Operating Deflection Shapes Detect Unbalance in Rotating Equipment

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This article demonstrates the use of the operational deflection shape (ODS) of a rotating machine as a means of detecting unbalance in its rotating components. The results of this work provide a new method for detecting machinery unbalance and offer a simplified approach for on-line fault detection in operating machinery.

An unbalanced rotating machine can cause parts to wear out quickly and account for a significant percentage of a machine's downtime. Not only is downtime expensive in terms of lost production, but costs of replacement parts, inventory, and energy consumption are also increased.

Traditionally, vibration signatures (level profiling of single-point vibration spectra), and orbit plots have been the preferred tools for detecting and diagnosing machinery unbalance. Although these tools may be effective when used by an expert, operational deflection shape (ODS) analysis offers a simpler, more straightforward approach for fault detection. Unbalance is more easily characterized by a visual as well as a numerical comparison of a machine's ODS when compared with its baseline ODS.

What's ODS?

An ODS is defined as any motion of two or more points on a machine or structure. Stated differently, an ODS is the motion of one point relative to all others. Motion is a vector quantity, and each of its components has both location and direction associated with it. Motion measured at a point in a specific direction is called a DOF (degree of freedom).

An ODS can be defined from any measured vibration data, either at a moment in time, or at a specific frequency. An ODS can be obtained from different types of time-domain responses (random, impulsive, or sinusoidal). An ODS can also be obtained from different types of frequency domain functions including linear spectra (fast-Fourier transfers, or FFTs), auto and cross-power spectra, FRFs (frequency response functions), transmissibility's, and ODSFRFs.[1]

Measuring an ODS

In general, an ODS is defined with a magnitude and phase value for each DOF that is measured on a machine or structure. This requires that either all responses are measured simultaneously or that they are measured under conditions that guarantee their correct magnitudes and phases relative to one another. Simultaneous measurement requires a multichannel acquisition system that can simultaneously acquire all responses. Sequential acquisition requires that a (fixed) reference response be acquired and that cross-channel measurements be calculated between it and other roving responses. This ensures that each DOF of the resulting ODS has the correct magnitude and phase relative to all other DOFs.

Baseline ODS versus Current ODS

The unbalance hypothesis posed here is that when an operating machine becomes unbalanced, its ODS will change. Unbalance will cause a change in the vibration level in many parts of a rotating machine. Therefore, an important question to ask is: "What constitutes a significant change in vibration level?" This will be answered by calculating a change in the machine's ODS. To measure a change in the ODS, the baseline ODS of a balanced machine will be compared with its ODS during current operation. The baseline is the ODS of the machine when it is properly balanced.

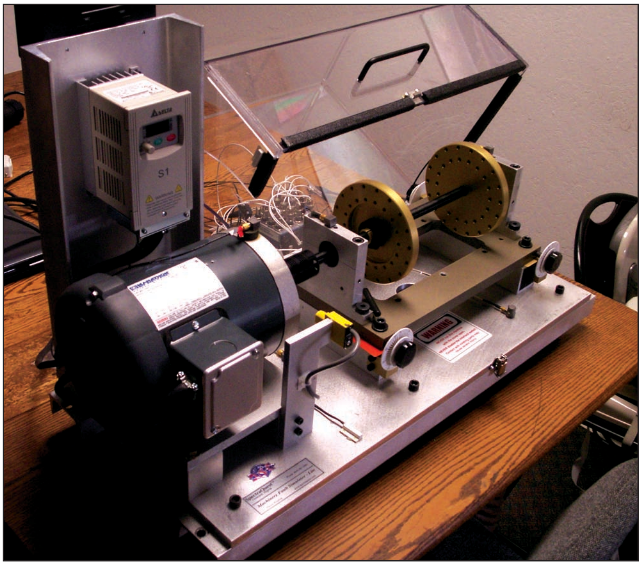

Figure 1. Machine fault simulator.

Shape Correlation Coefficient

An ODS is a complex vector with two or more components, each component having a magnitude and phase. Each component of the ODS is obtained from a vibration signal measured at a single DOF on the machine.

