All Vibration is a Summation of Mode Shapes

Brian Schwarz, Pat McHargue, Jason Tyler, Mark Richardson
Vibrant Technology, Inc.
Centennial, Colorado

IMAC XXXVII, Orlando, FL 2019

Vibrant TECHNOLOGY

Topics of this Presentation

- **Fundamental Law of Modal Analysis (FLMA)**: All vibration is a ***summation of mode shapes***

- ***FEA mode shapes*** will be used to ***“decompose”*** and then ***"expand"*** experimental data to include DOFs that were not experimentally acquired

- ***Only FEA mode shapes*** will be used, not their frequency or damping

- Mode shapes from an ***FEA model*** with ***free-free boundary conditions*** and ***no damping*** will be used

Vibrant TECHNOLOGY

What is a Mode of Vibration?

- A mode of vibration is a ***mathematical representation*** of a ***structural resonance***
- Any structure made out of ***elastic materials*** will ***exhibit resonant vibration***
- When ***dynamic forces are applied*** and ***energy is trapped*** within the boundaries of a structure, ***it will resonate***
- When energy is trapped within the material boundaries of a structure, it causes a ***"standing wave deformation".*** This is called a ***mode shape***
- Some modes will ***readily absorb energy*** causing a structure to resonate
- A structure in resonant vibration can be thought of as a ***mechanical amplifier.*** A ***small dynamic load*** can cause ***excessive deformation***

Vibrant TECHNOLOGY

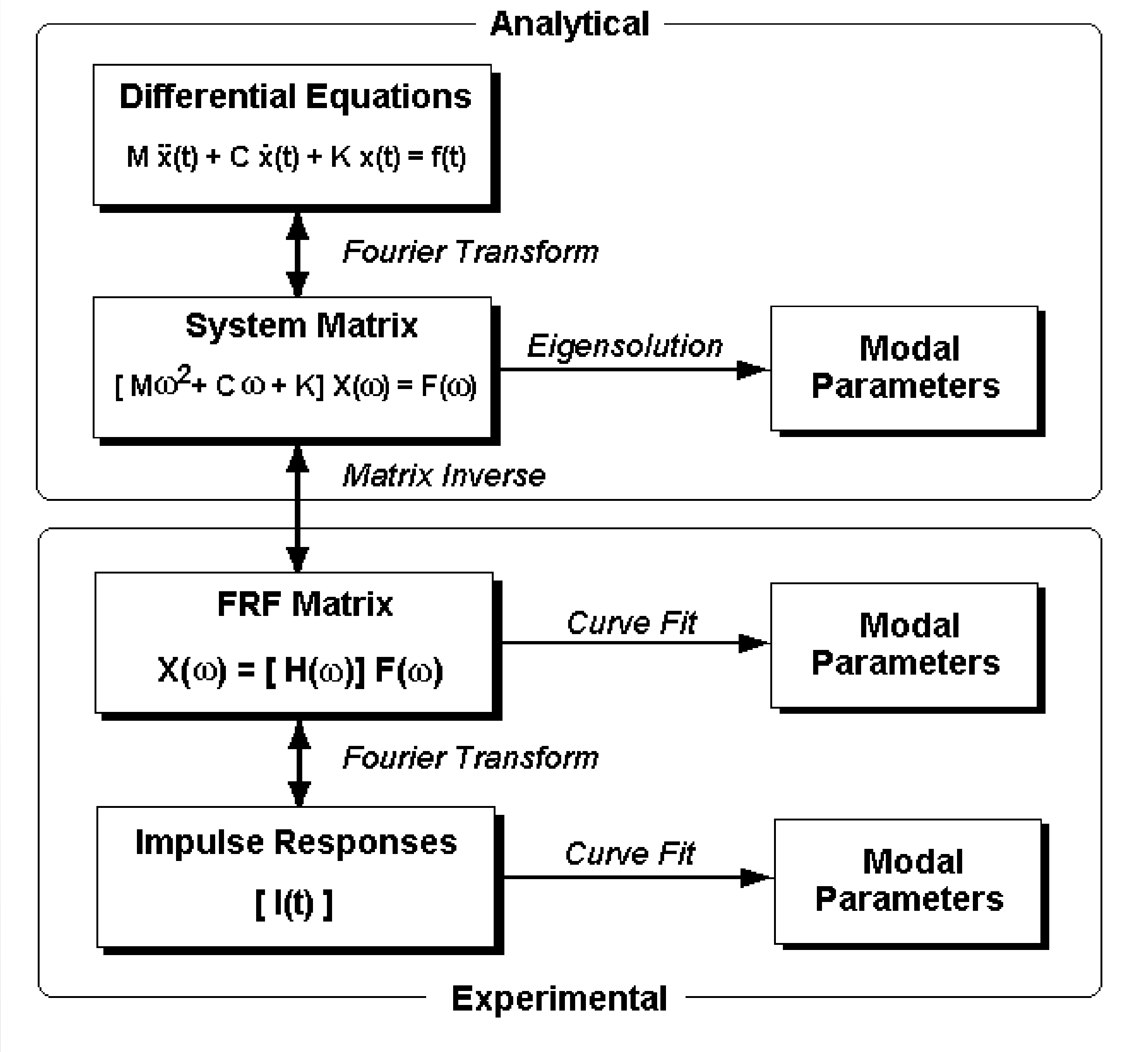
Two Ways to Create Mode Shapes

- **Experimental Modal Analysis (EMA)**: EMA mode shapes are obtained by ***curve fitting*** a set of experimentally derived time waveforms or frequency spectra that characterize the structural dynamics

- **Finite Element Analysis (FEA)**: FEA mode shapes are obtained as the ***eigensolution*** of a set of differential equations that characterize the structural dynamics

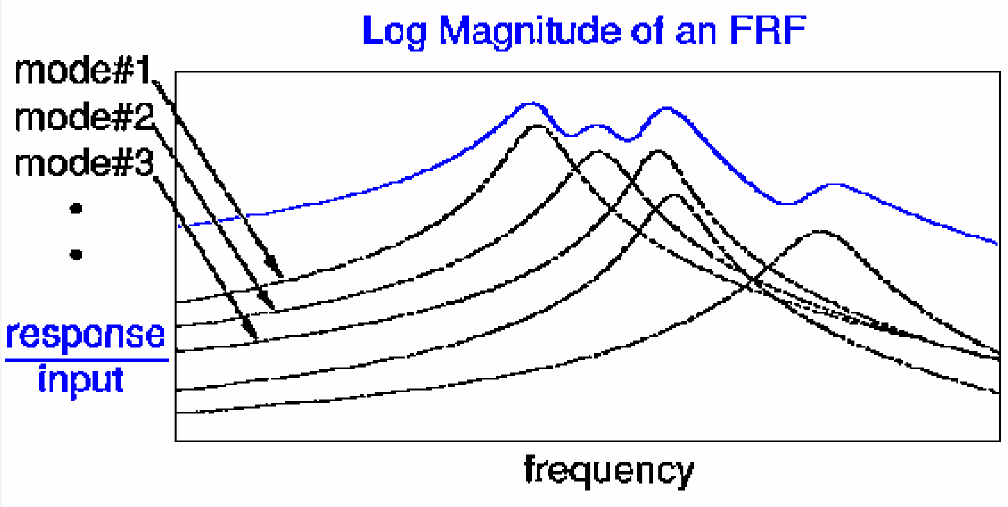
- ***Both EMA & FEA*** are ***based upon FLMA***

Two Ways to Create Mode Shapes



Modal Testing

- All ***dynamic response data*** is acquired as a ***time waveform***
- ***Without loss of information***, the ***FFT*** transforms each time waveform into its corresponding ***Fourier spectrum***
- An ***Auto spectrum, Cross spectrum***, ***FRF***, ***ODS FRF***, or ***Transmissibility*** is calculated froma Fourier spectrum
- ***All modal testing*** is ***based on FLMA***
- ***All vibration data*** is a ***summation of resonance curves***, each curve due to ***a mode of vibration***



Curve Fitting

➢ ***Multiple time waveforms or frequency spectra*** are needed to ***define EMA mode shapes***

