VIDEO MOTION AMPLIFICATION VS. OPERATING DEFLECTION SHAPES FOR MACHINERY DIAGNOSIS

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Abstract:

Operating Deflection Shapes (ODS) has been an important tool in visualizing the vibration of the machine and its system, including piping networks. The input for ODS is the phase-linked signal set from a group of accelerometers, moved over often hundreds of test points. The data is superimposed onto a CAD model, and then scaled-up vibrations are animated at frequencies of interest. This process is time-consuming and therefore expensive each time it is applied by experts, and is error-prone. An alternative method has been developed that is based on evaluation of high resolution/ high speed videos. The method provides information equivalent to a high-sensor-count ODS, by treating each pixel as an accelerometer, using the pixel's light intensity modulation to translate information embedded in the video into vibration motion able to be observed and interpreted by human investigators.

<u>Key Words</u>:
Motion Amplification; video; Operating Deflection Shape; Turbomachinery

Introduction:

Turbomachinery vibration is often useful in determining whether or not a turbomachine is operating properly, and for diagnosis of problems if the operation appears improper, or if reliability issues have been experienced (e.g. fatigue cracking, or premature wear of bearings and seals). For several decades, a visual method called Operating Deflection Shapes (ODS) has been an important tool in getting a complete and simultaneous view of the vibration of the machine and its system (e.g. piping, foundation, and driver or driven machine). The input for ODS is the phase-linked signal set from a group of accelerometers, moved over often hundreds of test points while one phase-reference accelerometer is kept at a consistent location and direction. The data is superimposed onto a simplified CAD model of the machine and system, and then the exaggerated (but to-scale) vibrations are animated at frequencies where the response is sufficient to be of interest to the researcher or troubleshooter. This process takes several days for complex machinery and systems, operated at a variety of process points.

A new method has been developed that is based on evaluation of high resolution/ high speed video taken of the operating machinery. The method provides information equivalent to a high-sensor-count ODS, by treating each pixel as an accelerometer, using the pixel's light intensity modulation to determine local vibration displacement frequency spectrum. From this information, realistic magnification of slow-motion video footage permits microscopic vibration to be amplified and thereby observed and interpreted by the human investigator.

ODS Methods:

Over thirty years ago, some researchers developed the concept of "seeing" vibration. Their approach was to acquire data at many locations and directions on a vibrating structure, and then allocating those motions to a very simple CAD model. This model was then animated on a computer video screen, or the extremes of the vibration in the model were plotted by a computer printer or plotter. This technique became known as Operating Deflection Shapes. The following outline summarizes the technique:

- Based on the "natural excitation" frequency spectra of the rotating equipment
- User acquires vibration data from various locations and directions on machine (hundreds of vibration measurements
- One sensor is always kept at the same location and direction, to provide a reference signal as other probes are "roved".
- A large database is built up of amplitude vs. frequency and phase angle
- A 3-D CAD model is constructed, and assigned motion from each individual vibration data point.
- The associated software is used to amplify the results filtered at specific frequencies of interest, creating animations of the CAD model of the equipment and related piping and foundation.

As an example, consider a high-pressure "charge pump" that was experiencing excessive vibration at a US nuclear plant. This pump runs at 4800 rpm (80 Hz), driven by an 1800 rpm motor through a speed increasing gear set. The pump type is a multistage barrel. Typical vibration levels in these pumps tend to be higher than industrial pumps, and are often over 0.2 in/sec rms in a healthy pump. Depending on the specific pump type, bearing clearances, and the plant experience, trip levels may be set between 0.3 and 0.5 in/sec rms. In this case, the pump was experiencing gradual vibration increase that had not been diagnosed, and was surpassing 0.4 in/sec rms. The phase angle reading of the peak vibration versus the location of the keyphasor on the shaft was shifting, varying between 0 and 180 degrees. A combination of operation modal analysis and operating deflection shape (ODS) evaluation was performed. The testing was performed tridirectionally at 200 locations on the pump, pedestal, and foundation. Rotor displacement was also recorded from permanently mounted proximity probes.

The detailed study determined that there was significant lateral/ horizontal vibration of one of the pump non-driven-end (NDE) mounting feet versus the top mounting surface of its pedestal. This is evident in Figure 1, which will be animated during the presentation of this paper.

