Using Operating Deflection Shapes to Detect Faults in Rotating Equipment

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ABSTRACT
This paper is the third in a series where an operating deflection shape (ODS) is used as the means of detecting faults in rotating machinery [1] [2]. In this paper, ODS comparison is used as a means of detecting unbalance and misalignment in a rotating machine. Our purpose is to use *significant changes* in the ODS as an early warning indicator of rotating machine faults.

For the examples presented in this paper, tests were performed on a machinery fault simulator on which various faults were introduced. Vibration data was simultaneously acquired from accelerometers and proximity probes on the simulator using a multi-channel spectrum analyzer system. ODS data was then extracted from the frequency spectra of the acceleration and displacement responses, and two different numerical measures were used to quantify changes in the ODS of the machine.

These changes can be used in an automated warning level (alert, alarm, and abort) detection scheme to give early warnings of machine faults. The results of this work provide a new simplified approach for implementation in an on-line machinery health continuous monitoring system.

INTRODUCTION
Unscheduled maintenance of rotating equipment in a process plant can account for a significant percentage of the plant's downtime. Not only is equipment downtime expensive because of lost production revenue, but most machine faults will result in increased costs of replacement parts, inventory, and energy consumption.

Traditionally, vibration signatures (level profiling of single-point vibration spectra), and time domain based orbit plots have been the preferred tools for detecting *and diagnosing* machine faults. Although these tools may be effective when used by an expert, ODS analysis offers a simpler, more straightforward approach for fault detection. Many machine faults are more easily characterized by a visual as well as a numerical comparison of a machine's ODS when compared with its Baseline ODS.

What is an ODS?
An ODS is defined as the ***deflection of two or more points on a machine or structure***. Stated differently, an ODS is the deflection of one point relative to all others. Deflection is a vector quantity, meaning that each of its components has both location and direction associated with it. Deflection measured at a point in a specific direction is called a DOF (Degree of Freedom).

An ODS can be defined from any vibration data, either at a moment in time, or at a specific frequency. Different types of time domain data, e.g. random, impulsive, or sinusoidal, or different frequency domain functions, e.g. Linear spectra (FFTs), Auto & Cross spectra, FRFs (Frequency Response Functions), Transmissibility's, ODS FRFs [4], can be used to define an ODS.

Measuring an ODS
In general, an ODS is defined with a *magnitude* & *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 which guarantee their correct magnitudes & phases relative to one another. Simultaneous measurement requires a multi-channel acquisition system that can simultaneously acquire all responses. Sequential acquisition requires that cross-channel measurements be calculated between a *(fixed) reference response* and all other *roving* responses. This ensures that each DOF of the resulting ODS has the correct magnitude & phase *relative* to all other DOFs.

Baseline versus Fault ODS
The hypothesis of this paper is the following;

Machine Fault Hypothesis: *When an operating machine encounters a mechanical fault, its ODS will change.*

Many faults will cause a change in the vibration levels 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 ODS of the machine. In order to measure

