Presented at IMAC XLII, January 29-February 1, 2024, Orlando, FL

Using a Cell Phone Video and ODS Correlation to Diagnose Unbalance in Rotating Machinery

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ABSTRACT

Nearly everyone carries a cell phone in their pocket, including field technicians, engineers, and plant managers. Extracting vibration signals from a cell phone video offers a low-cost alternative to traditional methods for monitoring the health of plant operating equipment.

In this paper, we present a new database search method that uses **order-based ODS** data extracted from a cell phone video to detect and identify unbalances in a rotating machine. Order-based Operating Deflection Shapes (**ODS's**) are used by a unique search method, called **FaCTs™,** that correlates a currently acquired **ODS** with **ODS's** of known machine unbalance conditions stored in a database.

FaCTs™ can be used to identify the location and amount of any mechanical fault that has a ***unique*** **ODS**, and it becomes more accurate as ***more*** **ODS** ***data is acquired, labeled, and archived*** in a machine-based database.

KEY WORDS

Frames Per Second (**fps**), Time Waveform (**TWF**), Digital Fourier Transform (**DFT**), Operating Deflection Shape (**ODS**), **ODS-FRF**, Degree of Freedom (**DOF**), Fault Correlation Tools (**FaCTs™**), Auto Power Spectrum (**APS**), Cross Power Spectrum (**XPS**)

INTRODUCTION

Most power plants, oil refineries, and manufacturing plants worldwide have implemented route-based machinery health monitoring programs for accessing the health of their rotating machinery. Digital vibration signals are the primary data used to detect and diagnose faults in operating equipment.

Traditionally, machine health monitoring has been done by attaching accelerometers to the surfaces of the operating equipment, and vibration signals are acquired from the accelerometers with a portable digital spectrum analyzer. This method of acquiring data is time consuming and expensive compared with using a cell phone camera. Furthermore, a cell video can record vibration of machine parts that are hot or inaccessible thus preventing the attachment of accelerometers to those surfaces.

Over the past 20 years, Optical Flow algorithms [1], [2] have been developed for extracting dynamic features and vibration time waveforms (**TWFs**) from a video recording. The capability of these algorithms is improving rapidly due to their use in many new applications, including autonomous vehicles, and robotic humanoid vision.

In previous papers [3], [8] we presented a new method for extracting **TWFs** from frames of a video. When combined with traditional digital signal processing methods, **TWF** data can be used to extract **ODS's** [4]-[6] so that the machine's deformation can be visualized on frames of the video at slower speeds with higher amplitudes.

In this paper, it is shown how nine different unbalance cases are uniquely identified from **order-based ODS data** from the tops of the bearing blocks of a rotating machine. A search algorithm called **FaCTs™** is used to identify each unbalance case by numerical comparison of its **ODS** with ***previously labeled and archived*** **ODS** data of ***nine different unbalance conditions***.

Rotating Machine

In this paper, **FaCTs™** is used to uniquely identify ***nine different unbalance cases*** of the rotating machine shown in Figure 1. It has a variable speed motor connected to the rotor with a rubber belt. The motor speed was adjusted so that the rotor speed was ***approximately 1000 RPM throughout all the video recordings***.