A calculation that measures the similarity between two complex vectors is the shape correlation coefficient (SCC). When this coefficient is used to compare two mode shapes it is called a MAC (or modal assurance criterion).[2,3] For comparing two ODSs, the SCC is defined as:

$$SCC = \frac{\left\| ODS_C \circ ODS_B^* \right\|}{\left\| ODS_C \right\| \left\| ODS_B \right\|} \tag{1}$$

where:
ODS_B = baseline ODS
ODS_C = current ODS
ODS_B^* = complex conjugate of ODS_B
$\| \;\|$ = magnitude squared
$\circ$ = degree of transmissibility (DOT) product between two vectors

The SCC is a normalized DOT product between the current ODS and the baseline ODS. It has values between 0 and 1. A value of 1 indicates that the ODS has not changed. As a "rule of thumb," an SCC value greater than 0.90 indicates a small change in the ODS. A value less than 0.90 indicates a substantial change in the ODS.

As a result, the SCC provides a single numerical measure of a change in the ODS of an operating machine. The ODS can have as many components (vibration signals from different DOF of the machine) as are necessary for detecting unbalance. Of course, the location and direction of the sensors are subjective and will vary from machine to machine.

One difficulty with the SCC is that it only measures a difference in the "shape" of two vectors. In other words, two vectors can be co-linear, or pointing in the same direction but have different magnitudes. If somehow the vibration levels increase in a machine

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so that the shape of the ODS does not change, the SCC will still have a value of 1, indicating no change.

Shape Percent Difference

A better measure of change in an ODS is the shape percent difference (SPD). The SPD detects both a change in level and in shape.

$$SCC = \frac{\left|ODS_C - ODS_B^*\right|}{\left|ODS_B\right|} \qquad (2)$$

where:

ODS_B = baseline ODS
ODS_C = current ODS
$|\ |$ = magnitude of vector

Because the SPD is a percentage relative to the baseline ODS, a value of 0 indicates no change in the ODS. A value of 1 means a 100% change in the ODS.

To summarize, both the SCC and SPD are in percentage units. When a machine is in balance, the SCC will be at or near 1 (100%), and the SPD will be at or near 0. As an unbalance condition begins to occur, the SCC will decrease, and the SPD will increase.

Data Acquisition

To verify our hypothesis, tests were performed using the machinery fault simulator shown in Figure 1. Triaxial accelerometers were attached to the top of both bearing housings and the motor. A triaxial and two uniaxial accelerometers were also attached to the base plate. These transducers provided a total of 14 vibration signals that were simultaneously acquired with a 16-channel data acquisition system.

A set of ODSFRFs was calculated between each of the channels of data and a single reference channel. An ODSFRF is a "hybrid" cross-channel measurement involving both an auto spectrum and a cross spectrum. It is formed by replacing the magnitude of the cross spectrum between a roving and reference signal with the auto spectrum of the roving response signal.

An ODSFRF has the phase of a cross spectrum, but its magnitude is a true measure of the magnitude of response, which is provided by the auto spectrum. Data were acquired at an operating speed of 2000 RPM for a variety of unbalance conditions. A typical ODSFRF is shown in Figure 2. It is clear that the dominant peaks in the ODSFRF are at the running speed and its higher orders (2000, 4000, 6000 RPM, etc.).

ODSs were created by surrounding the running speed or one of its orders with a peak cursor and saving the peak values as the ODS. The ODS is the peak values from a set of ODSFRFs at one of the orders of the machine.

Unbalance Conditions

Vibration data were acquired from the machine when it was considered in balance (baseline condition), and under seven different unbalance conditions. Unbalance was created by adding weights to either or both of the rotors on the simulator, as shown in Figure 3. Data were acquired for each of the following unbalance conditions:

1. Small unbalance – inboard rotor
2. Small unbalance – outboard rotor
3. Large unbalance – inboard rotor
4. Large unbalance – outboard rotor
5. Two large unbalances – 0° apart
6. Two large unbalances – 90° apart
7. Two large unbalances – 180° apart

For Case 1, a small unbalance weight (11.25 grams) was added only to the inboard rotor closest to the motor. For Case 2, the same small unbalance weight was added only to the outboard rotor farthest from the motor. Cases 3 and 4 were the same as Cases 1 and 2 , but a larger unbalance weight (22.5 grams) was used.

In Cases 5, 6 and 7, the same large unbalance weight was added to both rotors, but the weights were attached in different positions. In Case 5, they were attached at the same radial position on both rotors (with 0° difference between them). In Case 6, they were attached 90° apart from one another; in Case 7 they were attached 180°apart.

