



MEscope Application Note 12

Calculating ODS-FRFs from Bridge Impact Data

The steps in this Application Note can be carried out using any MEscope package that includes the **VES-3600 Advanced Signal Processing** option. Without this option, the steps can still be carried out using the **AppNote12** project, but the results cannot be saved. These steps might also require MEscope software with a *more recent release date*.

APP NOTE 12 PROJECT FILE

- To retrieve the Project for this App Note, [click here](#) to download **AppNote12.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

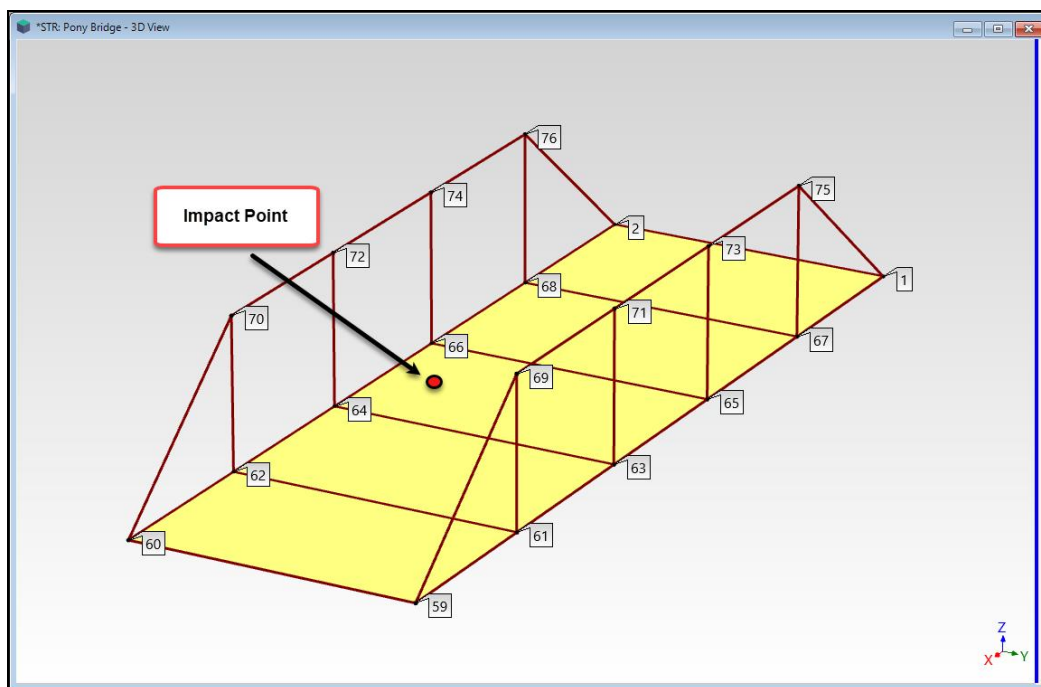
In this Application Note, test data acquired during an impact test of the bridge pony truss shown below is processed in MEscope to yield a set of **Operating Deflection Shape Frequency Response Functions (ODS-FRFs)**. The **ODS-FRFs** are then used to display the Operating Deflection Shapes (ODS's) of the bridge truss in animation on a 3D model of the pony truss.

Modal testing is *ideally done* under *controlled excitation* and *time-invariant (stationary)* conditions, using one or more sources of excitation.

- To calculate **Frequency Response Functions (FRFs)**, the excitation forces and their corresponding responses *must be simultaneously acquired*

Excitation force is typically measured with a *load cell*; and vibration response is typically measured with an *accelerometer*, although velocity or displacement sensors can also be used.

- In an **output-only** or **operational modal** test, the excitation *forces are not measured*



Model of a Bridge Pony Truss.

For this App Note, a pony truss of a bridge was excited with a *drop-weight impactor*. The impact points are labeled on the model below.

- An impactor was necessary to excite the lowest frequency modes of the bridge, which were *below 15 Hz*
- However, the impactor created peak forces that were *far greater than any load cell could withstand*

Since the impact force was not measured, FRF measurements could not be calculated. When the excitation force is not acquired, a *Transmissibility* measurement is typically calculated instead. A Transmissibility (TRN) is defined as,

$$\text{TRN} = \frac{\text{DFT (roving response)}}{\text{DFT (reference response)}}$$

- The **DFT** is the **Discrete Fourier Transform**
- A **DFT** is calculated from a uniformly-sampled time waveform using the FFT algorithm
- The reference response sensor *must remain fixed* throughout an *output-only* test

REQUIREMENTS FOR AN ODS

An Operating Deflection Shape (ODS) is *any motion at two or more DOFs* (points & directions) on a machine or structure.