➢ ***Each mode*** is defined with ***three parameters***

- **Modal frequency**

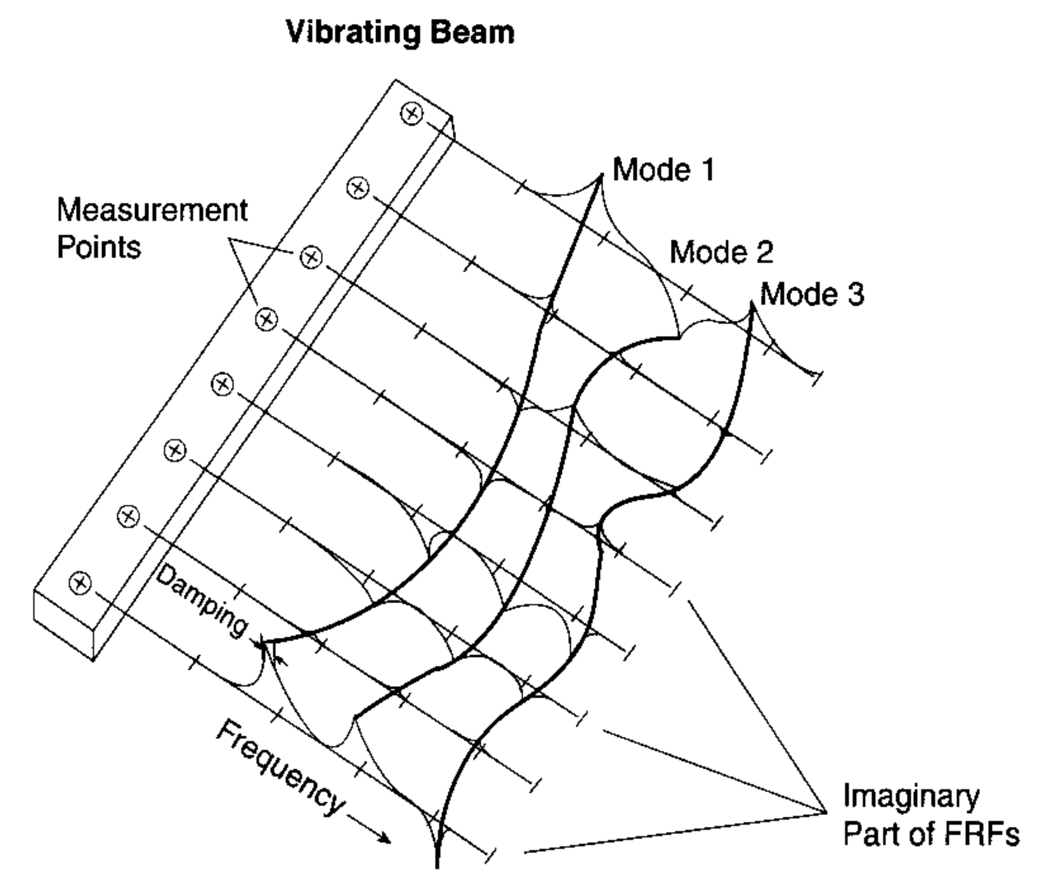
  (the **frequency** of a resonance peak)

- **Modal damping**

  (the **width** of a resonance peak)

- **Mode shape**

  (the **magnitude & phase** of each resonance peak at the **same frequency**)



Vibrant TECHNOLOGY

Expanding Experimental Data

- ***Two examples*** will illustrate FLMA

  1. ***Order-based ODS's*** of a rotating machine are ***decomposed & expanded*** from ***24 DOFs*** to ***2000 DOFs***

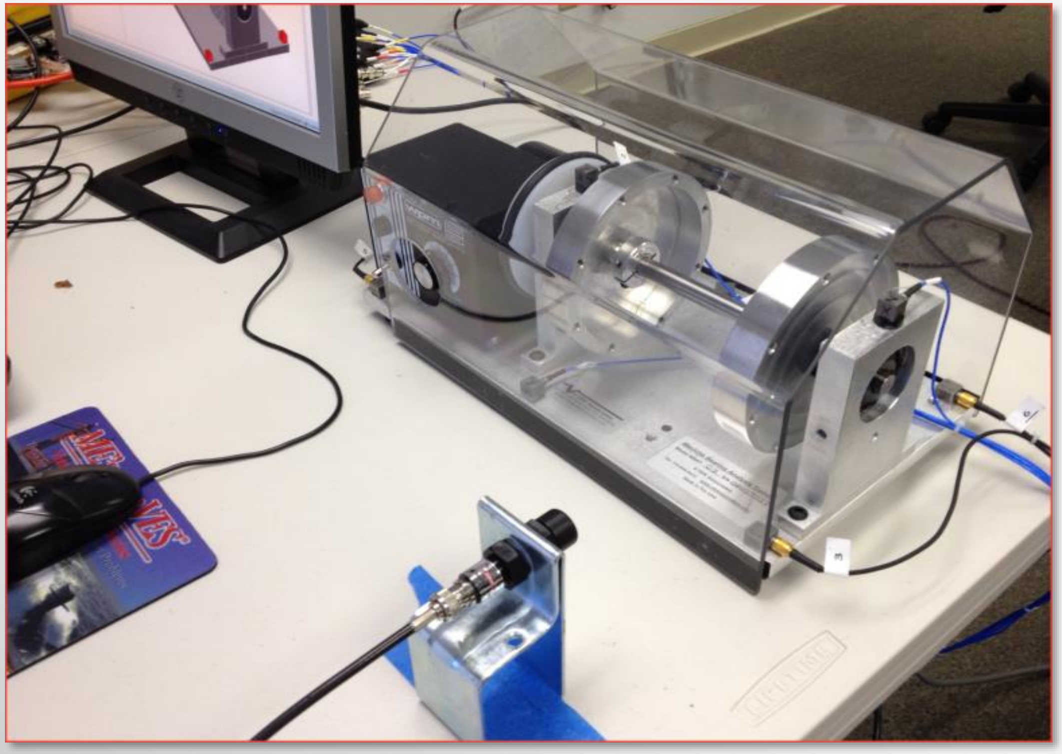
  2. ***Sinusoidal response time waveforms*** of a structure are ***decomposed & expanded*** from ***99 DOFs*** to ***315 DOFs***

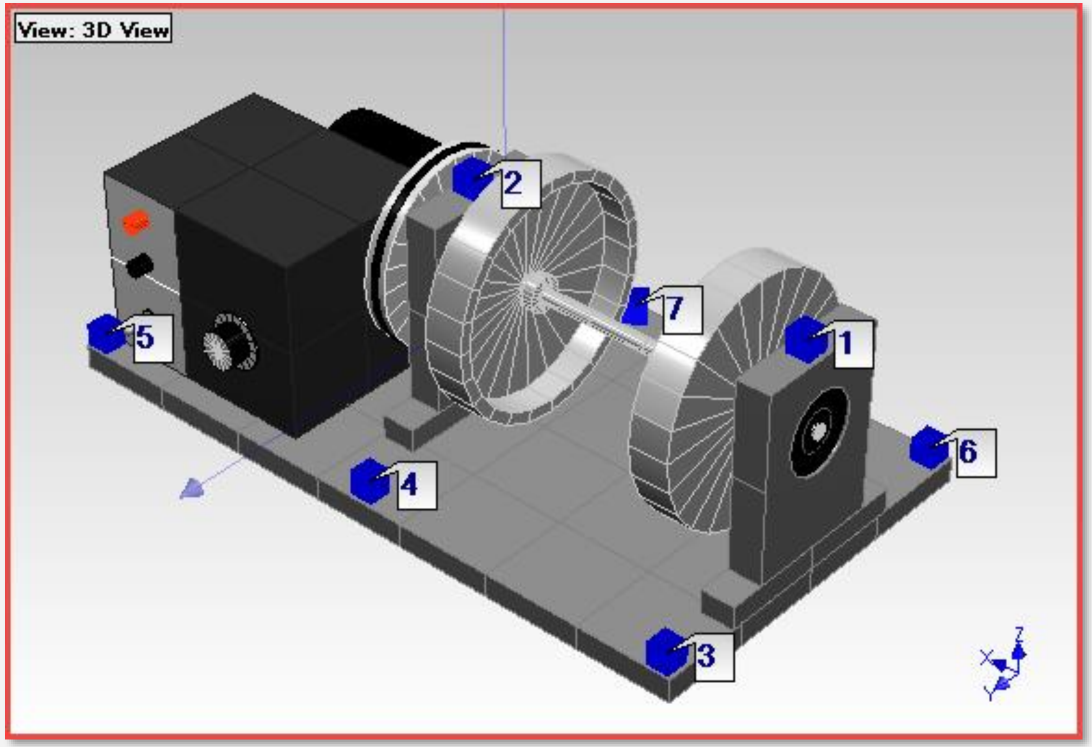
- In these examples only ***FEA normal mode shapes*** are used to ***decompose & expand*** experimental data

