VIBRANT

MEscope Application Note 24

Choosing Reference DOFs for a Modal Test

The steps in this Application Note can be carried out using any MEscope package that includes the **VES-3600 Advanced Signal Processing** and **VES-4000 Modal Analysis** options. Without these options, you can still carry out the steps in this App Note using the **AppNote24** project file. These steps might also require MEscope software with ***a more recent release date***.

APP NOTE 24 PROJECT FILE

- To retrieve the Project file for this App Note, **click here** to download **AppNote24.zip**

This Project contains ***numbered Hotkeys & Scripts of MEscope 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

INTRODUCTION

Finite Element Analysis (**FEA**) can provide guidance for conducting a modal test, also called an Experimental Modal Analysis (**EMA**). Utilizing a set of FEA mode shapes prior to performing a modal test reduces testing time and leads to better experimental results.

In this note FEA mode shapes are used to determine where excitation forces should be applied (or where a fixed response sensors be attached) to a real-world structure to extract its experimental mode shapes. In MEscope, the animated display of a “Shape Product” clearly shows the best locations for attaching a shaker or a reference accelerometer.

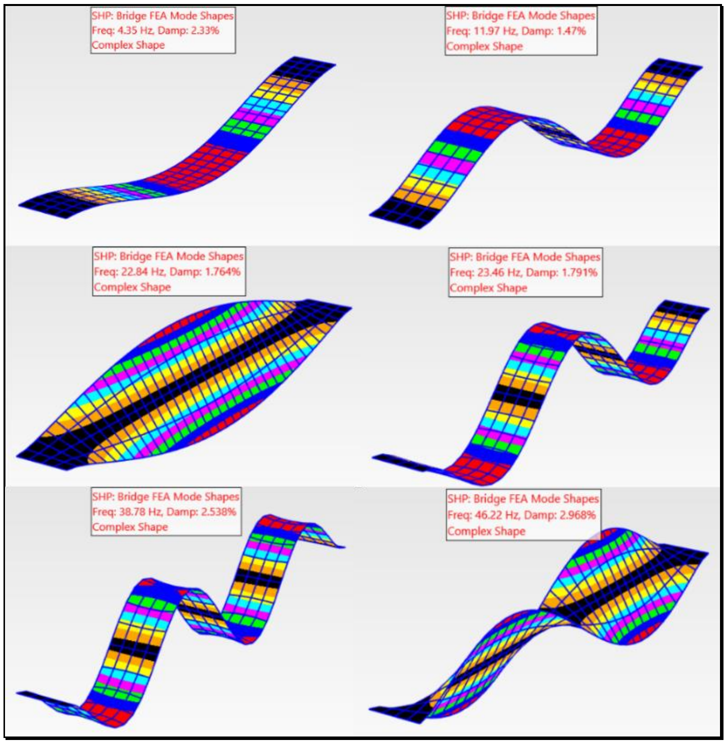
Experimentally derived mode shapes are called **EMA** mode shapes.

Mode shapes derived from an FEA model are called **FEA** mode shapes.

The FEA mode shapes used in this App Note were calculated using the **VES-8000 Finite Element Analysis** option in MEscope, but that option is not required to carry out the steps in this App Note.

Two important questions are addressed in this App Note,

1. ***How many references*** (shakers, fixed impact points, or fixed response sensors) are required to accurately identify the EMA mode shapes of the structure?
2. Where should the **reference sensors *be located***?



FEA Mode Shapes of Pinned-Pinned FEA Bridge Model.