- An ODS defines the *relative motion* between *two or more DOFs* on a machine or structure
 - A **frequency-based ODS** is defined at *a specific frequency*
 - A **time-based ODS** is defined at *a specific moment in time*
- Each shape component of an ODS must have the *correct magnitude & phase relative to all other shape components*

To ensure that all measured responses have the correct relative magnitudes & phases, one of the following acquisition methods must be employed.

- *Simultaneously acquire* all responses
- *Simultaneously acquire some Roving responses and a fixed Reference response*
 - A set of *simultaneously acquired data* is called a **Measurement Set**

MULTIPLE MEASUREMENT SETS

Most field vibration measurements are made with equipment that can only acquire a *few channels of data at a time*. Therefore, multiple Measurement Sets of data are required.

- Each Measurement Set consists of one or more **different Roving responses** and the **same Reference response**
- To preserve the *relative phase among all responses*, the same Reference response (or responses) must be acquired with all Measurement Sets

STATIONARY STRUCTURE

During a field test, the total time required to obtain all measurements can be substantial, and the machine or structure could undergo physical changes from the beginning to the end of the test.

If the physical properties of the structure or machine change during a test, its vibration characteristics could also change. For example, outdoor temperature changes due to sunshine can cause changes in material stiffness. Damping characteristics can change during a prolonged test. Unmeasured excitation force levels can also change during a test.

- A structure is said to be *stationary* if the *Auto spectrum* of one of its responses does not change from the beginning to the end of the test

When overlaid on one another, if two or more Auto spectra calculated for the same DOF of the test article *are essentially the same*, the structure is said to be stationary.

- If the *amplitude* of an **Auto spectrum** for the same DOF changes during a test, the structure is still considered to be stationary, but re-scaling is required to define ODS's from the data

HOW THE BRIDGE DATA WAS ACQUIRED

The bridge was excited with an *impactor* that consisted of a sliding weight (like a bar bell weight) on a pole mounted to a base-plate. The weight had handles on two sides so that two people could lift it. When the weight was lifted and then released, it slid down the pole and impacted the bridge.

The *impactor* was located at a fixed point near the middle of the bridge span, as shown in the first figure above. This location was chosen to excite as many resonances of the bridge as possible.

- A *uni-axial accelerometer* was mounted near the impactor to acquire the *Reference response* during each impact
- A *Roving tri-axial accelerometer* was used to acquire the 3D response at each of the numbered Point on the bridge trusses, as shown in the first figure above

During each impact of the bridge, a 4-channel analyzer was used to *simultaneously acquire* three tri-axial Roving acceleration signals and the Reference acceleration signal. The bridge was impacted three times for each Measurement Set, and *tri-spectrum averaging* was used in the analyzer to reduce extraneous noise.

TRANSMISSIBILITY

Transmissibility is the traditional way of making a frequency response measurement when the excitation force (or forces) cannot be measured.

- An **FRF** is defined as the ratio of the **DFT of a response** divided by the **DFT of a force** that caused the response
- A **Transmissibility** is calculated in the same way as an FRF, but the spectrum of a *fixed Reference response* is substituted for the spectrum of the excitation force in the denominator of the Transmissibility
- A **Transmissibility** is defined as the ratio of the **DFT of a Roving response** divided by the **DFT of a fixed Reference response**

DIFFICULTY WITH TRANSMISSIBILITY'S

- **Assumption 1:** If the spectrum of the un-measured force (or forces) is *assumed to be "a relatively flat spectrum"*, then a peak in the Auto spectrum of each response is caused by the excitation of a resonance
- The difficulty with a Transmissibility is that a *resonant frequency* is displayed as a *"flat spot", not as a peak*
- A *"flat spot"* is caused by the division of one response **DFT** by another where *both contain the same resonance curve*

A set of **ODS-FRFs** is created by multiplying a set of *Transmissibility's* by a *reference Auto Spectrum*, thus creating measurement functions with a peak at each resonance.

