MEscope Application Note 52

Order-Based ODS's are a Summation of Mode Shapes

The steps in this Application Note can be carried out using any MEscope package that includes the **VES-3600 Advanced Signal Processing & VES-4600 Advanced Modal Analysis** options. Without these options, you can still carry out the steps in this App Note using the **AppNote52** project file. These steps might also require MEscope ***software with a more recent release date***.

APP NOTE 52 PROJECT FILE

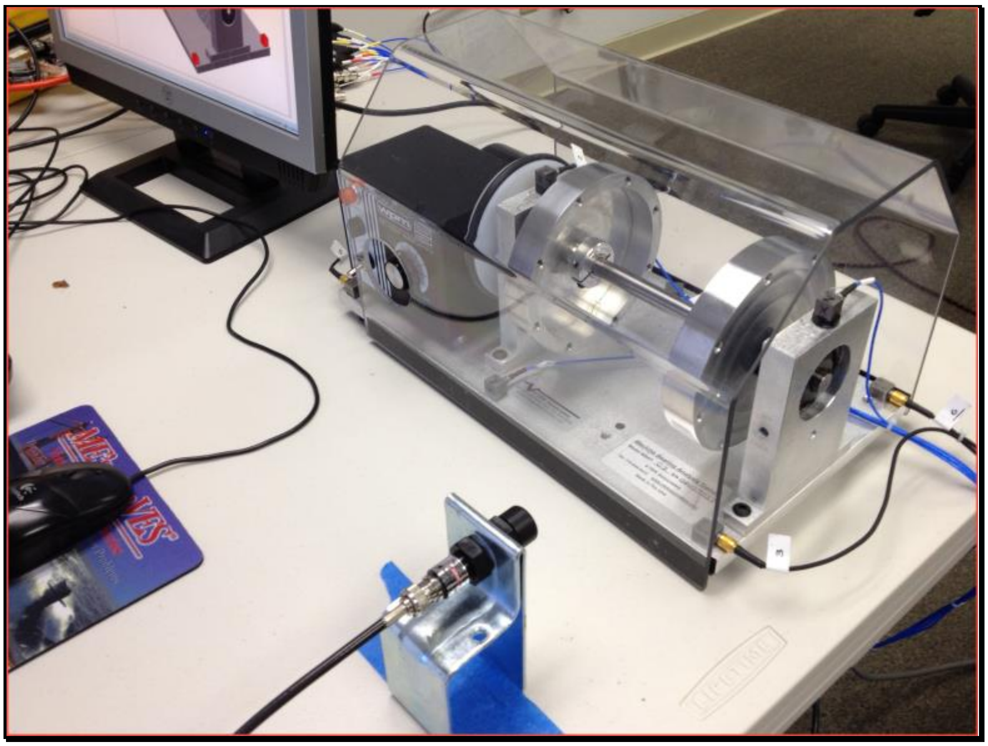
- To retrieve the Project for this App Note, **click here** to download **AppNote52.zip**

This Project contains ***numbered Hotkeys & Scripts*** for carrying out the steps of this App Note.

- ***Hold down*** **the Ctrl key** and ***click on a*** **Hotkey** to open its Script window

This App Note illustrates a universal law of modal analysis,

Universal Law of Modal Analysis: All vibration is a summation of mode shapes.



Variable Speed Rotating Machine

INTRODUCTION

In this App Note, ten **FEA mode shapes** of the base plate & bearing blocks of a rotating machine are used to ***curve-fit and expand*** the first-order **ODS** of the machine. **ODS**-FRFs were acquired while the machine was running at three different operating speeds. The **ODS**-FRFs were acquired at eight points on the machine using 4-channel data acquisition hardware with a uni-axial accelerometer as a fixed reference and a roving tri-axil accelerometer attached at each of eight test points.

The ***peak values*** of the ODS-FRFs at the running speed were saved as the **first-order ODS**.

