

# BLADE AND SHAFT CRACK DETECTION USING TORSIONAL VIBRATION MEASUREMENTS PART 2: RESAMPLING TO IMPROVE EFFECTIVE DYNAMIC RANGE

Kenneth P. Maynard, Martin Trethewey  
Applied Research Laboratory, The Pennsylvania State University  
State College, PA 16801 USA; email: kpm128@psu.edu

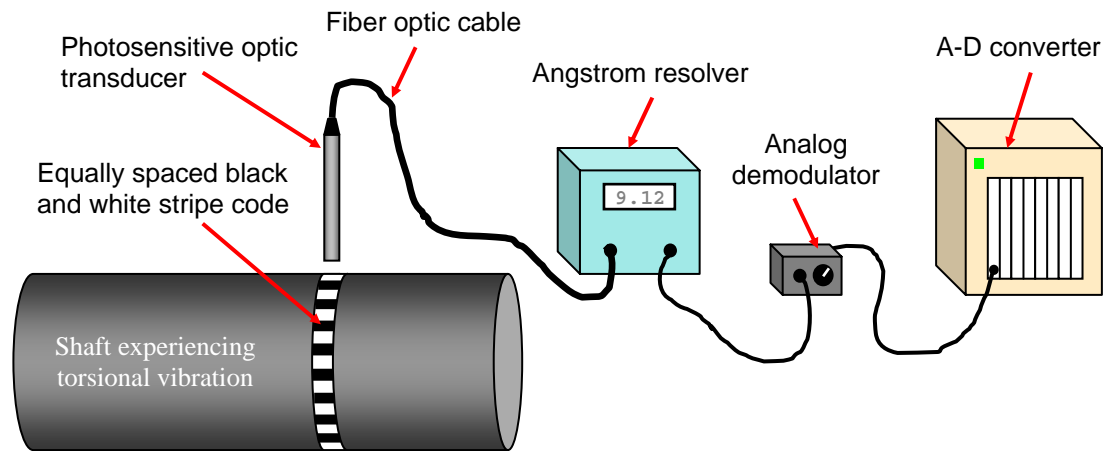
**Abstract:** The primary goal of the development project was to demonstrate the feasibility of detecting changes in blade bending natural frequencies (such as those associated with a blade crack) on a turbine using non-contact, non-intrusive measurement methods. The approach was to set up a small experimental apparatus, develop a torsional vibration detection system, and maximize the dynamic range and the signal to noise ratio. The results of the testing and analysis clearly demonstrated the feasibility of using torsional vibration to detect the change in natural frequency of a blade due to a change in stiffness such as those associated with a blade crack. However, it was found that harmonics of shaft operating speed, created as an unwanted artifact of the measurement method, resulted in spectral regions in which the effective dynamic range was inadequate to detect low-level torsional vibration associated with the natural frequencies. The loss of effective dynamic range was due to the “skirts” created by the sampling window. Application of order resampling, followed by frequency resampling, to the torsional vibration waveform increased the effective dynamic range and improved the ability to identify shaft torsional and blade bending natural frequencies.

**Introduction:** The detection of blade natural frequencies in the torsional domain requires that (1) the blade modes to be detected couple with shaft torsional modes; and (2) that the signal resulting from excitation of the blades by turbulence and other random processes is measurable. It is probably safe to say that, theoretically, condition (1) is always met. However, the difficulties associated with harvesting the potentially very small signals associated with blade 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 [1, 6].

Detection of the small torsional vibration signals associated with blade natural frequencies is complicated by transducer imperfections and by machine speed changes. The purpose of this paper is to propose and demonstrate resampling methods that facilitate the detection of the

blade natural frequencies by: (1) correcting for transducer imperfections; and (2) correcting errors as the machine undergoes gradual speed fluctuation.

