Vibrant Technology, Inc.

ME'scopeVES Application Note #15

Multiple Reference Curve Fitting To Find Closely Coupled Modes

INTRODUCTION

In this note, the capabilities of the Complex Mode Indicator Function (**CMIF**) and Multi-Variate Mode Indicator Function (**MMIF**) of the ME'scopeVES *Visual* Modal Pro option are used to find and estimate the modal parameters of two closely coupled modes.

In *Application Note #14*, these same Mode Indicators were used to find several repeated roots on an axi-symmetric structure. Repeated roots and closely coupled modes are similar, but technically there is a difference. A repeated root is two or more modes with *exactly* the same modal frequency, but different mode shapes. The mode shapes of a repeated root are also similar in shape but are "rotated" around the symmetric axes from one another. This was made clear by displaying the mode shapes for the circular disk in Application Note #14.

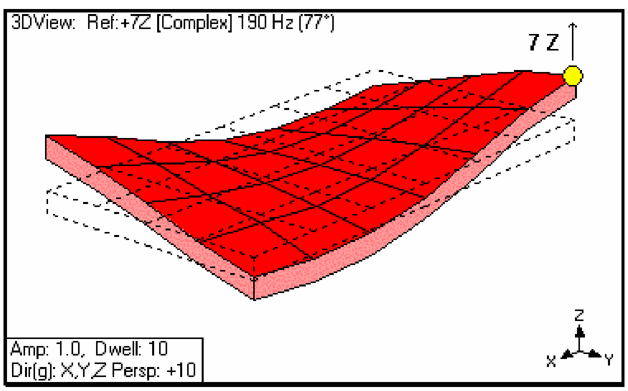


Figure 1A: 190 Hz ODS From Reference 7Z.

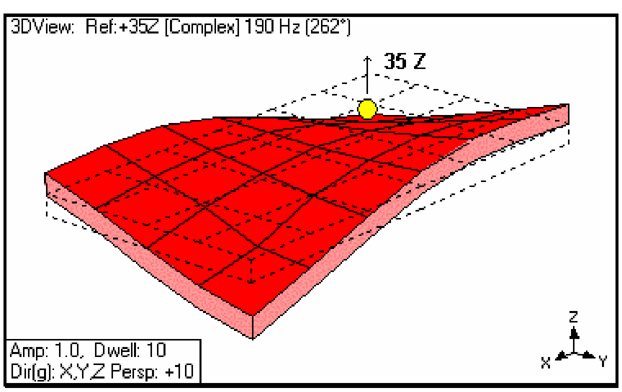
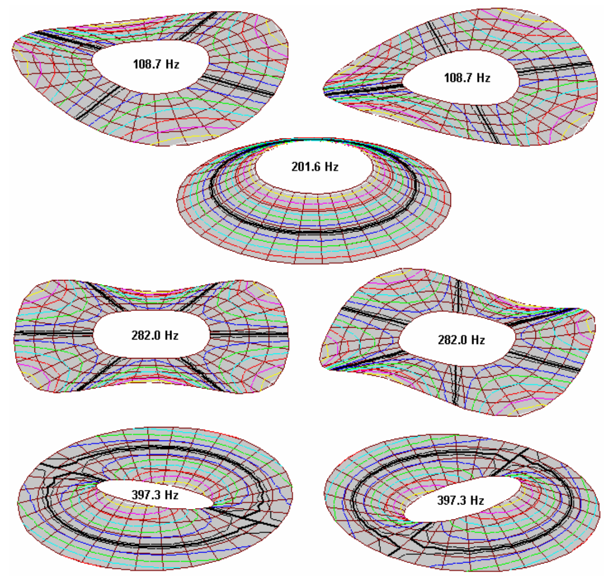


Figure 1B: 190 Hz ODS From Reference 35Z.



3 repeated-root modes and 1 distinct root of circular plate.

In this note, the mode shapes of two closely coupled modes of a rectangular plate will be identified from multiple reference FRF measurements. The plate is made of Poly Vinyl Chloride (PVC). Although only one resonance peak appears at 190 Hz in all measurements, the two modes actually have different modal frequencies and their mode shapes are quite different.

