Using Low-Level Vibration Measurements for ODS Analysis

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Operational Deflection Shape analysis was performed on a large fan foundation using normal background turbulence as the only excitation. The practical extraction of usable data from extremely small signals has recently become feasible by the introduction of analyzers using 24-bit front-ends combined with advances in measurement sensors.

A planned upgrade of pollution control equipment at a coal fired power plant required that a pair of Induced Draft (ID) fans have their impellors and motors replaced. The speed was to be increased from 600 to 900 RPM and the corresponding horsepower increased from 5000 to 7000 hp. Motor speed was controlled by a Variable Frequency Drive that matched fan speed to plant demand.

The required increase in operating speed gave rise to an engineering concern that foundation resonances could be encountered within the new speed range. Cursory foundation analysis confirmed that resonances should exist within the new operating speed range. However, input for such analysis required site specific soil properties, which did not exist.

Vibration testing is typically performed to identify fan foundation resonant frequencies and associated mode shapes. Soil properties are then adjusted in the foundation analysis so that calculated frequencies and mode shapes match those which are measured. Foundation modifications can then be designed to accommodate the increased weight and new operating speed range of the system.

Vibration testing of large fan foundations is generally accomplished by shutting the fan down and mounting a large variable speed eccentric mass shaker to the foundation. The shaker is then swept through a speed range of interest and the foundation's response is measured. Utility companies however do not like to lose megawatts; therefore, critical fans will not be shut down for such trivial tasks as gaining information to design a modified foundation. In this case, the fans would not be shut down until the planned outage for upgrading the equipment, leaving only minimal time to test, analyze, design and install modifications to the foundation.

Because of advances in both analyzers and accelerometers, a new approach was proposed: perform an Operational Deflection Shape (ODS) analysis during normal fan operation using flow turbulence as random excitation. Until only recently, the state-of-the-art fast Fourier transform analyzer used a 16-bit Analog-to-Digital Converter (ADC), which produced 65,500 lines of amplitude resolution. A common problem was that if input voltage was set so that the dominant spectral peak would not overload (fan running speed in this case), low level background noise – typically called "in the mud" – would only have enough resolution to look like a city skyline. In 1998, Dactron was the first instrument manufacturer to introduce a 24-bit Dynamic Signal Analyzer, called the SpectraBook. A 24-bit ADC has 16,777,000 lines of amplitude resolution allowing low level signals to be pulled "out of the mud."

Fan Structure

Figures 1 and 2 show overviews of one of the two fans that were tested. The pair of Stack ID fans pull boiler exhaust through pollution equipment then force the gases up a common smoke stack. The tested fan structure included the following weights: impellor 51,800 lbs; housing 108,000 lbs; motor 37,000 lbs; and foundation 619,910 lbs; total unit weight of 816,710 lbs. It was anticipated that a new fan impeller and motor would add 33,900 lbs, plus another 266,820 lbs for foundation modifications. Total weight of the modified unit was anticipated to increase by 37% to 1,117,430 lbs.

Figure 1. ID fan/stack.

The current foundation is embedded to 5 ft below grade with a footprint approximately 16 by 40 ft. Figure 3 presents a side view of the fan housing and motor pedestal, while Figure 4 shows a view of the embedded foundation as seen from the fan outboard end.

The purpose of testing was to identify rigid body resonant frequencies and associated mode shapes of the foundation. Geometric points were established to represent the foundation. ODS data were acquired in the X, Y and Z directions at all points. Rigid body modes were identified through animated operating shapes.

Accelerometers Keep Getting Better

It was not many years ago that foundation testing required the use of large, highly sensitive, seismic accelerometers that had a resolution of 1×10^{-4} g rms, as shown in Figure 5. By comparison, today's seismic accelerometers may have resolutions as fine as 1×10^{-6} g rms (a millionth of a g). Similar advances have also been made with general purpose accelerometers. Figures 5 and 6 contrast a seismic with a miniature triaxial accelerometer, PCB Model 356A16, that was used in this test. The triaxial accelerometer has the same resolution – 1×10^{-4} g rms – as the older seismic model. It has a sensitivity of 100 mv/g and a ±5% frequency response from 0.5 Hz to 5 kHz. Whereas its 0.55 in. size and 0.26 oz weight are not of concern when testing a foundation, there could be an issue

Figure 2. ID fan, motor end.

Figure 3. Fan housing and motor pedestal on embedded foundation.

Figure 4. Embedded foundation, fan outboard bearing pedestal.

Figure 5. Seismic accelerometer.

Figure 6. Miniature tri-axial accelerometer.

when testing other components, such as the fan's bearings or blades, if only limited access was available. Even though the advertised resolution is 1×10^{-4} g rms, this unit was successfully used to measure signals as low as 2×10^{-5} g rms during the test.

For this test, a pair of triaxial accelerometers was used along with a reference accelerometer, for a total of seven data channels. All accelerometers were attached to the foundation with Petro-Wax, a conformable mounting wax, requiring only that dirt be brushed off the measurement point.

