MEscope Application Note 25

Choosing 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 **AppNote25** project file. These steps might also require MEscope software with ***a more recent release date***.

APP NOTE 25 PROJECT FILE

- To retrieve the Project file for this App Note, **click here** to download **AppNote25.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 App Note, **FEA** mode shapes are used to determine ***where response sensors should be attached*** to a real-world structure to extract its experimental mode shapes. On the case of a ***roving impact test***, where should the structure be impacted?

In MEscope, the animated display of mode shapes clearly shows the best locations for attaching accelerometers, or for impacting the structure in a roving impact test.

- Experimentally derived mode shapes are called **EMA** mode shapes
- Mode shapes derived from an **FEA** model are called **FEA** mode shapes
- Most **FEA** mode shapes contain ***far more* DOFs** than **EMA** 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 the App Note,

- What is the ***minimum number of test* DOFs** (degrees-of-freedom or points & directions) ***required to distinguish one EMA mode shape from another***?
- ***How many test* DOFs *are required*** to obtain a satisfactory graphic display of the **EMA** mode shapes?

CHOOSING TEST DOFs

How many test DOFs are required, and how should the test DOFs be selected? Several factors are important,

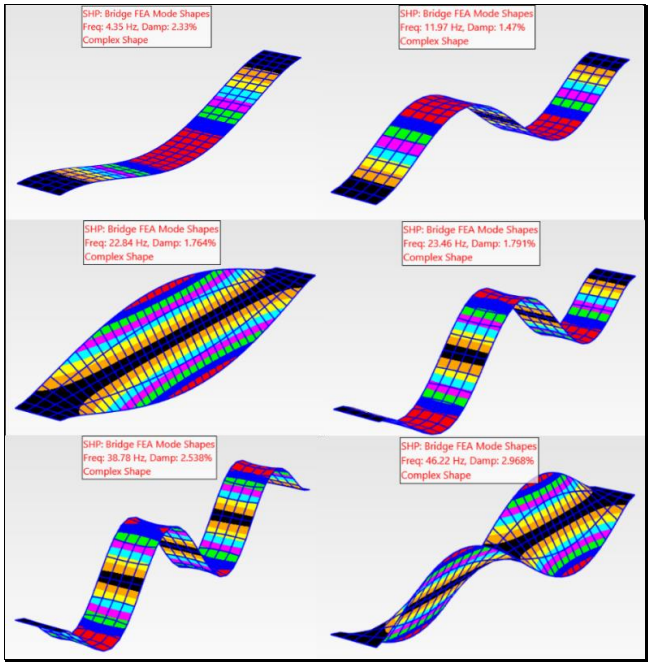
- Sufficient test DOFs ae required ***to allow unambiguous verification*** of every **EMA** mode shape
- If an **EMA** modal model of the structure is desired for **Structural Dynamics Modification (SDM)** or **MIMO Modeling & Simulation** studies, then ***at least one driving point acquisition*** (where the excitation DOF & response DOF are the same) must be made
- Only a single **FRF** is required to extract modal frequency & damping
- To make direct comparisons between **EMA** & **FEA** mode shapes, the test DOFs must be a subset of the **FEA** DOFs

Utilizing a set of **FEA** mode shapes prior to a modal test is a much better way to answer the following questions,

1. ***How many test* DOFs** should be used?
2. ***Which test* DOFs** should be chosen?

THE FEA MODE SHAPES

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. Each **FEA** mode shape has **185 DOFs** (degrees-of-freedom or points & directions). All DOFs are in the vertical Z-direction. All the mode shapes have ***modal damping of less than 3%.***

