MEscope Application Note 47

Multi-Input Multi-Output (MIMO) Forced Response

The steps in this Application Note can be carried out using any MEscope package that includes the VES-3600 Advanced Signal Processing & VES-4000 Modal Analysis options. Without these options, you can still carry out the steps in this App Note using the **AppNote47** project file. These steps might also require MEscope software with a ***more recent release date***.

APP NOTE 47 PROJECT FILE

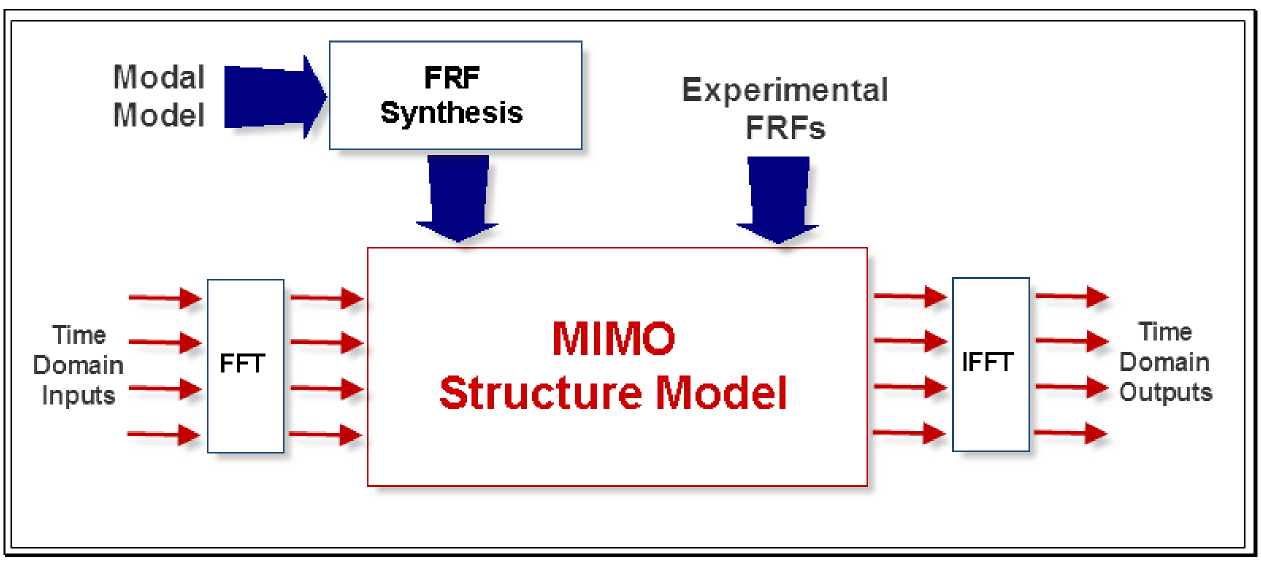
- To retrieve the Project for this App Note, **click here** to download **AppNote47.zip**

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

CALCULATING FORCED RESPONSE WITH TRANSFORM | OUTPUTS

The forced response of a structure due to multiple excitation forces is calculated using commands in the **VES-3600 Advanced Signal Processing** option. The following block diagram depicts this Multiple-Input Multiple-Output (MIMO) calculation process. When forces (**Inputs**) are provided as time waveforms, then response time waveforms (**Outputs**) caused by the forces are calculated. Either **synthesized or experimental FRFs** can be used to model the Input-Output dynamics of the structure.



MIMO Block Diagram

Each of the following commands is used in this App Note to calculate **multiple Outputs** due to **multiple force Inputs**.

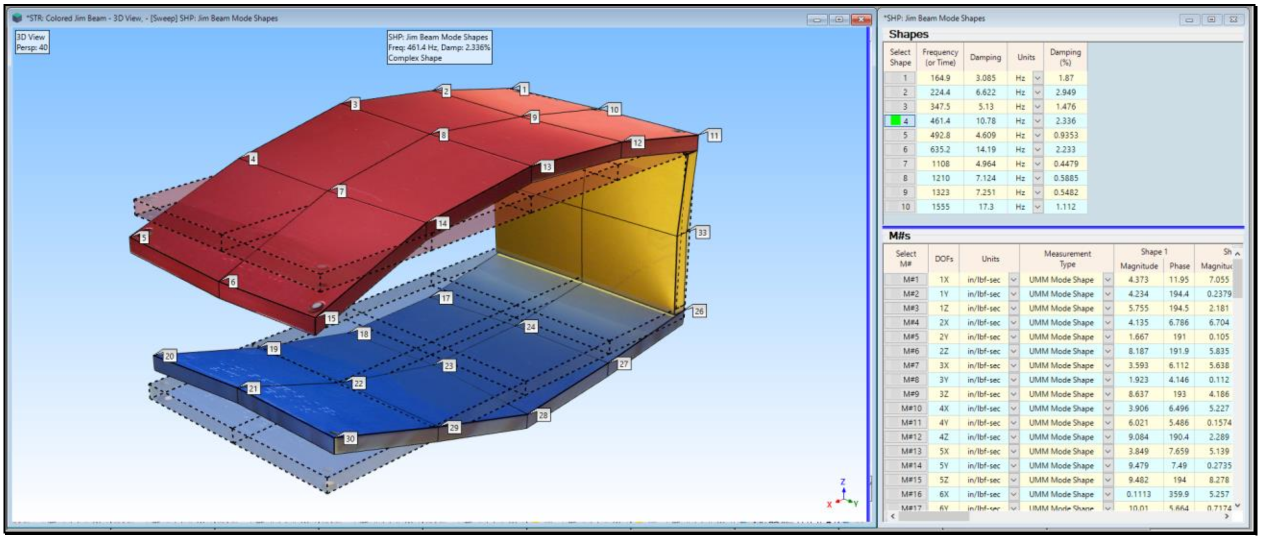
1. **Transform | Outputs** uses a Data Block of **time or frequency** domain force waveforms as (**Inputs**), and either **FRFs** or **mode shapes** to model the structural dynamics, and calculates a Data Block of response **time or frequency** waveforms as (**Outputs**)
2. **Transform | Sinusoidal ODS** uses either **FRFs** or **mode shapes** to calculate and animate a response **ODS** caused by **multiple sinusoidal forces at a single frequency**
3. **Tools | Sinusoidal ODS** in a Shape Table uses **mode shapes** to calculate and animate a response **ODS** caused by **multiple sinusoidal forces at a single frequency**