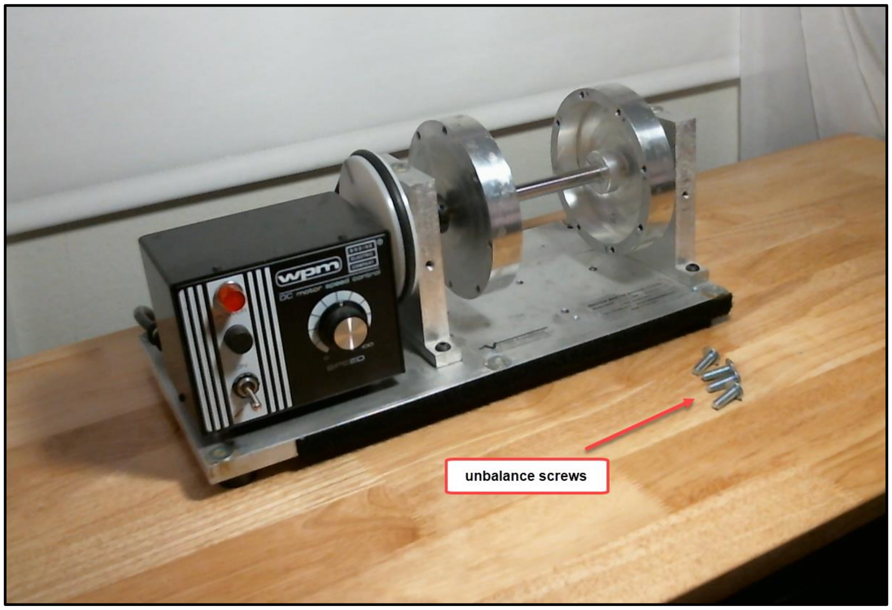


Figure 1. Rotating Machine Showing Unbalance Screws Added to Its Rotors

Video ODS™ Analysis

MEscope Video ODS™ [9] is a vibration analysis software package that extracts **TWFs** from a high-speed digital video recording and calculates the Digital Fourier Transform **(DFT)** of each **TWF.** A unique frequency function, called an **ODS-FRF**, is also calculated from each **TWF**. Unlike a **DFT**, and ODS-FRF is calculated using spectrum averaging to reduce extraneous noise and distortion from an **ODS-FRF**. An **ODS-FRF** can also be differentiated to convert it from displacement units to velocity units.

Using **ODS-FRFs**, **order-based ODS's** ***in velocity units*** can be extracted from a ***10 to 20 second video clip*** and used to uniquely diagnose unbalance conditions in rotating equipment.

Video ODS processing allows the user to ***"see"*** what the human eye cannot perceive from looking at the playback of a raw video; either because the vibration event is too fast, or the displacements are too small, or both. An animated **ODS** makes vibration visible and understandable so that all plant maintenance personnel can be involved in defining and implementing an asset management solution. An example of **order-based ODS** sinusoidal animation, the **TWFs** extracted from the raw video, and the **DFTs** calculated from the **TWFs** is shown in Figure 2.