**Background:** 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. The implementation of the technique was previously presented in [2, 6]. Figure 1 shows a schematic of the transducer system. It was determined that the shaft encoding, (accomplished by printing black and white stripes on paper or polyester and gluing it to the shaft) had some inherent sources of error. These included: (1) end effects (where the spacing between the first and last stripe on the strip are not spaced identically with the other stripes); (2) printer errors, due to digitization bias error in the printing process (associated in particular with



**Figure 1: Sensor system for torsional vibration [2]**

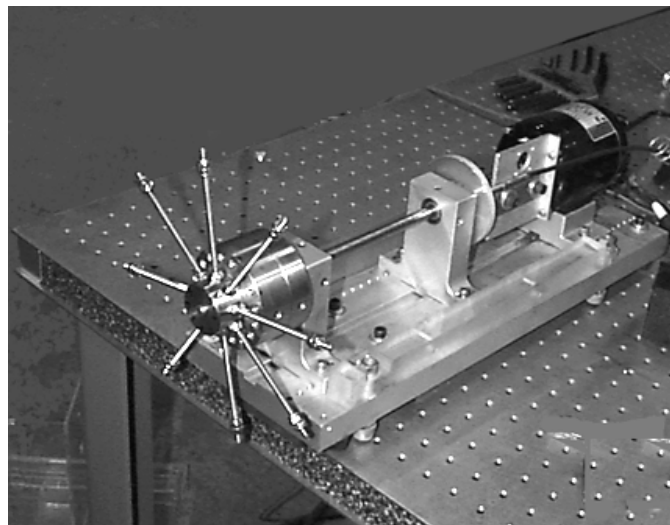
relatively small stripes); and (3) installation error.

These errors manifest themselves as side-band frequencies at a spacing equal to the speed of the shaft. In the demodulated spectrum, this is seen as harmonics of the shaft running speed. Since the torsional vibration signal of interest is very small, we are most interested in the character of signals that are orders of magnitude below these harmonics. In addition, normal spectral analysis techniques result in leakage of these harmonics in the spectrum when the harmonics are not centered in an analysis bin. This leakage results in “skirts”, which almost totally mask the frequencies of interest.

To reveal the details of the character of the torsional natural frequencies, removal of the skirts associated with harmonics of

shaft speed is necessary. To facilitate this, order resampling of the data is performed [4, 5]. Here, the sampling of the data is no longer associated with a constant sample rate; rather, the data is resampled to provide a waveform sampled at equal angular positions of the shaft. Thus, the data is resampled at a rate of  $N$  samples per revolution. Experimentation indicated that simple resampling without accounting for speed variations (even on induction motors, which operate at fairly constant speeds) results in broad harmonics and unwanted side-bands about the harmonics. Therefore, resampling assuming constant shaft acceleration was used [4].

**Implementation:** The procedure was implemented on a desktop rotor with eight threaded rods representing the blades, as shown in Figure 2 [2, 6].



**Figure 2: Desktop rotor apparatus**

The torsional data was first collected using standard constant frequency sampling techniques. The ensemble average (in the frequency domain) of 30 data records is shown in Figure 3. Note that the regions where the blade bending and shaft torsional natural frequencies are

expected provide little information.

Data is collected again, this time resampled using the constant acceleration order-resampling algorithm. A single record is shown in Figure 4.