A 2-reference set of FRFs can be used to identify 2 closely coupled modes, if there are any. But, the first question to ask is, *"How do we know if the structure has any closely coupled modes?"* This question can be answered by displaying the operating deflection shapes (ODS's) from each reference in animation.

If the ODS at each resonance peak in the FRFs is the same from either reference, then the structure has no closely coupled modes. If on the other hand, the ODS is different from different references, this is an indication of closely coupled modes.

Figure 1A shows the ODS at **190 Hz** from the FRFs with Reference **7Z**. Figure 1B shows the ODS at **190 Hz** from the FRFs with Reference **35Z**. Clearly, these are different shapes, indicating closely coupled modes.

DISPLAYING SHAPES IN ANIMATION

To display the mode shapes of the PVC Plate in animation:

Execute: **File | Project | Open**.

- Open the **App Note #15 ….PRJ** from the **Modal Analysis** subdirectory under the **ME'scopeVES** directory.

When the Project is opened, a Structure window, Data Block window, and Shape Table window will open in the Work Area.

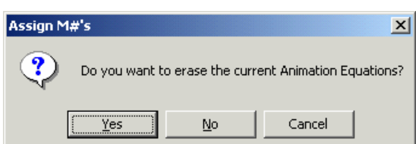
- Slide the **vertical blue splitter bar** to the left in the **PVC Plate.BLK** window to expose the **DOFs** column in the Traces spreadsheet.

- Scroll through the Trace properties in the spreadsheet, and notice that there are **70 FRF** measurements, **35** with reference **7Z** and **35** with reference **35Z**.

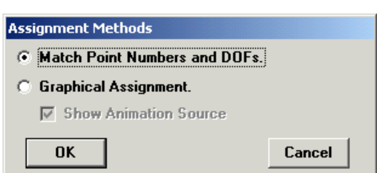
First, the FRFs will be assigned to the 3D model so that **Operating Deflection Shapes** (**ODS**) can be displayed in animation from them.

To assign the FRFs **(M#s)** to the 3D model in the **PVC Plate.STR** window:

Execute: **Assign | M#'s**. An **Assign M#'s** dialog box will open, asking if your want to erase the current animation equations on the 3D model.

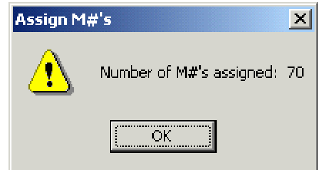


- Press the **Yes** button; an **Assignment Methods** dialog will open.



- Accept the default **Match Point Numbers and DOF's** choice and press **OK**.

When all of the **M#s** have been assigned to the model, the following dialog box will open.

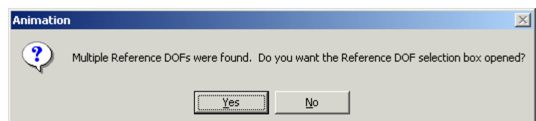


This message says that all **70 M#s** in the Data Block were assigned to DOFs of the 3D model. During shape animation you will be able to select a Reference DOF from which ODS's will be animated.

- Press **OK**.

To initiate animation:

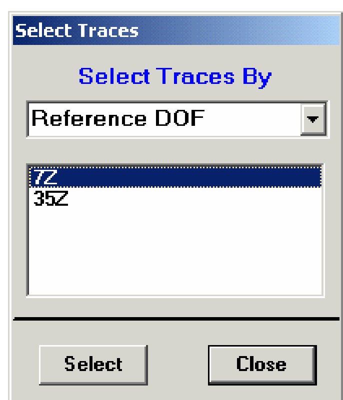
Execute: **Animate the Structure** on the Structure window Toolbar. An **Animation** dialog will open, indicating that you are attempting to display shapes from a multiple reference set of data.



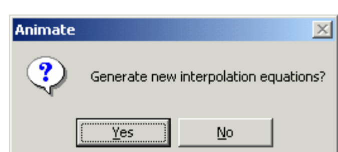
- Press **Yes**. A **Select Traces** dialog will open.

In the **Select Traces** dialog:

- Click on **7Z** and press **Select**.