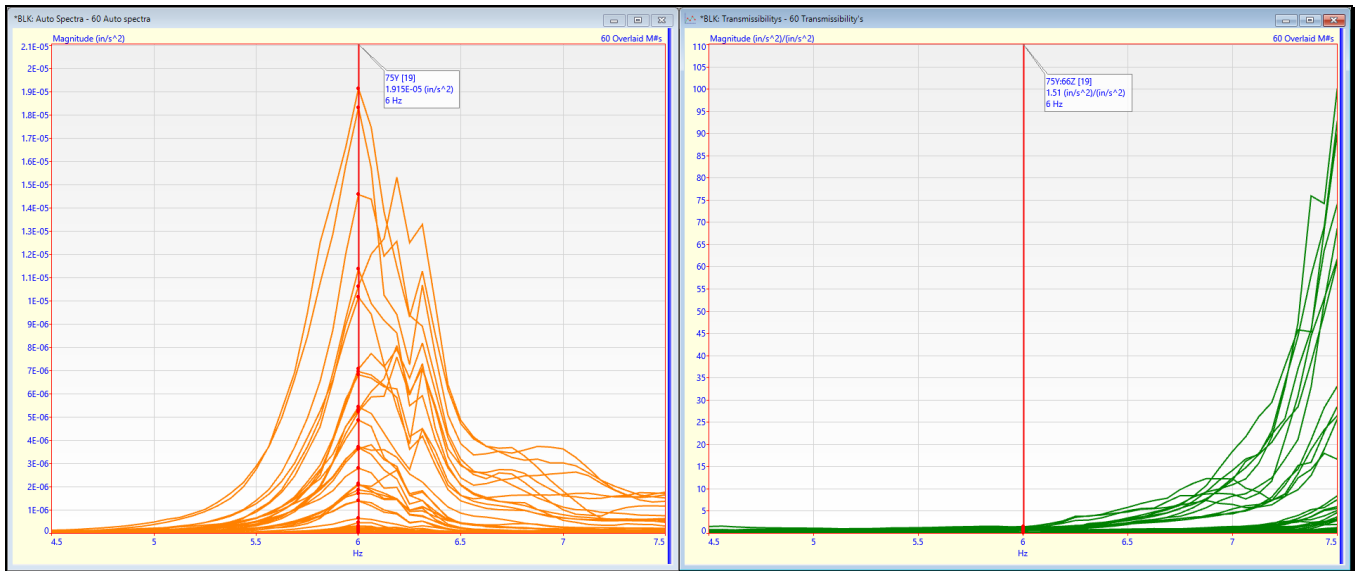
- An **ODS-FRF has a peak at each structural resonance**, so a **frequency-based ODS** can be displayed and extracted from a set of ODS-FRFs at each resonant frequency

STEP 1 - AUTO SPECTRUM VERSUS TRANSMISSIBILITY

- **Press Hotkey 1 Auto Spectra Versus TRNs**

The Auto spectra for all the **Roving DOFs** of the bridge are overlaid *on the left*, and the Transmissibility between each Roving DOF and the Reference DOF are overlaid *on the right*.

- A resonance peak is shown at 6 Hz in the Auto spectra and a **“flat spot”** is shown at 6 Hz in the Transmissibility’s.



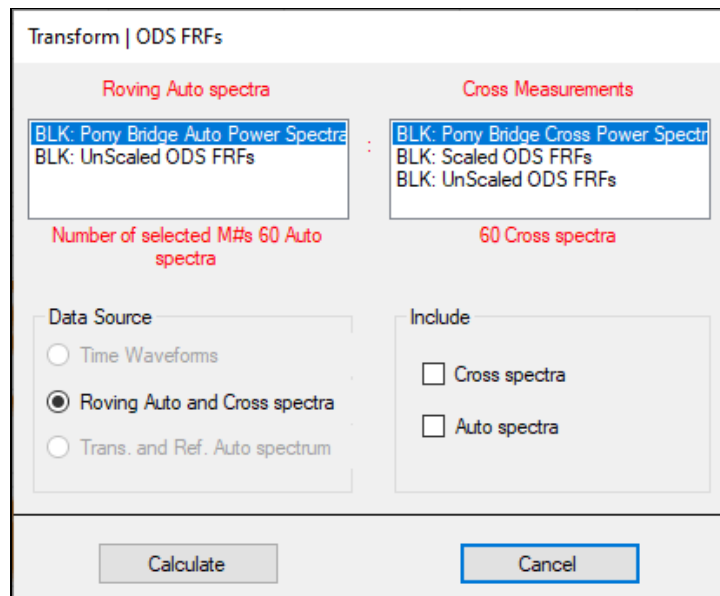
Auto spectrum & Transmissibility at the Same Frequency.

