VIBRANT

MEscope Application Note 18

Simulated Multiple Shaker Burst Random Modal Test

The steps in this Application Note can be carried out using any MEscope package that includes the **VES-3600 Advanced Signal Processing & VES-700** options. Without these options, you can still carry out the steps in this App Note using the **AppNote18** project file. These steps might also require MEscope software with *a more recent release date*.

APP NOTE 18 PROJECT FILE

- To retrieve the Project file for this App Note, **click here** to download **AppNote18.zip**

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

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

INTRODUCTION

In this Application Note, you will use the Multiple Input Multiple Output (**MIMO**) calculation and data acquisition features of MEscope to simulate a modal test using two shakers driven with burst random signals. The dynamics of the structure under test will be modeled using a **modal model**. This exercise will simulate a shaker test using *2 uncorrelated random signals* and an MEscope Acquisition window with **101** *data acquisition channels*. The following steps will be carried out in this exercise

1. Synthesize two burst random force time-domain waveforms using the **File | New Data Block** command
2. Use the Data Block with the burst random signals together with the **modal model** of Jim Beam in the **Transform | MIMO Outputs** command to calculate **99 forced response time waveforms** for the Jim Beam structure
3. Use the **Acquisition** window to *"acquire"* the force & response time waveforms from a Data Block file, and calculate **multiple reference FRFs, Multiple Coherences, and Partial Coherences**
4. Curve fit the multiple reference **FRFs** and compare **MAC** values between the resulting mode shapes and the modes of the original modal model

STEP 1 - JIM BEAM MODE SHAPES

- *Press* **Hotkey 1 Jim Beam Mode Shapes**
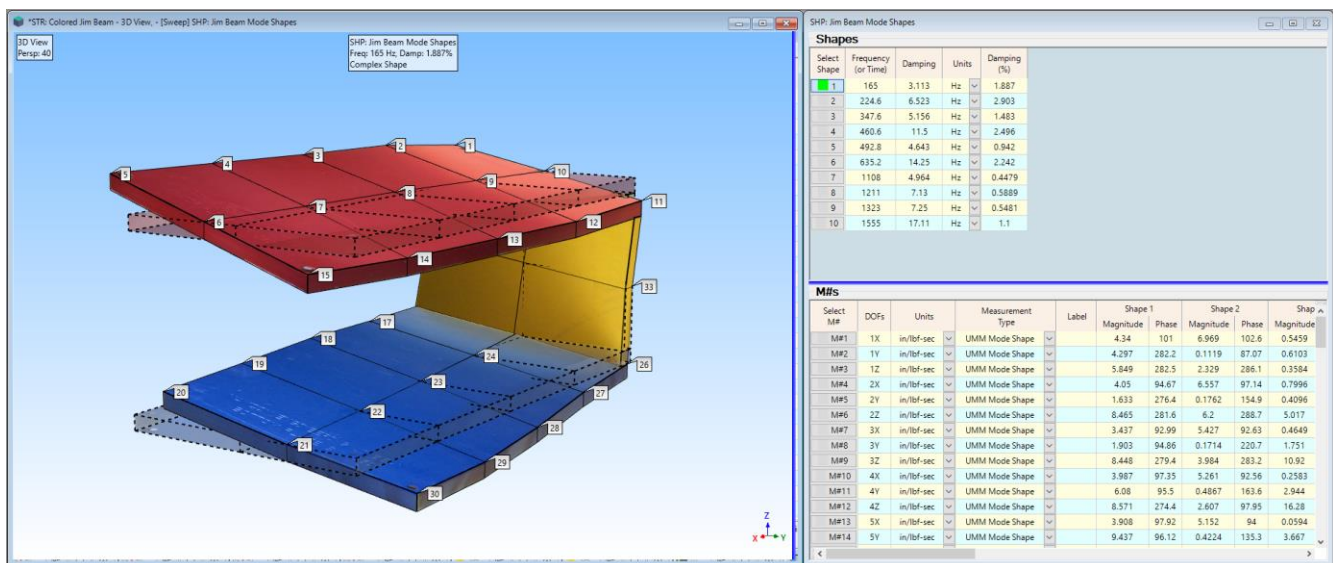
Mode Shapes of Jim Beam in Sweep Animation.

The Shape Table **SHP: Jim Beam Mode Shapes** has 10 modes in it, ranging in frequency from **165 Hz to 1555 Hz**. Each mode shape has **99 DOFs** that define the resonant deflection of the structure in *three directions* **(X, Y, Z)** at **33 Points**.

The mode shapes are scaled to **Unit Modal Masses (UMM)**. This is a **modal model** and it can be used to define the dynamic properties of the structure between *any two* Points & directions (**DOFs**) where its mode shape components are defined.

