Introduction to ODS Testing & Experimental Modal Analysis

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Vibrant TECHNOLOGY

Topics of this Presentation

- What *makes things vibrate?*
    - First Law of Modal Analysis (1st LoMA): *Any object with mass & elasticity will vibrate*
    - Second Law of Modal Analysis (2nd LoMA): *Forces cause vibration*
    - Third Law of Modal Analysis (3rd LoMA): *All vibration is a summation of mode shapes*
    - Fourth Law of Modal Analysis (4th LoMA): *All modes are excited at all frequencies*
- How is *mechanical vibration defined?*
- What is *an ODS?*
- What is *a Mode Shape?*

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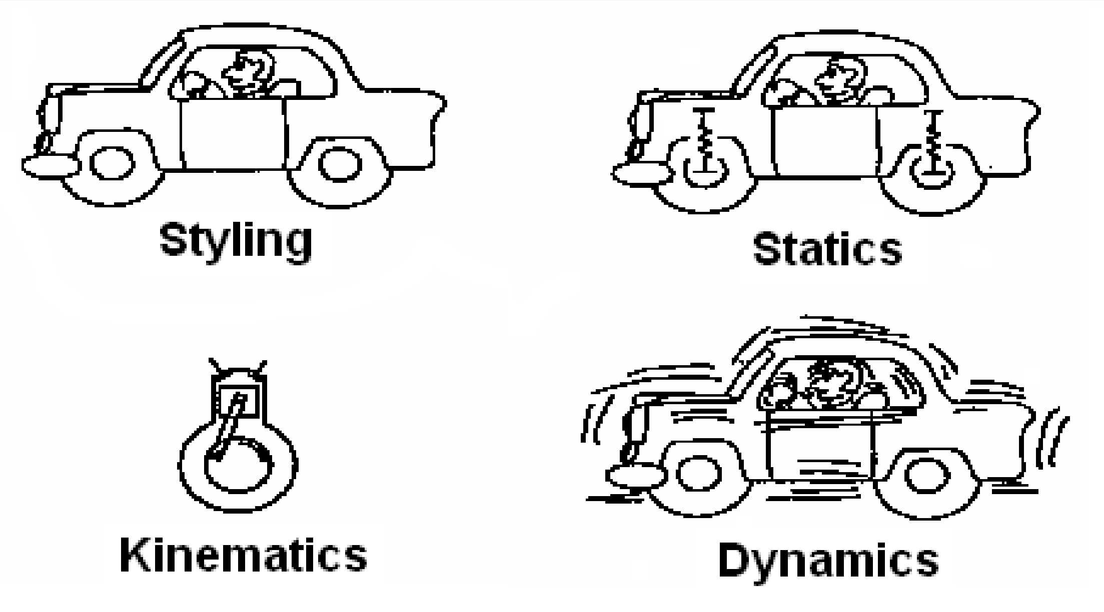
Mechanical Engineering Considerations

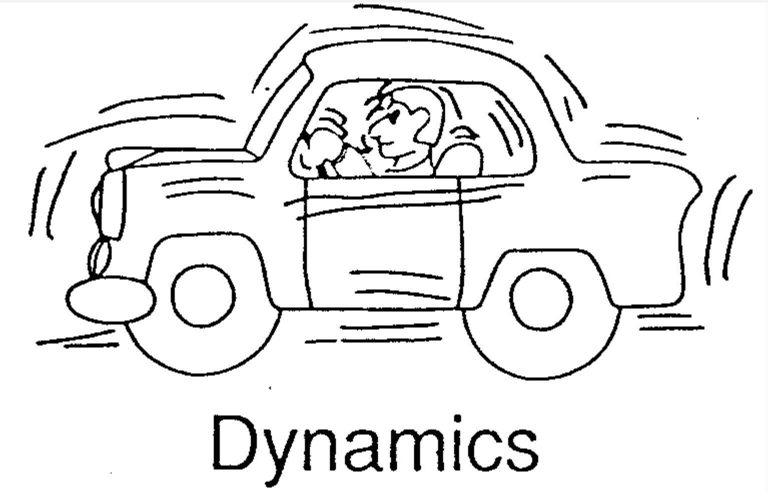
	No Forces	**Forces**
No Motion	Styling	Statics
Motion	Kinematics	***Dynamics***



Why Is Vibration Analysis Needed?

A Machine or Structure can have one or more of the following *vibration-related* problems

1. ***Difficult to control***
2. **Makes *too much noise***
3. ***Cannot maintain tolerances***
4. ***Wears out too fast***
5. ***Fatigues prematurely***
6. ***Fails unexpectedly***



Two Types of Vibration

- **First Law of Modal Analysis (1st LoMA)**: ***Any object*** **with** ***mass & elasticity*** **will vibrate**
- **Second Law of Modal Analysis (2nd LoMA)**: ***Forces cause vibration***

Forced Vibration: Internal or external forces which *cause rigid body motion*

Resonant Vibration: Internal or external forces which excite *one or more resonances*

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Resonant Vibration

- First Law of Modal Analysis (1st LoMA): *Any object with mass & elasticity will resonate*
- Second Law of Modal Analysis (2nd LoMA): *Forces cause vibration*

All vibration **is Forced vibration**

All resonances participate **in Forced vibration**

Spatial descriptions of vibration

Forced vibration => Operating Deflection Shape (ODS)

Resonant vibration => Mode Shape

What is an Operating Deflection Shape (ODS)?

- An ODS is a ***spatial description*** **of the** ***deformation*** **of a machine or structure**
- **A** ***time-based*** **ODS changes over time**
- **A** ***frequency-based*** **ODS changes with frequency**
- **An** ***order-based*** **ODS changes with machine speed**

  (order => a ***multiple of the running speed*****)**

An ODS Helps Answer the Following Questions

- What is the ***motion of one point relative to another***?
- ***Where*** is a ***machine moving the most***?
- ***How much*** is a machine moving? **(IPS < 1.0?)**
- ***Is a resonance participating*** in the response?
- Is there ***structure-born noise source***?
- Do corrective actions *reduce noise or vibration levels*?

What is a Mode of Vibration?

- A mode of vibration is a *mathematical representation* of a *structural resonance*
- When *dynamic forces are applied*, and *energy is trapped* within the boundaries of a structure, *it will resonate*
- When energy is trapped within the boundaries of a structure, it causes a *standing wave deformation, which* is called *a mode shape*
- A structure *will resonate* when its modes *readily absorb energy*
- A structural resonance can be thought of as a *mechanical amplifier*
  (A small dynamic load can cause *excessive deformation)*

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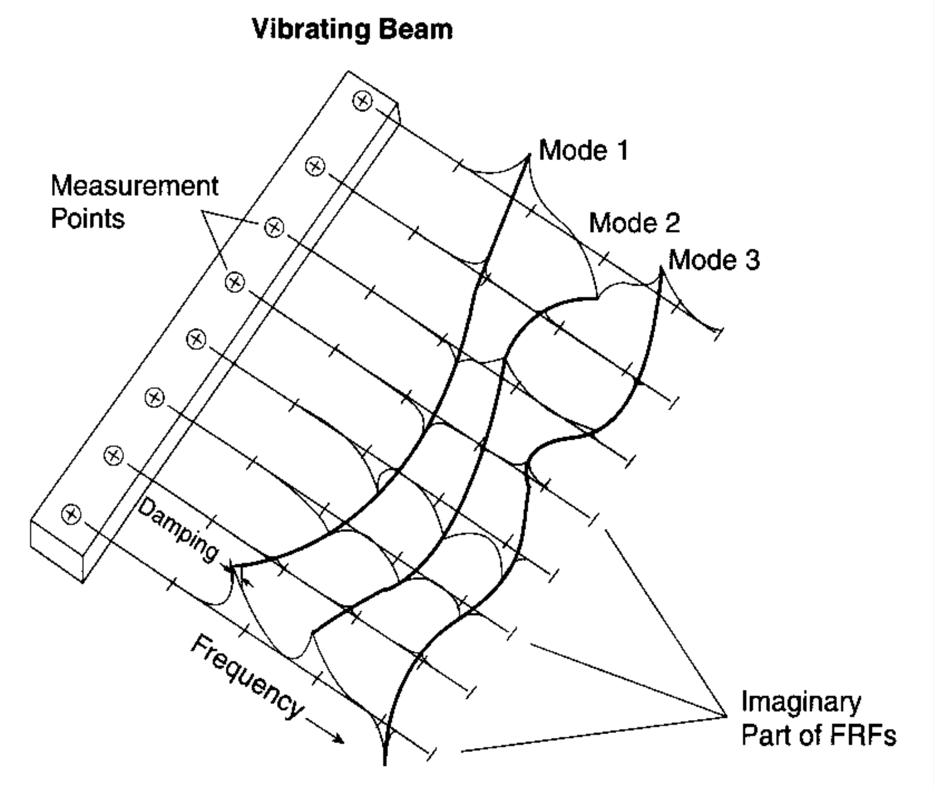
Modal Parameters From FRFs

- **Third Law of Modal Analysis (3rd LoMA):** ***All vibration is a summation of mode shapes***
- **Fourth Law of Modal Analysis (4th LoMA):** ***All modes are excited at all frequencies***

- **Each mode is *defined by three parameters***

- **Modal frequency**
  (***natural frequency*** of a resonance peak)
- **Modal damping**
  (***width*** of a resonance peak)
- **Mode shape**
  (***magnitude & phase*** of a resonance peak at the same frequency)



Trapped Energy Causes Resonant Vibration?

