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Spin Test Monitoring Using Blade Tip Timing Measurement

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Abstract

This paper presents two sets of results of spin test monitoring for aero engine disks using blade tip timing measurements. The first is for the detection of turbine disk rim cracks using the inter-blade spacing extracted from the tip timing data. The second is about detecting bore cracks of an integrally bladed ring (bling) structure using the second shaft order components in the aliased spectra of the blade tip timing data. The results show that multiple rim cracks of an engine disk can be detected and crack progression can be tracked by the inter-blade spacing, and that the bling bore cracks can be detected and tracked by the second shaft order components in the aliased spectra. Although the techniques were validated under spin test conditions, the principles should be readily applicable in real engine conditions.

Keywords: turbine engine, engine disk, spin test, crack detection, condition monitoring, blade tip sensor, tip timing.

Introduction

Undetected cracks in a turbine engine disk can often lead to catastrophic engine failures. Research into the detection of engine disk cracks has been conducted for a number of years. Between 2002 and 2003, the US Defense Advanced Research Projects Agency (DARPA) sponsored a lead-in program for turbine disk prognosis. Four spin tests were conducted on the F404 engine high-pressure turbine disk at a spin test facility of US Navy's Naval Air Warfare Center Aircraft Division (NAWCAD) in Patuxent River, Maryland, USA. All tests were conducted on seeded fault conditions, where several electric discharge-machined (EDM) notches were introduced around the test disks as crack initiation sites. Tests #1 and #2 had unexpectedly terminated due to the failure of cooling plates. Tests #3 and #4 had disk bursts from bore cracking and dovetail slot cracking, respectively. Five companies participated in sensor evaluation, data acquisition and analysis of the testing; they employed crack detection systems based on measurements from eddy-current displacement sensors, blade tip sensors and microwave displacement sensors.

Wang [1] analysed the shaft displacement (or proximity) data acquired by General Electric in Test #4. The analysis technique was based on the principle that a crack in rotating disks induces an additional unbalance that is proportional to the square of the rotational speed as the crack opens up due to tensile hoop stresses caused by centrifugal loading, and hence produces a unique vibration response that is a function of the fourth power of speed. In contrast, vibration response produced by standard mass unbalance is proportional to the square of

speed. As a crack is developing in a disk, one would expect that the crack induced unbalance response increase progressively with the increasing speed. When the crack is developed to an advanced stage, the overall vibration at very high speed is likely to be dominated by crack induced unbalance. For crack detection a complex unbalance index was obtained for each spin test cycle near top speed during the speed-up process, and amplitude and phase were trended against cycle numbers. Results showed that the trending plots can be effective in detecting changes of unbalance status due to cracks in a rotating disk. Blade tip sensors were used in the F404 test for the detection of disk cracks, some results can be found in [2,3,4]. With blade tip sensing technology, disk crack detection has advanced significantly. This paper presents two sets of results of spin test monitoring for aero engine disks using blade tip timing data.

As part of an ongoing effort by DARPA to evaluate the capability of engine health monitoring systems using the passive eddy current blade tip timing measurements, a follow on spin test was carried out on the first stage fan disk of the Rolls-Royce Spey engine in 2008 at NAWCAD. The results show that multiple rim cracks of an engine disk can be detected and crack progression can be tracked by the inter-blade spacing (IBS) extracted from the blade tip timing data. The technique is based on the principle that the crack opening displacement of a radial rim crack in rotating disks is a function of the crack length and the square of the rotational speed. The crack opening displacement leads to changes in the IBS. The IBS can be plotted against both the rotor speed and the spin test cycle number for crack detection and the tracking of crack progression. Some results of the test are presented in this paper. The details of the analysis method were presented in [5].

To further investigate the capability of blade tip measurement for crack detection, blade tip sensors were installed in another spin test conducted on an integrally bladed ring (bling) structure at NAWCAD in 2009. This paper presents a method of detecting bore cracks in the bling. The condition index for crack detection was derived from the second shaft order components in the aliased spectra from the under-sampled blade tip timing data. Result show that the bling bore cracks can be detected and tracked by the aliased second shaft order components.

Fan Disk Rim Crack Detection Using Inter-Blade Spacing

In 2008, as part of an ongoing effort, the US Navy was tasked to carry out a rotor spin test for turbine engine disk prognosis. This particular test was designated as PW17 spin test. The purpose of the PW17 test was to evaluate the capability of engine health monitoring systems using the passive eddy current blade tip timing measurements. The tests were conducted at NAWCAD's Rotor Spin Facility.