TRUNCATED DYNAMIC MODEL

This modal model is called a *truncated dynamic model* since it only includes the 10 of the lowest frequency modes of the Jim Beam. The real-world Jim Beam, which is made of three aluminum plates attached together with 6 cap screws, has *many more than 10 modes*. Nevertheless, it is assumed that these 10 modes *will adequately represent the dynamics* of the structure between 0 and 2000 Hz.

BURST RANDOM EXCITATION

To simulate a multiple shaker test, the response of the Jim Beam to two burst random time-domain force signals will be calculated using the **Transform | Outputs** command.

Burst random excitation signals are ideal for modal testing of large structures (such as aircraft & automobiles) using multiple shakers because both the acquired force & response signals are *completely containing* within their sampling window time-period **T**. Hence, the **FRFs** calculated from these signals are *leakage free*, and do not require any special time-domain windowing (such as a Hanning window).

Furthermore, burst random excitation can be combined with spectrum averaging to r*educe the effects of extraneous noise and non-linearities* from the **FRFs**. **FRFs** calculated from burst random excitation and spectrum averaging yield the *best linear approximation* of the dynamics of *non-linear real-world structures*.

> A set of **FRFs** calculated from burst random excitation & response signals is especially useful for extracting modal parameters using *linear FRF-based curve fitting methods.*

A burst random signal is *like a pure random signal*, but it is shut off prior to the end of the sampling window time **T**. This is done to allow the response of the structure to *decay to near-zero* before the end of the sampling window. Both burst random excitation and the response signals are completely contained within their sampling window time-period T, thus *eliminating any leakage effects* in their corresponding spectra.

BURST RANDOM RESPONSES

To simulate a multiple shaker test, the response of the Jim Beam to two burst random time-domain force signals will be calculated using the **Transform | Outputs** command. The two forces, together with the **modal model** for the Jim Beam, will be used to calculate time waveforms of the forced response of the Jim Beam.

The two random forces will be applied at Points 5 & 15 in the vertical direction, or **DOFs 5Z & 15 Z**. The modal model is used to synthesize **FRFs** between the shaker excitation DOFs and response DOFs in three directions (**X, Y, Z**) at 33 Points on the structure.

The synthesized **FRFs** with then be multiplied by the Fourier spectra (**DFTs**) of the two excitation forces (Inputs) to obtain the Fourier spectra of the 99 responses (Outputs). Finally, the response **DFTs** are Inverse Fourier transformed to yield the forced response time waveforms of the structure. This Multi-Input Multi-Output (**MIMO**) calculation is depicted in the figure below.
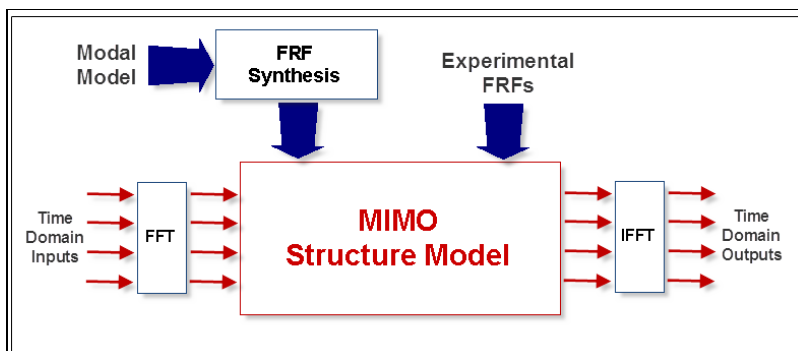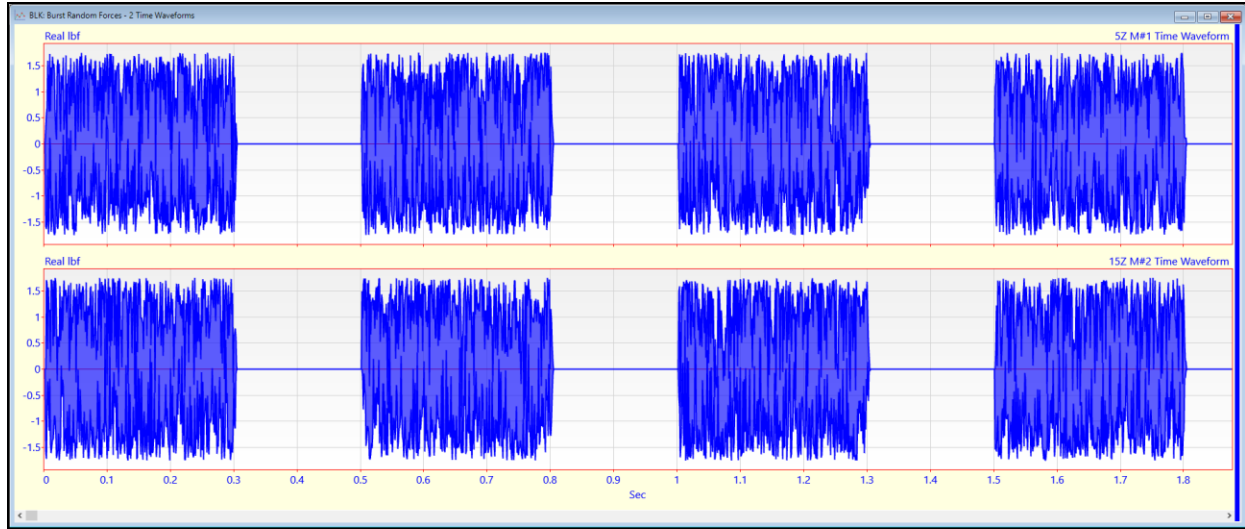
Zoomed Data Block Window Showing Burst Random Time Waveforms.