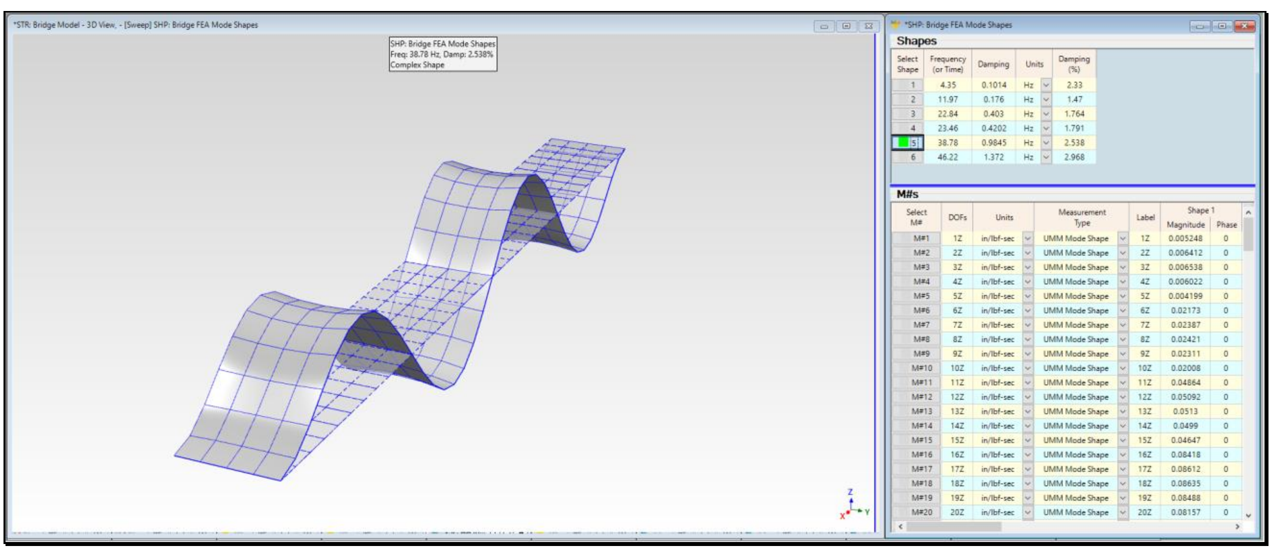
THE FEA MODEL

The FEA model of the test article is a small-scale model of a bridge with a span of 27 feet and a width of 3 feet. Both ends of the bridge are ***pinned to rigid supports***. The FEA modal model contains six modes below 50 Hz, as shown above. Each FEA mode shape has 175 DOFs (degrees-of-freedom or points & directions). All DOFs are in the vertical Z-direction. All the modes have modal damping of less than 3% of critical.

STEP 1 – FEA MODE SHAPE ANIMATION

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

Sweep animation will begin through the mode shapes in **SHP: Bridge FEA Mode Shapes**.



An FEA Mode Shape of the Bridge Model.

To select a mode shape for animation:

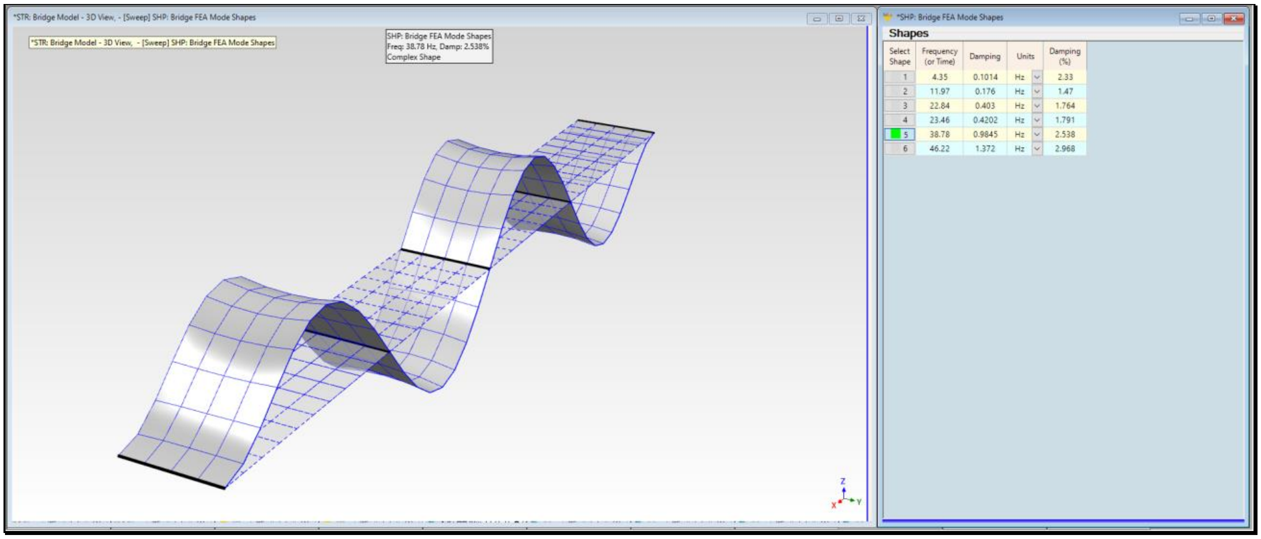
- Click on its **Select Shape** button in the **SHP: Bridge FEA Modes** window