STEP 1 - MODE SHAPES OF THE JIM BEAM

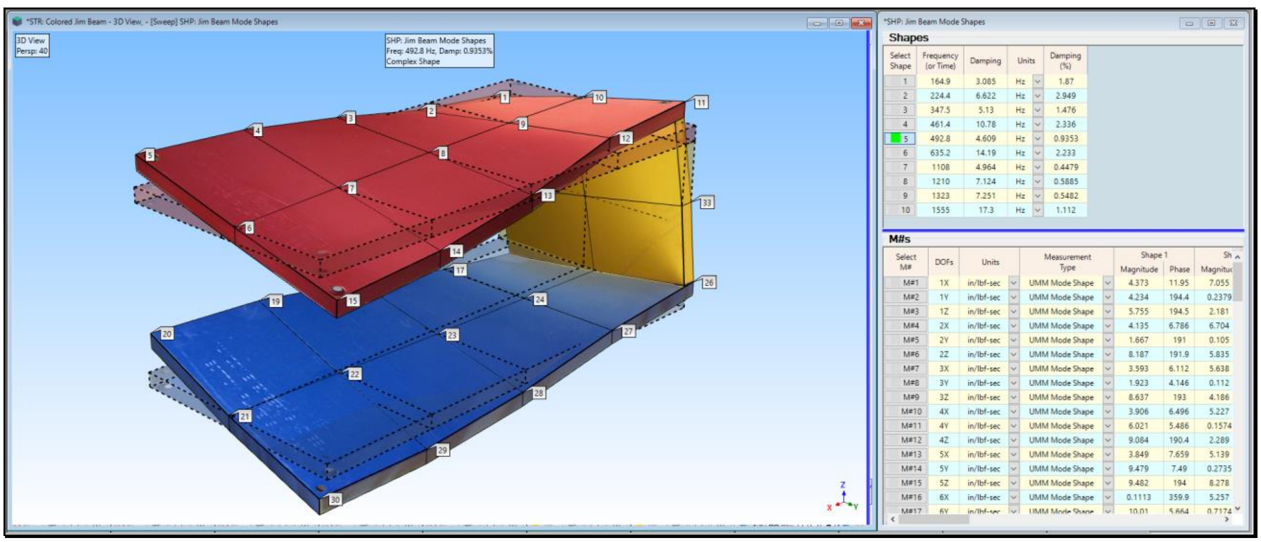
- ***Press* Hotkey 1 Mode shapes of the Jim Beam**

Sweep animation will begin through the **EMA mode shapes** in the Shape Table **SHP: Jim Beam UMM Mode Shapes** on the right. This structure has **a *bending mode at* 462 Hz** and ***a torsional mode at* 493 Hz**.

- ***Press* Select Shape *buttons 4 & 5*** to display each of **those two mode shapes** in animation
- **Shape 4** is the ***first bending mode*** and **Shape 5** is the ***first torsional mode*** of the Jim Beam



***462 Hz** Mode Shape*



***493 Hz** Mode Shape*

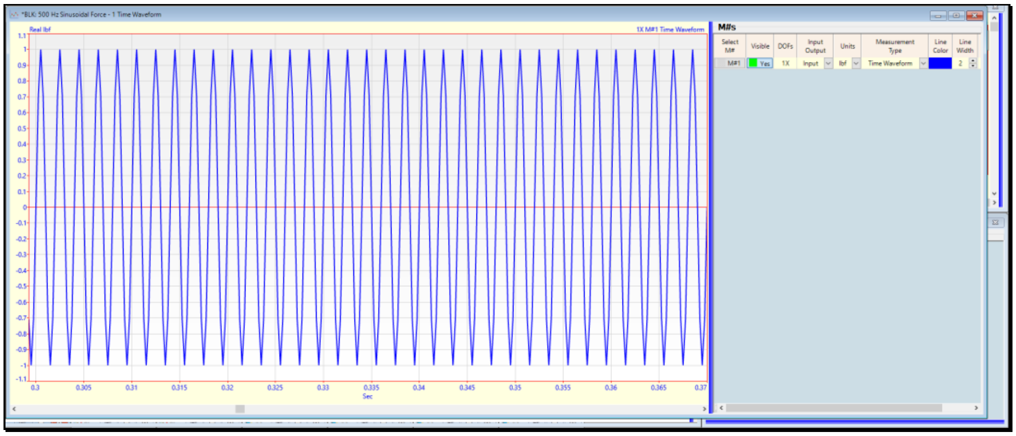
SINUSOIDAL EXCITATION FORCES

To calculate its forced response, the Jim Beam will be **simultaneously excited** by two **500 Hz sinusoidal forces**, one force applied at **Point 5** on the top plate in the vertical direction (**DOF 5Z)**, and the other force applied at the **Point 15** in the vertical direction (**DOF 15Z)**.

