Using Operating Deflection Shapes to Detect Unbalance in Rotating Equipment

Surendra N. Ganeriwala (Suri)
Spectra Quest, Inc
8205 Hermitage Road
Richmond, VA 23228
suri@spectraquest.com

Brian Schwarz & Mark H. Richardson
Vibrant Technology, Inc
5 Erba Lane, Suite B
Scotts Valley, CA 95066
mark.richardson@vibetech.com

ABSTRACT

In this paper, we demonstrate the use of the Operational Deflection Shape (ODS) of a rotating machine as a means of detecting unbalance in its rotating components. Our purpose is to use a ***significant change*** in the ODS as an early warning indicator of unbalance in its rotating components.

Tests were performed on a machinery fault simulator under various conditions of unbalance. Vibration data was simultaneously acquired using a multi-channel data acquisition system. Since unbalance produces a change in the ODS at the rotor ***running speed and its harmonics***, this data was extracted from frequency domain functions which were calculated from acquired acceleration data.

An ODS comparison was then performed at the running speed and its harmonics. The emphasis is on correlating changes in the ODS at the machine harmonics with various amounts and locations of unbalance weight. 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.

INTRODUCTION

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, 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 is an 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 ***Degree of Freedom*** (**DOF**).

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, e.g. random, impulsive, or sinusoidal. An ODS can also be obtained from different types of frequency domain functions including Linear spectra (FFTs), Auto & Cross power spectra, FRFs (Frequency Response Functions), Transmissibility's, and ODSFRFs [4].

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 correct ***relative magnitudes & phases*** among all shape components.

Simultaneous measurement requires a multi-channel 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 & phase ***relative*** to all other DOFs.

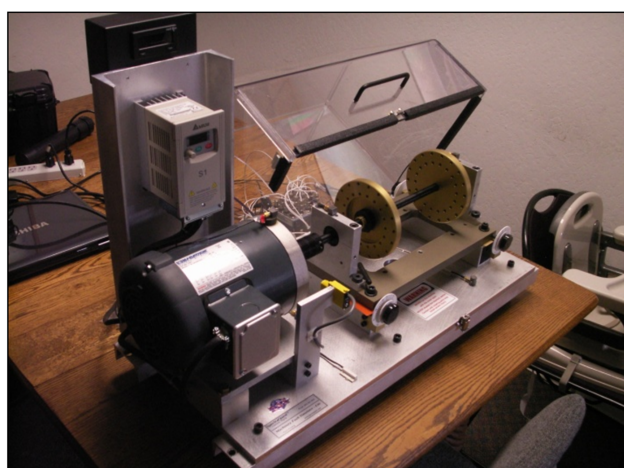


Figure 1. Machine Fault Simulator.

The hypothesis of this paper is the following;

Unbalance hypothesis: When an operating machine becomes unbalanced, its ODS will change significantly.

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 ODS. In order to measure a change in the ODS, the baseline ODS of a balanced machine will be compared with its ODS during current operation;

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

Shape Correlation Coefficient (SCC)

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.

A calculation which measures the similarity between two complex vectors is the Shape Correlation Coefficient. When this coefficient is used to compare two mode shapes it is called a MAC (Modal Assurance Criterion) [2]. The SCC is defined as;

$$\mathrm{SCC} = \frac{\left\| \mathrm{ODS}_C \circ \mathrm{ODS}_B^* \right\|}{\left\| \mathrm{ODS}_C \right\| \left\| \mathrm{ODS}_B \right\|}$$

where: $\mathrm{ODS}_B = \text{Baseline ODS}$

$\mathrm{ODS}_C = \text{Current ODS}$

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

$\| \;\|$ indicates the magnitude squared

$\circ$ indicates the 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. An SCC value greater than 0.90 indicates a small change in the ODS.

Rule of Thumb: An SCC value ***less than* 0.90** indicates a ***significant 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 detecting unbalance. However, the location & direction of the sensors is subjective and will vary from machine to machine.

One difficulty with the SCC is that it only measures the ***"co-linearity"*** of two vectors. In other words, if two vectors ***"lie along the same line"*** their SCC is 1.0. But two vectors can have different magnitudes. If somehow the vibration levels increase in a machine such that the only the magnitude of the ODS increases, the SCC will still have a value of 1.0, indicating no change.

Shape Percent Difference (SPD)

A different measure of change in an ODS is the Shape Percent Difference. The SPD also detects a change in magnitude of a shape.

$$\mathrm{SPD} = \frac{\left| \mathrm{ODS}_C - \mathrm{ODS}_B \right|}{\left| \mathrm{ODS}_B \right|}$$

where: $\mathrm{ODS}_B = \text{Baseline ODS}$

$\mathrm{ODS}_C = \text{Current ODS}$

$| \;|$ indicates the magnitude of the vector

The SPD is a ***percentage change relative to the Baseline ODS***. An SPD value of ***0.0 indicates no change*** in the ODS. An ***SPD value of 1.0 indicates a 100% change*** in the ODS.