Data Acquisition

Vibration data were acquired using an eight-channel Dactron SpectraBook with their RT Pro Modal Data Acquisition package. ODS analysis is a process where vibration data are acquired on a structure such that relative magnitude and phase can be determined between various points of interest. Presentation of graphical animation shows how the structure is moving in three-dimensional space. ODS analysis is generally used when a problematic structure is experiencing discrete forcing functions, such as from unbalance or other harmonically related components. If the forcing function happens to occur at a frequency near a structural resonance, the operational shape will correspond to a shape determined through experimental modal analysis.

In a practical sense, even if the forcing frequency is not near a resonance, the presented animation still shows a pattern of deformation associated with a resonance. Testing has found that the pattern of operating deformation corresponds to the mode shape as the frequency approaches, crosses over and departs from a resonant peak. A new shape, corresponding to the next higher resonant mode, occurs as the frequency crosses an antiresonance and approaches the next higher resonance. As an interesting aside, think of an antiresonance as nothing more than a resonance with a different boundary condition. This concept can be very helpful with correcting structural problems.

The purpose of this foundation test was to perform an ODS analysis without shutting down the fan. Therefore, instead of determining deformation at discrete forcing frequencies, flow turbulence from normal fan operation was used to furnish broadband excitation to stimulate foundation resonances. However, structural resonances of the entire system should be expected and were also excited. A high degree of engineering experience was then required to interpret and discern the desired rigid body foundation modes from flexible modes of the steel structure to which the foundation reacted.

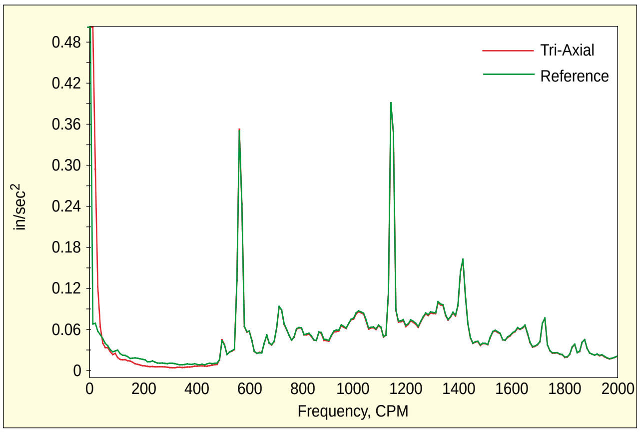

Figure 7. Overlay of reference accelerometer with tri-axial unit.

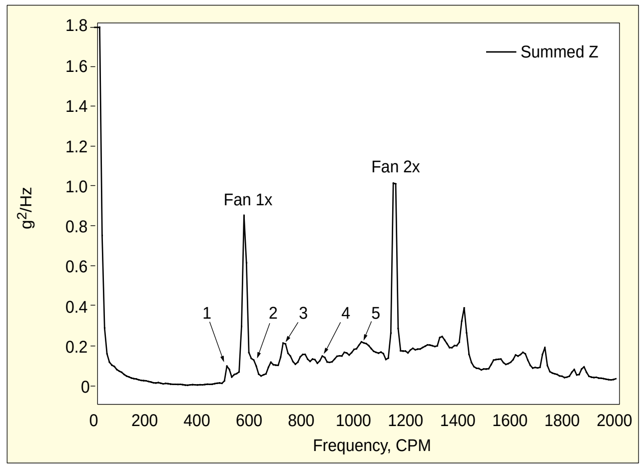

Figure 8. Summed power spectral density in the vertical direction.

In other words, this study had to judge whether the dog was wagging its tail or the tail was wagging the dog. Engineering judgments, as to whether a particular peak was a foundation mode, were based on a variety of issues, including: cleanness of shape, progressive sequence of shapes and redundancy of shapes. Mode shapes are always unique; if modes appear at different frequencies but with the same shape, it is an indication that another part of the structure is involved. For example, one mode may involve another part being in phase, while the second mode would involve the other part being out-of-phase.

As previously noted, measurement locations were selected around the perimeter to represent the embedded foundation geometry plus pedestal. The first task was to acquire preliminary data to find a reference measurement point. This involved looking at X, Y and Z spectra at several points, overlaying the data and choosing a point and direction that contained the most spectral peaks.

An accelerometer, generally accepted for foundation projects, was used as the reference sensor. Because miniature tri-axial accelerometers are not used for such projects, a second task was to compare the reference measurement with corresponding data from the triaxial unit. An overlay of data in Figure 7 shows that the miniature unit curve (red) is in excellent agreement with the reference curve (green). This curve also shows that the respective calibration values give identical results.

For data to be usable, the ratio of roving-to-reference must be a stationary value. To assure that steady state conditions had been achieved for each measurement set, Auto Spectra, Transfer Functions and Coherences were simultaneously monitored during the averaging process. When averaged data remained stationary, the measurement was as good as it was going to get. Because this test was based on a very low level of random background noise, 2000 averages were needed to achieve stationary values.