Because the **torsional mode at 493 Hz** is ***closest in frequency*** to the **500 Hz** excitation frequency, our intuition would say that the response **ODS** should be **dominated by the 493 Hz torsional mode**.

We will see that the **mode which participates most** in a structural response **depends on its mode shape** and **where the forces are applied** to the structure.

A sinusoidal force time waveform was created using the **File | New | Data Block** command and saved into Data Block **BLK: 500 Hz Sinusoidal Force,** shown below.



500 Hz Sinusoidal Force Time Waveform.

In **Step 2**, the **500 Hz sinusoidal waveform** is used to **create two In-Phase forces** and those force time waveforms are used to calculate the structural response of the Jim Beam when those forces are applied to **DOFs 5Z & 15Z**.

The two sinusoidal forces **simulate two motors** mounted at the corners of the top plate running at **500 Hz (30,000 RPM)**.

In **Step 3**, the **500 Hz sinusoidal waveform** is used to **create two out-of-phase forces** and those forces are used to calculate the structural response of the Jim Beam when those forces are applied to **DOFs 5Z & 15Z**.

EXPERIMENTAL FRFs FROM A ROVING RESPONSE IMPACT TEST

For MIMO calculations, the **FRFs** required to model the Input-Output dynamics of the structure can be either **measured experimentally** or **synthesized from modal parameters**. The experimental **FRFs** of the Jim Beam were calculated from data acquired during a **Roving Response Impact Test**. During acquisition, the structure was **impacted at DOF 15Z** and a tri-axial accelerometer was roved and attached to each of **33 test Points** on the beam.

The 99 experimental **FRFs** each have a unique **Roving DOF** (**1X through 33Z**) and the **same Reference DOF 15Z**.

Using those **single-reference FRFs from the Roving Response Test** for MIMO calculations, a sinusoidal force can only be applied to the Jim Beam at **DOF 15Z**.

SYNTHESIZING MULTI-REFERENCE FRFS FROM MODE SHAPES

To calculate time waveforms of the response caused by **Inputs at DOFs 5Z & 15Z**, a set of **multi-reference FRFs** is required that defines the Input-Output dynamics between **99 Roving (Output) DOFs** and **Reference (Input) DOF 5Z** and **Reference (Input) DOF 15Z**.

A set of **multi-reference FRFs** with **Reference DOFs 5Z & 15Z** can be synthesized using **UMM mode shapes**.

A set of **UMM mode shapes** is called a **Modal Model** because they **preserve the structural dynamics**.

In **Step 2 & Step 3**, **multi-reference FRFs** are synthesized using the **UMM mode shapes** in **SHP: Jim Beam UMM Mode Shapes**.

STEP 2 - RESPONSE TO TWO IN-PHASE SINUSOIDAL FORCES

- ***Press* Hotkey 2 Response to In-Phase Forces**

When **Hokey 2 is *pressed***, the response **due to two In-Phase 500 Hz sinusoidal forces** applied at **DOFs 5Z** & **15Z** is calculated.

A Data Block **BLK: Jim Beam Responses** containing the **response time waveforms** is displayed in the ***upper-right corner***, and the Shape Table **SHP: Jim Beam UMM Mode Shapes** containing the mode shapes of the Jim Beam is displayed in the ***lower-right corner***.

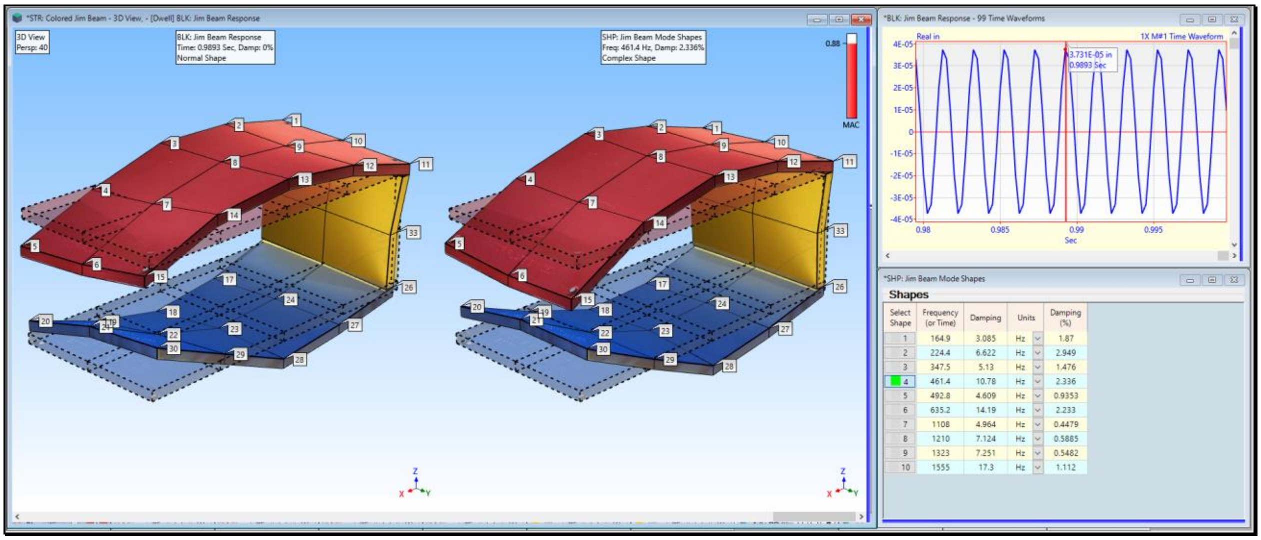
Dwell animation is begun from **BLK: Jim Beam Responses**, and the **500 Hz ODS** at the cursor position is displayed side-by-side with the ***closest matching*** mode shape in **SHP: Jim Beam UMM Mode Shapes**.