Vibrant TECHNOLOGY

Example #1: Expanding a 24-DOF ODS

- Data was acquired from ***eight tri-axial accelerometers*** during operation of the rotating machine at ***985, 1440, & 2280 RPM***

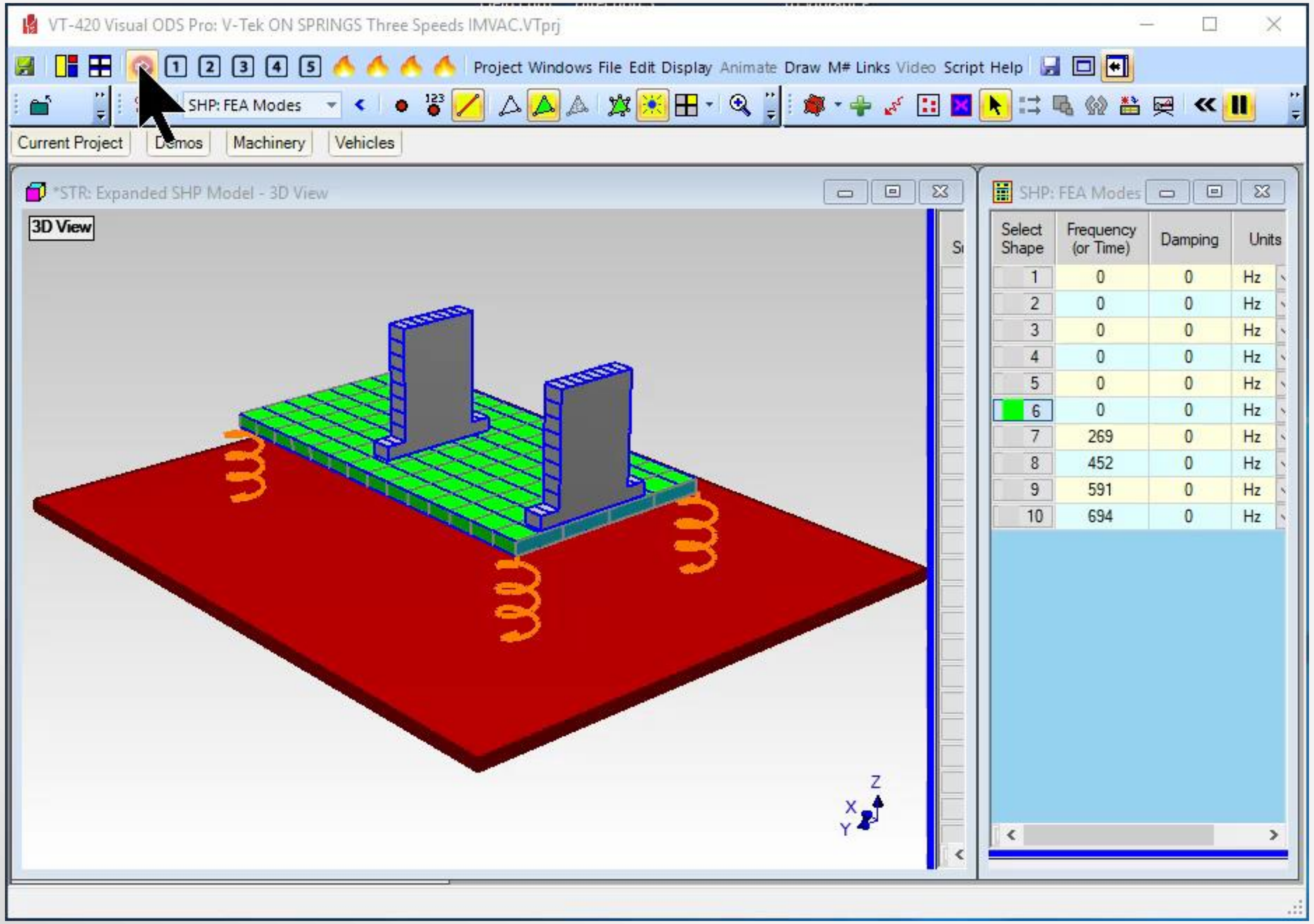




Vibrant TECHNOLOGY

FEA Mode Shapes of the Base Plate & Bearing Blocks

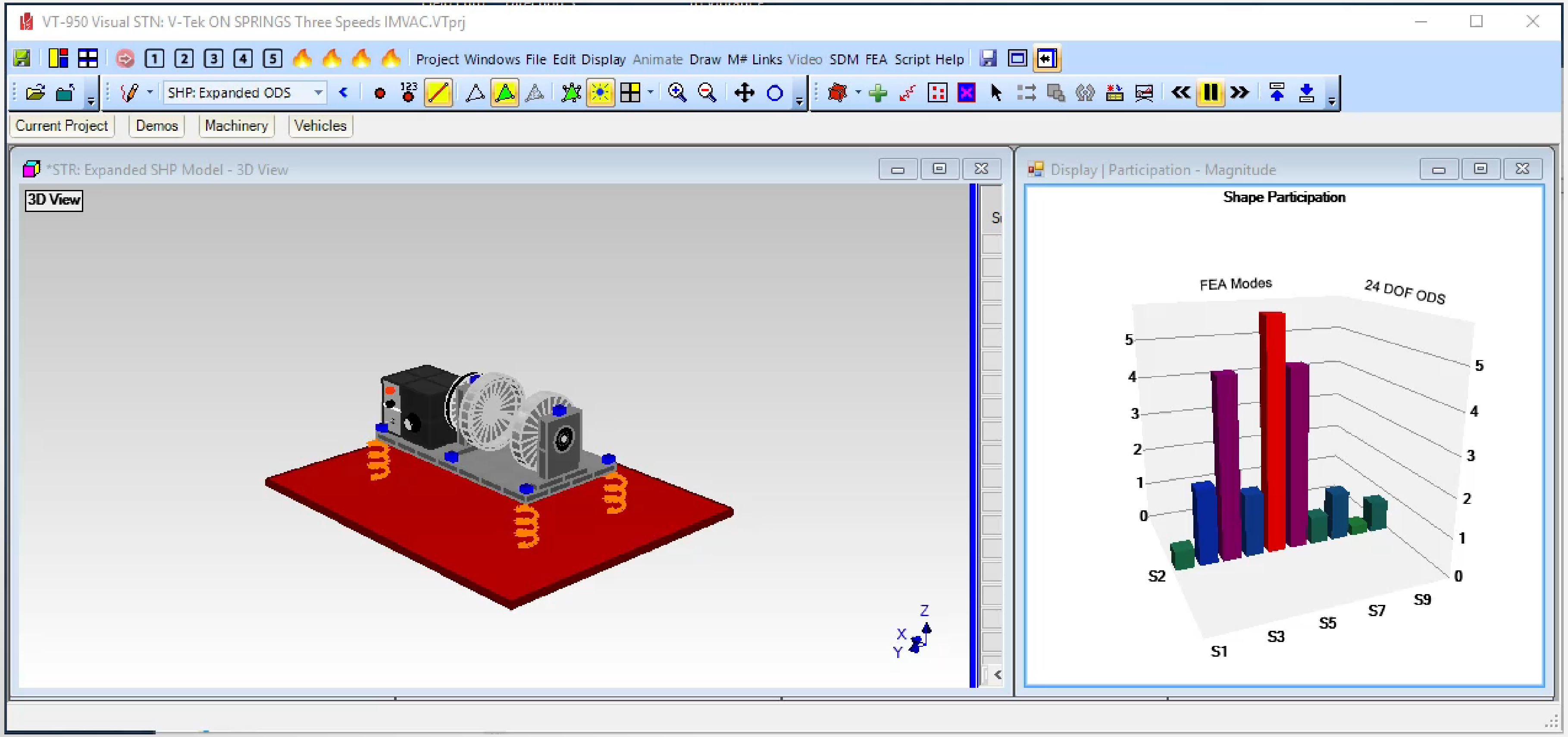
- ***Six Rigid Body*** **and *four Flexible Body* mode shapes were used to decompose & expand the ODS data**