THREE WAYS TO CALCULATE AN ODS-FRF

In MEScope, three different types of data can be used to calculate an **ODS-FRF**,

1. Roving & Reference **response time waveforms**
2. **Transmissibility** between a Roving & Reference response, and a **Reference Auto spectrum**
3. **Auto spectrum** of a Roving response and a **Cross spectrum** between the Roving & Reference response

When **Transform | ODS-FRFs** is executed in a Data Block window, the following dialog box opens



- If **Roving & Reference time waveforms** are provided, an **ODS-FRF** is calculated by first calculating a Transmissibility between the Roving & Reference response, and then multiplying the Transmissibility by the **Reference Auto spectrum**
- If a **Transmissibility** and a **Reference Auto spectrum** are provided, an **ODS-FRF** is calculated by multiplying the Transmissibility by the **Reference Auto spectrum**
- If **Roving Auto & Cross spectra** are provided, an **ODS-FRF** is calculated by replacing the magnitude of the Cross spectrum with the Auto spectrum

In this App Note Auto & Cross spectra are used to calculate ODS-FRFs.

When multiple Measurement Sets of data are acquired, each **ODS-FRF contains the correct magnitude** of a response (the Auto spectrum of a Roving response) together with **the correct phase relative to the Reference response** for each Measurement Set.

ODS-FRFs IN DISPLACEMENT, VELOCITY, OR ACCELERATION UNITS

Another advantage of an **ODS-FRF** is that it can be integrated from **acceleration to velocity units** or **doubly integrated to displacement** units.

- **Frequency-based ODS's** extracted from **ODS-FRFs** provide the **true deflection** of a structure or machine in engineering units