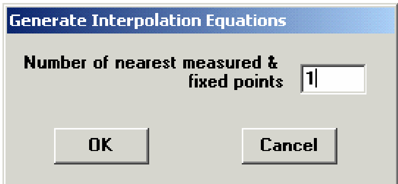


Next, an **Animate** dialog box will open.



- Press the **Yes** button.

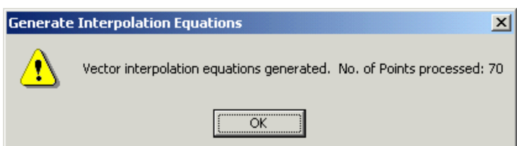
A **Generate Interpolation Equations** dialog will open, asking you to specify the *number of nearest neighboring measured Points* to use in generating equations for the *interpolated* Points.



The FRFs were only measured at Points on the top side of the plate. Interpolation equations will be used to animate each Point on the *bottom* side using the motion of the measured Point *directly* above it.

To generate interpolation equations using the Point directly above it as its nearest neighbor:

- Enter **1** in the dialog box, and press **OK**; a **Generate Interpolation Equation** confirmation will open.



- Press **OK**. Animation should now begin, using data from the Data Block.

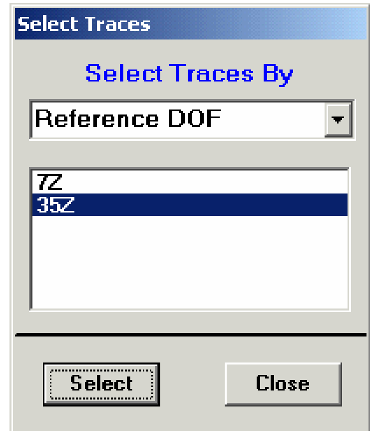
Execute: **Window | Arrange | For Animation** button on the **ME'scopeVES** window Toolbar.

Execute: **Display | Cursor | Line Cursor** in the Data Block window, and drag the cursor to **190 Hz**.

The **ODS** at **190 Hz**, using the measurements from Reference **7Z**, should be displayed. The ODS should look like the shape in Figure 1A (page 1). This ODS should be dominated by a mode shape, if indeed a single mode existed at that frequency.

- Select Reference **35Z** from the drop down list on the Data Block window Toolbar.

This ODS should look like the shape in Figure 1B (page 1). If a single mode existed at **190 Hz**, the ODS should be the same, no matter which reference it is displayed from. Clearly, the shape in Figure 1A is different from the shape in Figure 1B.



- Place the Line Cursor on one of the other peaks, and select one reference, and then the other.

For all other resonance peaks, the shape will be the same, regardless of the reference selected.

MULTIPLE REFERENCE CURVE FITTING

Multiple reference curve fitting uses the extra information in a set of multiple reference FRFs to extract the parameters of closely coupled modes. Either the **CMIF** or the **MMIF** method can be used to indicate closely coupled modes. Both methods yield the same results. The **Modal Peaks Function** *cannot be used in this case*.

First, the **CMIF** method will be used to identify the closely coupled modes, and estimate their modal parameters. Then, the **MMIF** method will be used to obtain the same results.

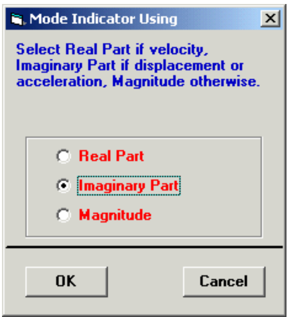
Execute: **Modes | Modal Parameters** command in the Data Block window to initiate curve fitting.

- Turn the cursors **OFF**.

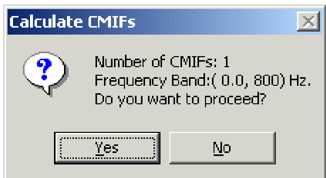
Execute: **Curve Fit | Clear All Fit Data**. The Data Block is now cleared of all prior curve fitting results.

On the **Mode Indicator** tab:

- Select the **CMIF** Mode Indicator, and press the **Count Peaks** button on the Curve Fitting panel. A **Mode Indicator Using** dialog will open.

