ODS Analysis versus Modal Analysis

Modal analysis is used to characterize resonant vibration in machinery & structures. If a noise or vibration problem is due to the excitation of a structural resonance, then the structure either has to be isolated from the excitation source, or physically modified to reduce the level of vibration.

- **ODS analysis** shows how a machine or structure is vibrating, and where excessive vibration levels occur for various Points & directions.
- **Modal analysis** indicates whether or not the excessive vibration is due to a structural resonance.
- **ODS’s & mode shapes** can be compared in MEscope to determine how a resonance participates in (or contributes to) the overall vibration level occurring in a machine or structure.

What is FRF-Based Curve Fitting?

Curve fitting is a process of matching a parametric model of an FRF (in a least squared error sense) to a set of experimental data.

- The unknown parameters of the parametric model are modal frequency, damping & residues (mode shape components)
- The outcome of curve fitting is a set of modal parameters (frequency, damping & mode shape) for each mode that is identified in the frequency span of the experimental data.

After curve fitting is completed, mode shapes are stored into a Shape Table from which they can be displayed in animation on a 3D model of the test article.

Curve Fitting Steps

1. **Determine** the Number of Modes in a frequency band of measurement data
2. **Estimate** modal Frequency & Damping for all modes in the frequency band
3. **Estimate** modal Residues (mode shape components) for each mode and each measurement

Curve Fitting Guidelines

1. **Overlay the Measurements**

   A resonance peak should appear at the same frequency in every FRF, except where node points (zero residues) of the mode shape occur.

   - Execute Format | Overlay to overlay the FRFs and look for resonance peaks at the same frequency in all FRFs

2. **Inspect the Impulse Response Functions (IRFs)**

   - Execute Transform | Inverse FFT to transform each FRF into its corresponding IRF
   - All of the IRFs should exhibit a damped sinusoidal decay to almost zero at the end of each M#, as shown below
Wrap around error (shown below) is not harmful to frequency domain curve fitting.

3. Use the Mode Indicator
   - Press the Count Peaks button on the Mode Indicator tab to count the number of resonance peaks (modes) in a cursor band

4. Use the Band cursor
   - Curve fit only those portions of the data that contain valid resonance peaks

If the Band cursor is displayed, only data in the cursor band is used for curve fitting. Otherwise, all of the data in each M# is used for curve fitting.

5. Verify Fundamental Mode Shapes

Low frequency modes have simple bending and torsional mode shapes.

Points that animate substantially different from neighboring Points on the structure model are indications of poor measurements, poor curve fits, or both.

- Estimate modal parameters for a few of the lower frequency (fundamental) modes
- Save the results into a Shape Table and display the mode shapes in animation to verify their validity.
6. Compare Results from Different Curve Fitting Methods

- Curve fit the FRFs using more than one curve fitting method, and compare mode shapes from different methods.
- Execute Display | MAC (Modal Assurance Criterion) to numerically compare mode shapes between different curve fitting methods.
- Execute Animate | Compare Shapes to display shapes in animation from two Shape Tables.

Illustrative Example

- Open the Demo Project from this Application Note
- Execute Curve Fit | Open Curve Fitting in the BLK: FRFs Data Block window.

When curve fitting is initiated, the following changes take place in the Data Block window;

- M#s are displayed in the upper left part of the Data Block window.
- A Mode Indicator is displayed in the lower left part of the Data Block window.
- The Curve Fitting Tabs are displayed on the right side of the Data Block window.
- The Curve Fit menu is enabled, and a Curve Fitting Toolbar, (containing frequently used commands), is displayed in the Toolbar area.

The Curve Fit panel contains Curve Fitting tabs above the Modal Parameters spreadsheet.

- The Curve Fitting tabs contain controls for setting up and executing the curve fitting steps.
- The Modal Parameters spreadsheet is for viewing and editing the modal parameter estimates extracted from the FRFs.

Modal parameter estimation is done in several steps, using the controls on the Curve Fitting tabs.

Data Block Showing Curve Fitting Panel.
Splitter Bars

During curve fitting, two additional **splitter bars** are displayed in the Data Block window.

- A **vertical red splitter bar** separates the Curve Fit panel from the M# and Mode Indicator graphs.
- The size of the Curve Fit panel can be changed by **dragging the red splitter bar horizontally** and the size of either graph can be changed by **dragging the horizontal blue splitter bar vertically**.
- A **horizontal blue splitter bar** separates the M# and Mode Indicator graphs.

Deleting All Fit Data

All curve fitting data is retained in a Data Block file when it is saved to a disk file as part of a Project. Therefore, it is recommended that all previous curve fitting data be deleted from the Data Block before starting a new curve fitting session.

- **Execute Curve Fit | Delete All Fit Data**
- **Click on Yes** in the dialog box that opens

**Step 1. Counting Modal Peaks**

The first step of modal parameter estimation is to determine how many modes are represented by resonance peaks in a frequency band in the FRFs.