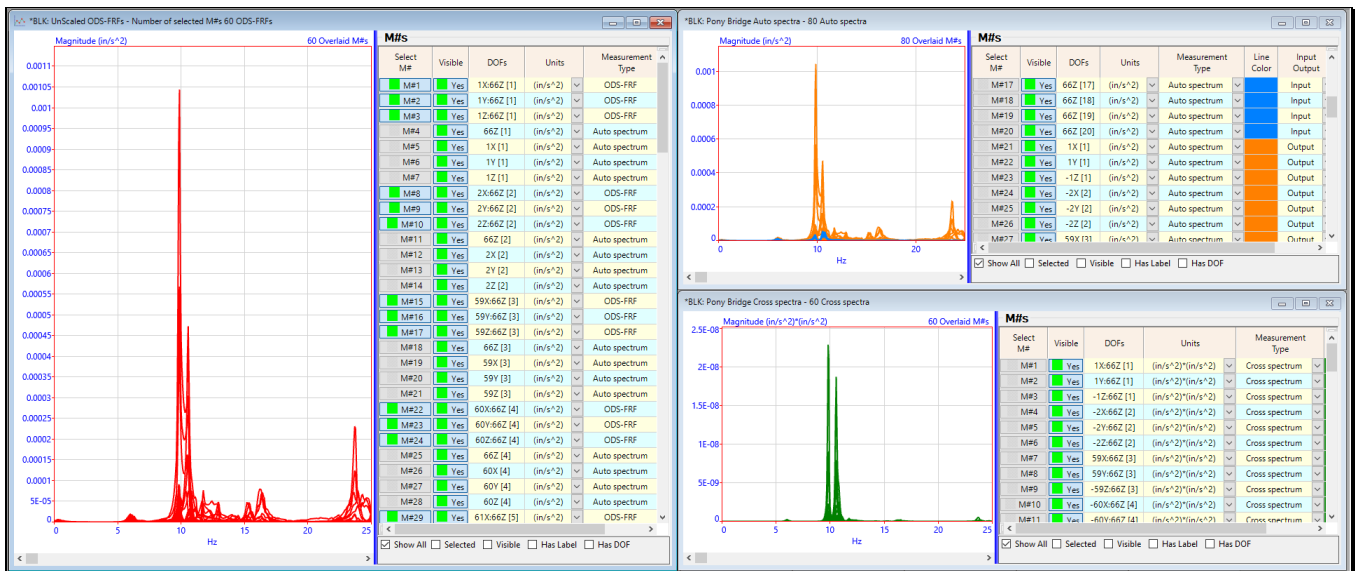
STEP 2 - CALCULATING ODS-FRFs

- **Press Hotkey 2 Calculate ODS-FRFs**

The **BLK: Unscaled ODS-FRFs** window will open with **60 ODS-FRFs** overlaid in it. Three **ODS-FRFs** represent the acceleration in the X, Y & Z directions at each of the 20 Points on the bridge.

BLK: Unscaled ODS-FRFs is shown on the *left below*, **BLK: Pony Truss Auto Spectra** on the *upper right*, and **BLK: Pony Truss Cross Spectra** on the *lower right*.

BLK: Pony Truss Auto Spectra contains both the Roving Auto spectra and the Reference Auto spectra calculated for the time waveforms acquired from the bridge pony truss. **BLK: Pony Truss Cross Spectra** contains the Cross spectra between each roving DOF and the Reference DOF.



Overlaid ODS-FRFs on the Left and Auto & Cross Spectra on the Right.

- **Drag the Blue Splitter bar to the left** to display the M# properties in each Data Block window

DIFFERENT FORCE LEVELS

Transmissibility is a *ratio of the DFTs of two responses*. The excitation force level can change throughout a test, which commonly occurs with impact testing.

- **Multiple Measurement Sets** of Transmissibility's can be calculated from data acquired with *as few as two simultaneous acquisition channels*
- **The Transmissibility in each Measurement Set is the ratio of a different Roving response divided by the same Reference response**
- **Assumption 2:** If a *varying excitation force level affects all responses in a linear manner*, then the variations in response levels are *"canceled out"* of a Transmissibility measurement

RESCALING ODS-FRFs

A Transmissibility *automatically accounts for the effects of a varying force levels* between multiple Measurement Sets, *but an ODS-FRF does not*.

- If **ODS-FRFs** are calculated from *multiple Measurement Sets* of data, they *must be corrected* to account for changes in the excitation force level between Measurement Sets

To correct the magnitudes of every **ODS-FRF** in a Measurement Set (**i**), each **ODS-FRF** is multiplied by a *scale factor (SF_i)* defined by,

$$SF_i = \sqrt{\frac{\sum_{k=1}^{Sets} \bar{G}_k}{Sets \cdot \bar{G}_i}}$$

Sets = number of Measurement Sets

\bar{G}_i = the *averaged value* of the *reference response Auto Spectrum* for Measurement Set(**i**)

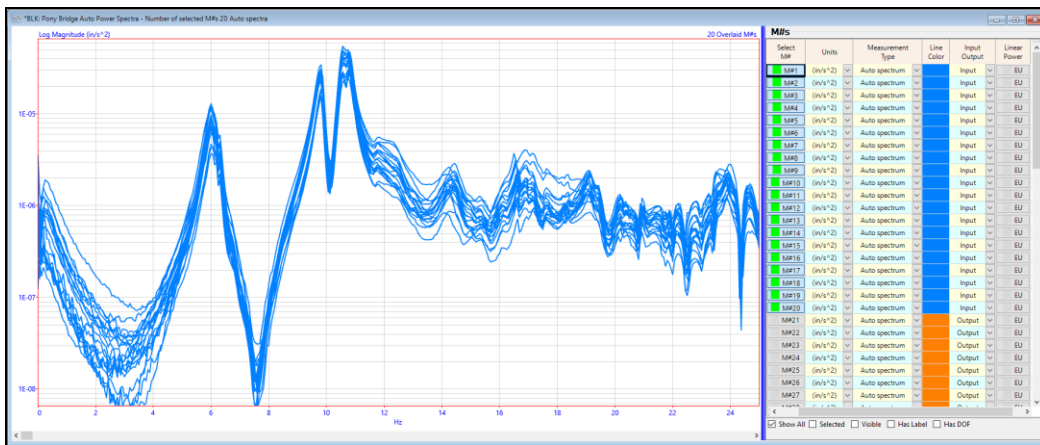
- The scale factor (**SF_i**) corrects each **ODS-FRF** magnitude according to the average level of all the reference response Auto spectra