To summarize, both the SCC and SPD can b expressed in ***percentage units***.

When a machine is in balance, the *SCC* will be ***at or near 100 %***, and the *SPD* will be ***at or near 0.0%***.

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. Tri-axial accelerometers were attached to the top of both bearing housings and the motor. A tri-axial and 2 uni-axial accelerometers were also attached to the base plate. These transducers provided a total of 14 vibration signals which 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 and Cross spectrum. It is formed by combining the ***phase*** of the Cross spectrum between a roving and reference signal with the RMS of the Auto spectrum (its ***magnitude***) of the roving response signal. The magnitude of an ODSFRF therefore, is a true measure of the magnitude of the machine's response, which is provided by the Auto spectrum.

Data was 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.).

ODS's 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.

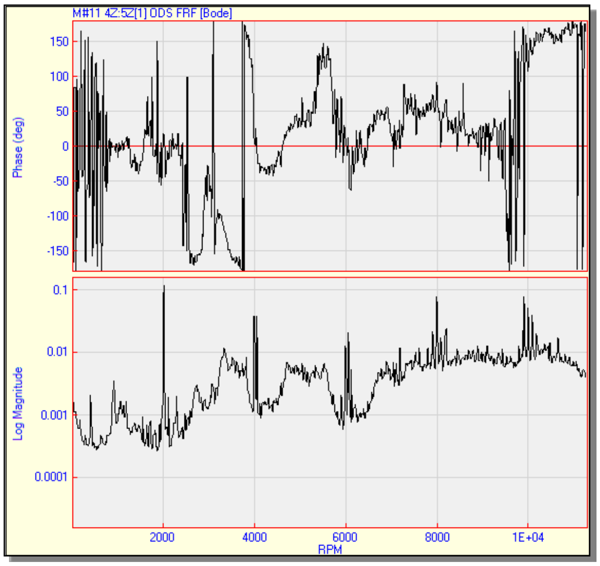


Figure 2. ODSFRF Showing Peaks at Machine Orders.

Unbalance Conditions.

Vibration data was acquired from the machine when it was considered to be in balance (the 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 indicated in Figure 3. Data was acquired for each of the following unbalance conditions;

1. Small unbalance (11.25 grams) - Inboard rotor
2. Small unbalance - Outboard rotor
3. Large unbalance (22.5 grams) - Inboard rotor
4. Large unbalance - Outboard rotor
5. Two large unbalances - 0 degrees apart
6. Two large unbalances - 90 degrees apart
7. Two large unbalances - 180 degrees apart

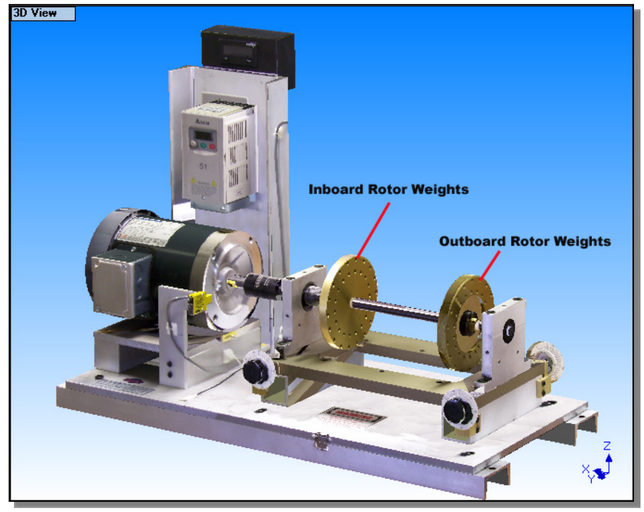
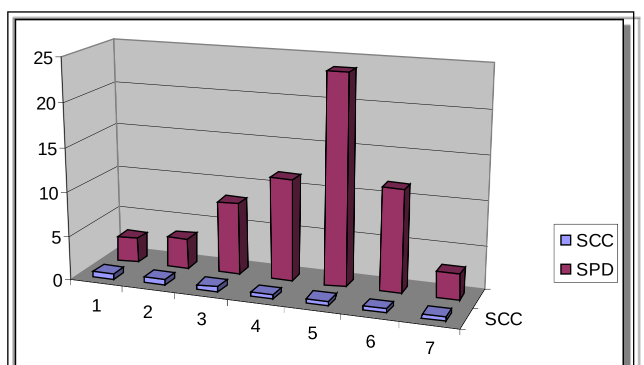


Figure 3. Unbalance Weights Attached to Rotors

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 & 4 were the same as cases 1 & 2, but a larger unbalance weight (22.5 grams) was used.

In cases 5, 6 & 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 degree difference between them). In case 6, they were attached 90 degrees apart from one another, and in case 7 they were attached 180 degrees apart.

Figure 4 contains the SCC and SPD values for the ODS's created from peak values at the running speed or ***first order*** (2000 RPM) of the machine.