STEP 2 - MODE SHAPE NODE LINES

- ***Press* Hotkey 2 Mode Shape Node Lines**

A **node line** is where a mode shape has **zero ("0") values.**

If a structure is excited ***on or near a* node line** of a mode shape, that mode will not ***participate or will participate very little*** in the overall vibration of the structure.



38.78 Hz Mode Shape With Five Node Lines.

The four bending modes at **4.35, 11.97, 23.46 & 38.78 Hz** have parallel node lines that run across the width of the bridge, in the Y-direction.

The **4.35 Hz** mode shape has **2 node lines** at the end-points of the bridge

The **11.97 Hz** mode shape has **3 node lines**, including one across the center span

The **23.46 Hz** mode shape has **4 node lines** including two near 1/3 and 2/3 of the span

The **38.78 Hz** mode shape has **5 node lines**, including one along the center of the bridge

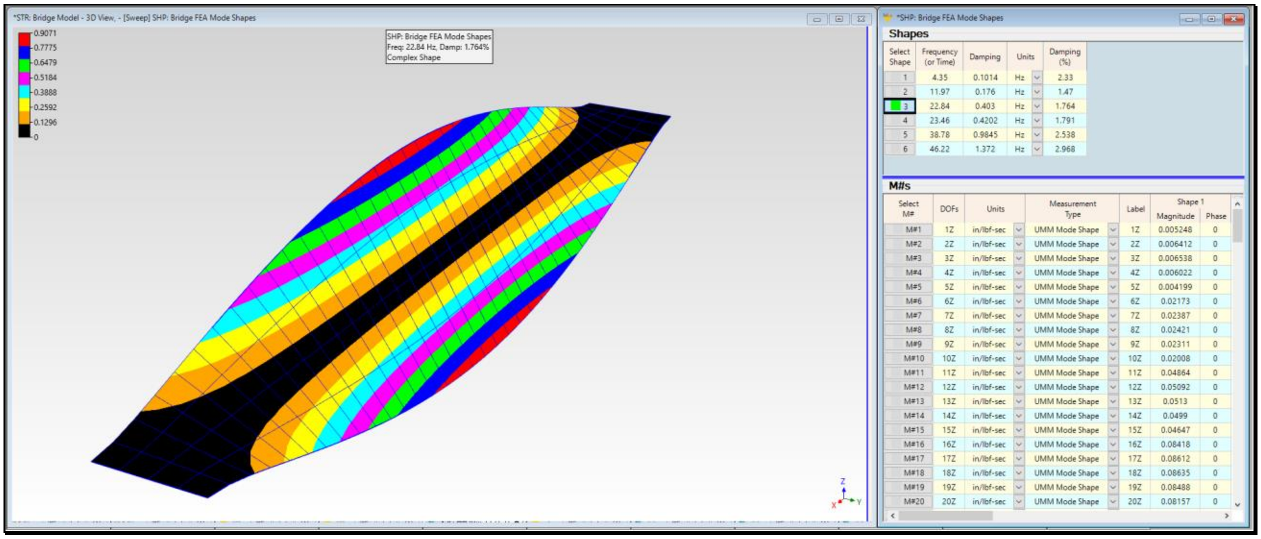
The two torsion modes (**at 22.84 Hz & 46.22 Hz**) have a **node line along the center** of the bridge (in the X-direction). The 46.22 Hz mode has a third Y-direction node line running **across the center** of the bridge.