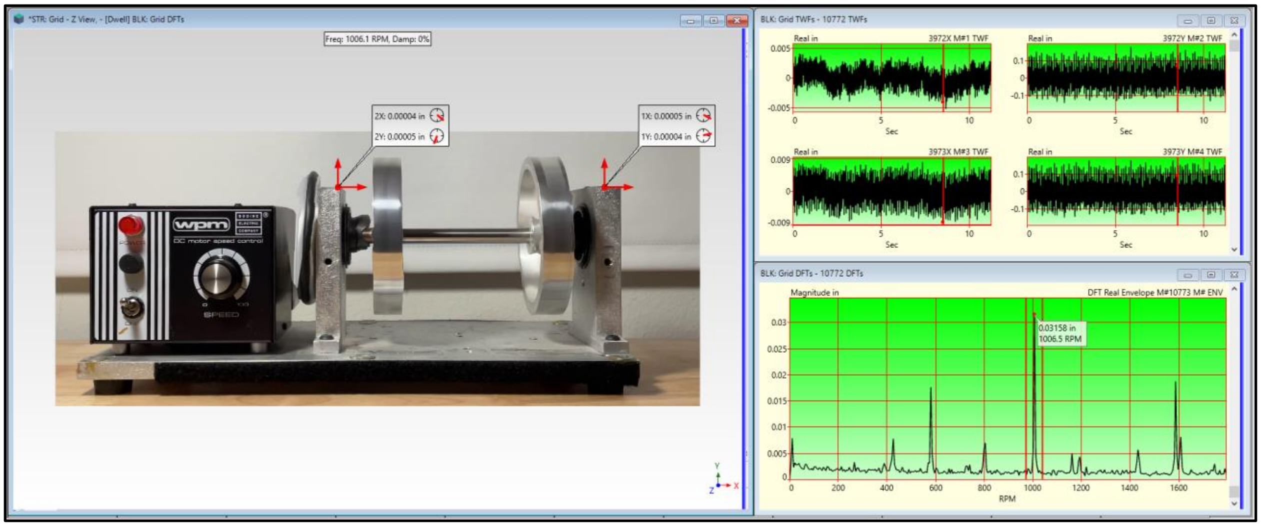


Figure 2. Frequency-Based ODS Animation from DFTs

Time-Based ODS Animation

A time-based **ODS** animation is created by sweeping a line cursor through a set of **TWFs** extracted from a video. To improve clarity, the sweep speed and amplitude of the **ODS** deformation can be modified during animation.

Frequency-Based ODS Animation

A frequency-based **ODS** animation is created with sinusoidal modulation of the **ODS** at the frequency of the cursor in a set of **DFTs** or **ODS-FRFs**. The modulation speed and the amplitude of the **ODS** deformation can be modified during animation to improve clarity.

ODS-FRFs

In any operating machine, the internal excitation forces cannot be directly measured. Only responses to the excitation forces can be measured. In the MEscope **Video ODS™** software, ***thousands of*** **TWFs** are typically extracted from a video recording of a machine. And a unique frequency domain function called an **ODS-FRF** can be calculated from each response **TWF**. Not only can **ODS-FRFs** yield the **order-based ODS's** of rotating equipment, but they can be ***differentiated from displacement to velocity units*** which are commonly used to assess vibration levels in rotating equipment.

The ***magnitude*** of an **ODS-FRF** is the **APS** of a ***roving response*** **DOF** of a machine. The ***phase*** of an **ODS-FRF** is the ***phase of the*** **XPS** between the response **DOF** and a ***fixed reference*** response **DOF**.

Aliased Order-Based ODS's

Nine videos were recorded during operation of the rotating machine shown in Figure 1. The videos were recorded at **60 fps (frames per second)**, or a **sampling rate of 3600 RPM**. Therefore, the maximum frequency of the **DFTs** and **ODS-FRFs** is **one half of the sampling rate**, or **1800 RPM**. Any peaks due to orders at ***frequencies greater than*** **1800 RPM** will ***"wrap around"*** **1800 RPM** and appear as peaks at lower frequences in the **DFTs** or **ODS-FRFs**. This phenomenon is called ***"aliasing".*** An example of an **ODS-FRF** with the two aliased order peaks is shown in Figure 3.