The modal parameters of a structure can be obtained in two ways,

1. **Experimental Modal Analysis (EMA): EMA mode shapes** are extracted by curve-fitting a set of experimentally derived time-domain or frequency-domain data that characterize the structural dynamics.
2. **Finite Element Analysis (FEA): FEA mode shapes** are calculated from a set of differential equations that characterize the structural dynamics.

In this App Note analytical **FEA mode shapes** are used to ***curve-fit*** and ***expand*** **ODS data** to include **DOFs** that were not experimentally acquired. It is shown how **FEA mode shapes** ***participate differently*** in the **first-order ODS** of a rotating machine at different operating speeds. The **participation** of the **FEA mode shapes** is then used to ***expand*** the **first-order ODS**, creating a representation of the **ODS** at ***both measured*** and ***un-measured*** **DOFs** of the machine.

This curve-fitting method has several unique advantages.

- ***Only*** **FEA mode shapes** are used for curve-fitting. Modal frequency & damping are not required.
- **FEA mode shapes** derived from an **FEA** model ***with free-free boundary conditions*** are used to curve-fit ODS data ***with real-world boundary conditions***.
- The **participation** of each mode shape in the ODS data is determined by solving ***least-squared-error curve-fitting*** equations.
- The **participation** of each mode shape is then used to ***expand*** the **ODS** data to include the **DOFs** of the **FEA mode shapes**.

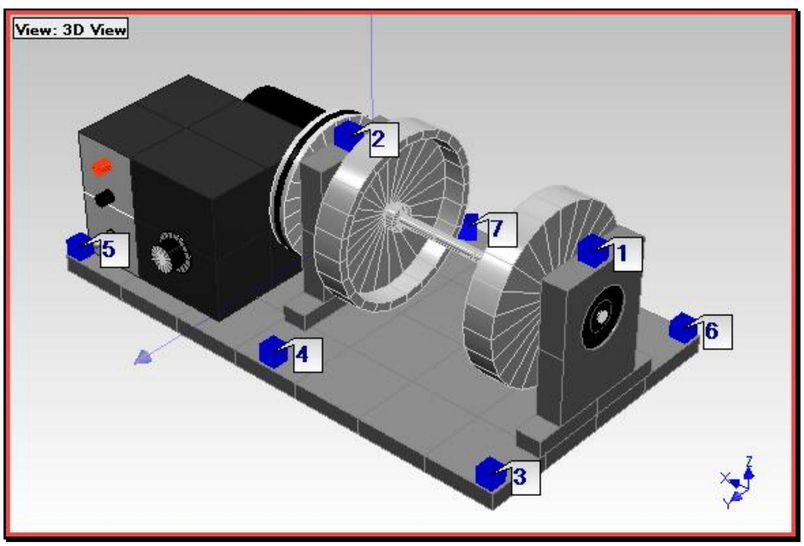
EXPANDING ORDER-BASED ODS's

In a rotating machine, the dominant forces are applied at ***multiples of the machine running speed, called orders***. An **order-based ODS** is assembled from the **peak values** at one of the orders in a set of **output-only frequency domain function**s.

Auto Spectra, **Cross Spectra**, or **ODS-FRFs** are typically calculated from output-only **TWFs** that are acquired while a machine is running.

When displayed in animation on a 3D model of the machine, an **order-based ODS** is a convenient way of visualizing distributed vibration levels caused by unmeasured internal cyclic forces.

- **Order-based ODS's** can be represented as a ***summation of mode shapes***.
- The **order-based ODS's** or their ***modal participation*** can be used for monitoring the health of a machine.



Model Showing Eight Tri-Axial Accelerometer Locations

The machine was supported on **four rubber mounts** (one under each corner), so it behaves much like a mass on a spring. Its ***rigid body motion participates significantly*** in its first-order **ODS**.

Hotkey 1 - FEA MODE SHAPES

Six ***rigid-body*** and four ***flexible-body*** **FEA mode shapes** were obtained from an **FEA** model of the **base plate & bearing blocks** of the machine.