The test article was the first stage fan disk (23 blades) of the Rolls-Royce Spey engine. The disk has a tip-to-tip diameter of 823mm (32.4"), the mean rotor diameters are roughly 284mm (11.2") and 152mm (6") for the outer rim and inner bore respectively. The test was a seeded fault test under LCF cyclic loading with the speed range of 5500rpm to 9000rpm. Two large EDM notches of 25.4mm (1") were introduced to the bottom of dovetail slots of blade #1 and blade #9 as crack initiation sites. The blade numbers were marked in reference to the 1/rev tachometer signal. The test ran for over 13200 cycles with interval inspections for monitoring crack growth using acetate replica & microscopic crack length measurement. The blade tip timing data were acquired using Hood Technology's sensors and data acquisition system (both hardware and software).

To detect a crack and track its progression, it is important to detect the changes caused by the growing crack as the number of cycles increase. For a sound disk the IBS will be showing the same characteristic from cycle to cycle, despite that the IBS may be changing (increasing or decreasing) as the rotating speed goes up and down. When a radial rim crack develops in the rotating disk, the crack opens up at certain rotating speed and the crack opening displacement (COD) is a function of the square of the rotational speed. As the crack grows the COD will be increasing with the crack length. As a result the IBS for the blades near the crack will be affected, e.g. some IBS's might increase and some decrease. Using this principle, the IBS can be plotted against both the rotor speed and the cycle number of spin test to detect the crack and to track its progression. For an uncracked disk, the changes of IBS from cycle to cycle would be minimal. For a cracked disk, however, the IBS would be changing with the cycle number which corresponds to crack length as the crack grows.

The analysis results are presented in two formats. A waterfall plot gives an overall picture of the IBS changes caused by crack growth and rotor speed for a single blade. The second format is the IBS versus cycle number at a particular rotor speed for all the blades. In the second type of plot, the IBS change or differential IBS is employed, allowing all blades to appear in one plot.

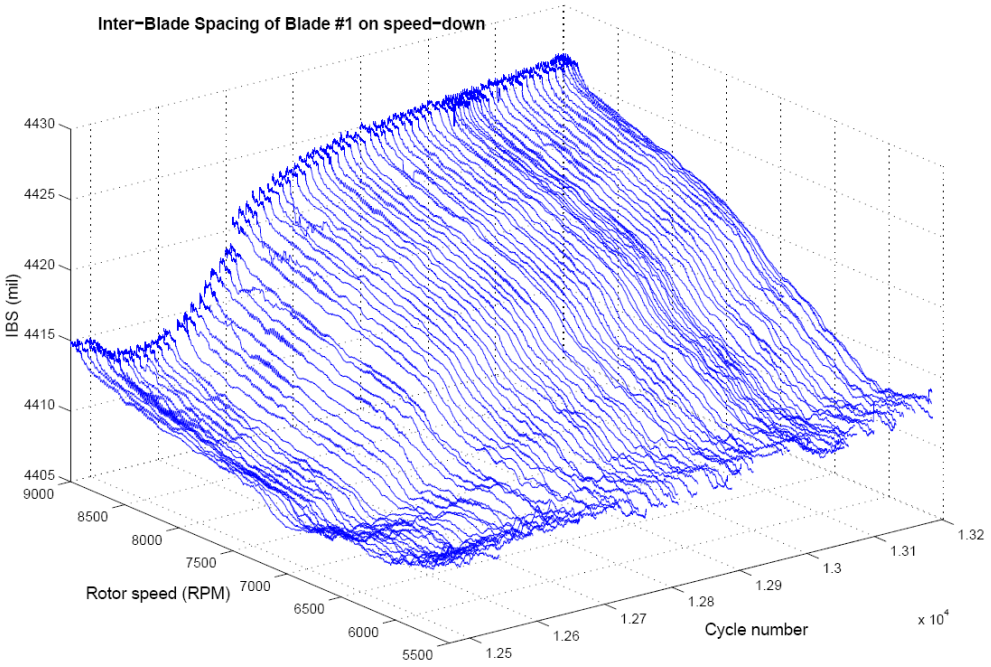


Figure 1: Waterfall plot of IBS between Blades #1 & #2 on speed-down

Because the EDM notches were inserted in slots #1 and #9 of the disk, it is expected that the IBS's of blade #1 and blade #9 be most directly affected when the notches develop into cracks and propagate. *Figure 1* to *Figure 3* are the waterfall plots showing the IBS values of blade #1, #9 and #15. Blades #1 and #9 should be the blades most affected by the cracks. Blade #15 is far away from EDM notches in dovetail slots #1 and #9; hence it should be much less affected by the cracks. We need to emphasize here that *a*) the waterfall plot is designed to illustrate the effects of rotor speed and crack length on the IBS for a single blade; *b*) both the rotor speed and the crack length will affect the values of IBS.