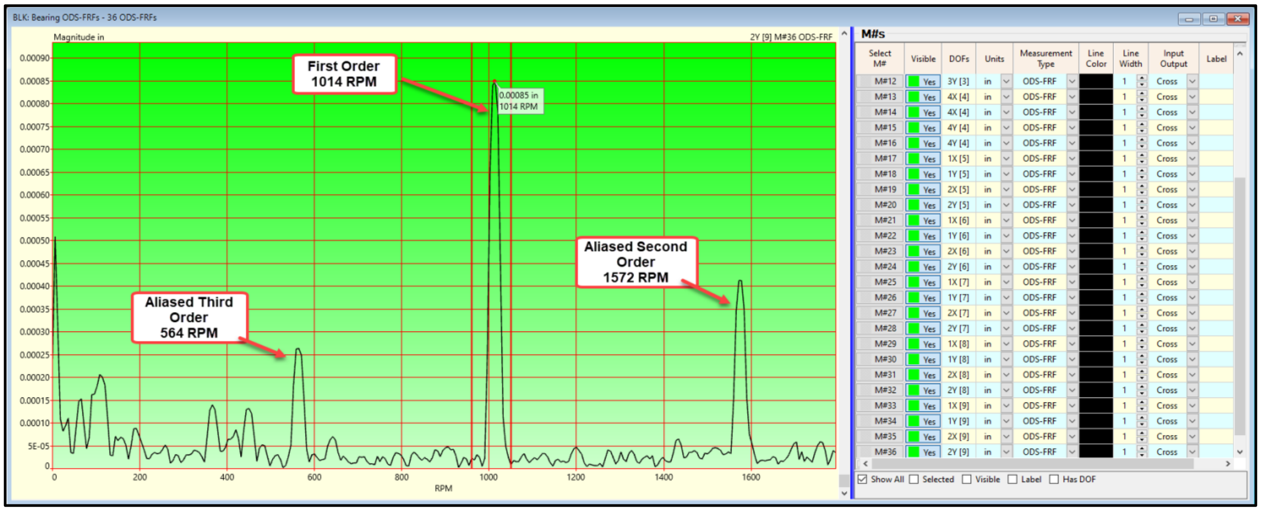


Figure 3. ODS-FRF Show First Three Order Peaks.

The maximum frequency of the **ODS-FRFs** is **1800 RPM**. The first order is **1014 RPM**. The **second order** is **1800 - (2028 – 1800) ➔ 1572 RPM**. The **third order** is **1800 - (3042 – 1800) ➔ 558 RPM**.

The time length (**T**) of the **TWFs** in Figure 2 is about **12 seconds**. One of the rules of the **FFT** algorithm is that the frequency resolution of a **DFT** or **ODS-FRF** derived from a **TWF** is **1/T**. Therefore, the frequency resolution of the **ODS-FRFs** is about **5 RPM**. So, the aliased third order peak at **564 RPM** is within one frequency sample of the calculated aliased frequency of the third order at **558 RPM**.

Trend Plot

The ***first three* order-based ODS's** for each of the nine unbalance cases were saved in an archival database. The Trend Plot of the three **order-based ODS's** is shown in Figure 4. Each **ODS** has four **DOFs**, **1X, 1Y, 2X, 2Y** at points **1 & 2** at the ***top of each bearing block*** of the machine. Those **DOFs** are shown in Figure 2.