These ten **FEA mode shapes** were obtained using the **VES-8000 FEA** option in MEscope.

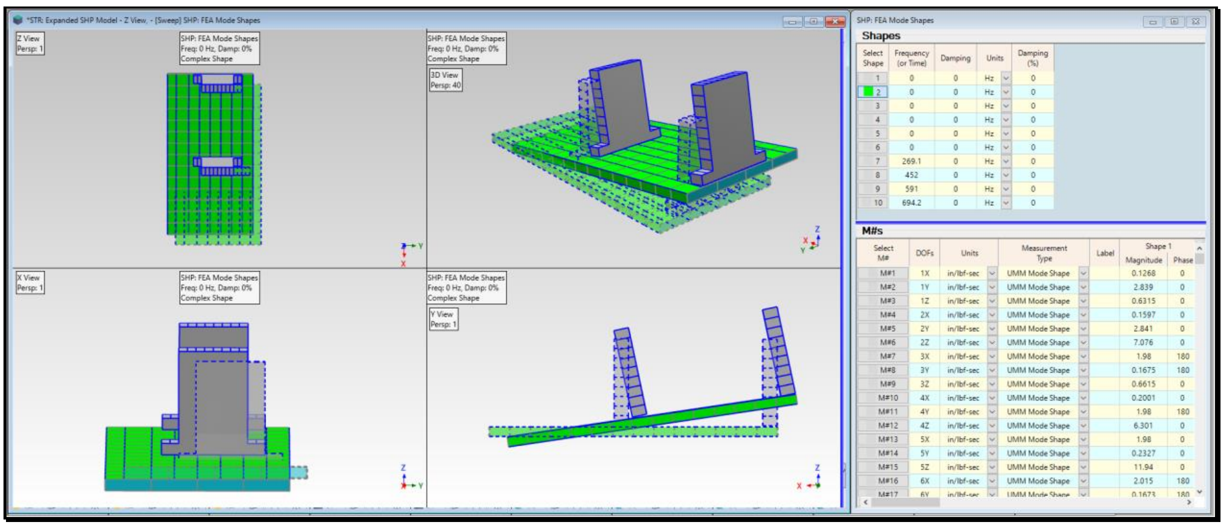
In this App Note, these **FEA mode shapes** are used to curve-fit and expand the experimental **ODS**'s.

- ***Press* Hotkey 1**

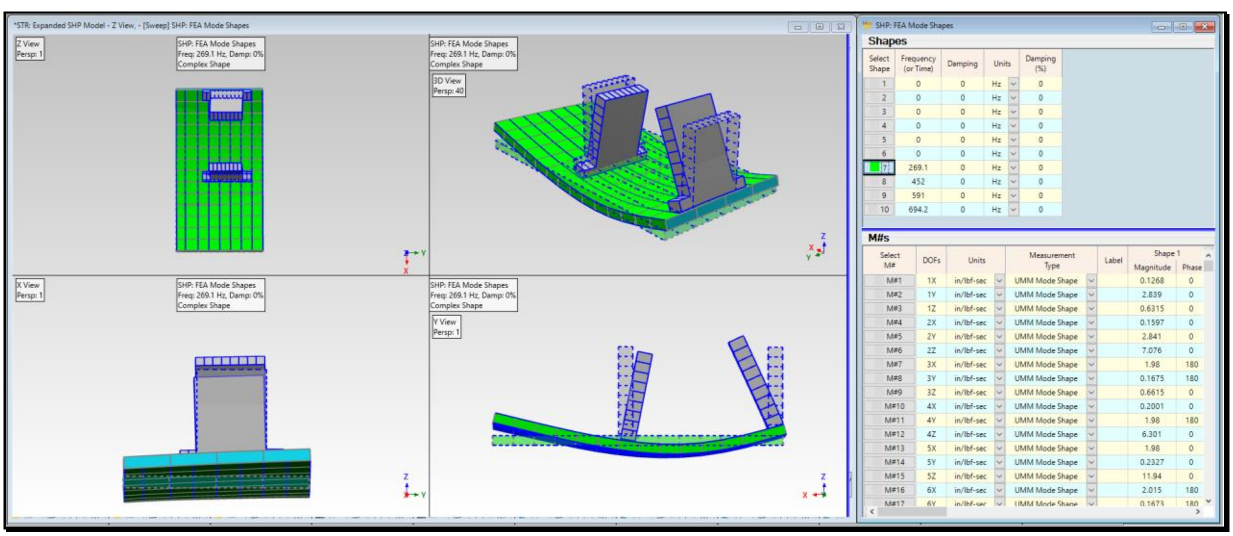
Sweep animation through the ten **FEA mode shapes** will begin. One of the ***rigid-body*** mode shapes and *a* ***flexible-body*** mode shape are shown in the two figures below.