STEP 3 - OVERLAYING THE REFERENCE AUTO SPECTRA

- **Press Hotkey 3** Overlay the Reference Auto Spectra

When **Hotkey 3 is pressed**, the **Reference Auto spectra** from **20 Measurement Sets** are overlaid.

- It is clear from the figure below that the *impact force level was different* for each of the **20 Measurement Sets**.



20 Reference Auto Spectra Overlaid.

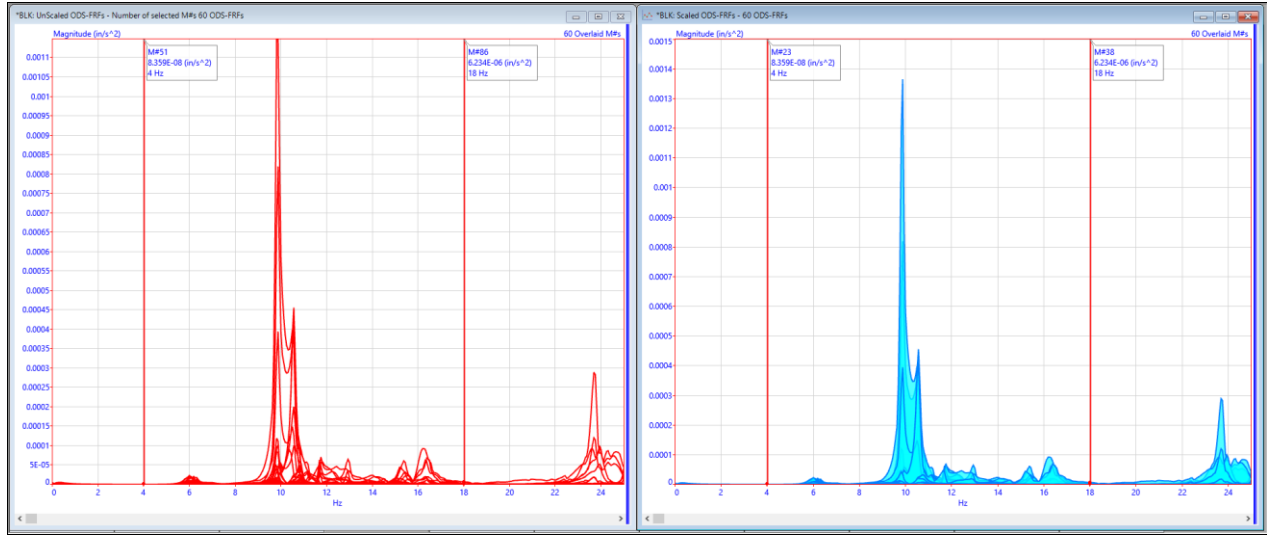
Therefore, after **ODS-FRFs** are calculated from the 20 Measurement Sets of Auto & Cross spectra, they must be re-scaled before meaningful frequency-based ODS's can be displayed from them.

STEP 4 - RE-SCALING THE ODS-FRFs

- **Press Hotkey 4 Re-Scale the ODS-FRFs**

The **ODS-FRFs** must be re-scaled to compensate for differences in the impact force levels applied when each of the Measurement Sets was acquired. This was observed by overlaying the Reference Auto spectra in **Step 2**. These same Reference Auto spectra will be used to re-scale the **ODS-FRFs**.

- A Band cursor was displayed from **4 to 18 Hz** so that the **Average Reference spectrum** was only calculated over that frequency span



Un-Scaled and Re-Scaled ODS-FRFs

When **Hotkey 4** is **pressed**, the **BLK: Scaled ODS-FRFs** window will open **on the right** with **60 scaled ODS-FRFs** overlaid in it. These re-scaled **ODS-FRFs** are used in the next step to display the frequency-based ODS at each resonance peak on a model of the bridge truss.