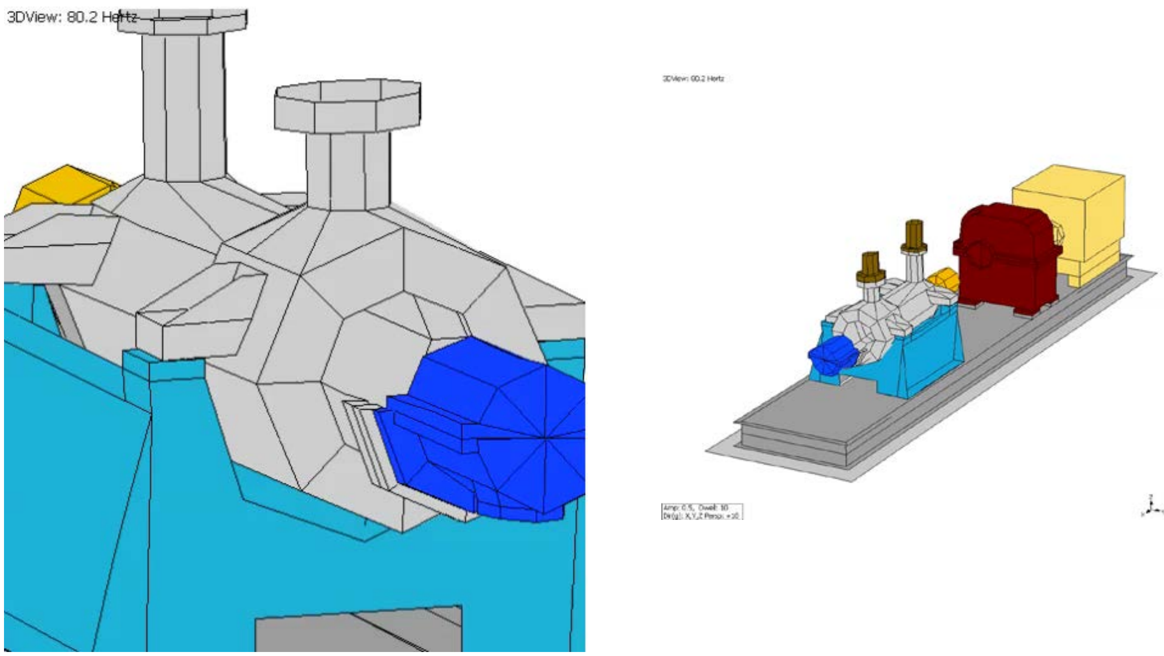

Figure 1: Soft foot evident in left center of the left-side picture. Data was taken on the entire pump/ driver/ pedestal/ foundation system, as shown in the right-side picture.

The diagnosis was that a casing (as supported by the pedestal) structural natural frequency (involving horizontal "tipping" of the casing NDE end) used to be 15% above the running speed, but was down drifting into (and sometimes beyond) the running speed of the pump, tuning in a resonance. The reason was that, when the foot was able to slide in frictional contact, it no longer supplied as stiff of a support of the casing. By tightening down on the foot attachment bolt, this "soft foot" condition was repaired, and the natural frequency involved shifted back up to order of 93 Hz, sufficiently separated from 1x running speed forces (e.g. residual imbalance) to avoid further resonance. Vibration levels decreased to below 0.1 in/sec rms.

The physical problem may seem trivial once its nature is perceived. However, some very good technical people at the plant wrestled with this problem for 6 months before a 3-D visual technique- in this case ODS- was applied. The perspective on the vibration distribution and its meaning was not there when the plant evaluated the vibration data point-by-point instead of as 'whole cloth".

Therefore, ODS was extremely useful in this case, rendering problem diagnosis and recommended solution straightforward once it was employed. However, in general ODS has its drawbacks as well. The pros and cons of ODS are summarized in the list below:

- ✓ Powerful and intuitive diagnostic tool
  - Can clearly demonstrate modes and frequencies of vibration
- ✓ Proven over decades of application
- ✗ Time consuming
  - Data acquisition – hundreds of data points
  - Post processing – compiling database to match model points
- ✗ Potential for bookkeeping error
  - Match all gathered data points to appropriate place on model
- ✗ Requires proximity – not appropriate for restricted access
  - Heat, radiation, accessibility/scaffolding requirements

This raises the thought, what if the investigator could truly see the vibration? Academic researchers, some of whom are listed in the References (Ref. 1-3) had this thought about 25 years ago, and have been gradually perfecting techniques. Basically, these techniques fall into two categories: 1) tracking of specific points, edges, or (as machine-vision scientists call them) "blobs", and 2) performing statistics, including signal vs. time as well as signal FFT frequency spectra, on the individual independent pixels. The former are called "Lagrangian Methods" by many researchers, and the later are called "Eulerian Methods". A rich literature basis exists for these methods. This paper's references emphasize the Eulerian technique

The motion-amplified video method may be summarized as follows:

- Uses high-speed, high resolution video
  - Eulerian method is equivalent of millions of accelerometers, 1 per pixel
- Analyzes/quantifies motion
  - Frequencies
  - Displacement (2-dimensional)
- Algorithms amplify motion to human visual threshold
  - Filterable by desired frequencies

Example: A High Speed Blower with Acute Noise Levels

Two small constant speed (3600 rpm) ducted fan blowers and motors installed for worker-required ventilation at a waste water facility provides an example. The vibration of each centrifugal 8-vaned blower and motor was actually quite modest, well within ISO 10816-3 specified vibration limits.

However, the room noise created by the blowers was as high as 120 dB at certain operating conditions. The authors applied both classical ODS as well as the new high-frequency high-resolution video motion amplification method to evaluate the problem. A view of the blowers and their layout in the room is shown in Figure 2:

Figure 2: Picture of the example blowers, motors, and ducting, and their layout in the machine room.