The **FEA mode shapes** have **1938 DOFs**, but 24 of their **DOFs** ***coincide with the same*** **24 DOFs** as the experimental **ODS's**.

The **FEA mode shapes** are curve-fit to the ODS's using data from their common **DOFs**.



Rigid-Body Mode Shape of Base Plate & Bearing Block.



First Flexible Mode Shape of Base Plate & Bearing Block.

NORMAL MODE SHAPES

Because the **FEA** model has no damping, the **FEA mode shapes** are ***real-valued***, having shape components with ***phase angles of 0 & 180 degrees***.

Mode shapes that have components with **phases of 0 & 180 degrees** are called **normal mode shapes**.

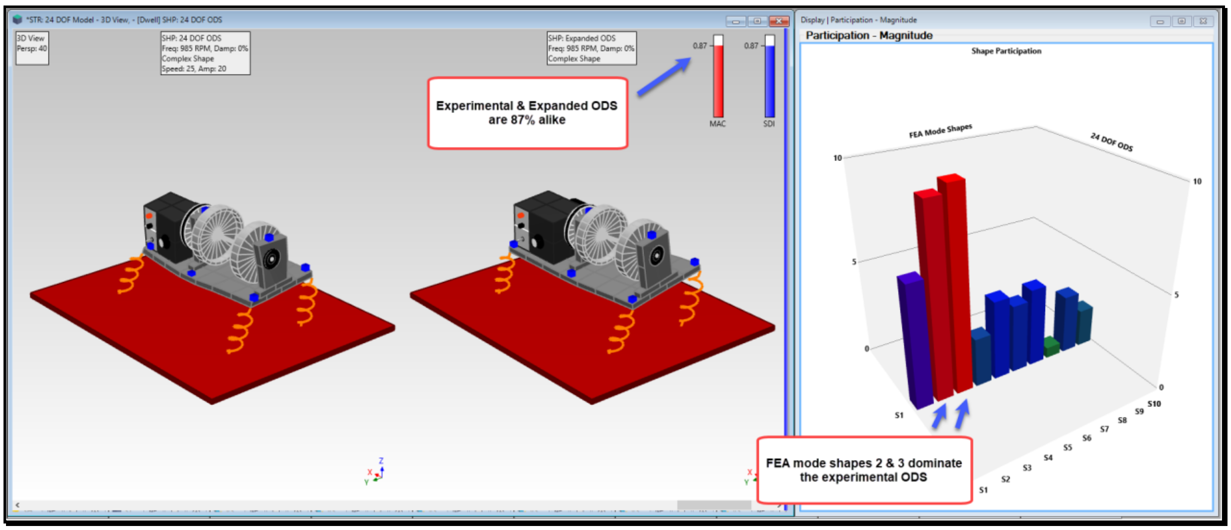
Hotkey 2 - EXPERIMENTAL VERSUS EXPANDED ODS AT 985 RPM

- ***Press* Hotkey 2**

When Hotkey 2 is pressed, the ***complex valued*** experimental **ODS** data is curve-fit with the ten ***normal*** **FEA mode shapes**, and the **participations** of the **FEA mode shapes** in the **ODS** are used to expand the **ODS**.

