

# VIBRANT MEscape Application Note 37

## Modal Sensitivity to Structural Stiffeners

The steps in this Application Note can be carried out using any MEscape package that includes the **VES-5000 SDM** and **VES-4000 Modal Analysis** options. Without these options, you can still carry out the steps in this App Note using the **AppNote37** project file. These steps might also require a *more recent release date* of MEscape.

### APP NOTE 37 PROJECT FILE

- To retrieve the Project for this App Note, [click here](#) to download **AppNote37.zip**

This Project file 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

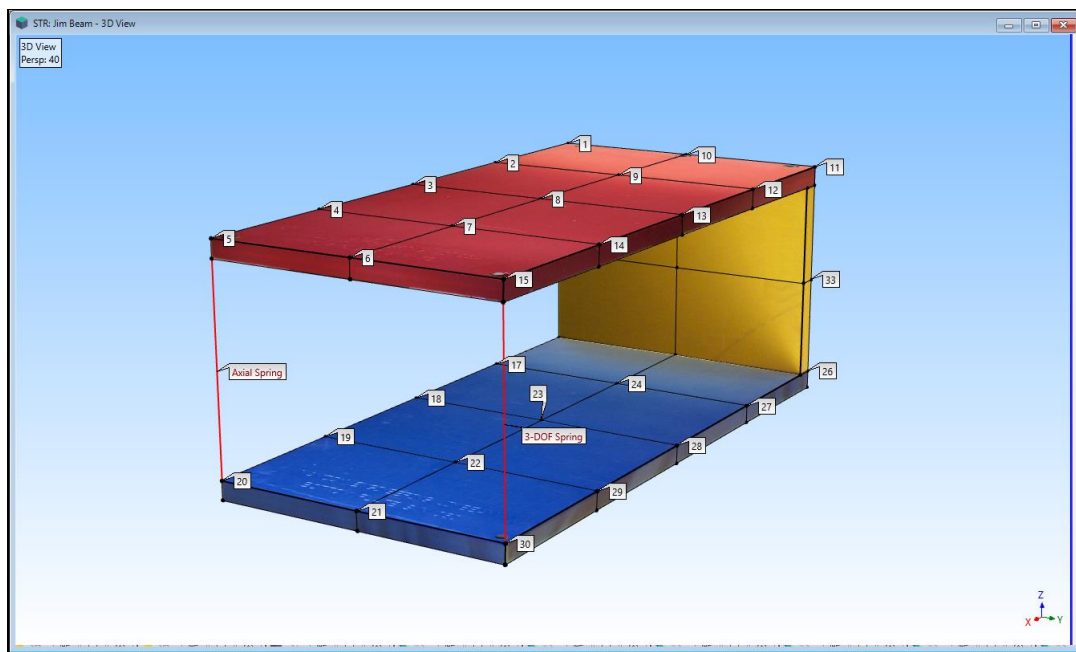
### MODAL SENSITIVITY

Because of its computational speed, **SDM** can be used to quickly solve for the modal parameters of *thousands of potential modifications* to a structure. The calculation and ordering of multiple **SDM** solutions from best to worst is called **Modal Sensitivity Analysis**.

In **Modal Sensitivity Analysis**, multiple **SDM** solutions are calculated over a solution space of modification element properties, and the solutions are *ordered from best to worst* based on how closely the **Solution frequency & damping** of each selected Shape Pair match the **Target frequency & damping**.

When **SDM** is used for Modal Sensitivity or **FEA Model Updating** studies, *thousands of potential property changes* can be *quickly evaluated and sorted* from best to worst based on how close a Solution is to Target values.

In this App Note, we will examine *how much stiffness* is required in each of two different **FEA Springs**, attached between the top & bottom plates of the Jim Beam shown below, to move selected modes to new frequencies.



*Axial & 3-DOF Stiffener Between Top & Bottom Plates of the Jim Beam*

Modal Sensitivity Analysis uses **Structural Dynamics Modification (SDM)** to perform *an exhaustive search* over a *user-defined solution space* for the best solution. This guarantees that the optimal solution will always be found

To perform a Modal Sensitivity Analysis, the following items are required,

1. **FEA modification elements** attached between DOFs of a model of the unmodified structure
2. **Target modal parameters** (frequencies & damping) for the modified structure
3. A **solution space** of FEA element properties over which to search for the best solution

The **best solution** is a set of **FEA** properties that *minimizes the difference* between the modal parameters of the **modified structure** and **Target modal parameters**

The **FEA** Object properties found by the Modal Sensitivity Analysis can then be used to calculate new modes for the modified structure.

