MEscope Application Note 41

Extracting OMA Mode Shapes from Random Responses

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 **AppNote41** project file. These steps might also ***require a more recent release date*** of MEscope.

APP NOTE 41 PROJECT FILE

- To retrieve the Project for this App Note, **click here** to download **AppNote41.zip**

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

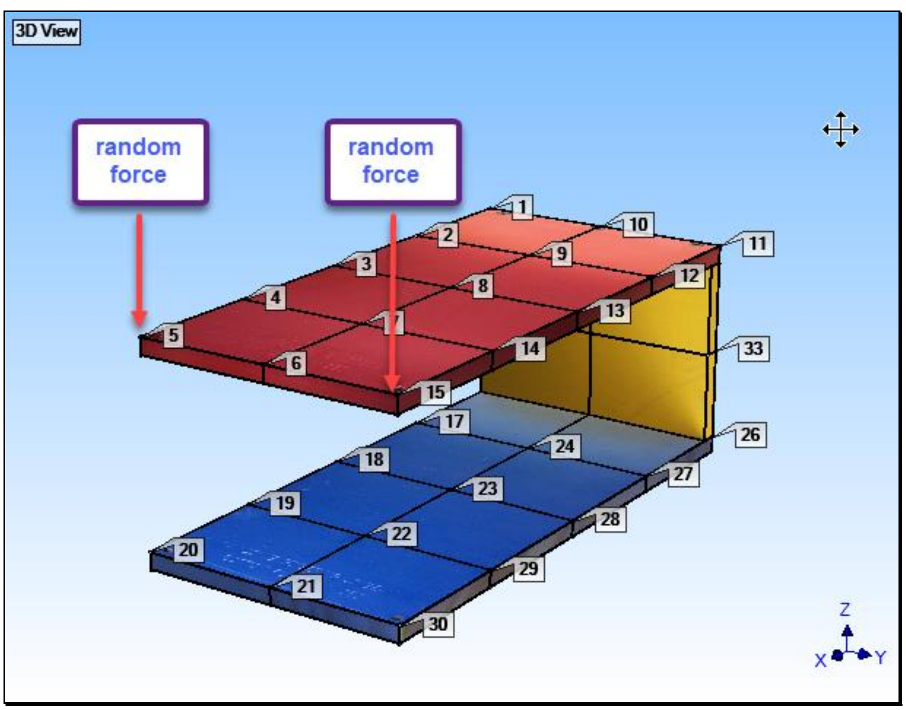
- ***Hold down* the Ctrl key** and ***click* on a Hotkey** to display its Script window

RANDOM RESPONSES

In this App Note, an output-only **OMA** test of the Jim Beam structure shown below is simulated using two shakers and random excitation signals. A ***"round trip"*** is performed starting with an **EMA** modal model of the Jim Beam. The modal model is used to synthesize **FRFs** which will then be used to calculate the acceleration responses due to two random forces applied at corners of the top plate, as shown below.

Then, **Cross spectra** are calculated from the ***random acceleration responses***, and they are ***curve fit*** to extract **OMA** mode shapes. Finally, the **OMA** mode shapes are compared with the original **EMA** mode shapes to demonstrate that the same modes can be extracted from ***output-only random response*** data.

A Data Block of TWFs of the two random forces has already been created and saved in this Project. Each random force TWF contains **50,000 samples** of time domain data. These forces (**Inputs**) are applied at **DOFs 5Z & 15Z** as shown below. Random responses to these forces will be calculated using a **dynamic MIMO model** of the Jim Beam which is synthesized using its **EMA** mode shapes.