A side-by-side animation of the ***original*** **24-DOF 985 RPM ODS** is displayed on the ***left-hand model*** and the **1938-DOF *expanded* 985 RPM ODS** is displayed on the ***right-hand*** model, is shown in the figure below.

Geometric interpolation is used on both models to deflect all the ***un-measured*** **DOFs**.



*24-DOF Experimental **ODS** versus 1938-DOF Expanded **ODS** at 985 RPM.*

The **MAC** & **SDI** bars displayed in the ***upper-right corner*** of the side-by-side animation are a numerical comparison of the ***original*** **ODS** and the ***expanded*** **ODS**.

The ***original*** **ODS** and the ***expanded*** **ODS** ***are 87% alike at the*** **24 DOFs** ***that are common between them***.

The shape participation bar chart ***on the right*** shows that ***all ten*** **FEA mode shapes** are excited at **985 RPM**, but ***rigid body*** **FEA mode shapes 2 & 3** ***dominate*** the **ODS**.

MAC & SDI

Both the **Modal Assurance Criterion** (**MAC**) and the **Shape Difference Indicator** (**SDI**) are used to measure both the **co-linearity** and the **difference** respectively between the ***experimental*** **ODS** and the ***expanded*** **ODS** in the comparison display above.

- **MAC & SDI** have values between **0 & 1**
- **MAC = 1 ➔** two shapes are **co linear**
- **MAC > 0.9 ➔** two shapes are **similar**
- **SDI = 1 ➔** two shapes are **identical**
- **SDI > 0.9 ➔** two shapes are **nearly alike**

SHAPE PARTICIPATION

The participation bar chart on the right side of the figure above shows the participation of each **FEA mode shape** in the **24-DOF *experimental* ODS**. The bars show that the ***rigid-body* FEA mode shapes (S1 to S6) *dominate*** the **ODS**, but they will ***participate differently*** at each speed.

Complex-valued participations were used to curve-fit the complex-valued **ODS** data with ***normal* FEA mode shapes**.

MAC & SDI values ***at or above 90%*** verify that complex-valued **ODS** data ***can be accurately represented as a summation*** of **FEA mode shapes**.