### STEP 1 - MODE SHAPES OF THE UNMODIFIED JIM BEAM

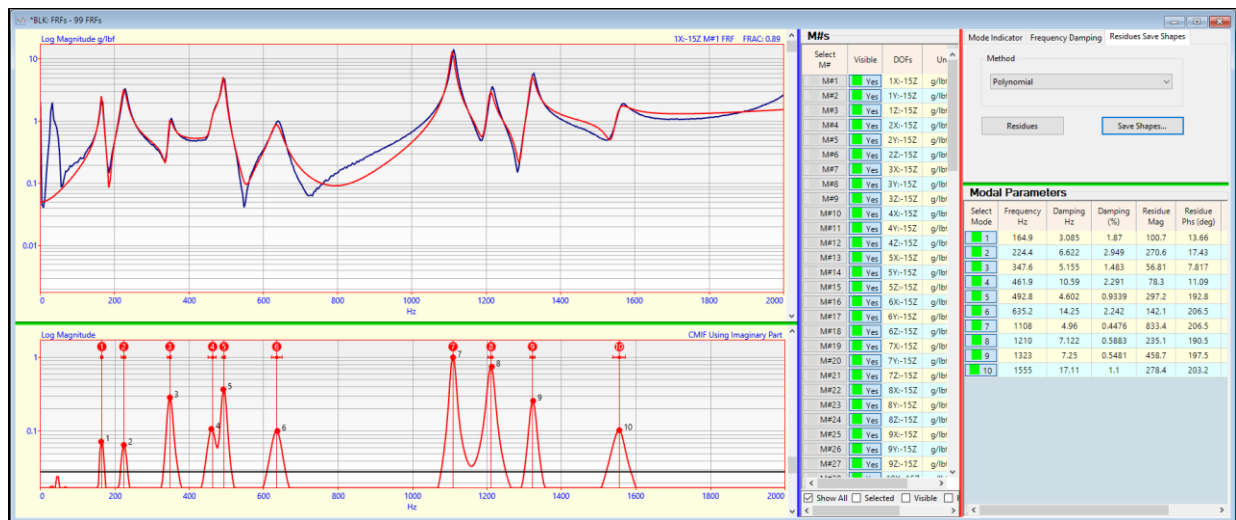
- **Press Hotkey 1 Jim Beam Mode Shapes**

When **Hotkey 1** is *pressed*, a **Modal Model** of the Jim Beam is created by first curve fitting a set of **FRFs** for the Jim Beam. Then a **Modal Model** of the Jim Beam is created which will be used for Modal Sensitivity Analysis.

### ROVING RESPONSE IMPACT TEST

The **FRFs** for the Jim Beam were calculated from force & response data acquired during a Roving Response Impact test of the Jim Beam. The beam was impacted at one corner of the top plate, at **DOF 15Z**. A tri-axial accelerometer was moved between impacts and attached to each of 33 labeled points on the top, bottom, & vertical plates of the Jim Beam structure. This provided 99 **FRFs** which are curve fit to estimate modal parameters.

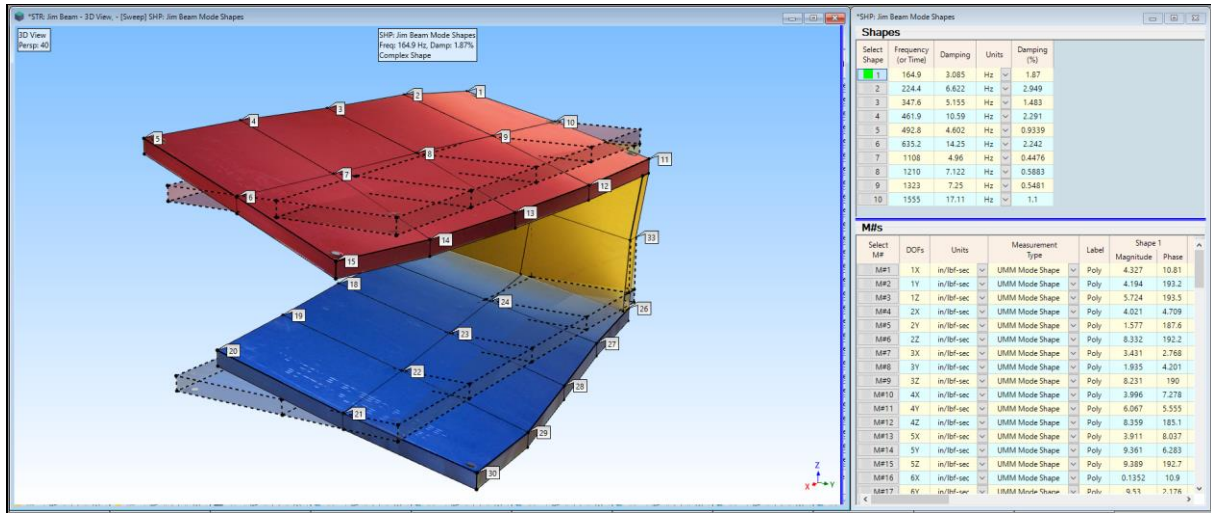
Mode shapes for *ten modes with 99 DOFs* in each mode shape are obtained by a **Quick Fit** of the **FRFs**.



