Vibrant Technology, Inc.

ME'scopeVES Application Note #12
Calculating ODF FRFs From Bridge Impact Data

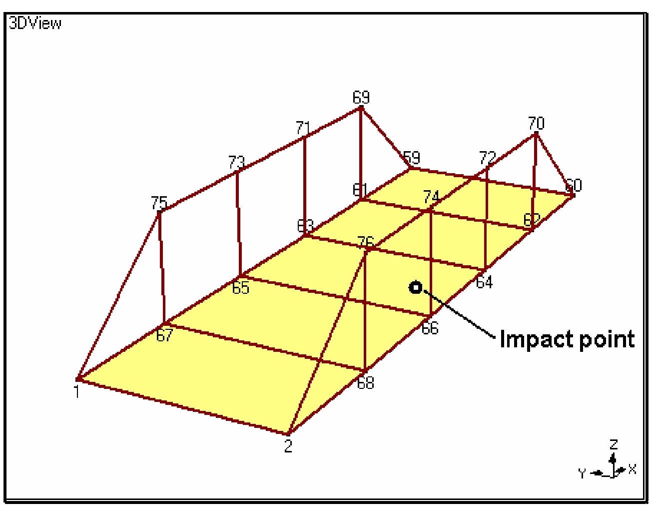
INTRODUCTION

In this Application Note, impact test data taken from a bridge test is processed in **ME'scopeVES** 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 of the bridge in animation.

Modal testing is usually done under controlled and time-invariant (stationary) conditions, using one or more exciters. Further, the *excitation forces* and their corresponding responses are *simultaneously measured*. Excitation force is measured with a load cell; response motion is typically measured with an acceleration (although velocity or displacement transducers can also be used).

In *ODS testing*, the excitation force is not measured. In this case, the bridge was excited with a drop-weight *impactor*, producing peak forces greater than any load cells on-hand for the experiment.

Since the impact force was *not* measured, traditional response/force Frequency Response Functions (FRFs) could not be made. In cases like this, a *transmissibility* FRF (response/reference response) is often calculated instead. However, the ODS FRF is a better choice, as is subsequently explained.



Consumnes River Bridge Pony Truss.

Requirements for an ODS

In general, an Operating Deflection Shape (ODS) is *any forced motion for two or more DOFs* (points & directions) on a machine or structure. An ODS, therefore, defines the *relative motion* between two or more DOFs on a structure. An ODS can be defined for a specific frequency or for a moment in time.

This definition of a "shape" requires that *all measured responses have correct magnitudes and phases relative to one another*. In order to insure that the vibration measurements taken from two or more DOFs have the correct *relative magnitudes & phases*, either of *two* methods of measurement can be employed.

- **Simultaneous Method**: Simultaneously acquire *all* responses together.

- **Measurement Set Method:** Simultaneously acquire *some* Roving responses, plus a (fixed) *Reference* response. This is called a **Measurement Set**. Each **Measurement Set** consists of different *Roving* responses and the same *Reference* responses. An entire test, then, consists of *two or more* **Measurement Sets**.

Most field vibration measurements are made with portable equipment that can only acquire a few channels of data at a time. Therefore, the **Measurement Set Method** is the more commonly used acquisition method.

With the **Measurement Set Method**, the same *Reference* response must be measured with each **Measurement Set** in order to preserve the *relative phase* among all responses in the test. If the phase of the *Reference* response is subtracted from the phase of each response in its **Measurement Set**, the responses from all **Measurement Sets** will have the correct phase relative to each other. This is the same as using the phase of the Cross Spectrum between each *Roving* response and the *Reference* response.

Steps in this Application Note may be followed using a **Visual ODS Pro** package or any package that includes the **VES - 300** option.

Non-Stationary Measurements

Using the **Measurement Set Method**, the time period required to obtain a set of measurements can be substantial, and the machine or structure *could physically change* during this time period.