Hotkey 3 - EXPERIMENTAL VERSUS EXPANDED ODS AT 1440 RPM

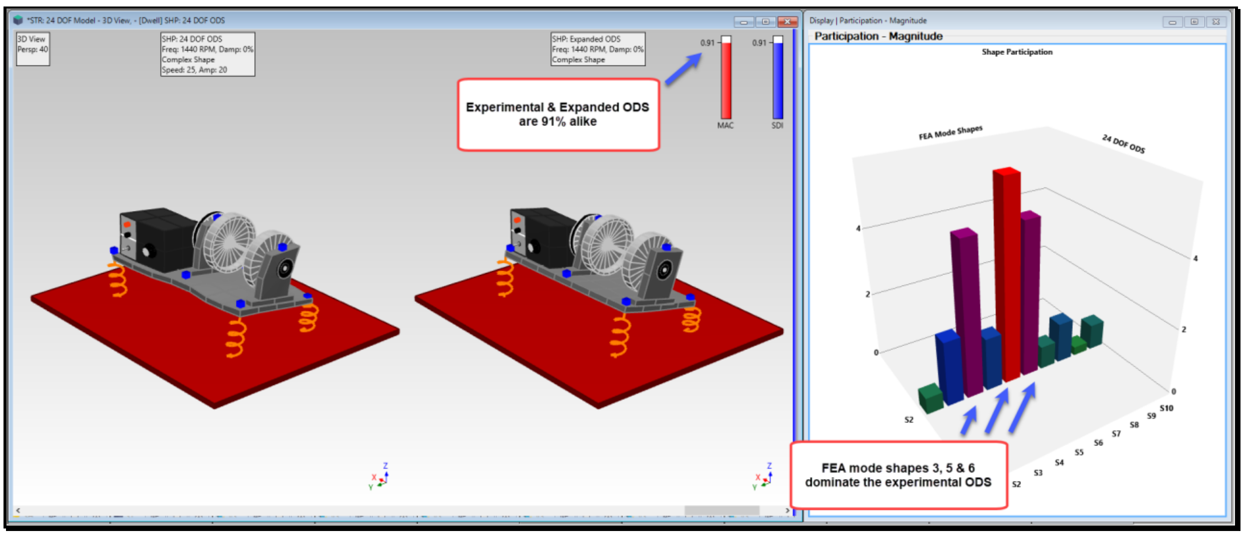
- ***Press* Hotkey 3**

When Hotkey 3 is pressed, the ***complex valued*** experimental **ODS** data is curve-fit with the ten ***normal* FEA mode shapes**, and the **participations** of the **FEA mode shapes** in the **ODS** are used to expand the **ODS**.

The **MAC** & **SDI** bars displayed in the ***upper-right corner*** of the side-by-side animation shown below are a numerical comparison of the ***original* 1440 RPM ODS** and the ***expanded* 1440 RPM ODS**.

The shape **participation** bar chart ***on the right*** shows that ***all ten* FEA mode shapes** are excited at **1440 RPM**, but ***rigid body* FEA mode shapes 3, 5 & 6 *dominate*** the **ODS**.

The ***original* ODS** and the ***expanded* ODS *are 91% alike at the* 24 DOFs *that are common between them***.