All the mode shapes **have a node line in the Y-direction** at the ends of the bridge because the ends are fixed.

STEP 3 – COLOR CONTOURS

- ***Press* Hotkey 3 Color Contours**

> Color contours are displayed to indicate the ***amount of deformation*** of each mode shape.
>
> Color contours are defined on the **Contour Colors** tab in the **Options** box of the animation Source, in this case the **File | Shape Table Options** box in **SHP: Bridge FEA Modes**.



Mode Shape Contour Colors.

The red areas are the **anti-nodes** of each mode shape.

> **Anti-nodes** are the locations of **maximum response** of each mode shape.
>
> **Anti-nodes** are ***highly desirable locations*** from which to either excite a structure or to attach a reference response sensor.

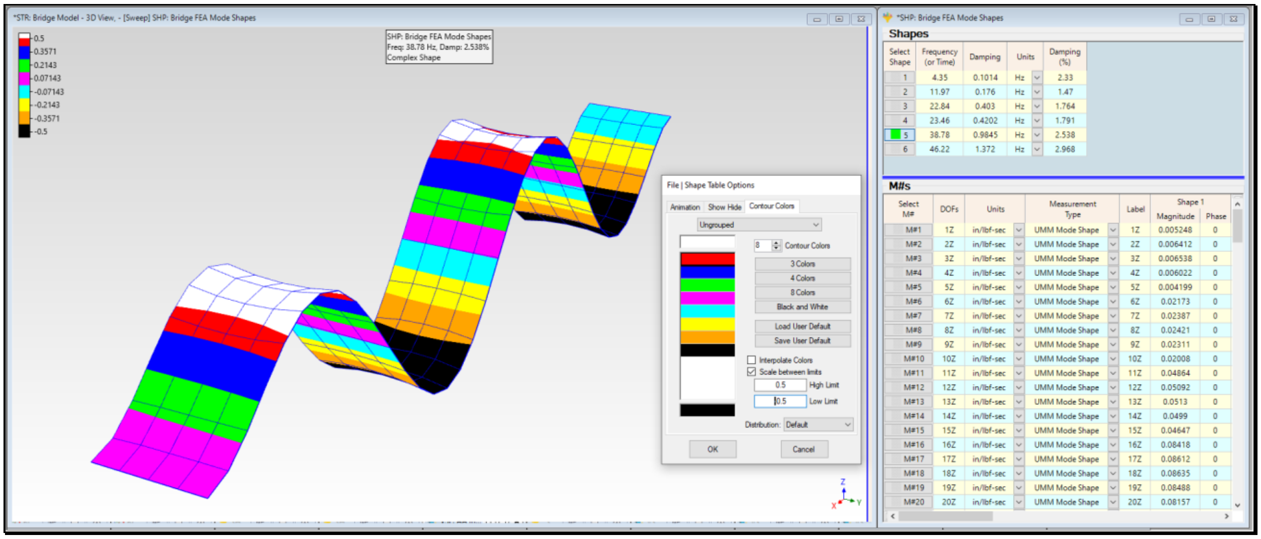
COLOR KEY

The Color Key is the ***"thermometer"*** that associates the ***magnitude of deformation*** with each contour color.

Color Contours and the Color Key can be also be displayed **between limits**.

- ***Check* Deflection | Contours | Surface Normals** in **STR: Bridge Model**
- Execute **File | Shape Table Options** in **SHP: Bridge FEA Mode Shapes** to open the dialog as shown below
- ***Check* Scale between Limits**
- Enter **0.5** for the **High Limit** and **-0.5** for the **Low Limit**

Color Contours are now displayed between the values of **+0.5** (color ➔ **white**), and **-0.5**(color ➔ **black**).