- **First Law of Modal Analysis (1st LoMA)**: ***Any object with mass & elasticity will vibrate***
- **Second Law of Modal Analysis (2nd LoMA)**: ***Forces cause vibration***

- **Resonant vibration is caused when *Energy* is,**
  1) ***Trapped within the boundaries*** **of a structure**
  2) ***Moves freely within the structural material***
  3) **Cannot readily escape**
- ***Striking a bell*** **causes it to resonate**
- ***Striking a sandbag*** **will not cause it to resonate**

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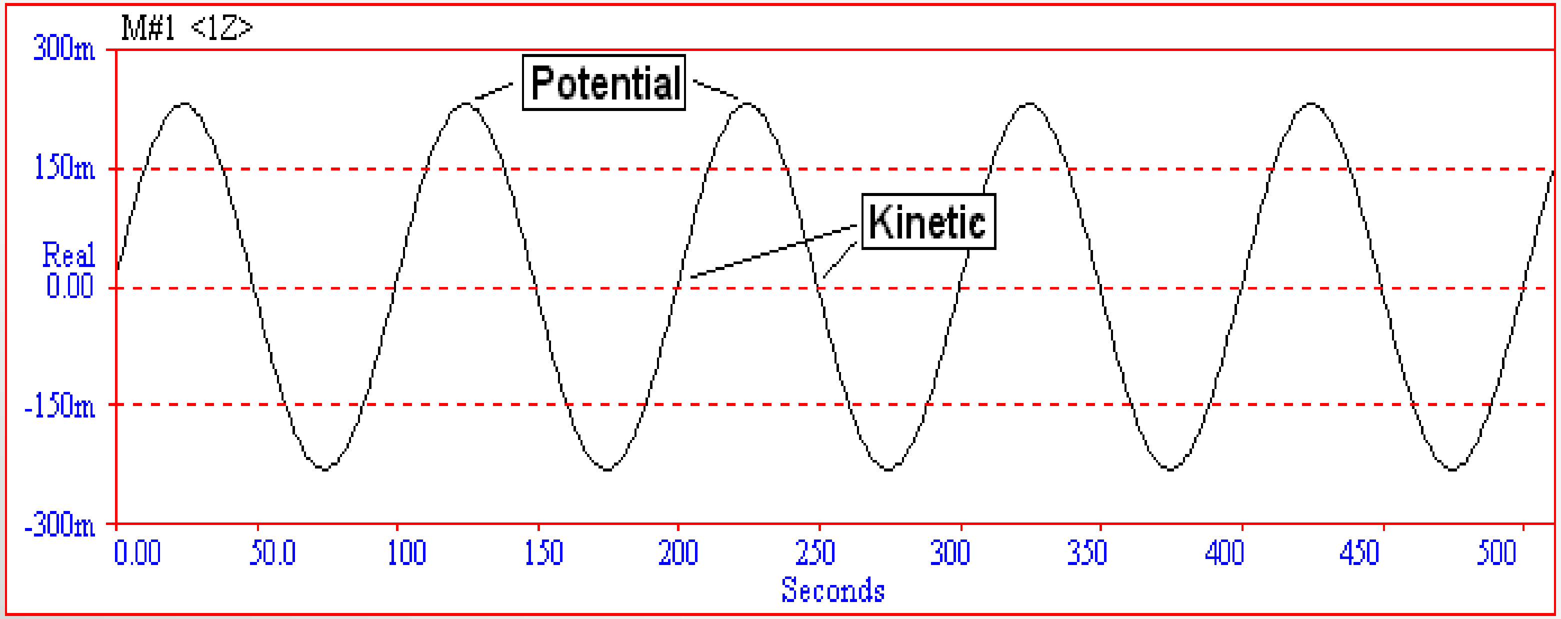
What Happens To Trapped Energy?

- **First Law of Modal Analysis (1st LoMA)**: ***Any object with mass & elasticity will vibrate***
- **Second Law of Modal Analysis (2nd LoMA)**: ***Forces cause vibration***

Trapped energy is converted between *potential & kinetic energy* within a structure



What Happens To Trapped Energy?

- First Law of Modal Analysis (1st LoMA): *Any object with mass & elasticity will vibrate*
- Second Law of Modal Analysis (2nd LoMA): *Forces cause vibration*

$$M \ddot{x}(t) + K\, x(t) = 0$$

$$\text{Inertia} + \text{Stiffness} = 0$$

- Trapped energy is exchanged between the *mass & elastic properties* in a structure
- The *mass (inertial) & elastic (stiffness)* forces are always *equal & opposite* to one another

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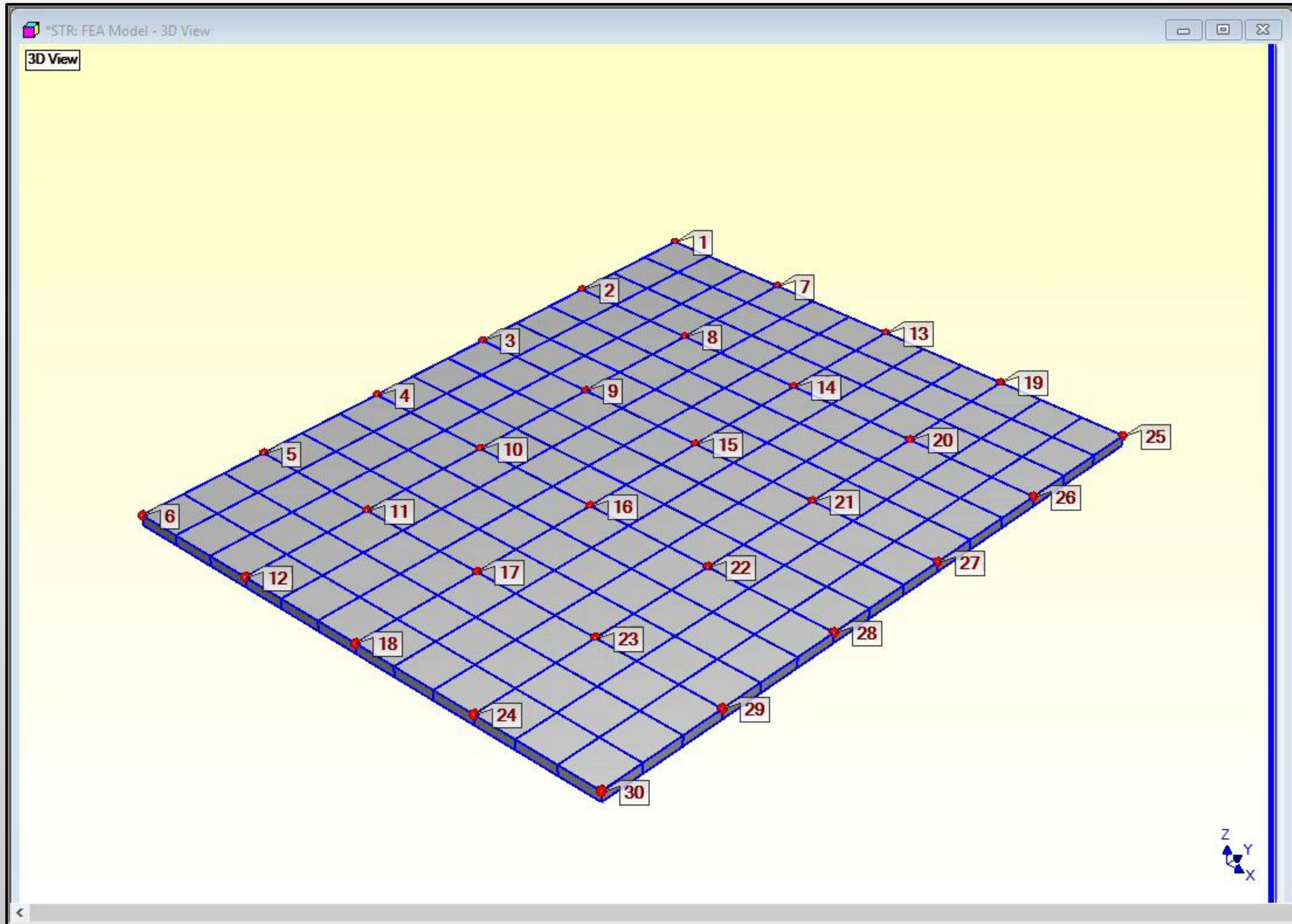
What Does Resonant Vibration Look Like?

- Trapped energy causes ***standing wave deformations*** at ***specific natural frequencies***
- These ***standing waves*** are called ***mode shapes***



*SHP: First Four Expanded Shapes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)
1	102	0.0304	Hz	0.03
2	129	0.248	Hz	0.192
3	208	0.443	Hz	0.213
4	242	0.108	Hz	0.0446

Select M#	DOFs	Units	Measuren Type
M#1	6X	g/lbf-sec	Residue Mode
M#2	6Y	g/lbf-sec	Residue Mode
M#3	6Z	g/lbf-sec	Residue Mode
M#4	12X	g/lbf-sec	Residue Mode
M#5	12Y	g/lbf-sec	Residue Mode
M#6	12Z	g/lbf-sec	Residue Mode
M#7	18X	g/lbf-sec	Residue Mode
M#8	18Y	g/lbf-sec	Residue Mode
M#9	18Z	g/lbf-sec	Residue Mode
M#10	24X	g/lbf-sec	Residue Mode
M#11	24Y	g/lbf-sec	Residue Mode
M#12	24Z	g/lbf-sec	Residue Mode
M#13	30X	g/lbf-sec	Residue Mode
M#14	30Y	g/lbf-sec	Residue Mode
M#15	30Z	g/lbf-sec	Residue Mode
M#16	5X	g/lbf-sec	Residue Mode

Video

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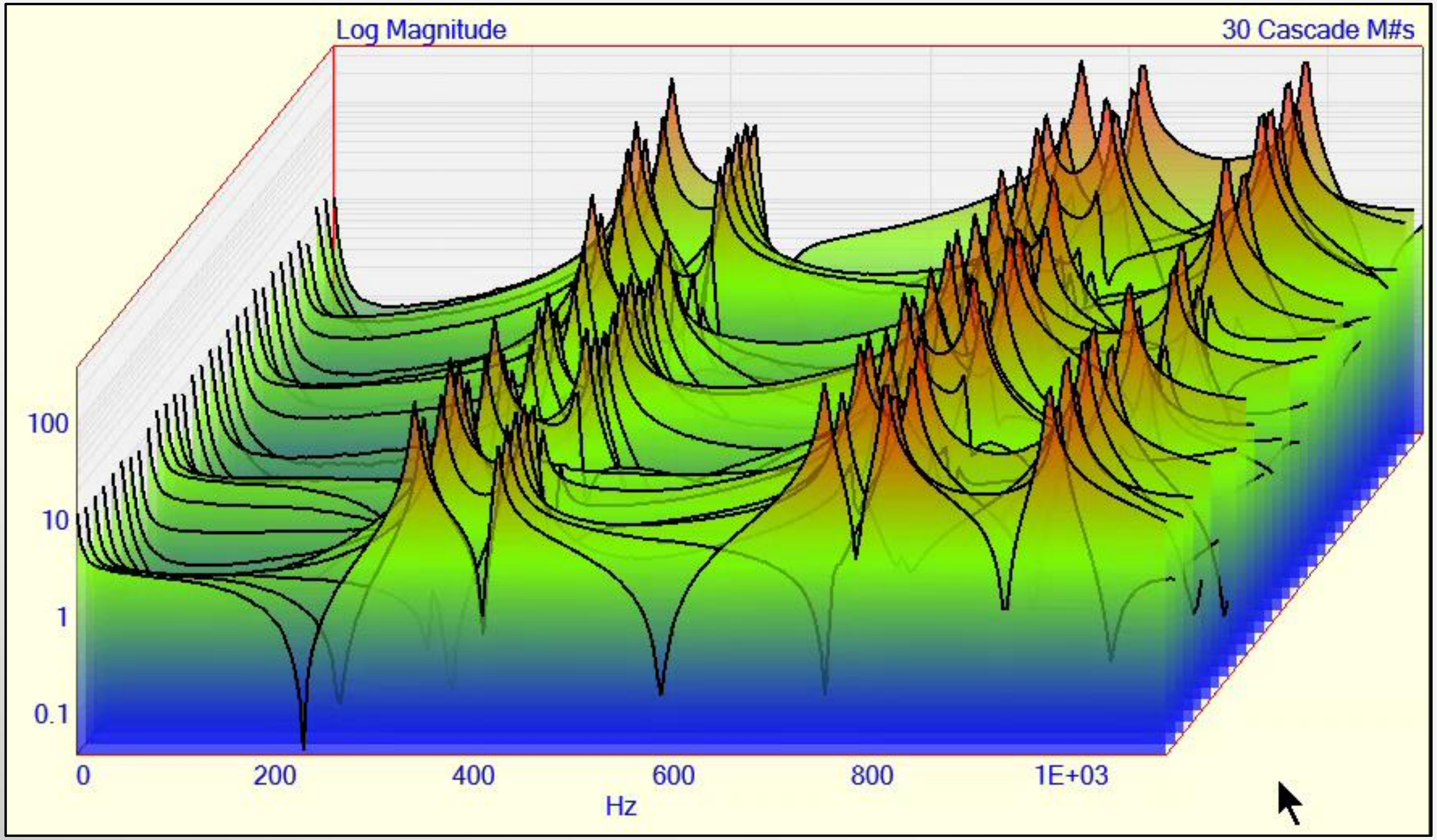
Resonances Are Dangerous!