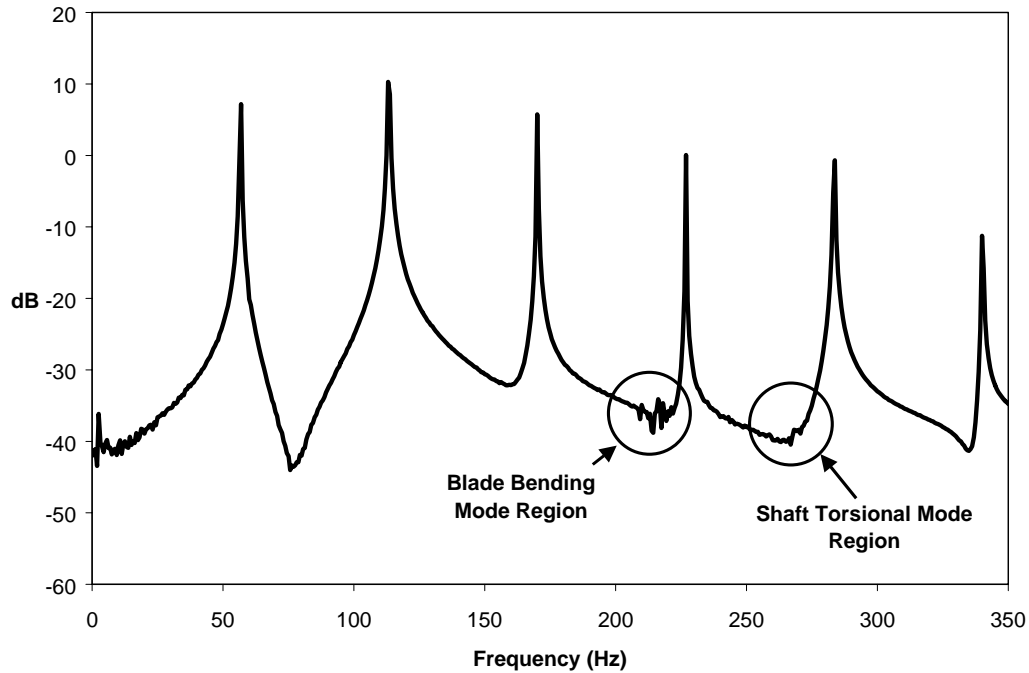


Figure 3: Standard spectrum

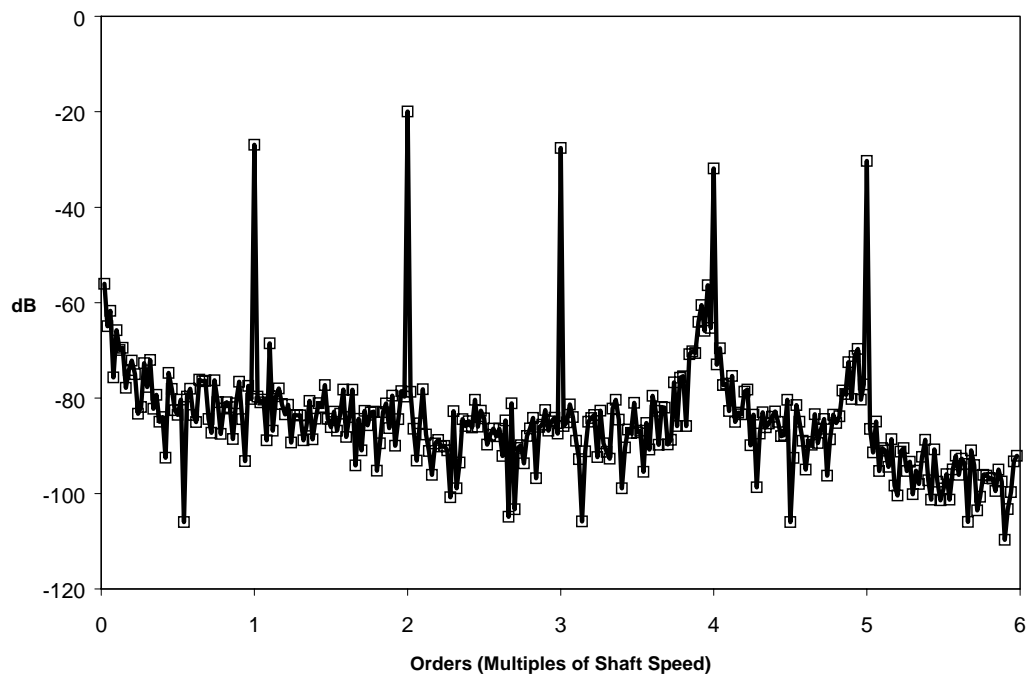
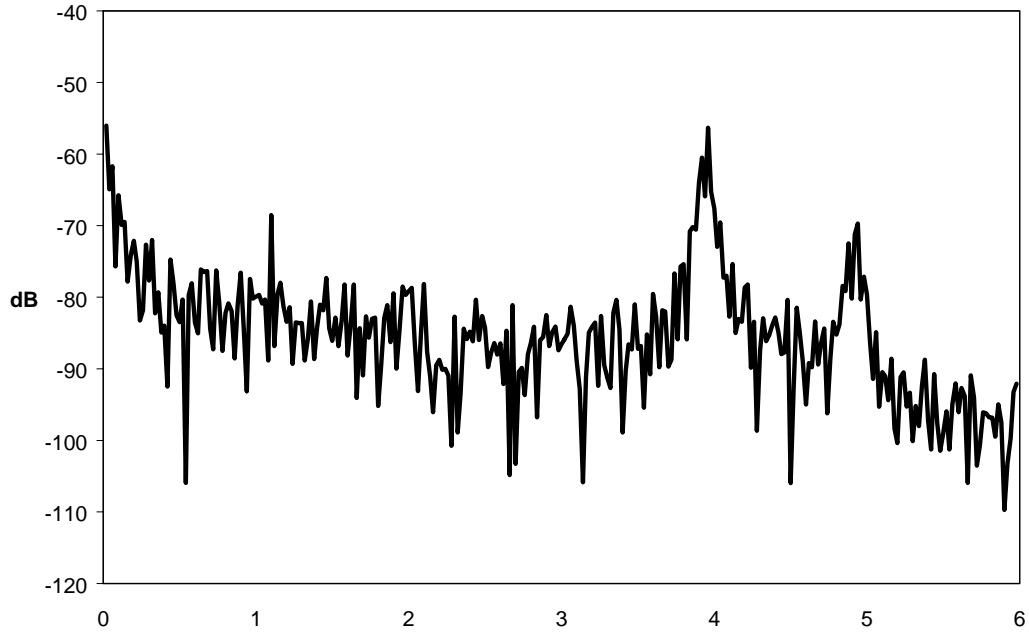


