameter, and flow passage length of 5m. Each stage has 79 rotor blades and 72 stator blades made of LM24 aluminium alloy, with a radial length of 90mm, and chord length of 59mm. The shaft's rotational speed is measured using a slotted through-scan optical device. Five non-contact optical probes will be located around the engine's casing for tip-timing purposes. Six strain gauges are located on three blades, four of which are conventional, and two are thin film. A 24 channel slip ring for the rotor blade mounted instrumentation is fitted.

The software package IDEAS© was used to model the blade's vibration characteristics. A finite element model, based on the individual blade clamped at the root end, was constructed using a free solid eight node tetrahedral mesh. An approximate structural damping factor of 0.02%, obtained from Kielb and Chang (1992), was included in the model prior to meshing. The blade's resonant frequencies were resolved using the Lanczos method, Petyt (1990). The resolved frequencies are shown in Table 1.

Mode	Finite Element Frequency.	Rolls Royce Frequency.
1.	720Hz.	687Hz.
2.	2070Hz.	2061Hz.
3.	3410Hz.	3542Hz.
4.	3930Hz.	4494Hz.

Table 1. Numerical and experimental test blade resonant frequencies

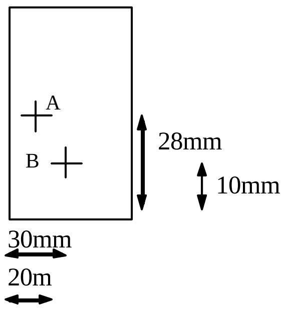

Figure 3. Illustration of the strain gauge location on the blade's suction side. Gauge A is located at approximately 45^{o} to the elastic axis, and gauge B is located approximately parallel to the elastic axis.

Figure 4. The electronic speckle interferometry system.

The resonant frequencies and mode shapes were also tested as part of some stress-tip correlation work done at Rolls-Royce plc. The test blades with mounted strain gauges, as illustrated in figure 3, were fixed in a crystal exciter, and an electronic speckle pattern interferometry system was used to evaluate the blade's resonant frequencies. The experimental set-up is shown in figure 4, and the frequency results are also shown in Table 1.

Capacitance Probe Characteristics.

Initial experiments were performed by using an actuator to position the capacitance probe head relative to a compressor rotor blade tip. In this way the clearance measurement performance of the capacitance probe system was investigated. This was followed by an investigation into the probe's response to movement in the blade tip clearance and tip timing (circumferential) directions, again using an actuator for positioning. A commercially available capacitance displacement transducer (CDT) based clearance measurement system is investigated. The measurement hardware used in this investigation has been developed by Fylde Electronics Laboratories Ltd., UK (FE-411-OSC and FE-419-CDT) and is sold by Rotadata Ltd., UK for clearance measurement applications, including turbomachine blade tip clearance measurement. The system consists of a capacitance displacement measurement probe connected by a cable to an electronics module. The electronics module provides a 0-10 V_{dc} output. This voltage is read by a PC with data acquisition hardware and software installed. The probe consists of a sensing head of 4 mm diameter connected to a central sensing conductor. This conductor is surrounded by a driven guard conductor, which is itself surrounded by an earthed outer screen.

Figure 5 - Capacitance Probe and Tri-axial Cable

The probe is connected to the electronics module via a tri-axial screened carbon-filled low-noise cable. The probe and cable assembly can be seen in Figure 5. The electronics module consists of a CDT amplifier and an oscillator. The oscillator produces a 16 kHz 5 V_{rms} sine wave signal. The oscillator is interconnected with the amplifier to energise the probe head through the central sensing conductor. The electronics module also drives the guard conductor at the same voltage as the central sensing conductor, thus eliminating spurious cable capacitance. The system provides a 0-10 V_{dc} capacitance signal which is fed to a 1/V precision converter to output a linear clearance signal over the range 0.1-10 V_{dc}.