Non-stationary vibration signals will result if the physical properties of the structure or machine (its mass, stiffness, & damping) change during the measurement time period. For example, fluids moving within the system can cause mass changes. Temperature changes can cause changes in material stiffness. Damping characteristics can also change during the course of a prolonged test. Furthermore, the excitation forces could change.

We can determine whether or not structural measurements are stationary by applying the following definition to successive measurements.

Stationary Measurement: A vibration signal is *stationary* if its *Auto Spectrum* does not change from measurement to measurement.

In other words, if two or more Auto Spectrum measurements are made from the same response DOF (point & direction) and overlaid on one another, the structure can be said to be stationary if they are all essentially the same measurement.

Modes From Stationary Measurements

Modes (resonances) are inherent properties of a structure. They will only change if the *physical properties* or *boundary conditions* of the structure change. Modes manifest as *peaks* in any response Auto Spectrum measurement. If the peaks in two successive measurements are at the same frequencies when the two Auto Spectra are overlaid, then we can conclude that the modes (and hence the physical properties) of the structure are *stationary*.

If only the signal levels are different when successive Auto Spectra are overlaid, then special post-processing must be applied to the signals to recover the Operating Deflection Shapes. In this case, it is assumed that the *unmeasured excitation forces* (and not the structure) are non-stationary. Recovery of ODS's when excitation levels change is one of the important capabilities of the ODS FRF calculations in **ME'scopeVES**.

TRANSMISSIBILITY

Transmissibility is the traditional way of making a frequency response measurement when the excitation force(s) cannot be measured. It is calculated in the same way as the FRF. Whereas the FRF is the ratio of response divided by force, *Transmissibility is the ratio of a Roving response divided by a (fixed) Reference response*.

Transmissibility is a *ratio of two responses*. Therefore, if the excitation force level varies from one measurement to the next, it can be assumed that its *effect on both responses is the same*, so that input force variation will be "*canceled out*" in the Transmissibility.

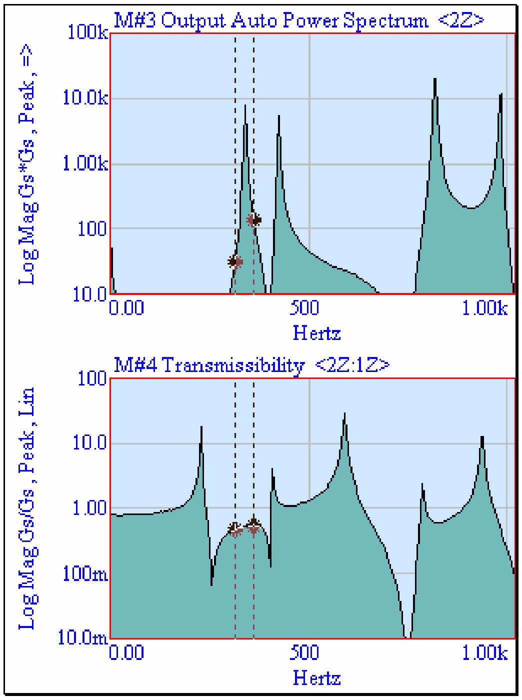
ODS's can be displayed from a set of Transmissibility's, measured between a fixed Reference response and two or more Roving responses. Multiple **Measurement Sets** of Transmissibility's can be measured one at a time using a 2-channel analyzer, where each **Measurement Set** uses a different Roving response divided by the Reference response from the same DOF.

Difficulty with Transmissibility's

The only difficulty with a Transmissibility measurement is that *peaks in the measurement are not evidence of resonances*. Rather, resonant frequencies are located at *flat spots*. (These flat spots are due to the division of one response Spectrum by another, where they each share common resonance peaks.) Therefore, if a set of *Transmissibility's* is used for displaying ODS's, *at least one Auto Spectrum must also be measured for locating resonance peaks*.