HOTKEY 1 - BROAD-BAND EXCITATION

- ***Press* Hotkey 1**

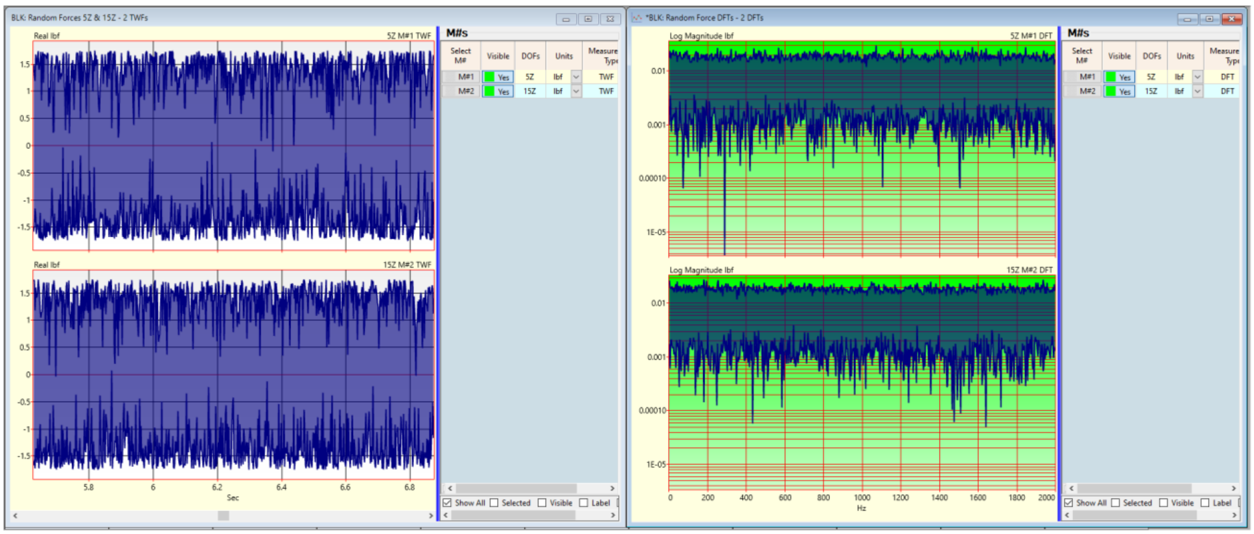
A Data Block of TWFs of the two random forces has already been created and saved in this Project. The **Input** forces are applied at **DOFs 5Z & 15Z** as shown on the left below. Each random force TWF contains **50,000 samples** of time domain data. Random responses calculated from these two force Input will also have **50,000 samples**.

This is enough data to perform spectrum averaging using **25 spectrum averages** with a **spectrum Block Size of 1000 samples,** with no overlap grossing when the **Cross spectra** are calculated.

The DFTs of the random forces are displayed below on the right. Notice that the random signals are defined with a band-width 2000 Hz.

> The "flat spectrum" and the band-width of the DFTs of the two random forces guarantees that all modes in the frequency range (0 to 2000 Hz) will be excited.

- In a real-world output-only data acquisition environment, where the excitation forces cannot be measured, their band-width is unknown
- The **DFTs** of the excitation forces must be assumed to be ***"relatively flat"*** in order to excite and extract OMA modes from output-only data



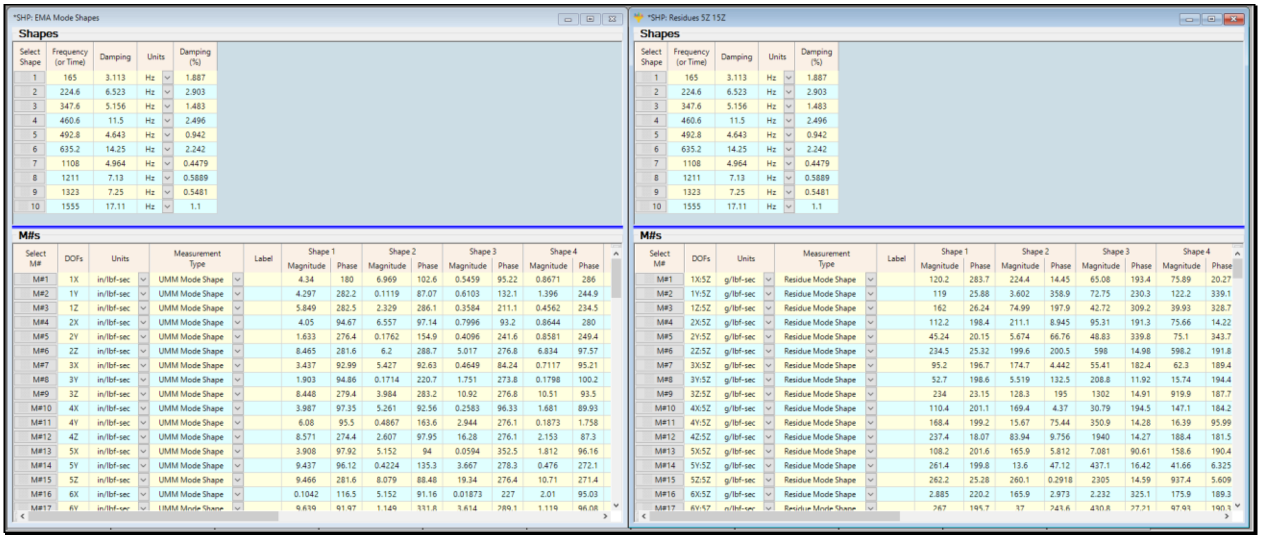
To calculate responses (**Outputs**) at each of the 33 points on the Jim Beam caused by the random excitation forces (**Inputs**), the **EMA** mode shapes are used to synthesize **FRFs** between the **2 Inputs** at **DOFs 5Z & 15Z** and **99 Outputs** at **DOFs 1X, 1Y, 1Z to 33X, 33Y, 33Z**.

