GAS TURBINE BLADE AND DISK CRACK DETECTION USING TORSIONAL VIBRATION MONITORING: A FEASIBILITY STUDY

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ABSTRACT

The primary goal of the this paper is to summarize field demonstrations of the feasibility of detecting changes in blade natural frequencies (such as those associated with a blade or disk crack) on operating turbines using non-contact, non-intrusive measurement methods. This paper primarily addresses the results of application of this non-intrusive torsional vibration sensing to a large wind tunnel fan and a jet engine high-pressure disk. During the operation of rotating equipment, blade natural frequencies are excited by turbulence, friction, and other random forces. These frequencies couple with shaft torsional natural frequencies, which may then be measured. Laboratory testing was conducted to affirm the potential of this method for diagnostics and prognostics of blade and shafting systems. Field installation at the NASA Ames National Full-Scale Aerodynamic Facility (NFAC) reaffirmed the ability to detect both shaft and blade modes. Installation on a high-pressure (HP) disk in a jet engine test cell the manufacturer’s facilities demonstrated that the fundamental mode of the turbine blades was clearly visible during operation. The results of these field tests have resulted in high confidence that this technique is practical for diagnosing and tracking blade and disk cracks.

KEY WORDS

Disk cracking; blade cracking; condition-based maintenance; failure prediction; torsional vibration.

BACKGROUND

The detection of blade and shaft natural frequencies in the torsional domain requires that the signal resulting from excitation of the rotating elements by turbulence and other random processes is measurable. If measurable, these natural frequencies may be tracked to determine any shifting due to cracking or other phenomena affecting torsional natural frequencies. Difficulties associated with harvesting the potentially very small signals associated with blade shaft vibration in the torsional domain could render detection infeasible. Thus, transduction and data acquisition must be optimized for dynamic range and signal to noise ratio (Vance, 1988; Maynard and Trethewey, 1999; Maynard et
The advantage of using shaft torsional natural frequency tracking over shaft lateral natural frequency tracking for detecting cracks in direct-drive machine shafts is twofold:

- A shift in natural frequency for a lateral mode may be caused by anything which changes the boundary conditions between the rotating and stationary elements: seal rubs, changes in bearing film stiffness due to small temperature changes, thermal growth, misalignment, etc. So, if a shaft experiences a shift in lateral natural frequency, it would be difficult to pinpoint the cause as a cracked shaft. However, none of these boundary conditions influence the torsional natural frequencies. So, one may say that a shift in natural frequency in a torsional mode of the shaft must involve changes in the rotating element itself, such a crack, or perhaps a coupling degradation.

- Similarly, finite element modeling of the rotor is simplified when analyzing for torsional natural frequencies: these boundary conditions, which are so difficult to characterize in rotor translational modes, are near non-existent in the torsional domain for many rotor systems. This means that characterization of the torsional rotordynamics is more straightforward, and therefore likely to better facilitate diagnostics.

Detection of the small torsional vibration signals associated with blade and shaft natural frequencies is complicated by transducer imperfections and by machine speed changes. The use of resampling methods has been shown to facilitate the detection of the shaft natural frequencies by: (1) correcting for torsional transduction difficulties (Maynard and Trethewey, 1999) resulting from harmonic tape imperfections (printing error and overlap error); and (2) correcting errors as the machine undergoes gradual speed fluctuation (Maynard et al., 2000; Groover, 2000). In addition, correction for more dramatic speed changes was addressed by Groover (2000). These corrections made laboratory testing quite feasible.

**Transducer setup and methodology**

The transducer used to detect the torsional vibration of the shaft included a shaft encoded with black and white stripes, an infrared fiber optic probe, an analog incremental demodulator and an A/D converter. Figure 1 shows a schematic of the transducer system.

![Figure 1: Schematic of transducer setup for torsional vibration measurement](image-url)
The implementation of the technique under laboratory conditions was previously presented in Maynard and Trethewey, 1999, and Maynard et al. 2000. Figure 2a shows the tabletop rotor with eight “blades”, and the resulting spectrum (Figure 2b) shows the blade group, and the individual detuned blade (“rogue blade”).

APPLICATION TO AGING TURBINES

In vehicular turbines, the loss of turbine blades has resulted in accidents and fatalities. With the aging of commercial and military fleets, fatigue cracking and failure of discs and blades becomes a more pressing issue. For example, some engines in one specific family of engines (currently used in about four thousand commercial aircraft) are approaching twenty years of age. Although these engines experienced little blade and disk cracking early in their lives, cracking has been detected during regularly scheduled inspections on aging engines. There is some concern that this cracking may accelerate as the engines continue to age, and may require increased inspections. The possibility of a crack precipitating and resulting in blade failure between scheduled inspections increases with age, and an in situ system could provide the user/maintainer with blade health information.

Similarly, military aircraft engines are exhibiting symptoms of aging, which include blade and disk failure. From 1982 to 1998, 55% of USAF engine caused mishaps were related to high-cycle fatigue (HCF) of engine parts (Davenport, 1998), predominately blades and disks at the blade attachment (Davenport, 2001). In addition, about 87% of the risk management inspections were related to this HCF. Thus, a large portion of the maintenance budget is associated with HCF of blades and disks at the blade attachment.