The following figure shows a response *Auto Spectrum* plotted above a *Transmissibility*. At the frequency of the resonance peak inside the cursor band (shown with dashed lines) in the Auto Spectrum, the Transmissibility has a *flat spot*, not a peak.

Moreover, the peaks in the Transmissibility do not correspond to resonances, but are merely the result of the division of the *Roving response* by the *Reference response* signal at frequencies where the Reference is relatively small.



Auto Spectrum and Transmissibility FRF Compared.

ODS FRF

An *ODS FRF* is formed by combining the *magnitude* of a *Roving* response *Auto Spectrum* with the *Phase* of the *Cross Spectrum* between the Roving response and the Reference response.

A set of ODS FRFs can be measured in the same way as a set of Transmissibility's, using the same multi-channel analyzer. But, instead of being a ratio of responses, the ODS FRF combines the *correct magnitude* of the response (the roving response Auto Spectrum) with the *correct phase* relative to the Reference response. More importantly, an ODS FRF *has peaks at the resonances*, so it is much easier to display ODS's from a set of ODS FRFs and observe where the structure actually has large deflections.

Correction of ODS FRF Magnitudes

Whereas the *Transmissibility* automatically takes care of the effects of a variable force level between measurements, the ODS FRF *does not*. Therefore the *magnitudes* of a set of ODS FRFs *must be corrected to account for changes in the excitation level* between **Measurement Sets**.

To correct for differing excitation levels, the magnitude of every ODS FRF in a Measurement Set (**i**) is multiplied by a *Scale Factor*, $\mathbf{SF_i}$, defined by equation (1).

$$SF_i = \sqrt{\frac{\sum_{k=1}^{Sets} \overline{G}_k}{Sets \cdot \overline{G}_i}} \qquad (1)$$

… where $Sets$ is the number of **Measurement Sets** and $\overline{G}_i$ is the *averaged value* of the *Reference response Auto Spectrum* for **Measurement Set**(**i**).

This Scale Factor corrects each of the ODS FRF magnitudes according to the *average level of all of the Reference response signals*. (This average value can be calculated for any desired range of frequency samples.)

In order to form a set of properly scaled ODS FRFs, the following measurements are needed:

1. The *Auto Spectrum* of each *Roving response*.
2. The *Auto Spectrum* of each *Reference response*.
3. The *Cross Spectrum* between each *Roving and Reference response*.

These three functions are simultaneously measured by the *tri-spectrum averaging* process that is implemented in *all* modern multi-channel FFT analyzers, and in **ME'scopeVES**.

HOW THE BRIDGE MEASUREMENTS WERE MADE

The bridge was excited with an *impactor* that consisted of a sliding weight on a pole mounted to a base-plate. The weight was lifted manually, then abruptly released. It then slid down the pole, impacted the base plate, and excited the bridge.

The *impactor* was located at a fixed point near the middle of the bridge span near one side, as shown in the figure of page 1. This location was chosen to avoid exciting at a node line of one of the bridge's mode shapes. A (uniaxial) *Reference accelerometer* was mounted near the impactor.

A *Roving tri-axial accelerometer* was used to measure 3-D responses at 20 points on the bridge trusses.

Measurements were made with a 4-channel analyzer, which simultaneously acquired the Reference acceleration and three tri-axial (Roving) acceleration signals during each impact of the bridge. The bridge was impacted 3 times for each measurement, and spectrum averaging was performed in the analyzer to reduce noise.

Each **Measurement Set** consisted of three Roving response Auto Spectra, an Auto Spectrum for the Reference response, and three Cross Spectra (between each Roving and the Reference response).

Variable Force Levels

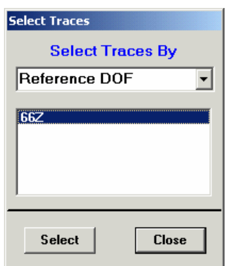
To observe the variable force levels between the 20 **Measurement Sets**:

 Execute: **File | Project | Open**

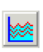
- Select the **Consumnes River Bridge–Pony Bridge.PRJ** from the **Examples\ODS** subdirectory.