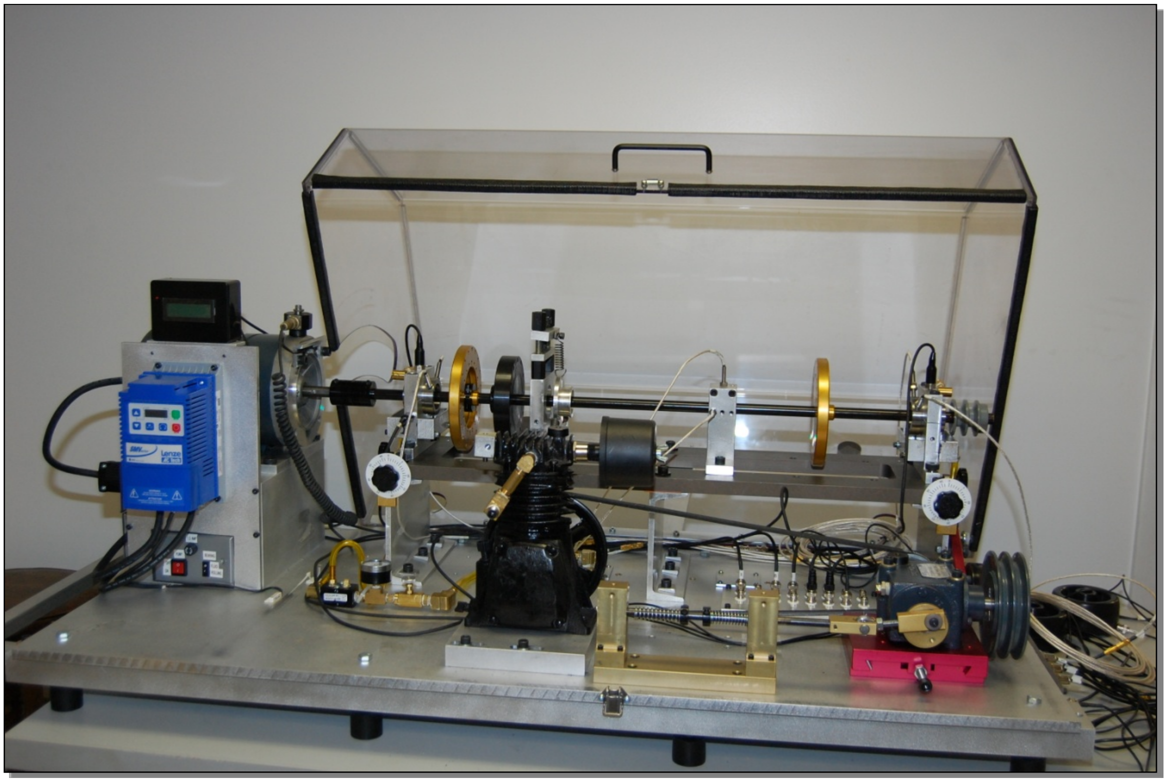


Figure 1. Machine Fault Simulator

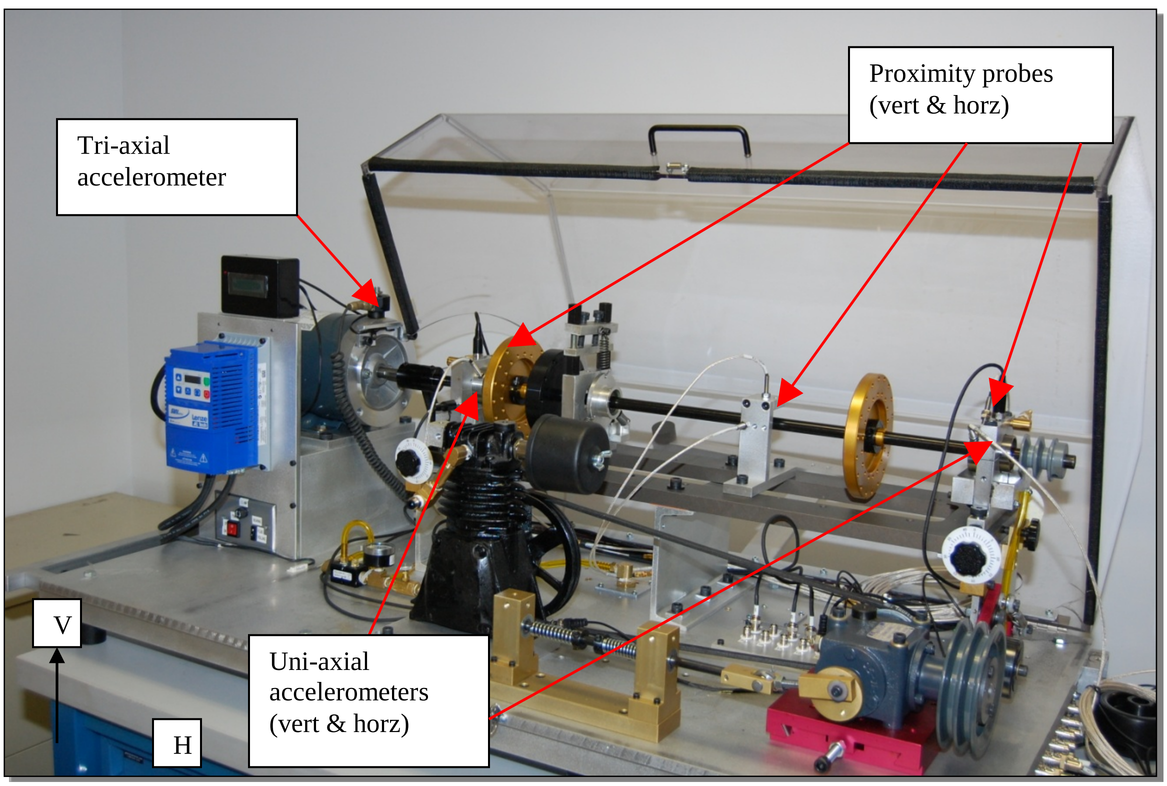


Figure 2. Sensor Locations

a change in the ODS, the ODS acquired when the machine is operating properly (called the Baseline ODS), is compared with its ODS during ongoing operation. After a fault begins to occur (or has occurred), the ODS is referred to as the Fault ODS.

Baseline ODS: The ODS of a machine when it is operating properly.

Fault ODS: The ODS of a machine when a fault begins to occur or has occurred.

Data Acquisition
To verify our hypothesis, tests were performed using the machinery fault simulator shown in Figure 1. Accelerometers and proximity probes were used to measure the simulator's vibration. The sensor locations are shown in Figure 2. The accelerometers provided 7 vibration signals and the proximity probes provided 6 vibration signals. These 13 channels of vibration data were simultaneously acquired with a multi-channel data acquisition system.

Time domain records were acquired, using 77824 samples at a sample rate of 5000Hz, for a total of 15.565 seconds of data on each channel. This data was post-processed and cross channel frequency domain measurements were calculated between all channels and a single reference channel.

ODSFRFs