*24-DOF Experimental **ODS** versus 1938-DOF Expanded **ODS** at 1440 RPM.*

Hotkey 4 - EXPERIMENTAL VERSUS EXPANDED ODS AT 2280 RPM

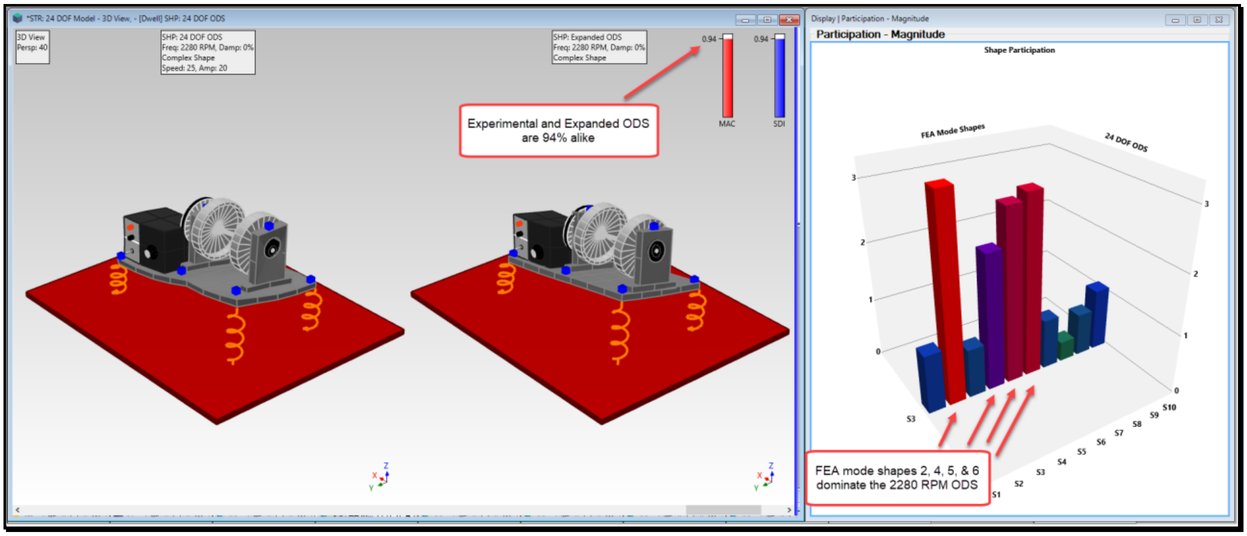
- ***Press* Hotkey 4**

When Hotkey 4 is pressed, the ***complex valued*** experimental **ODS** data is curve-fit with the ten ***normal* FEA mode shapes**, and the **participations** of the **FEA mode shapes** in the **ODS** are used to expand the **ODS**.

The **MAC** & **SDI** bars displayed in the ***upper-right corner*** of the side-by-side animation shown below are a numerical comparison of the ***original* 2280 RPM ODS** and the ***expanded* 2280 RPM ODS**.

The shape **participation** bar chart ***on the right*** shows that ***all ten* FEA mode shapes** are excited at **2280 RPM**, but ***rigid body* FEA mode shapes 3, 5 & 6 *dominate*** the **ODS**.

The ***original* ODS** and the ***expanded* ODS *are 94% alike at the* 24 DOFs *that are common between them***.

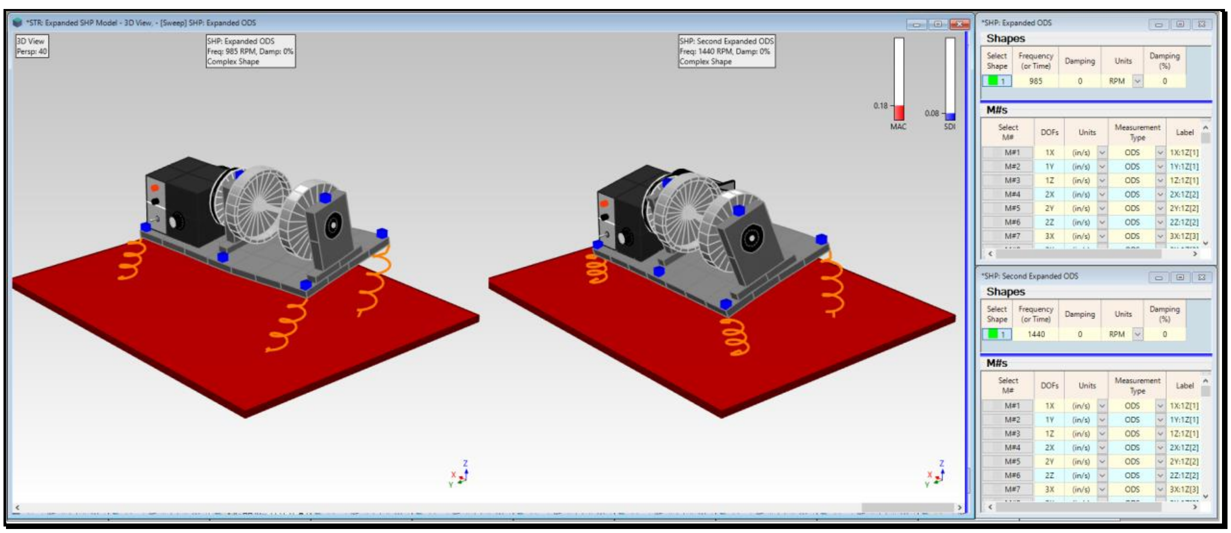


*24-DOF Experimental **ODS** versus 1938-DOF Expanded **ODS** at 2280 RPM.*

Hotkey 5 - 985 RPM VERSUS 1440 RPM ODS

We have seen how the **FEA mode shapes** participate differently in the **ODS** at three different speeds of the machine. So how different are the **ODS**'s from one another at these three different operating speeds?

