Using Operating Deflection Shapes to Detect Misalignment in Rotating Equipment

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ABSTRACT

In this paper, we demonstrate the effects of rotating machinery shaft misalignment on its dynamic behavior which is characterized in the form of an Operational Deflection Shape (ODS). In this approach, an ODS derived from multiple accelerometer signals acquired at various points on the machine is used to diagnose shaft misalignment.

Tests are performed on a machinery fault simulator under various operating conditions. Operating data is simultaneously acquired using a multi-channel data acquisition system. Since misalignment produces dominant motion at the rotor running speed and its harmonics, this data is used to construct an ODS.

The emphasis is on correlating the ODS of the machine when properly aligned with its ODS following induced shaft misalignment. The results of this work will provide a new perspective of machinery fault detection. The aim is to develop a more reliable tool for determining shaft misalignment and other machine faults from operating data.

INTRODUCTION

A poorly aligned machine can account for up to 30 percent of a machine's downtime. Not only is downtime expensive in terms of lost production, but it also increases costs in the form of more replacement parts, inventory, and energy consumption. Considering the importance of the shaft alignment, it is interesting to note that a widespread understanding and use of tools for detecting and diagnosing misalignment is still elusive. A survey of the literature reveals that [1], [2]:

1. Misalignment produces significant vibration levels.
2. A machine can have parallel misalignment without exhibiting significant 2X vibration levels.
3. Misalignment is strongly influenced by machine speed and coupling stiffness.
4. Softer couplings are more forgiving, and tend to produce less vibration.
5. Level profiling of a single-point vibration spectrum for a given operating condition does not provide a reliable indication of machinery misalignment.
6. Observation of spectra in several points & directions, at varying speeds, may be needed to effectively diagnose misalignment.

Traditionally, vibration signatures (level profiling of single-point vibration spectra) and orbit plots have been used as the preferred tools for detecting and diagnosing machinery misalignment. Although these tools may be effective when used by an expert, ODS analysis offers a simpler, more straightforward approach to detecting misalignment. Misalignment is more easily characterized by a visual, as well as a numerical, comparison of a machine's spatial vibration levels (its ODS), with its baseline ODS taken when the machine is properly aligned.

What is an ODS?

Traditionally, an ODS has been defined as the deflection of a structure at a particular frequency. However, an ODS can be defined more generally as any ***forced motion of two or more points on a machine or structure***. Specifying the motion of two or more points defines a shape. Stated differently, a shape is the motion of one point relative to all others. Motion is a vector quantity, which means that it has location and direction associated with it. Motion measured at a point in a specific direction is called a Degree of Freedom, or DOF.

An ODS can be defined from any forced vibration, either at a moment in time, or at a specific frequency. Hence, an ODS can be obtained from different types of time domain responses, be they random, impulsive, or sinusoidal. An ODS can also be obtained from many different types of frequency domain measurements, including Linear spectra (FFTs), Auto & Cross power spectra, FRFs (Frequency Response Functions), Transmissibility's, etc.

What is a Mode of Vibration?

Modes of vibration are associated with structural resonances. The majority of structures will resonate. That is, under the proper conditions, a structure will vibrate with excessive, sustained motion. Striking a bell with a hammer causes it to resonate. Striking a sandbag however, will not cause it to resonate.

Resonant vibration is caused by an interaction of the inertial and elastic properties of the materials within a structure. Furthermore, resonant vibration is the cause of, or a contributing factor to, many of the vibration related problems that occur in operating machinery. These problems include failure to maintain tolerances, noisy operation, uncontrollability, material failure, premature fatigue, and shortened life.

To better understand a structural vibration problem, we need to characterize the resonances of the structure. A common and useful way of doing this is to define its modes of vibration. Each mode is defined by its modal frequency, modal damping, and mode shape.

Mode Shape and ODS Contrasted

A mode of vibration is an inherent property of a structure. A mode doesn't depend on the forces or loads acting on the structure. The modes will change if the structure's material (mass, stiffness & damping) properties change, or its boundary conditions (mountings) change. Mode shapes don't have unique values, and hence don't have units associated with them. However, *mode shapes are unique*. That is, the resonant vibration level of one DOF relative to another is unique.