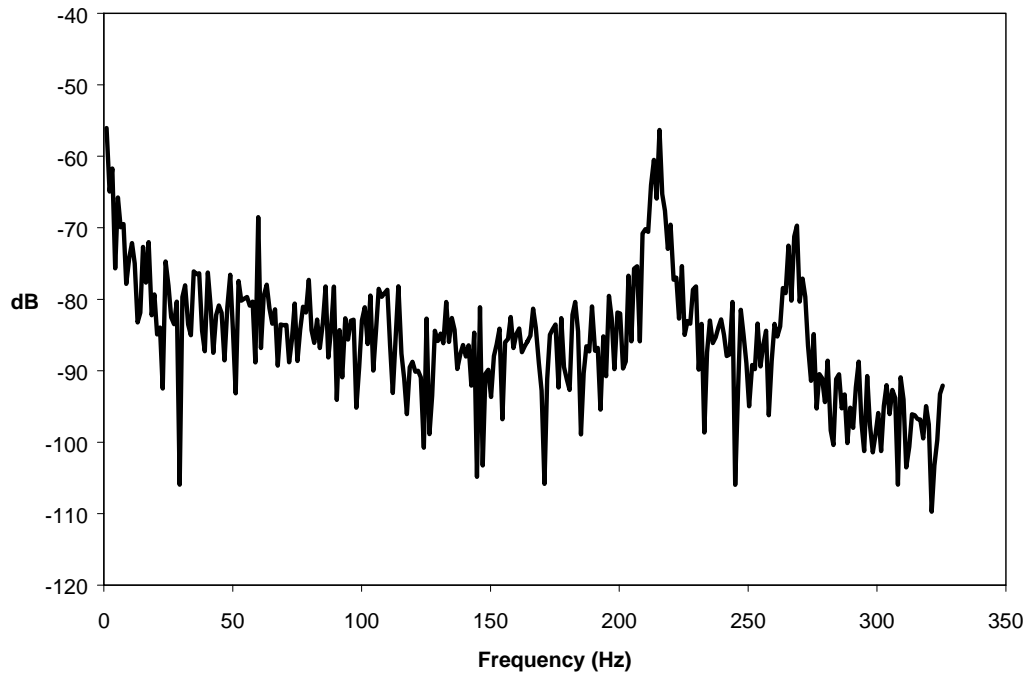
Figure 4: Single order spectrum, orders removed

Note each bin is individually marked in the figure. The order-related peaks are now essentially one bin wide, and are thus easily removed, as shown in Figure 5. However, due to gradual rotor speed

fluctuation, averaging in the order domain tends to blur the natural frequency locations. Thus, the individual spectrum records are resampled back into the frequency domain, as shown in Figure 6.



