MEscope Application Note 45

Finite Element Analysis (FEA) Mode Shapes

The steps in this Application Note can be carried out using any MEscope package that includes the **VES-8000 Finite Element Analysis** option. Without this option, you can still carry out the steps in this App Note using the **AppNote45** project file. These steps might also require MEscope software with a ***more recent release date***.

APP NOTE 45 PROJECT FILE

- To retrieve the Project for this App Note, **click here** to download **AppNote45.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

FINITE ELEMENT ANALYSIS (FEA))

In MEscope, the **FEA** option is used to create an **FEA** model from the *same* **3D** structure model that is used for displaying experimental ODS's and mode shapes in animation. In this App Note, a finite element model will be constructed by adding plate elements to a **3D** model of the Jim Beam test article. The **FEA** model will then be solved for its analytical **FEA** mode shapes, and they will be compared with **EMA** mode shapes of the Jim Beam.

FEA MODE SHAPES PRIOR TO A MODAL TEST

Prior to performing an Experimental Modal Analysis (**EMA**), building a finite element model, and solving for its **FEA** mode shapes provides the following information to assist you in setting up the modal test,

The ***approximate modal frequencies*** to excite during a test

The ***number*** & ***density*** of modes in a certain frequency range

The ***dominant direction of motion*** of each mode shape

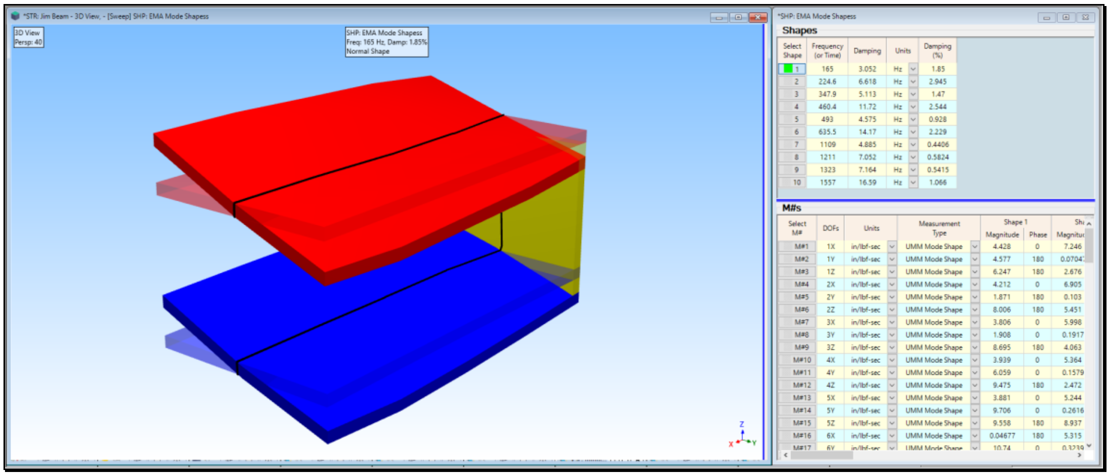
STEP 1 - SPATIAL ALIASING OF A MODE SHAPE

- ***Press*** **Hotkey 1 Z-Direction Mode Shapes**

Each three-dimensional **EMA** mode shape of the Jim Beam is displayed in animation.

- ***Press*** **Hotkey 1 Z-Direction Mode Shapes** ***again***

Each **EMA** mode shape is displayed in animation ***only in the Z-direction***.



165 Hz ***EMA*** *Mode Shape with Deflection Only in the Z-Direction.*

Each time you ***press*** **Hotkey 1**, the mode shapes are deflected either in three directions (X, Y, Z), or only in the vertical (Z-direction).

When **only the Z-direction** is displayed, the **165 Hz** mode shape **looks like a rigid body mode shape** of the beam.

It is **very unusual** for any structure with **free-free boundary conditions** to have a **rigid-body mode shape at 165 Hz**

If experimental data were only acquired from the Jim Beam in the Z-direction, **an apparent rigid-body mode shape** would have been extracted from the data. Clearly, the X & Y directions are needed to correctly determine the **dominant direction of motion** of this mode shape.

Spatial aliasing occurs when a test article has not been spatially sampled in enough Points & directions (degrees-of-freedom or **DOFs**) to adequately define the dominant motion of each mode shape

If experimental data is **not acquired in all three directions** at each Pont, it is **possible that spatial aliasing will occur**.

An **FEA** model of the test article can provide a set of **3D** mode shapes **before a modal test is conducted**. This is helpful for choosing sufficient excitation & response **DOFs** on the test article so that the **dominant direction of motion of each mode shape** is captured in the **EMA** mode shapes.

By observing **FEA** mode shapes in animation prior to a modal test, **spatial aliasing can be avoided**.