The two burst random signals shown above where created with the **File | New| Data Block** command and are displayed in the **BLK: Burst Random Forces** window.

Since 25 averages will be used calculate **FRFs** from the burst random data, each **M#** in **BLK: Burst Random Forces** contains *25 unique burst random signals*, one after another. Each burst random signal is **2000** samples long and is defined over a sampling window period of **T = 0.5 seconds**.

> Each M# in BLK: Burst Random Forces contains 50,000 samples, 25 burst random signals of 2000 samples each.
>
> Each random burst will excite the structure differently, so averaging together 25 response spectra together will *"average out"* any noise and non-linearities, leaving only *linear, noise-free spectra*.

A burst random width of **60%** means that the signal is *shut off* **at 60% of T**, or at **0.3 seconds**.

> A burst random width should be chosen to ensure that the structural response *has decayed to near zero* by the end of the sampling window. The decay of the structural response *depends on the damping* in the structure. The mode with *the smallest amount of modal damping* governs how quickly the response decays to near-zero.

We will see that a burst random width of 60% will ensure that the responses of the Jim Beam have *sufficiently decayed within 0.5 seconds*.

DIFFERENTIATING THE MODE SHAPES

To simulate a real-world shaker test, the simulated Jim Beam responses *should have acceleration unit*s. The **UMM** mode shapes in **SHP: Mode Shapes** have displacement units in their numerators.

> To differentiate **UMM** mode shapes from *displacement to acceleration* units, they must be converted to **Residue** mode shapes.

When **Hotkey 2 is** *pressed*, the **UMM** mode shapes are converted to Residue mode shapes with References 5Z & 15Z and those mode shapes are *differentiated twice*. The following commands are executed by the **Script for Hotkey 2**.

- Execute **Tools | Scaling | UMM to Residue Shapes** in the **SHP: Mode Shapes** window
- **Reference DOFs 5Z & 15Z** are used as Script parameters
- Save the converted **Residue** mode shapes into **SHP: Residue Mode Shapes**
- Execute **Tools | Differentiate** *twice* in **SHP: Residue Mode Shapes**
- Change the mode shape units to **g/lbf-sec** in **SHP: Residue Mode Shapes**

STEP 2 – BURST RANDOM RESPONSES

To calculate the responses of the Jim Beam due to burst random forces applied at **DOFs 5Z & 15Z**,