An ODS is quite different from a mode shape. An ODS depends on the forces or loads applied to a structure. It will change if the load changes. An ODS can have units, typically displacement, velocity, or acceleration, or displacement per unit of excitation force. It can be used to answer the question, *"How much is the structure really moving, at a particular time or frequency?"* Finally, while mode shapes are only defined for linear, stationary structural motion, ODS's can be defined for nonlinear and non-stationary motion. Modes are only used to characterize resonant vibration. ODS's can be defined for any type of forced or resonant vibration.

Measuring an ODS

In general, an ODS is defined with a *magnitude* & *phase* value for each DOF on a machine or structure. In other words, to define an ODS vector properly, both the *magnitude & phase* are needed. This means that either all responses are *measured simultaneously,* or that they are measured under conditions which guarantee their correct magnitudes & phases relative to one another. Simultaneous measurement requires a multi-channel acquisition system that can simultaneously acquire all responses of the machine. Sequential acquisition requires that data be acquired under a *repeatable operating condition* so that all DOFs of the resulting ODS have the correct relative magnitudes & phases.

Baseline ODS versus Current ODS

The hypothesis of this paper is the following;

Misalignment hypothesis: ***"When an operating machine becomes misaligned, its ODS will change."***

This hypothesis will be shown to be true with examples later in this paper. Of course, it's well known that misalignment causes a change in vibration levels, so a more important question to be answered is; "*What constitutes a significant change in vibration levels*?" This will be answered by calculating a change in the machine's ODS. In order to measure a change, the ODS after misalignment will be compared with a baseline ODS;

Baseline ODS: The ODS of the machine when it is properly aligned.

Shape Correlation Coefficient

An ODS of vibration data is a *complex* vector, each component of which has a *magnitude & phase*. Each component of the ODS is taken from a vibration signal measured at a single DOF on the machine. (An ODS can also contain other engineering data such as temperatures, pressures, voltages and currents. Unlike vibration, however, these are scalar quantities that have no phase associated with them.)

A straightforward calculation which measures the similarity between two complex vectors is the Shape Correlation Coefficient (or SCC). When this coefficient is used to compare two mode shapes it is called a Modal Assurance Criterion, (or MAC) [3]. The SCC is defined as follows;

$$\mathrm{SCC} = \frac{\left\| \mathrm{ODS_C} \circ \mathrm{ODS_B^*} \right\|^2}{\left\| \mathrm{ODS_C} \right\| \left\| \mathrm{ODS_B} \right\|}$$

where: $\mathrm{ODS_B}$ = Baseline ODS.

$\mathrm{ODS_C}$ = Current ODS.

$\mathrm{ODS_B^*}$ = complex conjugate of $\mathrm{ODS_B}$.

$\| \ \|$ indicates magnitude.

$\circ$ indicates the DOT product of the two vectors.

The SCC is a *normalized* DOT product between the current ODS and the baseline ODS of a machine. The SCC has values between 0 and 1. A value greater than or equal to 0.90 indicates a strong correlation between the two vectors. ***A value less than 0.90 indicates a substantial change in the ODS***.

Hence, 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 DOFs of the machine), as are necessary for determining shaft misalignment or any other vibration related fault.

Data Acquisition

To verify our misalignment hypothesis, tests were performed using the machinery fault simulator shown in Figure 1. Accelerometers were attached to the top of both bearing housings, the motor, and the base plate of the machine. The baseline ODS was measured using a 16 channel analyzer, which simultaneously acquired a tachometer signal on channel 1, and 15 accelerometer signals on the remaining channels. Data was taken in two different acquisitions (or

Figure 1. Machine Fault Simulator.

measurement sets), providing ODS's with a total of 29 DOFs in them. Figure 2 shows where data was acquired for 14 DOFs of the motor and bearing housings. The remaining 15 DOFs were measured at 5 locations on the base plate using tri-axial accelerometers.