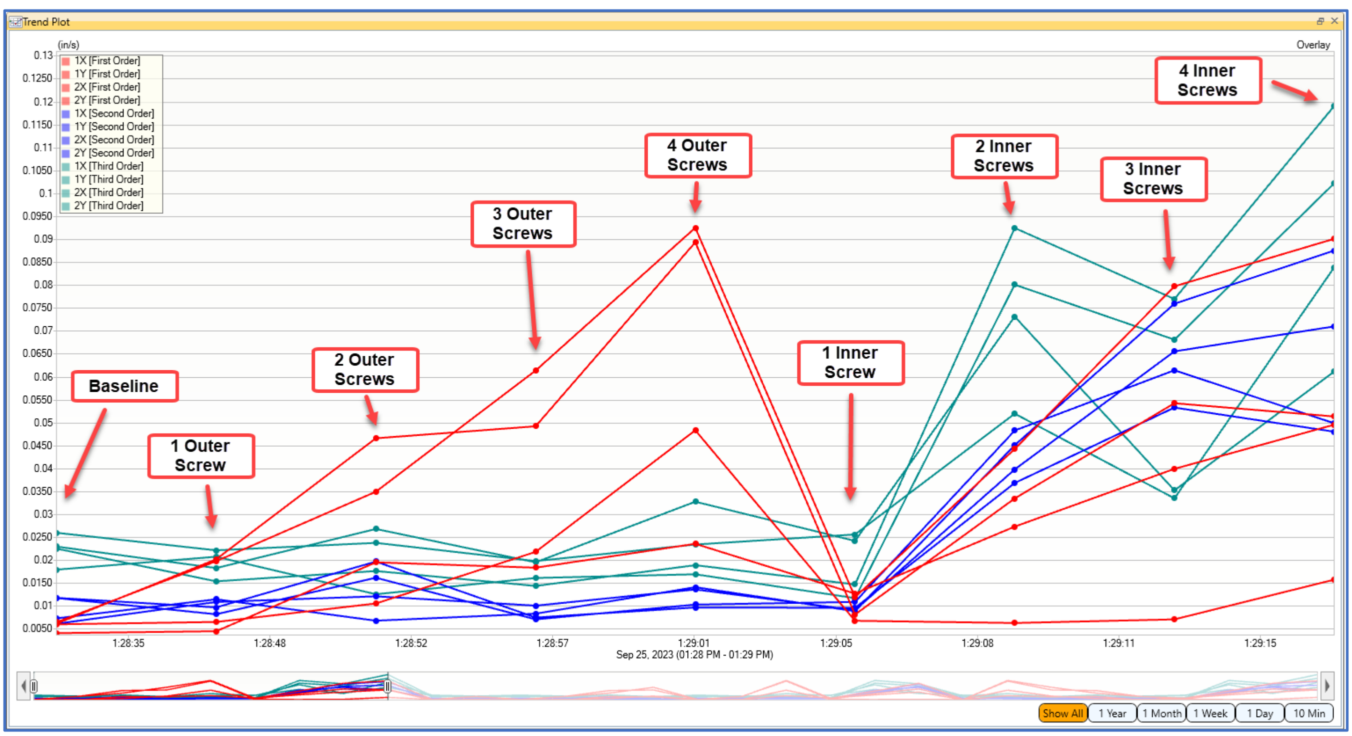
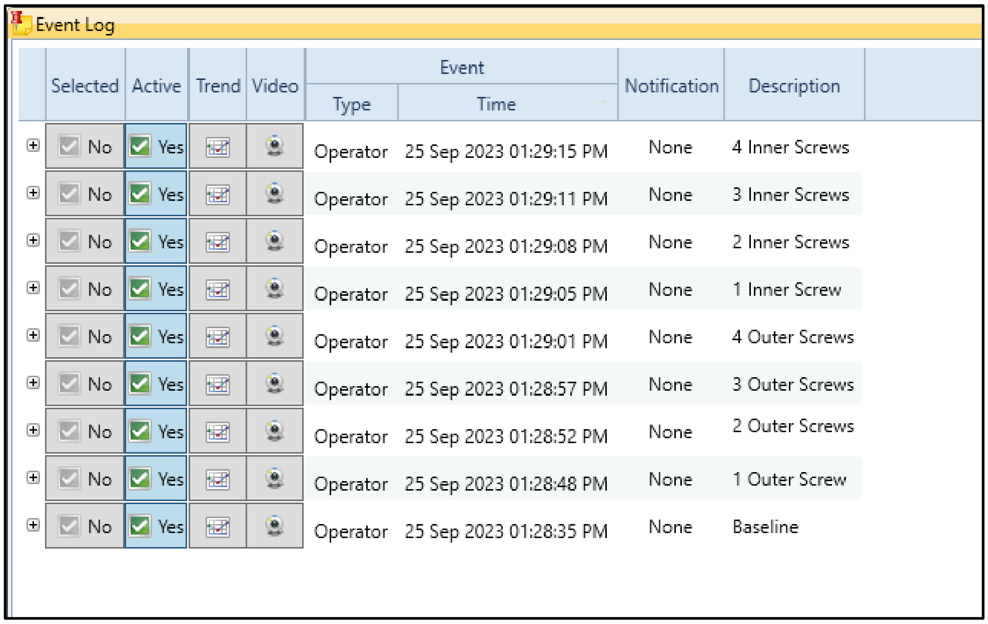


Figure 4. Trend Plot of First Three Order-Based ODS's for Nine Unbalance Cases.

Event Log

The first cell phone video recording was of the **Baseline** operation, with **no unbalance screws** added to the Outer and Inner rotors. Eight more videos were recorded for eight cases where unbalance screws were added to the Outer and Inner rotors. Each of the nine cases, (one Baseline and 8 unbalances) is labeled as an event. Those nine cases are labeled in the **Event Log** for the database, as shown in Figure 5.