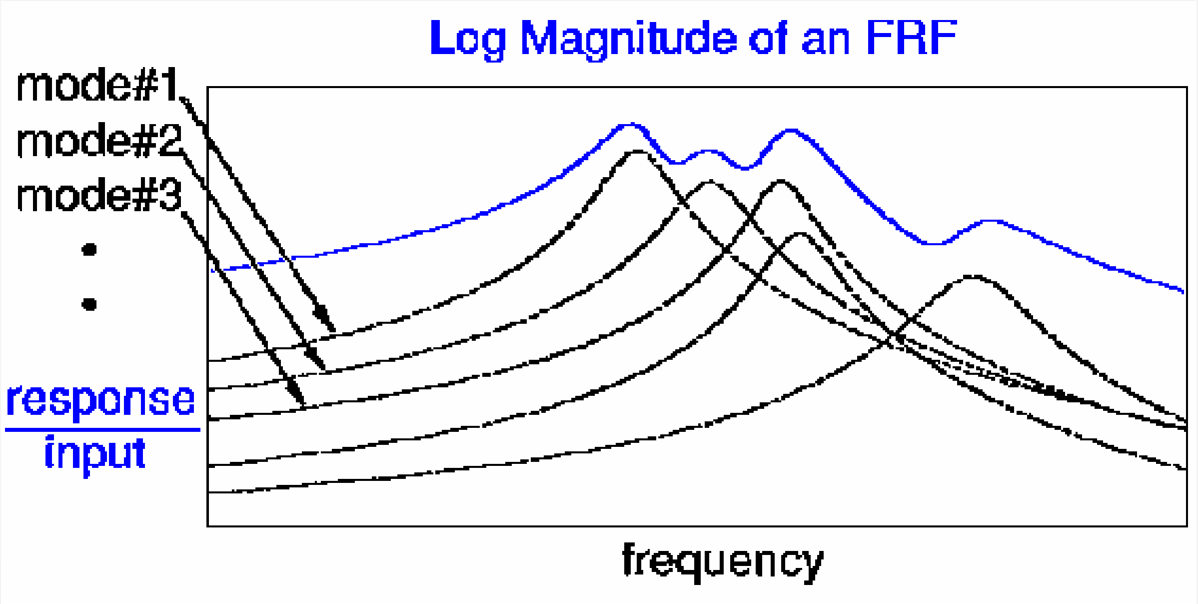
- Resonances act as *Mechanical Amplifiers*
- Energy input *at or near a natural frequency is easily absorbed*, resulting in *high amplitude vibration*



Video

All Vibration is a *Summation* of Resonance Curves

- **Third Law of Modal Analysis (3rd LoMA):** ***All vibration is a summation of mode shapes***
- **Fourth Law of Modal Analysis (4th LoMA):** ***All modes are excited at all frequencies***



- **The *FFT* transforms each time waveform into its corresponding Digital *Fourier Transform (DFT), without loss of information***
- ***Auto spectra, Cross spectra, Transmissibility's, FRFs, & ODS-FRFS* are *calculated from DFTs***
- **Each *resonance curve corresponds to a mode of vibration***

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Two Ways to Obtain Mode Shapes

- **Experimental Modal Analysis (EMA): EMA mode shapes are extracted from experimentally derived *time waveforms* or *frequency waveforms* that *characterize the structural dynamics***

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

- ***Both EMA & FEA* are based upon the *Laws of Modal Analysis (LoMA)***

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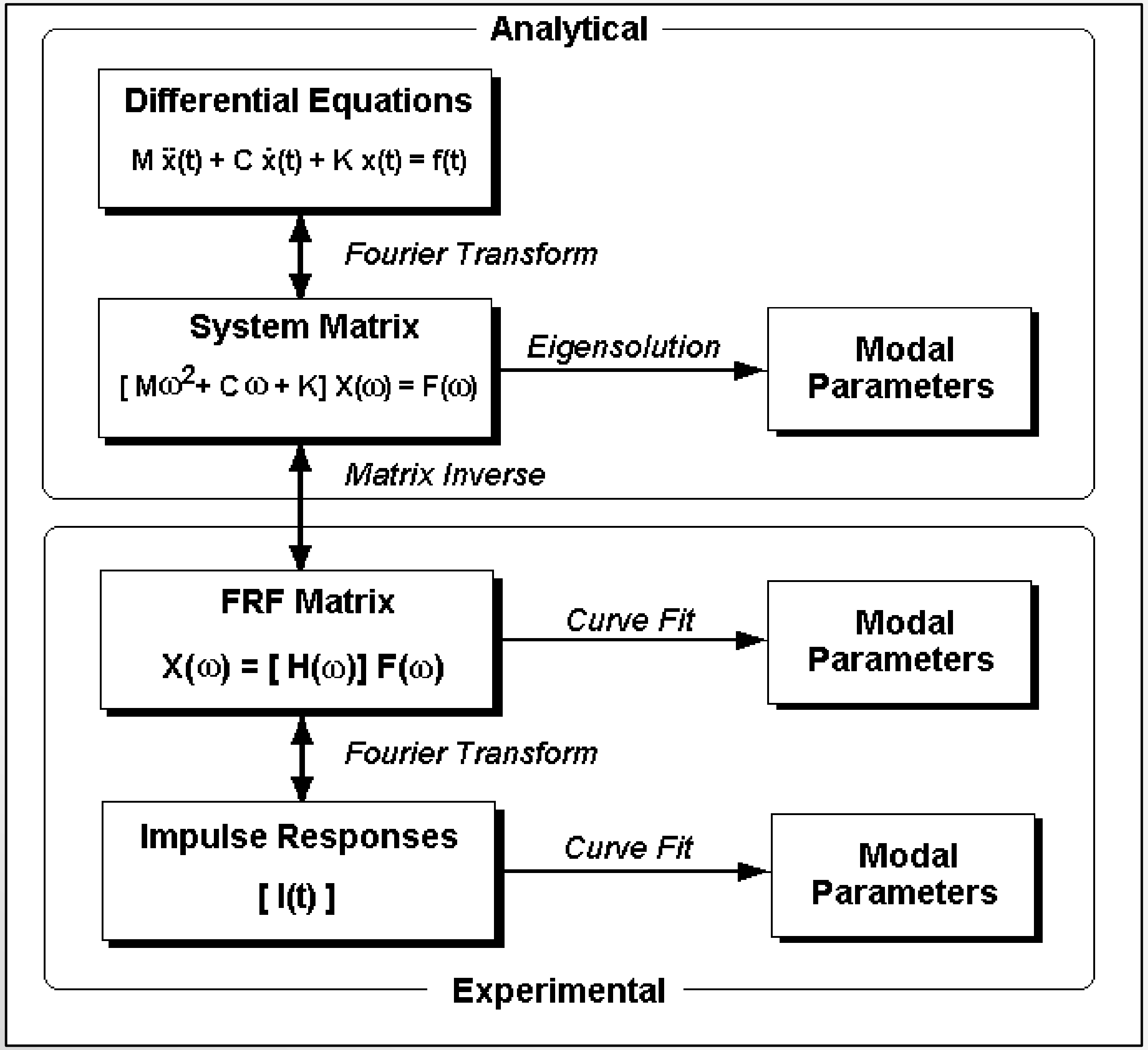
Two Ways to Obtain Mode Shapes



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Uses of Experimental Modal Analysis (EMA)

Product
Test & Measurement

- Trouble Shooting
- FEA Model Verification
- FEA Model Updating
- Dynamics Simulation
- Dynamics Modification

Machinery Maintenance
Structural Health Monitoring

- Trouble Shooting
- Route-Based Monitoring
- In-Situ Monitoring
- New Installation Qualification
- Post-Maintenance Verification
- Fault Diagnostics