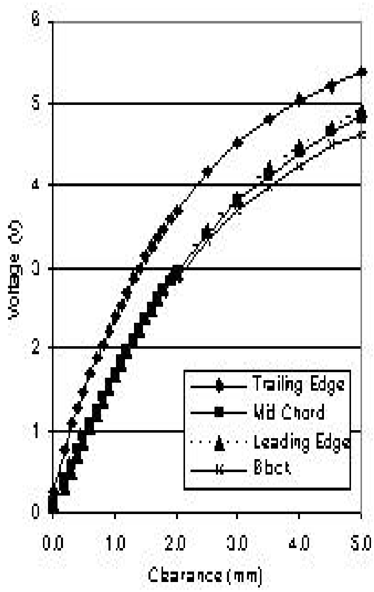

Figure 6 - Tip Clearance Test Results

The plot in Figure 6 shows the results of the capacitance clearance measurement system clearance tests. From Figure 6 it can be seen that the block, mid chord and leading edge clearance tests have very similar results, with their voltage-clearance curves closely matched. These three tests show fairly good linearity for clearances between 0.2 mm and 1.5 mm. Between 1.5 mm and 1.8 mm non-linearity is present and for clearances above 1.8 mm the output voltage-clearance relationship is clearly and increasingly non-linear. The small blade tip target area causes the non-linearity at lower clearances than stated by the probe manufacturer as the linear operating limitations of the system (0.2- 2.0 mm). This is because the manufacturer's data stipulates a sufficiently large target area (at least 30% greater than that of the probe head area). The probe head is 5 mm in diameter, while the blade tip thickness varies from 6 mm to 1.3 mm. The trailing edge test results apparently differ from the other three tests. Since the trailing edge presents a significantly smaller target area to the 4 mm diameter capacitance probe sensing head, the trailing edge test shows lower measured capacitances over the tested clearances. This produces the higher output voltages observed since the output voltage is derived from the capacitance signal through a 1/v converter. However, the trailing edge test results still show good linearity for clearances between 0.7 mm and 1.3 mm. Above 1.3 mm clearance the trailing edge voltage-clearance relationship shows increasing non-linearity

The characteristic of the probe's interaction with a compressor rotor blade tip is investigated in three- dimensional space. As well as probe response to movement in the tip clearance direction, movement in the tip timing direction is also considered. This will provide some insight into the capacitance tip clearance measurement system's ability to measure tip timing. The capacitance probe was mounted on an actuator. The probe was moved in steps of 1 mm, to an accuracy of 0.01 mm, past the stationary blade tip in the timing direction with clearance held constant. The voltage signal from the capacitance probe system was measured at each step position using a PC with data acquisition capability. Measurements were taken over the range of positions that the capacitance probe detected the presence of the blade tip, namely; from 20 mm either side of the blade tip centre. The procedure was repeated for various clearances between the blade tip and the probe from 0.2 mm to 5 mm. This allows a three dimensional plot of the characteristics of the capacitance probe's interaction with the blade tip to be visualised. The whole procedure was repeated for three points on the blade tip, namely; mid chord, leading edge and trailing edge. This enables comparisons to be made between different areas of blade tip, from a small area at the trailing edge to a much larger area at mid chord. The blade tip is 6 mm thick at mid chord, while only 1.3 mm thick at the trailing edge. Details of the blade are reported by Howard *et al*. (1993). As the probe head passes the blade tip, the tip target area increases then decreases as a segment of the circular probe moves over. The area chance is governed by the equation for the area of a segment of a circle, and is thus non-linear.

$$Area = r^2 a\cos\left(\frac{h}{r}\right) - \sqrt{r^2 - h^2}$$

Where r is the radius of the probe head and h is the distance from the probe centre to the blade edge. When the probe is centred over the blade tip, the system is relatively insensitive to movement in the timing direction. This is the desired condition for a tip clearance measurement system, but not ideal for measuring tip timing. This is illustrated by the flat troughs in Figures 7a and 7b. The steep sides of the curves in Figure 7 represent a high resolution in the tip timing direction when the suction and pressure side edges of the blade tip are centred under the probe head. At these points, small movements in the timing direction result in relatively large changes in the probe's target area on the blade, and hence large signal changes. The asymmetrical geometry of the rotor blade results in the traces in Figure 7 being slightly skewed. The probe's target area over the suction side edge of the blade tip is different from the target area over the pressure side edge. Hence the signals are not symmetrical about the tip centre (at Timing Direction 0 mm in Figures 7 and 8) as they would be for traces gathered from tests on a uniform beam. The skew effect is particularly apparent at the thick mid chord tip position. It is less apparent at the much thinner trailing edge where the probe head straddles both suction and pressure sides of the blade tip. The skew effect does not detract from the system's ability to measure timing since the effect remains constant and so timing constancy is maintained. The effect of different blade tip geometries is also illustrated in Figure 7.