CREATING AN FEA MODEL

The actual Jim Beam structure was constructed from three 3/8-inch-thick aluminum plates which were fastened together with cap screws. The dimensions of the Jim Beam are **12 in. long** by **6 in. wide** by **4.5 in. high**.

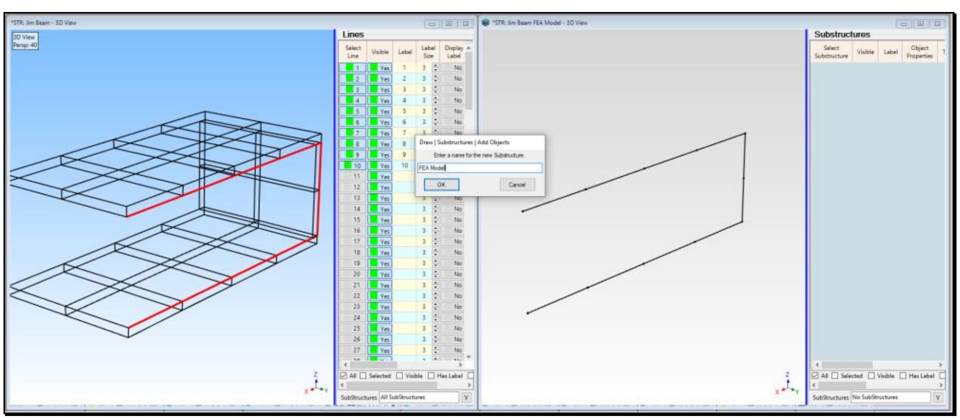
The following steps are carried out to create an **FEA** model from the experimental model in **STR: Colored Jim Beam**.

1. Create a **2D profile** Substructure from the **3D** Jim Beam experimental model
2. **Extrude** the profile into a **3D surface model** containing **Surface Quad** Objects
3. Use the **FEA Assistant** to create an **FEA** model by adding an **FEA Quad** element wherever there is a **Surface Quad**
4. **Mesh** the **FEA** model to **create more FEA Quad**s
5. Solve for the analytical **FEA** mode shapes of the **FEA** model

STEP 2- CREATING A 2D PROFILE

- ***Press* Hotkey 2 Create a 2D Profile**

Ten Lines are selected on one edge of the Jim Beam, and those Lines are copied into another Structure window **STR: FEA Model**, shown ***on the right below***.



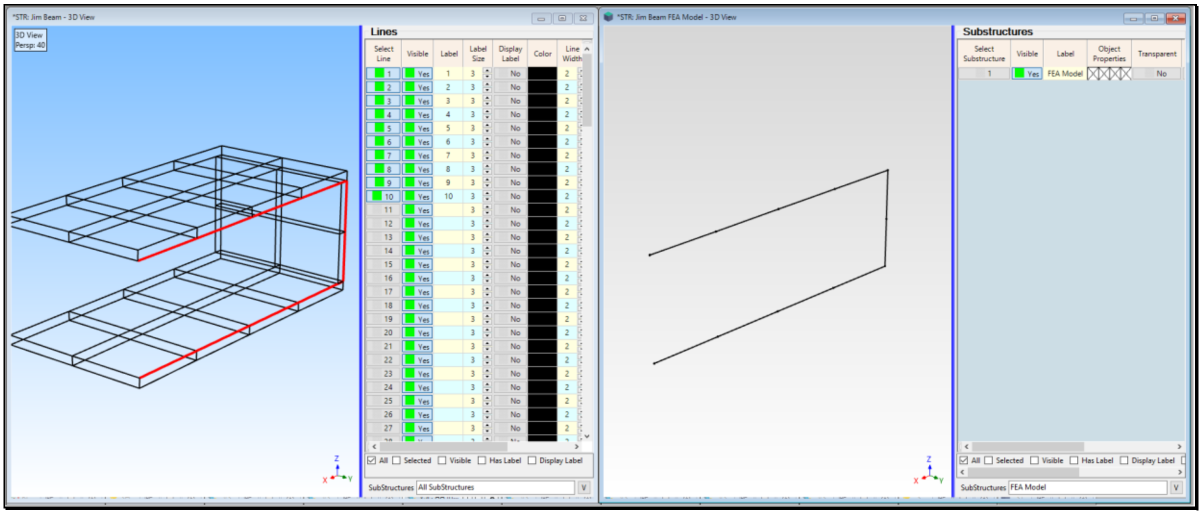
***2D** FEA Model Profile from the Selected Lines.*

DEFINING THE 2D PROFILE AS A SUBSTRUCTURE

To extrude a **2D Substructure** into a **3D FEA** model, the 10 Lines in **STR: FEA Model** ***must be defined*** as a Sub-structure.

