MEscope Application Note 30

Modeling a RIB Stiffener with Rotational DOFs

The steps in this Application Note can be carried out using any MEscope package that includes the **VES-4600 Advanced Modal Analysis** and **VES-8000 FEA** options. Without these options, you can still carry out the steps in this App Note using the **AppNote30** project file. These steps might also require MEscope software with a ***more recent release date***.

APP NOTE 30 PROJECT FILE

- To retrieve the Project file for this App Note, **click here** to download **AppNote30.zip**

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

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

ATTACHING A RIB STIFFENER TO AN ALUMINUM PLATE

In this App Note, **SDM** is used to calculate the mode shapes of an aluminum Plate with a RIB attached to its centerline. The new mode shapes are then compared with the mode shapes of an **FEA** model of the Plate & RIB, and with the **EMA** mode shapes obtained from an impact test of an actual Plate & RIB.

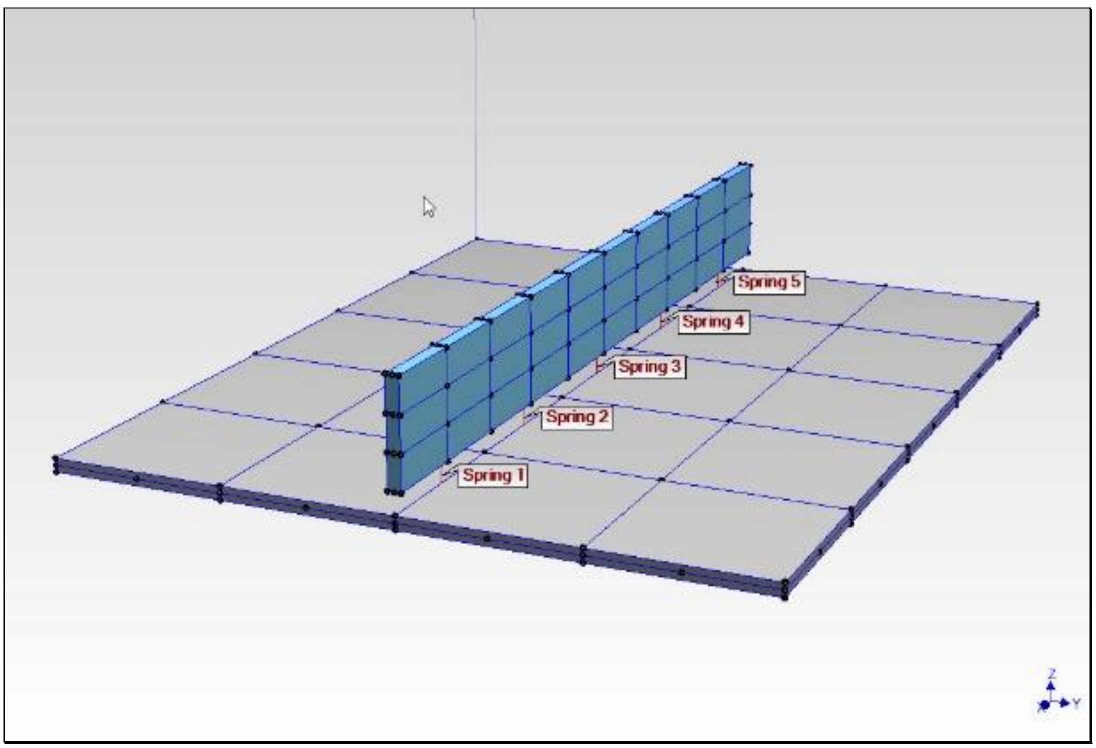
Mode shapes are compared in three cases,

1. **EMA vs. FEA** mode shapes of the Plate ***without the*** **RIB**
2. **SDM vs. FEA** mode shapes of the Plate **& RIB**
3. **EMA vs. SDM** mode shapes of the Plate **& RIB**

The Plate & RIB are shown in the figures below. The dimensions of the Plate are 20 inches (508 mm) by 25 inches (635 mm) by 3/8 inches (9.525 mm) thick. The dimensions of the RIB are 3 inches (76.2 mm) by 25 inches (635 mm) by 3/8 inches (9.525 mm) thick.

Plate with RIB Stiffener Attached

RIB and Five Attachment Cap Screws



***FEA** Springs Used to Model the Attachment Cap Screws*

The RIB stiffener was attached to the Plate using five cap screws, as shown in the figure above. When they are attached together, both **translational & torsional forces** are applied between the two substructures. Therefore, to correctly model the attachment of the RIB to the Plate, the **Modal Model**s of both substructures must contain **translational & rotational DOFs**, and the spring elements used to connect the RIB to the Plate **must model six DOFs** are each endpoint.

STRUCTURAL DYNAMICS MODIFICATION (SDM)

SDM has become a practical tool for improving the engineering designs of mechanical systems. It provides a very quick and inexpensive approach for investigating the effects of design modifications to a structure, thus eliminating the need for costly prototype fabrication and testing.

MODAL MODEL

SDM is unique in that it **works directly with a Modal Model** of the structure, either an **Experimental Modal Analysis EMA Modal Model**, a **Finite Element Analysis FEA Modal Model**, or a **Hybrid Modal Model** consisting of both **EMA** & **FEA** modal parameters. **EMA** mode shapes are extracted from experimental data and **FEA** mode shapes are extracted from an analytical finite element model. In this case, a **Hybrid Modal Model** consisting of both experimental & analytical data will be used.

A **Modal Model** is a set of ***scaled mode shapes***.

A **Modal Model** ***fully represents the dynamics*** of its mechanical structure.

SDM assumes that the **Modal Model** of the ***unmodified*** **structure** contains mode shapes which are scaled to **Unit Modal Masses**, called **UMM** mode shapes.

HYBRID MODAL MODEL

In **App Note 03** a RIB stiffener was attached to an aluminum Plate using **SDM**, but the **Modal Model** of the ***unmodified*** **Plate structure** only contained **translational DOFs**.

In this App Note, **Hybrid** mode shapes that contain both **translational & rotational DOFs** of the Plate & RIB are used. Because the RIB and Plate **exert torsional forces** on each other, using **Hybrid** mode shapes to model the dynamics of the two unmodified substructures gives more accurate results than if mode shapes with only translational DOFs are used. This is verified with experimental data acquired from an impact text of the real-world Plate & RIB.

A **Hybrid Modal Model** assigns the **frequency & damping** of each **EMA** mode shape to its ***closest-matching*** **FEA** mode shape.

A **Hybrid Modal Model** includes ***accurate*** **modal frequencies & damping**, and its mode shapes ***include rotational*** **DOFs**.

Use of a **Hybrid Modal Model** for ***both unmodified*** **substructures** is important because **both translational & rotational stiffnesses** are exerted between the Plate & RIB.