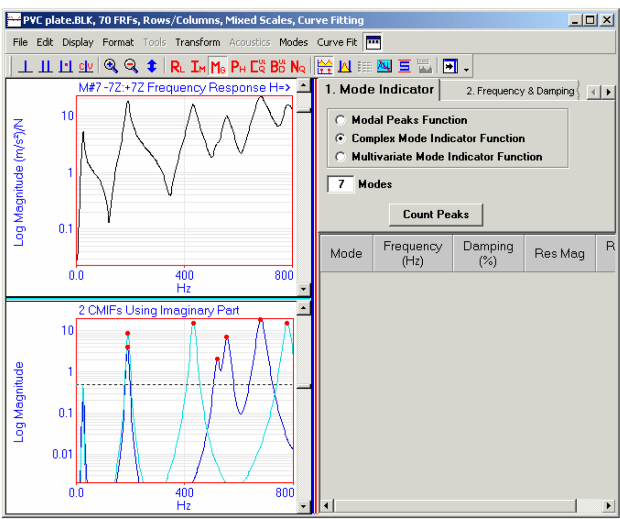


- Select **Imaginary Part** and press **OK**. A **Calculate CMIFs** dialog will open.



- Press **YES**.

Two **CMIF** curves will be calculated and displayed as shown in he following figure.



Two CMIF Curves Indicating 7 Modes.

Notice also that 10 peaks have been counted. The **Modes** box on the Curve Fitting panel contains a "**10**".

- Move the peak counter **threshold line** on the Mode Indicator graph **upward** by using its scroll bar, so that the *3 lowest frequency peaks are not counted*.

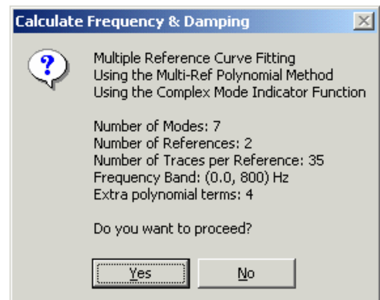
These lowest frequency peaks are for "*rigid body*" modes of the plate, which will be ignored.

Now the Modes box should have a "**7**" in it, indicating that 7 resonance peaks have been counted above the threshold line on the two CMIF curves.

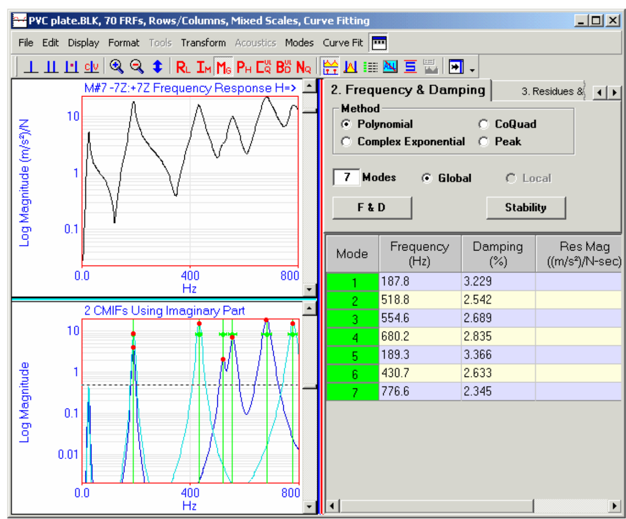
Notice that 2 peaks are indicated (with two **red dots**) at approximately **190 Hz**. This is an indication of two closely coupled modes. No other closely coupled modes are indicated by the CMIF curves.

On the **Frequency & Damping** tab:

- Press the **F & D** button to estimate modal frequencies and damping for all 7 modes. A **Calculate Frequency & Damping** dialog opens.



- Verify that **7** modes are to be fit using **2** references and **35** traces per reference. Press **Yes**.

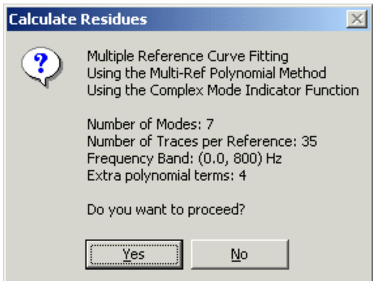


Notice that a mode was found at **187.8 Hz**, and the second one at **189.3 Hz**. Notice also that the first four modal frequencies in the spreadsheet correspond to peaks on the first (**blue**) CMIF curve, and the second three modal frequencies correspond to peaks on the second (**green**) CMIF curve.