Vibrant TECHNOLOGY

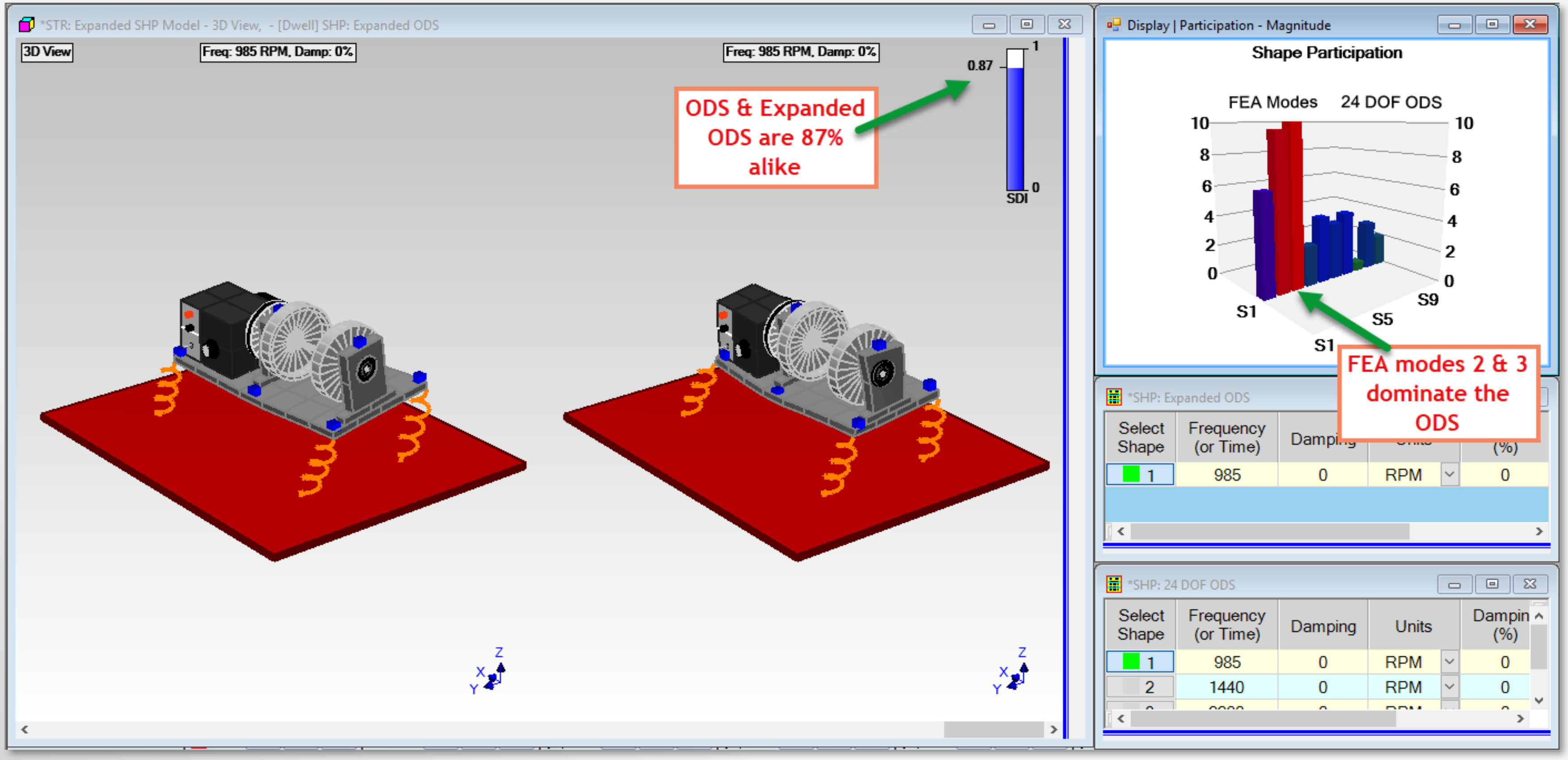
FEA Mode Shape Participation in the ODS at 985, 1440, & 2280 RPM

- Each ODS is ***complex valued***. **The FEA** *mode* shapes are ***normal (real valued) mode shapes***



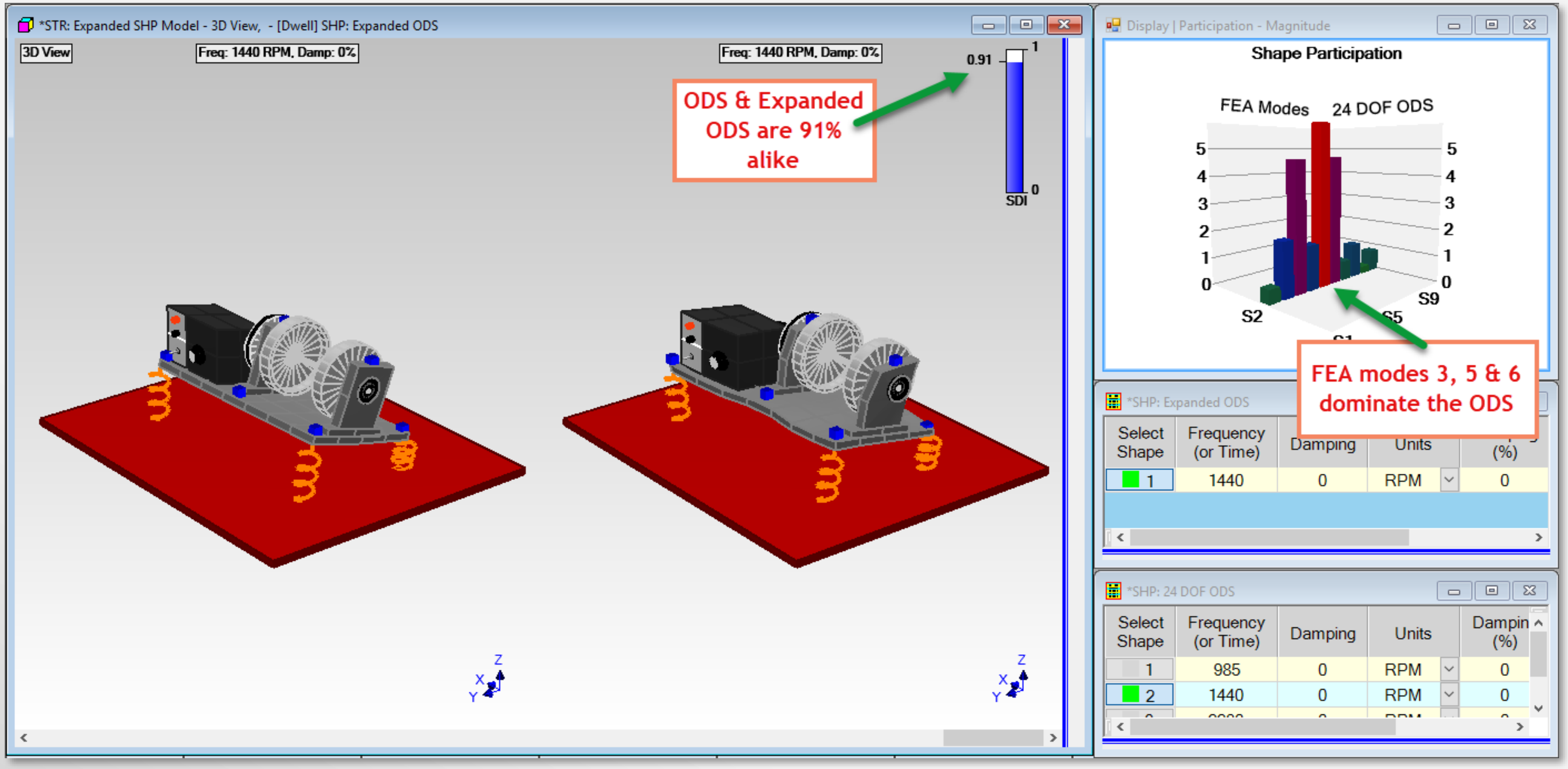
FEA Mode Shape Participation in the ODS at 985 RPM