To calculate ODS's, first 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 combining the *phase* of the Cross spectrum between a roving and the reference signal with the magnitude of the Auto spectrum of the roving response signal. The magnitude of an ODSFRF, provided by the Auto spectrum, is a true measure of the structural response.

Data was acquired at various *nominal* operating speeds of 800, 1000, 2000 & 3000 RPM) under a variety of fault conditions. A typical ODSFRF is shown in Figure 3. It is clear that the ODSFRF is dominated by peaks at the machine running speed (first order) and its higher orders (multiples of the running speed).

ODS's were obtained by saving the *peak cursor values* at the running speed, or one of its orders, as shown in Figure 3. Each peak cursor value is a DOF of the ODS.

The ODS is a collection of peak values from a set of ODSFRFs at one of the orders of the machine.

Figure 3 ODSFRF Showing Peaks at Machine Orders

Baseline Tests
With no faults, Baseline data was acquired from the simulator at operating speeds of 800, 1000, 2000 & 3000 RPM.

Machine Fault Conditions
The following faults were then introduced on the rotating machine simulator:

Unbalance Faults
Fault 1: One 4 gram unbalance screw on inboard rotor
Fault 2: Two 4 gram unbalance screws, one on each rotor

Angular Misalignment Faults
Fault 3: 10 mils angular misalignment on the outboard bearing
Fault 4: 20 mils angular misalignment on the outboard bearing

Parallel Misalignment Faults
Fault 5: 10 mils parallel misalignment on both bearings
Fault 6: 20 mils parallel misalignment on both bearings