Color Contours Scaled Between Limits and Interpolated.

SELECTING A REFERENCE DOF

Most modal testing, or Experimental Modal Analysis (**EMA**), is done using a **single-reference testing method**.

The fixed DOF in a single-reference modal test is called **the reference DOF.**

A single-reference modal test can be done several ways,

- A single shaker is used to provide excitation at a **single DOF**
- A **single DOF** is impacted with an instrumented impact hammer
- A **single uni-axial accelerometer** is ***attached to a single point*** on the test article and it is impacted at multiple DOFs

Single reference modal testing provides the best results when ***all the modes of interest at or near an* anti-node** at the **reference DOF**.

DRIVING-POINT FRFs

If no FEA mode shapes are available prior to a modal test, the best way to locate a good **reference DOF** (where all the modes of interest are responsive) is to make a series of driving point measurements and count the peaks in each FRF.

Some important facts about mode shapes & FRFs are useful for locating a good **reference DOF**.

The magnitude of each resonance peak in an FRF is proportional to the ***product of two mode shape components***, one corresponding to its **response DOF** and the other corresponding to its **reference DOF**.

The magnitude of each resonance peak in a driving point FRF is ***proportional to the square of the mode shape component*** for the driving point DOF.

If a **reference DOF *is chosen on a* node line** of a mode shape, a resonance peak for that mode ***will not appear in any* FRF** calculated from data acquired at the **reference DOF**.

In a set of FRFs, the first evidence that a mode of vibration has been excited is the appearance of a resonance peak in at least some of the FRFs.

When a driving-point FRF ***has a large peak for each mode of interest***, that is a **good reference DOF**.

Finding such a point using trial FRF measurements can be very time consuming though. Using FEA mode shapes to find a ***suitable*** **reference DOF** is a much more efficient method.

STEP 4 - SHAPE PRODUCT

- ***Press* Hotkey 4 Shape Product**

Multiplying several mode shapes together will yield a **Shape Product** that includes the node lines of all the mode shapes

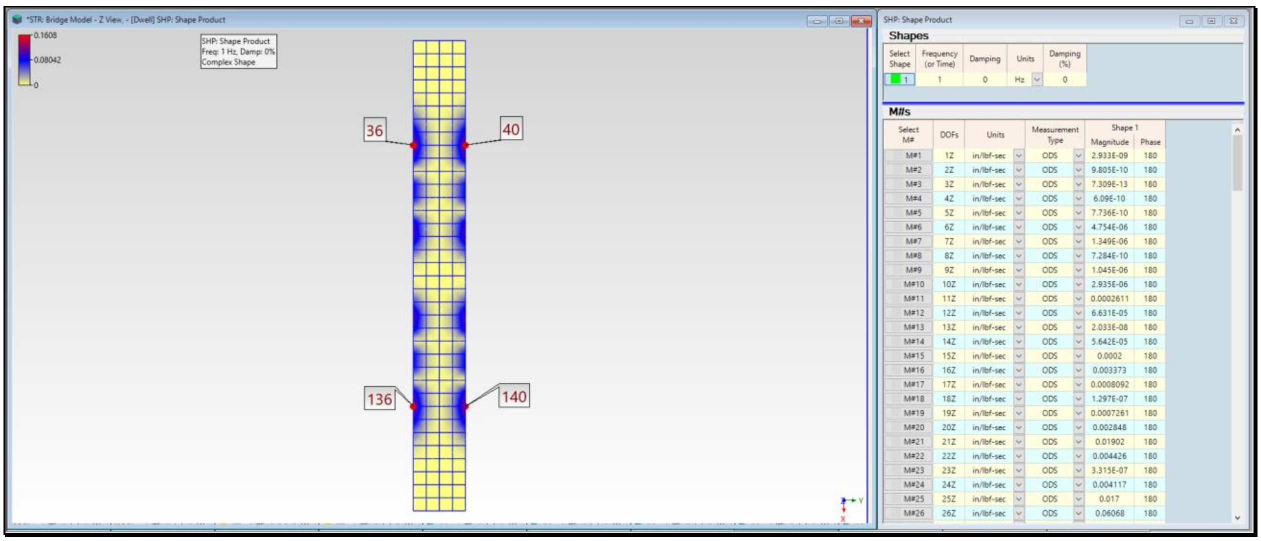
Rather than guessing at a good **reference DOF**, multiplying a set of FEA mode shapes together and animating their **Shape Product** is a much better way to locate a **reference DOF**.