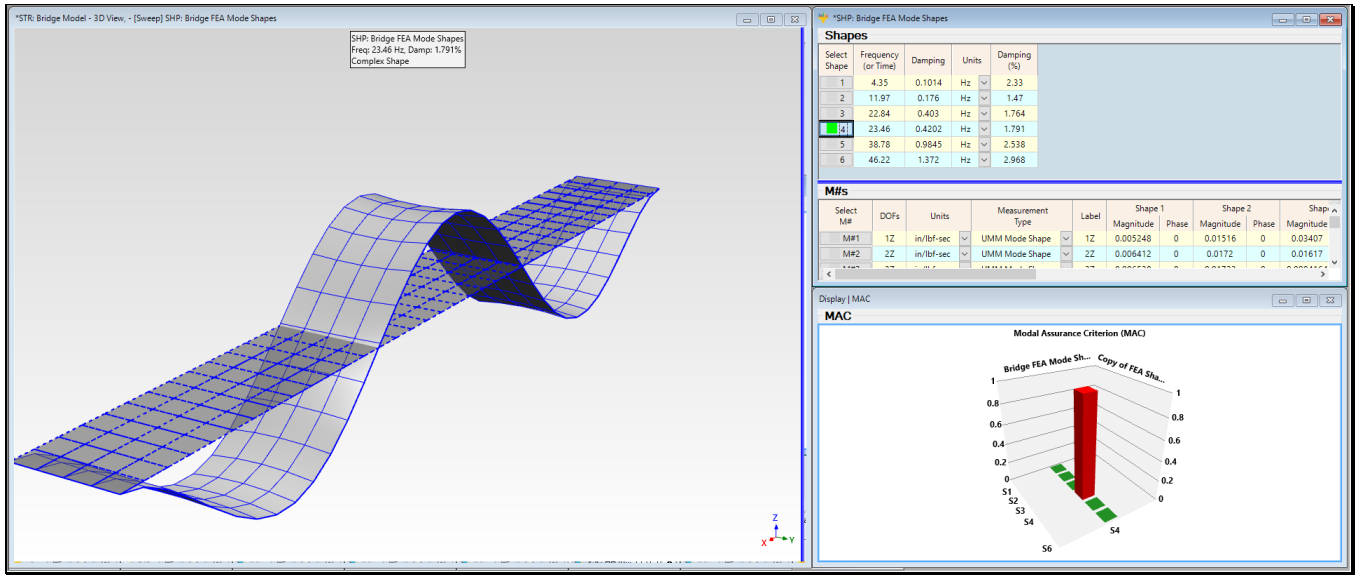


***FEA** Mode Shapes of Pinned-Pinned **FEA** Bridge Model.*

STEP 1 - FEA MODE SHAPES

- ***Press* Hotkey 1 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 Mode Shapes** window

SELECTING DOFs FOR A MODAL TEST

The **185 DOFs** of the **FEA** mode shapes shown above are more than adequate to distinguish between the six mode shapes. However, a ***modal test might far fewer than* 185 DOFs** to clearly define these six mode shapes of the bridge.

To select fewer DOFs for a modal test, the following questions must be answered,

- ***How many test* DOFs** should be used?
- ***Which test* DOFs** should be chosen?

To ***uniquely define*** each **EMA** mode shape, the ***smallest sub-set of the* 185 DOFs** of the **FEA** mode shapes should be acquired in a modal test.

MODAL ASSURANCE CRITERION (MAC)

In the lower-right corner of the figure above, the **Modal Assurance Criterion (MAC)** of the currently displayed mode shape with all other mode shapes is displayed.

MAC is a measure of the ***co-linearity*** of two mode shape vectors.

If two shapes ***lie on the same straight line***, they are ***co-linear*** and their **MAC ➔ 1.0**.

If two shapes ***do not lie on the same straight line***, they are ***linearly independent*** and their **MAC ➔ *less than* 1.0**.

The following ***rules of thumb*** are used with **MAC**.

MAC values ➔ ***between 0 & 1***

MAC = 1.0 ➔ two shapes ***are co-linear***

MAC >= 0.9 ➔ two shapes ***are similar***

MAC < 0.9 ➔ two shapes ***are linearly independent***

In the figure above, each currently displayed mode shape has a **MAC ➔ 1.0** ***with itself***, and a **MAC ➔ 0.0** ***with all other mode shapes***.

Another way of interpreting a **MAC** plot is that ***low off-diagonal values*** indicate that the mode shapes are ***linearly independent*** of one another.

Mode shapes with ***off-diagonal* MAC *values close to zero*** are said to be ***orthogonal*** (***at right angles***) to one another.