Microphone signals identified the problem frequency as 474 Hz, which was the blower rotating vane passing frequency. The question remained why, particularly given the low vibration levels. A representative ODS of one of the blowers is shown in Figure 3.

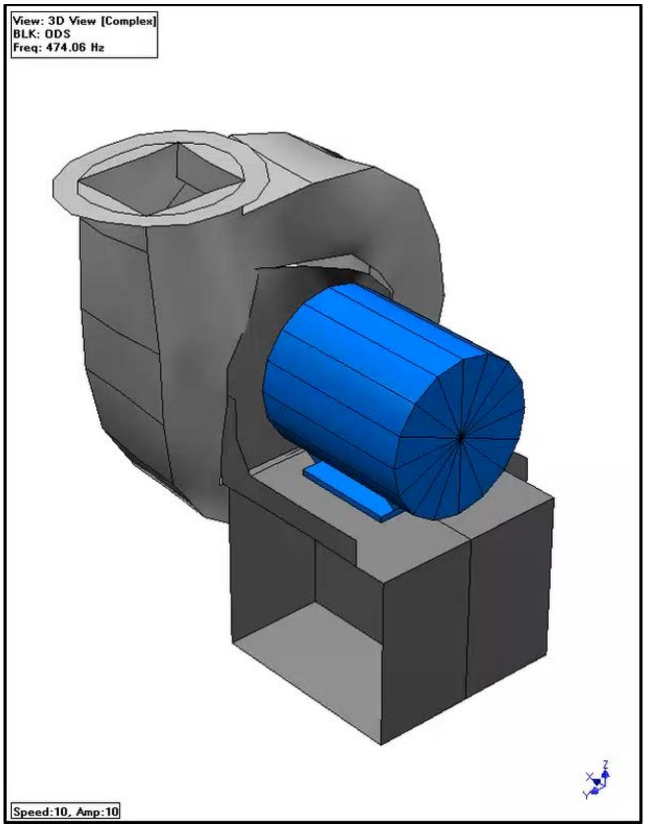

Figure 3: ODS model of the subject blower, exhibiting “undulating” axial motion of the upper flat side of the blower casing (vibration filtered to 474 Hz).

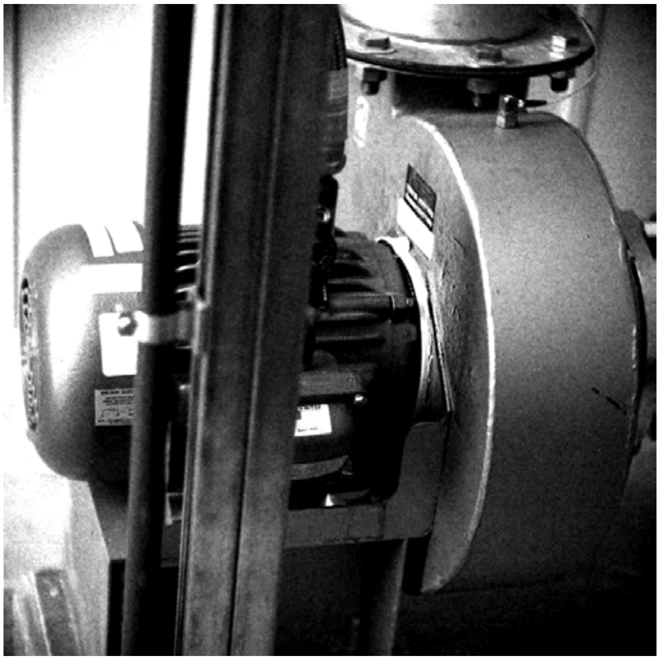

Figure 4: Motion-amplified video of the subject blower, exhibiting the same (but more easily visualized) “undulating” axial motion of the upper flat side of the blower casing.

Once the shape was identified and evaluated, it was clear that the blower was in resonance with the vane passing frequency. The upper sidewall of the casing unfortunately possessed a natural frequency very close to the vane passing frequency, and as the blower underwent changes in loading, the induction motor slip changed and the vane passing frequency drifted into and out of precise resonance with the sidewall natural frequency. When resonance was precisely tuned in, the noise level reached its 120 dB peak.

Other examples of pumps and turbines will be provided in the presentation of this paper.

Summary:

As presented, the new video-based motion amplification procedures and equipment coming onto the market can be very useful for vibration-based diagnosis of machinery. It has advantages over the classic ODS method in many (not all) instances, and typically takes much less time and "logistics" to implement.

The benefits are:

- ✓ It is a powerful and intuitive diagnostic tool
  - Realistically demonstrates modes and frequencies of vibration
  - Easy for non-experts to understand (management, etc.)
  - Comprehensive set of data points
- ✓ It does not requires "contact" – perfect for restricted areas
  - Heat, radiation, accessibility/scaffolding requirements
- ✓ It is fast
  - Millions of data points ready to evaluate in minutes, not days
- ✓ It is cost-effective
  - Helps focus effort for accelerometer-based ODS

Motion-amplified video certainly appears to represent an important addition to a vibration diagnostic tool kit.

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