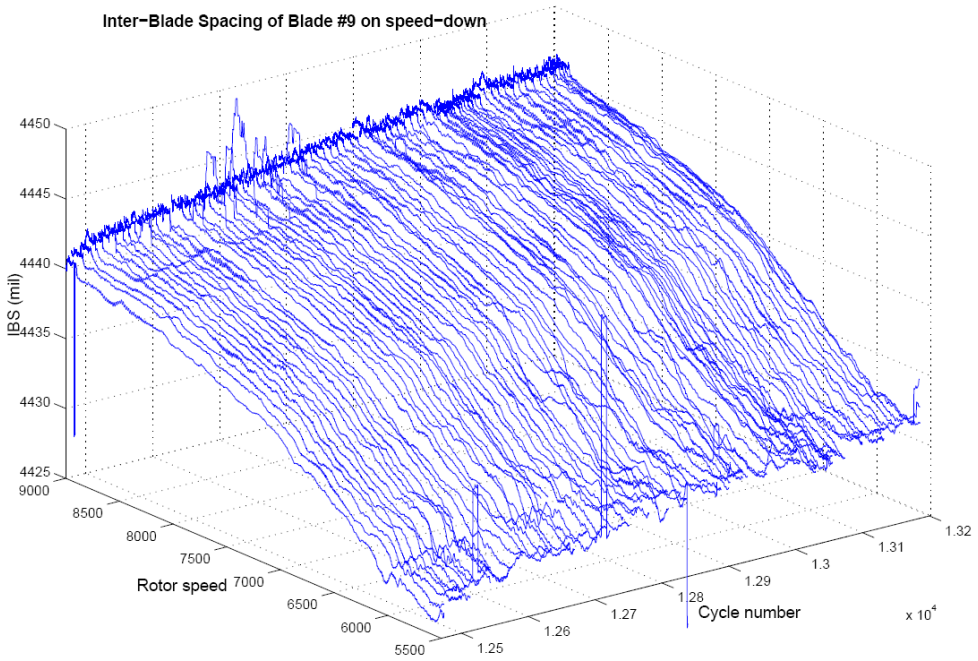


Figure 2: Waterfall plot of IBS between Blades #9 & #10 on speed-down

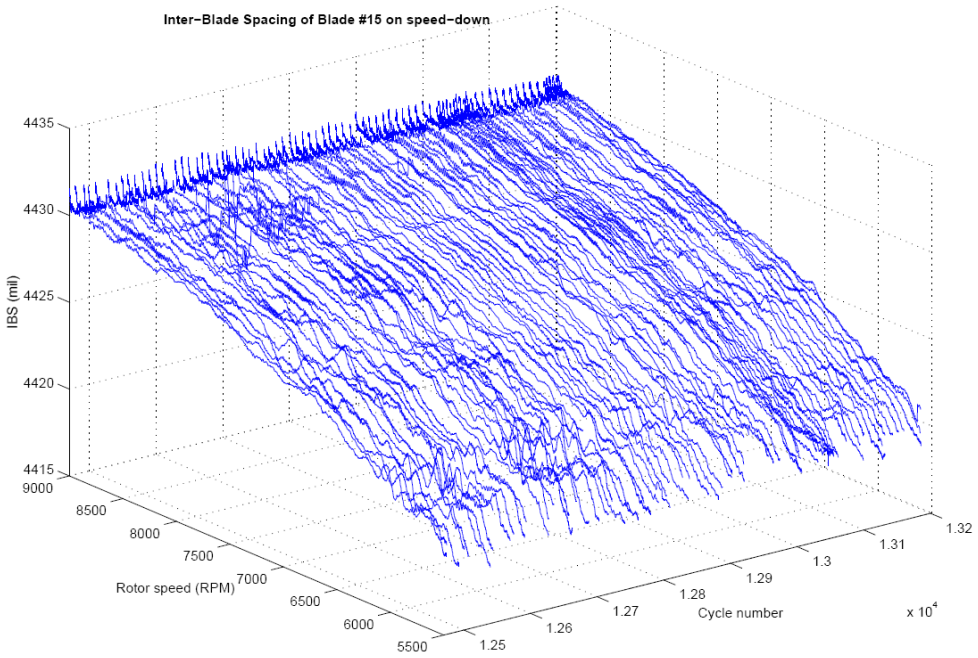


Figure 3: Waterfall plot of IBS between Blades #15 & #16 on speed-down

Figure 1 is for blade #1 on speed-down from the last continuous run of the spin test, from cycle #12470 to #13202. Obviously, the IBS values have an increasing trend with the cycle number. *Figure 2* show that this part of the tip timing data has a number of outliers which may have caused some abnormal IBS values in the plot. For the unaffected blade #15 on speed-down, *Figure 3* shows a constant pattern of IBS values with respect to the cycle number. We do not intend to show a waterfall plot for every blade. A general observation is that the waterfall plots for unaffected blades are like flat planes, but those for affected blades are more like curved surfaces.

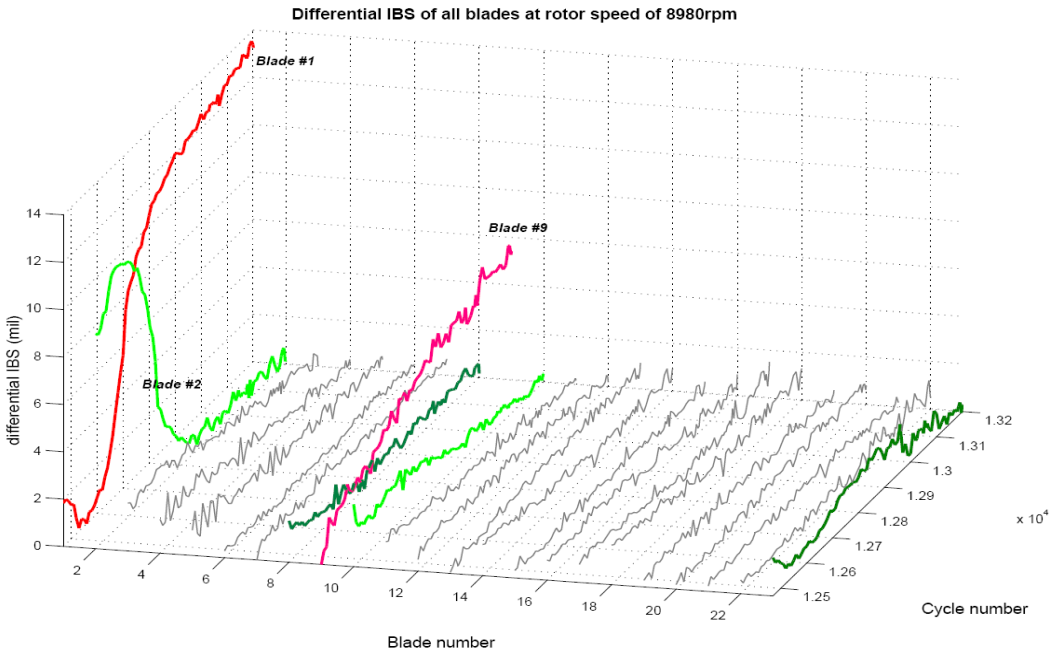


Figure 4: Differential IBS of all blades versus cycle number

The IBS plots for each blade would have different minimum and maximum values but their variation are within the range of 20 mils (about 0.51mm). In order to compare the IBS changes for all blades, we can set the minimum IBS to zero. If we take a slice of the IBS plots at a fixed rotor speed (e.g. 8980rpm) for each blade and set the minimum IBS of each blade to zero, we can have the trend of IBS change for every blade at that speed. *Figure 4* is the plot of IBS change against cycle number at the rotor speed of 8980rpm on speed-down for each and every blade. This is to show the effect of crack growth on the IBS for all blades. For blade #1, #9 and #15, the plots are the slice at speed 8980rpm from the waterfall plots shown in *Figure 1* to *Figure 3*, respectively. It is necessary to point out that the total circumference at the blade tip is always constant. When some IBS's increase some other IBS's must decrease so that the sum of IBS's remains the same.