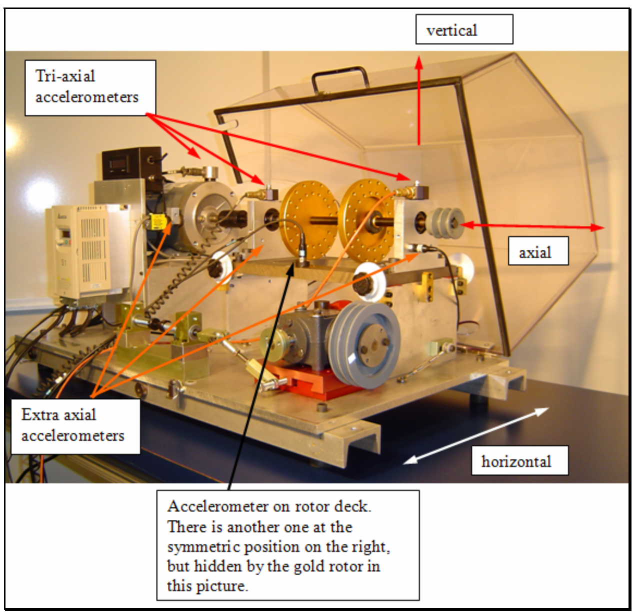

Figure 2. Accelerometers on Motor & Bearings.

Data was acquired at two different operating speeds; 2000 and 4000 RPM. 131,071 samples of time domain accelerometer data were acquired over a 25.6 second time period at a sampling rate of 5120 Hz. This data was then transformed using an FFT into its linear or Fourier spectra.

Comparing Baseline ODS's

Figure 3 shows a comparison display of the 2000 & 4000 RPM baseline ODS's displayed on a 3D photo model of the fault simulator machine.

The ODS's are the peak values of the Fourier spectra of the machine accelerations at running speed.

Notice that two data blocks of spectrum data are displayed below the comparison display of the two ODS's. These two data blocks each contain 29 frequency spectra, displayed in an overlaid format. The spectra of data acquired at 2000 RPM are on the left and the spectra of data acquired at 4000 RPM on the right.

Notice also that the peaks in each data block appear at two different frequencies. This is because the first measurement set of data (the 14 motor & bearing DOFs) was acquired at a slightly different RPM than the second measurement set of data (the 15 base plate DOFs). A peak cursor (which finds the peak value of each spectrum in a band), was used to define each ODS using this data with speed variations in it. The peak cursor band is shown in the two data blocks.

The SCC (MAC) displayed on the right of the structure models has a ***value of 0.02***. This very low SCC value indicates that the baseline ODS is completely different at these two operating speeds. Table 1 breaks down the ODS's further by comparing their SCC values on the base plate (0.22), the motor & bearings (0.03) and all 29 DOFs (0.02). These values indicate that the baseline ODS's are most alike on the base plate, very different on the motor & bearings, and also very different overall.

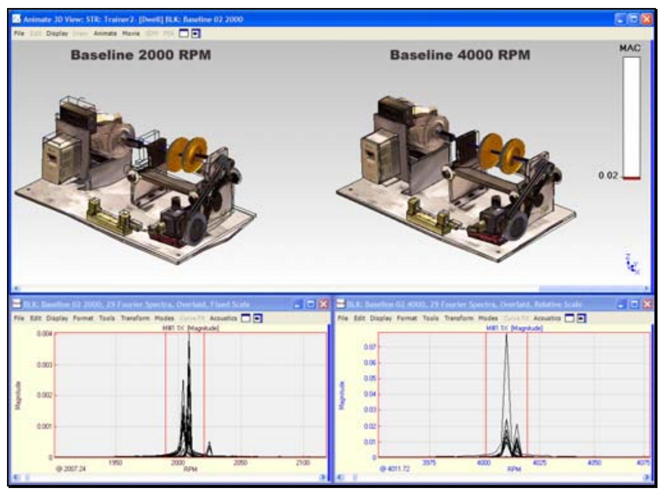

Figure 3. Baseline ODS's - 2000 & 4000 RPM.