*Quick Fit of the Jim Beam FRFs.*

After the **FRFs** are curve fit and the mode shapes are scaled to **UMM mode shapes**, the mode shapes of the Jim Beam are displayed using sweep animation through the shapes in a Shape Table *on the right-hand side* as shown below.

When mode shapes are scaled to **UMM** mode shapes, they are called a **Modal Model** because they preserve the dynamic properties of the structure, and can therefore be used by **SDM** to calculate the effects of structural modifications.



Deflection of the 165 Hz Mode Shape

- Press **Select Shape** in the Shape Table *on the right-hand side* to display its mode shape

From the animated display of each mode shape it is apparent that the *dominant motion* of all mode shapes is in the **vertical Z-direction**, *except for the 165 Hz mode shape*.

The **165 Hz** mode shape is a *twisting* of the **vertical back plate**, so the *dominant motion* of the top & bottom plates is *in the horizontal plane*.

## STEP 2 - MODES CREATED BY THE STIFF AXIAL SPRING

- Press **Hotkey 2 Modes Created by the Stiff Axial Spring**

When **Hotkey 2** is *pressed*, **SDM** is used to calculate the new modes of the Jim Beam with the *stiff Axial Spring* attached between **Point 5 on the top plate** and **Point 20 on the bottom plate**.

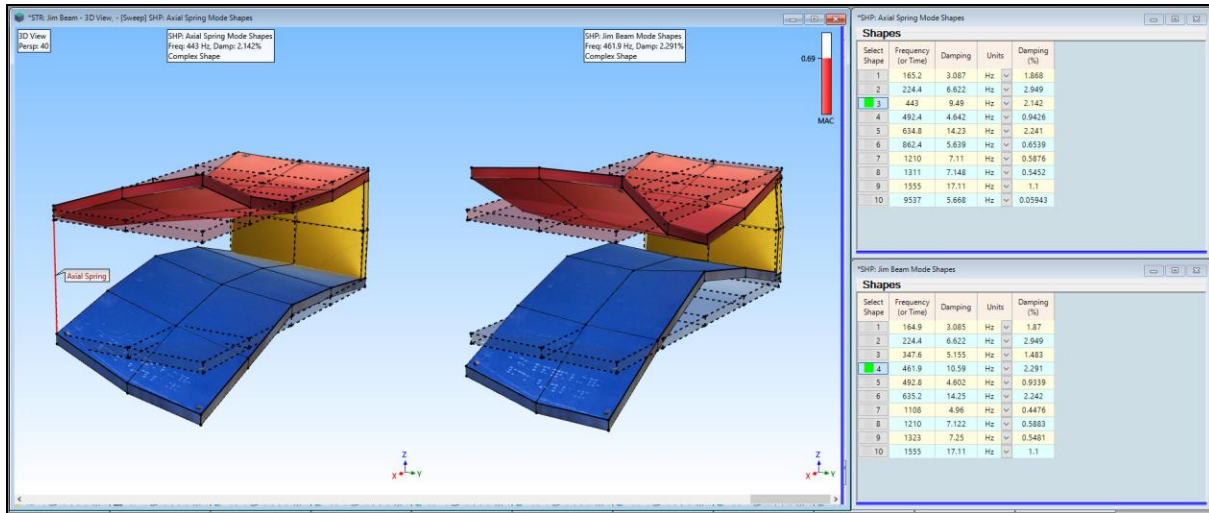
An **Axial Spring** only applies stiffness to a structure *in the direction of its own axis*.

After the new mode shapes are calculated, sweep animation will display each mode shape from the **SHP: SDM Mode Shapes** Shape Table using *several cycles of sine dwell animation*. Each new mode shape is displayed side-by-side with its *closest-matching* mode shape from the *unmodified* Jim Beam.

Each new mode shape of the *modified* Jim Beam that has a **Maximum MAC** value with a mode shape from the *unmodified* Jim Beam is its *closest-matching* mode shape.

The mode shapes of **Shape 1 & Shape 2** in both Shape Tables have a **MAC** → **1.00**. The Axial Spring did not influence these two modes because there is *no relative motion* of these two mode shapes in the axial direction of the spring.

- Click on **Shape 3 (443 Hz)** in **SHP: Axial Spring Mode Shapes**



New Mode Shape at 443 Hz.

This *new mode shape* clearly shows the effect of the Axial Spring. The *unmodified structure* had modes at 348 & 462 Hz, both of which no longer exist in the modified structure.

**MAC → 0.69** between the new mode shape at 443 Hz and the *closest matching* mode shape of the *unmodified structure* at 462 Hz indicates that the 443 Hz mode is a new mode shape.

Two new mode shapes (at 443 Hz & 826 Hz) were created by attachment of the **stiff Axial Spring**.

None of the other modes between 165 Hz & 1555 Hz were affected by this stiffener.