STEP 2 - 9 POINT MODAL TEST

- ***Press* Hotkey 2 9-Point Modal Test**

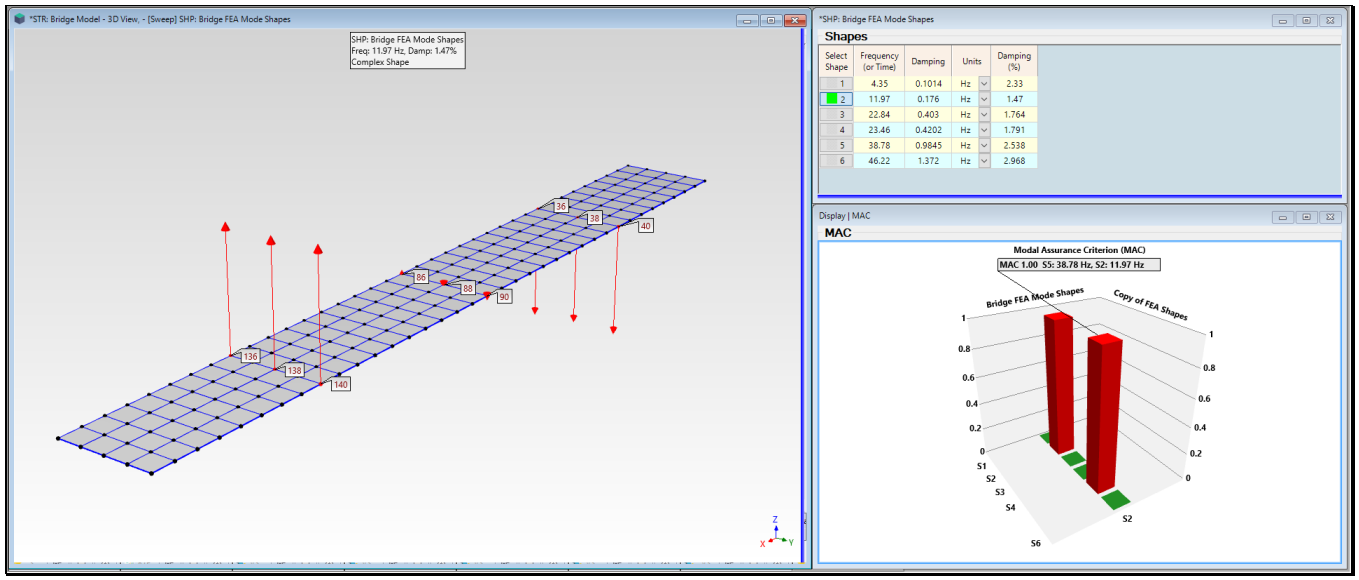
When **Hotkey 2 is *pressed***, sweep animation will begin through the mode shapes in **SHP: Bridge FEA Mode Shapes**. Each **FEA** mode shape with nine DOFs selected is displayed using vectors. Only **nine mode shape DOFs** are selected, a shown below. Since both end points of the bridge are fixed, those points do not need to be included in the DOF selection.

The choice of DOFs for a modal test should result in mode shapes that are ***distinctly different from one another***.

MAC can be used to determine whether a set of mode shape DOFs are linearly independent of one another.

RULE-OF-THUMB USING A MAC PLOT

Mode shape DOFs should be chosen so that the ***off-diagonal* MAC *values*** in a **MAC** plot ***are less than 0.80***.



Bridge Modal Test Using Nine Test Points.

The **MAC** bar chart ***on the lower-right*** indicates that mode shapes ***with these nine selected* DOFs** are not sufficiently independent of one another to uniquely distinguish one mode shape from another

The MAC plot shows that using these DOFs, mode shape S2 is the same as (co-linear with) mode shape S5.

SPATIAL RESOLUTION

If the nine mode shape DOFs selected in **Step 2** were selected as test DOFs, their off-diagonal **MAC** values indicate that they would not provide **EMA** mode shapes ***with sufficient linear independence*** to distinguish one from another.

It is clear from the display of the **FEA** mode shapes in **Step 1** that they all have a ***sinusoidal deflection*** along the length of the bridge (the X-Axis). The fifth mode shape (**38.78 Hz)** exhibits ***two cycles of sinusoidal deflection*** along the length of the bridge.

Rule-of-Thumb: Assuming that each mode shape exhibits a ***sinusoidal deflection*** over the span of a test article, test points should be chosen so that ***at least* 10 DOFs *per cycle of sinusoidal deflection*** of each mode shape are acquired.