- ***Click*** on **New Substructure** in the dialog box that opens
- Enter a name **"FEA Model"** into the next dialog box that opens

The ***selected*** Substructure **FEA Model** is displayed as shown below

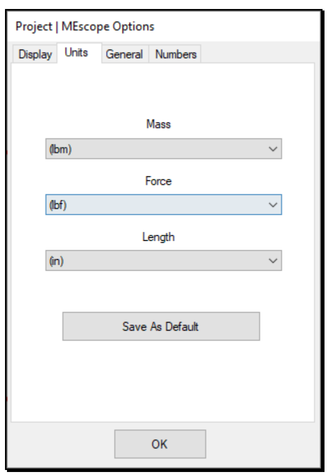


*Selected **2D** Profile Substructure.*

CHANGING ENGINEERING UNITS

The **2D** Substructure will be scaled to **English** units, but it can be re-scaled to different engineering units if desired. To change the engineering units,

- Execute **Project | MEscope Options** in the MEscope window
- On the **Units** tab, select the desired **Mass, Force, & Length** units, as shown below



STEP 3 - SCALING & EXTRUDING THE 2D PROFILE OF THE JIM BEAM

- ***Press* Hotkey 3 Extrude the 2D Profile into a 3D Model**

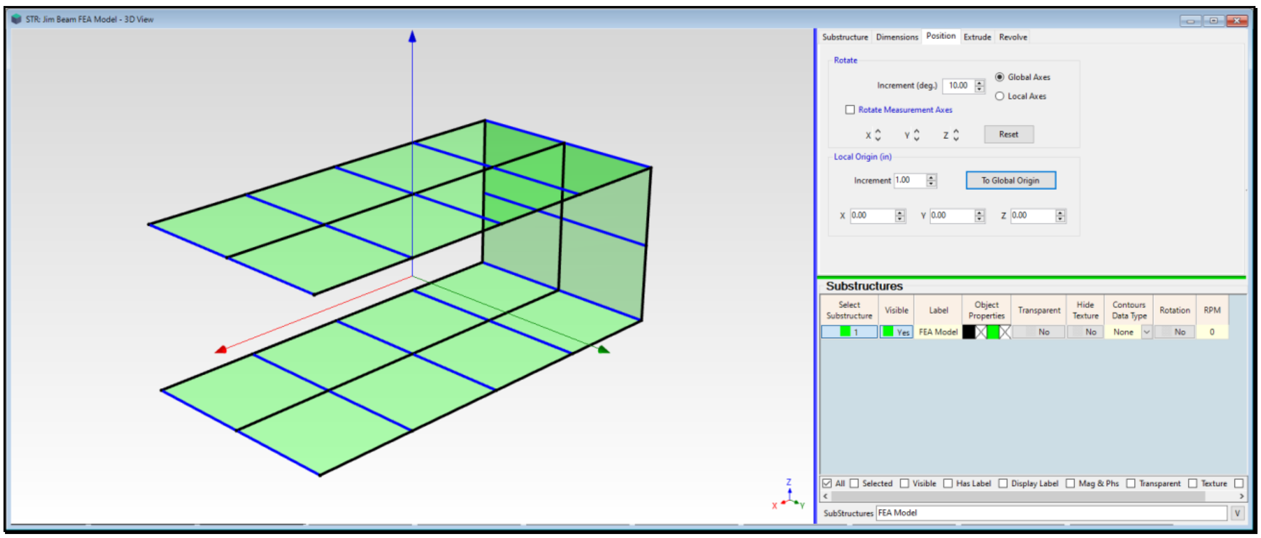
When **Hotkey 3 is *pressed***, the **Drawing Assistant** tabs are displayed in **STR: FEA Model**. First, the **2D** Profile will be scaled to match the actual size of the test article before extruding it into a **3D** surface model.

- On the **Dimensions** tab, ***un-check*** **Lock Aspect Ratio**, and enter the following dimensions

X ➔ 12.0 (in), Y ➔ 0.0 (in), Z ➔ 4.5 (in)

EXTRUDING THE 2D PROFILE OF THE JIM BEAM

- On the **Extrude** tab, ***select*** **Y** as the **Extrude Axis**
- Enter **Length ➔ 6 (in), Points ➔ 3**
- ***Click*** on the **Extrude** button
- On the **Position** tab, ***press*** the **To Global Origin** button to center the **3D** Extruded Substructure about the global origin, as shown below



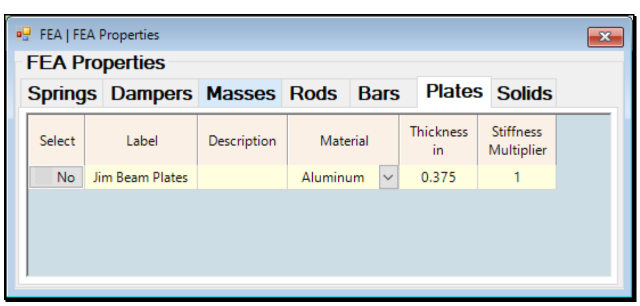
*Extruded **3D** Surface Model.*

ADDING FEA QUADS TO THE MODEL

An **FEA Quad** plate element is added to a **3D** model **wherever there is a visible Surface Quad**.