### SDM AND THE LAW OF MODAL ANALYSIS

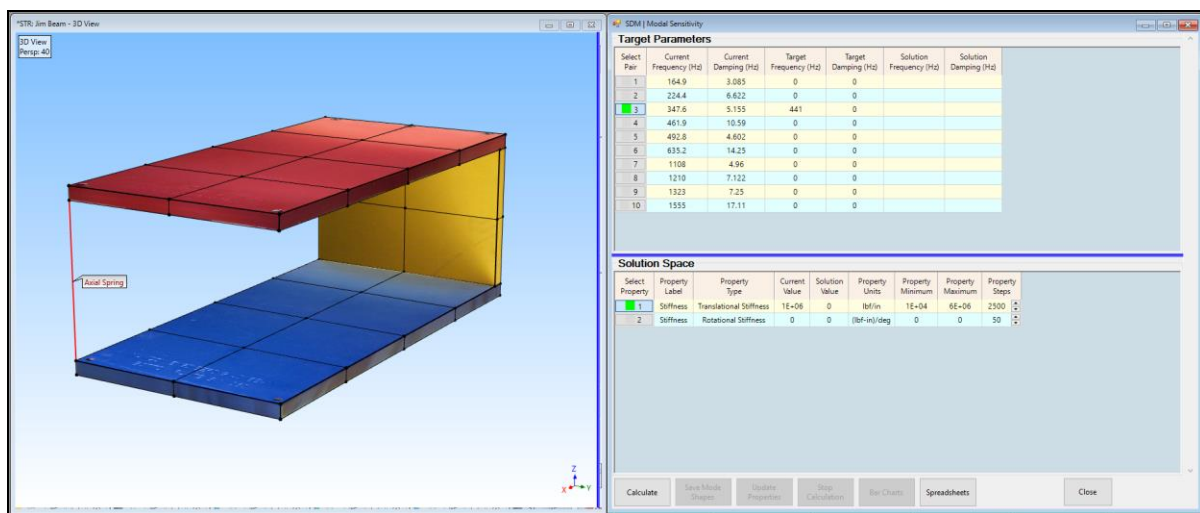
SDM created two new mode shapes from a *weighted summation* of the mode shapes of the *unmodified Jim Beam*. SDM utilizes a fundamental **Law of Modal Analysis**,

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

### STEP 3 - MODAL SENSITIVITY TO THE AXIAL SPRING

- Press Hotkey 3 Modal Sensitivity to the Axial Spring

The STR window and the Modal Sensitivity window will open side-by-side as shown below.



Modal Sensitivity Window for the Axial Spring.

## UPPER SPREADSHEET

The Modal Sensitivity window contains two spreadsheets and a row of buttons at the bottom. The *upper* spreadsheet is used to choose the **Target Frequency & Target Damping**, and to select the **Shape Pairs** to be used for ordering Solutions from best to worst.

- *Depress* the **Select Pair 3** button
- Enter a **Target Frequency** of **441 Hz** in the row of **Shape Pair 3**

The **Solution & Target Frequency** for **Shape Pair 3** will be used to calculate an **Error function** for ordering the solutions.

## LOWER SPREADSHEET

The following numbers should be entered on the *lower* spreadsheet enter,

- *Depress* the **Select Property 1 Translational Stiffness** button
- Enter **Property Minimum** → **10000 lbf/in** for **Property 1**
- Enter **Property Maximum** → **6 E6 lbf/in** for **Property 1**
- Enter **Property Steps** → **2500** for **Property 1**

If you are using different engineering units, enter equivalent values.

Units are changed on the **Units** tab in the **File | MEscape Options** box.

- *Press* the **Calculate** button on the bottom of the Modal Sensitivity window

**2500** solutions will be calculated and ordered from *best to worst* according to how close the **Solution** modal frequency is to the **Target Frequency (441 Hz)**.

The screenshot shows the SDM | Modal Sensitivity window with two spreadsheets. The top spreadsheet, 'Target Parameters', lists 10 shape pairs with columns for Current Frequency, Current Damping, Target Frequency, Target Damping, Solution Frequency, and Solution Damping. Row 3 is highlighted in green and has a red box around it with the text 'Best Solution'. The bottom spreadsheet, 'Solution Space', lists properties with columns for Property Label, Property Type, Current Value, Solution Value, Property Units, Property Minimum, Property Maximum, and Property Steps. Row 1 is highlighted in green and has a red box around its Solution Value (1.719E+04) with the text 'Best Solution'. The bottom of the window contains buttons for Calculate, Save Mode Shapes, Update Properties, Stop Calculation, Bar Charts, Spreadsheets, and Close.