DOFs	SCC
Base Plate	**0.22**
Motor & Bearings	**0.03**
All DOFs	**0.02**

Table 1. Baseline SCC values - 2000 & 4000 RPM.

These very different baseline ODS's demonstrate that a *machine's ODS will change significantly with operating speed*, even when it is properly aligned. This speed dependency of the ODS also means that data must be acquired at *approxi-*

mately the same machine speed as the baseline ODS in order to measure a change in the ODS.

Parallel Misalignment

To simulate a parallel misalignment of the rotor shaft with the motor shaft, the center of the rotor shaft was offset from the motor shaft by 25 mils at both bearing blocks, as depicted in Figure 4b. Figure 4 depicts both the parallel and angular misalignment that were simulated with the machine fault simulator.

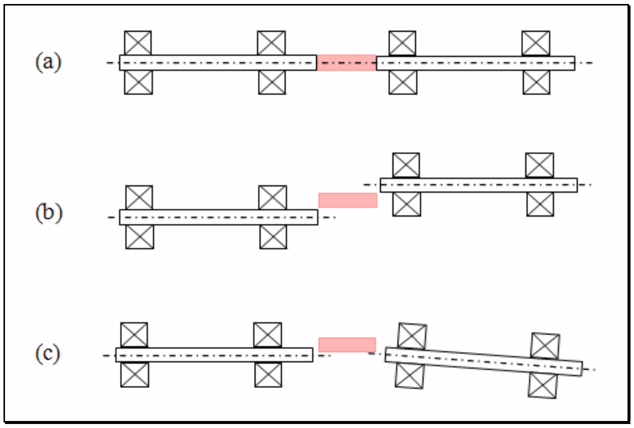

Figure 4. Parallel (b) & Angular (c) Misalignment.

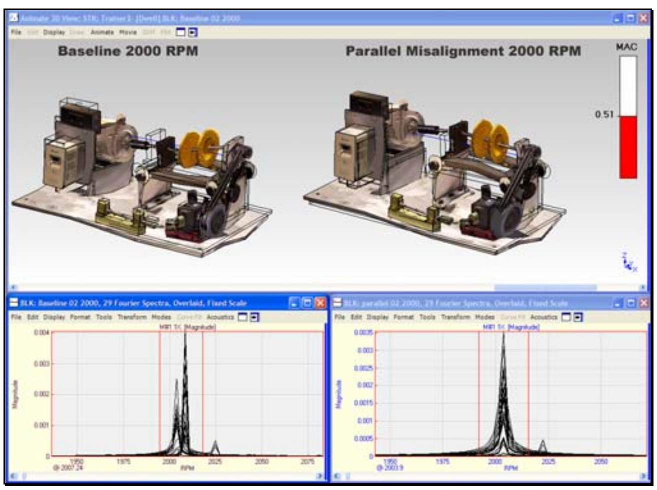

Figure 5. Parallel Misalignment- 2000 RPM.

RPM	DOFs	SCC
2000	Base Plate	0.99
2000	Motor & Bearings	0.00
2000	All DOFs	0.51
4000	Base Plate	0.84
4000	Motor & Bearings	0.94
4000	All DOFs	0.83

Table 2. SCC Values for Parallel Misalignment.

Figure 5 shows a comparison of the baseline ODS with the misalignment ODS at 2000 RPM. The All DOF SSC value (**0.51**) ***strongly indicates parallel misalignment***. Notice also that the base plate ODS has *not changed* (**0.99**), whereas the motor & bearing ODS is *completely different* (**0.00**) due to the misalignment.