By multiplying mode shapes together, all the DOFs on a **node line *of any mode shape*** will cause the **resulting Shape Product** to have a node line ***for the same* DOFs**.

When the **Shape Product** is displayed in animation of a 3D model, all the ***anti-nodes***, (where the **Shape Product** is ***non-zero***) will be clearly visible.

In animated display with Color Contours enabled, all DOFs of a Shape Product for anti-nodes will have a different color than node lines.

Color contours of a Shape Product ***corresponding to the* anti-nodes** point out the best choices for a **reference DOF**.



Color Contours Showing Anti-Nodes of the Shape Product.

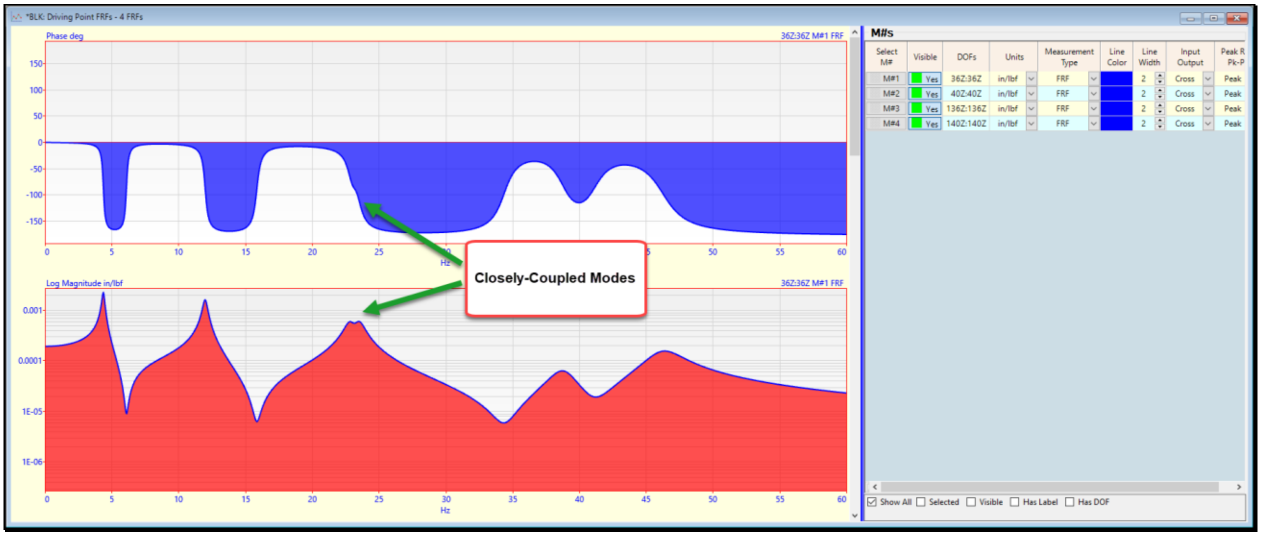
The color contour display of the **Shape Product** clearly shows that there ***six (6) equally attractive* reference DOFs** on either side of the bridge. Any one of these DOFs would be a **good reference DOF** for exciting the bridge with a shaker, or for locating a reference sensor to perform a roving impact test.

Four DOFs (**36Z, 40Z, 136Z & 140Z**) are all good choices for a **reference DOF**.