From *Figure 4*, we can see that the IBS of blade #1 has increased by about 14 mils (0.356mm) with accompanied IBS decrease of blade #2 by about 11 mils (0.279mm). The IBS's for blades #3 and #4 have also decreased slightly. Therefore, the increase in blade #1 is compensated by the decreases in blades #2~#4. The changes around blade #9 are not as large as those around blade #1, but the mechanism of IBS increase/decrease is identical. Blade #9 has increased by about 5 mils (0.127mm) with its surrounding ones decreasing by various small amounts. For other blades far away from the cracks, as shown in the rest of *Figure 4*, the IBS changes are essentially un-noticeable. Based on the IBS changes of Blades #1 and #9 from cycle #12470 to #13202, it appeared that the crack developed from the notch at slot #1 propagated more than the other crack at slot #9. This was confirmed by the crack measurements after the spin test.

Bling Bore Crack Detection Using Aliased Second Shaft Order

The bling structure and its application to aircraft engines have been studied for a number of years, with the promise of a weight saving up to 70% comparing to conventionally bladed

disks. Rolls-Royce has successfully demonstrated the use of titanium metal matrix composite (Ti-MMC) blings in an engine [6]. *Figure 5* is a diagram comparing the structures of bladed-disk, integrally bladed disk (blisk) and integrally bladed ring (bling).

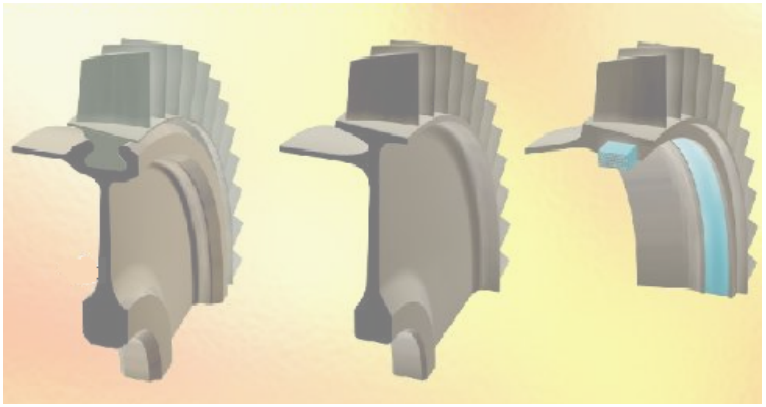


Figure 5: Conventionally bladed-disk, integrally bladed disk (blisk, up to 50% weight saving [6]) and integrally bladed ring (bling, up to 70% weight saving [6])

In an effort to further examine the capability of blade tip measurement for crack detection, two types of blade tip sensors, i.e. eddy current and optical sensors, were installed in another spin test conducted on a bling structure at NAWCAD in 2009. This was a damage tolerance test on a sub-scale bling with pre-flaws. The test article was about 239mm (9.4") in diameter; it had 30 dummy blades (slugs). The bling was pre-flawed with 6 equally spaced radial-body EDM notches and 6 equally spaced corner-bore EDM notches. The test was run continuously under low cycle fatigue loading with rotor spin speed between 2900 and 29000 rpm. Towards the end of the test, a bore crack was propagated unexpectedly which led to the burst of the bling at cycle #3974. Surprisingly, the crack was not initiated from any of the pre-flaws.

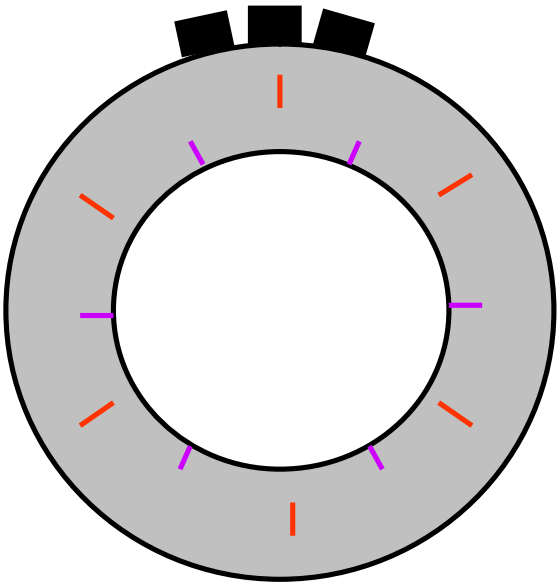


Figure 6: Sub-scale bling test article

Data from the eddy current sensor showed some evidence of sensor triggering problem possibly due to the small gaps between the slugs, so that this paper only presents the result of analysing the data from the optical sensor. The IBS method presented in the previous section

was first applied to the tip timing data, but was proven incapable of detecting any changes caused the growth of crack in the bling structure.