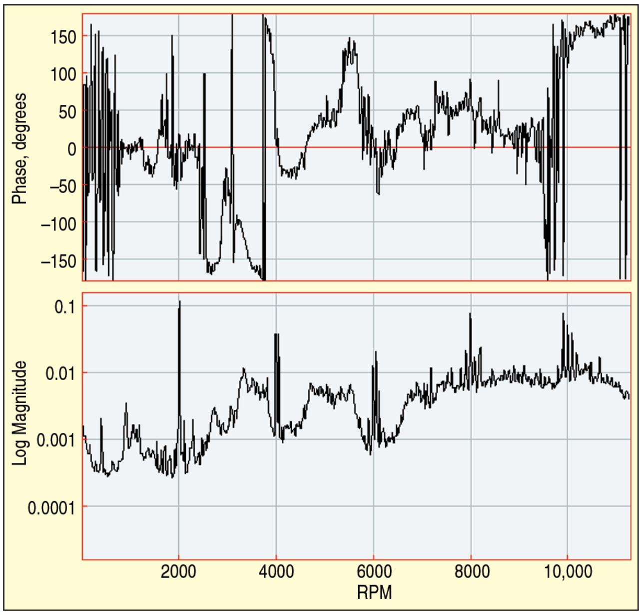

Figure 2. ODSFRF showing peaks at machine orders.

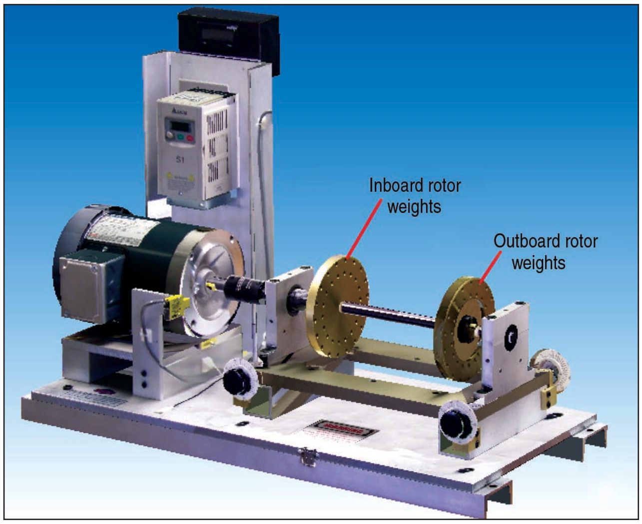

Figure 3. Unbalance weights attached to rotors.

Figure 4 contains the SCC and SPD values for the ODSs created from peak values at the running speed or first order (2000 RPM) of the machine. Both the SCC and SPD strongly indicate the unbalance condition for all seven cases. However, the SPD also indicates the vibration level or severity of the fault. Cases 1 through 4 indicate an increasing level of vibration from the inboard to outboard rotor and also from the use of the smaller to the larger unbalance weight.

Cases 5, 6, and 7 show how the vibration level is affected by the locations of the weights on the two rotors. Case 5 gave the highest SPD value (highest change in vibration level), because the two large unbalance weights were aligned with one another on both rotors and provided the maximum amount of unbalance.

The SPD values also show that Case 7, with the two large unbalance weights 180° apart, created about the same change in the vibration level as Case 2, with the single small weight attached to the inboard rotor. Similarly, the SPD values indicate that Case 4 created about the same change in vibration level as Case 6 even though weights were applied quite differently in these two cases.

Figure 5 contains the SCC and SPD values for the ODSs created from peak values at the second order (4000 RPM). Again, we can draw the same conclusions from the second-order ODS comparisons as we did from the first-order comparisons. Figure 6 contains the SCC and SPD values for the ODSs created from peak data at the third order (6000 RPM).

One incorrect result appears in these results. The SCC indicates

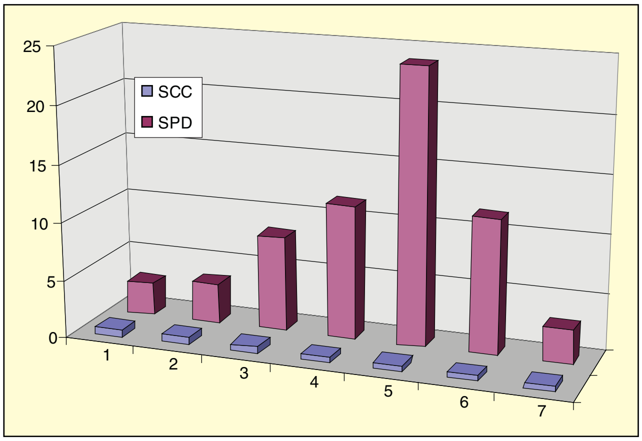

Figure 4. First-order (2000 RPM) ODS comparisons.