HOTKEY 2 - CONVERTING UMM TO RESIDUE MODE SHAPES

- ***Press* Hotkey 2**

To be used for **FRF** synthesis, the **EMA** mode shapes must be converted into **Residue** mode shapes that have Roving **DOFs 1X, 1Y, 1Z to 33X, 33Y, 33Z** and Reference **DOFs 5Z & 15Z**. The **Residue** mode shapes are then used to synthesize **192 FRFs** between all **99** Roving **DOFs** and the two Reference **DOFs 5Z & 15Z**.

When **Hotkey 2 is *pressed***, two Shape Tables are displayed as shown below. The original **EMA** mode shapes are displayed on the left and the **Residue** mode shapes are displayed on the right.



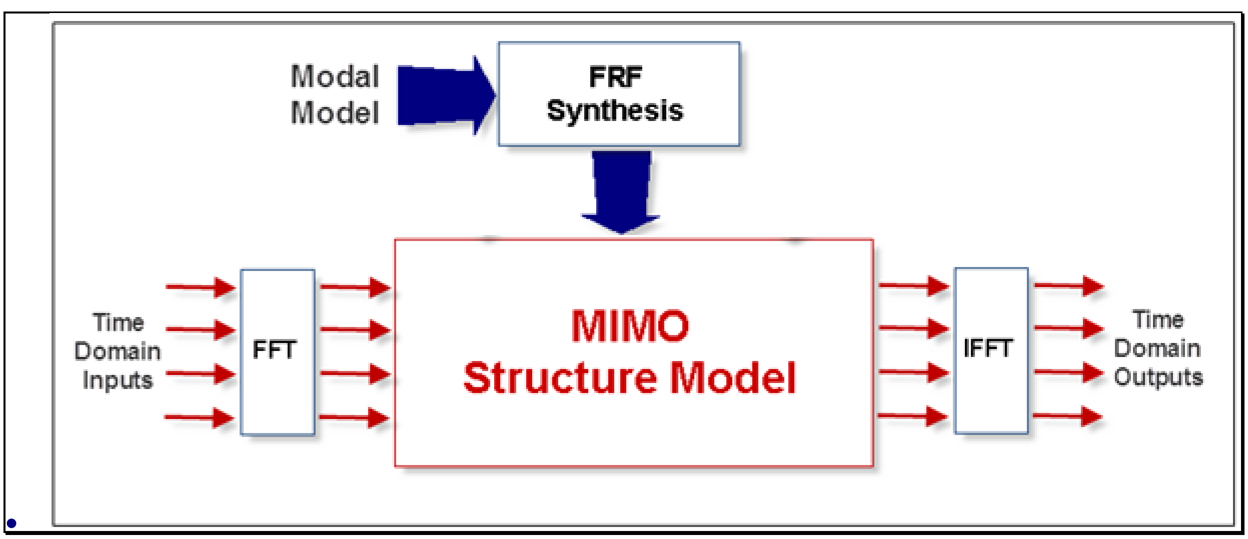
EMA MODE SHAPES

- Each mode shape **M#** only has a **Roving DOF**
- Each mode shape **M#** has units of **in/(lbf-sec)**. (***displacement / force-sec***)
- Each mode shape **M#** has **Measurement Type → UMM Mode Shape**. (***Unit Modal Mass*** *scaling preserves the dynamic properties of the structure*)