Using this Rule-of-Thumb,

- ***About 20 equally-spaced test points*** should be chosen in the X-direction on the bridge

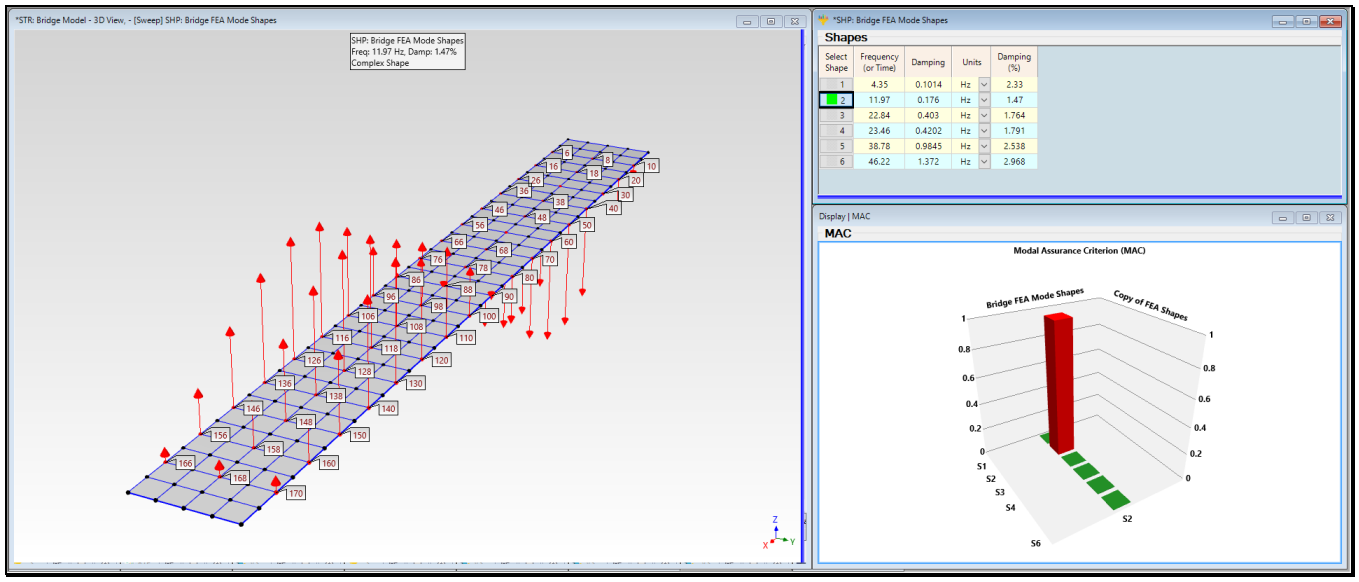
The deflection of all six mode shapes in the Y-direction is approximately a straight line. Therefore,

- ***Three equally-spaced*** test points in the Y-direction is sufficient to distinguish the mode shapes

STEP 3 - 51 POINT MODAL TEST

- ***Press* Hotkey 3 51-Point Modal Test**

If the bridge is ***sampled at every other point*** in both the X & Y directions, that would provide a grid with 51 test points to be used in a modal test.



Bridge Modal Test Using 51 Test Points

As shown above, selecting every other point on the **FEA** model of the bridge results in a grid of **17** points along the X-axis and **3** points along the Y-axis giving a total of **51** test points. This provides a realistic animation of the mode shapes using the deflection at 51 test points.

The **MAC** bars in the lower-right corner clearly show that the six modes are ***orthogonal to one another*** using these 51 DOFs for a modal test. Their ***off-diagonal* MAC *values are zero "0"***.

Two different modal tests could be performed using these test DOFs,

- A ***single reference modal test*** acquiring ***responses at* 51 DOFs** with **DOF 40Z** as the reference
- A ***multiple reference modal test*** acquiring ***responses at* 51 DOFs** with ***any number of the* DOFs** identified as good reference DOFS in App Note 24

Performing a modal test using 51 test points ***is a lot of work***.