- *Press* **Hotkey 2 Random Responses**

The burst random forces and **Residue** mode shapes are displayed *on the left*. The burst random forces and the calculated Burst Random responses are displayed **BLK: Simulated Inputs & Outputs** *on the right* below.
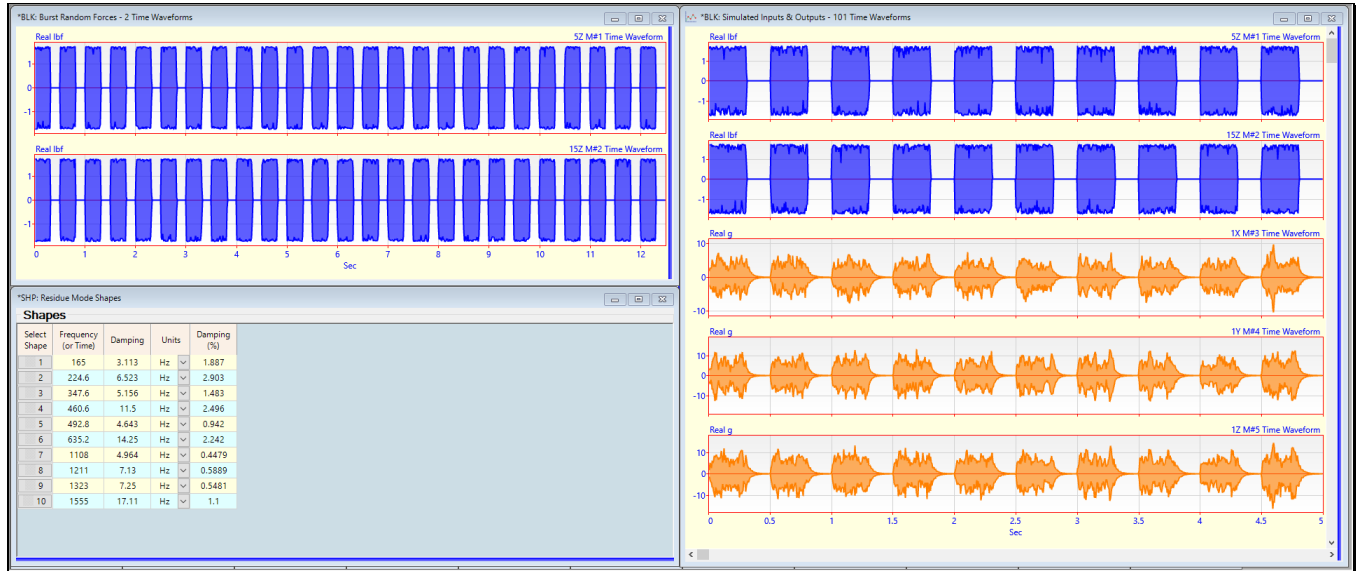
Calculated Resonse Outputs to Two Burst Random Inputs.

From the responses, it is clear that *shutting off the burst random signals at* **60%** of each sampling window (**T= 0.5 seconds**) was sufficient to allow the structural response to *decay to near-zero* before the end of each sampling window.

The two forces (designated as **Inputs**) and the 99 responses (designated at **Outputs**) are saved in **BLK: Simulated Inputs & Outputs** as shown above.

In the next step, *all 101 channels of data* are *"simultaneously acquired"* from **BLK: Simulated Inputs & Outputs** by an Acquisition window. *2000 samples at a time* while performing 25 spectrum averages.

STEP 3 - MULTI-CHANNEL ACQUISITION FROM A DATA BLOCK

The Acquisition window (**ACQ: Data Block Acquisition**) shown below is already step up to *acquire 25 averages* of data and calculate multi-reference **H1 FRFs** together with **Multiple & Partial Coherences** from the **99 burst random responses** caused by the **2 burst random excitation forces**.

- On the **Sampling** tab, **Number of Samples ➔ 2000** and **Averages ➔ 25**

- On the **Measurement** tab, **H1 FRF** and **Coherence** are *both checked*
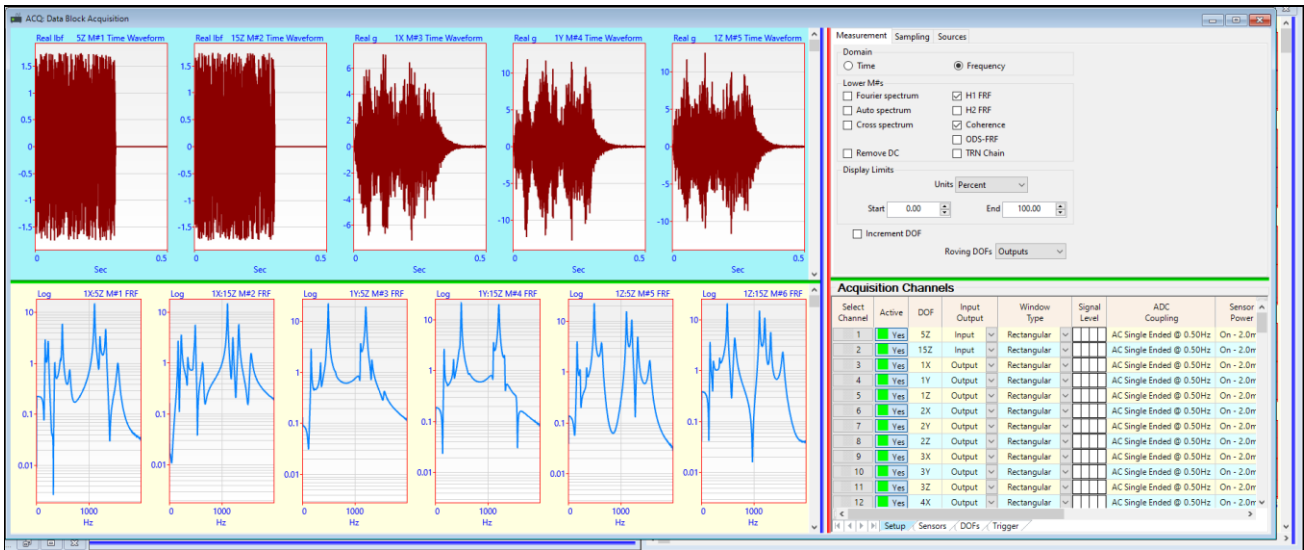
Acquisition Window Setup to Acquire 25 Averages.