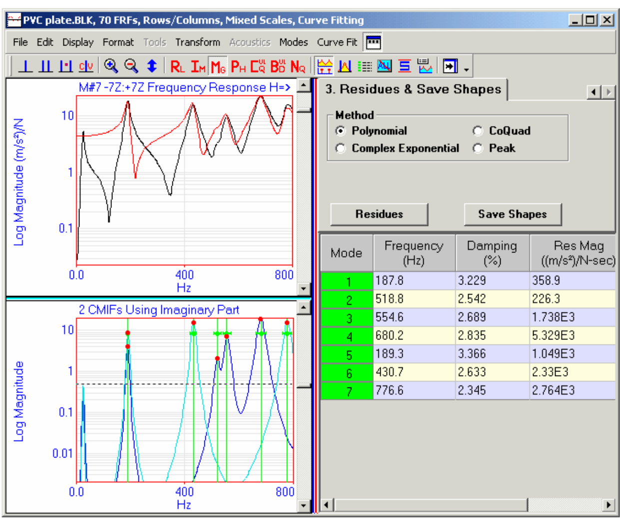
Notice also that the **Polynomial** curve fitting method was used to estimate the modal parameters, and the other methods are not available.

NOTE: The ordering of modes in the spreadsheet should not be changed (sorted) during multiple reference curve fitting until after residues are estimated.

- Press the **Residues** button to estimate residues for the **7** modes in the spreadsheet. A dialog **Calculate Residues** will open.



- Verify that CMIF Multiple Reference Curve Fitting using the Polynomial Method is to be applied for **7** modes to **35** traces per reference. Press **Yes**.



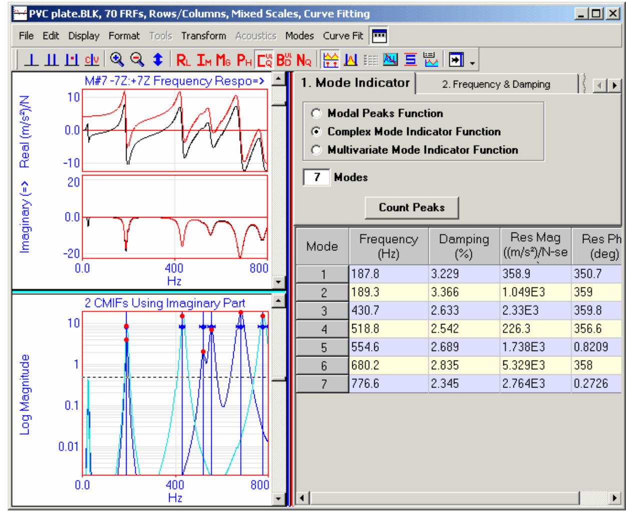
CMIF Curve Fitting Results.

When residue estimation has been completed, the spreadsheet will be filled with residue magnitudes & phases for each mode in each measurement, and a **red Fit Function** will be overlaid on each measurement.

Execute: **Curve Fit | Sort Modes By Frequency** to rearrange the modes in frequency ascending order.

- Display the **CoQuad** format, and scroll through the Traces to examine the curve fitting results.

Notice in the figure below that the **Imaginary Parts** of the Fit Functions and measurements match very closely for all Traces.

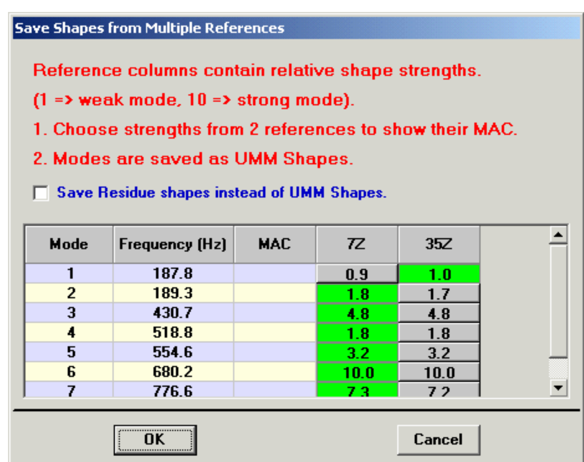


CMIF fit in Co/Quad format, modes sorted by frequency.