- The ***high SDI value*** verifies that a ***complex valued ODS*** is accurately represented as a ***summation of FEA normal mode shapes***



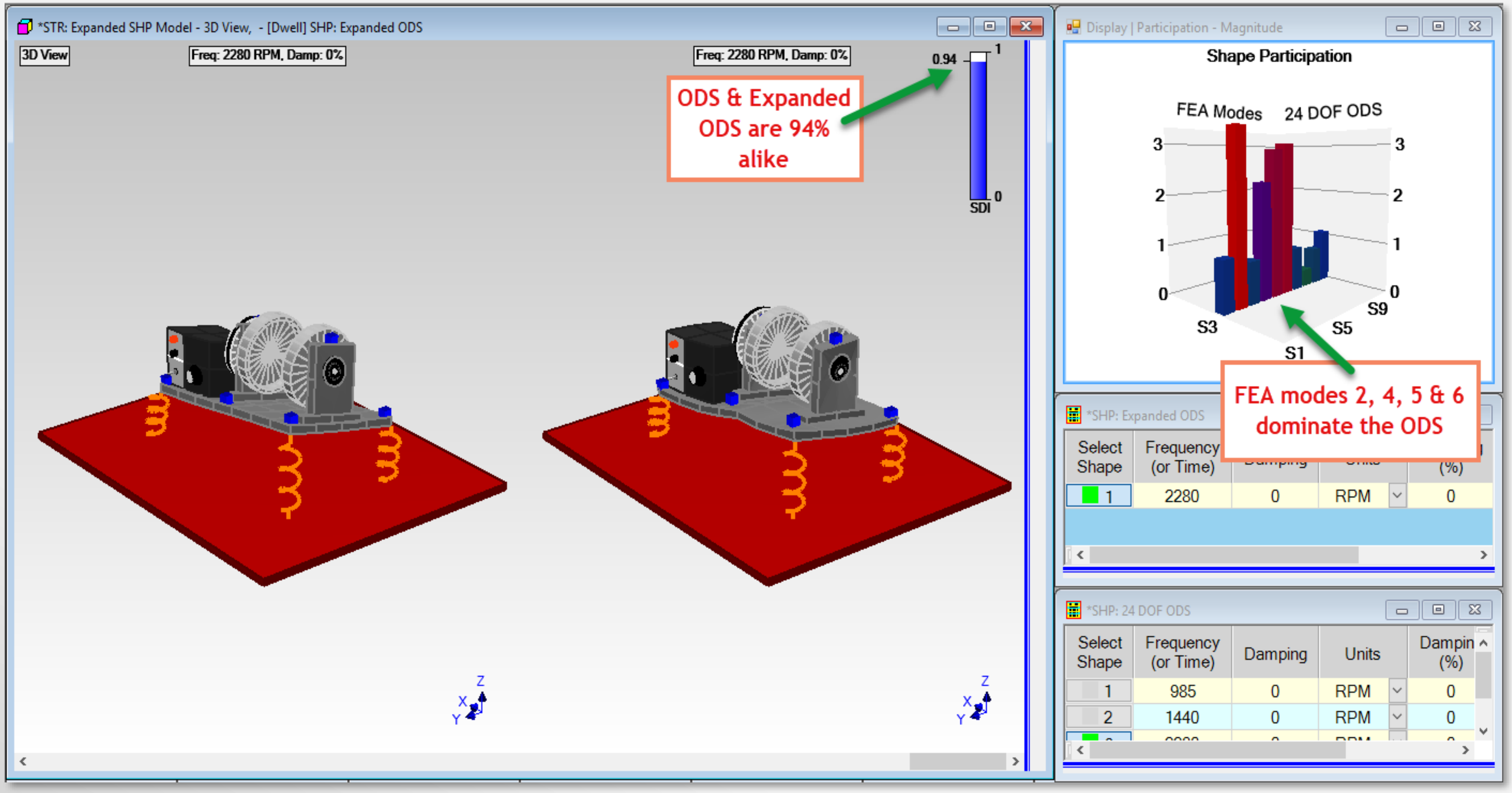
FEA Mode Shape Participation in the ODS at 1440 RPM

- The ***high SDI value*** verifies that a ***complex valued ODS*** is accurately represented as a ***summation of FEA normal mode shapes***



FEA Mode Shape Participation in the ODS at 2280 RPM

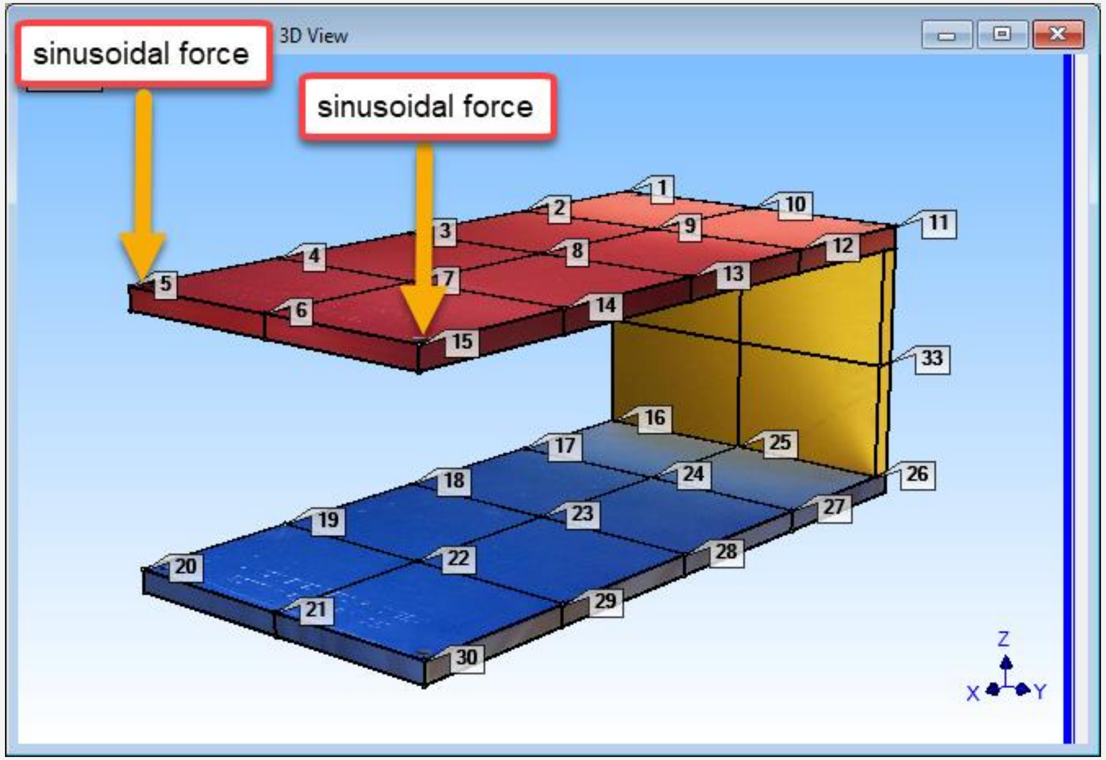
- The ***high SDI value*** verifies that a ***complex valued ODS*** is accurately represented as a ***summation of FEA normal mode shapes***