Event Log

Selected	Active	Trend	Video	Event Type	Event Time	Notification	Description
No	Yes			Operator	25 Sep 2023 01:29:15 PM	None	4 Inner Screws
No	Yes			Operator	25 Sep 2023 01:29:11 PM	None	3 Inner Screws
No	Yes			Operator	25 Sep 2023 01:29:08 PM	None	2 Inner Screws
No	Yes			Operator	25 Sep 2023 01:29:05 PM	None	1 Inner Screw
No	Yes			Operator	25 Sep 2023 01:29:01 PM	None	4 Outer Screws
No	Yes			Operator	25 Sep 2023 01:28:57 PM	None	3 Outer Screws
No	Yes			Operator	25 Sep 2023 01:28:52 PM	None	2 Outer Screws
No	Yes			Operator	25 Sep 2023 01:28:48 PM	None	1 Outer Screw
No	Yes			Operator	25 Sep 2023 01:28:35 PM	None	Baseline

Figure 5. Event Log Showing Nine Machine Unbalance Cases

FaCTs™

At Vibrant Technology, we have developed an algorithm, called **FaCTs™**. **FaCTs™** searches a database of ***labeled*** **ODS** data, each **ODS** associated with and labeled with a particular machine fault. When a new **ODS** is saved in the database, **FaCTs™** searches the database of labeled **ODS's** and displays a bar chart of the ***ten closest matching*** **ODS's** together with the mechanical fault associated with each labeled **ODS**.

FaCTs™ uses a correlation coefficient between two shapes called the **Shape Difference Indicator (SDI)** [11], to search the database of labeled **ODS's** for a machine. **FaCTs** finds the ***top ten closest matches*** of **ODS's** based on the **SDI** value of the current **ODS** with each labeled **ODS** in an archival database.

- **FaCTs** has values **between 0.0 and 1.0**
- **FaCTs** = **1.0** ➔ two **ODS's are** ***identical***
- **FaCTs >= 0.9** ➔ two **ODS's are** ***similar***
- **FaCTs** < **0.9** ➔ two **ODS's are** ***different***

Baseline Case

When no unbalance screws were added to either one of the rotors, its **ODS** was labeled as the **Baseline**. When the **Baseline** case is archived into the database, the **FaCTs** bar chart in Figure 6 clearly identifies it by its ***unique*** **ODS** compared to the other unbalance cases. All the other **FaCTs** bars are ***much less than*** **1.0**.

Figures 7 through 14 show the **FaCTs** bar charts for the eight unbalance cases, where screws were added to either the Outer or Inner rotor. Each case has a ***unique*** **ODS** compared to the ODS's of all other unbalance cases. Each unbalance case ***was uniquely identified by*** **FaCTs** because its corresponding **ODS** ***was unique*** when compared to the other unbalance cases.