On the other hand, the **Real Parts** exhibit an offset between the Fit Function and measurements for many Traces. This is because the Real Parts contain a greater influence of other modes *outside the band* of the measurements.

During curve fitting, this bias was accounted for by using *extra polynomial terms*. However, the **Fit Functions** (which were synthesized using *only* the modal parameters) do not account for this bias. Nevertheless, since the **Imaginary Parts** of the Fit Functions match the waveform "shape" of the measurements, this is an indication that the modal parameters are accurate.

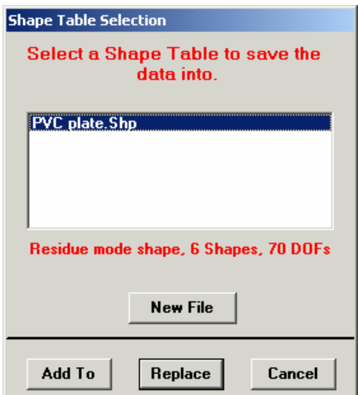
- Press the **Save Shapes** button to save the modal parameters into a Shape Table. The **Save Shapes for Multiple References** dialog will open.



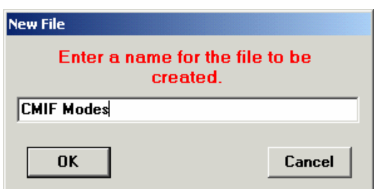
This dialog lists the *strength* of each mode at each reference. The strongest reference is selected for each mode.

- Click on the *unselected* reference for each mode to display the **MAC** (Modal Assurance Criterion) value between the shape estimates for each reference. In this case, all MAC values are "**1**", indicating that the shape estimates from either reference are the same.

- Press the **OK** button. A **Shape Selection** dialog will open.



- Press the **New File** button; a **New File** dialog will open.



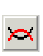
- Enter "**CMIF Modes**" for the name of the new Shape Table file, and press **OK**.

- Execute **Curve Fit | Close** in the Data Block window to terminate curve fitting.

DISPLAYING THE MODE SHAPES

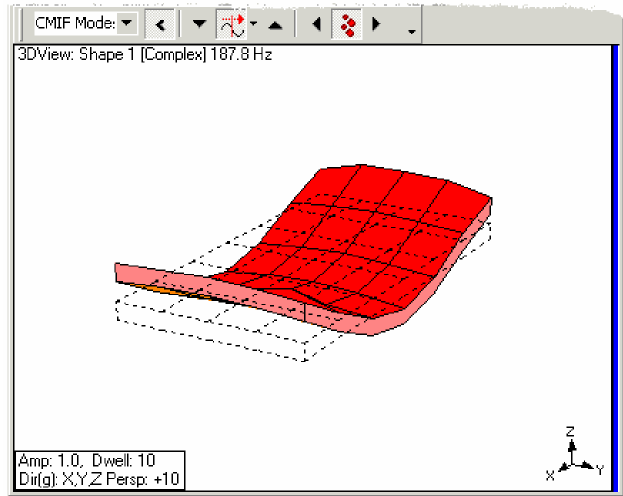
To display mode shapes from the Shape Table:

- Select **CMIF Modes.SHP** in the **Animation Source** drop down list on the Structure window Toolbar.



Execute: **Animate the Structure** on the Structure window Toolbar.

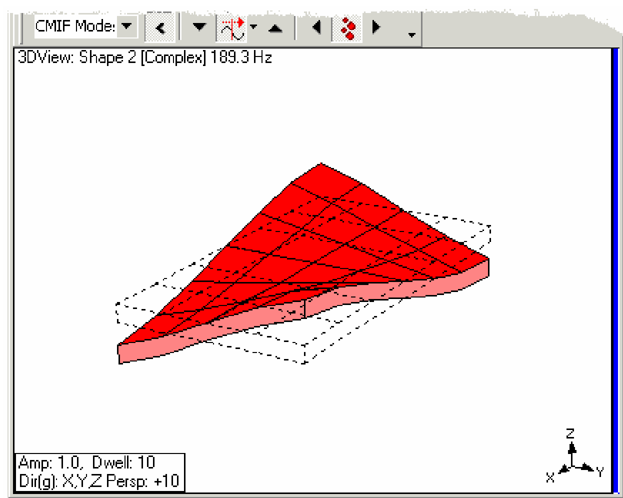
- Press the **Shape 1** button to display the **187.8 Hz** mode shape.