Each **peak** in an FRF is evidence of **at least one mode**.

- Scroll through the M#s by **dragging the vertical scroll bar** to the right of the M#s display.

There are two ways to determine the number of modes represented by **peaks** in the FRFs;

1. **Overlay all M#s**, visually inspect them for resonance peaks, **un-check the Count Peaks box** and **enter the number of peaks into the Modes box on the Frequency Damping tab**
2. **Press the Count Peaks button** on the **Mode Indicator** tab of the Curve Fit panel.

**Count Peaks Button**

The **Count Peaks** button on the **Mode Indicator** tab of the Curve Fit panel is used to calculate a Mode Indicator function using **all (or selected) M#s** and count the resonance peaks **above** the **Noise Threshold** line on the Mode Indicator.

- **Select a Mode Indicator from the Method list** on the Mode Indicator tab
- **Press the Count Peaks button**

A dialog box will open allowing you to choose a part of the M# data to use for calculating the Mode Indicator. The **Real Part**, **Imaginary Part**, or **Magnitude** of **all (or selected) M#s** of FRF data is used to calculate the Mode Indicator.
• **Press** the OK button to calculate the Mode Indicator and count its peaks.

After the Mode Indicator has been calculated and its peaks counted, a graph of the Mode Indicator is displayed on the **lower left** in the window.

• The peaks above the **Noise Threshold** (*horizontal line*) on the Mode Indicator graph are counted.

• Each modal peak counted is indicated with a **red dot** on the Mode Indicator.

• The **Peaks** box on the Mode Indicator tab contains the number of peaks counted, in this case **10 peaks**.

![Mode Indicator Showing 10 Resonance Peaks.](image)

**Step 2. Estimating Frequency & Damping**

In many cases (especially with **noisy** data), it is better to **build up** a list of modal frequencies & damping in the Modal Parameters spreadsheet by curve fitting in **small cursor bands** using as few modes as possible. In this example, since the FRFs are relatively noise free, frequency & damping for all **10** resonance peaks will be estimated at once.

**Fitting One FRF**

To estimate frequency & damping by curve fitting **only** the **first M#**,

• **Drag** the vertical scroll bar (next to the graph) to its topmost position to display the first M#.

• **Hold down** the Ctrl key and **click** on the graph to **select** the M#.

Notice that the graph **background changes color** to indicate the **selected M#**.

• On the Frequency Damping tab, make sure the **Global Polynomial** is selected in the Method list on the Polynomial tab

• **Press** the Frequency Damping button on the Polynomial tab

• **Click** on No and then Yes in the dialog boxes that open.
Frequency & damping estimates for **10 modes** will be listed in the Modal Parameters spreadsheet, as shown below.

![Modal Parameters Spreadsheet](image)

**Frequency & Damping Curve Fit of One M#.**

**Vertical Frequency Lines**

The frequency estimate for each mode in the Modal Parameters spreadsheet is displayed as a **vertical line** on the Mode Indicator graph.

- Display the Band Cursor and surround several of the vertical lines on the Mode Indicator
- Notice that the corresponding modes are **selected** in the Modal Parameters spreadsheet

**Half Power Point Damping**

The damping estimate for each mode is displayed as a **horizontal line** crossing the vertical frequency line where,

**Width of the Damping Line** = \(2\ \sigma\), \(\sigma = \text{half power point} \) (or **3 dB point**) damping (in Hz)

The half power point damping (\(2\ \sigma\)) is approximately equal to the width of the resonance peak at **70.7 %** of the FRF **peak magnitude** value.

The **half power point** damping (\(2\ \sigma\)) is approximately equal to the width of the resonance peak at **half (50%)** of the FRF **peak magnitude squared**.

The FRF **magnitude squared** is considered a power quantity, hence the name **half power point damping**.

- Execute **Display | Zoom** and zoom the display around several resonance peaks, as shown below.
Global Frequency & Damping Estimates

Even though frequency & damping can be estimated from one FRF, more accurate estimates are usually obtained by doing a **Global** curve fit on **all** (or **several selected**) FRFs.

- **Double click** on the Select Mode column in the Modal Parameters spreadsheet until **all modes are selected**
- **Execute Curve Fit | Modal Parameters | Delete Modes** to delete the **selected** modes from the Modal Parameters spreadsheet.
- **Hold down** the Ctrl key and **click** on the selected M# to **un-select** it.
- **Press** the Frequency Damping button again on the Polynomial tab
- **Click** on Yes in the dialog box that opens.

Now frequency & damping estimates extracted by curve fitting all 99 FRFs, are added to the Modal Parameter spreadsheet.
Global Frequency & Damping Estimates from 99 FRFs.