**Figure 5: Single order spectrum, orders removed**



**Figure 6: Resampled to frequency domain**

Now, ensemble averaging of the resulting individual spectra results in the spectrum of Figure 7. Note that the blade bending natural frequencies and shaft torsional natural frequency are quite evident.

Figure 8 shows a single blade that has

become separated from the group. The natural frequency of this single blade was tuned to be about 4 Hz lower than the other blades when tested with the rotor wheel mounted in a vice (201 Hz vs. 205 Hz for the group). Note that in the demodulated spectrum of Figure 7, the

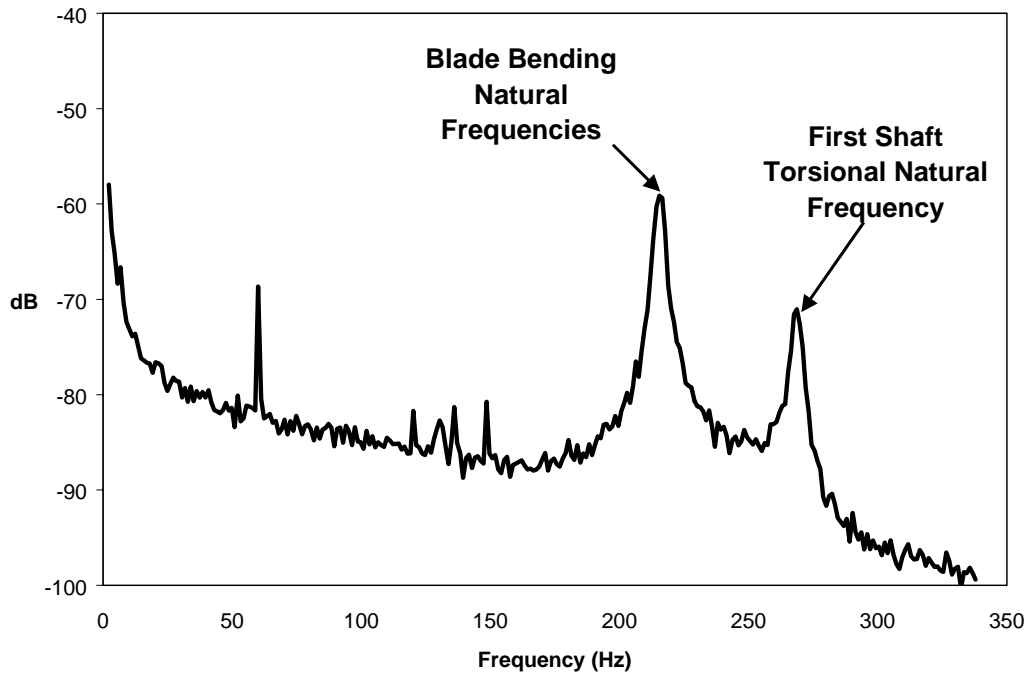


Figure 7: Resulting averaged spectrum, all blades tuned (30 averages)