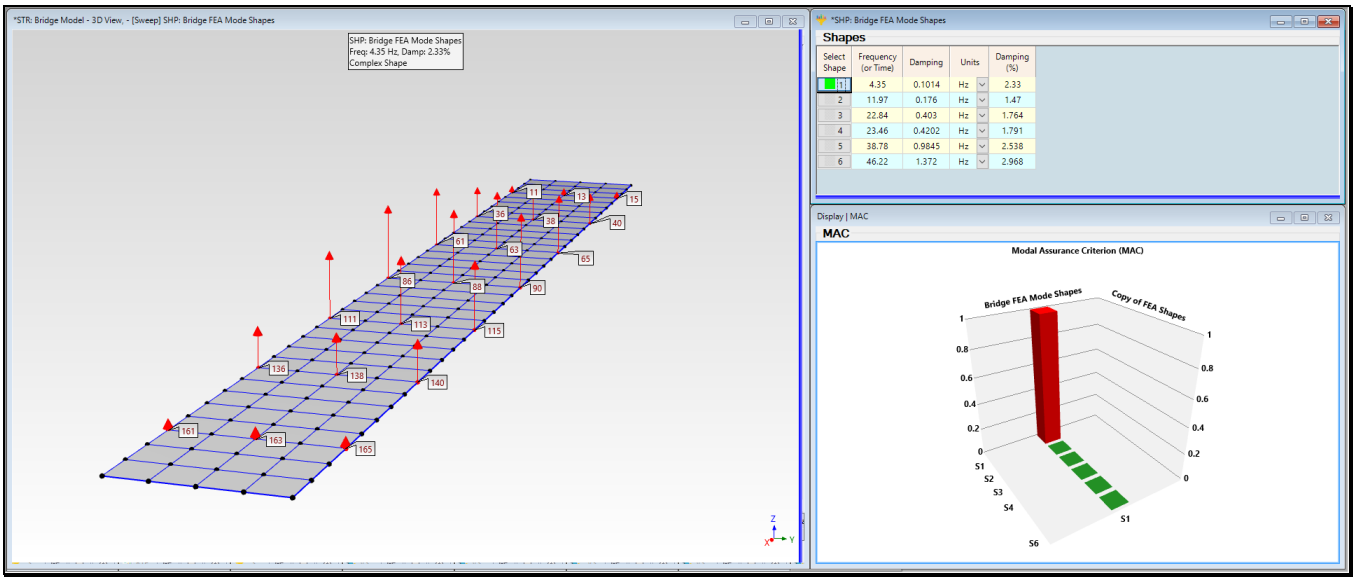
Is it possible to obtain usable mode shapes with fewer test points?

STEP 4 - 21 POINT MODAL TEST

- ***Press* Hotkey 4 21-Point Modal test**

The spatial sampling provided by the 51 test points provided enough points to identify six unique mode shapes. But what if a smaller number of grid points is used? Would it still provide six unique mode shapes?

- While maintaining 3 test points in the y-direction, suppose the test points in the X-direction are ***reduced from 17 to 7 points***.



Bridge Modal Test Using 21 Test Points

As shown above, selecting only **7** points along the X-axis and **3** points along the Y-axis giving a total of **21** test points still gives good results. All the mode shapes are easily distinguished in animation using the deflection of **21** test points.

The **MAC** bars in the lower-right corner show that the six modes are still ***orthogonal to one another*** using only 21 DOFs for a modal test. Their ***off-diagonal* MAC *values are zero "0"***.

Using just 21 test points is ***less than half*** the number required by the spatial aliasing **Rule of Thumb**.

But both the **MAC** Plot and the animated display indicate that the six mode shapes are still uniquely defined.

SUMMARY

In this App Note, two important tools were used to determine how many test points to use and where to locate them in a modal test.

Assuming that the mode shapes are sinusoidal along the length of the bridge, a simple 10 point-per-cycle **Rule-of-Thumb** was used to determine the minimum number of test points along the length of the bridge.

However, it was found that for this simple bridge model, ***less than half the number of points*** along the length of the bridge were required.

A **Modal Assurance Criterion (MAC)** bar chart was also used to graphically show the for each case of selected test points the **EMA** mode shapes with those selected DOFs would be ***linearly independent*** of one another, and therefore ***uniquely identified***.

For both the 51-point and 21-point modal tests, the **MAC** bar chart showed ***off-diagonal* MAC ➔ "0"**, meaning that even with those reduced numbers of DOFs versus the original **185 DOFs** of the **FEA** mode shapes, all six **EMA** mode shapes would be ***orthogonal to one another***.

For most structures, the off-diagonal **MAC** plot values ***will not be zero* "0",** but if the test DOFs are chosen so that the ***off-diagonal* MAC** plot values ***are less than* 0.8**, the **EMA** mode shapes ***should be uniquely different*** from each other.

It is important to remember that ***only the* FEA mode shapes** were used to determine how many DOFs to use and where to sample the surface during a modal test.

Modal frequencies are usually different between **FEA** mode shapes and **EMA** mode shapes, but are not required.

STEP 5 - REVIEW STEPS

To review the steps of this App Note,

- ***Press* Hotkey 5 Review Steps**