MEscope Application Note 03

Modeling a RIB Stiffener with SDM

The steps in this Application Note can be carried out using any MEscope 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 **AppNote03** project file. These steps might also require MEscope software with a ***more recent release date***.

APP NOTE 03 PROJECT FILE

- To retrieve the Project for this App Note, **click here** to download **AppNote03.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 display its Script window

INTRODUCTION

In this App Note, the **VES-5000 Structural Dynamics Modification (SDM)** option is used to model the addition of a RIB stiffener to the centerline of an aluminum plate. **FEA** Bars (beam elements) and **FEA** Quads (plate elements) are both available in the library of **FEA** Objects in MEscope, and both are used as two different ways to model the RIB stiffener.

- **SDM** uses the **FEA** Objects attached to a 3D model of the plate together with the mode shapes of the ***un-modified plate*** to calculate the new modes of the plate with the RIB attached

Both the Modal Assurance Criteria (**MAC)** the Shape Difference Indicator **(SDI**) are used to compare the new mode shapes calculated by **SDM** with the **FEA** mode shapes of the ***unmodified plate***, and with the **FEA** mode shapes of the plate with the RIB attached.

Plate with RIB Stiffener Attached

The real-world test article is a 3/8-inch thick 20 by 25-inch rectangular plate constructed of 6061-T6511 aluminum. The stiffening RIB is 25 by 3 inches and is 3/8-inches thick. The RIB is attached to the plate with five cap screws.

In this App Note, only **FEA** mode shapes of the ***unmodified plate*** and the ***plate with RIB*** are compared with the **SDM** mode shapes. The **FEA** mode shapes were obtained with the **VES 8000 FEA** option.

- EMA mode shapes of this test article are compared with **SDM** mode shapes in **App Note 30**

MODELING STRUCTURAL DYNAMICS MODIFICATIONS

There are only two ways to ***reduce vibration levels*** in a machine or structure,

- ***Isolate*** the structure from its excitation forces
- ***Physically modify*** the structure or its boundary conditions

The vibration of a machine or structure will change if,

- A physical property (**mass, stiffness, or damping**) is changed
- A **boundary condition** is changed
- Two or more structural components are **coupled together**

LAW OF MODAL ANALYSIS

- **LoMA:** ***All vibration*** is a ***summation of mode shapes***

The **Structural Dynamics Modification (SDM)** method is based on the above Law of Modal Analysis **(LoMA)**.

- With **SDM** you can model any one of the three types of modification: ***a physical change, boundary conditions***, or ***component coupling***

SDM calculates the new modal parameters (**frequency, damping, & mode shape**) that result from those structural modifications.

SDM converts all structural modifications internally to ***changes in the mass, stiffness & damping properties*** of the structure. Those mass, stiffness, & damping changes are then used together with the modes of the ***unmodified structure*** to calculate the new modes of the modified structure.

MODAL MODEL

- **SDM *is unique*** in that it utilizes a modal model of the ***unmodified structure***

A modal model can contain mode shapes obtained from,

Experimental Modal Analysis ➔ EMA mode shapes

Finite Element Analysis ➔ FEA mode shapes

Hybrid Modal Model ➔ EMA mode shapes & **FEA mode shapes**

A modal model preserves all the dynamic properties of a structure (its mass, stiffness & damping properties), and therefore can be used to fully represent the dynamics of the ***unmodified structure***.

Once the dynamic properties of an ***unmodified structure*** are defined in the form of its modal model, **SDM** can be used to predict the effects of modifications to the structure on its mode shapes.

Modifications can be as simple as ***additions*** or ***removals of*** point masses, linear springs, or linear dampers. Or more complex modifications can be modeled using **FEA** elements such rods & bars, plates (membranes) and solid elements.

SDM is computationally very efficient because it solves an eigenvalue problem in ***modal space***. The eigenvalue problem size is determined by the number of mode shapes in the modal model.

Another advantage of **SDM** is that the modal model of the ***unmodified structure*** must only contain mode shape data for the ***DOFs (points & directions) where the modification elements are attached*** to the structure.

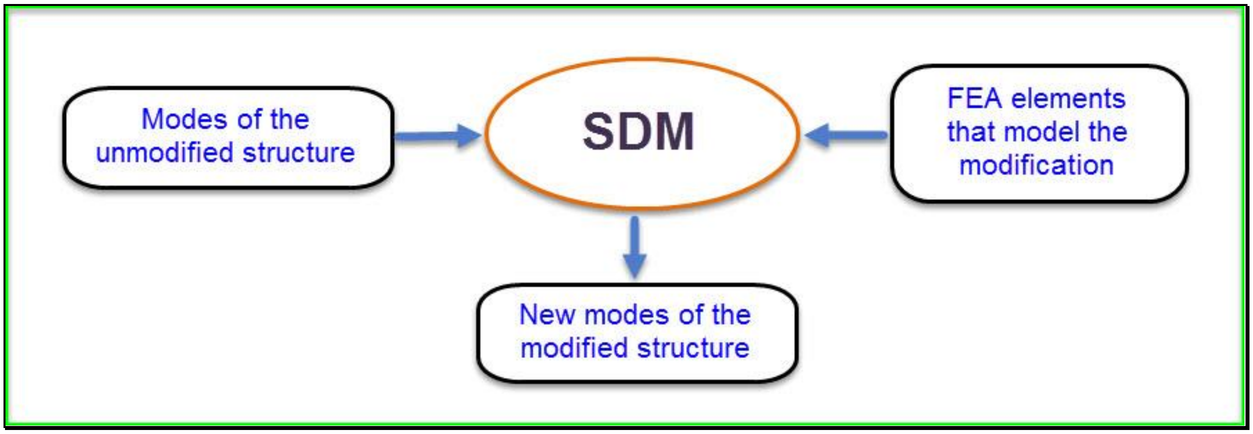


Diagram Showing Calculation of New Mode Shapes Using SDM.