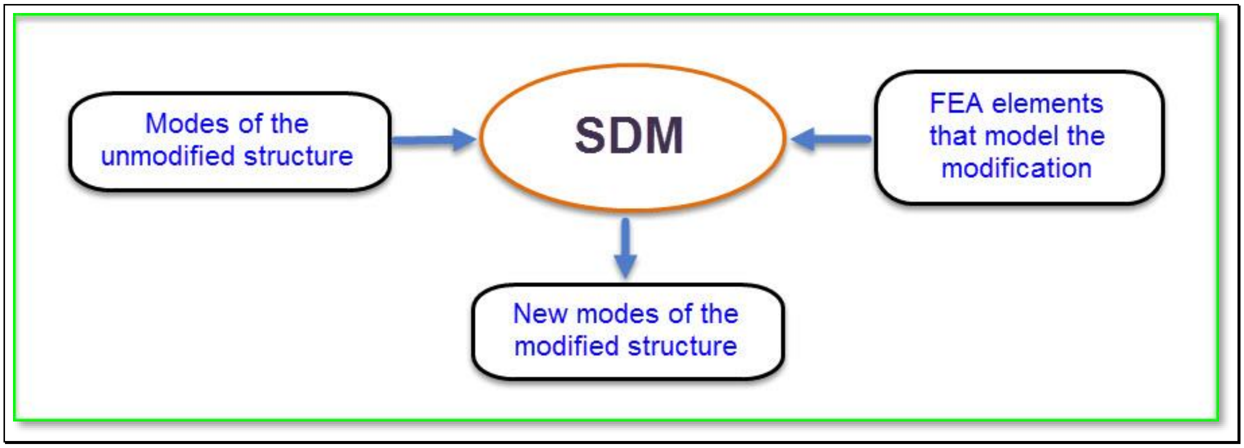
DESIGN MODIFICATIONS

Once the dynamic properties of an ***unmodified structure*** are defined in the form of its **Modal Model**, **SDM** can be used to predict the dynamic effects of mechanical design modifications on the modes of the structure. These modifications can be as simple as **additions or removals** of point masses, linear springs, or linear dampers. More complex modifications can also be modeled using **FEA** elements such as rods & beams, plate elements (membranes) and solid elements.

SDM ***is computationally efficient*** because it solves an eigenvalue problem in ***modal space***, whereas **FEA** mode shapes are obtained by solving an eigenvalue problem in ***physical space***.

The **Modal Model** of the ***unmodified structure must only contain mode shape data for the*** **DOFs** (points & directions) where the modification elements are attached.

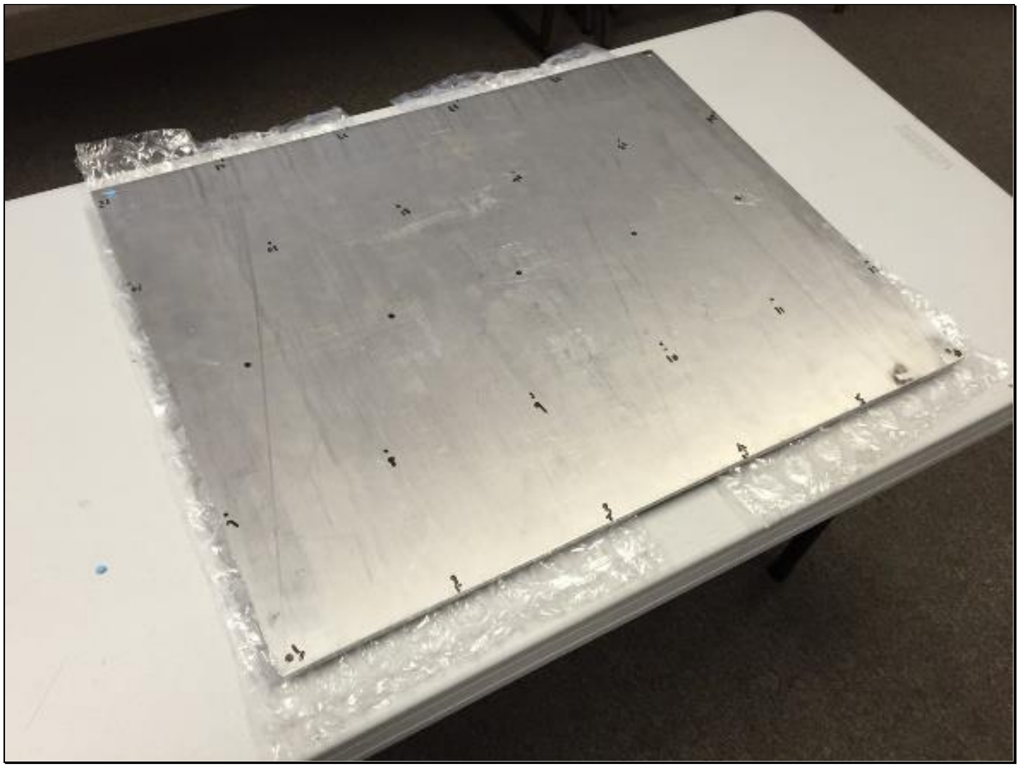
SDM provides a new **Modal Model** of the ***modified*** **structure**, as depicted in the diagram below.



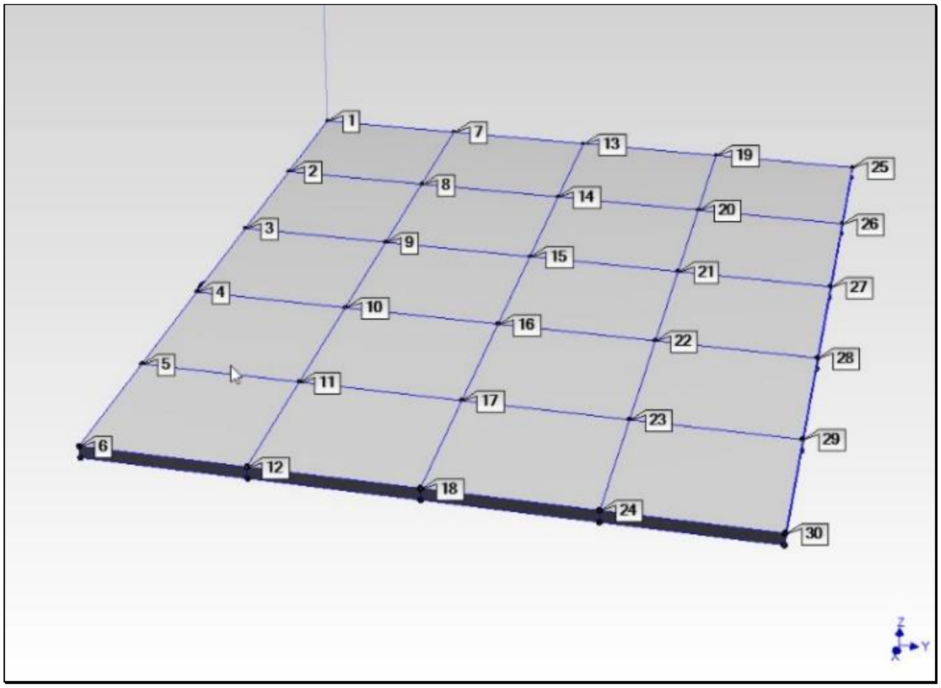
MODELING THE CAP SCREW STIFFNESSES

The stiffness between the Plate & RIB was modeled in **SDM** using **five 6-DOF springs** located at the five cap screw locations.