STEP 5 - SYNTHESIZING DRIVING POINT FRFs

- ***Press*** **Hotkey 5 Driving-Point FRFs**

The correctness of the reference DOFs can be verified by synthesizing their driving-point FRFs and examining them for resonance peaks.



Synthesized Driving Point FRFs

All four driving-point FRFs ***are identical***.

- ***Rapidly Scroll*** the display of the FRFs to verify that they are the same

All six resonance peaks are clearly visible, but the **two modes at 22.8 & 23.5 Hz *are closely-coupled***.

In a real-world modal test, measurement noise and distortion (non-linearity) would make closely-coupled resonant peaks hard to identify, and curve fitting the FRFs might not extract the mode shapes of the closely-coupled modes.

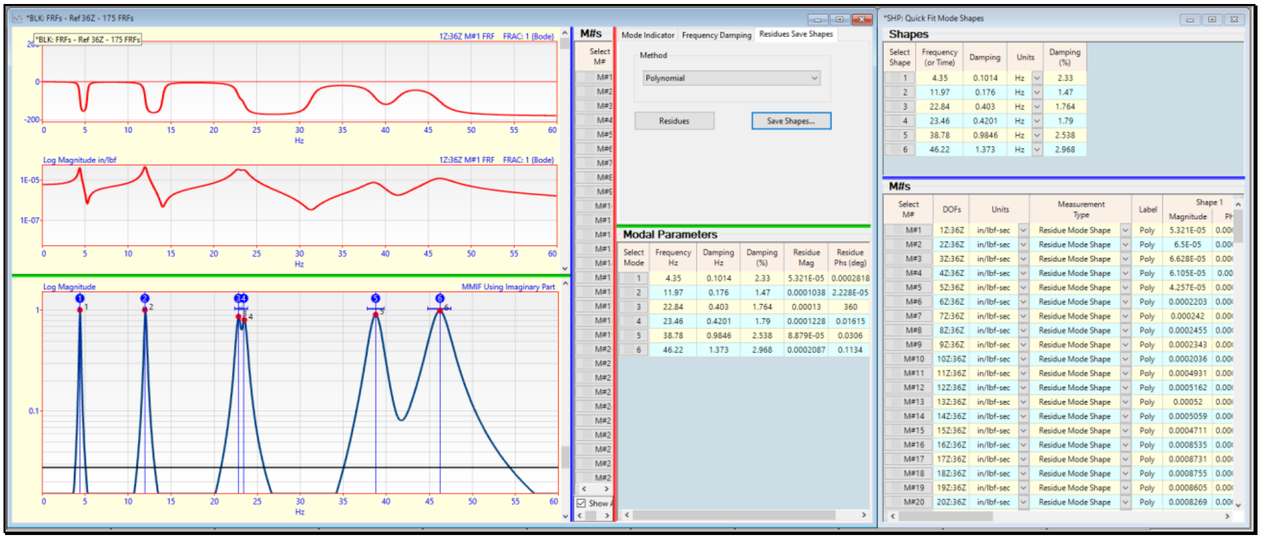
- ***More*** **FRF** ***frequency resolution*** and ***random excitation*** combined with ***spectrum averaging*** are two ways to improve the extraction of closely-coupled mode shapes

STEP 6 - CURVE FITTING SINGLE REFERENCE FRFs

- ***Press* Hotkey 6 Curve Fit 36Z FRFs**

When **Hotkey 6 is *pressed***, the six bridge FEA mode shapes are used to synthesize a set of single-reference FRFs using one of the previously identified reference DOFs. Since the FRFs are ***linear and noise -free***, curve fitting them will yield a set of mode shapes the ***perfectly match*** with the original FEA mode shapes.

The curve fitting tabs will open in the **BLK: FRFs - Ref 36Z** window, as shown below



Curve Fit of 175 Single Reference FRFs

FRF-BASED CURVE FITTING

Since the synthesized FRFs are linear, noise-free, and all six resonance peaks are visible and therefore can be counted, the **Quick Fit** curve fitting method can be used on them to extract the six mode shapes.