In the **Pony Bridge Auto Power Spectra** Data Block:

 Execute: **Edit | Select Traces | By**. A **Select Traces** dialog box will open.



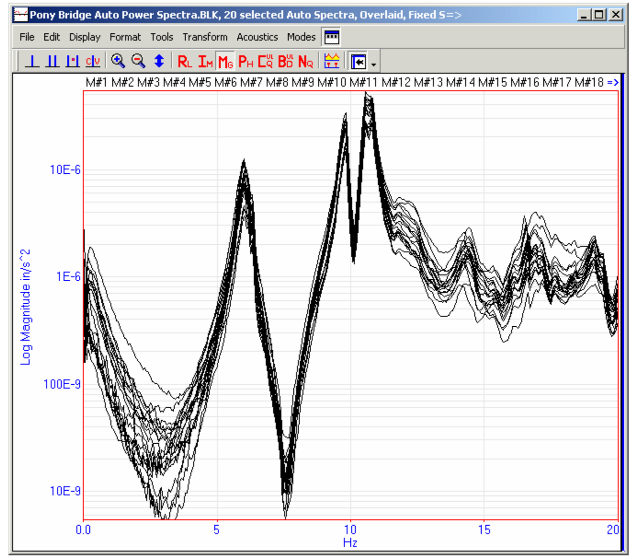
- Select **Reference DOF** from the list, and click on **Select**. All 20 of the *Reference* Auto Spectra are selected. Click on **Close**.

 Execute: **Format | Overlay Selected Traces**.

- Zoom the display over the frequencies **0** to **25 Hz**.

 Execute: **Display | Maximize**.

The resulting display overlays all 20 *Reference* Auto Spectra. It is clear from this plot that *the impacting force level is different* between the 20 **Measurement Sets**.



20 Reference Auto Spectra Overlaid to show deviations.

This data clearly requires that the *ODS FRF magnitudes be re-scaled* using equation (1) before meaningful ODS's can be obtained from these 20 **Measurement Sets**.

LABELING THE AUTO AND CROSS SPECTRA FOR ODS FRF CALCULATION

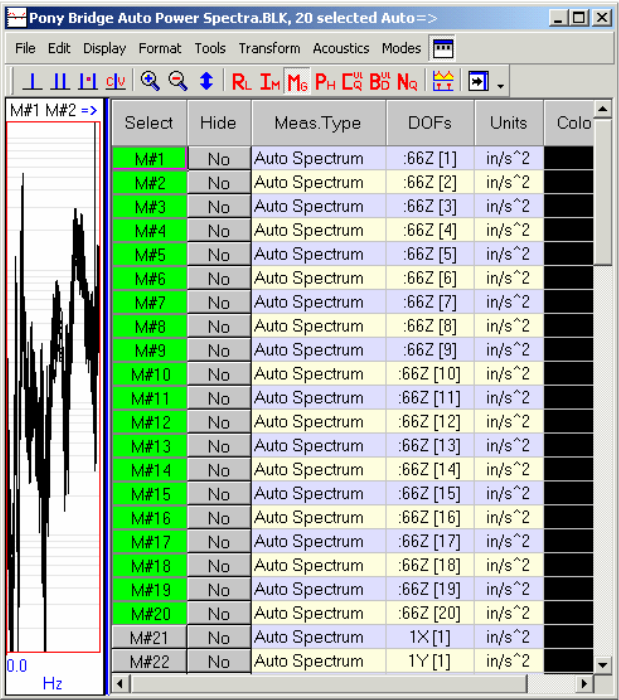
The DOFs of the Auto Spectra and Cross Spectra *must be correctly labeled prior to calculating ODS FRFs*. In this case, the measurements are already labeled with the proper DOFs. We will simply observe how they were labeled before calculating ODS FRFs.