FEA PLATE & RIB MODELS

The aluminum plate was modeled using the **VES-8000 FEA** option in MEscope. The ***unmodified plate*** (without the RIB attached) was modeled with **80 FEA Quad** plate elements. The plate with the RIB attached was modeled with **100 FEA Quad** elements, as shown in the figures below.

- Each **FEA** Quad plate element was 3/8-inches thick and was defined between 4 nodes (or Points) on the plate
- The RIB was modeled with 2 rows of **FEA** Quads, each 1.5 inches high by 2.5 inches wide by 3/8-inches thick

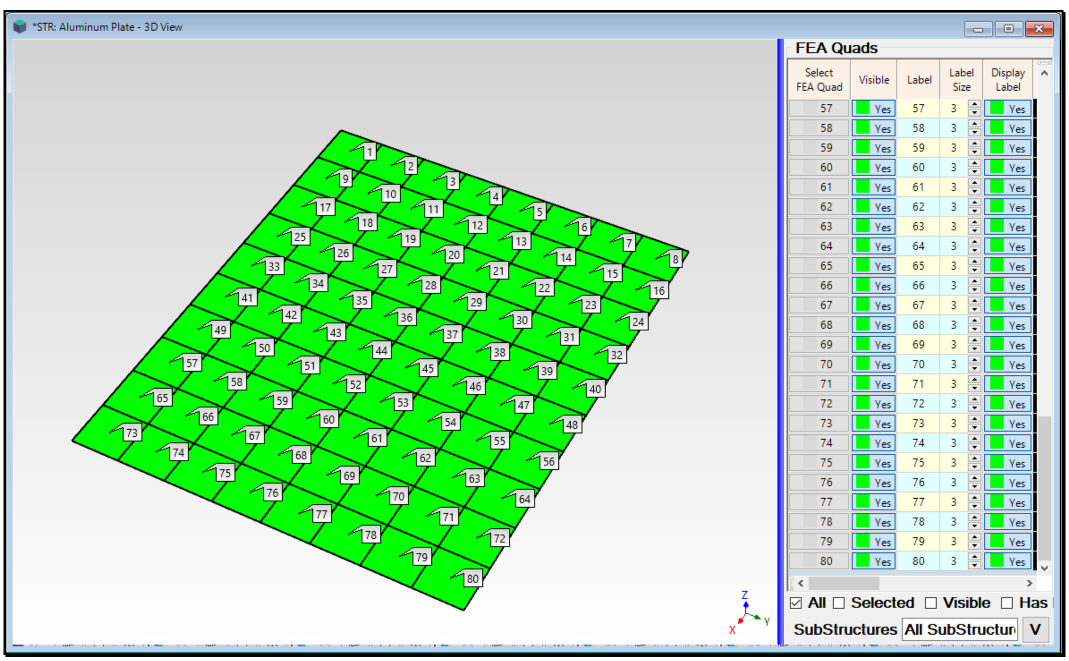
The 11 nodes on the bottom of the RIB coincide with the nodes on the centerline of the plate.

The **FEA** Quad elements were given the following material properties:

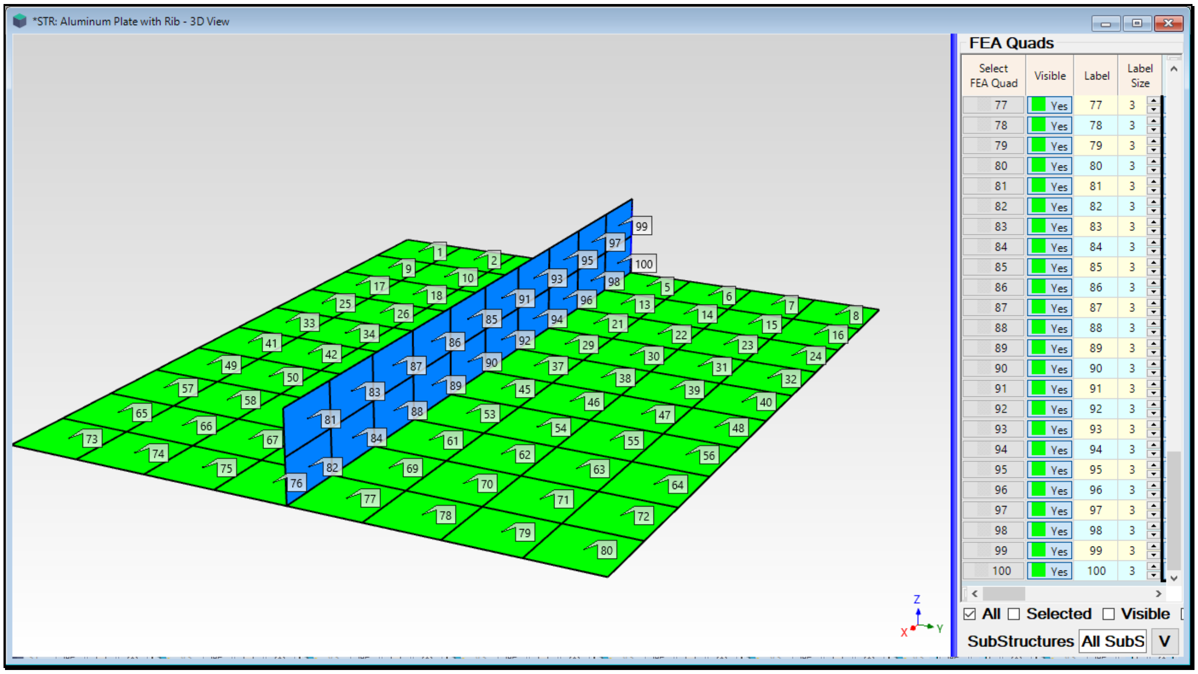
Modulus of Elasticity: 10^7 lb/in^2

Poisson's Ratio: 0.33

Density: 0.101 lb/in^3



***FEA** Model of the Plate (80 **FEA** Quads).*



*FEA Model of the **Plate with RIB** (100 **FEA** Quads).*

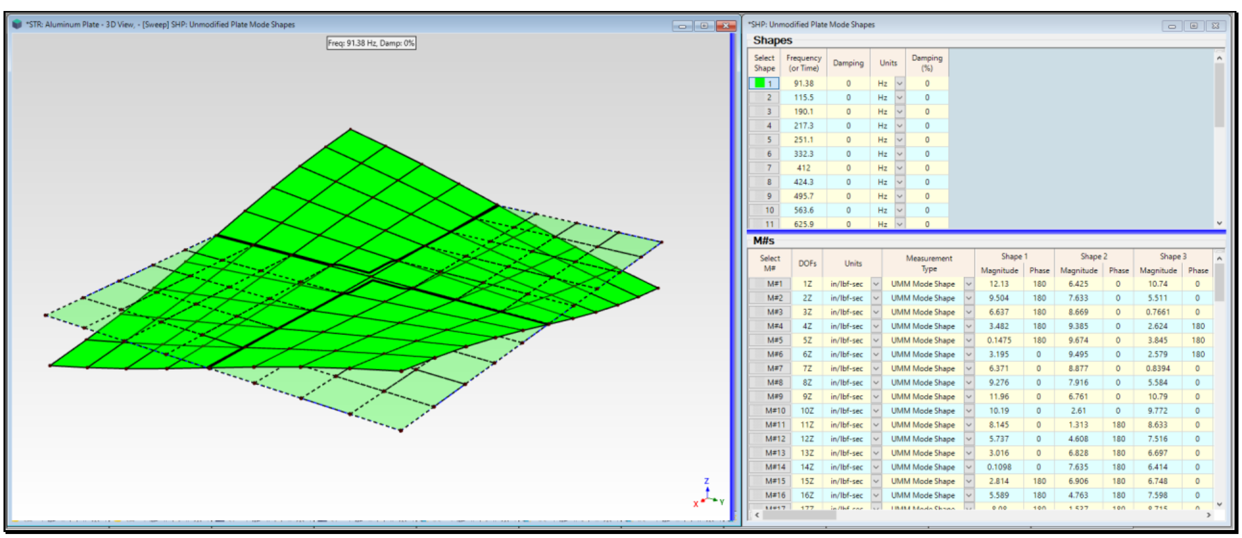
Two sets of **FEA** mode shapes are calculated in this App Note; one set for the plate ***without the RIB***, and one set for the plate ***with the RIB attached to its centerline***.

STEP 1 – FEA MODE SHAPES OF THE UNMODIFIED PLATE

- ***Press* Hotkey 1 Plate FEA Mode Shapes**

A sweep animation of the **FEA** mode shapes in the Shape Table **SHP: Unmodified plate Mode Shapes** will begin, a shown below. **SHP: Unmodified plate Mode Shapes** contains **24 mode shapes** ranging in frequency from **91.4 Hz** to **1421.4 Hz**.

- The **six rigid body mode shapes** are deleted from the modal model
- The **rotational DOFs** are deleted from the model
- The **translational DOFs in the X & Y direction**s are deleted from the modal model



*First Flexible-Body Mode Shape of the **Unmodified plate**.*

The **modal damping** of all modes is **0.0**. D***amping is usually not included*** in an **FEA** model because it is difficult to model.

- ***Press* a Select Shape button** in the Shape Table **SHP: *Unmodified plate* Mode Shapes** to display its mode shape
- The mode shapes with a ***nodal line (zero values) on the centerline*** of the plate will ***not be affected*** by attaching a RIB stiffener to the centerline
- The mode shapes ***without a nodal line on the centerline*** of the plate will ***be significantly affected*** by attaching a RIB stiffener to the centerline

UNIT MODAL MASS (UMM) SCALING

In the figure above, the **M#s (DOFs)** of the mode shapes in **SHP: Unmodified plate Modal Model** have a **Measurement Type** called **UMM Mode Shape**

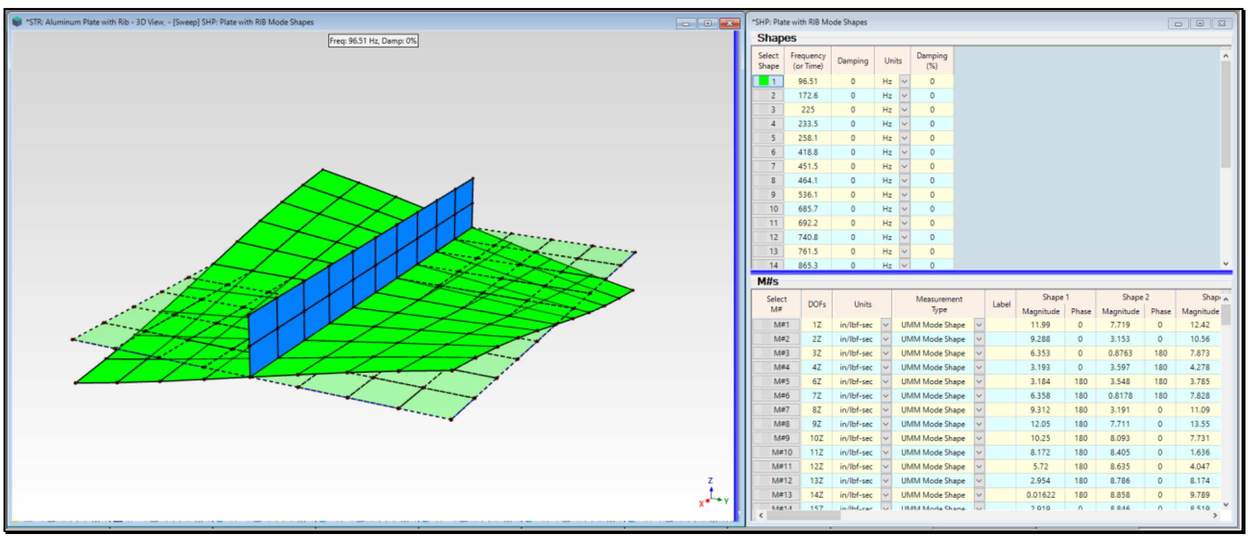
- To be used by **SDM**, the mode shapes of the ***unmodified structure*** must have **Unit Modal Mass (UMM)** scaling
- **UMM mode shapes** preserve the dynamic properties (mass, stiffness, & damping) of a structure