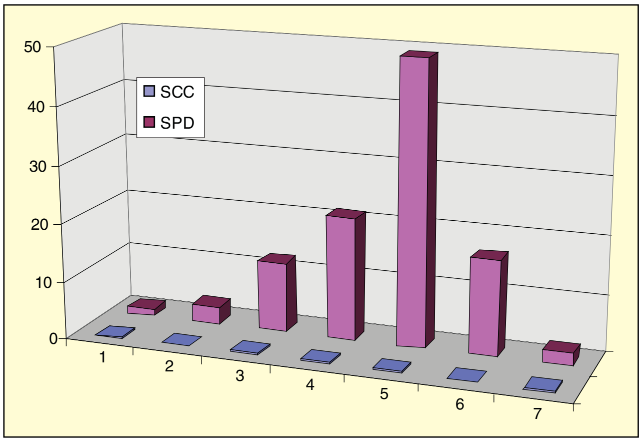

Figure 5. Second-order (4000 RPM) ODS comparisons.

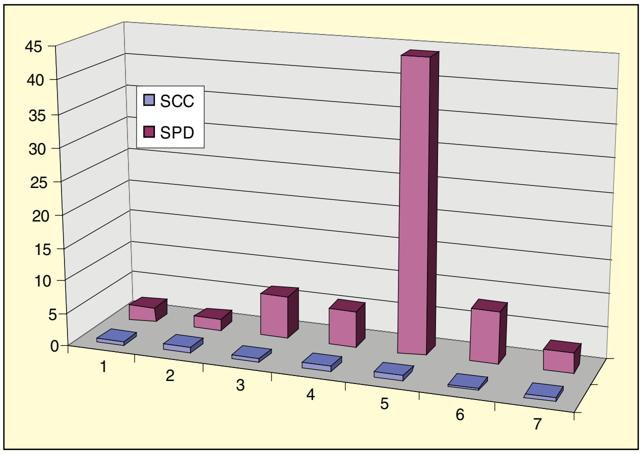

Figure 6. Third-order (6000 RPM) ODS comparisons.

a balanced condition for Case 2, with a value of 0.97. On the other hand, the SPD results are similar to those from the first- and second-order comparisons but don't quantify the severity of the unbalance conditions quite as well as the comparisons of the first- and second-order ODSs.

Conclusions

Seven different cases of unbalance were simulated using a rotating machine fault simulator. Accelerometer data from 14 different DOFs (nine DOFs on the motor and bearings and five DOFs on the base plate) was acquired using a 16-channel data acquisition system with the machine running at 2000 RPM. ODSs were constructed using the peak values at the first-, second-, and third-order frequencies from seven sets of ODSFRF functions.

Comparisons between baseline (balanced) ODSs and those of seven different unbalance cases were compared. These results confirmed our original hypothesis; namely, that "when an operating machine becomes unbalanced, its ODS will change."

Two different numerical measures of the difference between the baseline and current ODS were calculated; the SCC (shape correlation coefficient) and SPD (shape percent difference). The SCC only indicates whether two shapes are co-linear. The SPD proved to be more useful in this case, because it is a true measure of the difference between the baseline and current ODS. By measuring the change in the vibration, the SPD also measures the severity of the fault caused by an unbalance condition.

This is the second in a series of articles investigating the use of ODS comparisons as a means of detecting machine faults. In a previous report,[4] we showed how ODS comparison can be used to detect shaft misalignment.

Other machine faults, such as bearing oil whirl and loose connections, might also be detected through the use of ODS comparisons. An operating shape could also contain other engineering data, such as temperatures, pressures, voltages, currents, etc., for determining machine faults. The machinery fault simulator used to obtain these results is a product of Spectra Quest, Inc. The ODS analysis software is part of a MechaniCom Machine Surveillance System™ software, a product of Vibrant Technology, Inc.

References

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