Vibrant TECHNOLOGY

Example #2: Expanding Sinusoidal Response Time Waveforms

Impact Test using a Roving Tri-axial Accel

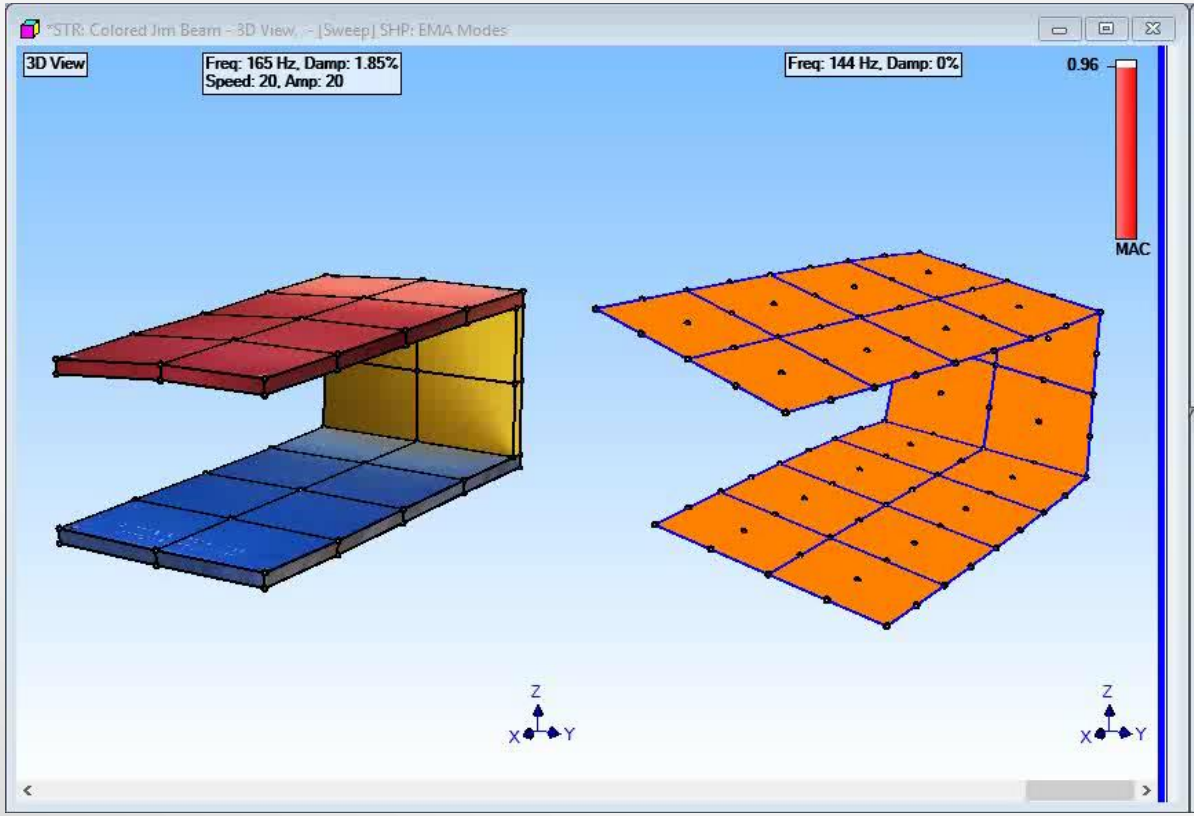


33 Test Points => Mode Shapes with 99 DOFs

Vibrant TECHNOLOGY

EMA & FEA Mode Shapes

- EMA mode shapes with ***99 DOFs***, FEA *mode* shapes with ***315 DOFs***
- ***High MAC values*** indicate ***strong co-linearity*** between EMA & FEA mode shapes



*SHP: EMA Modes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)
1	165	3.05	Hz	1.85
2	225	6.62	Hz	2.95
3	348	5.11	Hz	1.47
4	460	11.7	Hz	2.54
5	493	4.57	Hz	0.928
6	635	14.2	Hz	2.23
7	1.11E+03	4.88	Hz	0.441
8	1.21E+03	7.05	Hz	0.582
9	1.32E+03	7.16	Hz	0.542
10	1.56E+03	16.6	Hz	1.07

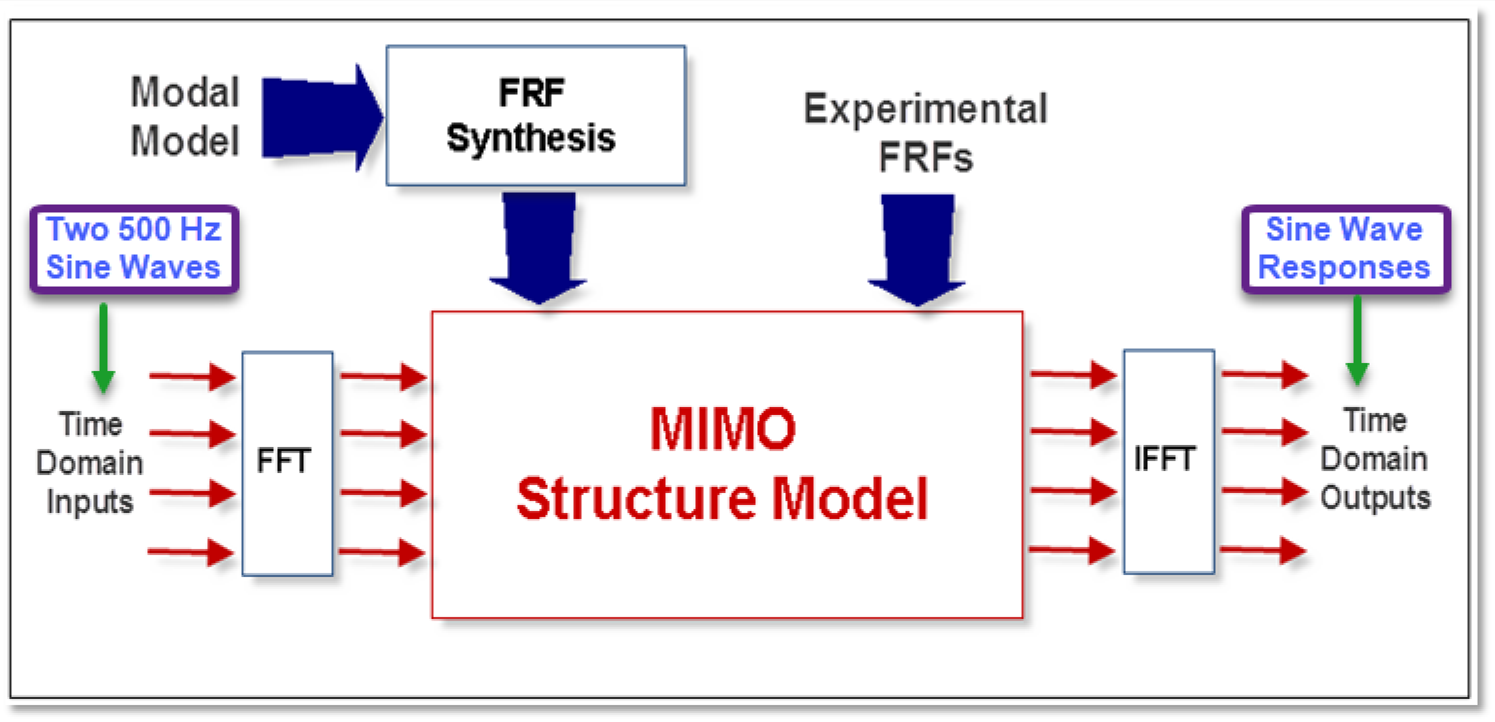
SHP: FEA Modes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)
1	144	0	Hz	0
2	204	0	Hz	0
3	311	0	Hz	0
4	414	0	Hz	0
5	443	0	Hz	0
6	583	0	Hz	0
7	1E+03	0	Hz	0
8	1.09E+03	0	Hz	0
9	1.17E+03	0	Hz	0
10	1.39E+03	0	Hz	0