The ***closest matching*** mode shape has a **Maximum MAC** with the **ODS** from the Data Block.

- ***Drag*** the **Line** cursor to another peak in **BLK: Jim Beam Responses**

MAC ➔ 0.88 between the ODS at each peak in **BLK: Jim Beam Responses** and the **462 Hz** mode shape.

MAC ➔ *greater than* 0.9 indicates that the **462 Hz** mode shape **dominates the structure response** to the **In-Phase** forces at **500 Hz**.



Select Shape	Frequency (or Time)	Damping	Units	Damping (%)
1	164.9	3.085	Hz	1.87
2	224.4	6.622	Hz	2.949
3	347.5	5.13	Hz	1.476
4	461.4	10.78	Hz	2.336
5	492.8	4.609	Hz	0.9353
6	635.2	14.19	Hz	2.233
7	1108	4.964	Hz	0.4479
8	1210	7.124	Hz	0.5885
9	1323	7.251	Hz	0.5482
10	1555	17.3	Hz	1.112

*Response to **In-Phase** Forces Which is Dominated by the **462 Hz** Mode Shape.*

The MAC value between the **500 Hz ODS *on the left*** and its ***closest matching*** mode shape ***on the right*** remains the same for all Line cursor positions. The **462 Hz** mode shape is **38 Hz less than the excitation frequency**, yet it is being excited by the **In-Phase** sinusoidal forces at **500 Hz.**

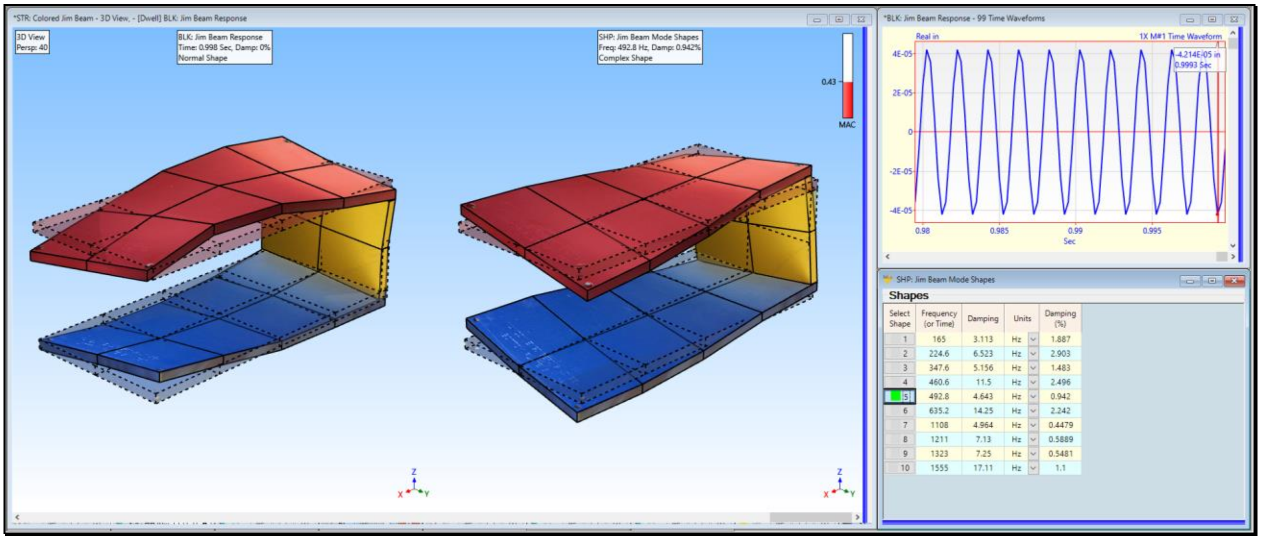
- ***Press Select* Shape 5** in **SHP: Jim Beam UMM Mode Shapes** to display the **493 Hz** mode shape

MAC ➔ 0.43 between the **500 Hz ODS** and the **493 Hz mode shape**.

MAC ➔ *less than* 0.9 means that the **493 Hz mode** is **not strongly excited by the 500 Hz forces**, even though it is **only 7 Hz less** in frequency than the excitation frequency.

The **493 Hz mode shape does not participate significantly** in the **500 Hz** response of the Jim Beam caused by the **In-Phase** forces.

Because its mode shape components are In-Phase at **DOFs 5Z & 15Z**, the **462 Hz** mode **dominates the response** to the In-Phase forces at **500 Hz**.