Using the blade tip timing data, we derived the blade tip vibration (displacement) data in reference to the fixed marker position for the 1/rev measurement. The displacement data were sampled synchronously at 30 samples per revolution, which was obviously under-sampled. Hence they would not be suitable to fully analyse the blade vibration characteristics, but may be useful for change detection. *Figure 7* shows the spectral waterfall plot of blade vibration on deceleration, where we can see three white bands corresponding to rotor speeds of 11800, 18800 and 27500rpm. These bands may be caused by triggering errors in the tip timing data acquisition system. In order to reduce effects of noise and asynchronous signal content, we applied 20 times synchronous averaging to the displacement data. Spectral analysis was then applied to the averaged data.

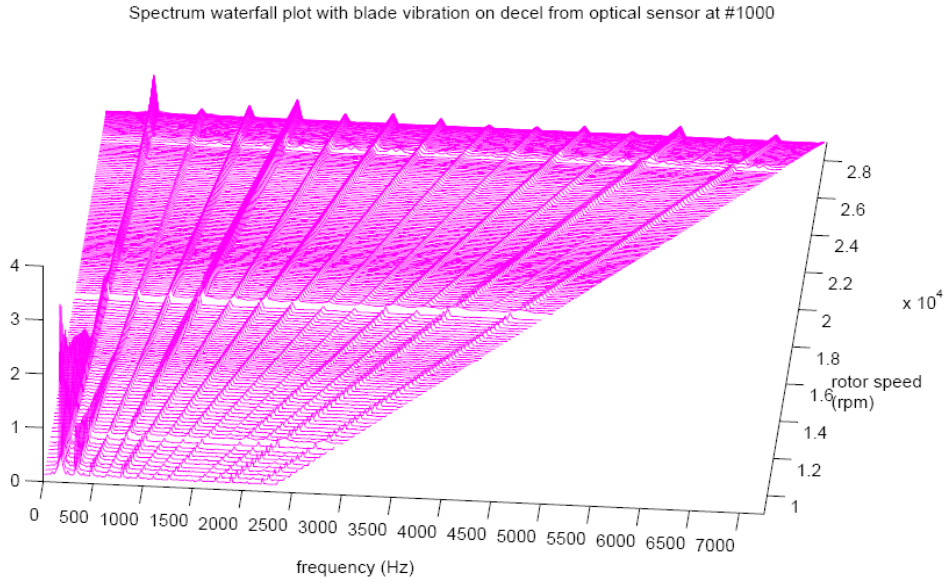


Figure 7: blade vibration spectra at changing rotor speed

A disk bore crack causes disk deformation [2], e.g. disk ovalisation, which is likely to cause changes to the first few shaft orders in the vibration spectrum. However, because of the small signal bandwidth of only 15 shaft orders, it is possible that the first few shaft orders are aliased by the modulation sidebands at the blade pass harmonics. For example, aliased 1st order would be a complex sum of the true 1st and the $(n\times30\pm1)^{th}$ orders, where n is the harmonic number of the blade pass frequency. The same applies to the aliased 2nd order, i.e. aliased 2nd order = 2nd + $(30\pm2)^{th}$ + $(60\pm2)^{th}$ …, and so forth. Therefore, the aliased 1st and 2nd orders could be the reinforced/reduced 1st and 2nd orders. Depending on phase relationship, they may not be increasing with rotor speed and may not be the direct measures of deformation for an egg-shaped and an oval-shaped rotor (the true 1st and 2nd orders are direct measures). Apparently, there is no cross order interference, e.g. 1st order/sideband related components interacting with 2nd order/sideband related components.

Figure 8 shows some aliased spectra of blade tip displacement data from cycle numbers #100 to #3974 (end of test). We found that the aliased 2nd order components have a large and almost monotonic change with the cycle number, whereas the changes at other shaft orders are relatively small. Hence, the magnitude of the 2nd order component in the aliased spectra was chosen as the condition index to trend the development of bore cracking in the bling.