Vibrant TECHNOLOGY

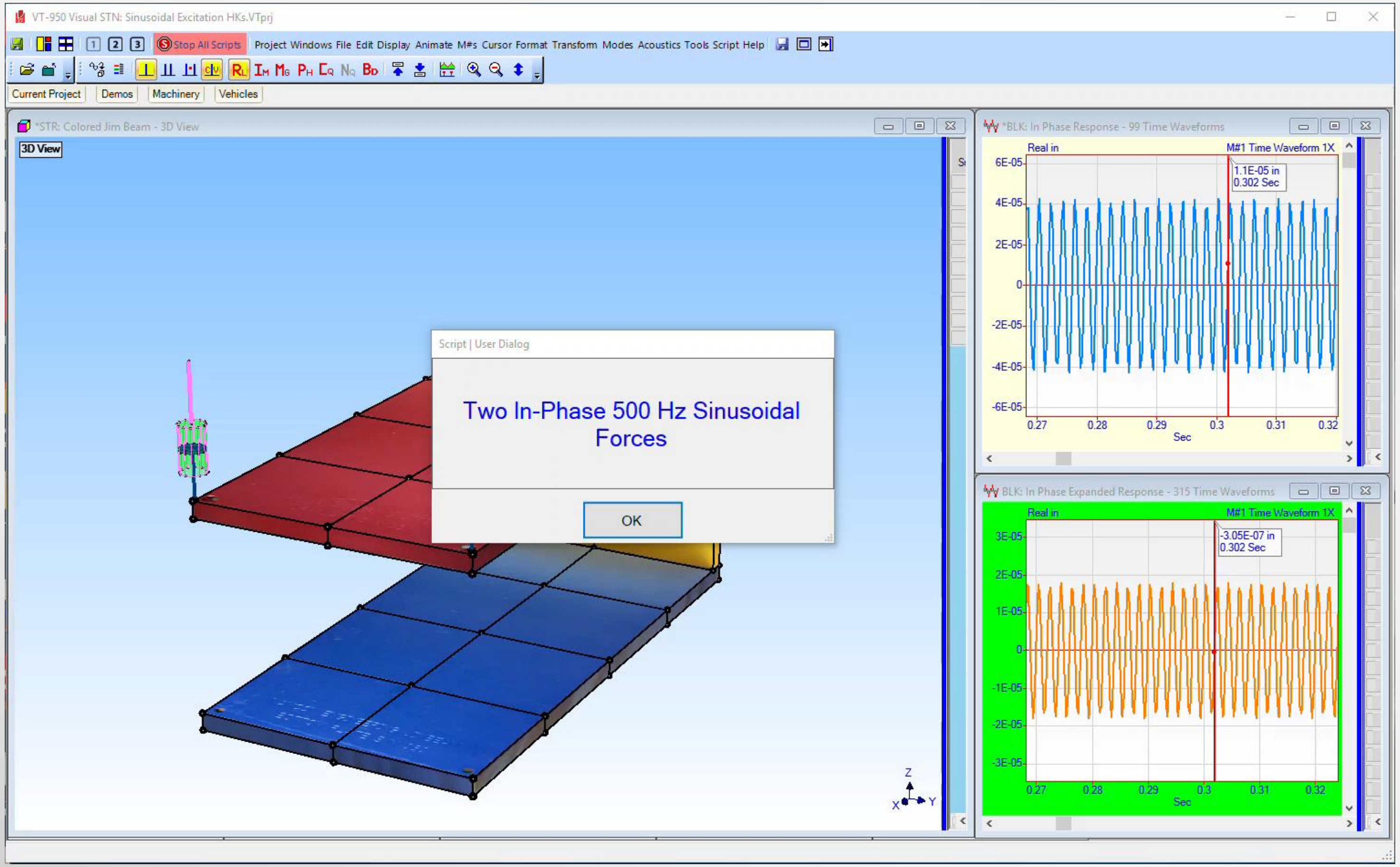
Two Sinusoidal Excitation Cases were Simulated

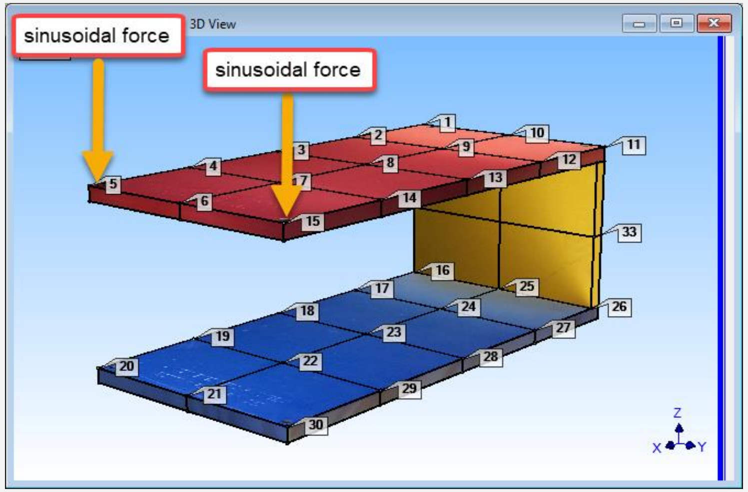
1. Two 500 Hz ***In-Phase*** sinusoidal excitation forces
2. Two 500 Hz ***Out-of-Phase*** sinusoidal excitation forces



Responses to In-Phase & Out-of-Phase Excitation

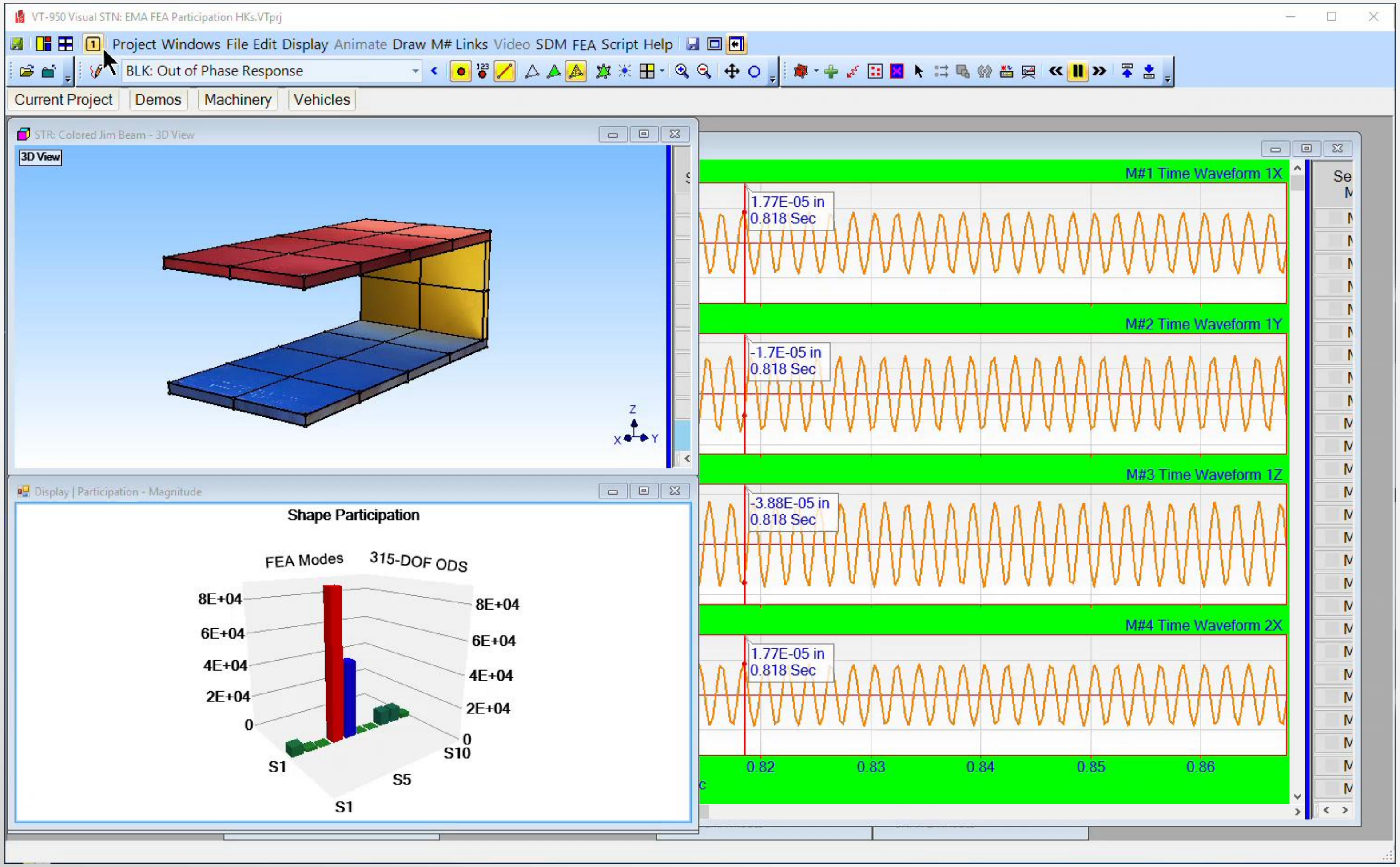
- ***High MAC values*** indicate ***strong co-linearity*** between EMA & FEA sinusoidal response