- Execute **FEA | FEA Assistant** in the **STR: FEA Model** window to display the **FEA Assistant** tabs
- ***Click*** on the **Add FEA Objects** tab
- ***Press*** the **New** button next to the **Plates** button

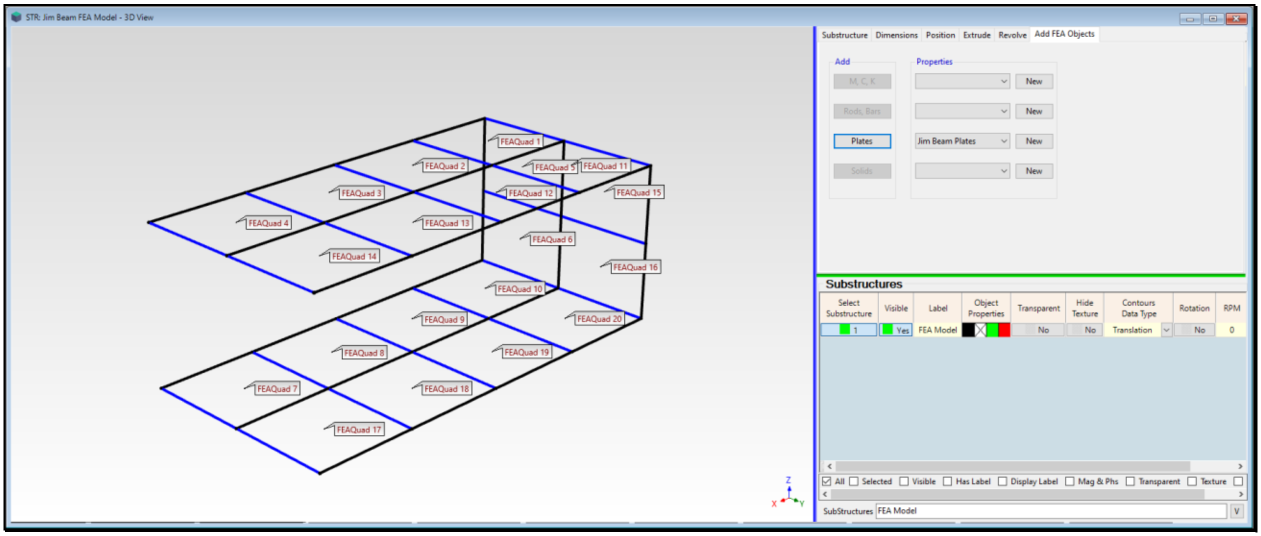
The **FEA | FEA Properties** box will open. **Jim Beam Plates** has already been added to the **Plates** spreadsheet in the **FEA | FEA Properties** box.



With the **FEA | FEA Assistant** tabs still displayed,

- ***Press*** the **Plates** button on the **Add FEA Objects** tab.

Twenty FEA Quads are added to the **3D** model as shown below.



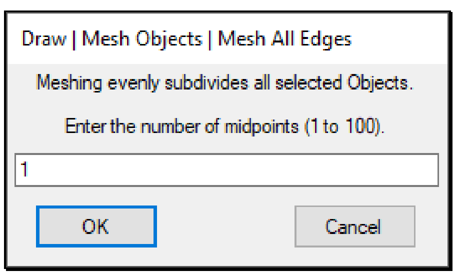
20 ***FEA Quads*** *Attached to the* ***3D*** *Model*