Select Pair	Current Frequency (Hz)	Current Damping (Hz)	Target Frequency (Hz)	Target Damping (Hz)	Solution Frequency (Hz)	Solution Damping (Hz)
1	164.9	3.085	0	0	165.2	3.086
2	224.4	6.622	0	0	224.4	6.622
3	347.6	5.155	441	0	441	9.272
4	461.9	10.59	0	0	492.4	4.651
5	492.8	4.602	0	0	634.6	14.19
6	635.2	14.25	0	0	749.8	6.207
7	1108	4.96	0	0	1210	7.097
8	1210	7.122	0	0	1300	6.88
9	1323	7.25	0	0	1553	11.85
10	1555	17.11	0	0	1558	10.89

Select Property	Property Label	Property Type	Current Value	Solution Value	Property Units	Property Minimum	Property Maximum	Property Steps
1	Stiffness	Translational Stiffness	1E+06	1.719E+04	lbf/in	1E+04	6E+06	2500
2	Stiffness	Rotational Stiffness	0	0	(lbf-in)/deg	0	0	50

*Best Solution for 441 Hz Target Frequency*

## SOLUTION SCROLL BAR

After the calculation has been completed, the **Solution Frequency** and **Solution Damping** are displayed in the *upper* spreadsheet, and a **scroll bar** is displayed on the *right-hand side* of the window. The solution **Stiffness** is displayed in the *lower* spreadsheet,

All of the solutions are displayed by scrolling the scroll bar.

The *best* solution is displayed when the scroll is *at the top* of the scroll bar

The *worst* solution is displayed when the scroll is *at the bottom* of the scroll bar

The best solution that created a third mode at **441 Hz** is *much less than* the stiffness (**1 E6**) that created the third mode at **443 Hz**.

As you scroll through the solutions, notice that many other solutions *near the top scroll bar position* are *close to the best solution*.

## BRICK WALL EFFECT

**Modal Sensitivity Analysis** is useful for determining how much stiffness can be applied to a structure to shift its modes to higher frequencies. The table below shows the *“brick wall effect”* of stiffening the Jim Beam with an Axial stiffener **between Point 5 & Point 20**.

From the Table below, it is apparent that *a large increase in the stiffness* of the Axial spring is required to move the third mode **from 441 Hz to 443 Hz**.

- To verify the Table values, enter any Target frequency in the Table below as the **Target Frequency** of the **Shape Pair 3** in the *upper* spreadsheet, and press the **Calculate** button again

Target Frequency (Hz)	Solution Frequency (Hz)	Solution Stiffness (lbf/in)
441.00	441.05	17191
441.25	441.30	19588
441.50	441.49	21985
441.75	441.77	26779
442.00	441.97	31573
442.25	442.26	43557
442.50	442.51	65130
442.75	442.75	129850
<b>443.00</b>	<b>442.99</b>	<b>597600</b>

An Axial Spring stiffness of **17191 lbf/in** is required to create a third mode at **441 Hz**

An Axial Spring stiffness of **597600 lbf/in** is required to create a third mode at **443 Hz**

To increase the third mode frequency **by 2 Hz**, *34 times more Axial stiffness is required*

## SAVING A SOLUTION

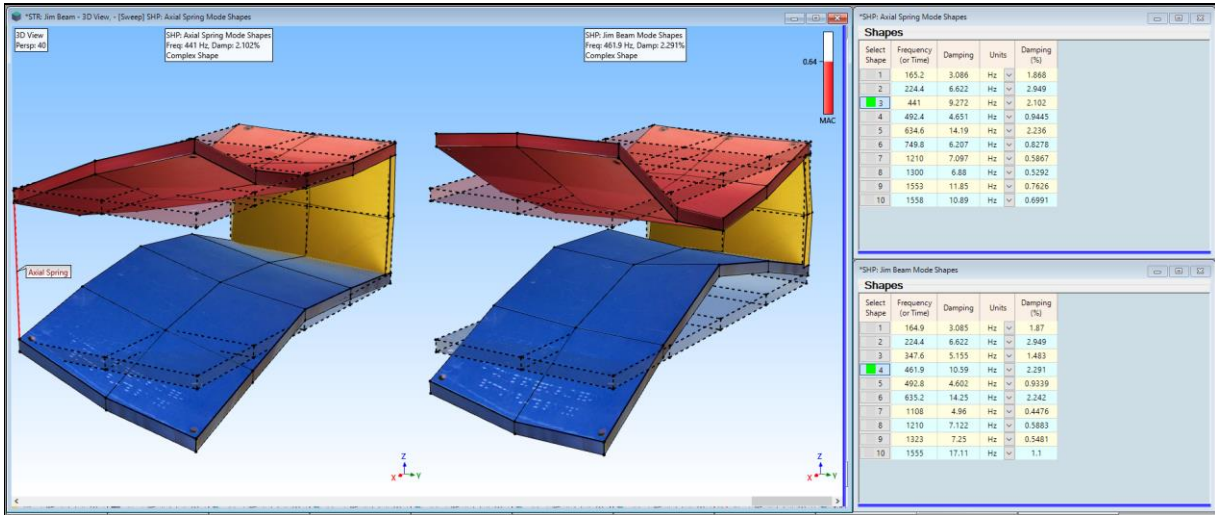
- Press the **Save Mode Shapes** button on the bottom of the **Modal Sensitivity** window to save the mode shapes of the *current* **Solution** into **SHP: Axial Spring Mode Shapes**

## STEP 4 - MODES CREATED BY THE LESS STIFF AXIAL SPRING

After you have saved mode shapes from the Modal Sensitivity window, you can display each new mode shape side-by-side with the *closest matching* mode shape of the *unmodified* Jim Beam.