STEP 2 – FEA MODE SHAPES OF THE PLATE WITH RIB

- ***Press* Hotkey 2 Plate & RIB FEA Mode Shapes**

A sweep animation of the **FEA** mode shapes in the Shape Table **SHP: Plate with RIB Mode Shapes** will begin, a shown below. **SHP: Plate with RIB Mode Shapes** contains **24 mode shapes** ranging in frequency from **96.5 Hz** to **1285 Hz**.

The RIB stiffener created a first flexible-body (torsional) mode shape with a slightly higher frequency (**96.5 Hz** vs. **91.4 Hz**) than the first torsional mode shape of the ***unmodified plate***. **Shape 24** has a lower frequency (**1285.2 Hz vs. 1421.4 Hz**) than the ***closest-matching*** mode shape of the ***unmodified plate***. This new mode shape reflects shows the ***added weight of the* RIB** to the plate.



First Flexible-Body Mode Shape of Plate with RIB.

STEP 3 - MODELING THE RIB WITH FEA BARS

- ***Press* Hotkey 3 FEA Bars**

Ten **FEA Bars** have already been added to the centerline of the model in **STR: Aluminum Plate**, as shown below.

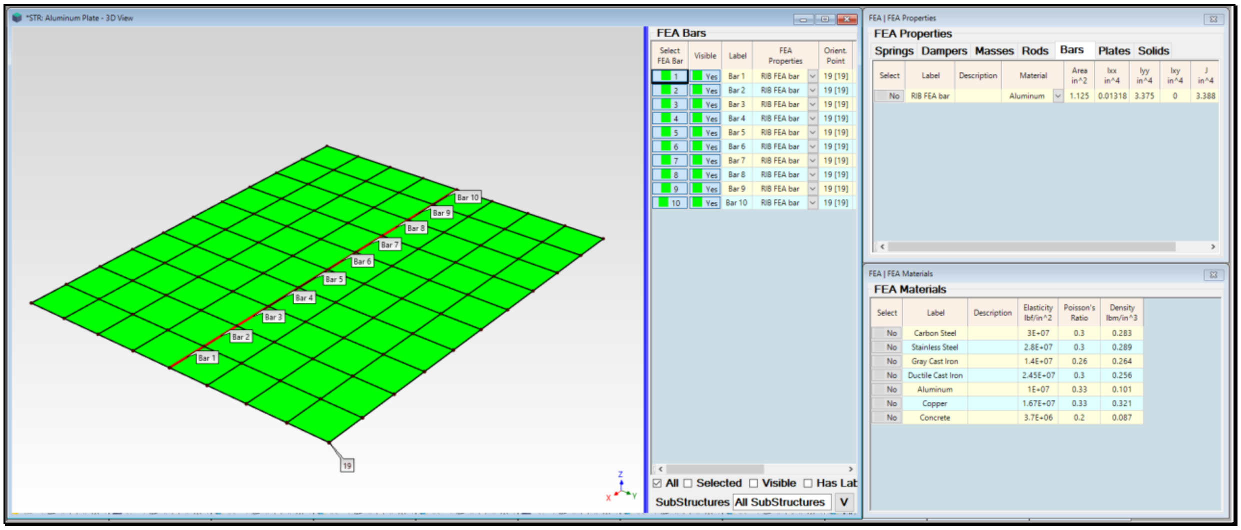
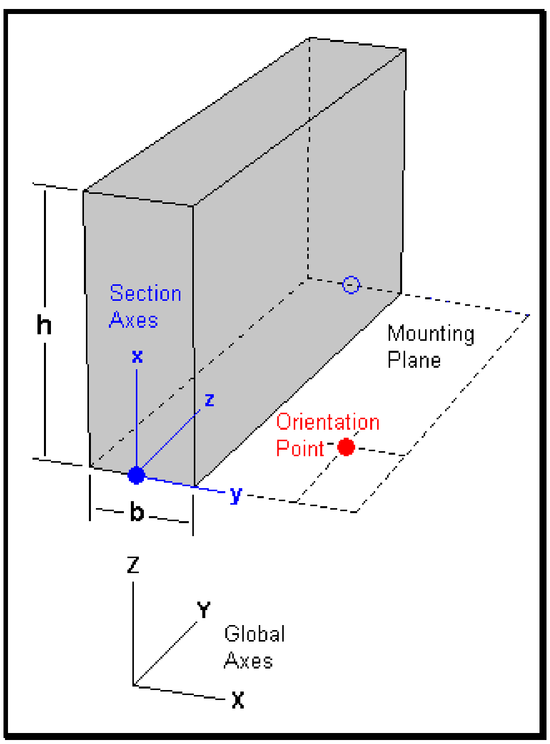


Plate Showing 10 ***FEA*** *Bars and Orientation Point 19.*

- An **FEA Bar** is a beam with a ***fixed cross-section***
- An **FEA Bar** is attached to a structure model at its two endpoints
- An **FEA Bar** ***applies stiffness*** & ***inertial restraint*** to the structure at its endpoints

In this case, only **Z**-direction translational motion is defined in the mode shapes of the ***unmodified plate***, so the **FEA** Bar will only affect the Z-direction deflection of the plate.