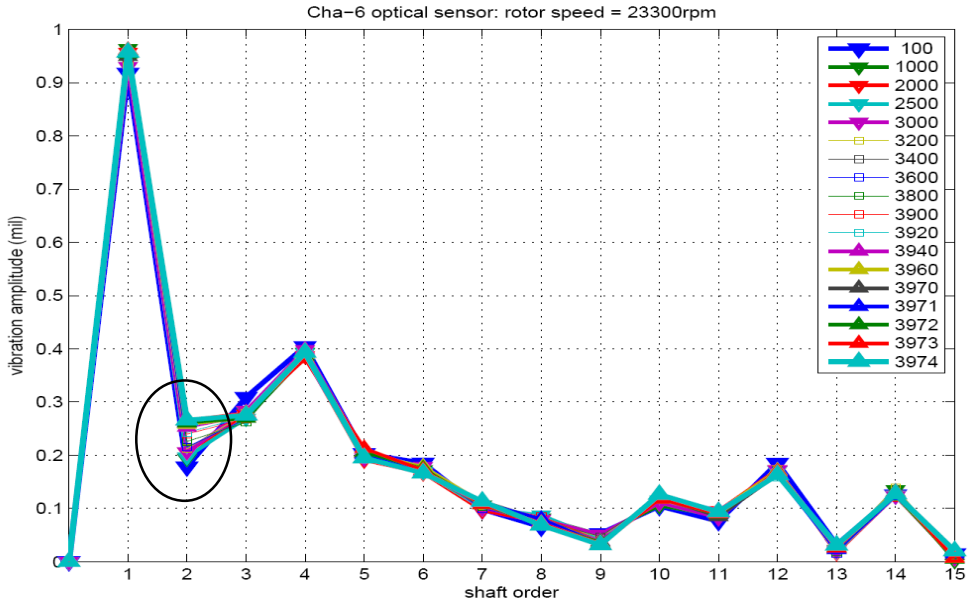


Figure 8: Aliased spectra of blade tip displacement from cycle numbers #10 to the end of test

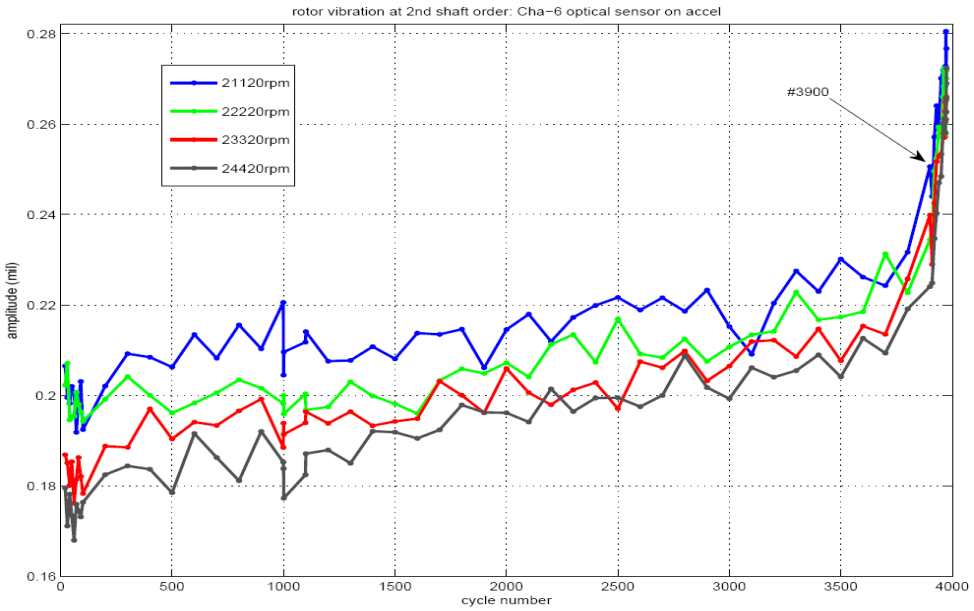


Figure 9: tracking the 2nd shaft order from aliased spectra with cycle number at 4 different speeds

Figure 9 shows the trending curves at 4 different rotor speeds, where the trends are very similar. *Figure 10* shows the trend for one speed at about 25000rpm. The rapid change started between cycles #3700 and #3800 and turned into an exponential change from cycle #3900. In view of monitoring the spin test and aborting the test to preserve the test article, cycle #3940 would be probably a good point to call for aborting the test based on past observations and experience of spin test data analyses.