DOFs of the Reference AUTO SPECTRUM's.

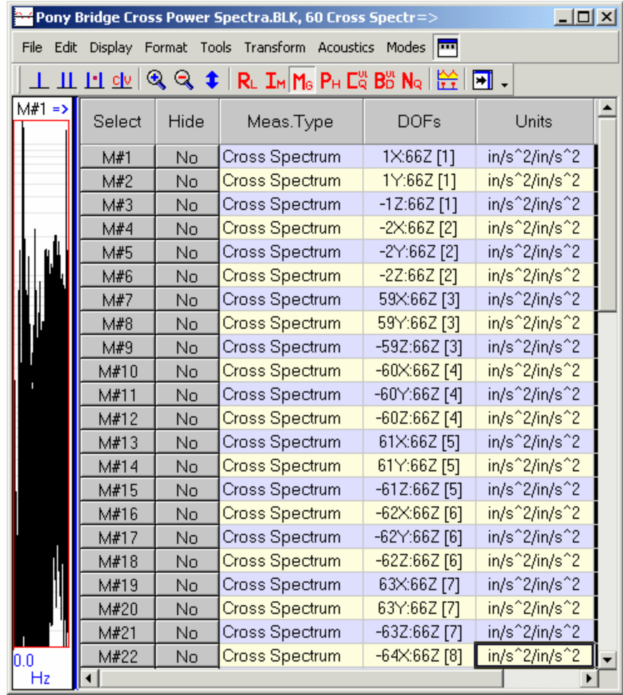
To observe the DOFs of the Reference Auto Spectra:

- Slide the **vertical blue bar** to the left in the **Pony Bridge Auto Power Spectra** Data Block to display the Traces spreadsheet.
- Scroll the spreadsheet to display the first 20 **M#'s**. (They should still be *selected*.)

Notice in the **DOFs** column (shown in the following figure) that the DOF of each *Reference* Auto Spectrum is **:66Z** followed by a different **Measurement Set** number, **[1]** through **[20].** The **colon** (**:**) in front of the DOF indicates that it is a Reference DOF.



Traces Spreadsheet shows Reference Auto Spectrum DOFs.



Traces Spreadsheet showing Cross Spectrum DOFs.

DOFs of the Roving AUTO SPECTRUM's.

- Scroll through the other (*unselected*) Traces in the spreadsheet, and inspect their DOFs.

Notice that each *unselected* Auto Spectrum has a *Roving DOF* (no colon in front) and is also part of one of the **Measurement Sets**, **[1]** through **[20].** Notice also, that each **Measurement Set** has **3** *Roving* Auto Spectra showing tri-axial response (**X**, **Y**, & Z directions) at each point.

DOFs of the Cross Spectra

To observe the DOFs of the Cross Spectra:

- In the **Pony Bridge Cross Power Spectra** Data Block, slide the **vertical blue bar** to the left to display the Traces spreadsheet.

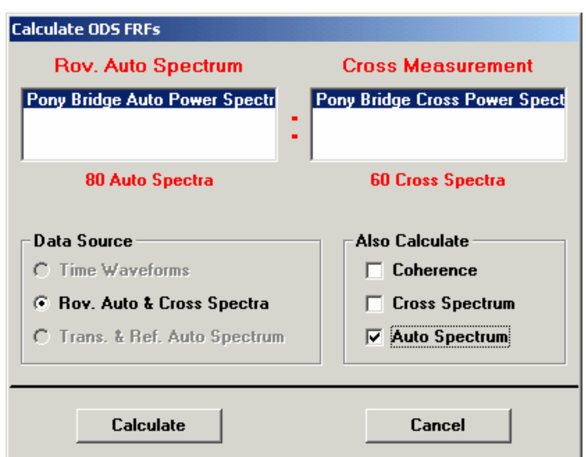
Notice in the **DOFs** column of the following figure that each Cross Spectrum has a *Roving DOF* followed by a colon and the *Reference DOF*, followed by a **Measurement Set** number.