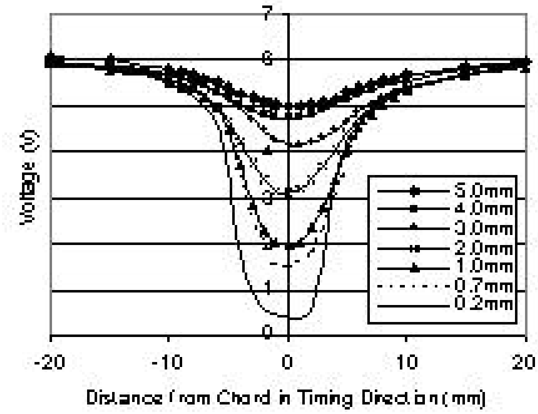

Figure 7a -Probe Characteristic Test at Blade Tip Leading Edge

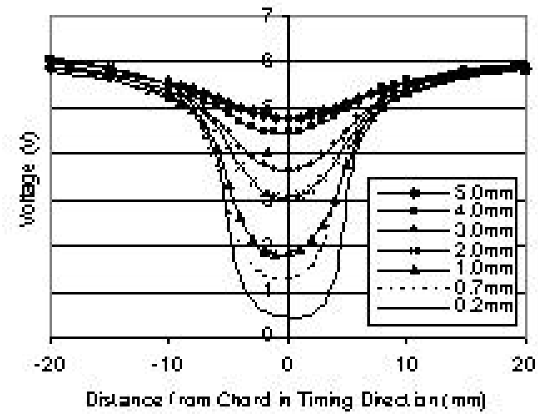

Figure 7b -Probe Characteristic Test at Blade Tip Mid Chord

The large probe target areas of the blade tip at mid chord and at leading edge positions show large voltage swings when the probe is swept past those positions. The smaller target area of the blade tip trailing edge produces a smaller voltage swing when the probe is swept past. This suggests it is possible to measure tip timing more accurately at the leading edge and at mid chord than at the trailing edge using the capacitance tip clearance probe.

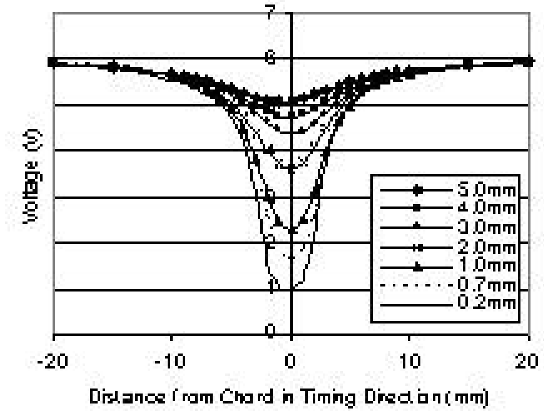

Figure 7c -Probe Characteristic Test at Blade Tip Trailing Edge

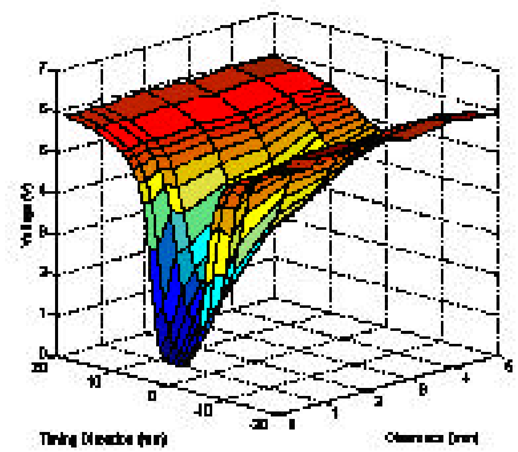

Figure 8 - Three Dimensional Probe Characteristic

The capacitance probe tip clearance measurement system was used in a series of impulse response tests on a compressor rotor blade. Measurements were taken simultaneously using the capacitance probe and the blade-mounted strain gauges. Tests were carried out with the probe head set at several clearances from 0.2 mm to 5 mm. The process was repeated at three points on the blade tip. These were the three points corresponding to the points for which the strain gauge tip displacement measurement system was calibrated as described in the previous section. Results from tests at the three considered points on the blade tip showed that the capacitance probe system's response was largely independent of the blade tip position measured. The results at clearance 0.2 mm shown in Figure 9a for blade tip at mid chord were mirrored for results at that clearance measured over the tip's leading and trailing edges. The capacitance probe system showed decreasing amplitude of response signal as tip clearance increased. A response was still discernible up to clearances of approximately 3 mm, above which the blade tip vibration apparent from the strain gauge signal was not picked up by the capacitance probe system. Figure 10 shows the tip deflection calculated from the strain signal using the calibration data for the blade tip leading edge. Also plotted on the same axes is a constant scaled capacitance probe signal from the blade tip leading edge at 0.2 mm clearance with the DC voltage level removed. The strain signal shows the characteristic 'ski slope' response of the R-C filter in the energising and amplification circuit. The decay duration of the filter's step response is four times the R- C time constant, as expected.