*493 Hz Mode Shape Does Not Participate in the In-Phase **500 Hz** ODS.*

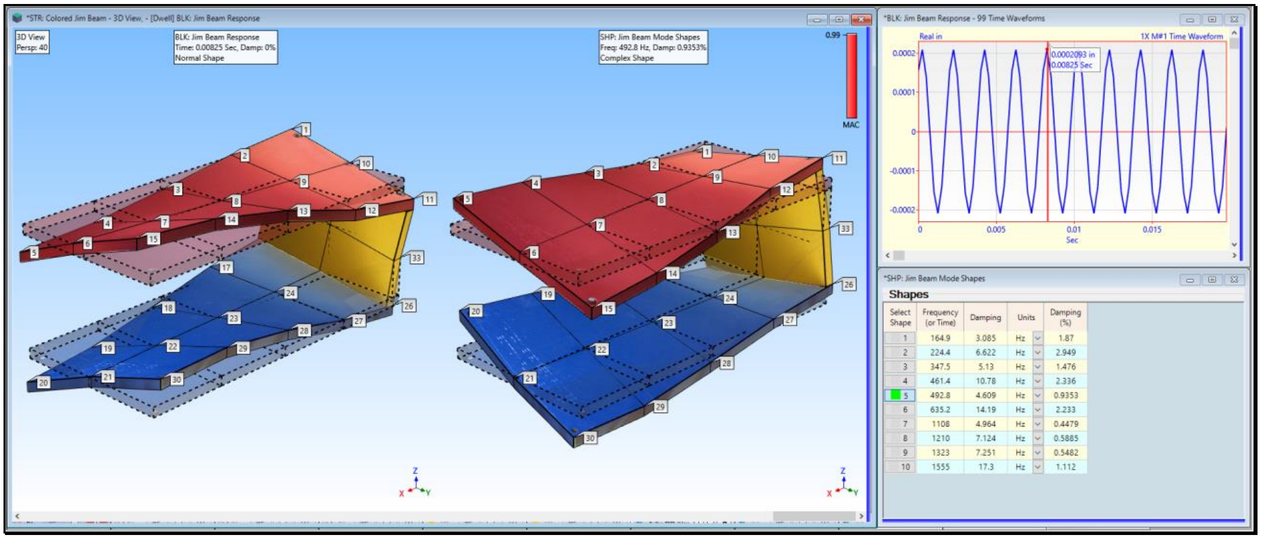
STEP 3 - RESPONSE TO TWO OUT-OF-PHASE SINUSOIDAL FORCES

- ***Press* Hotkey 3 Response To Out-of-Phase Forces**

When **Hotkey 3 is *pressed***, the response **due to two out-of-phase 500 Hz sinusoidal forces** applied at **DOFs 5Z** & **15Z** is calculated.

A Data Block **BLK: Jim Beam Responses** containing the **response time waveforms** is displayed in the ***upper-right corner*** and the Shape Table **SHP: Jim Beam UMM Mode Shapes** containing the mode shapes of the Jim Beam is displayed in the ***lower-right corner***.

Dwell animation is begun from the cursor position in **BLK: Jim Beam Responses**, and the **500 Hz ODS** at the cursor position is displayed side-by-side with the **closest matching mode shape** in **SHP: Jim Beam UMM Mode Shapes**.



*Response to Out-of-Phase Forces Which is Dominated by the **493 Hz** Mode Shape.*

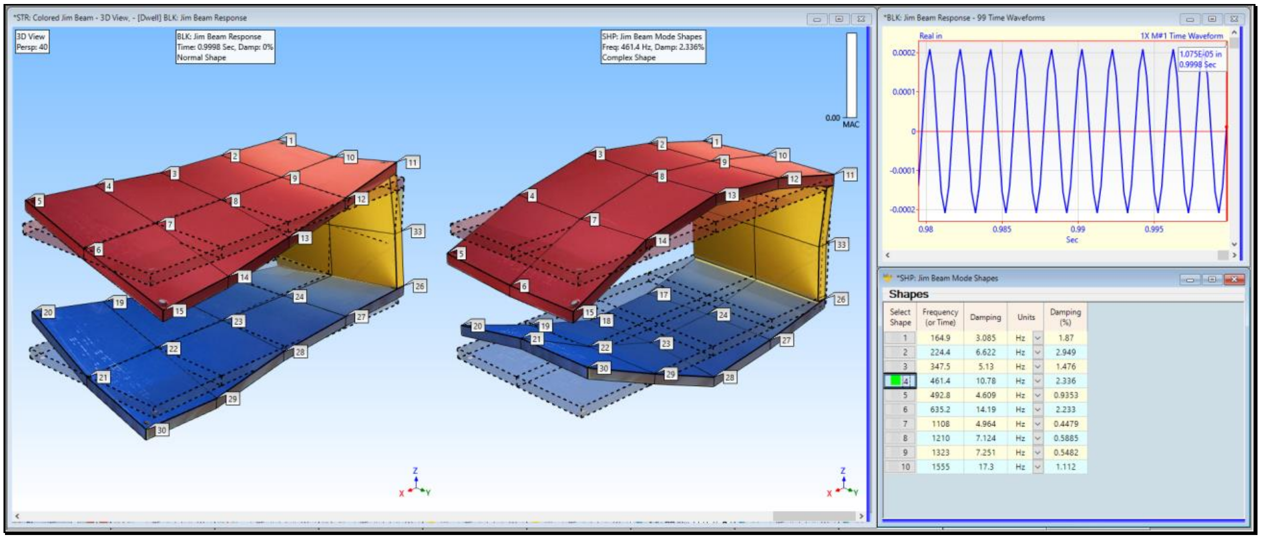
- ***Drag* the Line cursor to any peak in BLK: Jim Beam Responses**

MAC → 0.99 between the **500 Hz ODS** and the **493 Hz mode shape**.