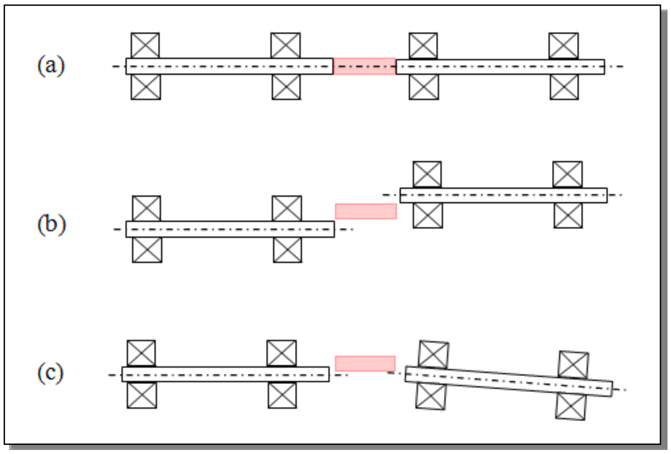


Figure 4. Parallel and Angular Misalignment

Numerical Comparison Of ODS's

Two different numerical methods were used to compare ODS's from before (Baseline ODS) and after a machine fault was introduced (Fault ODS). One method is called the SCC (Shape Correlation Coefficient), and the other is the SPD (Shape Percent Difference). Both of these calculations yield a percentage value. The SCC measures the co-linearity of the two ODS's, and the SPD is the percent difference between the Baseline and the Fault ODS.

SCC (Shape Correlation Coefficient)

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

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

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

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

$\mathrm{ODS_F} =$ Fault ODS

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

$\|\ \|$ indicates the magnitude squared

$\circ$ indicates the DOT product between two vectors

The SCC is a *normalized DOT product* between two complex ODS vectors. 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.*

The SCC provides a single numerical measure of a change in the ODS of an operating machine. The ODS can have as many DOFs as are necessary for detecting machine faults. Many DOFs may be required in order to detect certain kinds of faults. The location and direction of the sensors is 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, meaning that they lie along the same line, but they can still have different magnitudes. If the vibration levels increase in a machine but the "shape" of the ODS does not change, the SCC will still have a value of 1, indicating no change.

SPD (Shape Percent Difference)

A different measure of change in an ODS is the SPD (Shape Percent Difference). The SPD measures both a change in level and in shape.

$$\mathrm{SPD} = \frac{\left| \mathrm{ODS_F} - \mathrm{ODS_B} \right|}{\left| \mathrm{ODS_B} \right|}$$

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

$\mathrm{ODS_F} =$ Fault ODS

$|\ |$ indicates the magnitude of the vector

If $|\mathrm{ODS_F}| < |\mathrm{ODS_B}|$ then the SPD is negative

The SPD measures the percentage change relative to the Baseline ODS. A value of 0 indicates no change in the ODS, and a value of 1 means a 100% change in the ODS.

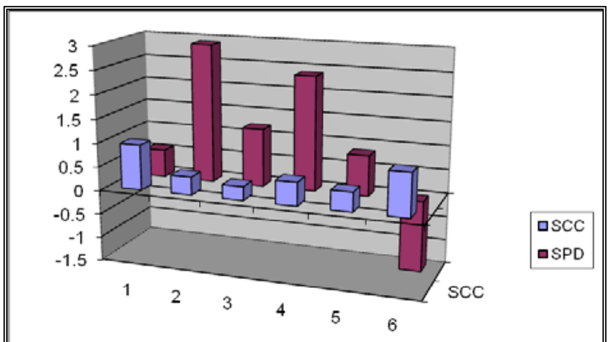
To summarize, when a machine is operating properly, the *SCC will be at or near 1*, and the *SPD will be at or near 0*. As a fault condition begins to occur, the *SCC will decrease toward 0*, and the *SPD* will *increase* or *decrease* depending on the change in machine vibration levels.