The time & frequency sampling parameters on the **Sampling** tab in **ACQ: Data Block Acquisition** match those used to create the time waveforms in **BLK: Burst Random Forces**, 25 burst random time waveforms of 2000 samples each.

> With burst random signals, there is no need to trigger on an Input signal. Each excitation burst and the resulting responses will be properly acquired because *each sampling time window of 2000 samples* has the same time length, **T = 0.5 sec**.

In the **Window Type** column of the **Acquisition Channels** spreadsheet above, all channels have a **Rectangular** window applied to them. This is the default time domain window, and is also referred to as a **Uniform** or **Boxcar** window, or **None**.

> A **Rectangular** window *does not alter the time waveform* before it is transformed to a **DFT**.

To begin multi-channel data acquisition from the **BLK: Simulated Inputs & Outputs** Data Block,

- *Press* **Hotkey 3 Multi-Channel Acquisition**

As data is acquired, the acquired time waveforms are displayed in the *upper graphics* area, while the calculated **FRFs** & **Coherences** are displayed in the *lower graphics* area of **ACQ: Data Block Acquisition**.

When all 25 averages of data have been acquired, the **FRFs** & **Coherences** are saved into Data Block **BLK: FRFs & Coherence**, and it is displayed as shown below.
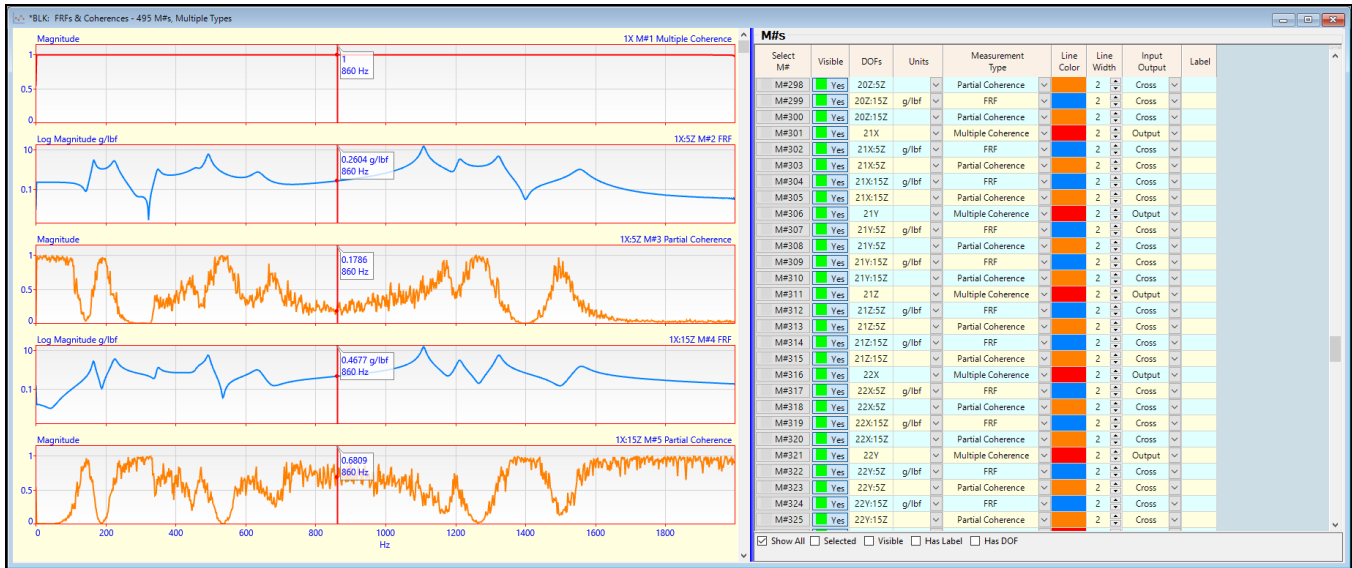
Multiple Coherence, FRF 1X:5Z, Partial Coherence 1X:5Z, FRF 1X:15Z, Partial Coherence 1X: 15Z.