Because its mode shape components at **DOFs 5Z & 15Z** are Out-of-Phase, the **493 Hz mode** is **easily excited by the out-of-phase forces** and it **dominates** the **ODS**.

- ***Press Select* Shape 4** in **SHP: Jim Beam UMM Mode Shapes** to display the **462 Hz** mode shape

No other mode except the 493 Hz mode participates in the response caused by **500 Hz Out-of-Phase** excitation forces.



***462 Hz** Mode Shape Does Not Participate in the Out-of-Phase 500 Hz Response.*

SYNTHESIZING MULTI-REFERENCE FRFS FROM MODE SHAPES

To calculate time waveforms of the response caused by **Inputs at DOFs 5Z & 15Z**, a set of **multi-reference FRFs** is required that defines the Input-Output dynamics between **99 Roving (Output) DOFs** and **Reference (Input) DOF 5Z** & **DOF 15Z**.

A set of **multi-reference FRFs** with **Reference DOFs 5Z & 15Z** can be synthesized using **UMM mode shapes** to provide the Input-Output dynamics necessary to calculate responses caused by **Inputs at 5Z & 15Z**.

In **Step 2 & Step 3, multi-reference FRFs** were synthesized using the mode shapes in **SHP: Jim Beam UMM Mode Shapes**.

In **Step 4 & Step 5**, **multi-reference FRFs** are synthesized using the following steps.

1) Curve fit the **experimental FRFs** to obtain **Residue mode shapes** with **99 Roving DOFs** and **Reference 15Z**.

2) Convert the **Residue mode shapes** to **UMM mode shapes** with **99 Roving DOFs** in them.

3) Convert the **UMM mode shapes** to **Residue mode shapes** with **99 Roving DOFs** and **Reference DOFs 5Z** & **DOF 15Z**.

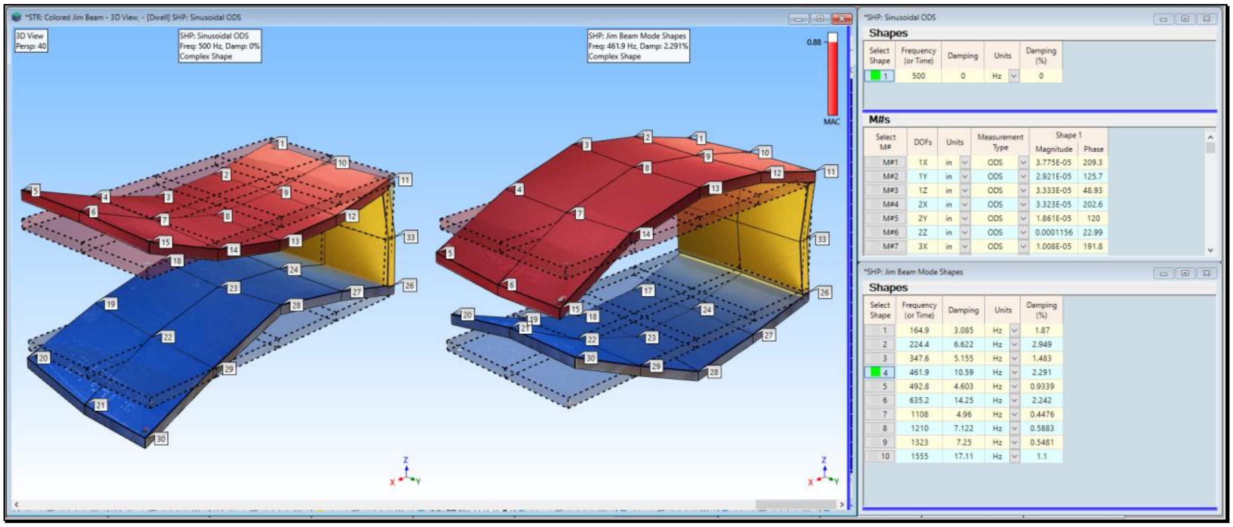
4) Use the **Residue mode shapes** to synthesize **multi-reference FRFs** between **99 Roving DOFs** and **Reference DOFs 5Z** & **DOF 15Z**.

STEP 4 - SINUSOIDAL ODS FROM IN-PHASE FORCES USING FRFs

- ***Press* Hotkey 4 Sinusoidal ODS from In-Phase Forces using FRFs**

When **Hotkey 4 is *pressed***, the single-reference **FRFs** are curve fit and the resulting **Residue mode shapes** are converted to **UMM mode shapes**. Then **multi-reference FRFs** are synthesized from the **UMM mode shapes**, and the sinusoidal **ODS** is calculated using two **500 Hz In-Phase** forces by executing the **Transform | Sinusoidal ODS** command in Data Block **BLK: Multi-Ref FRFs 5Z 15Z**.

The **500 Hz ODS** is displayed in animation side-by-side with its ***closest matching*** mode shape, as shown below.



*Sinusoidal **ODS** from **In-Phase 500 Hz** Forces*

MAC ➔ 0.88 between the **500 Hz sinusoidal ODS** and the **462 Hz** mode shape.

The **462 Hz** mode shape is **38 Hz less than the excitation frequency** but it is excited by the **In-Phase** sinusoidal forces and **dominates the 500 Hz** response.

- ***Press Select* Shape 5** to display the **493 Hz** mode shape

MAC ➔ 0.07 between the **500 Hz ODS** and the **493 Hz** mode shape.