- **Press Hotkey 4 Modes Created by the Less Stiff Axial Spring**

The mode shape of the third mode does not change no matter which Target Frequency is used from the table above.



Third Mode Shape at 441 Hz Created by Less Stiff Axial Spring.

## STEP 5 - MODES CREATED BY A STIFF 3-DOF STIFFENER

- **Press Hotkey 5 Modes Created by a Stiff 3-DOF Stiffener**

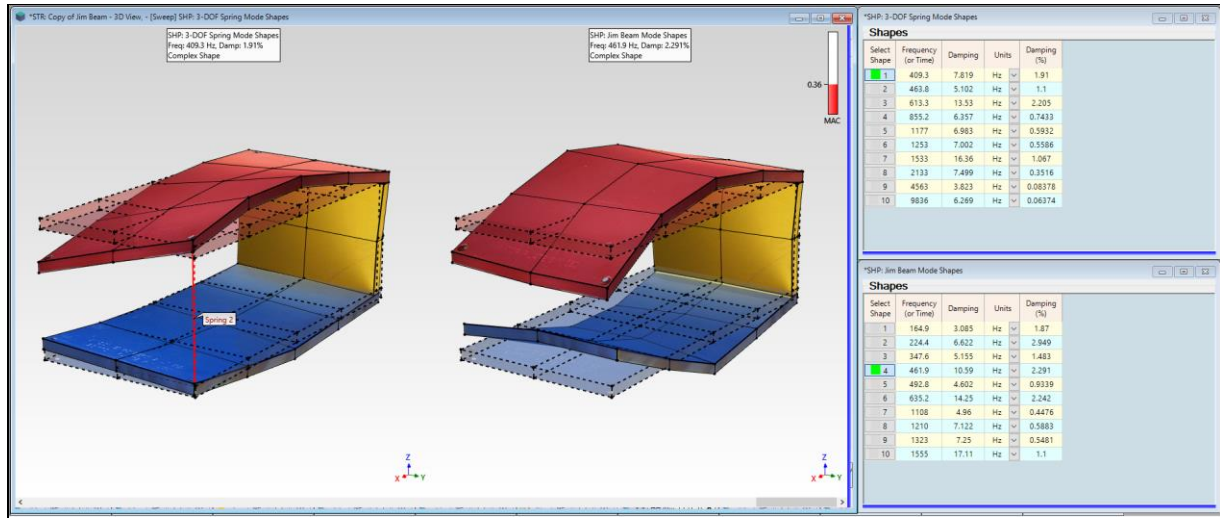
When **Hotkey 5** is pressed, SDM is used to calculate the new modes of the Jim Beam with a **stiff 3-DOF Spring** attached between **Point 15 on the top plate and Point 30 on the bottom plate**.

**A 3-DOF Stiffener** applies stiffness to a structure *in three directions* at both of its endpoints.

After the new mode shapes of the Jim Beam are calculated, sweep animation will display each shape with *several cycles of sine dwell animation*. Each new mode shape is displayed side-by-side with its *closest-matching* mode shape of the *unmodified* beam.

The effect of this stiffener is apparent when the new mode shapes are displayed in animation.

- **Click** on a **Select Shape** button in **SHP: 3-DOF Spring Mode Shapes** to display a *closest matching* pair of mode shapes
- All mode shape pairs with **MAC** → **greater than 0.90** mean that the 3-DOF stiffener *had no effect* on that mode shape of the Jim Beam
- All mode shape pairs with **MAC** → **less than 0.9** indicate that the 3-DOF stiffener *created a brand-new mode shape*
- The 3-DOF Stiffener *replaced the 165 Hz & 224 Hz* mode shapes with a new **409 Hz** mode shape.