RESIDUE MODE SHAPES

- Each mode shape **M#** has both a **Roving & Reference DOF**
- Each mode shape **M#** has units of **g/(lbf-sec)**. (***acceleration / force-sec***)
- Each mode shape **M#** has Measurement Type **→ Residue Mode Shape**
- There are ***twice as many*** **Residue** mode shape **M#s** as **UMM** mode shape **M#s** because there are ***two* reference DOFs**

The random responses to the two random force Inputs applied at DOFs 5Z & 15Z are calculated using the **Transform | Outputs** command in MEscope. This calculation is depicted in the diagram below.



MIMO Calculations Block Diagram

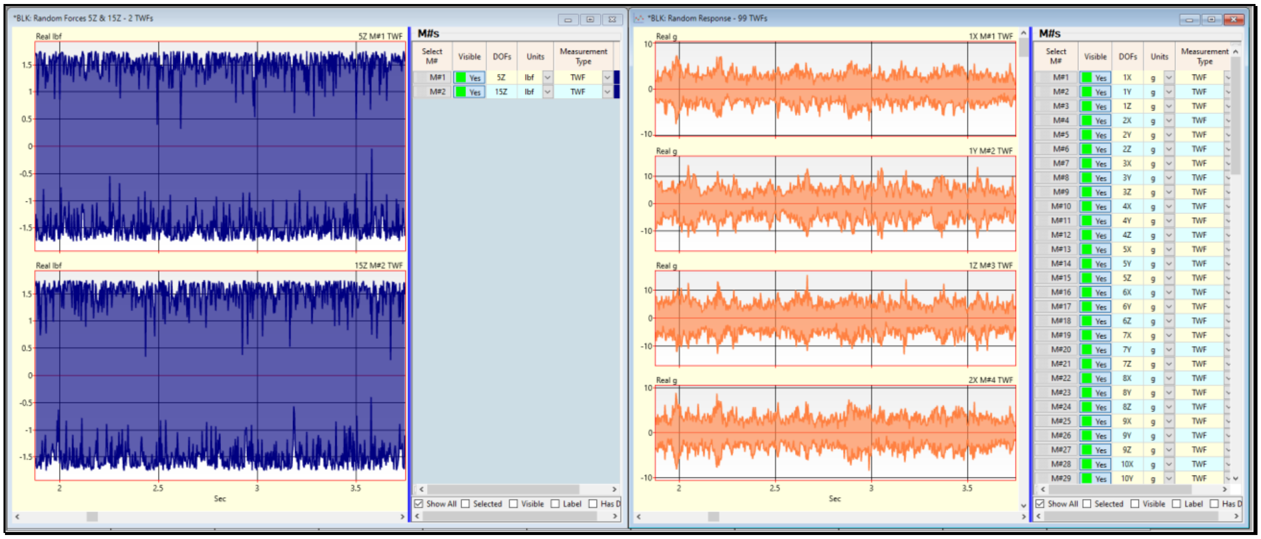
HOTKEY 3 - CALCULATING RANDOM RESPONSES

- ***Press* Hotkey 3**

When **Hotkey 3 is *pressed***, the **Modal Model** of **Residue** mode shapes is used to ***synthesize the necessary* FRFs** between the two random forces (**Inputs)** at **DOF 5Z & 15Z** and the responses (**Outputs**) at **99 DOFs** of the Jim Beam. The random force **Inputs** are displayed ***on the left***, and the random response **Outputs** are displayed ***on the right***, shown below.

- Place the mouse pointer in the graphics area of either Data Block, and ***spin the mouse wheel*** to Zoom in on the random data

Each **M#** in both Data Blocks contains **50,000 samples** of **TWF** data.