- Each **6-DOF FEA** spring models ***three translational*** & ***three rotational*** **stiffnesses** at its two endpoints
- Each **6-DOF FEA** spring is given ***a large*** **stiffness** to model the RIB ***tightly fastened*** to the Plate
  - **Translational stiffness: 1E+06 lbs/in (or 1.75E+05 N/mm)**
  - **Rotational stiffness: 1E+06 in-lbs/degree (or 1.75E+05 mm-N/degree)**



Aluminum Plate Supported on Bubble Wrap



Impact Test Points to Obtain 30 FRFs in the Z-Direction.

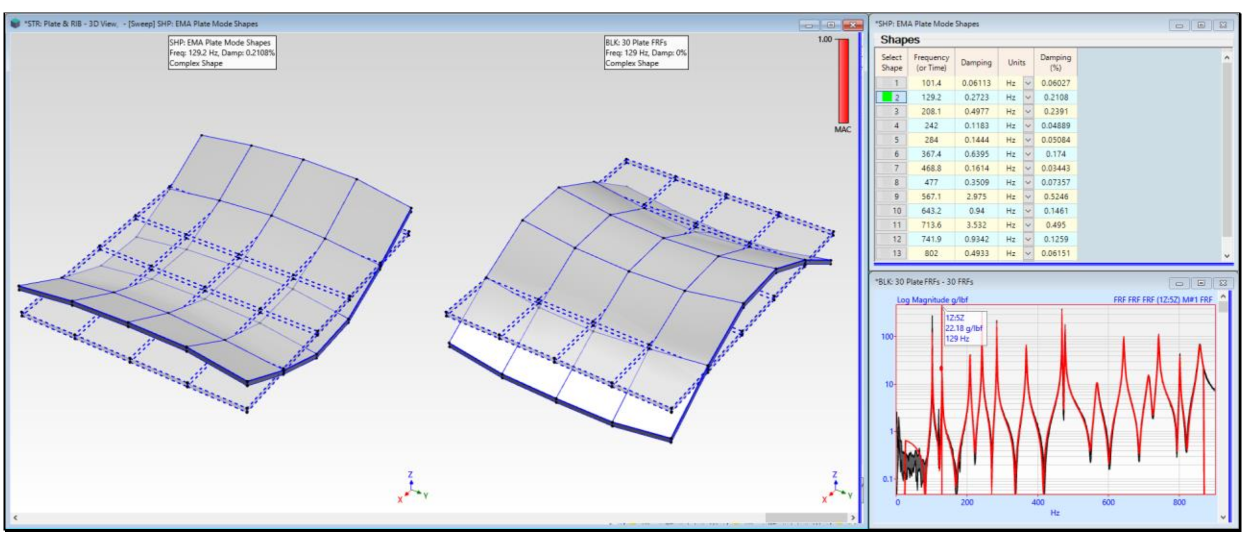
STEP 1 - COMPARING EMA MODE SHAPES WITH ODS's OF THE PLATE

- ***Press* Hotkey 1 EMA Mode Shapes vs. ODS's of the Plate**

FRFs were calculated from data acquired on the Plate during a roving Impact test. During the test, the Plate was impacted in the vertical direction at **30 points**, as shown above. The Plate was supported on bubble wrap on a tabletop as shown above. This is ***nearly a*** **free-free boundary condition**.

When **Hotkey 1 is *pressed***, the **EMA** modal shapes of the Plate are estimated by curve fitting the FRFs of the Plate. A curve fit function is overlaid on one of the FRFs as shown below. Each **EMA** mode shape has **30 DOFs** (**1Z** through **30Z**).

Then a side-by-side animation of each **EMA** mode shape and its ***closest matching*** ODS from the FRFs is begun, as shown below.



*Side-By-Side Animation of each **EMA** Mode Shape & its Closest Matching ODS From the FRFs.*

- ***Click*** on a **Select Shape** button in **SHP: EMA Mode Shapes *on the upper-right*** to display a mode shape and its ***closest matching*** **ODS**
- Scroll through the FRFs ***on the lower-right*** to display each **red curve fit function** overlaid on its FRF

STEP 2 - COMPARING FEA & EMA MODE SHAPES OF THE PLATE

- ***Press*** **Hotkey 2 FEA vs. EMA Plate Mode Shapes**

An **FEA** model of the Plate was constructed in MEscope using ***80 FEA Plate (membrane) elements***. The following properties of the aluminum Plate were used,

Young's modulus of elasticity: 1E+07 lbf/in^2 (or 6.895E+04 N/mm^2)

Density: 0.101 lbm/in^3 (or 2.796E-06 kg/mm^3)

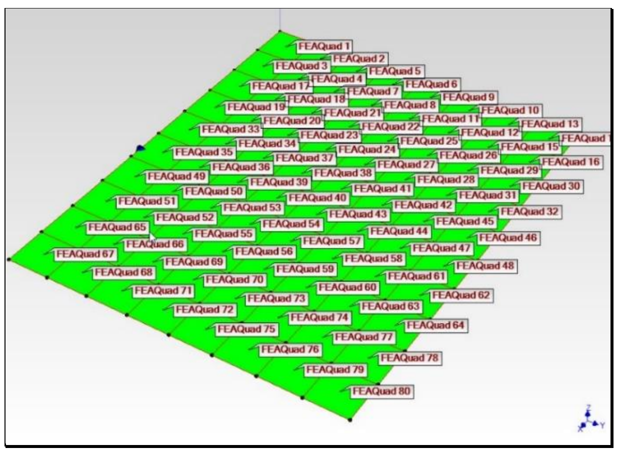
Poisson's Ratio: 0.33

Plate thickness: 0.375 in (or 9.525 mm)