- ***Press* Hotkey 5**



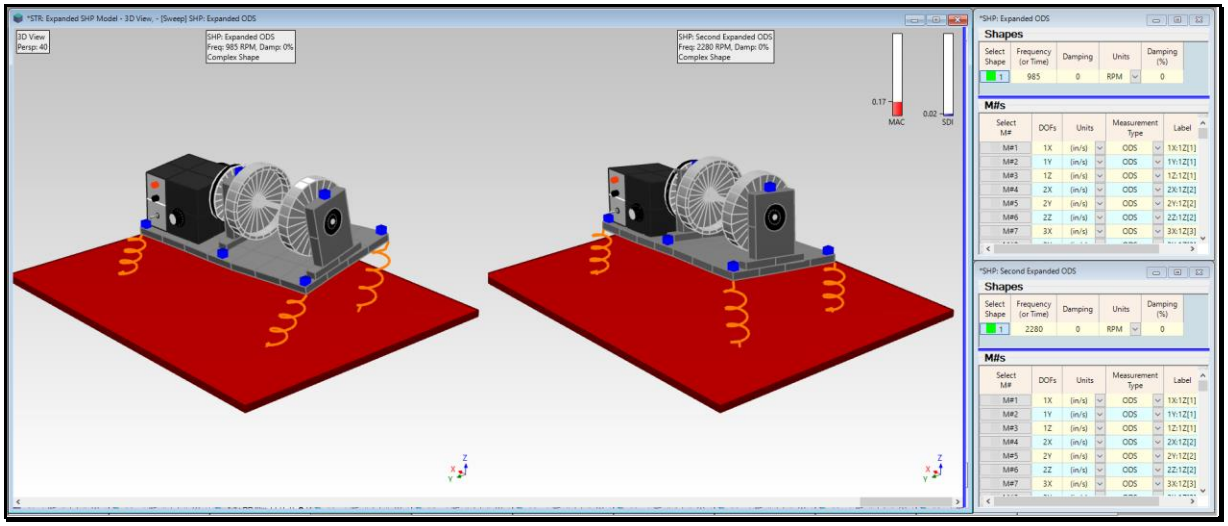
*985 RPM **ODS** VERSUS 1440 RPM **ODS***

MAC & SDI are calculated between ***all* 1938 DOFs** of the two expanded **ODS**'s.

Low **MAC & SDI ➔** the first-order **ODS *has changed significantly*** between speeds **985 RPM & 1440 RPM**.

Hotkey 6 - 985 RPM VERSUS 2280 RPM ODS

- ***Press* Hotkey 6**



*985 RPM **ODS** VERSUS 2280 RPM **ODS***

Low **MAC & SDI** ➔ the first-order **ODS** ***has changed significantly*** between speeds **985 RPM & 2280 RPM**.

CONCLUSIONS

In this App Note, ten **FEA mode shapes** of the base plate & bearing blocks of a rotating machine were used to curve-fit and expand the first-order **ODS** of a rotating machine. **ODS** data was acquired while the machine was running at three different speeds. **ODS** data was acquired using 4-channel data acquisition hardware with a uni-axial accelerometer as a fixed reference and a roving tri-axil accelerometer attached at eight different points on the machine.

This App Note illustrated how ten **FEA mode shapes** of a machine modeled with **free-free boundary conditions** can be used to expand its operating data, thus conforming a fundamental law,

Fundamental Law of Modal Analysis: *All vibration* is a *summation of mode shapes*.

This decomposition & expansion of operating data using **FEA mode shapes** offers some important advantages,

- **Real-world ODS data** can be ***accurately curve-fit*** using mode shapes.
- ***Normal* FEA mode shapes** can be used to curve-fit ***complex-valued* ODS** data.
- **Normal** mode shapes derived from an **FEA** model with ***free-free boundary conditions** & **no damping*** can be curve-fit to real-world vibration data that includes ***real-world boundary conditions & damping***.

Hotkey 7 - REVIEW STEPS

To review the steps of this App Note,

- ***Press* Hotkey 7 Review Steps**