Frequency & Damping Terminology

Modal frequency & damping are defined in several different ways,

\[ p(k) = -\sigma(k) + j\omega(k) = \text{pole location of mode}(k) \text{ (Hz)} \]
\[ \omega(k) = \text{damped natural frequency of mode}(k) \text{ (Hz)} \]
\[ \sigma(k) = \text{damping decay constant (also called the 3 dB bandwidth or half power point damping)} \text{ of mode}(k) \text{ (Hz)} \]
\[ \zeta(k) = \text{damping ratio} \]
\[ \Omega(k) = \text{undamped natural frequency of mode}(k) \text{ (Hz)} \]

\[ \Omega(k) = \sqrt{\omega(k)^2 + \sigma(k)^2} \text{ (Hz)} \]
Step 3. Estimating Residues

After modal frequencies & damping have been estimated, modal *residues* (mode shape *components*) are estimated during a *second* curve fitting step.

- Execute **Display | mooZ** to restore the full graphics display.
- **Press** the **Residues** button on the **Residues, Save Shapes** tab.
- **Click** on **Yes** in the dialog box that opens.
Estimates of residue *magnitude & phase* for all 10 modes and each FRF M# are added to the Modal Parameters spreadsheet.

- **Scroll** through the M#s and release the mouse button to list the residues for the M# being displayed.

![Residue Curve Fit of 10 Modes and 99 FRFs.](image)

**Fit Function**

After the modal frequency, damping, & residue have been estimated, a red *Fit Function* is also overlaid on each M#, as shown above.

- The *Fit Function* is calculated using the modal parameter estimates.
- If the modal parameters are accurate, then the *Fit Function* will lie on top of the FRF data.

**Using the Band Cursor**

If the Band Cursor is displayed, curve fitting is done using data from within the cursor band. It is often more convenient to curve fit using several cursor bands to avoid noise or non-resonance peaks in the FRFs.

- Execute Curve Fit | Fits Functions | Clear Fit Functions and *click* on Yes in the dialog box.
- Execute Display | Cursors | Band Cursor and *drag* the edges of the band to enclose the 10 resonance peaks, as shown below.
- *Press* the Residues button again and *click* on Yes in the dialog box.

Notice that the red *Fit Function* is only displayed over the cursor band because only that data was used for curve fitting. The residue estimates will also be slightly different when residue curve fitting is done in cursor bands instead of using all of the FRF data.
Quick Fit

The quickest way to curve fit FRFs is to “divide & concur”;

1. Display the band cursor in a small band of data enclosing several resonance peaks
2. Execute Quick Fit
3. Move the band cursor to enclose several more resonance peaks, and execute Quick Fit again

When Curve Fit | Quick Fit is executed, the following three curve fitting steps are carried out,

1. If there is no Mode Indicator, a new Mode Indicator is calculated using the current method on the Mode Indicator tab, and its peaks above the noise threshold line are counted
2. Frequency & damping are estimated for the number of peaks counted, using the current curve fitting method on the Polynomial tab.
3. A Residue is estimated using the modal frequency & damping estimates from for each selected mode in the Modal Parameters spreadsheet, using the current curve fitting method on the Residues tab.

When all resonance peaks can be easily identified and counted in a set of FRFs, all of the data can be curve fit in one execution of the Quick Fit command. To Quick Fit all 99 Jim Beam FRFs using all of the data in each M#,

- Make sure all cursors are not displayed
- Make sure all M#s are un-selected.
- Execute Curve Fit | Delete All Fit Data, and click on Yes in the dialog box that opens.
- Execute Curve Fit | Quick Fit
• The Quick Fit results will be displayed, as shown below.

Comparing Shapes using MAC

While still curve fitting, mode shapes in the Modal Parameters spreadsheet can also be compared with shapes in a Shape Table using the MAC value between shape pairs.

Saving Shapes

After all curve fitting has been completely, the modal parameter estimates in the Modal Parameters spreadsheet can be saved into a Shape Table.

- **Press** the Save Shapes button on the Residues, Save Shapes tab.
- **Press** the New File button in the dialog box that opens to create a new Shape Table.
- **Enter** "My Mode Shapes" into the next dialog box that opens and **click** on OK.

The Shape Table window will open, listing the mode shapes of the 10 modes of the Jim Beam obtained from the Quick Fit. Notice that the mode shapes are called Residue Mode Shapes. The Residue for each mode and each FRF is a component of the Residue Mode Shape for that mode.
Shape Table Showing 10 Mode Shapes.

Animating Shapes from a Shape Table

- If the STR: Colored Jim Beam window is not open, open it from the Project Panel.
- Close all other windows except the SHP: My Mode Shapes window and the STR: Colored Jim Beam window.
- Execute Window | Arrange Windows | For Animation in the MEscope window.

When Window | Arrange Windows | For Animation is executed, the active window retains its size and all other windows are arranged with it in the Work Area.

- Execute Animate| Animate Shapes in the SHP: My Mode Shapes window.
- Press each of the Select Shape buttons in the Shape Table window to display each mode shape in animation.
Animating a Shape from "My Mode Shapes".

**Terminating Curve Fitting**

- Execute Curve Fit | Close Curve Fitting

*All* curve fitting data is saved in the Data Block file when its Project (VTprj) file is saved on disk.