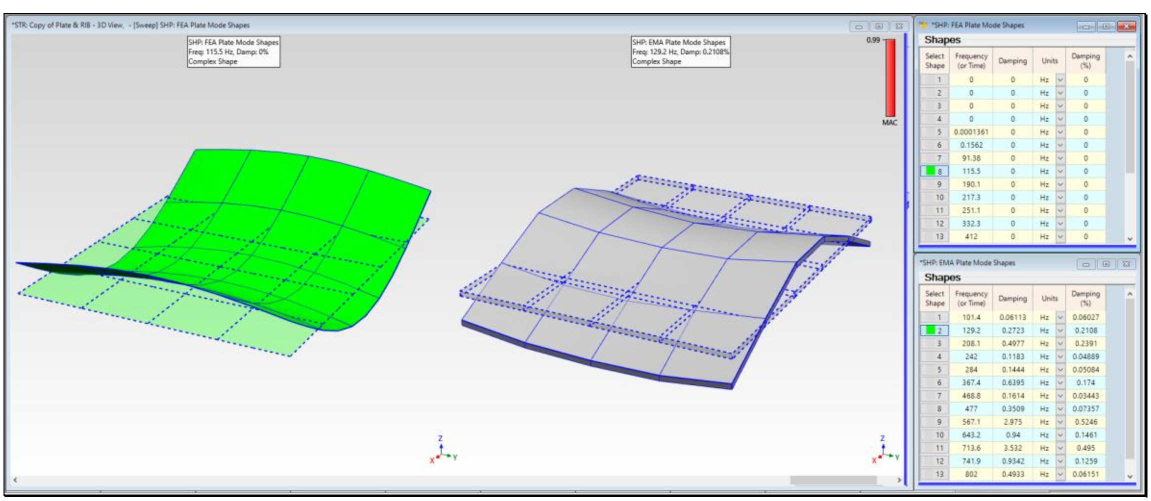
The **FEA** model shown below has a grid of 99 points (or nodes) and 80 **FEA** Quad Plate elements.

When **Hotkey 2 *is pressed***, **20 FEA** mode shapes (***6 rigid-body & 14 flexible-body*** **mode shapes**) of the Plate are calculated. Then side-by-side animation of each **FEA** mode shape and ***its closest matching*** **EMA** mode shape is begun.

- ***Click*** on a **Select Shape** button in **SHP: FEA Plate Mode Shapes** to display an **FEA mode shape** and its ***closest matching*** **EMA mode shape**



***FEA** model with 80 **FEA** Quad Plate Elements*



*Closest Matching **FEA & EMA** Mode Shapes for the Plate Without RIB*

MODE SHAPE COMPARISON

The shape animation sweeps through a display of each **FEA** mode shape, **starting with Shape 7**.

The **first six FEA** mode shapes are ***rigid-body*** mode shapes

FEA mode shapes **7 through 20** are ***flexible-body*** mode shapes, and each of them ***closely matches*** with an **EMA** mode shape

Each **FEA** mode shape has **594 DOFs (*3 translational & 3 rotational* DOFs)** for each of the 99 Points on the **FEA** model. The **FEA** mode shapes are **UMM** mode shapes, properly scaled so ***they are a*** **Modal Model** of the Plate.

The **Modal Assurance Criterion** (**MAC**) value ***in the upper right corner*** of the mode shapes display indicates how ***closely matched*** each pair of mode shapes is.

The ***worst-case matching pair*** of mode shapes has **MAC → 0.98**

The MAC values indicate ***close correlation*** between the FEA & EMA mode shapes for matching translation **DOFs (1Z** through **30Z*)***

MODAL FREQUENCY COMPARISON

The modal frequencies of the closest matching **FEA** & **EMA** mode pairs are listed in the Table below. Each **FEA** mode shape has a **frequency *lower than*** the **frequency *of its closest matching* EMA** mode shape.

The higher **EMA** modal frequencies mean that the **stiffness** of the actual aluminum Plate ***is greater than*** the **stiffness** of the **FEA** model

FEA Model Updating could be used to reduce the frequency differences by ***modifying the physical properties*** of the **FEA** Plate model. (**FEA Model Updating** of the Plate is the topic of **App Note 29**.)

Shape Number	FEA Frequency (Hz)	EMA Frequency (Hz)	EMA Damping (Hz)	MAC
1	91.38	101.5	0.04487	0.98
2	115.5	129.1	0.264	0.99
3	190.1	208.1	0.4977	0.99
4	217.3	242.0	0.1089	0.99
5	251.1	284.0	0.1444	0.99
6	332.3	367.5	0.6455	0.98
7	412.0	468.7	0.1659	0.98
8	424.3	477.0	0.3509	0.99
9	495.7	567.1	2.979	0.99
10	563.6	643.2	0.9498	0.99
11	625.9	713.6	3.583	0.98
12	653.6	741.9	0.9449	0.99
13	688.7	802.0	0.4814	0.98
14	756.6	858.6	3.087	0.98

*Closest Matching **FEA** & **EMA** Mode Shapes for the Plate without RIB.*

HYBRID MODAL MODELS

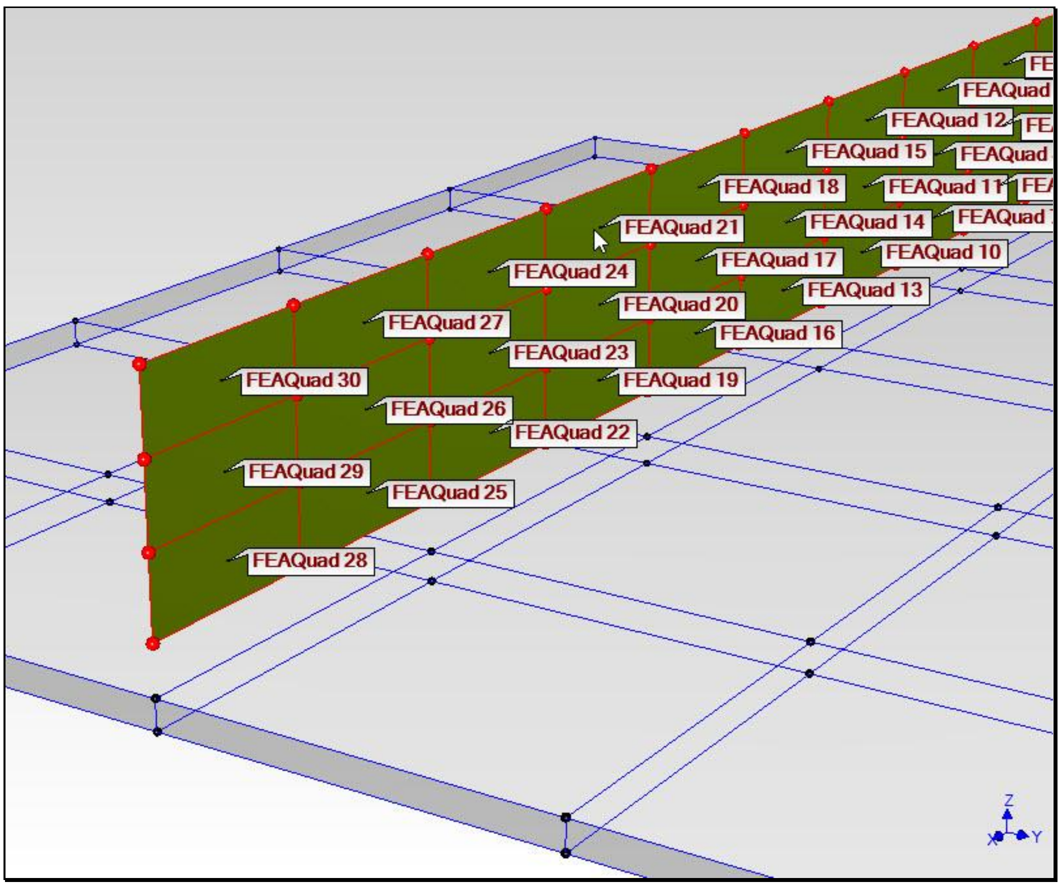
To correctly model the stiffness between the Plate & RIB, the modal frequency & damping of each **EMA** mode shape was combined with each ***closely matching*** **FEA** mode shape to create a **Hybrid Modal Model**.