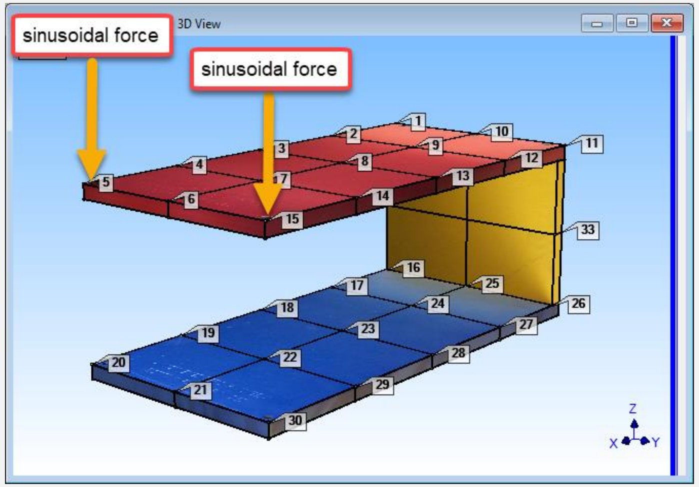




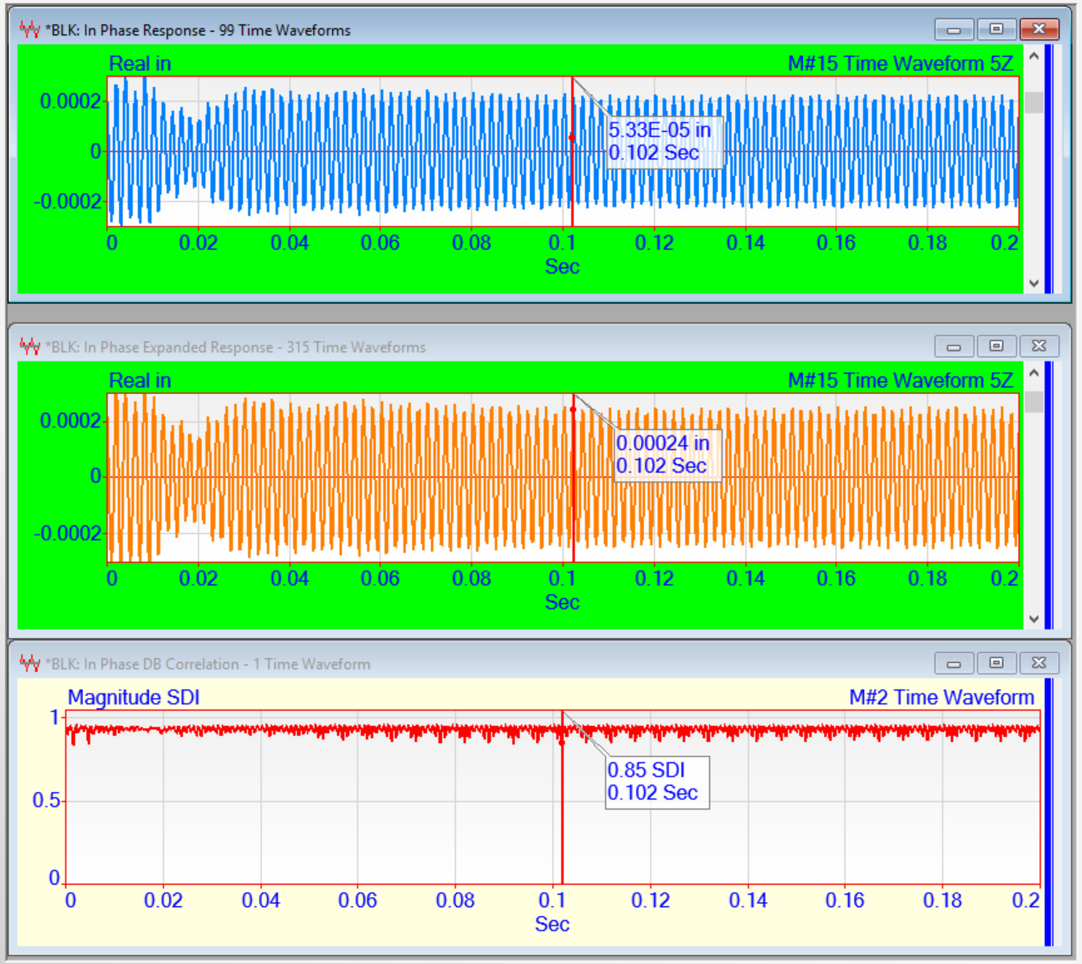
Vibrant TECHNOLOGY

Mode Shape Participation - In-Phase & Out-of-Phase Excitation

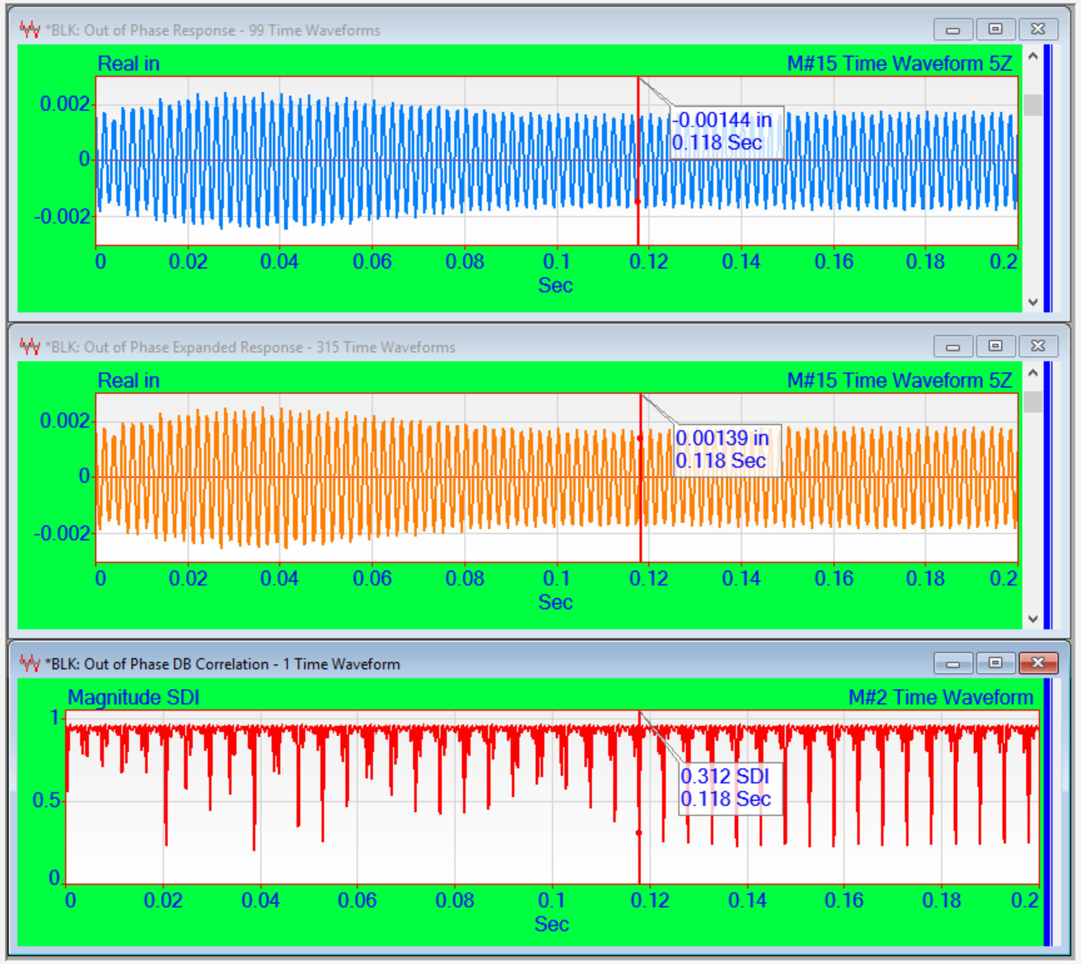




Correlation Between EMA-Based & FEA-Expanded Responses



In-Phase Responses



Out-of-Phase Responses

Vibrant TECHNOLOGY

Summary

- **Fundamental Law of Modal Analysis (FLMA)**: All vibration is a ***summation of mode shapes***
- ***FEA mode shapes*** were used to ***“decompose”*** and then ***"expand"*** experimental data to include DOFs that were not experimentally acquired
- ***Only FEA mode shapes*** were used, not their frequency or damping
- Mode shapes from an ***FEA model*** with ***free-free boundary conditions*** and ***no damping*** were used
- ***Complex*** experimental data which includes ***real-world boundary conditions*** and ***real-world damping*** can be decomposed & expanded using ***FEA normal mode shapes***

Vibrant TECHNOLOGY