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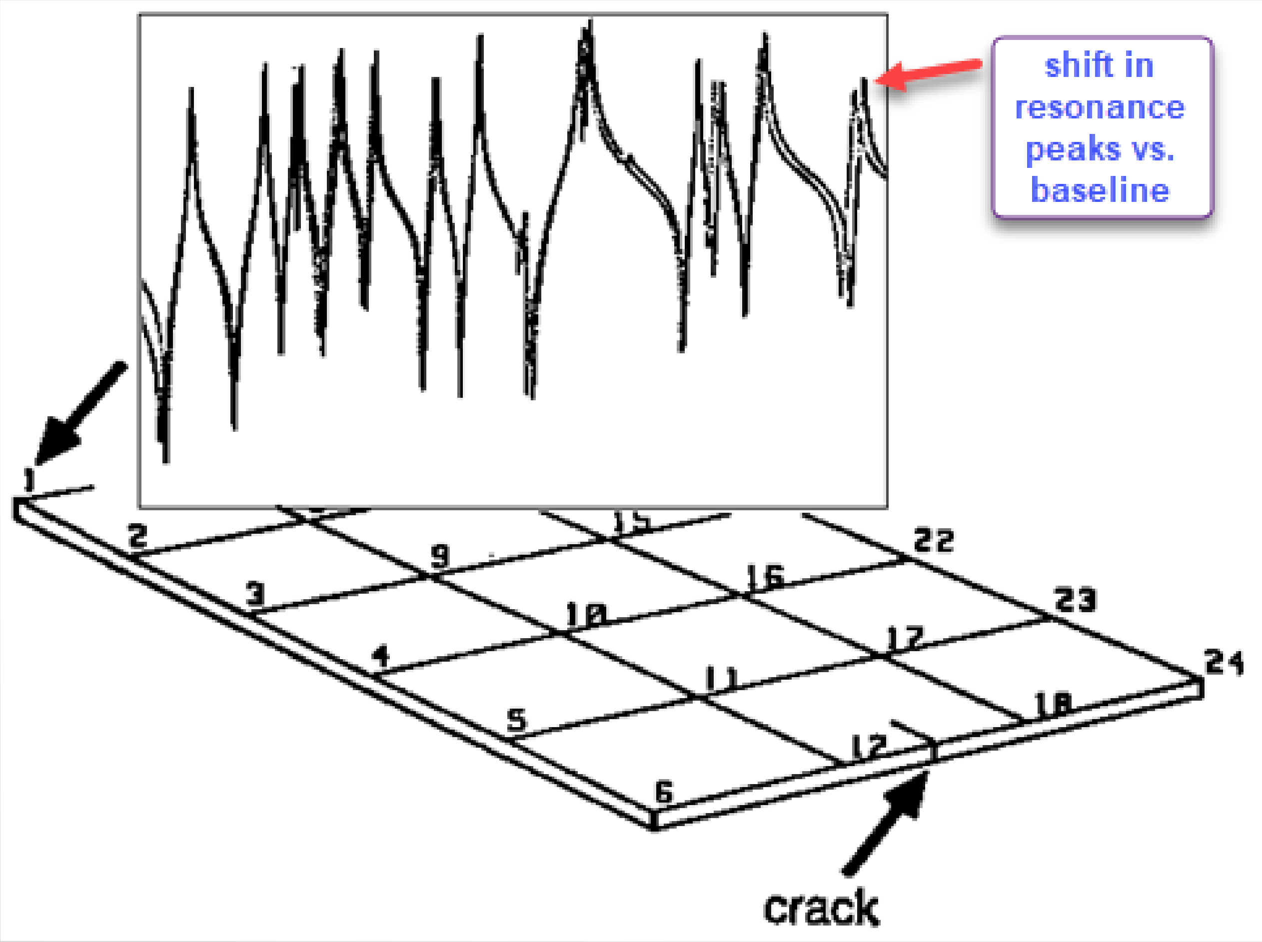
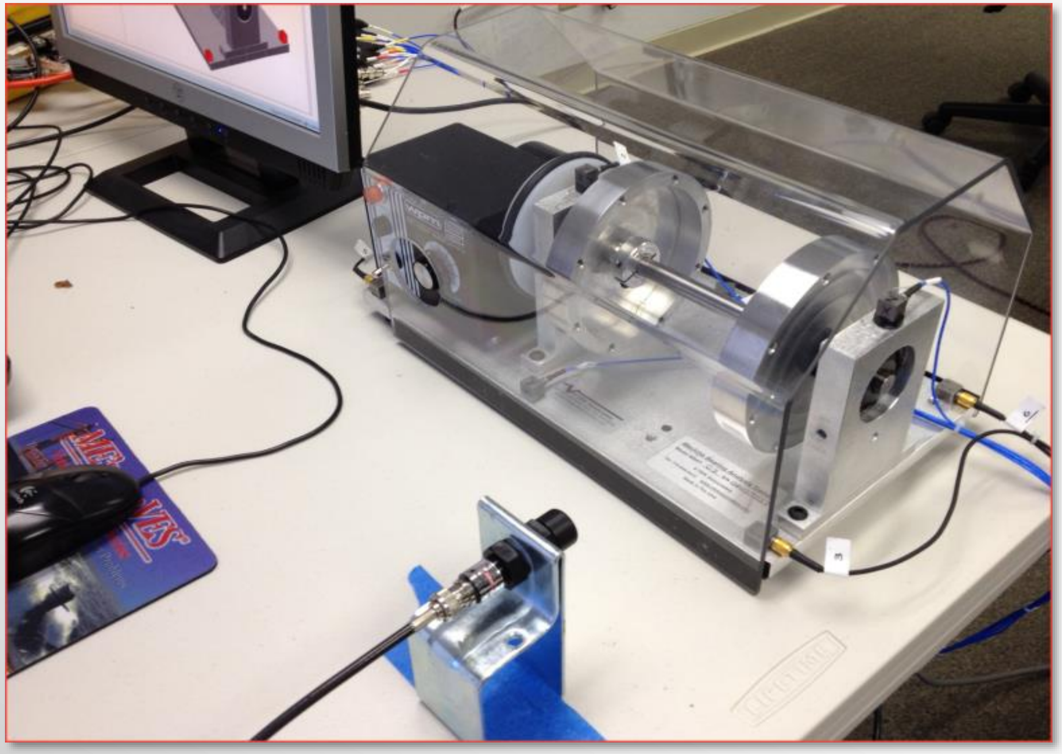
Modes Are Sensitive Indicators Of Physical Changes

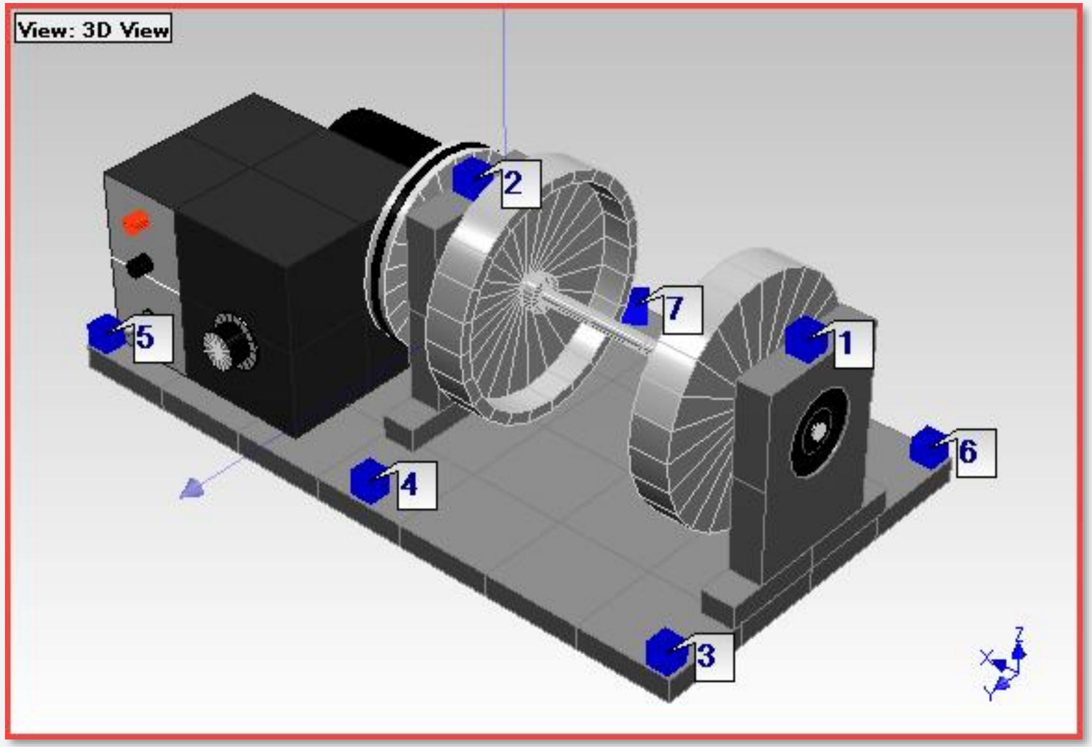
Physical damage will cause a *shift in the modal frequencies* of a machine or structure



Operating Deflection Shapes Using 24-Channel Acquisition

During operation of this rotating machine, data was acquired at eight locations using *eight tri-axial accelerometers* and *24-channel simultaneous data acquisition*





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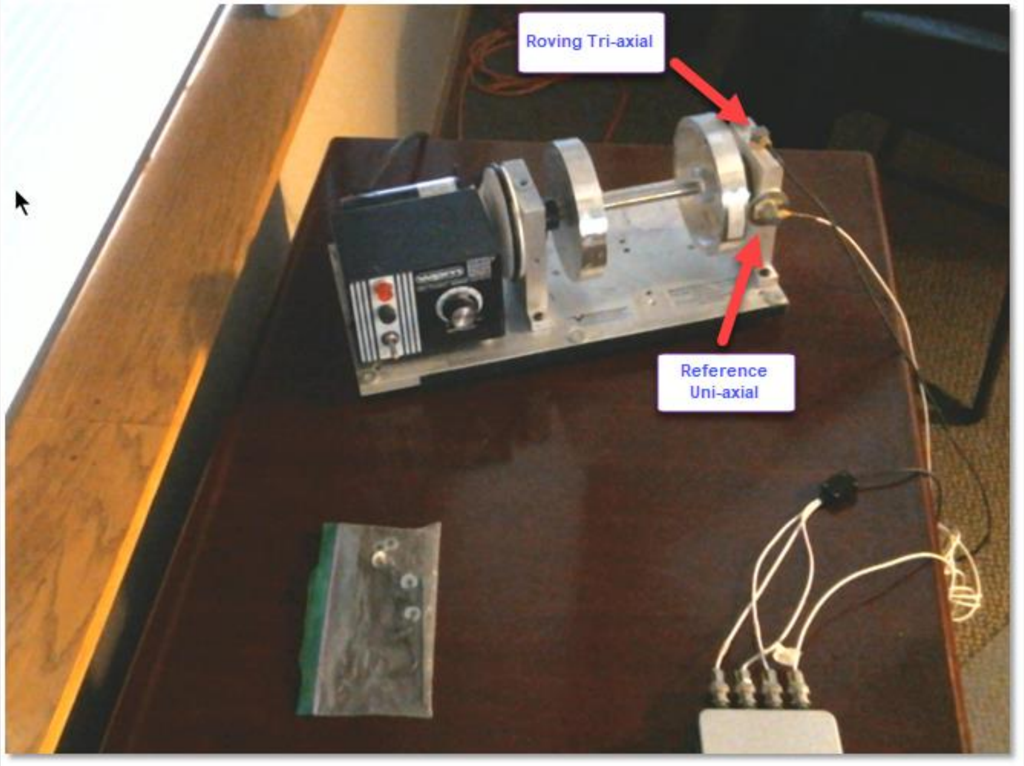
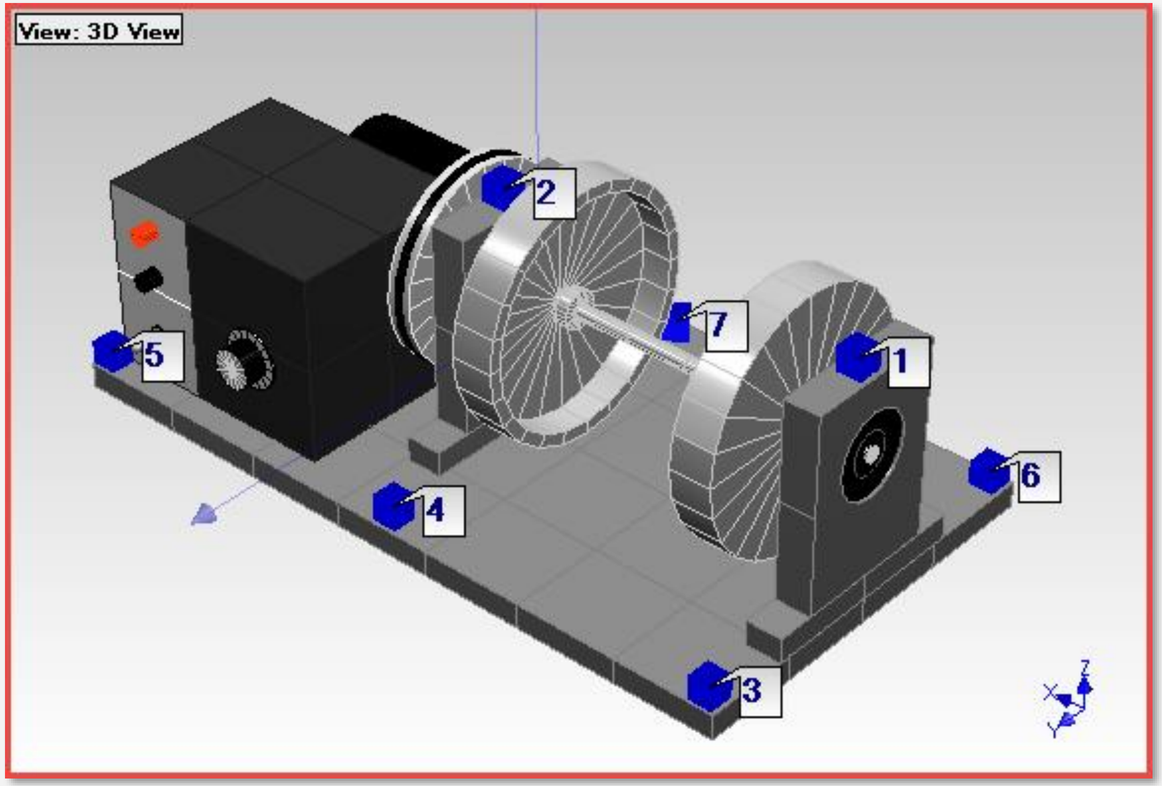
Operating Deflection Shapes Using 4-Channel Acquisition