Comparing Baseline ODS's

Even under a no fault condition, the ODS of a machine can change with operating speed, so it is important to compare ODS's that were acquired at the same operating speed in order to detect faults. First, Baseline ODS's from four different operating speeds will be compared to quantify their differences. Baseline ODSs were compared in the following cases;

Case 1: 800 versus 1000 RPM
Case 2: 800 versus 2000 RPM
Case 3: 800 versus 3000 RPM
Case 4: 1000 versus 2000 RPM
Case 5: 1000 versus 3000 RPM
Case 6: 2000 versus 3000 RPM

Both the SCC and SPD values for these 6 cases are shown in Figure 5. For Case 1, the SCC value (0.95) indicates that the Baseline ODS at 800 RPM is essentially the same as at 1000 RPM. However, the SPD indicates that the vibration level has grown by 58% from 800 to 1000 RPM.



	1	2	3	4	5	6
SCC	0.95	0.38	0.29	0.49	0.4	0.9
SPD	0.58	2.91	1.21	2.39	0.85	-1.47

Figure 5. Baseline ODS Comparisons

Cases 2, 3, and 4 indicate the greatest changes in the ODS between two different operating speeds. The *first critical speed* of the machine shaft is **1590 RPM**, so these large changes in the ODS are expected.

In Case 6, the SCC value (0.90) indicates that the ODS's are co-linear (similar in shape), but the SPD value (-1.47) indicates that the ODS has *decreased* in magnitude from 2000 to 3000 RPM. This *decrease* in vibration level occurred because at 3000 RPM, the machine is operating beyond its critical operating speed.

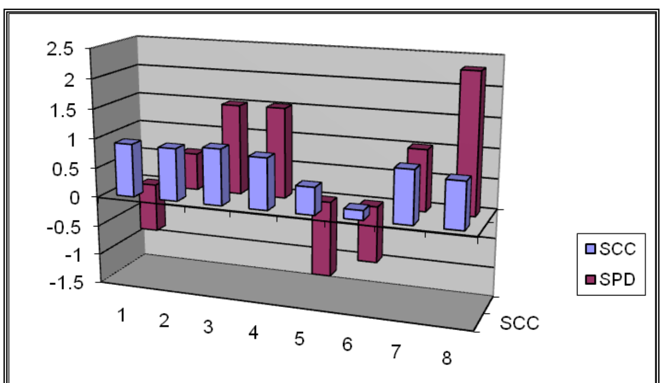
Unbalance Cases

Two unbalance faults were simulated in the rotating machine simulator by adding unbalance screws to the (gold) rotors on the shaft. Fault 1 was created by adding an unbalance weight of 4 grams to the inboard rotor. Fault 2 was created by adding an unbalance weight of 4 grams to each of the rotors. ODS data was then obtained for the following 8 cases.

Case 1: Fault 1 (One 4 gram unbalance) at 800 RPM
Case 2: Fault 1 at 1000 RPM
Case 3: Fault 1 at 2000 RPM
Case 4: Fault 1 at 3000 RPM

Case 5: Fault 2 (Two 4 gram unbalances) at 800 RPM
Case 6: Fault 2 at 1000 RPM
Case 7: Fault 2 at 2000 RPM
Case 8: Fault 2 at 3000 RPM

The SCC and SPD values for these 8 cases are plotted in Figure 6. In each case the Baseline ODS for a different machine speed is compared with the Fault ODS at the same speed.



	1	2	3	4	5	6	7	8
SCC	0.9	0.89	0.95	0.87	0.46	0.16	0.89	0.78
SPD	-0.82	0.62	1.51	1.52	-1.28	-0.95	1.02	2.32

Figure 6. Unbalance ODS Comparisons

The values in Figure 6 clearly indicate that Fault 1 is less severe than Fault 2. The SCC is on the borderline of no change in the OD for Cases 1 to 4, but indicates a significant change for Cases 5 to 8. The SPD indicates a significant change in all cases, with the smallest change being 62% difference in the ODS for Case 2.