CALCULATING ODS FRFs

When the Auto Spectra and Cross Spectra are properly labeled, to calculate a set of ODS FRFs:

- Double click on the **Select** column in the **Pony Bridge Auto Power Spectra** Data Block spreadsheet to *unselect all Traces*.

Execute: **Transform | ODS FRFs** in *any* Data Block. A **Calculate ODS FRFs** dialog will open.



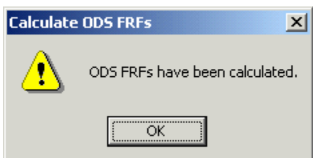
- Select **Pony Bridge Auto Power Spectrum** from the **Rov. Auto Spectrum** list of Data Blocks, and **Pony Bridge Cross Spectrum** from the **Cross Measurement** list of Data Blocks.

NOTE: All *Roving* Auto Spectrum and Cross Spectrum measurement data can also be placed in the *same* Data Block file for use with this command.

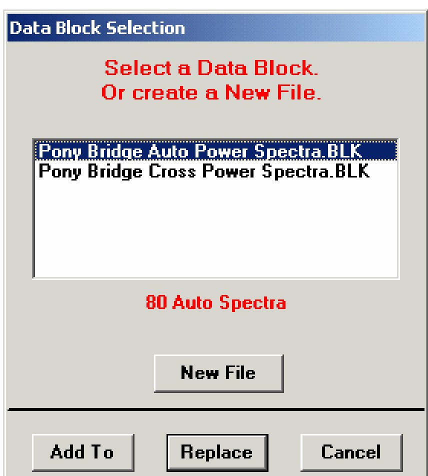
- *Check* the **Auto Spectrum** box under **Also Calculate**. (This is done to preserve the Auto Spectra in the new Data Block file with the ODS FRFs for scaling.)

- Click on the **Calculate** button.

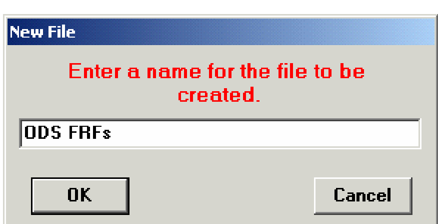
When the calculation is complete, a confirming **Calculate ODS FRFs** dialog will open.



Click on **OK**. A **Data Block Selection** dialog will open.



- Press the **New File** button. A **New File** dialog will open.



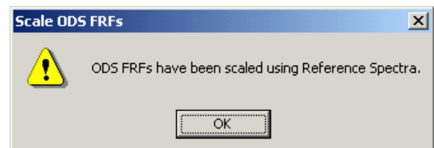
- Enter **ODS FRFs** as the name for the file and click on **OK**.

The **ODS FRFs** Data Block (with 140 Traces) will open. This block contains 60 ODS FRFs, 60 Response Auto Spectra and 20 Reference Auto Spectra. The *Response* Auto Spectra are required to *scale* the measurements in accordance with equation (1).

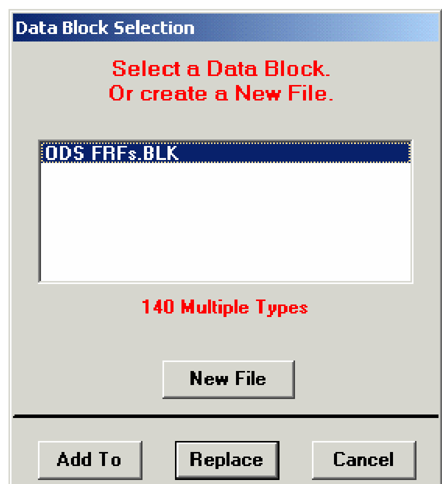
Scaling the ODS FRFs

To scale the ODS FRFs to compensate for deviations in the impact force:

Execute: **Transform | Scale ODS FRFs**. A **Scale ODS FRFs** dialog will open.