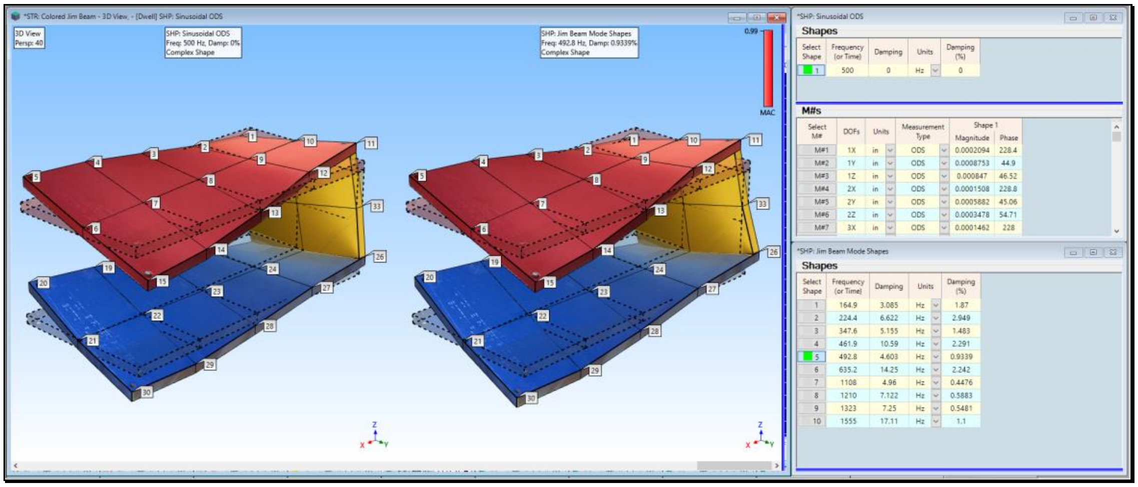
MAC ➔ *less than* 0.9 indicates that the **493 Hz** mode shape **is not strongly excited by the 500 Hz forces** even though it is **only 7 Hz less than the excitation frequency**.

STEP 5 - SINUSOIDAL ODS FROM OUT-OF-PHASE FORCES USING FRFs

- ***Press* Hotkey 5 Sinusoidal ODS from Out-of-Phase Forces using FRFs**

When **Hotkey 5 is *pressed***, the single-reference **FRFs** are curve fit and the resulting **Residue mode shapes** are converted to **UMM mode shapes**. Then **multi-reference FRFs** are synthesized using the **UMM mode shapes**. Then a **sinusoidal ODS** is calculated using two **500 Hz out-of-phase** forces by executing the **Transform | Sinusoidal ODS** command in Data Block **BLK: Multi-Ref FRFs 5Z 15Z**.

Then the **500 Hz ODS** is displayed in animation side-by-side with the ***closest matching*** mode shape, as shown below.



*Sinusoidal **ODS** from Out-of-Phase 500 Hz Forces*

MAC ➔ 0.99 between the **500 Hz sinusoidal ODS** and the **493 Hz mode shape**.

Because of its mode shape components at **DOFs 5Z & 15Z**, the **493 Hz** mode **is easily excited by the out-of-phase forces** and **dominates** the **500 Hz sinusoidal ODS**.

- ***Press Select* Shape 4** to display the **462 Hz** mode shape

No other mode shape participates in the Out-of-Phase 500 Hz response of the Jim Beam.

SINUSOIDAL ODS USING MODE SHAPES

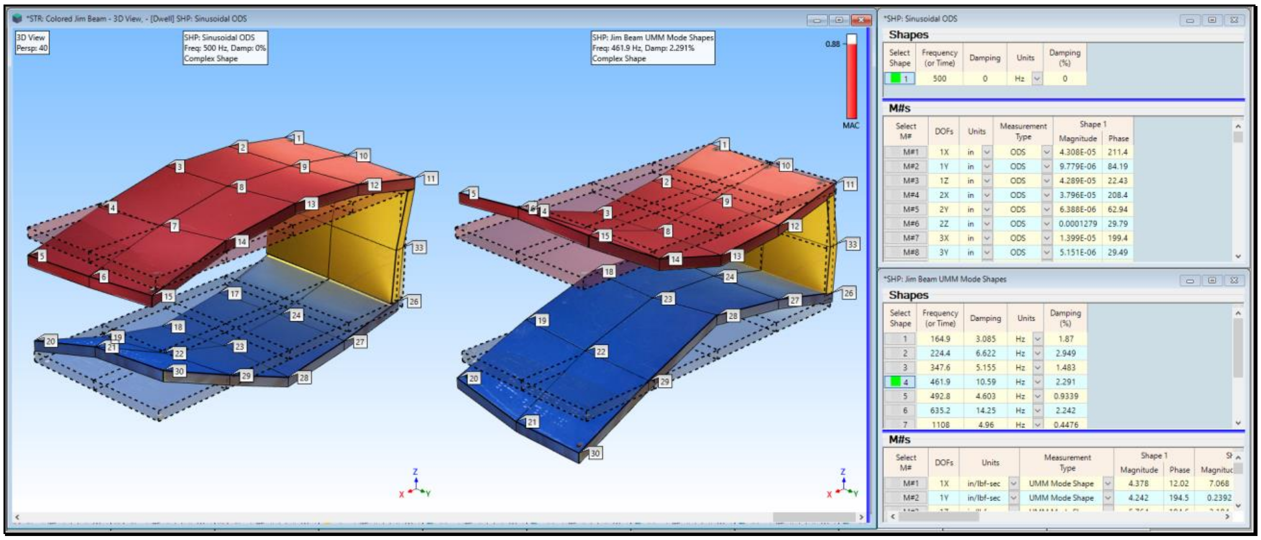
In Steps 6 & 7, the **Tools | Sinusoidal ODS** command is executed from **SHP: Jim Beam UMM Mode Shapes.** This command synthesizes **multi-reference FRF values at a single frequency**, and calculates the **sinusoidal ODS** caused the two forces at **DOFs 5 Z & 15Z**.