In most cases, **EMA** mode shapes ***have fewer*** **DOFs** than **FEA** mode shapes of the same structure. But in most cases, **EMA** mode shapes have ***more accurate*** **modal frequencies** than **FEA** mode shapes.

Damping is difficult to model, so ***most*** **FEA models** ***have no damping in them***. Hence, **FEA** mode shapes have no modal damping. On the other hand, **EMA** mode shapes ***always have non-zero modal damping*****.**

If pairs of **FEA** & **EMA** mode shapes are ***highly correlated*** (their **MAC** values are high), a **Hybrid Modal Model** can be created by adding the frequency & damping of each **EMA** mode shape to its ***closely matching*** **FEA** mode shape.

Since **FEA** mode shapes have **translational & rotational DOFs**, using a **Hybrid Modal Model** for both the Plate & RIB, and using **6-DOF FEA** springs to connect them together using **SDM**, more accurate mode shapes of the Plate & RIB are the result.



RIB ***FEA*** *Model with Quad Plate Elements*

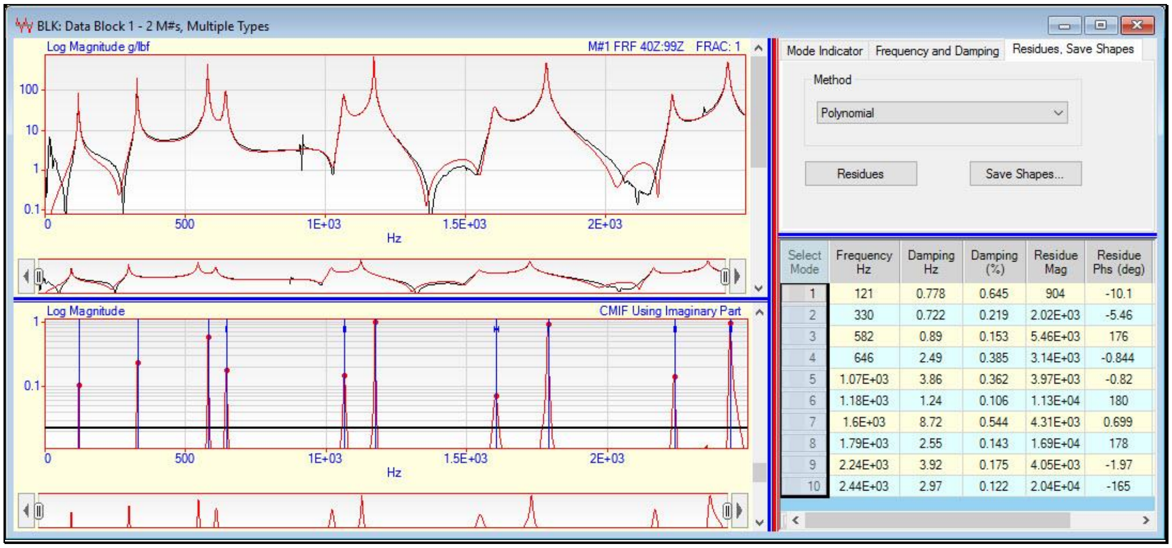
RIB HYBRID MODAL MODEL

An **FEA** model of the RIB with free-free boundary conditions (**no fixed boundaries**) was created using 30 **FEA** Quad Plate elements, as shown above. The frequencies of the first 16 **FEA** modes of the RIB are listed in the Table below.

With ***free-free boundary conditions***, the ***first six modes*** of the **FEA** model have ***rigid-body*** **mode shapes** with zero modal frequencies.

RIB IMPACT TEST

The RIB was only impacted once, and the resulting FRF calculated from the impact data was curve fit to obtain the **EMA** modal frequency & damping of its **EMA** modes. The curve fit of the FRF measurement is shown in the figure below. The resulting **EMA** modal frequencies & damping are listed in the Table below.



Curve Fit of a RIB FRF.

Shape Number	FEA Frequency (Hz)	EMA Frequency (Hz)	EMA Damping (Hz)
1	0		
2	0		
3	0		
4	0		
5	0		
6	0		
7	117	121	0.778
8	315	330	0.722
9	521	582	0.89
10	607	646	2.49
11	987	1.07E+03	3.86
12	1.07E+03	1.18E+03	1.24
13	1.45E+03	1.6E+03	8.72
14	1.67E+03	1.79E+03	2.55
15	1.99E+03	2.24E+03	3.92
16	2.32E+03	2.44E+03	2.97

RIB Modal Frequencies & Damping

The **EMA modal frequencies** of the RIB ***are higher*** than the **FEA** modal frequencies, for the same reasons as those discussed for the Plate.

Assuming that the **EMA modal frequency & damping *are more accurate***, they were combined with the **FEA** mode shapes of the RIB to create a **Hybrid Modal Model** of the RIB.

SUBSTRUCTURE BLOCK DIAGONAL FORMAT

The figure below shows how the points on the RIB are **numbered with higher numbers** than the points on the Plate.