187.8 Hz Bending Mode Shape.

This is the *first bending mode* of the plate, which is to be expected as one of the lower frequency modes of a rectangular plate.

- Press the **Shape 2** button to display the **189.8 Hz** mode shape.



189 Hz Torsion Mode Shape.

This is clearly the *first torsion mode* of the plate, which is also expected to be one of the lower frequency modes of a rectangular plate.

You can display the other mode shapes and verify that the ODS's displayed directly from the Data Block were "dominated" by these mode shapes.

CURVE FITTING WITH MMIF

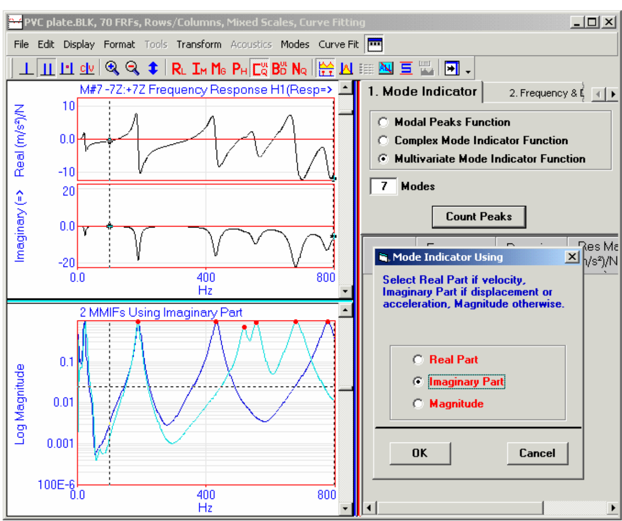
Now, the MMIF method will be used to obtain the same results as above.

Execute: **Modes | Modal Parameters** in the Data Block window to initiate curve fitting.

Execute: **Curve Fit | Clear All Fit Data**.The Data Block is now cleared of all prior curve fitting results.

In the **Mode Indicator** tab:

- Select the **MMIF** Mode Indicator, and press the **Count Peaks** button.
- Select **Imaginary Part** in the resulting **Mode Indicator Using** dialog; press **OK**.
- Press **Yes** in the resulting **Calculate MMIFs** dialog.
- Two **MMIF** curves will be calculated and displayed as shown below.



Two MMIF Curves Indicating 7 Modes above 100 Hz.

- Turn the **Band Cursor ON** and drag the lower band to about **100 Hz**.

This will exclude the lowest frequency peaks ("*rigid body*" modes of the plate), from the peak count. Now the Modes box should have a "**7**" in it, indicating that **7** resonance peaks have been counted above the threshold line on the two MMIF curves.

In the **Frequency and Damping** tab:

- Press the **F & D** button to estimate modal frequencies & damping for all 7 modes.

In the resulting Calculate Frequency & Damping dialog,

- Press **Yes** to proceed.

Notice that the first closely coupled mode was found at **189.4 Hz**, and the second one at **187.7 Hz**. Notice also that the first three modal frequencies in the spreadsheet correspond to peaks on the first (**blue**) MMIF curve, and the second four modal frequencies correspond to peaks on the second (**green**) MMIF curve.

- Press the **Residues** button to estimate residues for the 7 modes in the spreadsheet.