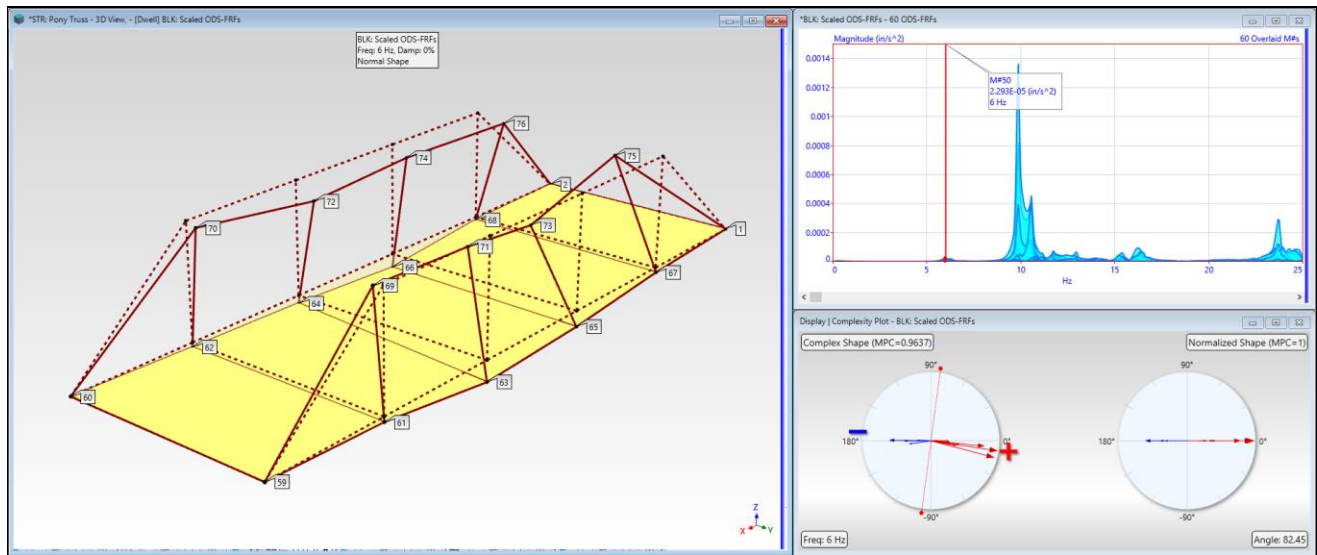
STEP 5 - DISPLAY FREQUENCY-BASED ODS's

- **Press Hotkey 5 Display Frequency-Based ODS**

In order to display ODS's in animation on the bridge model, an **M# Link** is created linking each **M#** in the **BLK: Scaled ODS-FRFs** window to a DOF of the bridge model in **STR: Pony Bridge**. This is done with a Script command.

Animation will begin from the **Line** cursor position in **BLK: Scaled ODS-FRFs**. The animated shape is also being *normalized* to remove some of the random phase from the ODS. The **Complexity Plot** on the *lower right* shows the complex ODS and the normalized ODS data side-by-side.

- **Drag** the cursor to another resonance peak to display its frequency-based ODS



ODS of the Bridge Truss at 6 Hz Dominated by the First Bending Mode Shape.

STEP 6 - REVIEW STEPS

To review the steps of this App Note,

- **Press Hotkey 6 Review Steps**

CONCLUSIONS

Multiple Measurements Sets of *impact response-only data* were post-processing in MESC to calculate a set of **ODS-FRFs** from which ODS's were displayed in animation.

- To display a valid ODS from a set of ODS-FRFs, they must have *correct magnitudes & phases relative to one another*

This is guaranteed if all response channels of data are *simultaneously acquired*. Unfortunately, most structural testing is done by acquiring a few channels of data at a time in *multiple Measurement Sets*.

When the Reference response Auto spectra from 20 Measurement Sets were overlaid, their levels were different, indicating that the impact force levels were different between Measurement Sets. These differences among Measurement Sets were corrected by re-scaling each Measurement Set of **ODS-FRFs** using an *average Reference response* from all 20 Measurement Sets.

After the **ODS-FRFs** were re-scaled, realistic ODS's were observed by displaying ODS's at the resonance peaks in the **ODS-FRFs**, including a *dominant first bending mode shape of the bridge truss at 6 Hz*,