STEP 4 - MESHING THE FEA MODEL

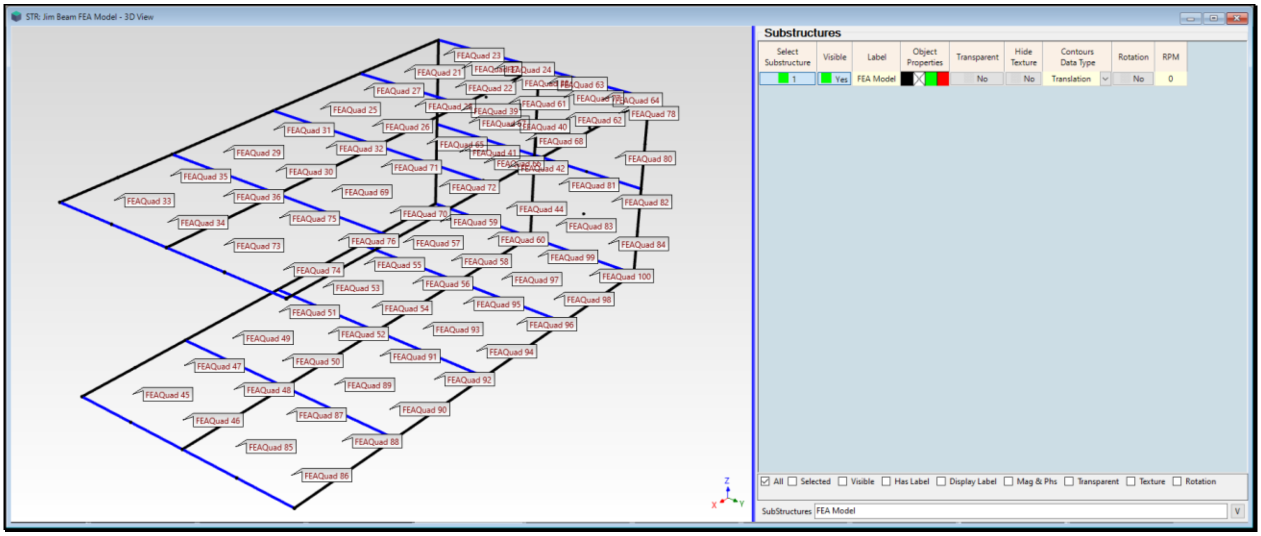
With the **FEA Quads** attached to it, the **3D** model in the **STR: FEA Model** window **is now an FEA model**.

To improve the accuracy of the **FEA** mode shapes, the **FEA** model will be meshed to create more **FEA Quads**. During the meshing operation, each **FEA Quad** will be replaced with four new **FEA Quad**s, therefore creating a total of **80 FEA Quad**s on the **FEA** model.

- **Press Hotkey 4 Mesh the FEA Model**
- ***Enter*** **"1"** in the dialog box as shown below



The structure model will now contain **80 FEA Quad**s, as shown below.



*FEA Model with 80 **FEA Quads**.*

STEP 5 - NUMBERING POINTS ON THE FEA MODEL

- ***Press* Hotkey 5 Number the FEA Points**

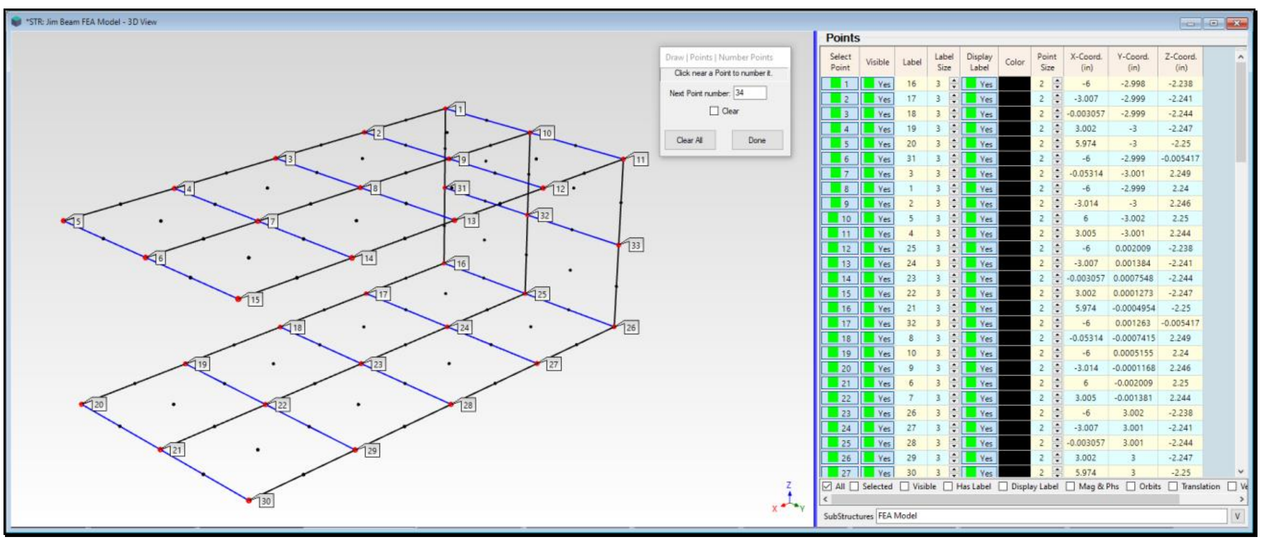
To compare the **FEA** & **EMA** mode shapes using the **Modal Assurance Criterion (MAC)**, each Point on the **FEA** model that coincides with a test Point on the Jim Beam **must have the same Point number**.