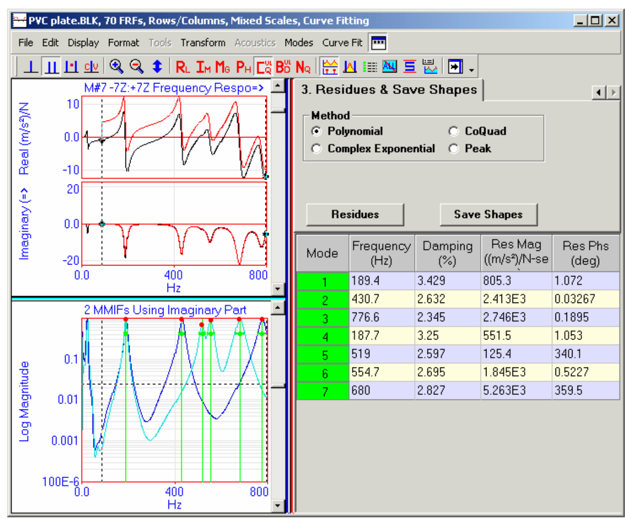


Figure 6. MMIF Curve Fitting Results.

When residue estimation has been completed, the spreadsheet will be filled with residue magnitudes & phases for each mode in each measurement, and a **red Fit Function** will be overlaid on each measurement.

Execute: **Curve Fit | Sort Modes By Frequency** to sort the modes into frequency ascending order.

- Scroll through the Traces to examine the curve fitting results.
- Press the **Save Shapes** button to save the modal parameters into a Shape Table.
- Press the **OK** button. Another dialog box will open. Press the **New File** button.

- Enter "**MMIF Modes**" for the name of the new Shape Table file, and press **OK**.

- Execute **Curve Fit | Close** in the Data Block window to terminate curve fitting.

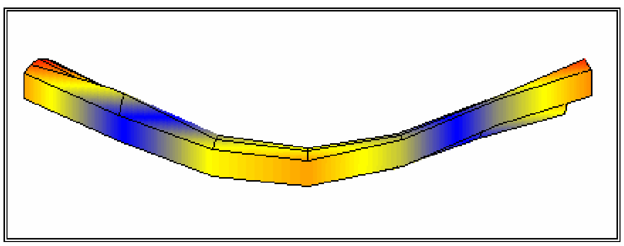
Displaying MMIF modes

To display mode shapes from the **MMIF Modes** Shape Table:

- Select **MMIF Modes.SHP** from the animation source drop down list on the Structure window Toolbar.

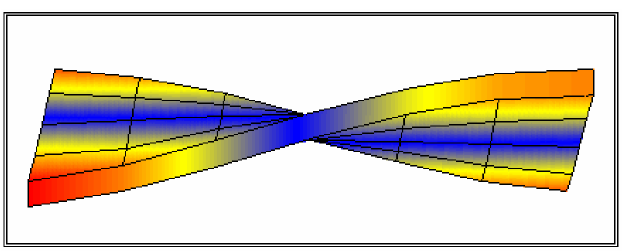
 Execute: **Animate the Structure** on the Structure window Toolbar.

- Press the **Shape 1** button to display the **187.7 Hz** mode shape.



This is clearly the *first bending mode* of the plate, as expected.

- Press the **Shape 2** button to display the **189.4 Hz** mode shape.



This is the *first torsion mode* of the plate, as expected.

CONCLUSIONS

In this Application Note, the animation display of ODS's directly from a set of multiple reference FRFs was used to obtain the first indication of *closely coupled modes*. For lightly damped structures such as this PVC plate, the ODS is typically "dominated" by a single mode at or near a resonant frequency. Therefore, the ODS at a resonant frequency should look like the dominant mode shape, *no matter which reference is chosen* for ODS display.

As shown in Figure 1, the ODS at the **190 Hz** resonance peak for reference **7Z** was distinctly different from the ODS for reference **35Z**.

To correctly estimate the modal parameters of these closely coupled modes, two different mode indicators (CMIF & MMIF) were applied to the multiple reference FRF measurement set. Both indicators clearly indicated the presence of two resonance peaks near 190 Hz.

Both methods also yielded "*modal participation factors*", which were then used by the Polynomial curve fitting method to estimate the modal parameters of the closely coupled modes. (These participation factors can be viewed by executing the **Modes | Copy to New File | CMIFs** or **MMIFs** commands.)

Curve fitting revealed that the two modal frequencies were approximately **187** & **189 Hz**. The **187 Hz** mode was the *first bending mode* and the **189 Hz** mode was the *first torsional mode* of the plate.