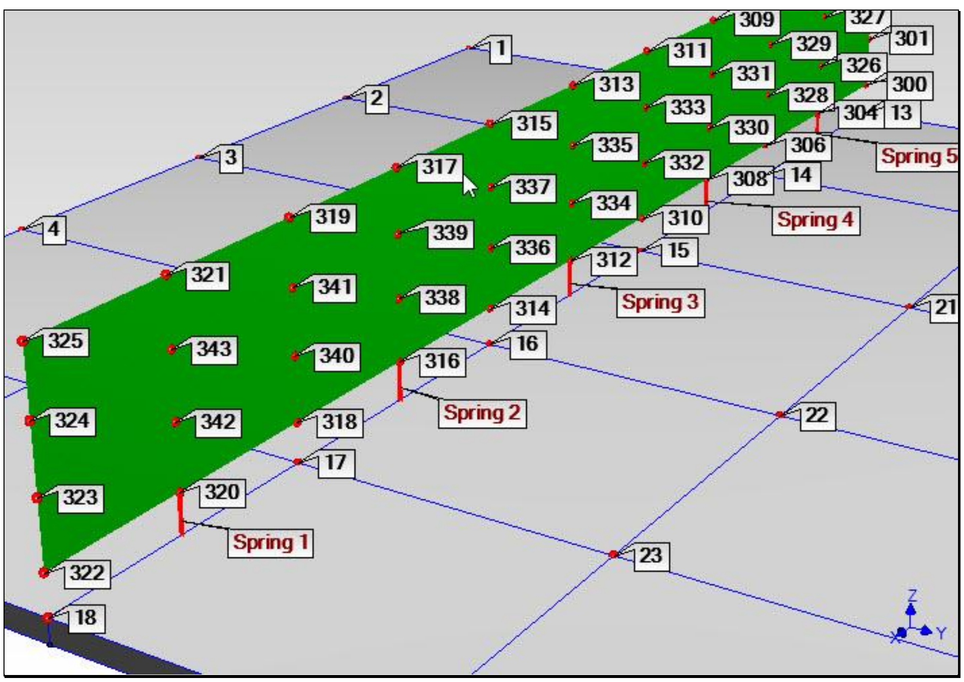
For sub-structuring, the **DOFs** of the RIB mode shapes must have different point numbers than the **DOFs** of the Plate mode shapes.

Different point numbers ensures that the mode shapes of the ***unmodified*** **Plate** and ***unmodified*** **RIB** will be saved in ***block diagonal* format** in the same Shape Table.

When the **Modal Model** of the RIB is added to the **Modal Model** of the Plate, the unique numbering of the points on both the RIB and Plate creates a **Modal Model** in ***block diagonal* format**.

In ***block diagonal* format**, the mode shapes of the Plate have **zero valued shape components** for DOFs on the RIB.

Likewise, the mode shapes of the RIB have **zero valued shape components** for the DOFs of the Plate.

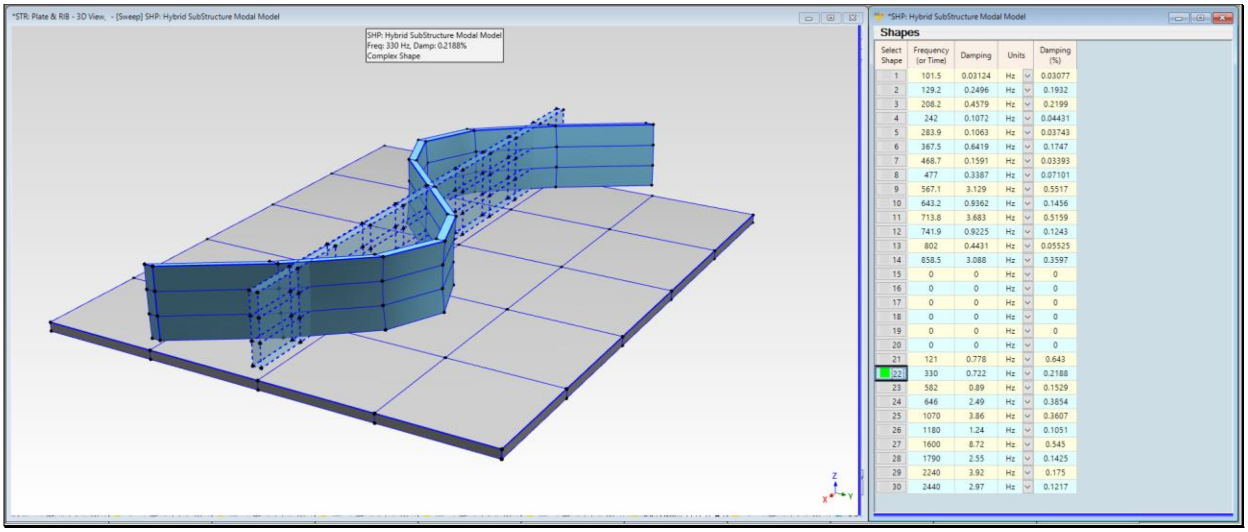


Point Numbers of the RIB and Plate

STEP 3 - SUBSTRUCTURE MODAL MODEL

- **Press Hotkey 3 Substructure Modal Model**

To use **SDM** to calculate the new mode shapes of the RIB attached to the Plate, the **Hybrid Modal Model** of the RIB must be added to the **Hybrid Modal Model** of the Plate to create a **Modal Model** for the ***entire unmodified* structure**.



*Animated Display of a Mode Shape of the Substructure **Modal Model**.*

- ***Click*** on **Select Shape** button **1 to 14** to display a mode shape of the Plate
- ***Click*** on **Select Shape** button **15 to 30** to display a mode shape of the RIB

The substructure **Modal Model** contains **30** mode shapes with **429 translational & 429 rotational DOFs**.

The Plate portion of the **Modal Model** contains **14** mode shapes with **297 translational & 297 rotational DOFs**.

The RIB portion of the **Modal Model** contains **16** mode shapes with **132 translational & 132 rotational DOFs**.

STEP 4 – COMPARING SDM & FEA MODE SHAPES OF THE PLATE & RIB

To calculate the **SDM** mode shapes for the Plate & RIB attached together with 5 **FEA** Springs,

- **Press Hotkey 4 SDM vs. FEA Plate & RIB Mode Shapes**

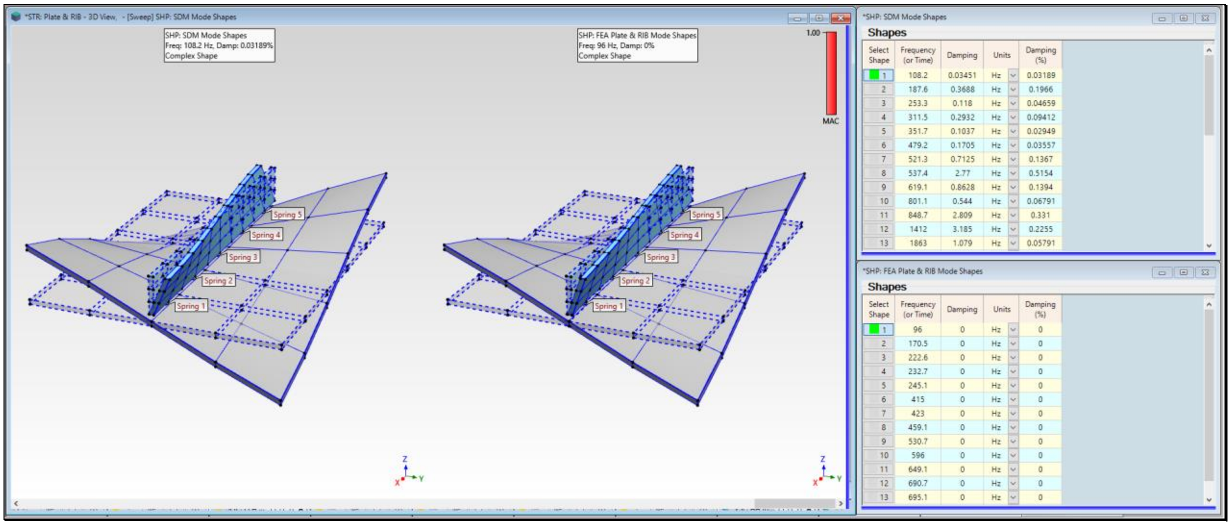
Five FEA Springs are used by **SDM** to model the five cap screws that were used to attach the actual RIB to the Plate. The **FEA Springs** were used together with the **substructure Modal Model** of the ***unmodified*** **Plate & RIB sub-structures** as inputs to **SDM**.