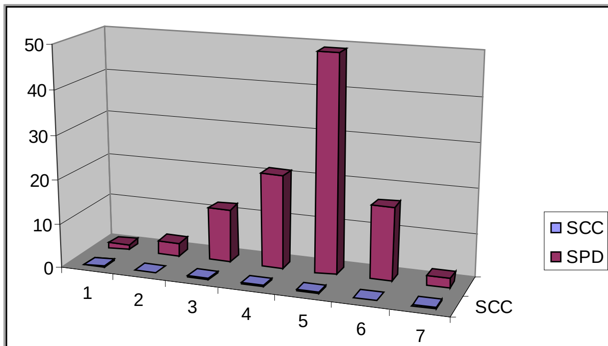
	1	2	3	4	5	6	7
SCC	0.6	0.64	0.57	0.48	0.52	0.45	0.47
SPD	2.83	3.46	8.23	11.53	23.8	11.62	2.96

Figure 4. First Order (2000 RPM) ODS Comparisons

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, & 7 show how the vibration level is affected by the locations of the weights on the two rotors. Case 5 has the ***highest SPD value*** because the two large unbalance weights were aligned with one another on both rotors, thus providing the maximum amount of unbalance.

The SPD values also show that case 7, with the two large unbalance weights ***180 degrees 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.

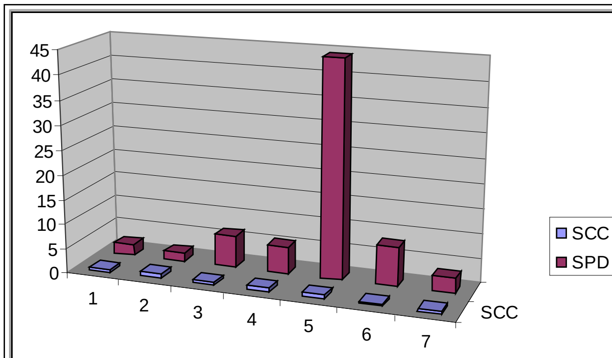


	1	2	3	4	5	6	7
SCC	0.03	0.07	0.24	0.23	0.27	0.23	0.25
SPD	1.15	3.01	12.18	21.18	49.06	16.57	2.21

Figure 5. Second Order (4000 RPM) ODS Comparisons

Figure 5 contains the SCC and SPD values for peak values at the ***second order (4000 RPM)***. The ***same conclusions*** can be drawn from the ***second order*** ODS comparisons as those from the first order comparisons.

Figure 6 contains the SCC and SPD values from peak values at the ***third order (6000 RPM)***. One incorrect result appears in these results. The SCC indicates a ***balanced condition*** for case 2, with a value of **0.97**. The SPD results are similar to those from the first & second order, but they don't quantify the severity of the unbalance conditions as well as the ODS comparisons for the first & second orders.



	1	2	3	4	5	6	7
SCC	0.45	0.97	0.57	0.86	0.74	0.41	0.46
SPD	2.26	1.7	6.49	5.49	44.2	8.11	3.17

Figure 6. Third Order (6000 RPM) ODS Comparisons

CONCLUSIONS

Seven different cases of unbalance were simulated using a rotating machine fault simulator. Accelerometer data from 14 different DOFs (9 DOFs on the motor & bearings and 5 DOFs on the base plate) was acquired using a 16 channel data acquisition system, with the machine running at 2000 RPM. ODS's were created using the peak values at the first, second, and third order frequencies, from seven sets of ODSFRF functions.

Comparisons between baseline (balanced) ODS's and the ODS's 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 **Shape Correlation Coefficient (SCC)** and **Shape Percent Difference (SPD)**. The SCC only indicates whether or not two shapes are ***co-linear***. The SPD, a true difference between the current the baseline ODS, measures the ***severity*** of the fault caused by an unbalance condition.

This is the second in a series of technical papers investigating the use of an ODS as a means of detecting machine faults. In a previous paper [1], 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**, which also includes other engineering data such as temperatures, pressures, voltages, currents, etc., can also be used for detecting 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™ software, a product of Vibrant Technology, Inc.

REFERENCES

1. Surendra N. Ganeriwala (Suri), Zhuang Li, Richardson, Mark "Using Operating Deflection Shapes to Detect Shaft Misalignment in Rotating Equipment" Proceedings of International Modal Analysis Conference (IMAC XXVI), February, 2008.
2. R.J. Allemang, D.L. Brown "A Correlation Coefficient for Modal Vector Analysis", Proceedings of the International Modal Analysis Conference, pp.110-116, 1982.
3. M.H. Richardson, "Is It a Mode Shape or an Operating Deflection Shape?" Sound and Vibration magazine, March, 1997.
4. B. Schwarz, M.H. Richardson, "Measurements Required for Displaying Operating Deflection Shapes" Proceedings of IMAC XXII, January 26, 2004.