During operation of this rotating machine, data was also acquired at *eight locations* using a *fixed uni-axial*, a *roving tri-axial accelerometer* and a *4-channel simultaneous acquisition*

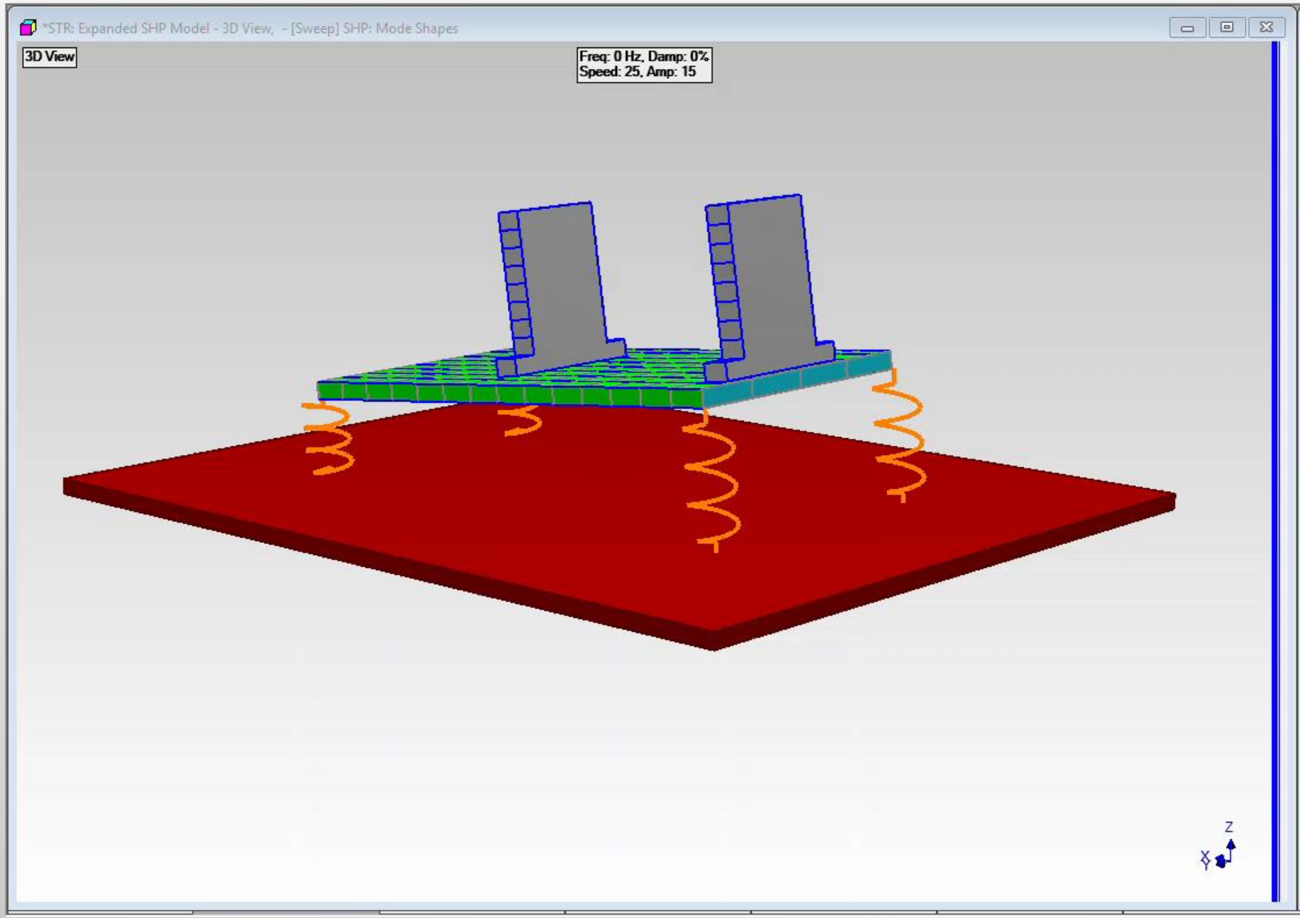




Mode Shapes of the Base Plate & Bearing Blocks

Third Law of Modal Analysis (3rd LoMA): ***All vibration*** **is a** ***summation of mode shapes***

Six Rigid Body **and** ***four Flexible Body*** **mode shapes describe** ***most of the dynamics*** **of the machine**



*SHP: Mode Shapes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)
1	0	0	Hz	0
2	0	0	Hz	0
3	0	0	Hz	0
4	0	0	Hz	0
5	0	0	Hz	0
6	0	0	Hz	0
7	269	0	Hz	0
8	452	0	Hz	0
9	591	0	Hz	0
10	694	0	Hz	0

Select M#	DOFs	Units	Measurement Type
M#1	1X	in/lbf-sec	UMM Mode
M#2	1Y	in/lbf-sec	UMM Mode
M#3	1Z	in/lbf-sec	UMM Mode
M#4	2X	in/lbf-sec	UMM Mode
M#5	2Y	in/lbf-sec	UMM Mode
M#6	2Z	in/lbf-sec	UMM Mode
M#7	3X	in/lbf-sec	UMM Mode
M#8	3Y	in/lbf-sec	UMM Mode
M#9	3Z	in/lbf-sec	UMM Mode
M#10	4X	in/lbf-sec	UMM Mode
M#11	4Y	in/lbf-sec	UMM Mode

Video

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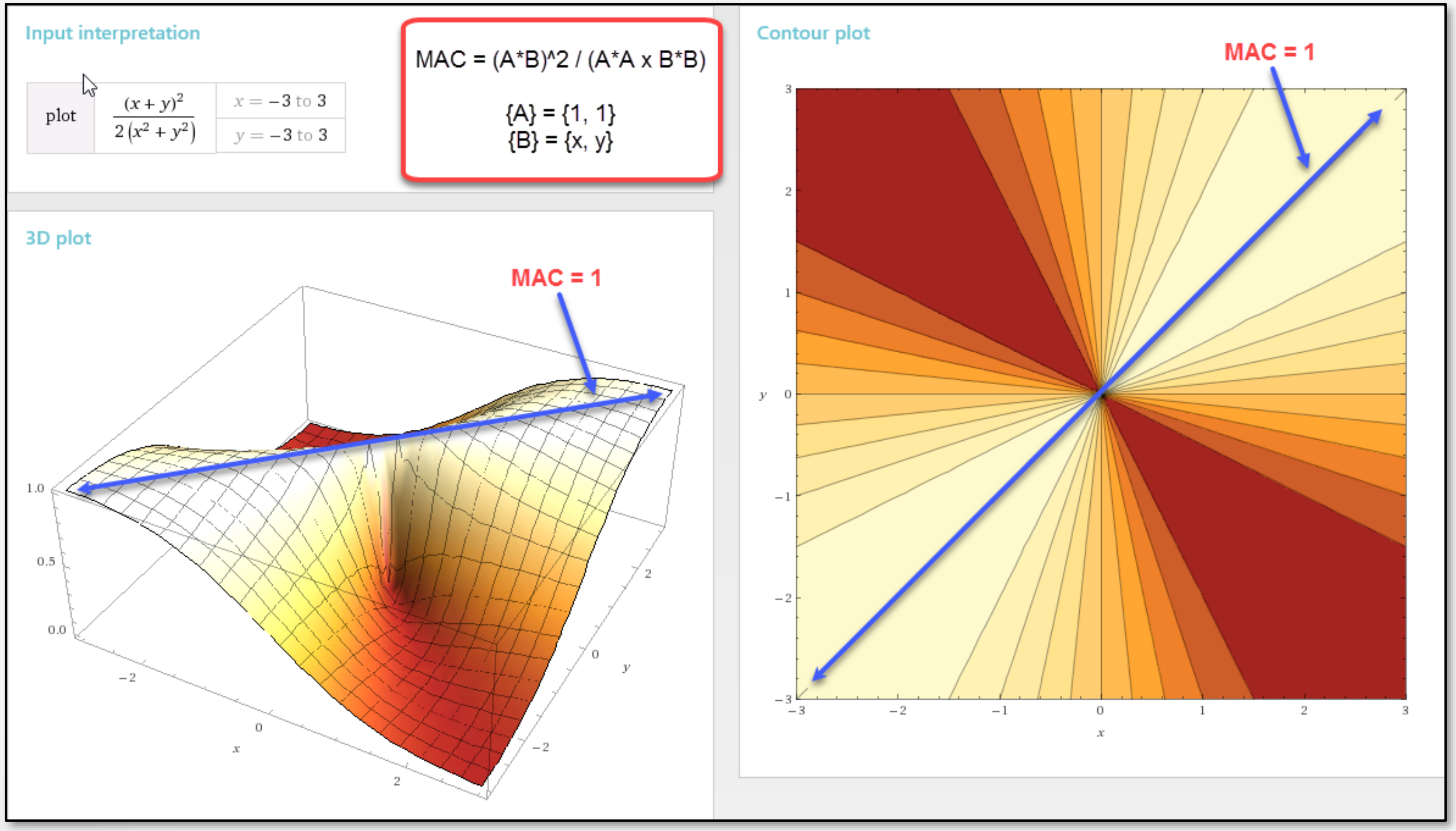
Modal Assurance Criterion (MAC)