The mode shapes in the ***substructure*** **Modal Model** have **858 DOFs**, but only the **mode shape DOFs *at the attachment points*** of the **FEA** springs are used by **SDM** to calculate the new mode shapes of the RIB attached to the Plate.

When **Hotkey 4 is *pressed***, both **SDM** mode shapes and **FEA** mode shapes of the Plate & RIB are calculated.

An **FEA** model consisting of the 80 Quad Plate elements of the Plate, 30 Quad Plate elements of the RIB, and the five 6-DOF springs is solved for the **FEA** mode shapes using the **VES 8000 FEA option** in MEscope.

After both **SDM** & **FEA** mode shapes have been calculated, side-by-side animation of ***closest matching pairs*** of **SDM** and **FEA** mode shapes is initiated, as shown below.



*Side-By-Side Display of Closest Matching Pairs of **SDM** & **FEA** Mode Shapes*

- ***Click*** on a **Select Shape** button in ***either*** **Shape Table** ***on the right*** to display an **SDM** mode shape and its ***closest matching*** **FEA** mode shape

The **MAC** value for each pair of mode shapes is also displayed in the ***upper right corner*** of the mode shape display.

The **SDM** and **FEA** frequencies and mode shapes are compared in the Table below.

The ***first nine mode shapes*** have **MAC ➔** ***above*** **0.90**, indicating a ***strong correlation*** between the SDM & FEA mode shapes

Each **SDM modal frequency** ***is higher than*** the modal frequency of its ***matching*** **FEA** mode shape

The lower **FEA** mode shape frequencies can result because,

1. The **FEA** material properties ***are inaccurate***
2. A ***finer*** **FEA** ***element mesh is required***

Shape Pair	**FEA Frequency (Hz)**	**SDM Frequency (Hz)**	**SDM Damping (Hz)**	**MAC**
1	96.0	108.2	0.03451	1.00
2	170.5	187.6	0.3688	0.99
3	222.6	253.3	0.118	0.98
4	232.7	311.5	0.2932	0.92
5	245.1	351.7	0.1037	0.98
6	415.0	479.2	0.1705	0.98
7	423.0	521.3	0.7125	0.91
8	459.1	537.4	2.77	0.95
9	530.7	619.1	0.8628	0.91

***SDM** & **FEA** Mode Shape Pairs for the Plate & RIB*

The mode shapes **numbered in red** ***clearly reflect the torsional influence*** between the RIB & Plate.

The ***first nine mode shape pairs*** show that ***all bending along the centerline of the Plate has been eliminated*** by attaching the RIB to the centerline

The **stiffness** exerted by the **6-DOF FEA** springs at their attachment points ***accurately modeled*** the **stiffness** of the five cap screws

Attaching the RIB to the Plate has created new mode shapes that did not exist prior to the modification. Using mode shapes to ***model the dynamics of the unmodified*** **substructures** verifies a **Fundamental Rule of Modal Analysis**,