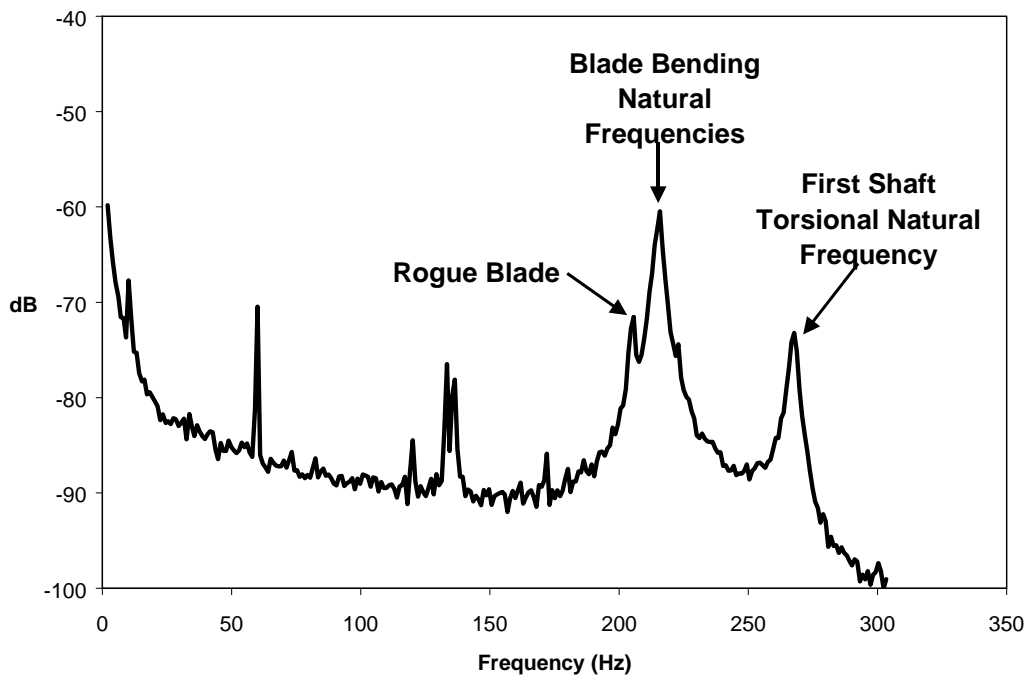


Figure 8: Resulting averaged spectrum, one blade mistuned (30 averages)

group frequency is about 216 Hz, and the single blade frequency corresponds to about 206 Hz. The difference of the 4 Hz (mounted in the vice) and 10 Hz (in the demodulated spectrum) spreads between the single detuned blade and the group

correlates well with previous testing of blades with an induced cut [2, 6]. A comparison of Figure 3 with Figures 7 and 8 demonstrates the dramatic improvement in the effective dynamic range.

**Summary:** Resampling in the order domain clarifies the torsional natural frequency and its character by eliminating the skirts, thus improving the effective signal to noise ratio. However, to account for slight speed variations, converting back to the frequency domain with each ensemble is necessary. This method results in a clear representation of the rotor system natural frequencies in the torsional domain.

Note that this methodology is adequate only when the speed of the shaft can be considered constant for each ensemble (although it may vary from ensemble to ensemble). If the speed varies significantly during the collection of a single ensemble, more sophisticated secondary resampling techniques (involving an inverse Fourier transform of the resampled data after order removal) must be employed.

With regard to detection of blade natural frequency shifts, the results are encouraging. Detuning a single blade by two percent resulted in a clear manifestation in the demodulated spectrum. In fact, twice the method accurately diagnosed our desktop rotor when the natural frequency shifted (due to a bent blade and due to loosening of the blade).

#### **Acknowledgement:**

This work was supported by the Southern Company through the Cooperative Research Agreement *Torsional Vibration and Shaft Twist Measurement in Rotating Machinery*; and by *Multidisciplinary University Research Initiative for Integrated Predictive Diagnostics*, sponsored by the Office of Naval Research.

#### **Reference:**

1. Vance, John M., *Rotordynamics of Turbomachinery*, John Wiley & Sons, New York, 1988, pp. 377ff.
2. Maynard, K. P., and Trethewey, M., "On The Feasibility of Blade Crack Detection Through Torsional Vibration Measurements," Proceedings of the 53<sup>rd</sup> Meeting of the Society for Machinery Failure Prevention Technology, Virginia Beach, Virginia, April 19-22, 1999, pp. 451-459.
3. McDonald, D, and Gribler, M., "Digital Resampling: A Viable Alternative for Order Domain Measurements of Rotating Machinery," Proceedings of the 9<sup>th</sup> Annual International Modal Analysis Conference, Part 2, April 15-18, 1991, Florence, Italy, pp. 1270-1275.
4. Potter, R., "A New Order Tracking Method for Rotating Machinery," Sound and Vibration, September, 1990, pp. 30-35.
5. Hernandez, W., Paul, D., and Vosburgh, F, "On-Line Measurement and Tracking of Turbine Torsional Vibration Resonances using a New Encoder Based Rotational Vibration Method (RVM)," SAE Technical Paper 961306, Presented at the Aerospace Atlantic Conference, Dayton, OH, May 22-23, 1996.
6. Maynard, K. P., and Trethewey, M., "Blade and Shaft Crack Detection Using Torsional Vibration Measurements, Part 1: Feasibility Studies," Noise and Vibration Worldwide, December 2000, pp. 9-15.