When **Hotkey 5 is *pressed***, the **Draw | Points | Number Points** dialog box will open in the graphics area, as shown below

- ***Press*** the **Clear All** button to clear all the existing Point labels
- ***Click near each* of the 33 Points** to number it as shown below

When all 33 Points are numbered as shown below,

- Pr***ess*** the **Done** button



*Point Numbering on the **FEA** Model.*

STEP 6 - SOLVING FOR THE FEA MODE SHAPES

The **FEA** Model is now ready to be solved for its **FEA** mode shapes.

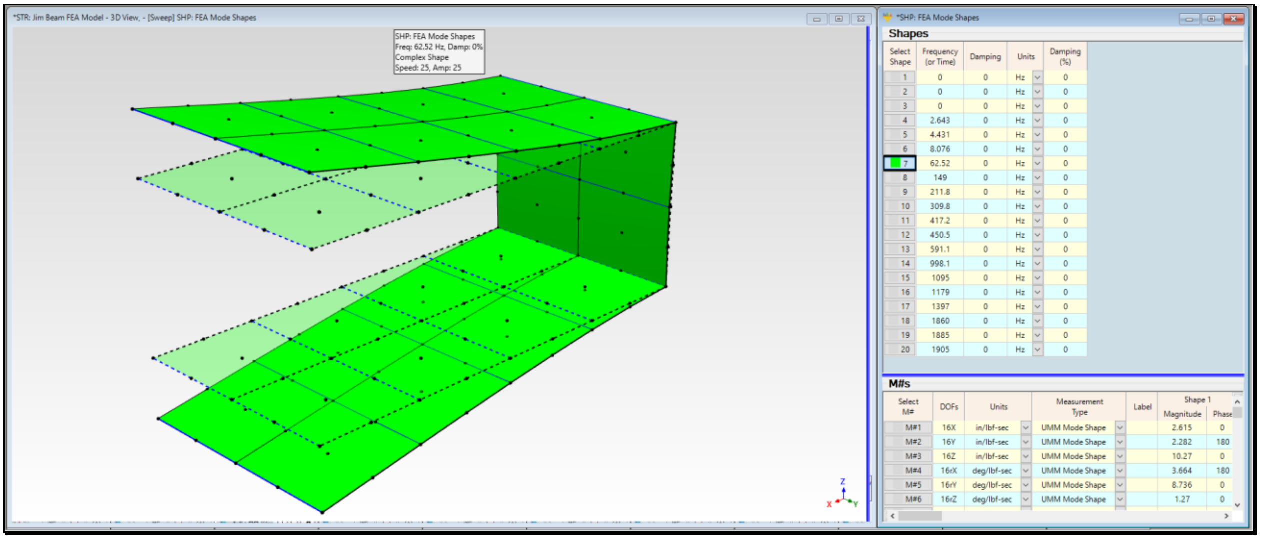
- ***Press* Hotkey 6 FEA Mode Shapes**

The **FEA** model has **105 Points** (or nodes). **FEA** mode shapes were calculated with **six DOFs per Point** (**3 translational** & **3 rotational DOFs**).

Each mode shape has a total of **630 DOFs**.

The first six **FEA** modes are **rigid-body mode shapes** of the structure, with frequencies **at or near "0" Hz**.