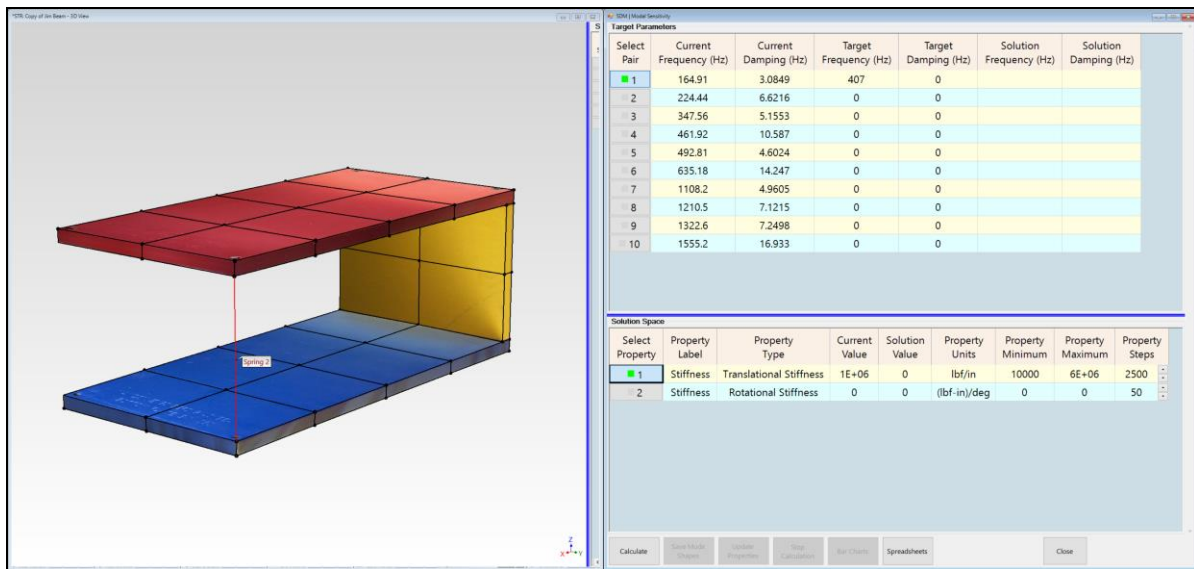


*New Mode Shape at 409 Hz.*

**STEP 6 - MODAL SENSITIVITY TO THE 3-DOF STIFFENER**

- **Press Hotkey 6 Modal Sensitivity to the 3-DOF Stiffener**

The STR window and the Modal Sensitivity window will open side-by-side as shown below.



*Modal Sensitivity Window for 3-DOF Stiffener.*

**UPPER SPREADSHEET**

The Modal Sensitivity window contains two spreadsheets and a row of buttons at the bottom. The *upper* spreadsheet is used to choose the **Target Frequency & Target Damping**, and to select the **Shape Pairs** to be used for ordering Solutions from best to worst.

- **Depress the Select Pair 1 button**
- Enter a **Target Frequency** of **407 Hz** in the row of **Shape Pair 1**

The **Solution & Target Frequency** for **Shape Pair 1** will be used to calculate an **Error function** for ordering the solutions.



## LOWER SPREADSHEET

The following numbers should be entered on the *lower* spreadsheet enter,

- **Depress the Select Property 1 Translational Stiffness** button
- Enter **Property Minimum** → **10000 lbf/in** for **Property 1**
- Enter **Property Maximum** → **6 E6 lbf/in** for **Property 1**
- Enter **Property Steps** → **2500** for **Property 1**

If you are using different engineering units, enter equivalent values.

Units are changed on the **Units** tab in the **File | MEScope Options** box.

- **Press the Calculate** button on the bottom of the Modal Sensitivity window

**2500** solutions will be calculated and ordered from *best to worst* according to how close the **Solution** modal frequency is to the **Target Frequency (407 Hz)**.

## SOLUTION SCROLL BAR

After the calculation has been completed, the **Solution Frequency & Solution Damping** are displayed in the *upper spreadsheet*, and a **scroll bar** is displayed *on the right-hand side* of the window. The solutions are displayed by scrolling the scroll bar.

The *best* solution is displayed when the scroll *is at the top* of the scroll bar

The *worst* solution is displayed when the scroll *is at the bottom* of the scroll bar

The screenshot shows the 'SDM | Modal Sensitivity' window with two tables. The 'Target Parameters' table has 10 rows, with row 1 highlighted in green. The 'Solution Space' table has 2 rows, with row 1 highlighted in green. Red boxes labeled 'Best Solution' point to the highlighted rows in both tables. The 'Calculate' button is highlighted in blue at the bottom.

Select Pair	Current Frequency (Hz)	Current Damping (Hz)	Target Frequency (Hz)	Target Damping (Hz)	Solution Frequency (Hz)	Solution Damping (Hz)
1	164.9	3.085	407	0	407	7.698
2	224.4	6.622	0	0	462.4	5.207
3	347.6	5.155	0	0	597.6	12.3
4	461.9	10.59	0	0	810.1	7.929
5	492.8	4.602	0	0	909.9	6.696
6	635.2	14.25	0	0	1172	6.647
7	1108	4.96	0	0	1279	6.812
8	1210	7.122	0	0	1555	16.9
9	1323	7.25	0	0	1899	4.304
10	1555	17.11	0	0	4054	6.248

Select Property	Property Label	Property Type	Current Value	Solution Value	Property Units	Property Minimum	Property Maximum	Property Steps
1	Stiffness	Translational Stiffness	1E+06	1.634E+05	lbf/in	1E+04	6E+06	2500
2	Stiffness	Rotational Stiffness	0	0	(lbf-in)/deg	0	0	50

*Best Solution for 407 Hz Target Frequency*

## BRICK WALL EFFECT

Again, we can use Modal Sensitivity Analysis to determine how much stiffness can be applied to a structure to shift modes to higher frequencies. The table below shows the “*brick wall effect*” of stiffening the Jim Beam with the 3-DOF stiffener.