Five M#s are displayed for **each Roving DOF** in **BLK: FRFs & Coherence**,

1. One **Multiple Coherence** function for the Roving **DOF**
2. An **FRF** between the Roving **DOF** and the force (Input) at **DOF** 5Z
3. A **Partial Coherence** between the Roving **DOF** and the force (Input) at **DOF** 5Z
4. An **FRF** between the Roving **DOF** and the force (Input) at **DOF** 15Z
5. A **Partial Coherence** between the Roving **DOF** and the force (Input) at **DOF** 15Z

MULTIPLE COHERENCE

Multiple Coherence measures how much of a measured response *is linearly related to* (correlated with or caused by) all measured Inputs, in this case force Inputs at **5Z & 15Z**. **Multiple Coherence ➜ 1** indicates that a response *is linearly related to all the measured Input forces*.

When **Hotkey 2 was** *pressed*, 99 burst random responses were calculated from two burst random forces using 10 mode shapes to represent the dynamics of the Jim Beam between the force Inputs and the response Outputs. Therefore, the responses are *perfectly correlated* with the forces.

PARTIAL COHERENCE

Partial Coherence measures how much of a measured response is due to each measured force Input.

Partial Coherence ➜ 1 indicates that a response *is linearly related to one of the measured Input forces*.

The *sum of the Partial Coherences ➜ close to "1"* at each frequency.

If the Partial Coherence *has a high value* at a frequency, this indicates that the force applied at that **DOF** *is exciting the structure*. On the other hand, *if a* **Partial Coherence** *is close to zero* at a frequency, this indicates that the force applied at that **DOF** *did not excite the structure*.

STEP 4 - CURVE FITTING THE FRFS

- *Press* **Hotkey 4 Multi-Ref Quick Fit**

To curve fit the multi-reference **FRFs**, only the **FRFs** were saved into another Data Block **BLK: Multi-Ref FRFs**. Then they were curve fit using the **Multi-Reference Quick Fit** method.

When Multi-Reference curve fitting is completed, modal parameter estimates are displayed in the **Modal Parameters** spreadsheet on the *lower right* on the **BLK: Multi-Ref FRFs** window, and a **red Fit Function** is overlaid on each FRF.

- Use the **vertical scroll bar** on the *right of the* **FRF** *graphics* to scroll through the **FRFs** and display their modal parameters

All ten modes originally used to model the dynamics of the Jim Beam have been recovered from the multi-reference **FRFs**.
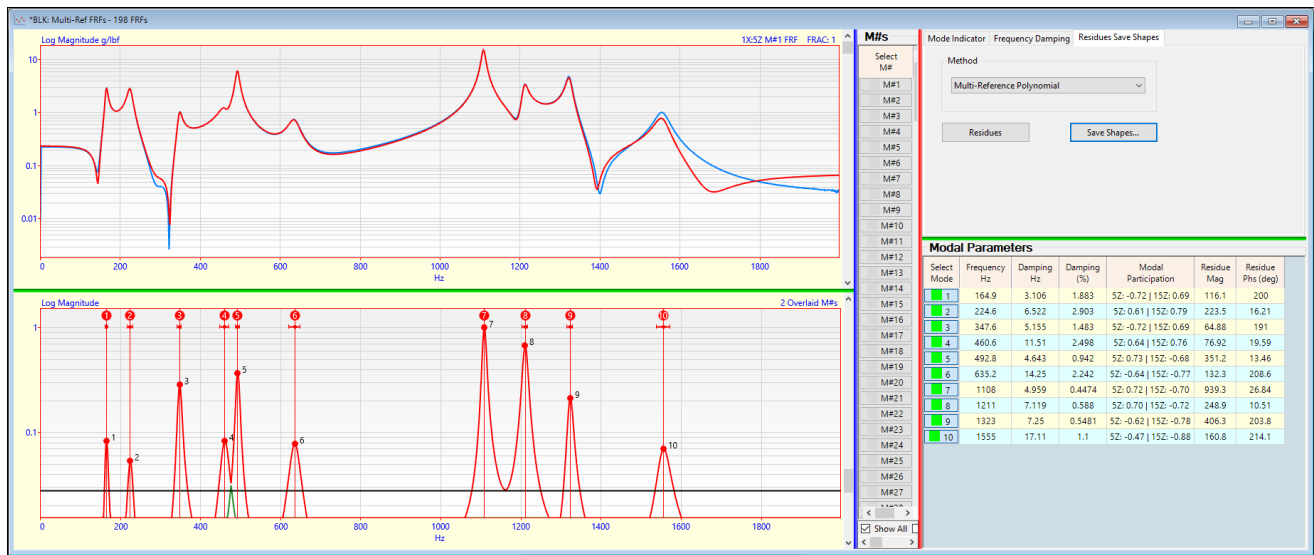
Multi-Ref Quick Fit Results.

USING MAC & SDI TO COMPARE MODE SHAPES

The mode shapes extracted from the **FRFs** with Multi-Ref Quick Fit and saved in the **SHP: Multi-Ref Quick Fit Mode Shapes** Shape Table will be compared with the original mode shapes in **SHP: Residue Mode Shapes** in two ways.