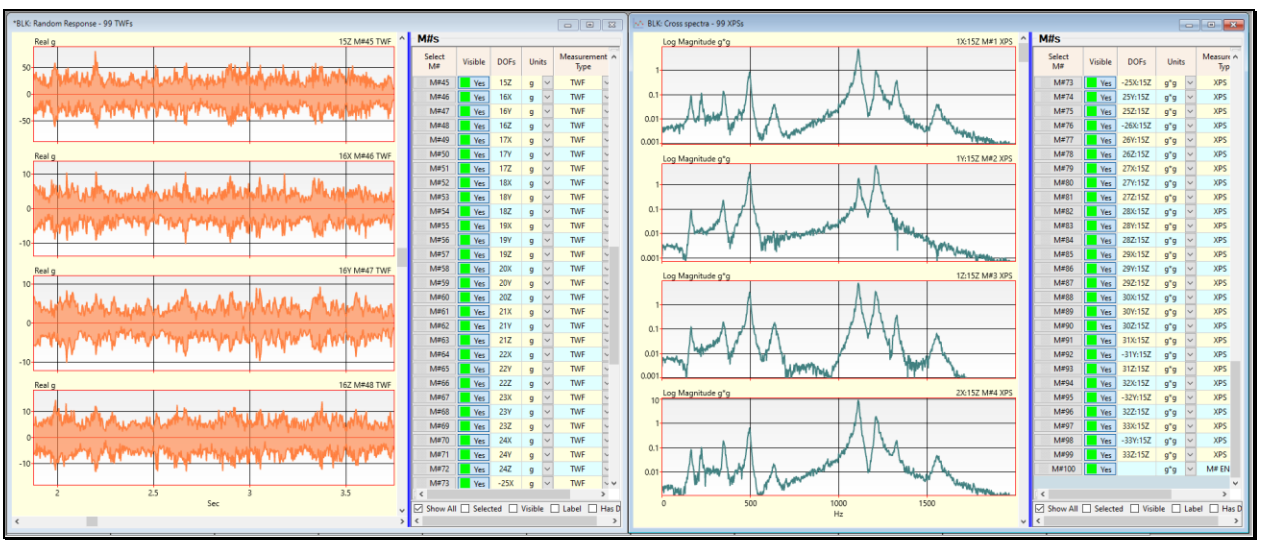


Random Forces on the Left and Responses on the Right.

HOTKEY 4 - CALCULATING CROSS SPECTRA

- ***Press* Hotkey 4**

When **Hotkey 4 is *pressed***, Cross Spectra are calculated from the random responses. The 99 random responses are displayed on the left, and the 99 Cross Spectra with reference response **15Z** are displayed ***on the right***, as shown below.



Acceleration Random Responses on the Left and Cross Spectra on the Right.

CHOOSING A REFERENCE DOF

Notice that all **99 M#s** in the **BLK: Random Responses** are designated as **Outputs**. To calculate Cross Spectra for curve fitting, ***at least one of the responses*** must be a ***reference response.***

Any one of the 99 responses can be chosen as a reference response (***designated as an* Input *or* Both** in MEscope). The response **M#** at **DOF 15Z** was used as ***both an Output & Input*** by changing its **Input Output** property to **Both.**

An ***active response*** **DOF**, (where all resonances of interest are excited), should be chosen as the ***reference response*** **DOF.**

HANNING WINDOW

Because the response **TWFs** ***are continuous random signals***, (also called ***pure random*** signals), to ***reduce leakage*** in their **DFTs**, the responses must have a **Hanning window** applied to them before applying the FFT.

If a Hanning window is applied to ***pure random*** **TWFs** ***leakage surrounding each resonance peak*** in their **DFTs** and hence their Cross Spectra ***will be reduced***.

SPECTRUM BLOCK SIZE

The **FFT** calculates a **DFT (Digital Fourier Spectrum)** with a spectrum Block Size ***equal to one-half*** of its **TWF** Block Size before the FFT is applied to it.

When **Hotkey 4 is** ***pressed***, Cross Spectra are calculated from the random response **TWFs** using by averaging **25 DFTs of 1000 samples each** together.