The first **flexible-body mode shape** is at **62 Hz.**



*Sweep Animation of **FEA** Mode Shapes.*

STEP 7 - COMPARING FEA AND EMA MODE SHAPES

- ***Press* Hotkey 7 Compare FEA & EMA Mode Shapes**

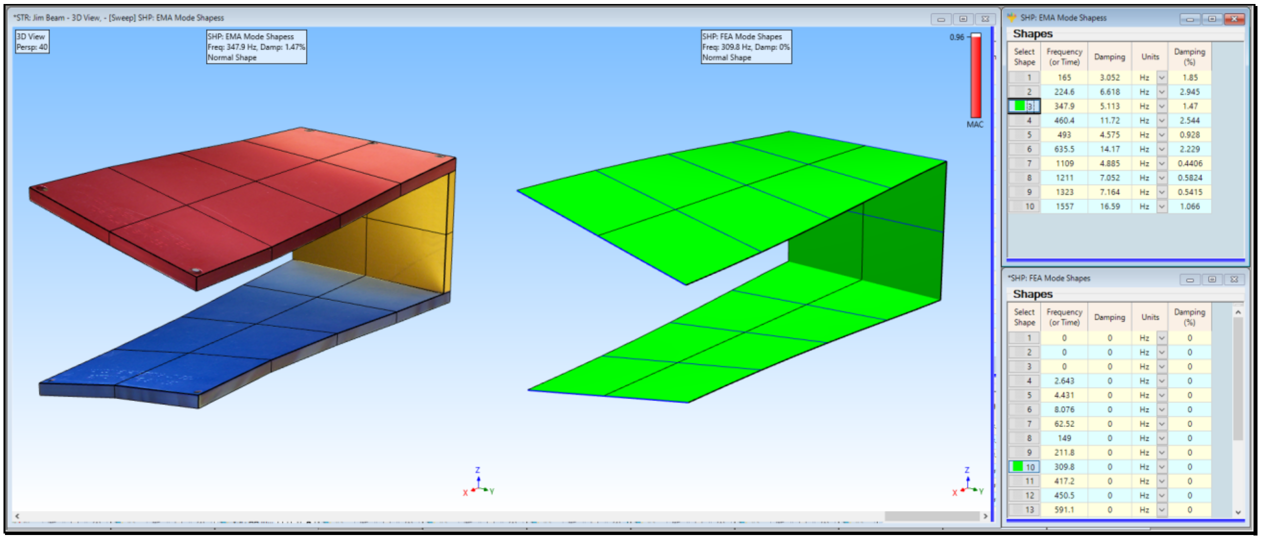
There are two ways to compare mode shapes

1. **Graphically** using the **Animate | Animate a Pair** command
2. **Numerically** by calculating **MAC** for each pair of **FEA** & **EMA** mode shapes

When **Hotkey 7 is *pressed***, closest matching pairs **EMA** & **FEA** mode shape are displayed together in sweep animation. An **EMA** mode shapes is displayed ***on the left*** and its ***closest matching*** **FEA** mode shape ***on the right***.

As the animation sweeps through each of the **EMA** mode shapes, the **FEA** mode shape that is ***closely matched*** (has the **maximum MAC** value) with the **EMA** mode shape is also displayed.

If two shapes have a **MAC** ➔ ***greater than* 0.90**, their modal frequencies might be different but their mode shapes are ***closely matching*** at the **33 Points** where they have common **DOFs**.



*Comparison of **FEA** & **EMA** Mode Shapes with Maximum MAC*

MAC VALUES

The **Modal Assurance Criterion (MAC)** is a numerical comparison between a pair of mode shapes.

- **MAC ➔ 1.0 ➔** two shapes are ***co-linear*** (their values lie on the ***same straight line***)
- **MAC ➔ *greater than* 0.90 ➔** two mode shapes are ***similar***
- **MAC ➔ *less than* 0.90 ➔** two mode shapes are ***different***

MATCHING DOFS

MAC values are **calculated for a pair of mode shapes** by using **only those shape components with matching DOFs**.

Each **EMA** mode shape of the Jim Beam has **99 Translational DOFs**. Each mode shape is defined in **three directions** (**X, Y, Z**) at **33** Points.

Each **FEA** mode shape of the Jim Beam has **630 DOFs**, **315 translational DOFs** & **315 rotational DOFs**.

The **translational DOFs** of each **FEA** mode shape are defined in the **same three directions (X, Y, Z) at the same 33 Points** as each **EMA** mode shape.

Those **translational shape components** with **matching DOFs** are used to calculate **MAC** for a pair of **FEA** & **EMA** mode shapes.

SHAPE NORMALIZATION

The **FEA** mode shapes have real valued components.

Then FEA mode shapes only have **real valued** components, and are called **normal mode shapes**.

The **EMA** mode shapes have **complex valued** components (with **magnitude & phase**) and are called **complex mode shapes**.

To compare the **EMA** & **FEA** mode shape more closely, both during animation, and using MAC, the **EMA** mode shapes **have been normalized**.

When a complex shape is **normalized**, the **magnitude** of each shape component **remains unchanged**, but the **phase** is **changed to 0 or 180 degrees**.