STEP 6 - SINUSOIDAL ODS FROM IN-PHASE FORCES USING MODE SHAPES

- ***Press* Hotkey 6 Sinusoidal ODS from In-Phase Forces using Mode Shapes**

When **Hotkey 6 is *pressed***, a **sinusoidal ODS** is calculated by executing the **Tools | Sinusoidal ODS** command in **SHP: Jim Beam UMM Mode Shapes** using **two 500 Hz In-Phase** forces.

Then the **500 Hz sinusoidal ODS** is displayed in animation side-by-side with the ***closest matching*** mode shape, as shown below.



*Sinusoidal **ODS** from **In-Phase** 500 Hz Forces.*

MAC ➔ 0.88 between the **500 Hz sinusoidal ODS** and the **462 Hz** mode shape.

The **462 Hz** mode shape is **38 Hz less than the excitation frequency** but is excited by the In-Phase sinusoidal forces and **dominates** the **500 Hz sinusoidal ODS**.

- ***Press Select* Shape 5** to display the **493 Hz** mode shape

MAC ➔ 0.05 between the **500 Hz sinusoidal ODS** and the **493 Hz** mode shape.

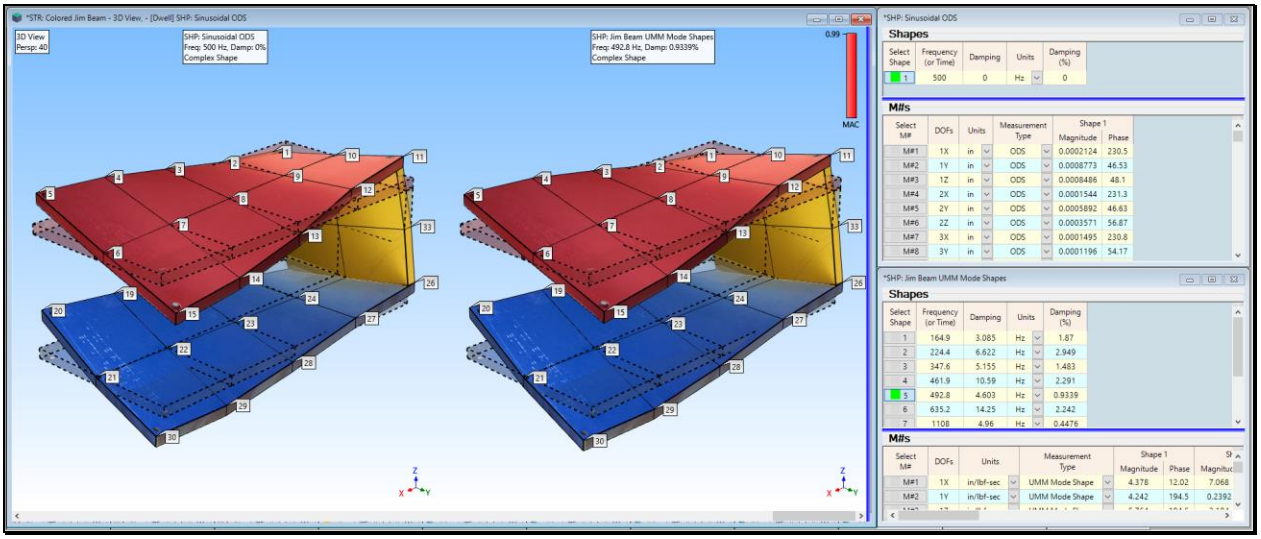
MAC ➔ *less than* 0.9 indicates that the **493 Hz** mode **is not strongly excited by the 500 Hz forces** even though it is **only 7 Hz less than the excitation frequency**.

STEP 7 - SINUSOIDAL ODS FROM OUT-OF-PHASE FORCES USING MODE SHAPES

- ***Press* Hotkey 7 Sinusoidal ODS from Out-of-Phase Forces using Mode Shapes**

When **Hotkey 7 is *pressed***, a **sinusoidal ODS** is calculated by executing the **Tools | Sinusoidal ODS** command in **SHP: Jim Beam UMM Mode Shapes** using **two 500 Hz In-Phase** forces.

Then the **500 Hz sinusoidal ODS** is displayed in animation side-by-side with the ***closest matching*** mode shape, as shown below.



Sinusoidal ***ODS*** *from Out-of-Phase 500 Hz Forces*

MAC ➔ 0.99 between the **500 Hz sinusoidal ODS** and the **493 Hz** mode shape.

Because of its mode shape components at **DOFs 5Z & 15Z**, the **493 Hz** mode is **easily excited by the out-of-phase forces** and **dominates** the **500 Hz sinusoidal ODS**.

- ***Press Select* Shape 4** to display the **462 Hz** mode shape

No other mode shape participates in the Out-of-Phase 500 Hz response of the Jim Beam.

STEP 8 - REVIEW STEPS

To review the steps of this App Note,

- ***Press* Hotkey 8 Review Steps**