Cross-section of a rectangular ***FEA*** *Bar.*

FEA BAR CROSS-SECTIONAL PROPERTIES

The **FEA Bar** cross-section is described by its ***area*** and ***four area moments*** (**I_{xx}**, **I_{yy}**, **I_{xy}** and **J**) calculated with respect to the local ***cross-section axes*** at the ***bottom center*** of the cross-section shown in the figure above. The properties of a ***rectangular cross-section*** are calculated with the following equations,

$$\text{Area} = \int dA = b\int_0^h dx = h\int_{-b/2}^{b/2} dy = bh$$

$$I_{xx} = \int y^2 dA = h\int_{-b/2}^{b/2} y^2 dy = \frac{b^3 h}{12}$$

$$I_{yy} = \int x^2 dA = b\int_0^h x^2 dx = \frac{bh^3}{3}$$

$$I_{xy} = \int xy dA = \int_0^h x\left(\int_{\frac{-b}{2}}^{b/2} y dy\right)dx = 0$$

$$J = \int \left(x^2 + y^2\right)dA = I_{zz} = I_{xx} + I_{yy}$$

All ten **FEA Bars** have the same width **b** (**3/8** inch) and height **h** (**3** inches).

Area = (3/8) x (3) = **1.125 in^2**

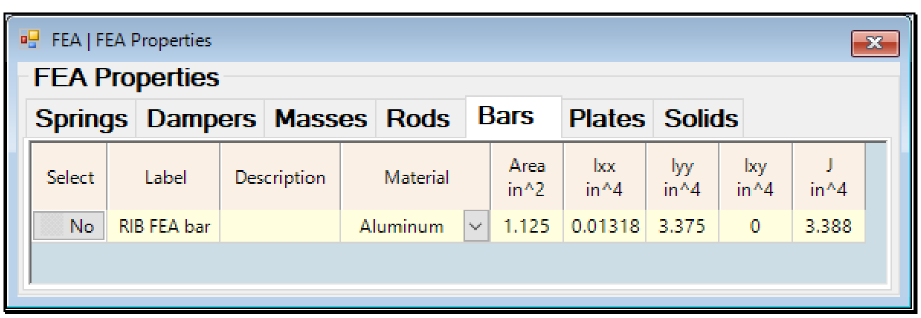
I_{xx} = (1/12) x (3/8)^3 x (3) = **0.01318 in^4**

I_{yy} = (1/3) x (3/8) x (3)^3 = **3.375 in^4**

I_{xy} = 0.0 in^4

J = 0.01318 + 3.375 = **3.388 in^4**

These properties have already been entered into the **FEA Properties** window, shown below.



Select	Label	Description	Material	Area in^2	Ixx in^4	Iyy in^4	Ixy in^4	J in^4
No	RIB FEA bar		Aluminum	1.125	0.01318	3.375	0	3.388

***FEA** Bar Properties.*

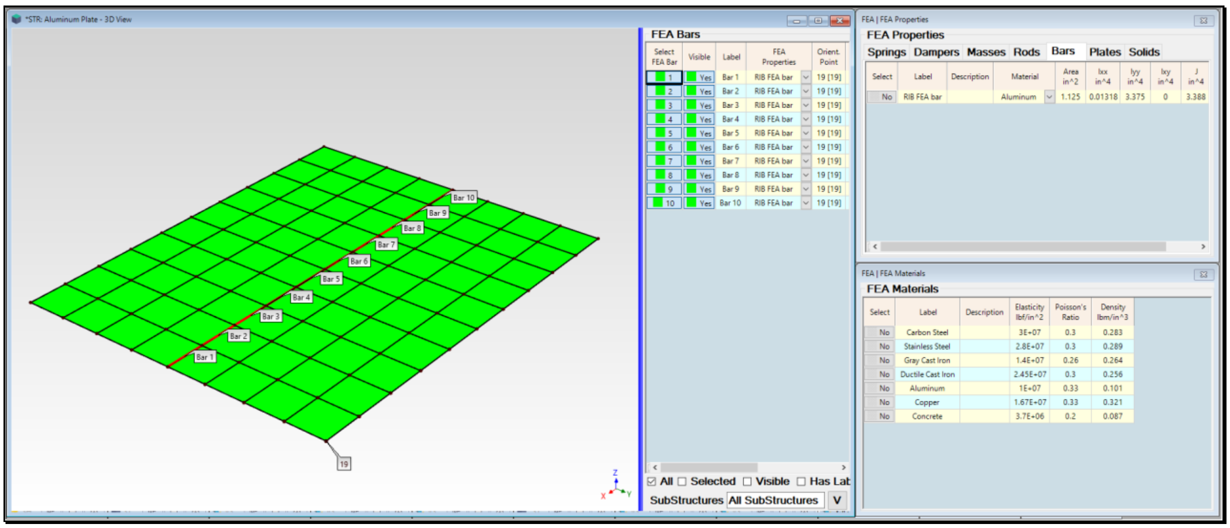
These bar properties are labeled **RIB FEA Bar** and have already been assigned to the **FEA** Properties of the **FEA Bars** in the Objects spreadsheet.