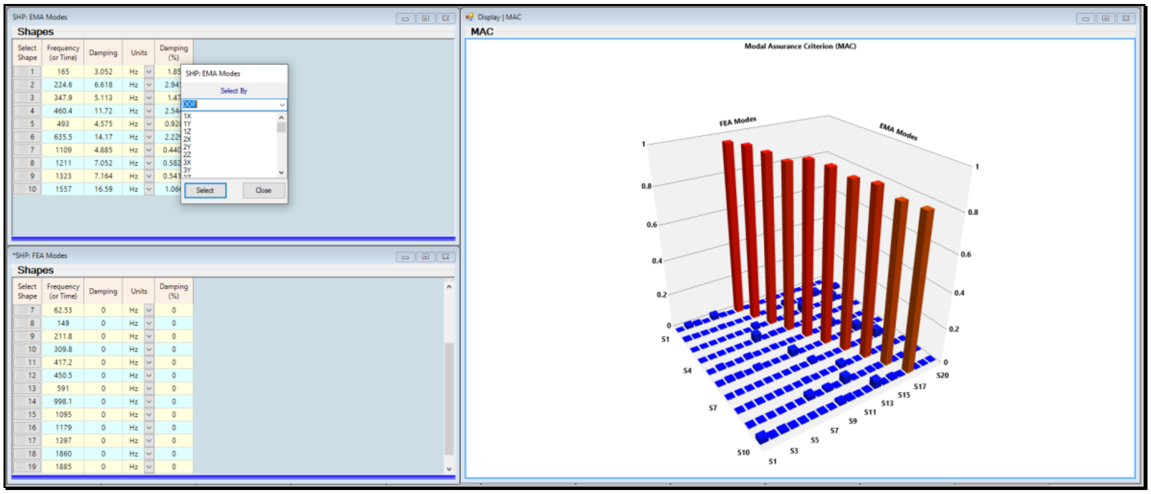
When **Animate | Normalize Shapes** is ***checked*** in the **STR: Jim Beam** window the **EMA** mode shapes are **normalized**.

STEP 8 - MAC BAR CHART

- ***Press* Hotkey 8 MAC Bar Chart**

When **Hotkey 8 is *pressed***, the **MAC** value for each each **EMA** mode shape in Shape Table **SHP: EMA Mode Shapes** is calculated for itself and each FEA mode shape in the Shape Table **SHP: FEA Mode Shapes**.

A Bar chart showing the MAC value between each **EMA** & **FEA** mode shape pair is displayed, as shown below.



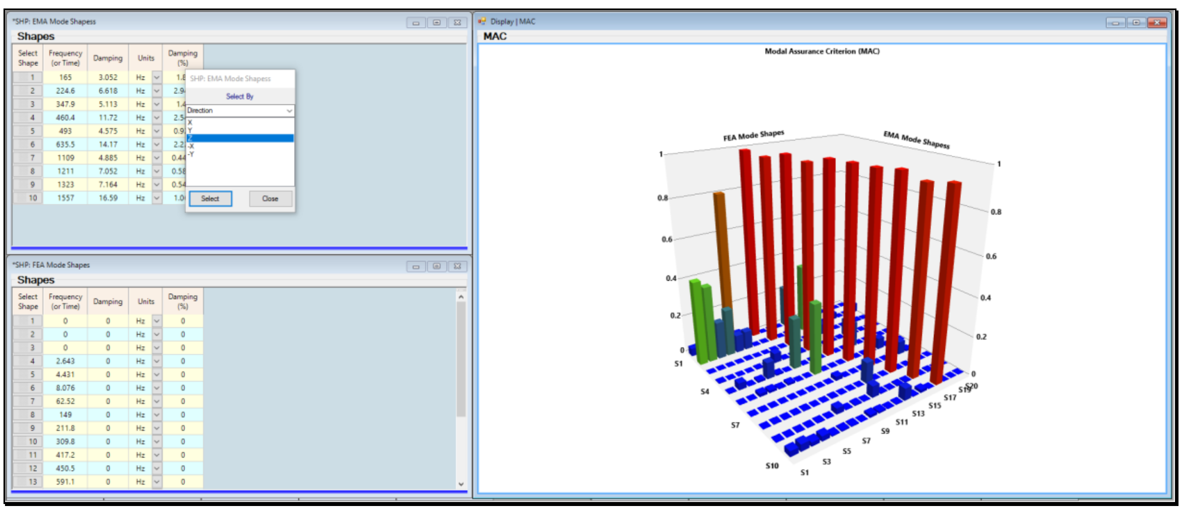
*MAC Plot of **EMA** & **FEA 3D** Mode Shape Pairs.*

Ten mode shape pairs have **MAC ➔ *greater than* 0.9**, meaning that **ten pairs of EMA & FEA mode shapes are *closely matched***.

MAC COMPARISON ONLY IN THE Z DIRECTION

Since most of the mode shapes have **dominant motion in the (vertical) Z direction**, it is useful to compare **MAC** values for the modes using only the **Z-direction DOFs**.

- ***Select* Direction** from the drop-down list in the dialog box as shown below
- ***Select* Z** in the list of directions
- ***Press* the Select button**



*MAC Plot for Z Direction **DOFs** Only*

The same ten mode shape pairs have **MAC ➔ *greater than* 0.9,** meaning that the FEA & EMA **flexible-body mode shape pairs are essentially the same in the Z direction**, at their 33 common Points.