Numerical comparison between *two shapes*

- MAC = 1 ➔ two shapes are *co-linear*
- MAC > 0.9 ➔ *almost co-linear*
- MAC < 0.9 ➔ *not co-linear*



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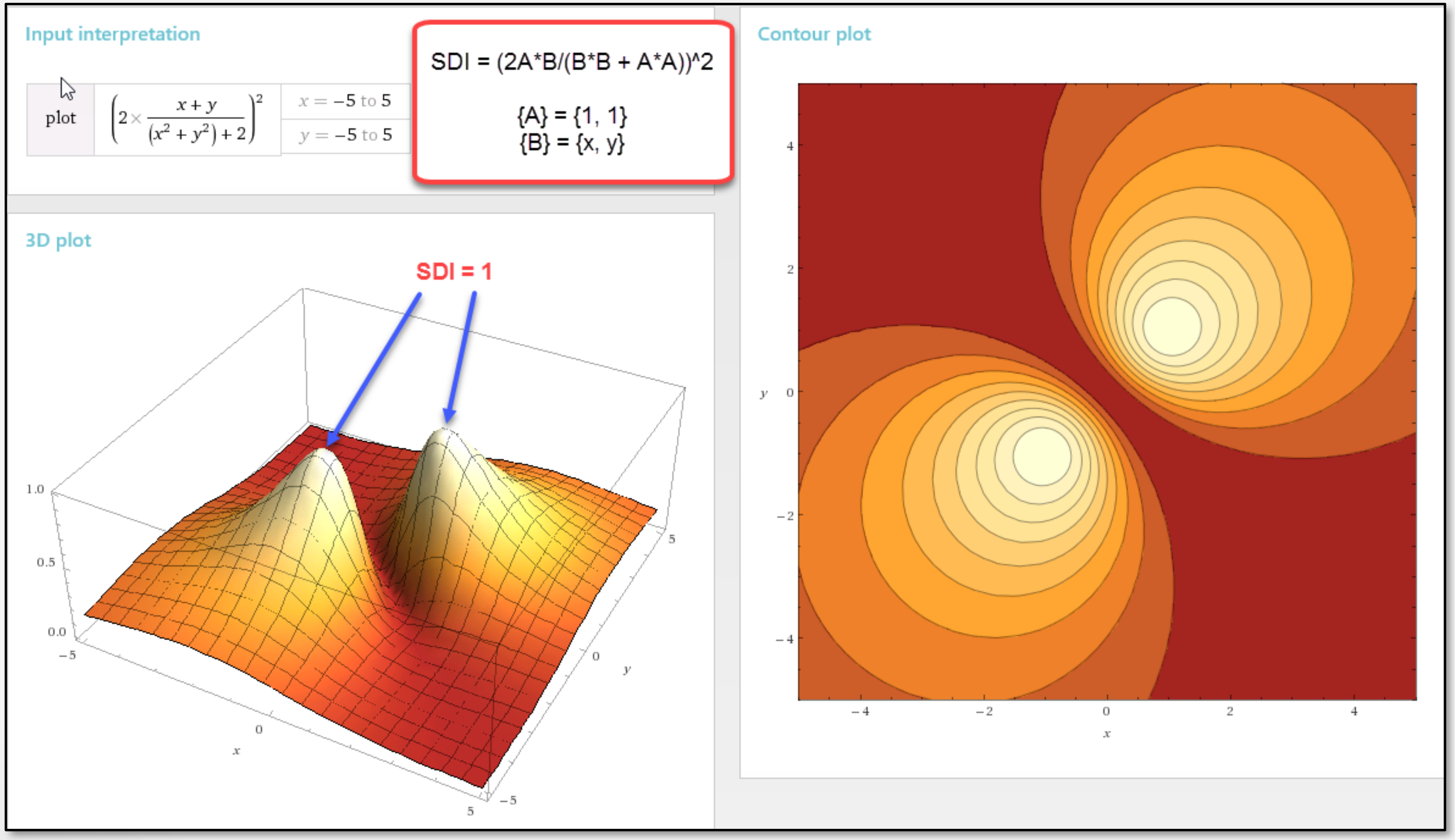
Shape Difference Indicator (SDI)

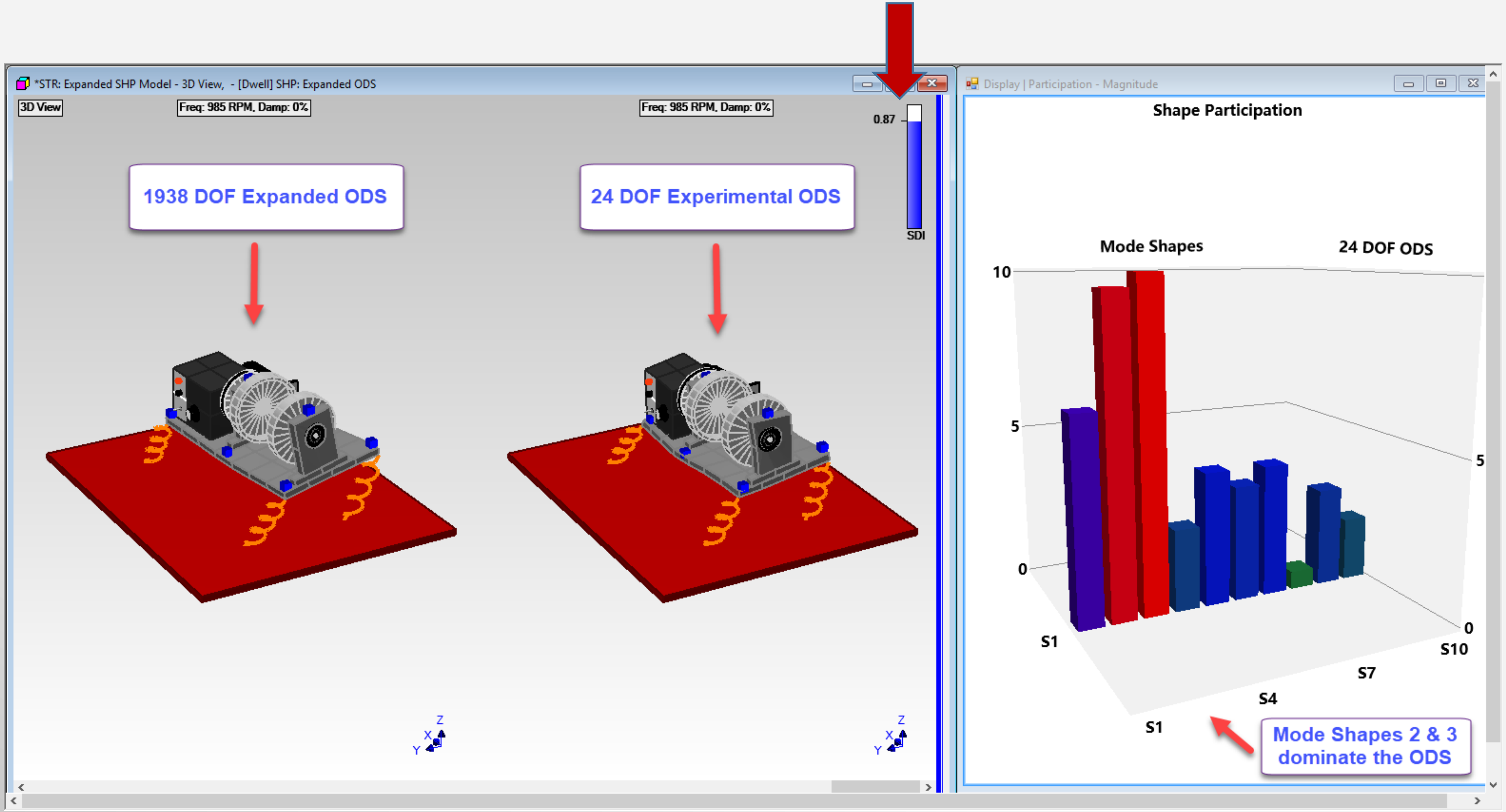
Numerical comparison* between *two shapes

- **SDI = 1 ➔ two shapes are *the same***
- **SDI > 0.9 ➔ *almost the same***
- **SDI < 0.9 ➔ *not the same***



Mode Shape Participation in the ODS at 985 RPM

The *high SDI value (0.87)* verifies that the *ODS is accurately represented* as a *summation of mode shapes*



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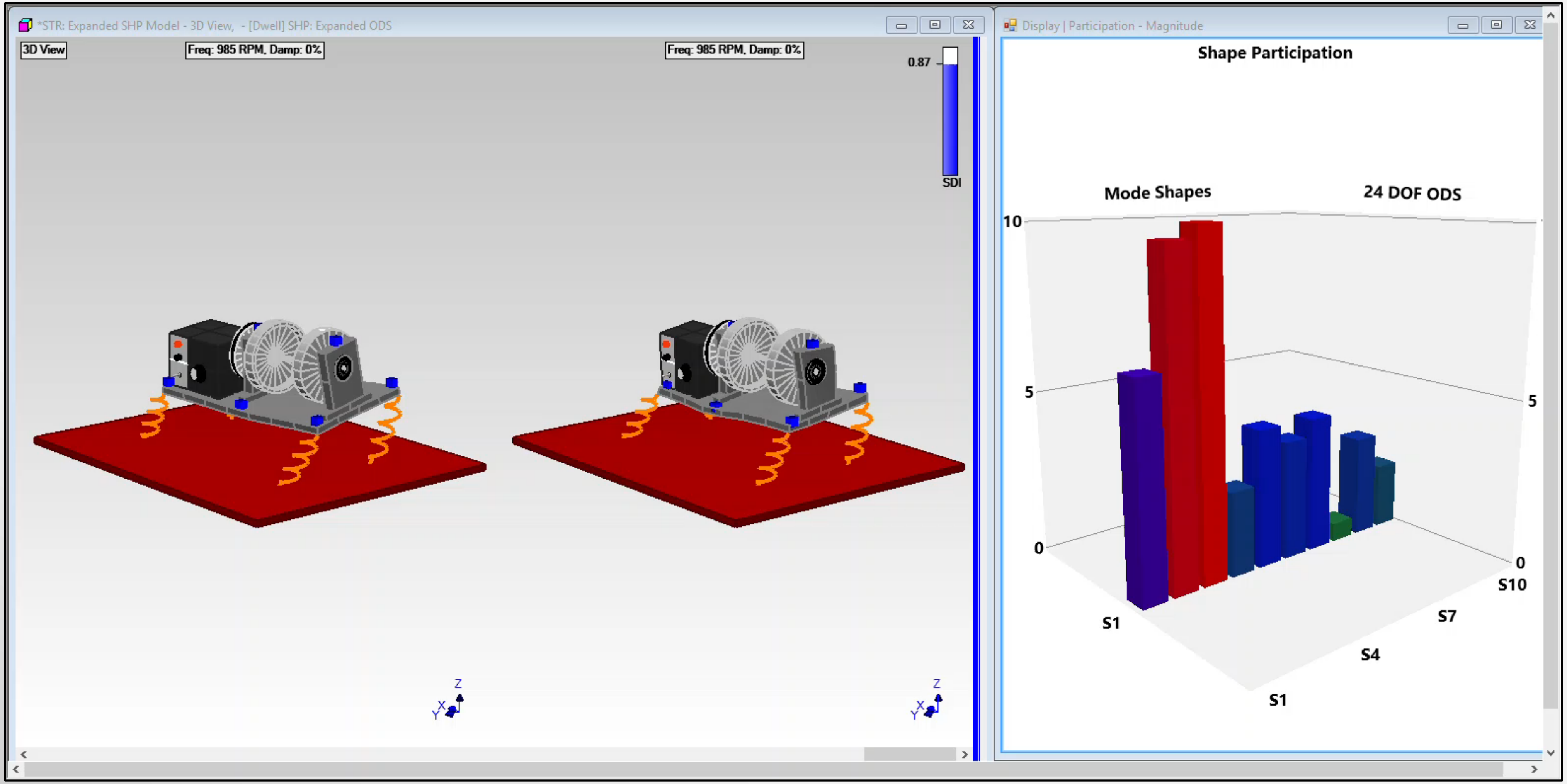
Mode Shape Participation in the ODS at 985 RPM