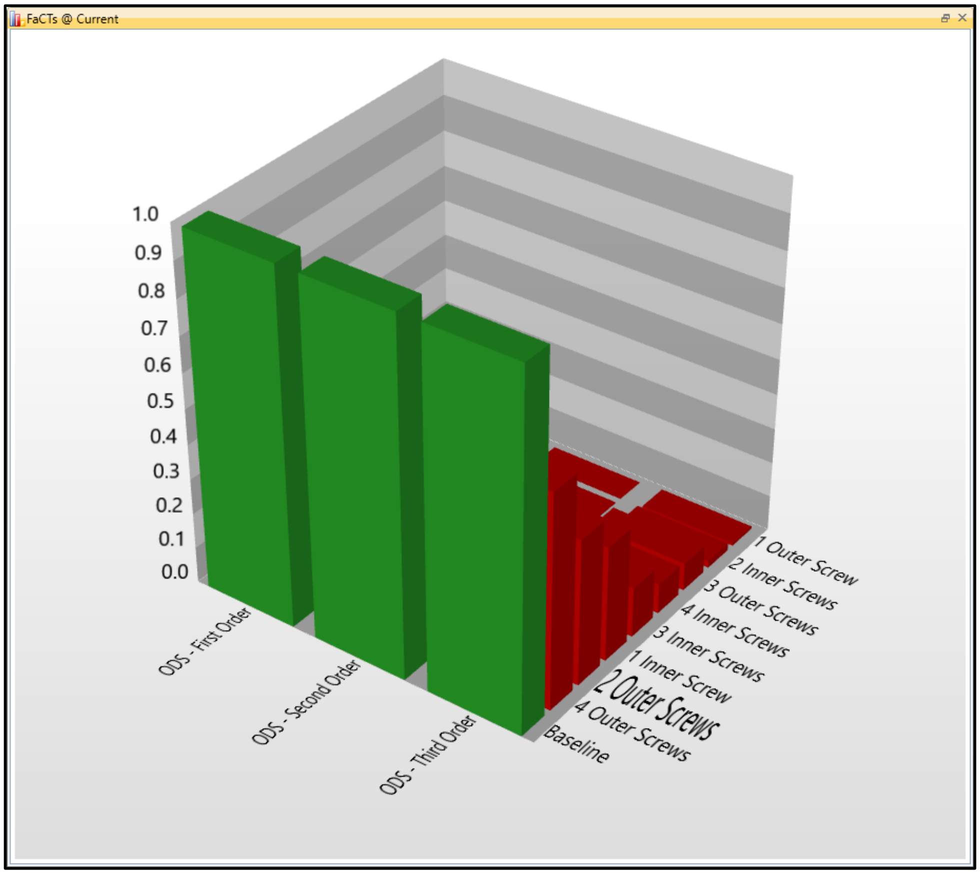


Figure 6. Baseline ODS Versus Other Eight Unbalance Cases

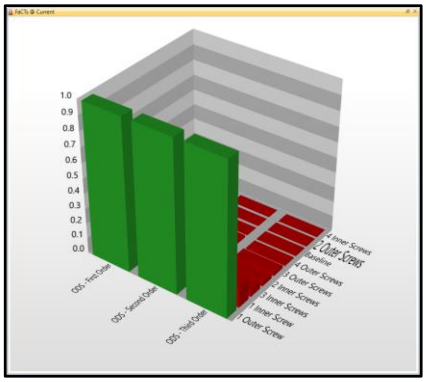


Figure 7. One Outboard Screw

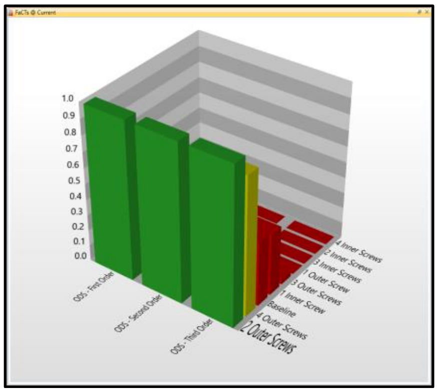


Figure 8. Two Outboard Screws

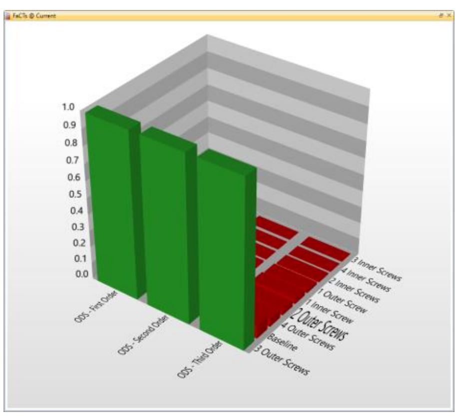


Figure 9. Three Outboard Screws

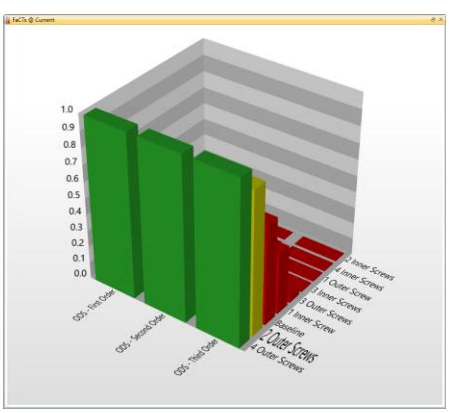


Figure 10. Four Outboard Screws

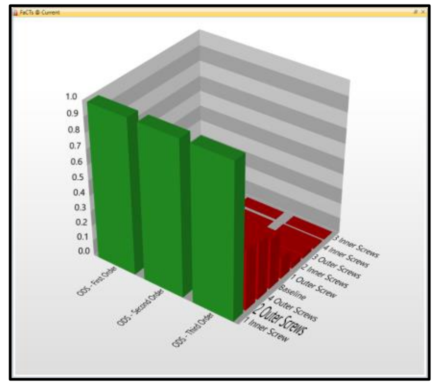


Figure 11. One Inboard Screw

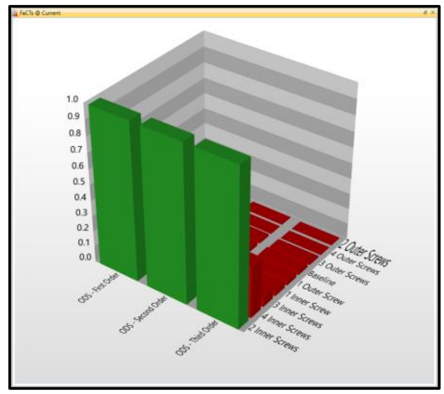


Figure 12. Two Inboard Screws

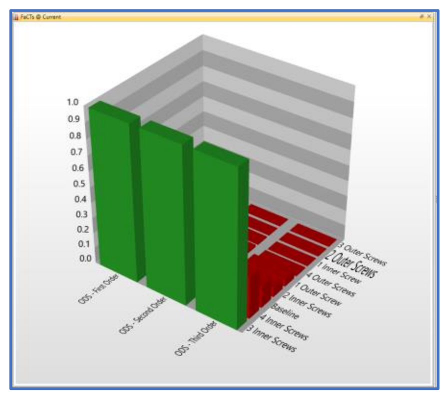


Figure 13. Three Inboard Screws

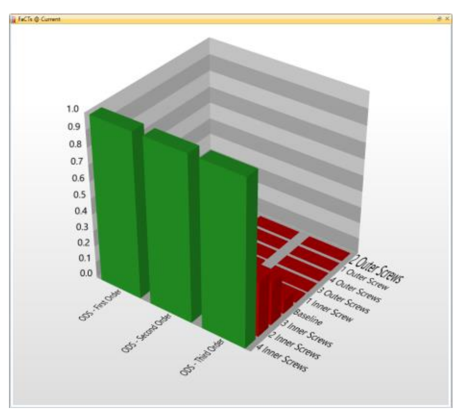


Figure 14. Four Inboard Screws

CONCLUSIONS

Nine different unbalance cases were created on a small rotating machine by adding screws to its inboard and outboard rotors. The first case with ***no screws added*** was labeled as the **Baseline** case. With each case, a 10 to 15 second cell phone video was recorded, with the machine running at approximately **1000 RPM**.

Using the MEscope **Video ODS™** [9] software, time waveforms (**TWFs**) were extracted from each cell phone video and post-processed to obtain **ODS-FRFs** for each unbalance case. Then the ***peak values*** in the **ODS-FRFs** of the ***first three*** **order-based ODS**'s of the machine were stored in an archival database. The **first order ODS** and the aliased second and third **order-based ODS's** were stored. Each set of three **ODS's** was labeled with their corresponding unbalance case.

Then, when the **ODS** for each case was again stored into the database, **FaCTs** correctly identified each case by comparing its **ODS** with the **labeled ODS's** already in the database. This method of numerically comparing a current **ODS** data with **labeled ODS's** saved in a machine-based database can be used by a plant maintenance department for monitoring the health of rotating equipment.

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[9] - MEscope™ is a trademark of Vibrant Technology, Inc. www.vibetech.com

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