- Displaying a **MAC** bar chart between the two Shape Tables
- Displaying an **SDI** bar chart between the two Shape Tables

MODAL ASSURANCE CRITERION (MAC)

MAC is a measure of the *co-linearity* of two shape vectors. If two shapes *lie on the same straight line*, they are *co-linear* and **MAC ➔ 1.0**. If two shapes *do not lie on the same straight line*, they are *linearly independent* and **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 different* (*are linearly independent*)

SHAPE DIFFERENCE INDICATOR (SDI)

SDI is a measure of the *equality* of two shape vectors. If two shapes have *equal components*, SDI ➔ 1.0. If two shapes *do not have equal components*, SDI ➔ *less than 1.0*.

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

SDI values ➔ *between 0 &1*

SDI = 1.0 ➔ two shapes *have equal components*

SDI >= 0.9 ➔ two shapes *are similar*

SDI < 0.9 ➔ two shapes *are different* (*some matching components are not equal*)
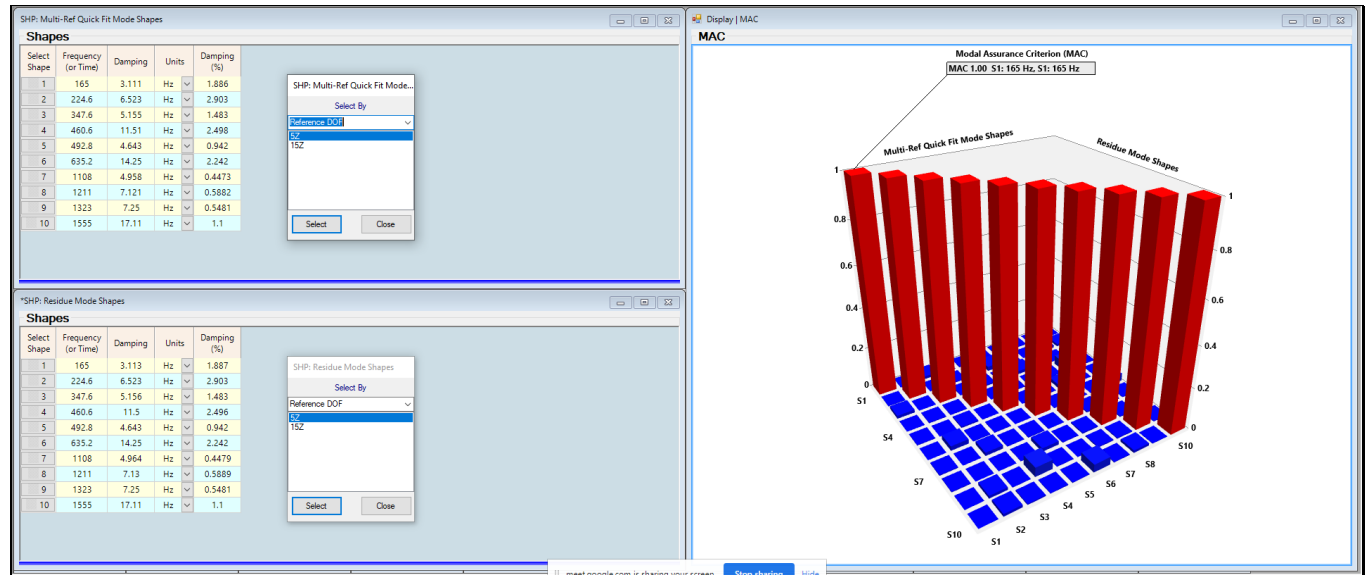
STEP 5 - COMPARE MODE SHAPES USING MAC

- *Press* **Hotkey 5 Compare Mode Shapes using MAC**

The mode shapes estimated in **Step 4** also have **multi-reference M#s**, so the **Select By Reference DOF** box will open for both the Shape Tables **SHP: Multi-Ref Quick Fit Mode Shapes** and **SHP: Residue Mode Shapes**.

- *Select* a **Reference DOF (5Z or 15Z)** to display the **MAC** bar values between the two Shape Tables for the *selected* references

A diagonal **MAC** bar ➔ **1** indicates that a **Multi-Ref Quick Fit** mode shape estimate *is co-linear with* an original **Residue** mode shape.

The **Multi-Ref Quick Fit** mode shape frequency & damping estimates also *closely match* those of the original ten **Residue** mode shapes.