Video

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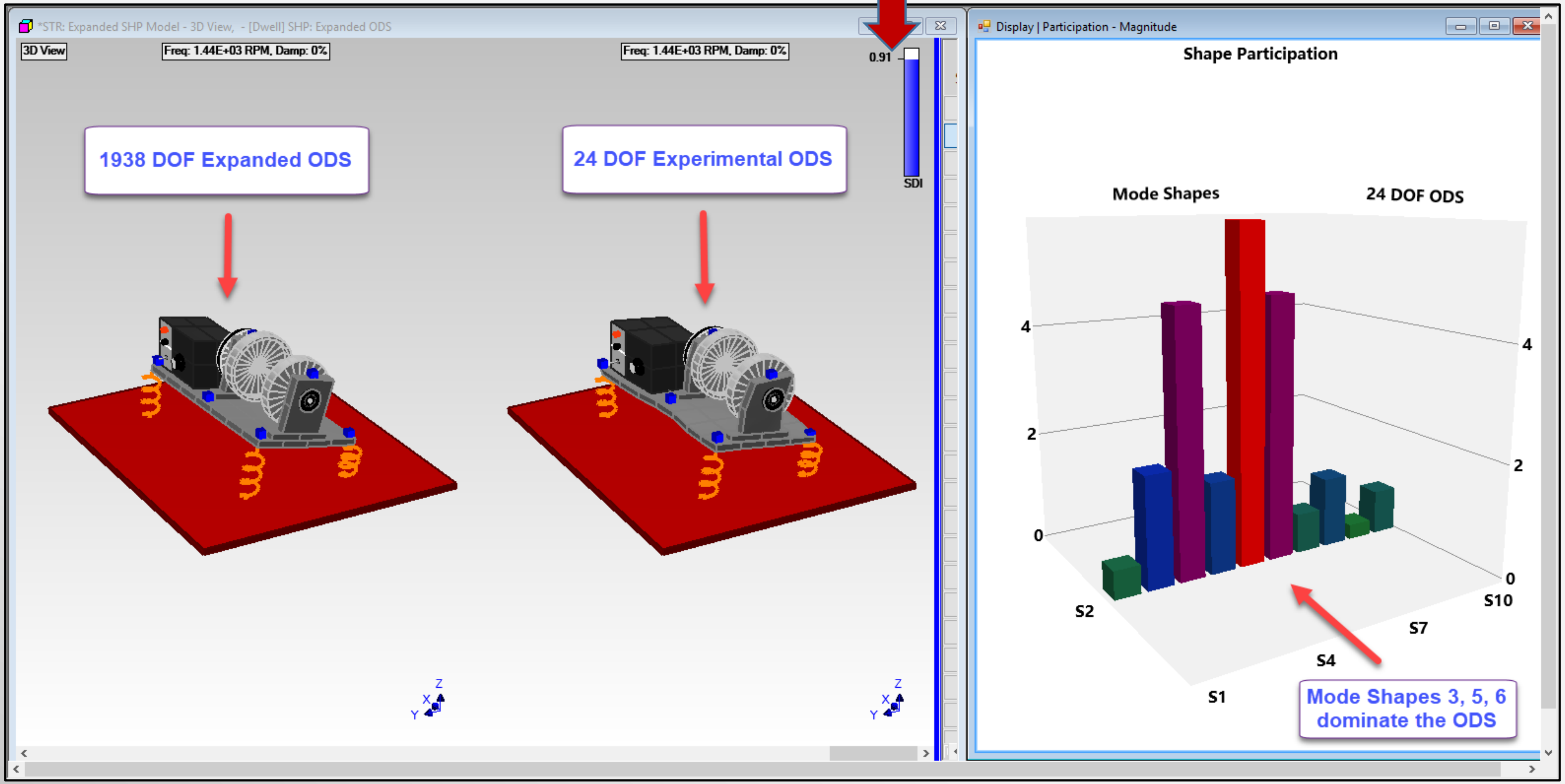
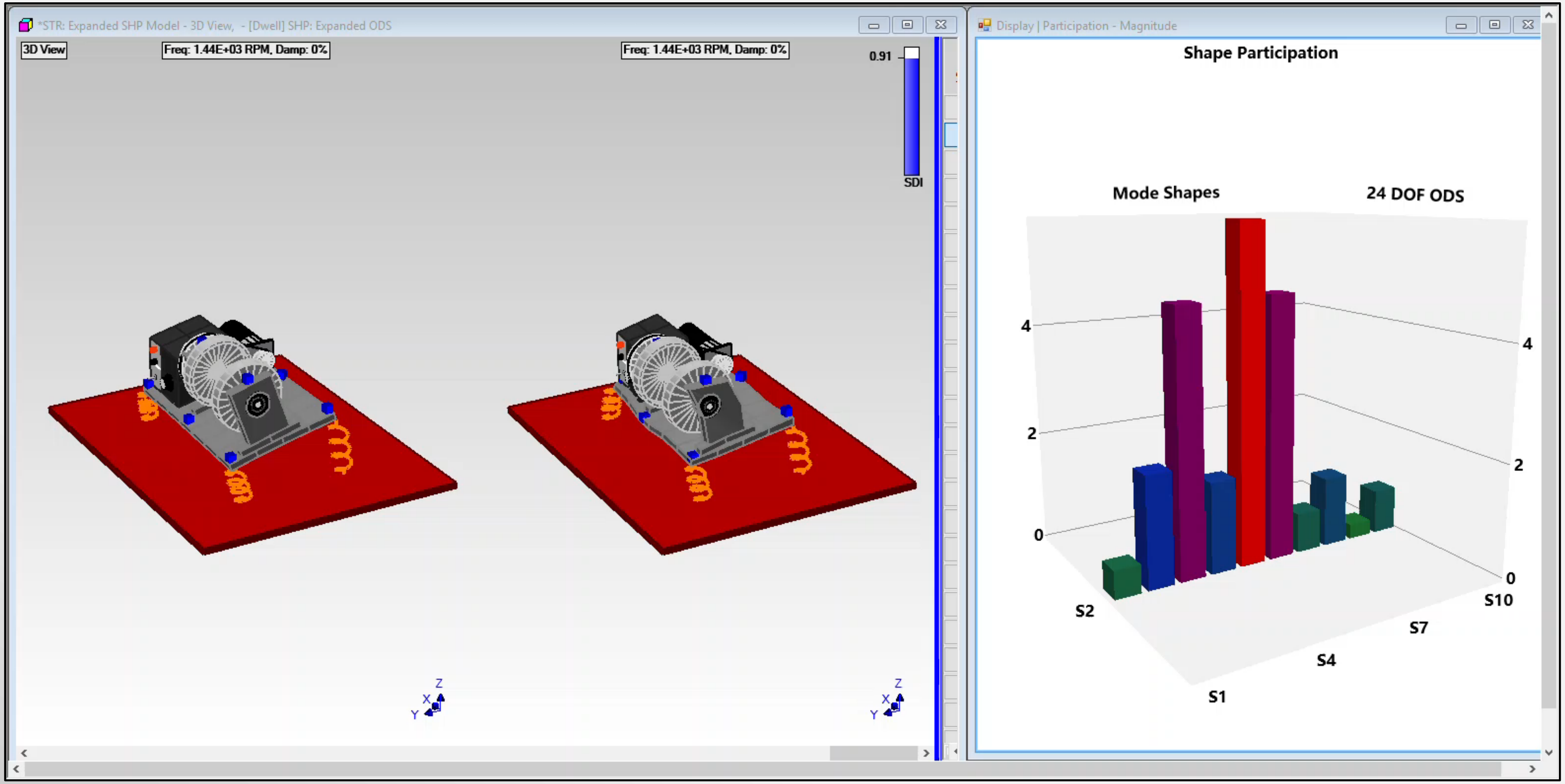
Mode Shape Participation in the ODS at 1440 RPM

The *high SDI value (0.91)* verifies that the *ODS is accurately represented* as a *summation of mode shapes*