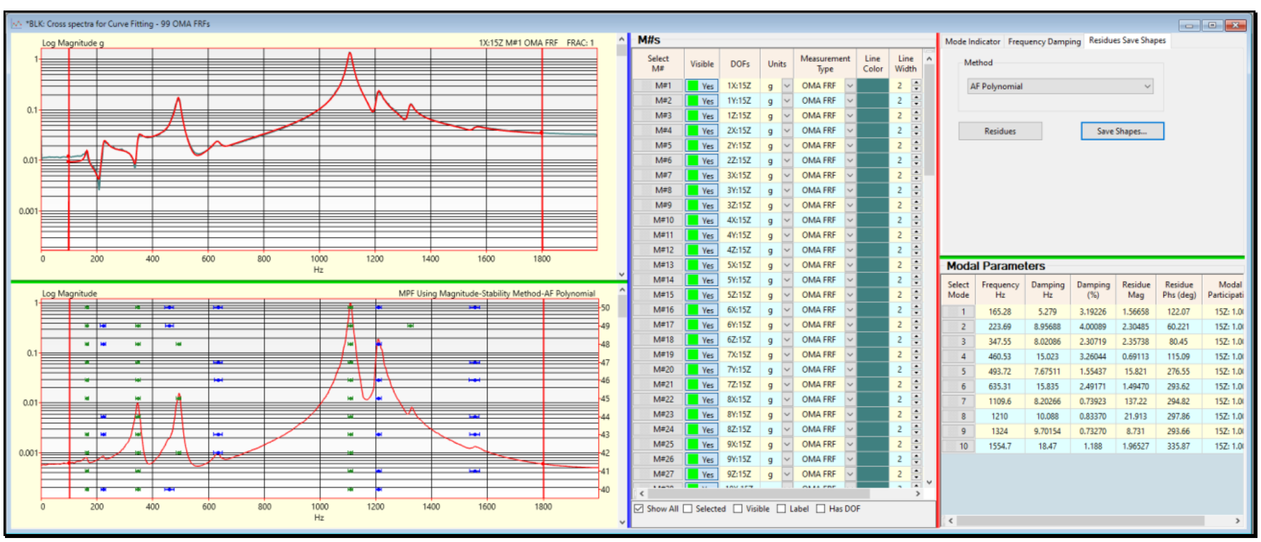
- The Block Size of the random response **TWFs** is 50,000 samples
- For spectrum averaging, there is enough data in each random response **TWF** to calculate **25 DFTs** with 1000 samples in each **DFT**

These calculations ***simulate the same process*** that would be used in a spectrum analyzer to ***post-process random output-only data*** acquired from a machine or structure.

HOTKEY 5 - CURVE FITTING THE CROSS SPECTRA

- ***Press*** **Hotkey 5**

When **Hotkey 5 is** ***pressed***, the Cross Spectra are curve fit using a **Stability diagram** to extract **OMA** mode shapes, as shown below.



Stability Diagram Showing 10 Stable Pole Groups.

DECONVOLUTION WINDOW

All the curve fitting methods in MEscope are **FRF-based curve fitting** methods which utilize an **FRF *analytical model*** to curve fit experimental data. However, **Cross Spectra, Auto Spectra**, and **ODS-FRFs** do not have ***the complex waveform*** of an **FRF**.

A **DeConvolution** window ***must be applied*** to **Cross Spectra, Auto Spectra**, and **ODS-FRFs** to extract modal parameters from them using **FRF-based curve fitting** methods.

When **Hotkey 5 is *pressed***, a **DeConvolution** window is applied to the Cross spectra prior to curve fitting them.

- ***Scroll though*** the **Cross spectra** on the ***upper-left*** to observe the **red Fit Function** overlaid on the ***log magnitude*** of each **DeConvolution** windowed Cross Spectrum

STABLE POLE GROUPS

The **AF Polynomial** method was used to curve fit the windowed Cross Spectra. The **Stability Diagram** is displayed in the ***lower-left corner*** of the curve fitting window. ***Stable pole groups*** are displayed on top of the **Mode Indicator** in the **Stability Diagram**.