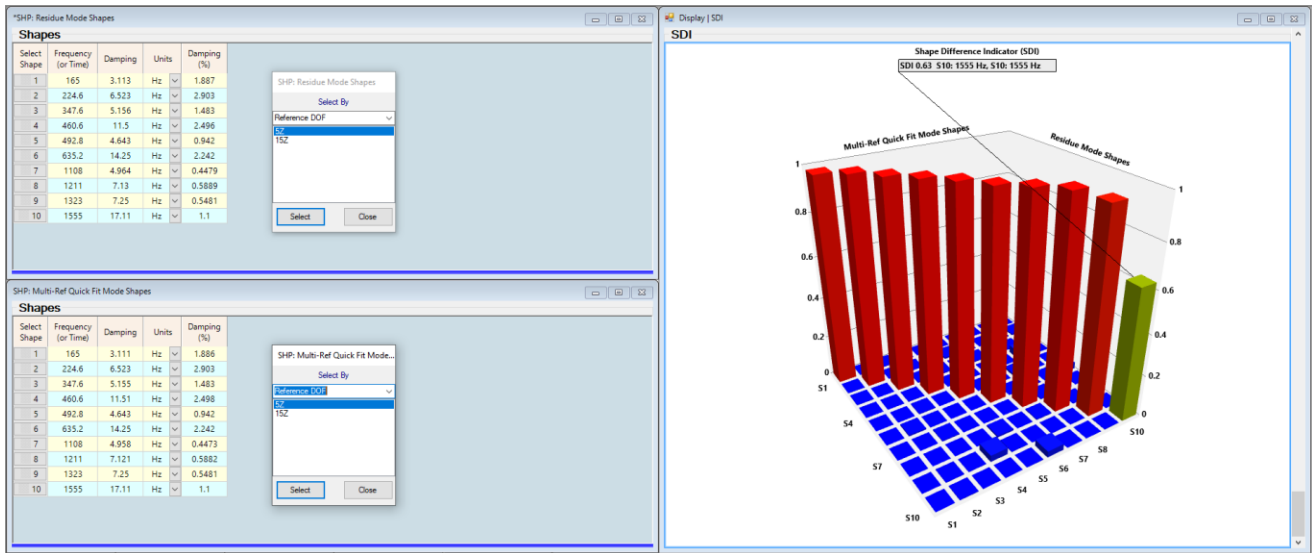*MAC Values Between Multi-Ref Quick Fit & Residue Mode Shapes.*

STEP 6 - COMPARE MODE SHAPES USING SDI

- *Press* **Hotkey 6 Compare Mode Shapes using SDI**

The mode shapes estimated in **Step 4** also have **multi-reference M#s**, so the **Select By Reference DOF** box will open for both the Shape Tables **SHP: Multi-Ref Quick Fit Mode Shapes** and **SHP: Residue Mode Shapes**.

- *Select* a **Reference DOF (5Z or 15Z)** to display the **SDI** bar values between the two Shape Tables for the *selected* references

A diagonal **SDI** bar ➔ **1** indicates that a **Multi-Ref Quick Fit** mode shape estimate *is equal to* an original **Residue** mode shape.

SDI Values Between Multi-Ref Quick Fit & Residue Mode Shapes.

STEP 7 - REVIEW STEPS

To review all the steps of this App Note,

- *Press* **Hotkey 7 Review Steps**

CONCLUSIONS

A two-shaker 101-channel modal test was simulated by using an Acquisition window to acquire time domain force and response waveforms from a Data Block file. The forced responses (Outputs) were calculated using the **Transform | Outputs** command and the following data,

- Two synthesized *uncorrelated burst random excitation forces* (Inputs)

- A **modal model** of the Jim Beam consisting of *ten Residue mode shapes* with *acceleration numerator units*

The simulated force & response time waveforms were *"acquired"* by the Acquisition window from a Data Block, and multiple reference **FRFs**, plus Multiple & Partial Coherences were calculated.

The multiple reference **FRFs** were then curve fit, and the resulting mode shapes compared with the **Residue** mode shapes of the **modal model** used to model the dynamics of the Jim Beam in a **MIMO** simulation. The mode shape estimates from a Multi-Reference Quick Fit of the **FRFs** were *nearly identical* to the original Residue mode shapes.

These results verify that a multiple shaker modal test *using burst random excitation* yields *leakage-free* **FRFs** that *preserve the linear dynamic properties* of a test article.

In a real-world modal test, spectrum averaging will **"filter out"** *non-linearities and extraneous noise* from the FRF estimates.

Curve fitting *low noise linear FRF estimates* always yields *more accurate mode shape estimates*.

The **Multiple Coherences** *were at or near "1"* for all frequencies, indicating that the measured responses were *linearly related* to the measured forces at all frequencies. However, there were no other unmeasured forces or extraneous noise contributing to the measured responses.

The **Partial Coherences** (one for each force Input*) summed to values at or near "1"* for all frequencies, again indicating that the measured forces *were linearly related* to the measured responses. The Partial Coherences further showed the *percentage of each force* that caused each response at each frequency.