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

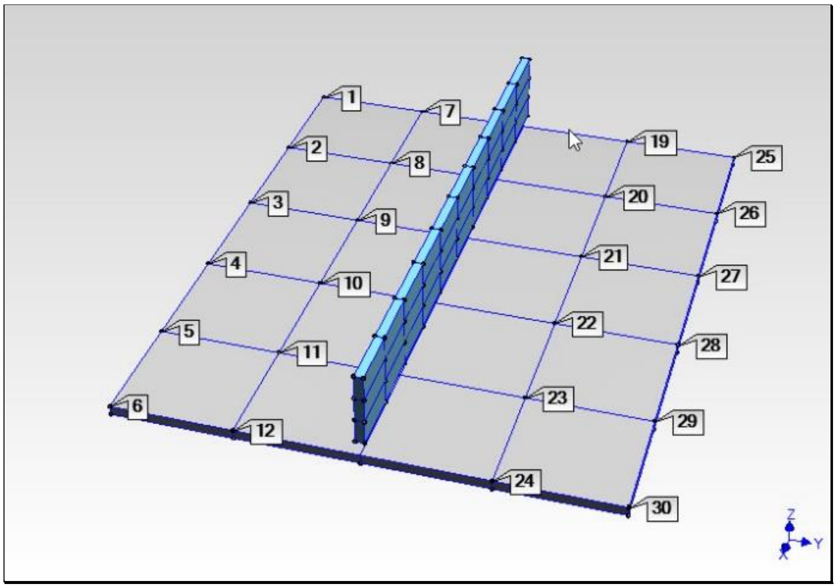
STEP 5 - COMPARING EMA & SDM MODE SHAPES OF THE PLATE & RIB

- ***Press* Hotkey 5 EMA vs. SDM Plate & RIB Mode Shapes**

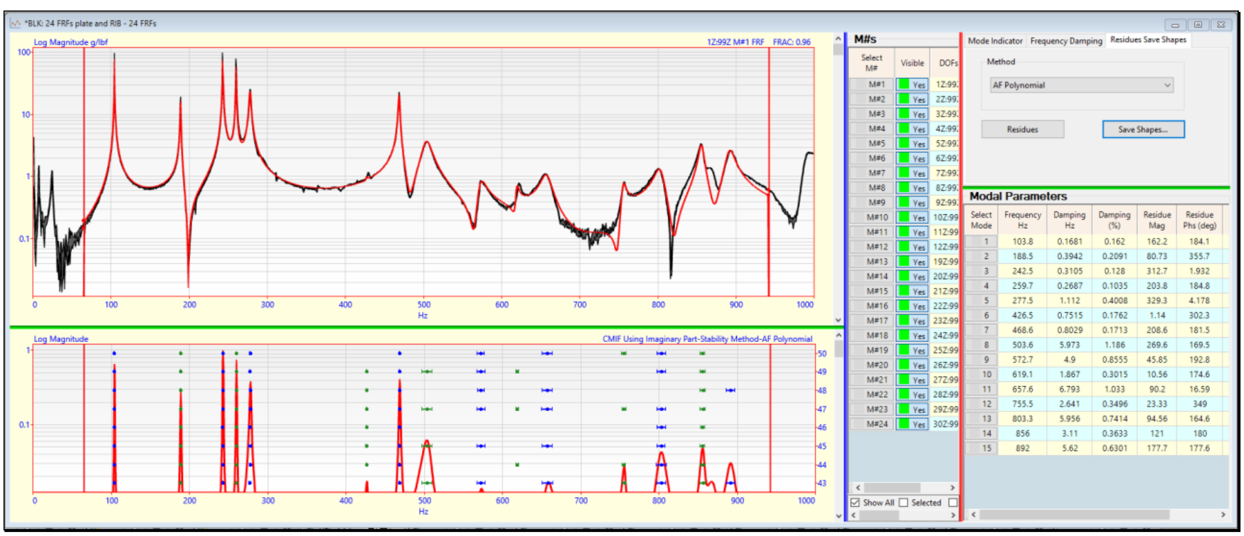
To further validate the new mode shapes calculated by **SDM**, the Plate & RIB was tested again using a **Roving Impact test**. The Plate was impacted at only 24 points, in the ***vertical direction (Z-direction)*** to provide **EMA** mode shapes ***with enough* DOFs *to compare*** with the **SDM** mode shapes at the same DOFs.

> **MAC** is calculated for a pair of mode shapes using data ***from the same* DOFs** of each mode shape.
>
> **UMM** mode shape scaling ***is not necessary*** to compare mode shapes using **MAC**.

When **Hotkey 5 is *pressed***, the 24 FRFs from the Roving Impact test on the Plate are curve fit to estimate the **EMA** mode shapes for the Plate & RIB. The curve fit of a typical FRF of the Plate & RIB is shown below.

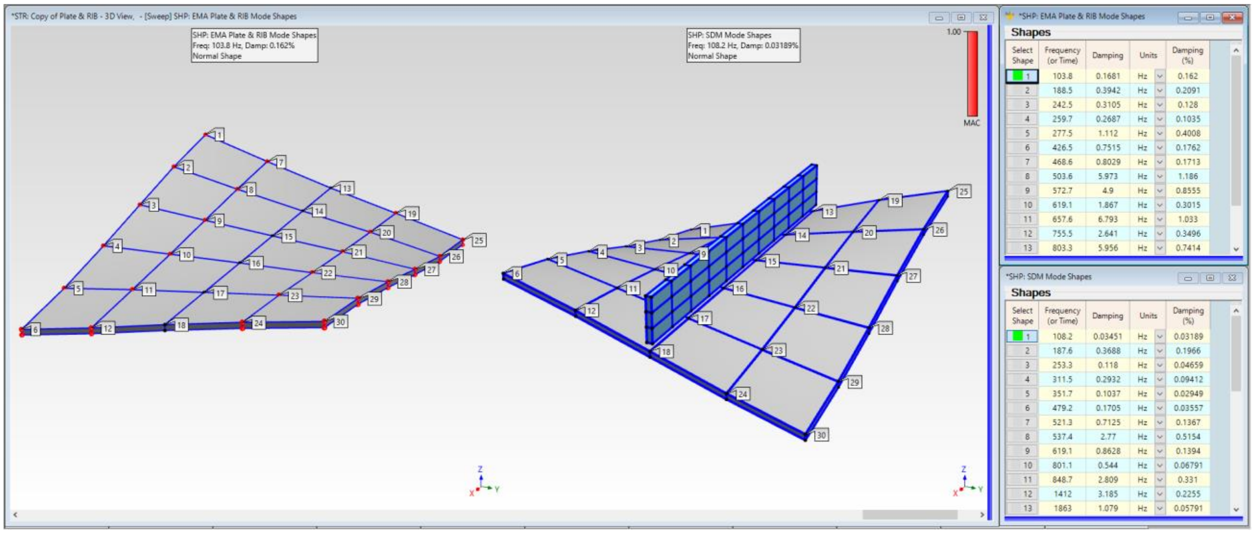


Impact Points on Plate & RIB



Curve Fit of an FRF from the Plate & RIB

Then, the **SDM** mode shapes of the Plate & RIB are calculated again and compared with the **EMA** mode shapes. Each **SDM** mode shape is compared in sweep animation with its ***closest matching*** **EMA** mode shape, and the **MAC** value for each matching pair is also displayed.



*Animated Display of Closest Matching **EMA** & **SDM** Mode Shapes*

Shape Pair	EMA Frequency (Hz)	EMA Damping (Hz)	SDM Frequency (Hz)	SDM Damping (Hz)	MAC
1	103.775	0.168082	108.224	0.0345102	0.99
2	188.532	0.394235	187.594	0.368779	0.99
3	242.546	0.310464	253.271	0.117998	0.99
4	277.526	1.11224	311.499	0.29319	0.97
5	259.706	0.268717	351.704	0.103731	0.98
6	468.592	0.802932	479.208	0.170474	0.98
7	503.623	5.97258	521.285	0.71248	0.97
8	572.692	4.89965	537.407	2.76984	0.97
9	619.114	1.86654	619.101	0.862819	0.79
10	803.259	5.95561	801.09	0.544049	0.88
11	891.974	5.62049	848.693	2.80934	0.86

*Closely Matched **EMA** & **SDM** Mode Shapes for the Plate & RIB*

CONCLUSIONS

After verifying that pairs of **EMA** & **FEA** mode shapes of the ***unmodified*** **Plate** were in close agreement, the **modal frequency & damping** of each **EMA** mode shape was combined with its ***closely-matched*** **FEA** mode shape to create a **Hybrid Modal Model** for the ***unmodified*** **Plate**.

In like many, a **Hybrid Modal Model** of the RIB was created which included it ***six rigid-body*** **mode shapes**. The rigid-body mode shapes, which were obtained from the FEA model, are necessary to model the free-boy dynamics of RIB prior to attaching it to the Plate.

The close agreement between the **SDM, FEA, & EMA** mode shapes for the ***first three flexible-body*** mode shapes verify that the stiffness of the five cap screws used to attach the RIB to the Plate was correctly modeled in SDM using **6-DOF FEA** springs and **Hybrid** mode shapes.

Several options could be tried to obtain closer agreement between the **SDM**, **FEA** & **EMA** mode shapes.

Use more **6-DOF FEA** springs between the Plate & RIB to model the joint stiffness between the two substructures

Increase the **finite element mesh** of the Plate & RIB to provide more accurate **FEA** mode shapes for their **Hybrid Modal Models**

Include more **Plate & RIB mode shapes** in the substructure **Modal Model**s to provide a more complete dynamic model of the two substructures

STEP 6 - REVIEW STEPS

To review the previous steps in this App Note,

- **Press Hotkey 6 Review Steps**