BAR ORIENTATION POINT

When **Hotkey 3 is *pressed***, the plate with 10 **FEA** Bars attached to its centerline, and the **FEA Properties** labeled **RIB FEA bar,** and the **FEA Materials** are displayed together, as shown below.

- The cross-sectional properties of each bar are calculated with respect to a ***set of local cross-section axes***
- **Orientation Point 19** of the **FEA** Bar cross-section is chosen in the **FEA Bars** spreadsheet
- An Orientation Point can be ***any Point*** that is ***not in line with the attachment points*** of the **FEA** Bar
- The Y-axis of each cross-section is assumed to ***lie in the plane defined by the* Orientation Point *and the two* FEA Bar *attachment points***

Point 19 has already been chosen as the cross-section **Orientation Point** for ***all*** **10 FEA Bars** in their Objects spreadsheet, as shown below. **Orientation Point 19** is also shown below.



*Model with **FEA** Bar Properties & Orientation Point 19.*

CHECKING UNITS

It is important to make sure that the engineering units of the model with the modification **FEA** Objects attached in the **Structure (STR)** window match the units of the **UMM mode shapes** of the ***unmodified structure*** in their **Shape Table (SHP)** window.

- Before using **SDM**, the units on the **Units** tab in the **File | MEscope Options** box ***must match the* M# *units*** in the Shape Table containing the ***modal model*** of the ***unmodified structure***

Each shape **M#** in **SHP: Plate FEA Mode Shapes** window has units of **in/lb-sec**. Therefore, the structure model in **STR: Aluminum Plate** must have length units of **inches** (or **in**), force units of **lbf** (or **lb**), and mass units of **lbm**.

- Execute **File | MEscope Options** to open the options box and verify the Structure (**STR**) window units on the **Units** tab
- If you change units, make sure that both the Point coordinates in the Structure (**STR**) window and the shapes in the Shape Table (**SHP**) are ***re-scaled*** to match the new units

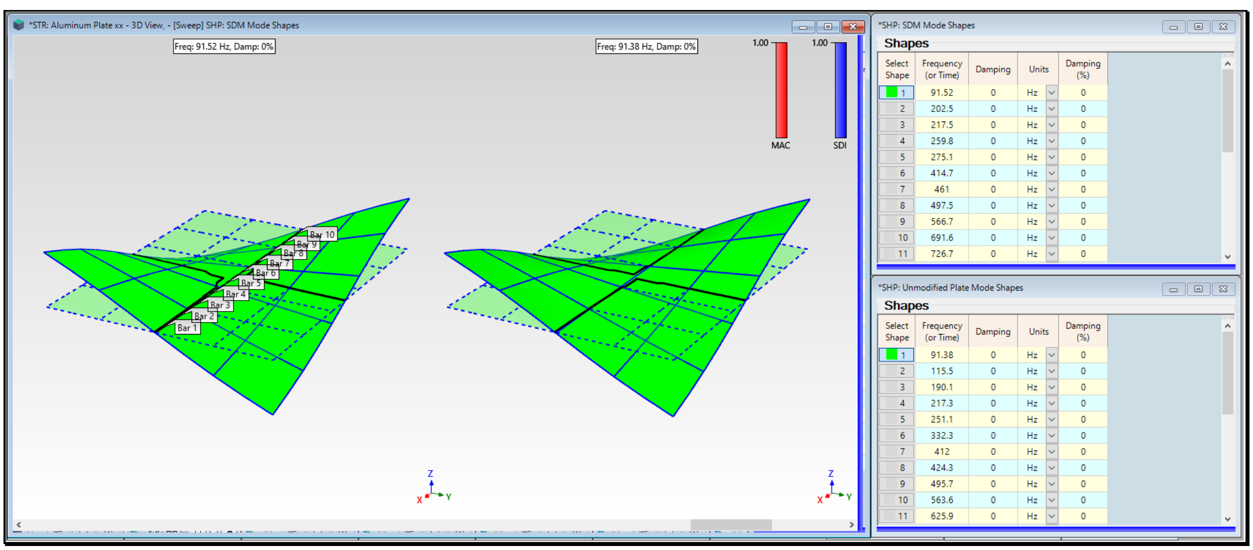
STEP 4 – COMPARE SDM WITH UNMODIFIED PLATE MODE SHAPES

The model in **STR: Aluminum Plate** is now ready to compute the effect of the RIB stiffener on the modes of the plate.

- ***Press* Hotkey 4 Calculate SDM Mode Shapes**

When **Hotkey 4 is *pressed***, the **SDM | Calculate New Modes** command will use the modes of the ***unmodified structure*** in **SHP: Plate FEA Mode Shapes** together with the **FEA Bar**s attached to the structure model in **STR: Aluminum Plate** to solve for the new modes of the modified structure.

After the new modes have been calculated, sweep animation from **SHP: SDM Mode Shapes** will begin, with a side-by-side comparison of each SDM mode shape with the ***closest-matching*** mode shape of the ***unmodified plate*** from **SHP: Plate FEA Mode Shapes**.



*SDM Mode Shape of the Plate with **FEA** Bars vs. the Closest-Matching Mode Shape of the **Unmodified Plate.***

To examine the mode shape pairs more carefully,

- Execute **Animate | Pause Continue** in the **STR: Aluminum Plate** window
- ***Click*** on a **Select Shape** in **SHP: SDM Mode Shapes** to display it and its ***closest matching*** mode shape of the ***unmodified* plate**

As you click on each shape in **SHP: SDM Mode Shapes,** an **SDM** mode shape is displayed ***on the left side*** together with an **FEA** mode shape **on the right side** that has the ***maximum* MAC *value*** with the **SDM** mode shape.