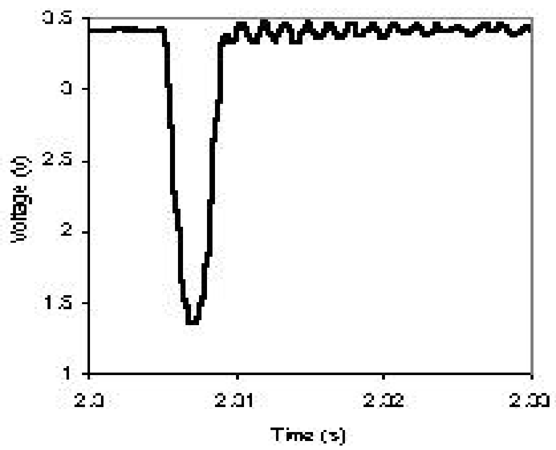

Figure 9a - Impulse Response: Probe at 0.2 mm Clearance from Blade Tip Mid Chord

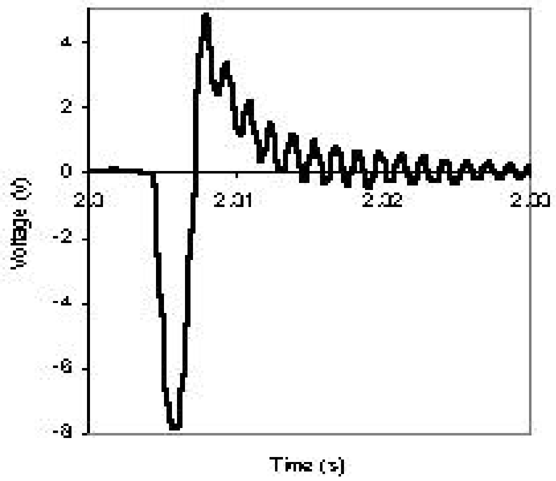

Figure 9b - Impulse Response: Strain Signal

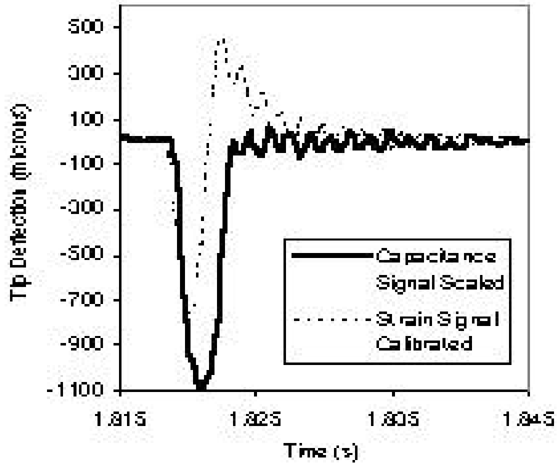

Figure 10a - Tip Deflection Derived from Strain and Capacitance Probe Signal

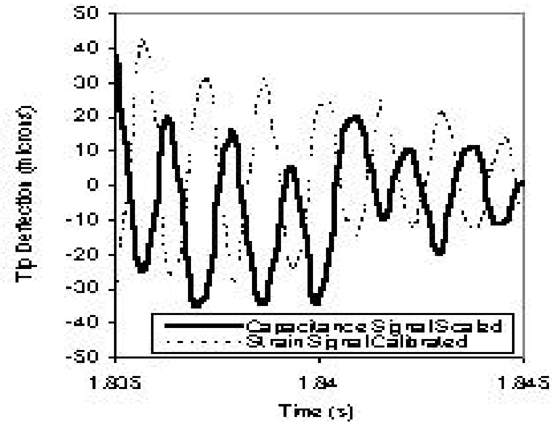

Figure 10b - Tip Deflection Derived from Strain and Capacitance Probe Signal

The capacitance signal in Figure 10a shows a non- linear response to the vibration in the timing direction, as indicated would be the case from the probe characteristic tests. The capacitance signal has been scaled to have the same amplitude of free vibration as the linear strain signal. The non-linearity of the capacitance signal manifests at the impulse where the trough is much lower than that of the linear strain signal. Figure 10b shows that there is a phase lag from the strain to capacitance signals. This is due to the fact that the strain is measured at the root of the blade while the capacitance probe examines the blade tip. Figure 10b also shows that the capacitance probe system has successfully detected blade tip vibrations of amplitudes as low as 20 microns. Spectral analysis of the capacitance signal shows good agreement with the first natural frequency of the blade throughout the impulse response testing.