The modal parameters for the six modes are displayed in the Modal Parameters spreadsheet next to the Mode Indicator. The mode shapes were also saved in the **SHP: Quick Fit Mode Shapes** on the right. A **red Fit Function** is overlaid on each FRF.

- ***Scroll*** through the FRFs to examine the modal parameters and Fit Function for each FRF

STEP 7 - MODE SHAPE COMPARISON

- ***Press* Hotkey 7 Compare Mode Shapes**

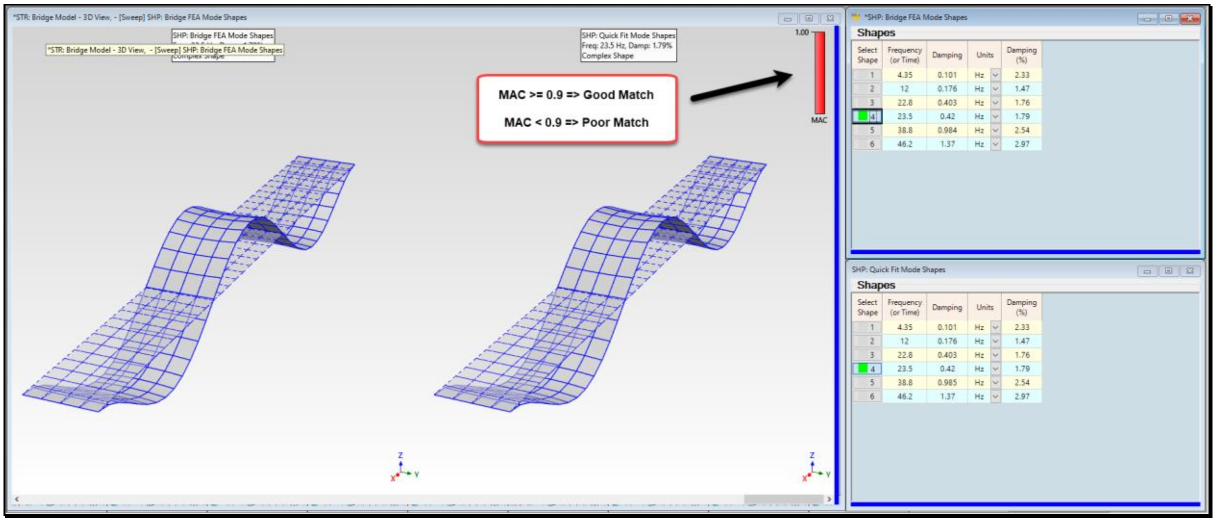
The mode shapes in **SHP: Quick Fit Mode Shapes** are called **Residue Mode Shapes**, whereas the mode shapes in **SHP: Bridge FEA Mode Shapes** are called **UMM Mode Shapes**. **Application Note 05** explains the difference between these two types of mode shape scaling.

- **Residue Mode Shapes** can be converted to **UMM Mode Shapes** and vice versa

Regardless of how it is scaled, the ***"shape"*** of a mode shape does not change. Pairs of shapes can always be compared numerically using the **Modal Assurance Criterion (MAC)**.

To display mode shape from **SHP: Bridge FEA Mode Shapes** side-by-side with the ***closest matching*** mode shape from **SHP: Quick Fit Mode Shapes**,

- The ***closest matching mode shape*** is the one that has the **Maximum MAC** among all mode shapes in the comparison Shape Table



FEA Mode Shape Versus Quick Fit Mode Shape.

Each mode shape pair has a **MAC value of 1.0**.

- **MAC = 1.0 ➔** two mode shapes ***are identical***

A visual comparison of the frequency & damping of each Quick Fit mode shape with the frequency & damping of each bridge FEA mode shape in the Shape Tables on the right also verifies the accuracy of the **Polynomial** curve fitting method used by the **Quick Fit** command, even when ***two modes are closely coupled***.

REVIEW STEPS

To review the steps of this App Note,

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