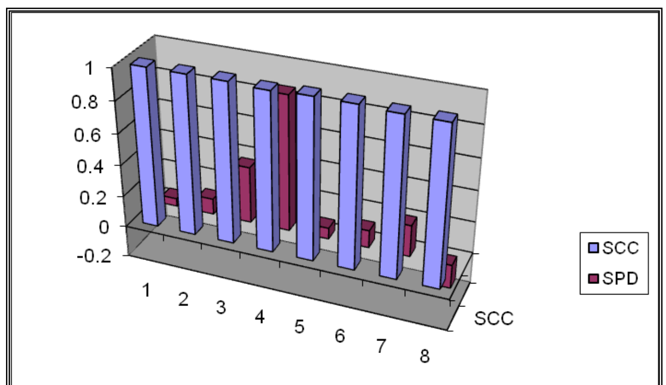
Angular Misalignment Cases

Two angular misalignment faults were simulated in the rotating machine simulator by turning screws at the base of each shaft bearing block to move it out of alignment with the motor shaft. Fault 3 was created by adding **10 mils** of misalignment to the outboard bearing block. This is depicted in Figure 7. Fault 4 was created by adding **20 mils** of misalignment to the outboard bearing block. ODS data was then obtained for the following 8 cases.

Case 1: Fault 3 (10 mil angular misalign) at 800 RPM
Case 2: Fault 3 at 1000 RPM
Case 3: Fault 3 at 2000 RPM
Case 4: Fault 3 at 3000 RPM

Case 5: Fault 4 (20 mil angular misalign) at 800 RPM
Case 6: Fault 4 at 1000 RPM
Case 7: Fault 4 at 2000 RPM
Case 8: Fault 4 at 3000 RPM

The SCC and SPD values for the 8 angular misalignment cases are plotted in Figure 7. In each case the Baseline ODS for a different machine speed is compared with the Fault ODS at the same speed.



	1	2	3	4	5	6	7	8
SCC	1	1	1	0.99	1	1	0.99	0.99
SPD	0.05	0.1	0.36	0.86	0.07	0.11	0.2	-0.15

Figure 7. Angular Misalignment ODS Comparisons

The values in Figure 7 give a mixed result. The SCC is almost 1.0 for all cases, meaning that the Baseline ODS and Fault ODS are co-linear at all speeds. However, the SPD indicates a change of the ODS in all cases, and the percent difference between the Baseline ODS and Fault ODS increases with machine speed for all Cases, except the last one. In Case 8, the difference becomes negative with less magnitude than Case 7, but still indicates a 15% change in the ODS.

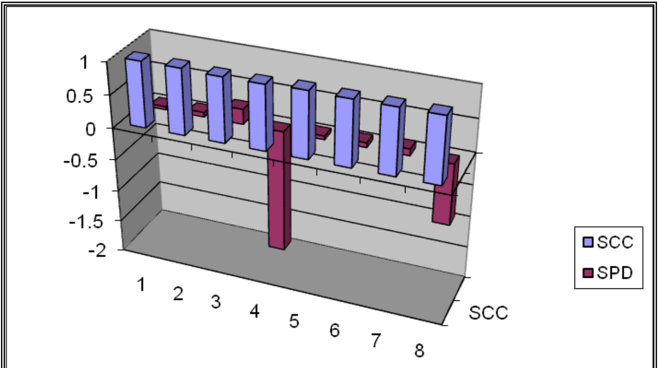
Parallel Misalignment Faults

Two parallel misalignment faults were simulated in the rotating machine simulator by turning screws at the base of each shaft bearing block to move it out of alignment with the motor shaft. Fault 5 was created by adding **10 mils** of misalignment to both bearing blocks. This is depicted in Figure 8. Fault 6 was created by adding **20 mils** of misalignment to both bearing blocks. ODS data was then obtained for the following 8 cases.