Algorithm Validation and Blade Crack Modelling.

Preliminary testing will involve the experimental evaluation of both the excitation system and the optical probes. The basic components of the piezoelectric blade excitation system will include; a function generator, with a maximum output voltage of 20V peak to peak; a buffer amplifier; a high frequency transformer; an oscilloscope; and the piezoelectric component with a maximum input voltage requirement of 200V. Testing will take place in order to establish the output voltage capability of the piezoelectric circuit over the frequency range 100Hz to 4000Hz. Following this, the piezoelectric generated tip displacements will be evaluated, using the strain gauge output and their corresponding stress-blade tip displacement correlation factors. The basic components of the optical probe will include bifurcated fibre optic bundles, a receiver, and emitter. Blade time of arrival measurement will be based on light reflection as the blade passes under the probe. Initially, the performance of the tip-timing algorithms will be evaluated. Using the compressor test rig, the following parameters will be varied:

- Probe spacing on the resonance (PSR).
- Probe 1 offset on the resonance.
- Measurement noise.

PSR is a measure of the amount of one single blade vibration cycle captured by the non-contact probes located around the engine's casing. It is the ratio of the blade's time of arrival difference between the first and last probe, to the period of the blade's resonant vibration response between the first and last probes. Similarly, the probe 1 offset is a measurement of the first probe's angular position on the blade's resonant vibration response. Finally, the measurement noise is associated with both; DC offsets caused by blade untwist and lean; and AC noise, which can be generated by a variety of phenomena, ranging from blade buffeting to the instrumentation's electronics itself. Testing the algorithms capability to detect cracks will involve the measurement of shifts, representative of a crack, in the three dynamic parameters; modal frequency; modal damping; and vibration amplitude. Mode localisation will not be considered, since the bladed assembly is considered not to exhibit any significant inter-blade coupling. he experimental parameters will include:

- Crack length.
- Crack opening displacement.
- Crack location.

The required magnitude of each parameter will be established from the finite element analysis. saw notch will be used to initiate the crack, followed by controlled cyclic loading at the first bending frequency. Loading will be controlled in such a manner that the maximum stress intensity factor is well below the test blade's fracture toughness, ensuring a minimum crack opening displacement. Controlled increased crack opening displacements will be induced with static loading, gradually increasing the stress intensity factor.

Measured shifts in the three dynamic parameters, obtained from the tip-timing algorithms, will be compared to both the finite element analysis and strain gauge output results. Further work, beyond the scope of this reported study, would involve constructing a set of guidelines incorporating the four parameters, and their application to different crack scenarios. If successful, this approach could provide the capability for land based condition checks between flights, utilising removable probes to measure the blade dynamic characteristics as the engine is accelerated through its resonant frequencies. The technique would also be readily applicable to online condition monitoring of the fan blades, which are known to be more susceptible to FOD, and exhibit large measurable tip displacements in a relatively clean environment. The approach could eventually be incorporated into the engine's online condition monitoring system.

REFERENCES

Chivers, J., 1989, "A Technique For The Measurement Of Blade Tip Clearance In A Gas Turbine", AIAA 89-2916

Friend, R. 1999. 'Turbine Engine Research in the United States Air Force.' IEEE Aerospace Conference Proceedings, V7, (2001), p 73165-73178.

Heath, S., 1999, "A New Technique For Identifying Synchronous Resonances using Tip Timing", ASME, International Gas Turbine and Aeroengine Congress and Exhibition, Indianapolis, Paper No. 99-GT-402.

Howard, M.A., Ivey, P.C., Barton, J.P. and Young, K.F. 1994 "Endwall Effects at Two Tip Clearances in a Multistage Axial Flow Compressor with Controlled Diffusion Blading". ASME J. Turbomachinery. Vol 116, pp 635-647

I. B. Carrington, J. R. Wright, J. E. Cooper & G. Dimitriadis, 2001, "A Comparison of Blade Tip Timing Data Analysis Methods", Proceedings of the Institute of Mechanical Engineers, Aerospace Engineering, Vol. 215, Part G.

M. Petyt, 1990, "Introduction to Finite Element Vibration Analysis", Cambridge University Press

Kielb R.E. & Hsiao-Wei. D. Chang, 1992 "Recent Advancements in Turbomachinery Forced Response Analysis", AIAA Aerospace Sciences Meeting and Exhibit, 30^{th} , Reno, NV, AIAA Paper 92-0012.

Sieg, S. 2000. 'High Cycle Fatigue and the War Fighter.' 5^{th} National HCF Conference, Chandler, Arizona