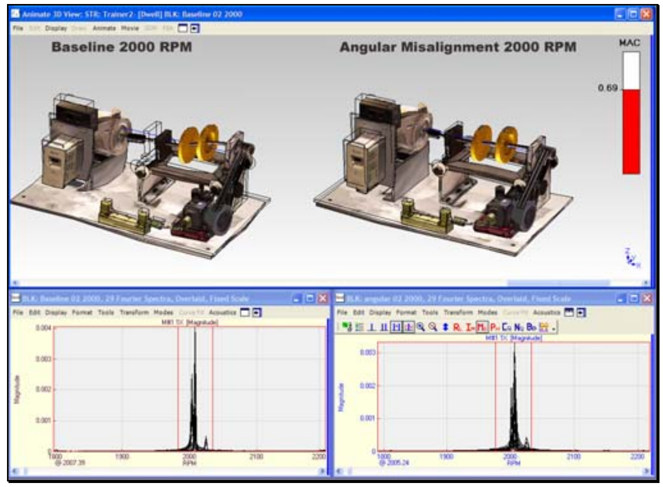

Figure 6. Angular Misalignment - 2000 RPM.

RPM	DOFs	SCC
2000	Base Plate	0.95
2000	Motor & Bearings	0.29
2000	All DOFs	0.69
4000	Base Plate	0.77
4000	Motor & Bearings	0.89
4000	All DOFs	0.85

Table 3. SCC Values for Angular Misalignment.

The results for parallel misalignment at 4000 RPM are also shown in Table 2, but these SCC values reveal a different dynamic behavior than at 2000 RPM. At 4000 RPM, the shaft & motor ODS has *not changed* (**0.94**), but the base plate ODS has *changed substantially* (**0.84**). Perhaps resonances of the base plate are being excited at this operating speed. Nevertheless, the overall ODS has also *changed significantly* (**0.83**) to indicate the parallel misalignment problem.

Angular Misalignment

To simulate an angular misalignment of the rotor shaft with the motor shaft, the inboard and outboard bearings were offset by 6.2 mils and 26 mils respectively to obtain about 0.1 deg misalignment the rotor shaft, as depicted in Figure 4c. Figure 6 shows a comparison of the baseline ODS with the ODS following angular misalignment. Again, a low SCC value (**0.69**) ***strongly indicates angular misalignment*** at 2000 RPM.

The breakdown of SCC values in Table 3 again shows that the base plate ODS has *not significantly changed* (**0.95**), while the motor & bearing ODS is *significantly different* (**0.29**).

The results for angular misalignment at 4000 RPM are also shown in Table 3. At 4000 RPM, the shaft & motor ODS has *changed* (**0.89**) less than the base plate ODS (**0.77**), but the overall ODS has *changed significantly* (**0.85**) to indicate the angular misalignment problem.

CONCLUSIONS

Both parallel and angular misalignment were simulated using a rotating machine fault simulator. Accelerometer data from 29 different DOFs (14 DOFs on the motor & bearings and 15 DOFs on the base plate) was acquired in two measurement sets using a 16 channel data acquisition system. ODS's were constructed using the peak data values of the Fourier spectra of the accelerometer signals, a running speeds of 2000 & 4000 RPM.

Comparisons of a baseline ODS (before misalignment) with the ODS after misalignment showed a significant change in the ODS in all cases. These results prove our original hypothesis; namely, that shaft misalignment in a rotating machine is strongly indicated by changes in its ODS.

The results also showed, however, that the sensitivity of the ODS measurement depends on locations & directions (DOFs) of the accelerometers used to make up the ODS. Tables 2 & 3 pointed out that an ODS made up of accelerometer ***signals taken only from the base plate would not have indicated misalignment at 2000 RPM***.

Furthermore, the results showed a rather unexpected result, namely, that an ODS made up of accelerometer ***signals taken only from the motor & bearings would not have indicated misalignment at 4000 RPM***. Clearly then, the placement and use of a sufficient number of transducers on a machine is critical for detecting misalignment.

Other machine faults, such as unbalance, bearing oil whirl, and loose connections might also be detected in their early stages of development through the use of ODS comparisons as demonstrated here. These faults will be investigated in follow-on papers on this subject. The simplicity of this approach to machinery fault detection makes it a strong candidate for implementation in a online early warning system.

The machinery fault simulator and data acquisition system used to obtain these results are products of Spectra Quest, Inc. The ODS analysis and display software is part of a Machine Surveillance System™ software package developed by MechaniCom, a subsidiary of Vibrant Technology, Inc.

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