- Press **OK**. A **Data Block Selection** dialog will open.



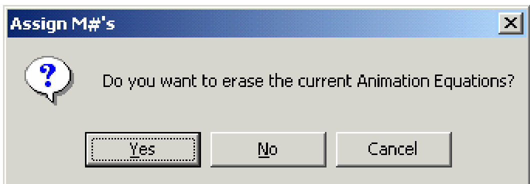
- Select **ODS FRFs.BLK** in the list and press **Replace**.

The scaled **ODS FRFs** will replace the previous Traces in **ODS FRFs.BLK**. (Note that there are now only 60 Traces of ODS's.) The measurements are now ready for animated display.

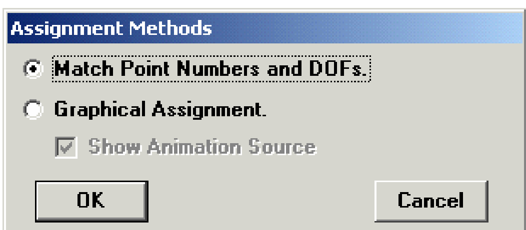
ANIMATED DISPLAY OF ODS's

In order the animate from the ODS FRF Traces, they must be assigned to the DOFs of the bridge model.

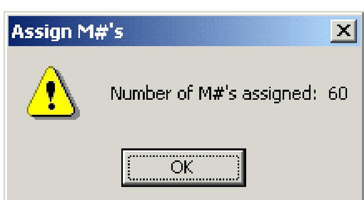
Execute: **Assign | M#'s** in the **ODS FRFs** Data Block. An **Assign M#'s** dialog will open.



- Press **Yes** to erase prior Animation Equations and proceed. An **Assignment Methods** dialog will open.



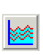
- Select **Match Point Numbers and DOFs** and press **OK**. An **Assign M#'s** dialog will open.
-



- Click on **OK**.

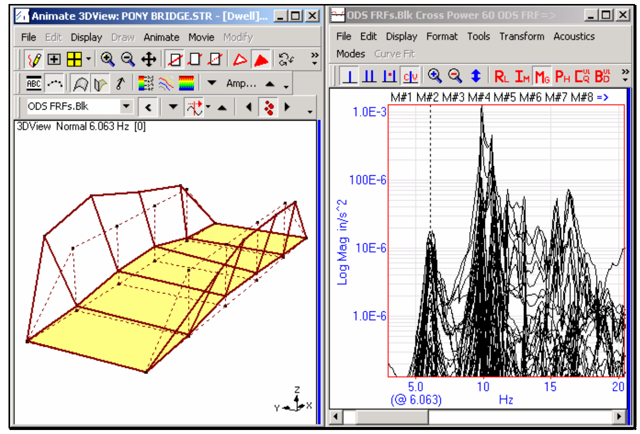
The model is now ready for animation.

Execute: **Animate the Structure** in the Structure window.



Execute: **Format | Overlay Traces** in the **ODS FRFs** Data Block, and Zoom the display from **0** to **20** Hz.

- Move the **Line** cursor to one of the peaks in the Data Block display.



ODS of the Truss Bridge.

Execute: **Draw the Structure** to exit animation.

CONCLUSIONS

Non-stationary measurement data was post-processing in **ME'scopeVES** to calculate a set of **ODS FRFs** from which ODS's were displayed. A valid ODS must have DOFs with *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 acquired a few channels at a time in multiple Measurement Sets.

The **Measurement Sets** were shown to be *non-stationary* by overlaying the *Reference* response Auto Spectra on one another. Since the *Reference* response levels were different, this indicates that the excitation force levels were different between **Measurement Sets**. These differences among Measurement Sets were corrected by scaling each **Measurement Set** of ODS FRFs using an *average Reference response* from all of the Measurement Sets.