- The ***first 20 mode shapes*** exhibit ***little or no bending*** of the plate along its centerline
- The ***first 20 mode shapes*** reflect the ***strong stiffening influence*** of the **RIB** stiffener modeled with 10 **FEA** Bars

TRUNCATED MODAL MODEL

The last 4 mode shapes (**Shapes 21 through 24**) don't reflect the influence of the RIB stiffener. These are called ***computational modes***, and they result because the modal model of the ***unmodified structure*** is a ***truncated modal model***.

- The modal model is a ***truncated dynamic model*** because ***not all the mode shapes of the real-world unmodified* plate** were included in the modal model

Ideally, a real-world aluminum plate structure has an ***infinite number of mode shapes***. The truncated modal model used to represent the dynamics of the ***unmodified* plate** has ***only 24 mode shapes*** in it.

- When a truncated modal model is used, the **SDM** solution includes ***computational modes*** at ***higher frequencies*** with ***unrealistic mode shapes***

These computational modes ***compensate for the higher frequency modes*** that were left out of the truncated modal model.

- If a truncated modal model includes the ***lower frequency modes*** that ***model most of the dynamics*** of the ***unmodified* structure**, **SDM** yields ***realistic mode shapes for the modified* structure**

MAXIMUM MAC PAIR

When **Hotkey 4 is *pressed***, the ***closest-matching pair*** of modes shapes is displayed side-by-side in the structure window graphics area. The pair of mode shapes with **Maximum MAC** is the mode shape selected and displayed ***on the left*** from the **Animation Source**, together with the mode shape displayed ***on the right*** from the Comparison Source.

- **MAC** is a numerical measure of the ***co-linearity*** (***linear dependence***) of two shapes
- **MAC = 1.0** ➔ two shapes are ***co-linear (they lie on the same straight line)***
- **MAC >= 0.9** ➔ two shapes are ***similar***
- **MAC < 0.9** ➔ two shapes are ***different***
- ***Eleven pairs*** of mode shapes have **MAC >= 0.9**, meaning that the RIB stiffener ***had no influence*** on eleven modes of the ***unmodified plate***
- ***Nine mode shapes*** in **SHP: New Mode Shapes** are ***brand-new modes***, with mode shapes that reflect the ***influence of the RIB stiffener***

SDI BAR

A **Shape Difference Indicator (SDI)** bar is also displayed next to the MAC bar in the **STR: Aluminum Plate** window.

- **SDI** is a measure of the ***numerical difference*** between two shapes
- **SDI = 1.0** ➔ two shapes have ***equal shape components***
- **SDI >= 0.9** ➔ two shapes have ***similar shape components***
- **SDI < 0.9** ➔ two shapes have ***different shape components***
- ***Eleven pairs*** of mode shapes have **SDI >= 0.9**, meaning that the SDM calculated UMM mode shapes with essentially the same components in them as the **FEA** mode shapes of the ***unmodified* plate** which are also UMM mode shapes

STEP 5 - COMPARE SDM WITH FEA MODE SHAPES OF PLATE & RIB

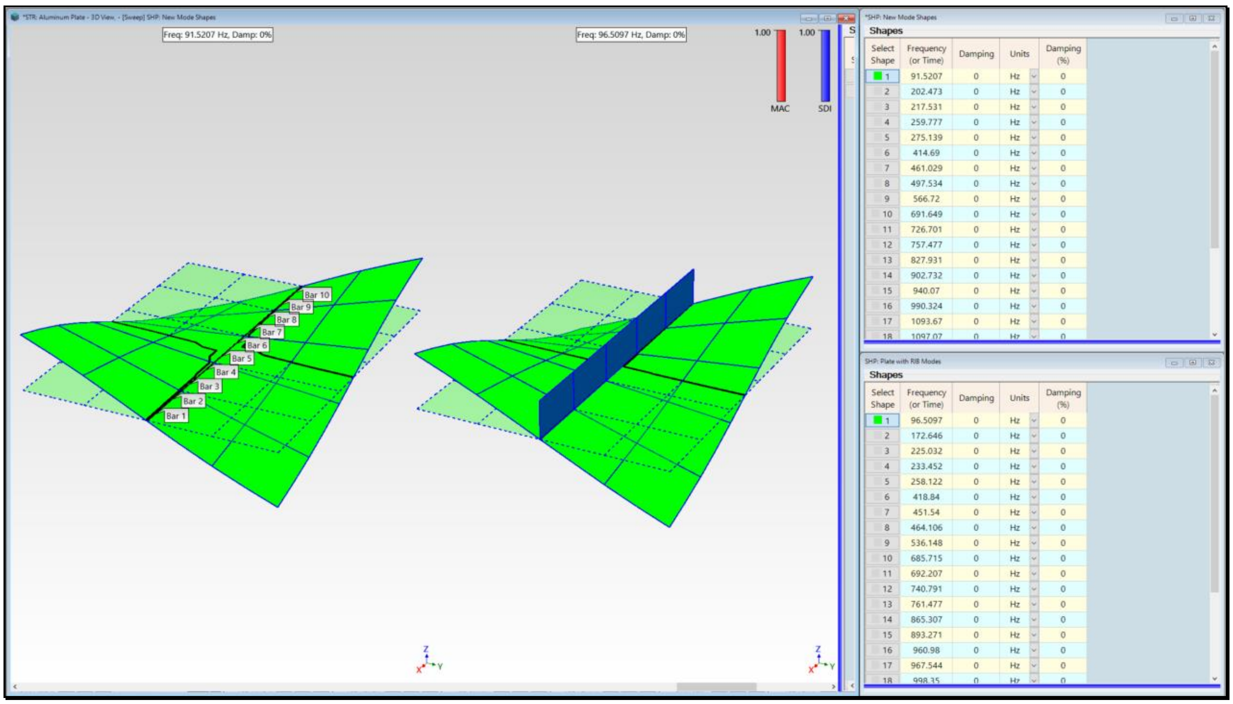
- ***Press* Hotkey 5 SDM vs FEA Mode Shapes**

When this **Hotkey is *pressed***, the new modes calculated with **SDM** are compared with the **FEA** mode shapes of the **FEA** model in **STR: Aluminum Plate with RIB**.