A *large increase* in the stiffness of the 3-DOF stiffener is required to move the first mode **from 407 Hz to 409 Hz**.

- To verify the stiffnesses in the Table, enter any Target frequency in the Table below as the **Target Frequency** of the *selected Shape Pair 1* in the *upper* spreadsheet, and press the **Calculate** button

Target Frequency (Hz)	Solution Frequency (Hz)	Solution Stiffness (lbf/in)
407.00	406.99	163410
407.25	407.24	177790
407.50	407.51	196960
407.75	407.75	218540
408.00	408.00	247300
408.25	408.25	285650
408.50	408.50	338380
408.75	408.75	419880
<b>409.00</b>	<b>409.00</b>	<b>558900</b>

A 3-DOF stiffness of **163,410 lbf/in** is required to create a mode shape at **407 Hz**.

A 3-DOF stiffness of **558,900 lbf/in** is required to create a mode shape at **409 Hz**.

To increase the first mode shape frequency *by 2 Hz, 3.4 times more stiffness is required*.

## SAVING A SOLUTION

- Press the **Save Mode Shapes** button on the bottom of the Modal Sensitivity window to save the mode shapes of the *current Solution* into **SHP: 3-DOF Stiffener Mode Shapes**

## STEP 7 - MODES CREATED BY THE LESS STIFF 3-DOF STIFFENER

After you have saved the mode shapes from the Modal Sensitivity window,

- Press Hotkey 7 Modes Created by the Less Stiff 3-DOF Stiffener**

Each new mode shape is displayed side-by-side with its *closest matching* mode shape from the *unmodified* Jim Beam.

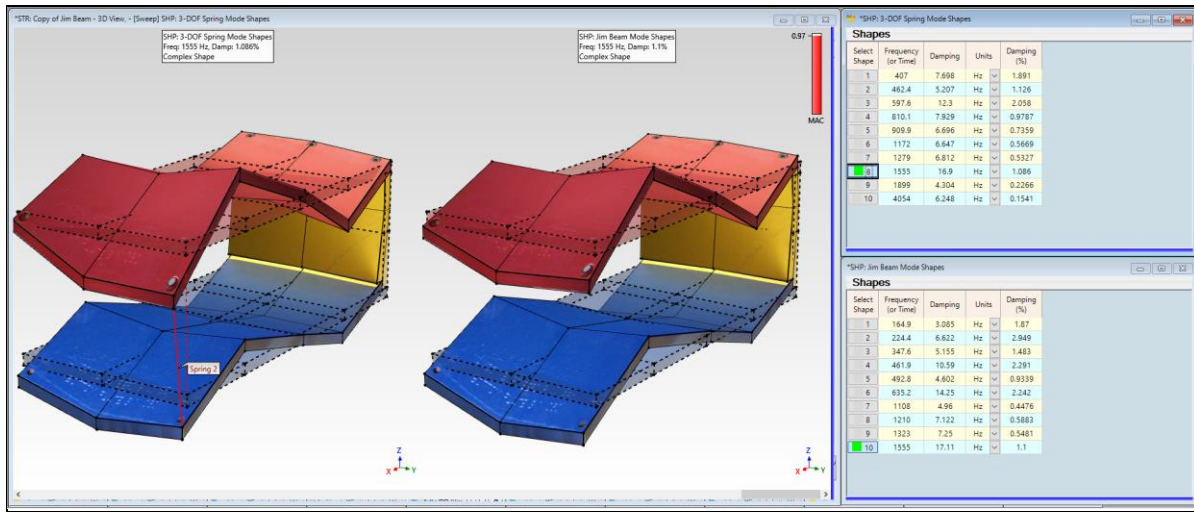
The mode shape of the first mode does not change no matter which Target Frequency is used from the table above.

This shows that it is possible to modify the Jim Beam using *much less than 1 E6 lbf/in* stiffness in the 3-DOF Stiffener.

- Click** on a **Select Shape** button in **SHP: 3-DOF Stiffener Mode Shapes** to display a *closest matching* pair of mode shapes

On one closest matching pair of mode shapes had MAC  $\rightarrow$  **greater than 0.90** meaning that the 3-DOF stiffener *had no effect* on the **1555 Hz** mode shape of the Jim Beam

All other mode shape pairs had MAC  $\rightarrow$  **less than 0.9** indicating that the 3-DOF stiffener created new mode shapes that *replaced all by one mode shape* of the Jim Beam



The 155 Hz Mode Shape Was Not Affected by the 3-DOF Stiffener.

## STEP 8 - REVIEW STEPS

To review the steps of this App Note,

- **Press Hotkey 8 Review Steps**