NASA AMES NATIONAL FULL-SCALE AERODYNAMIC COMPLEX (NFAC) FANS

The NFAC facility is the largest wind tunnel in the world, able to test a full-scale 737 in the largest section (see Figure 3). The fans used to drive the wind tunnel, shown in Figure 4, have experienced some blade cracking in the past, and the repairs made continued inspection unpractical. NASA decided to use modal impact testing of the blades to track the natural frequencies of the blades to detect shifts that might be associated with cracking. However, it was determined that the frequency might shift as much as ten percent simply by rotating the rotor 360° and retesting the same blade. Since this was on the order of the expected shift due to cracks, other methods were considered. A feasibility study was conducted using torsional vibration on an operating fan.
The shaft was encoded with zebra tape, and testing was performed during operation of the fans. The results are shown in Figure 5. The first two peaks correspond to overall shaft torsional frequencies, based on simple dynamic models developed by the vendor in the 70s. The third peak, near 13.5 Hz, corresponds to the blade group. Of particular interest is the tight packing of the fifteen blade modes, especially knowing that the impact testing on a single blade could vary by 1 Hz or more during a single test session. We believe that the variable pitch mechanism (VPM) does not provide a repeatable boundary support for the blades when it is not operating, but provides uniform and repeatable results during operation, when the VPM is preloaded.

Subsequent to this testing, impact testing was performed on a blade with the oil pump operating to attempt to allow torsional coupling. The resulting natural frequency was found to be about 14.6 Hz. This testing demonstrated the ability of this measurement system to detect blade natural frequencies during operation of the NFAC fans.
INSTRUMENTATION OF AN AIRCRAFT JET TURBINE

The HP turbine of a commercial jet engine was instrumented to determine the feasibility of detecting the blade natural frequencies during operation using torsional vibration. The testing was performed in a warm air test facility, under load at about 9400 RPM. Figure 6 shows the fully assembled commercial engine and the HP disk as installed in the warm air test facility.

Several individual blades were tested by the engine manufacturer to determine the natural frequencies. These blades were fixtured to simulate the boundary conditions during operation. The modal testing results are summarized for the three specimen blades in Table 1.

The instrumentation included a 200-stripe zebra tape and fiber optic probes. In addition, the output from a 60-tooth speed encoder was used as backup. The zebra tape did not survive the test, and the speed signal from the 60-tooth gear was used. The use of the 60-tooth wheel limited the frequency range of the data to one-half the number of teeth times the

<table>
<thead>
<tr>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
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<tr>
<td>Blade F12</td>
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<td>3943</td>
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<td>6041</td>
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<td>Std. Dev.</td>
<td>19</td>
<td>47</td>
<td>49</td>
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Table 1: Results of Modal Testing of Sample Blades
speed of the shaft, or about 4500 Hz. Figure 8 shows the torsional spectrum of the HP turbine rotor. Note that torsional natural frequencies of the shafting system should change very little with speed, and coupled blade and shaft torsional modes increase very slightly with speed due to stiffening by axial force. So, we look for frequencies that are not shifting with speed. Note that the first peak at about 2400 Hz is close to the first mode from the blade modal testing.

Earlier experimental and analytical work, however, indicates that blade natural frequencies can be significantly altered by coupling with shaft torsional modes (Maynard and Trethewey, 1999; Maynard et al. 2000). It was shown that, for a small desktop rotor with much larger blade to rotor mass ratio, the difference might be more than 30%, and that the frequency may be higher or lower than rig impact testing results. Although intuition might imply that for relatively small blades coupling would be less of a factor, the effects of torsional coupling should be clarified using a dynamic torsional model.

**SUMMARY AND CONCLUSIONS**

The techniques developed for detecting torsional natural frequencies in the laboratory were implemented on a large wind tunnel fan that has experienced blade cracking, and a jet engine that has experience cracking in the disc at the blade root. The goals of the implementation project were to demonstrate the feasibility of field application in fans and turbines, and to establish a baseline for each class of machine. The data acquired clearly demonstrated the feasibility of field implementation, and established baseline natural frequencies for blades and shafts.

However, interference from tape related spectral content was experienced. This interference was not experienced in the laboratory due to shaft size, access, and environmental differences. It is believed that this spectral content is associated not with tape printing error or overlap, but was introduced by the installation. This may be overcome by using a more precisely fabricated encoding device (such as the
60-tooth speed encoder at the jet engine test facility), or by developing correction algorithms for the installation error.

**Future work**

Research to establish the size of detectable cracks in each class of machine is needed. For instance, turbine engines have experienced cracking in the HP disk at the blade root. It is important that we estimate the size of the detectable crack and the remaining useful life of the disk at the frequency shift detection threshold to establish the torsional vibration method as practical in field machines. Correction of the installation errors must be accomplished to remove ambiguity and make the technology widely accessible. This work is currently underway.

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**REFERENCES:**