The **FEA** mode shapes for the plate with RIB were calculated and displayed when **Hotkey 2 was *pressed***, and the SDM mode shapes were calculated and displayed when **Hotkey 4 was *pressed***. Both sets of mode shapes are calculated again in this step.

The RIB was modeled with ***two rows of FEA Quads*** in **STR: Aluminum Plate with RIB**, with 11 **FEA** Quads in each row. The bottom row is ***attached to the same centerline Points*** as the **FEA** Bars.

A mode shape from **SHP: SDM Mode Shapes** is displayed ***on the left***, and the mode shape with Maximum MAC is from **SHP: FEA Plate with RIB Mode Shapes** is displayed ***on the right***.



***SDM** & **FEA** Modes Shape with Maximum MAC Displayed Side-By-Side.*

- ***The first 15 mode shape pairs are closely matched***, with only a couple pairs having **MAC < 0.9**
- Each **FEA** modal frequency ***is less than the modal frequency*** of ***its closest matching* SDM** mode shape

This confirms that **SDM** & **FEA** calculated similar mode shapes, even though their frequencies are different and they each used different FEA elements to model the RIB stiffener.

STEP 6 – COMPARE MODE SHAPES USING MAC & SDI BAR CHARTS

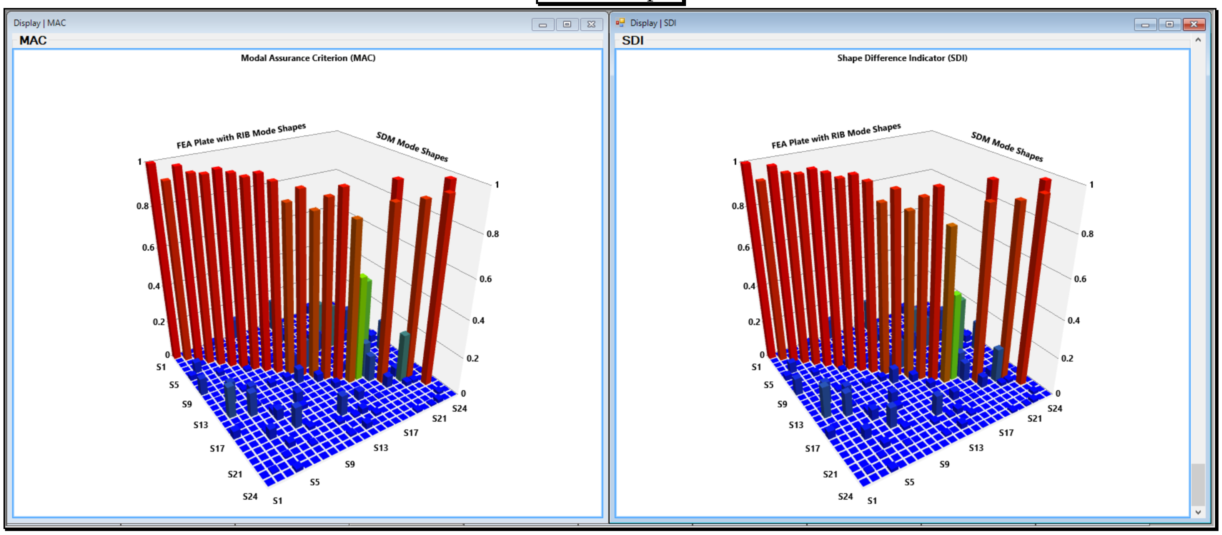
- ***Press* Hotkey 6 MAC & SDI Charts**

In this Step, both MAC and SDI are calculated between ***all* SDM *mode shapes*** and ***all* FEA *mode shapes*** even though the RIB was modeled in two different ways.

- The **SDM** mode shapes were calculated from a model where 10 **FEA** Bars were used to model the RIB
- The **FEA** mode shapes were calculated from a model where 20 **FEA** Quads were used to model the RIB

The **MAC** bar chart is displayed ***on the left*** and the **SDI** bar chart ***on the right***, as shown below.

Mode Shapes



*MAC & SDI Bars Comparing **SDM** Mode Shapes with **FEA** Mode Shapes.*

- Both bar charts show values of 0.85 or higher for mode shape pairs **1 through 21**

Both bar charts confirm that the ***first 15 SDM & FEA mode shape pairs*** are not only ***co-linear***, but their shape components are also ***close in numerical value***.

CONCLUSIONS

Some factors that might account for the differences between the **SDM** mode shapes and the **FEA** mode shapes are,

- **10 FEA Bar** elements modeled the RIB with **SDM**. **20 FEA Quad**s modeled the RIB in the **FEA** model
- A ***truncated modal model*** (***with only 24 modes***) was used by **SDM** to represent the dynamics of the ***un-modified* plate**
- The mode shapes of the ***truncated modal model*** used by **SDM *only contain translational* DOFs**. The **FEA** mode shapes ***included rotational* DOFs**
- Each **SDM** mode shape had **99 DOFs**. Each **FEA** mode shape had **726 DOFs**. The **FEA** model contained ***121 Points with 6* DOFs** at each Point

STEP 7 – REVIEW STEPS

To review the previous Steps in this App Note,

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