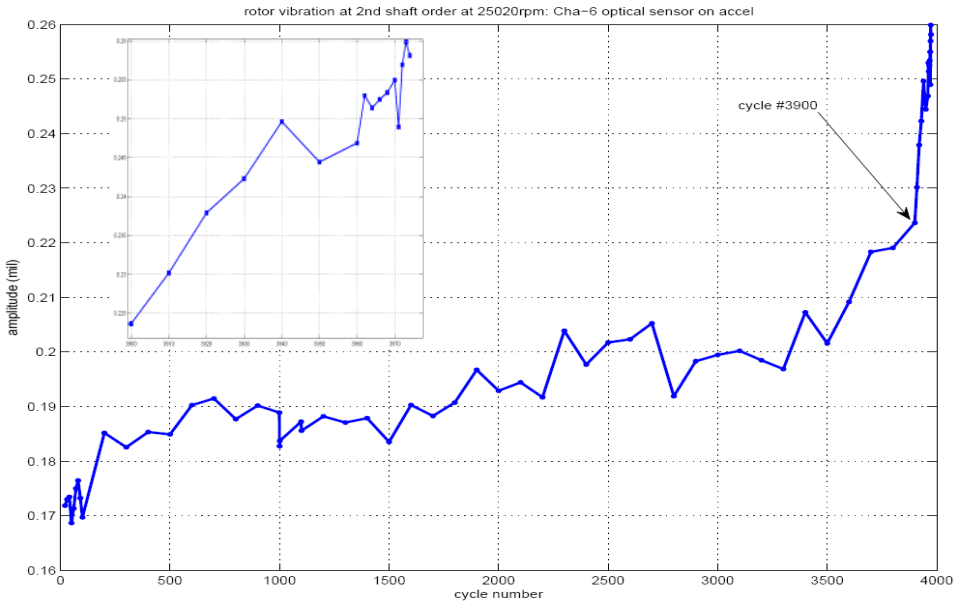


Figure 10: tracking the 2nd shaft order from aliased spectra with cycle number at the speed of 25000rpm

Discussions

This paper has presented two sets of results of monitoring crack growth in spin testing for aero engine disks using blade tip timing measurements. Analysis results from the PW17 test have shown that multiple rim cracks can be detectable by trending IBS changes for each and every blade. In this case, the crack opening displacement was amplified by the deflection of the large unshrouded fan blades, which allows the changes in IBS to be detectable. This IBS change detection method can be very sensitive to disk radial rim cracks because of the direct measurement by blade tip sensors.

Analysis results of the bling test have indicated that bling (or disk) bore cracks caused undetectable IBS changes and they may be detectable by trending the 2nd shaft order component in the spectra of blade vibration signal. Because the blade vibration data is derived from the under-sampled blade tip timing data, its spectra are likely to be aliased. This means that the 2nd order components are not the true 2nd order, so may not be a *direct* reflection of disk ovalisation. However, the aliased 2nd order would be the complex sum of the true 2nd order and the 2nd sidebands surrounding the blade pass harmonics, and there is no cross order interference. For crack detection and trending, the focus has been on detecting changes caused by the growing crack hence we believe that aliased 2nd order component is a suitable option.

Comparing the two sets of results, it is concluded that the slug tip displacement in the bling test was not big enough for IBS method to be effective, as oppose to the PW17 test where the large unshrouded fan blades amplified the opening displacements of the rim cracks. On the other hand, the aliased spectral method may not be effective for cases of multiple cracks like the PW17 test. Although both techniques were validated as suitable to monitoring spin test conditions, the principles should also be applicable to real engine conditions.

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References

1. Wang, W., "Disk Crack Detection and Diagnosis for Gas Turbine Engines," *27th IEEE Aerospace Conference* (paper 11.1313), March 4-11 2006, Big Sky, Montana, USA.
2. Tappert, P., von Flotow, A., Mercadal, M., Hardman, B., and Drumm, M., "Low Cycle Fatigue Rotor Burst Prognostics Using Blade Tip Sensors: Crack Detection on Aero-Engine Hardware." *Hood Technology Technical Paper*, November 2003.
3. Fila, L., Emmerling, W., Altobelli, D., Lewicki, D., Frankenberger, C., and Seng, S., "A Successful Seeded Fault Engine Test to Detect Cracks in Engine Disk (TF-41 SFET)." *24th IEEE Aerospace Conference* (paper 11.0101), March 9-15 2003, Big Sky, Montana, USA.
4. Seng, S., "Turbine Engine Fan Disk Crack Detection Test." *FAA Technical Report - DOT/FAA/AR-04/28*, September 2004.
5. Wang, W. and Muschlitz G., "Disk Crack Detection in Spin Testing Using Tip Timing Data." *Proceedings of 31st IEEE Aerospace Conference* (paper 11.1473), March 6-13 2010, Big Sky, Montana, USA.
6. Cantor, B., Grant, P., and Assender, H., *Aerospace Materials* (pp77-78), Institute of Physics Publishing, Bristol, UK, 2001.