Case 1: Fault 5 (10 mil parallel misalign) at 800 RPM
Case 2: Fault 5 at 1000 RPM
Case 3: Fault 5 at 2000 RPM
Case 4: Fault 5 at 3000 RPM

Case 5: Fault 6 (20 mil parallel misalign) at 800 RPM
Case 6: Fault 6 at 1000 RPM
Case 7: Fault 6 at 2000 RPM
Case 8: Fault 6 at 3000 RPM

The SCC and SPD values for the 8 parallel misalignment cases are plotted in Figure 8. In each case the Baseline ODS for a different machine speed is compared with the Fault ODS at the same speed.



	1	2	3	4	5	6	7	8
SCC	1	1	0.98	0.98	1	0.99	0.99	0.99
SPD	0.045	0.067	0.23	-1.93	0.054	0.07	0.1	-0.94

Figure 8. Parallel Misalignment ODS Comparisons

The values in Figure 8 also give a mixed result. The SCC is close to 1.0 for all cases, meaning that the Baseline ODS and Fault ODS are co-linear at all speeds. But, the SPD indicates a change of the ODS in all cases, and the percent difference between the Baseline ODS and Fault ODS increases with increased machine speed in all cases. Cases 4 and 8 indicate large changes in the ODS.

CONCLUSIONS

The Operating Deflection Shape was used in this paper to detect simulated faults in a rotating machine. In two previous papers [1] [2], only accelerometer data was used to sense vibration signals. In this paper, proximity probes, which measure the displacement of the shaft relative to its bearing housing in two directions, were also used.

Seven DOFs of vibration data were acquired from the motor & bearings using accelerometers, and 6 DOFs were acquired from the shaft bearings using proximity probes. These 13 channels of acquired data were post-processed, and a set of ODSFRFs was calculated for each fault condition. ODS's were then created by using the peak values at the first order (running speed) of the machine from each set of ODSFRF functions.

Three different types of common rotating machinery faults were simulated; unbalance, angular misalignment, and parallel misalignment. Two different unbalance faults and four misalignment faults were simulated.

Operating data was acquired at 4 different operating speeds, 800, 1000, 2000 & 3000 RPM. The first critical speed of the machine was at 1590 RPM. By comparing Baseline (no fault) ODS's for the different operating speeds, it was clear that the ODS's for speeds below the critical speed were quite different from the ODS's above the operating speed. This is expected whenever a resonance is excited.

In each test case, the Baseline ODS was numerically compared with the ODS acquired after a fault was simulated (the Fault ODS). A total of 24 different fault cases were evaluated.

Two different numerical measures of the difference between the Baseline and Fault ODS were calculated; the SCC (Shape Correlation Coefficient) and SPD (Shape Percent Difference). The SCC indicates whether or not the two shapes are co-linear. The SPD measures the *difference* between the two ODS's, hence it also measures the *severity* of the machine fault.

In all cases, the SPD indicated a *"significant"* change in the ODS when faults were introduced. This confirmed our original hypothesis; *"When an operating machine encounters a mechanical fault, its ODS will change"*.

The high values of the SPD shown in most cases indicated that it has a strong sensitivity to changes in the ODS. Therefore, the SPD could be used to detect lesser changes in machine responses, providing early detection of impending fault conditions.

This is the third in a series of technical papers investigating the use of ODS comparisons as a means of detecting machine faults. In these papers, only unbalance and misalignment faults have been simulated.

Other machine faults such as bearing oil whirl, loose connections, gear tooth faults, soft foot (improper foundation) might also be detected by ODS comparisons.

In addition to vibration, an *"operating shape"* could also contain other monitored data such as temperatures, pressures, voltages, currents, and flow rates. These parameters could also be correlated with certain kinds of machine faults. The simplicity of this approach to machinery fault detection makes it a strong candidate for implementation in an online fault detection system.

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™, a product of Vibrant Technology, Inc.

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