Data Reduction

Data were imported to Vibrant Technology's ME'scopeVES for generation of animated operating shapes. There are basically two data methods that could be used: 1) Auto Power Spectra with Cross Power Spectra; or 2) Transfer Functions. The Auto and Cross Power method has advantages because data visually have peaks that are easily interpreted. Conversely, the Transfer Function method essentially uses the roving accelerometer data divided by the reference data to calculate a pseudo Frequency Response Function, which is difficult to visually interpret because it contains flat spots at forcing frequencies rather than peaks. For example, the Transfer Function for Figure 7 data would be a constant value of 1.0; that is, output is equal to input. After data have been imported to ME'scope, the cursor can be interactively moved across the data plot and animated motion will be displayed at any frequency.

Vibration data were acquired in the X, Y and Z directions with the fan operating at a steady state condition of 576 RPM.

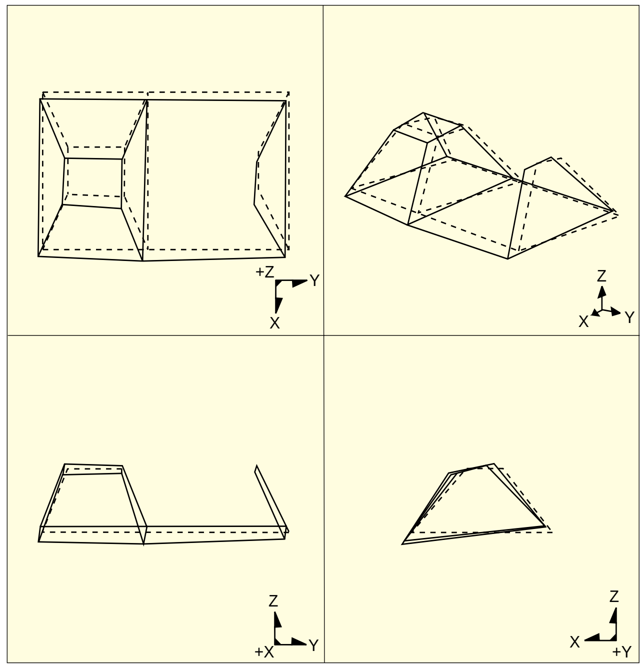

Figure 9. Lateral Rocking at 609 rpm.

To differentiate between modes that involved motion in the X versus Y versus Z directions, data were summed in the respective directions to create directional power spectra within RT Pro. Dominant frequencies in the summed data, other than fan operational harmonics, represent modes of interest for that direction.

Mode Shapes. Summed data for the vertical direction contain any motion that occurs in the vertical direction, including out-of-phase motion due to rocking. Vertical data are presented for information in Figure 8, and each of the resonant frequency values was evaluated to assess whether it was a resonance of the foundation, the structure above the foundation or an interaction between the foundation and attached structure. Figure 8 shows the fan's running speed and second harmonic, along with the depicted five rigid body foundation resonances that were found. Modes of the foundation were found at the following speeds:

1. 506 rpm Longitudinal Translation.
2. 609 rpm Lateral Rocking.
3. 731 rpm Lateral Translation with Rocking.
4. 928 rpm Vertical Bouncing.
5. 1,096 rpm Longitudinal Rocking.

An embedded foundation should have six rigid body modes. The missing sixth mode would involve rotation about a vertical axis. This mode was not found, however, probably because it was not excited by flow turbulence.

This variable speed fan has historically been unable to achieve its full rated speed of 600 rpm because of high vibration. This analysis clearly showed why – a rocking resonance situated at 609 rpm. In addition to the problematic resonance at 609 rpm, a translational resonance also existed at 506 rpm, well within the fan's operating speed range. From a machinery diagnostic view point, the spectrum shows a high 2× component, most probably due to misalignment at the coupling or between the fan's bearings. Figure 8 also shows that four of the five modes are already in the new proposed speed range and the fifth mode will probably be lowered to also be in the range.

Animated Shapes. A simple geometry was established in ME'scope. Data were then imported from RT Pro and reduced to animated shapes. Figure 9 presents the pattern of motion found at 609 RPM. The solid line shows the foundation's displaced location, while the dashed line depicts its stationary position. The four views of Figure 9 show the foundation to be rocking in the lateral direction.

Conclusions

A thought provoking challenge was undertaken to devise a test method for identifying rigid body foundation resonances of an 800,000 lb fan structure without hindering plant operation by shutting down the fan. The introduction of 24-bit Dynamic Signal Analyzers, coupled with advances in accelerometer design, allowed the challenge to be met by performing an Operating Deflection Shape analysis using low level random background noise from flow turbulence as excitation.

Identified frequencies and corresponding patterns of deformation were used to determine soil properties. The soil properties were then used to design foundation modifications to accommodate a higher horsepower fan running at a higher speed.

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