All the pole estimates in a **stable pole group** are indicated with the ***same color***

Stable pole group colors ***alternate between two colors***. Those two colors are the ***second & third colors*** on the **Contour Colors** tab in the **File | Data Block Options** box

HOTKEY 6 - COMPARING OMA WITH EMA MODE SHAPES

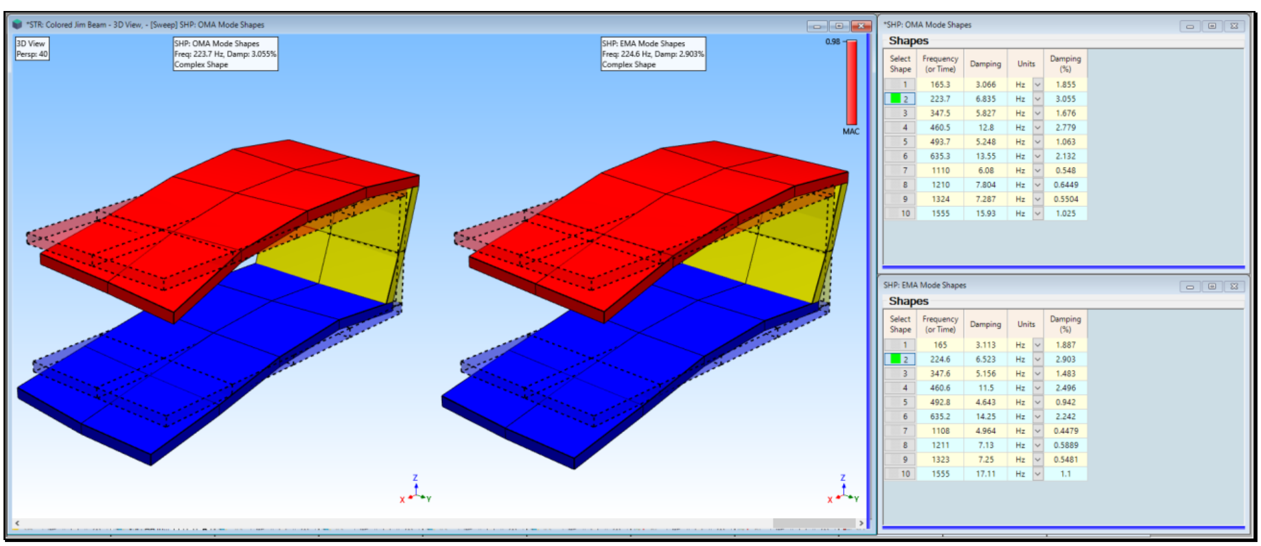
- ***Press* Hotkey 6**

When **Hotkey 5 is *pressed***, a side-by-side animated display will begin with an **OMA** mode shape ***on the left*** and an original **EMA** mode shapes ***on the right***.

The ***Modal Assurance Criterion* (MAC)** is used to numerically match mode shape pairs. Each pair of mode shapes with **Maximum MAC** is displayed together.

- **MAC** has values between 0 &1
- If **MAC** is greater than 0.9 ➔ two shapes are ***strongly co-linear***, or correlated.
- If **MAC** ➔ is less than 0.9 ➔ two shapes are ***weakly co-linear***, or uncorrelated.

The **MAC** for each mode shape pair is also displayed in the ***upper-right corner*** of the display. This numerical comparison of mode shape pairs confirms that curve fitting a set of ***output-only* Cross spectra** can recover the mode shapes used to model the input-output dynamics of the Jim Beam.



***OMA** Mode Shape on the Left and **EMA** Mode Shape with Maximum MAC on the Right.*

ROUND TRIP`

This completes the ***round-trip simulation*** of the excitation of the Jim Beam using two random forces applied to corners of its upper plate. Ten **EMA** mode shapes were used to synthesis an FRF-based dynamic model of the Jim Beam. Random response **TWFs** (**Outputs**) caused by the random force **TWFs** (**Inputs)** were calculated using **Transform | Outputs**, one of the **MIMO (Multi-Input Multi-Output)** commands in MEscope.

These calculated random response **TWFs** are the same as any random response **TWFs** that would be acquired from a real-world test article using a multi-channel data acquisition system.

Then, the random response **TWFs** were used to calculate Cross Spectra between all the responses and a reference response at **DOF 15Z** on the upper plate. Finally, the Cross Spectra were curve fit to extract OMA modes of the Jim Beam. These **OMA** modal parameters ***closely matched*** the original **EMA** modal parameters of Jim Beam.

HOTKEY 7 - REVIEW STEPS

To review all the steps of this App Note,

- ***Press*** **Hotkey**