Mode Shape Participation in the ODS at 1440 RPM



Video

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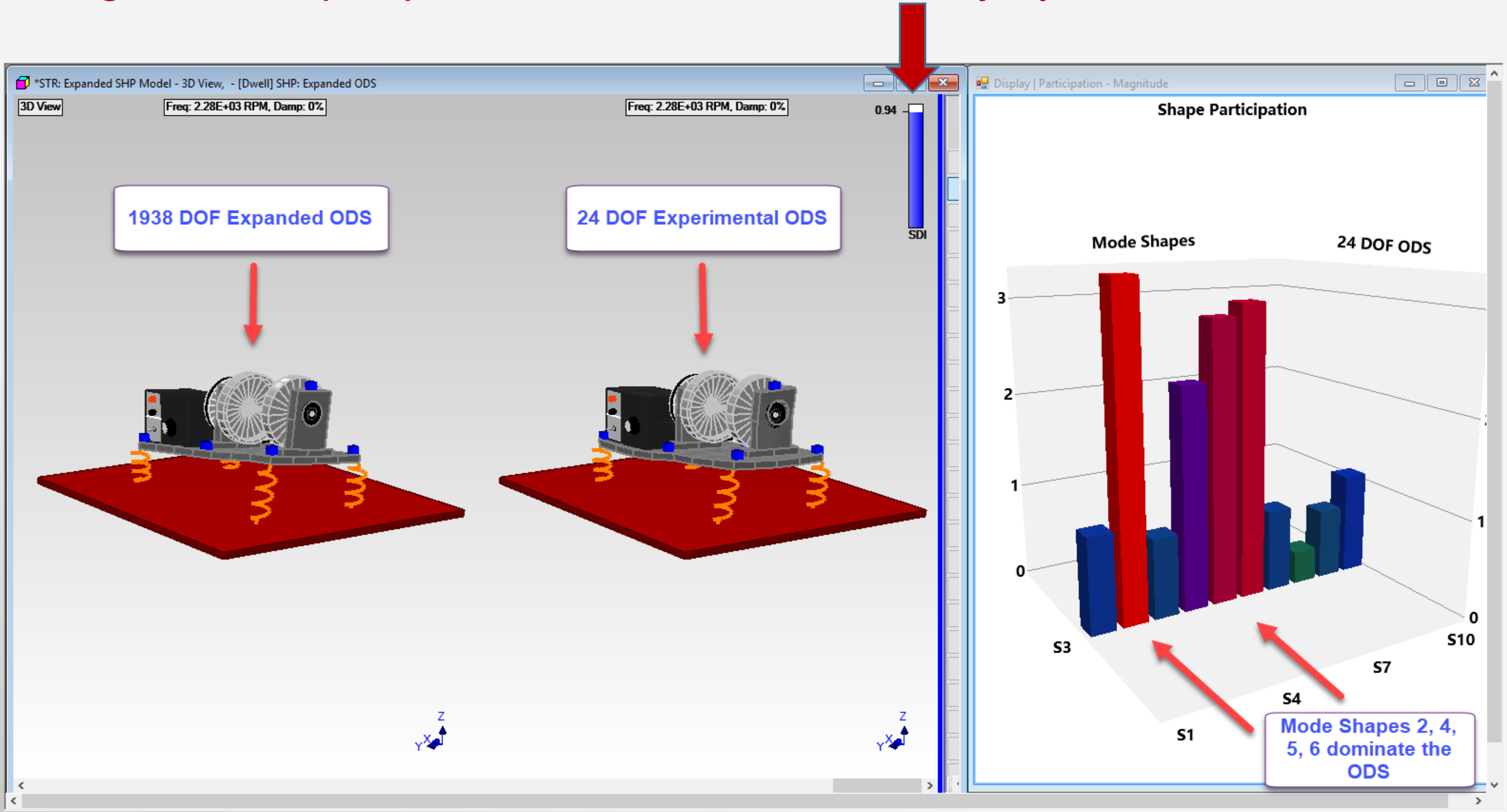
Mode Shape Participation in the ODS at 2280 RPM

The *high SDI value (0.94)* verifies that the *ODS is accurately represented* as a *summation of mode shapes*



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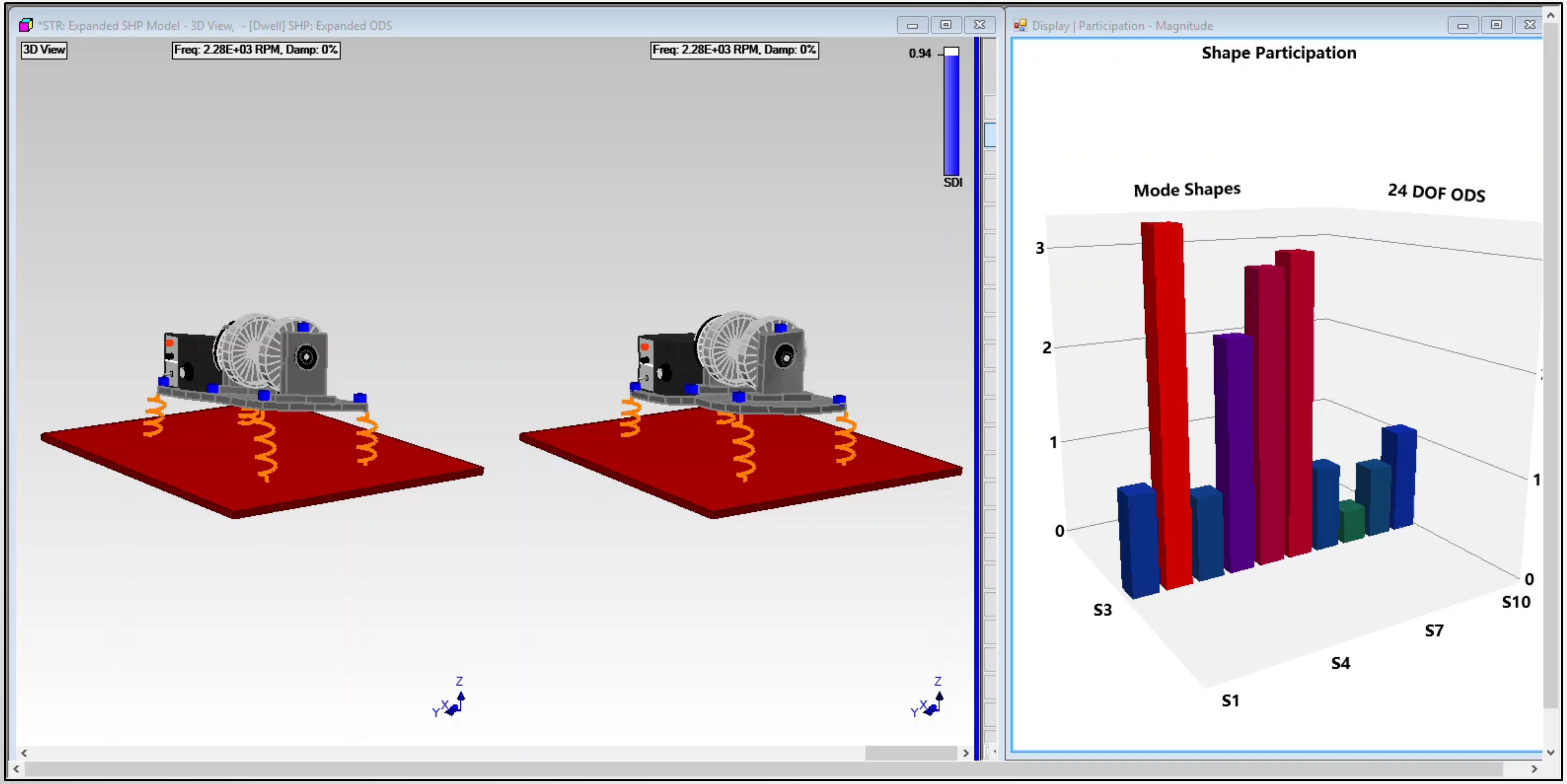
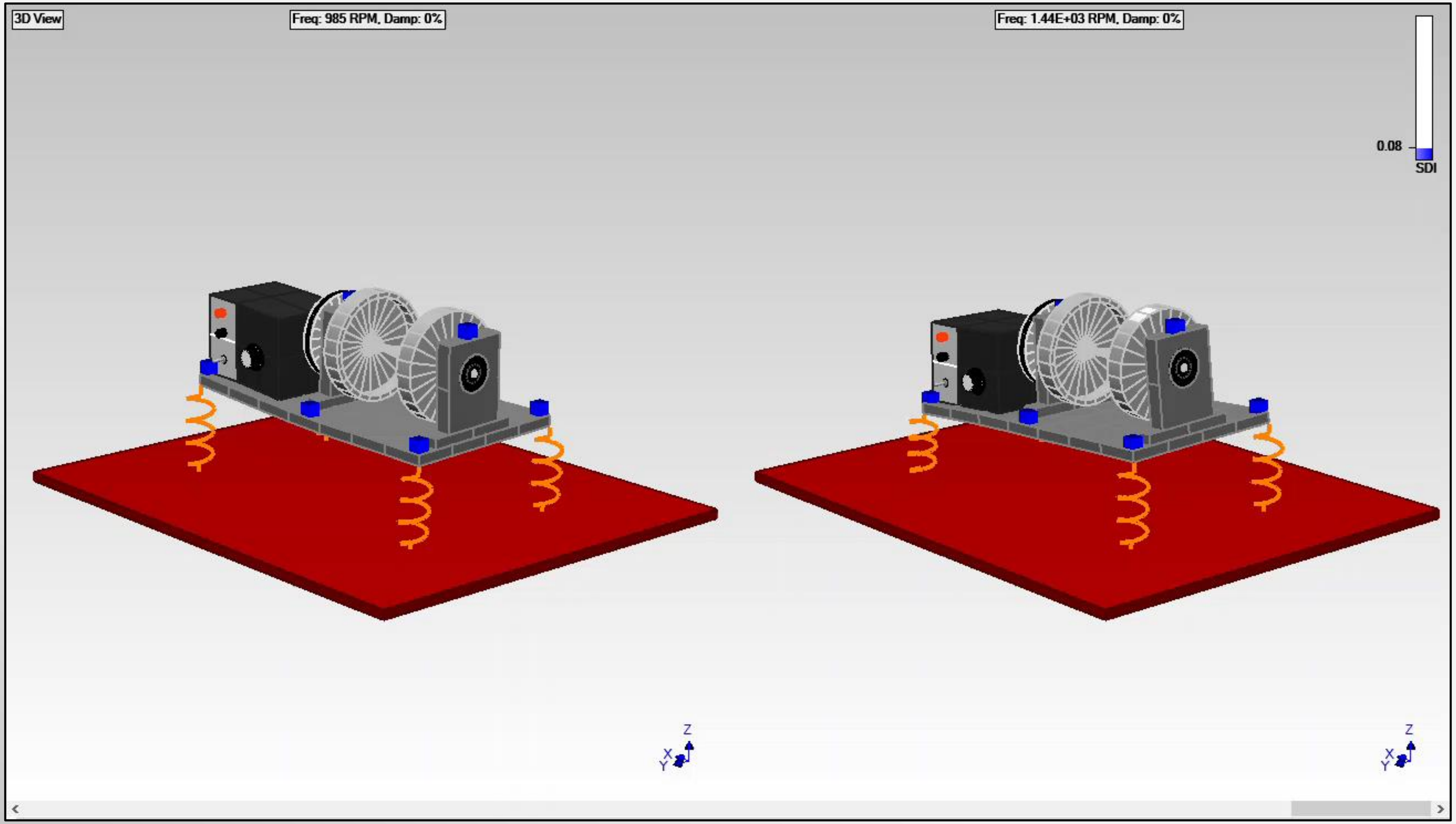
Mode Shape Participation in the ODS at 2280 RPM



Video

985 RPM versus 1440 RPM ODS

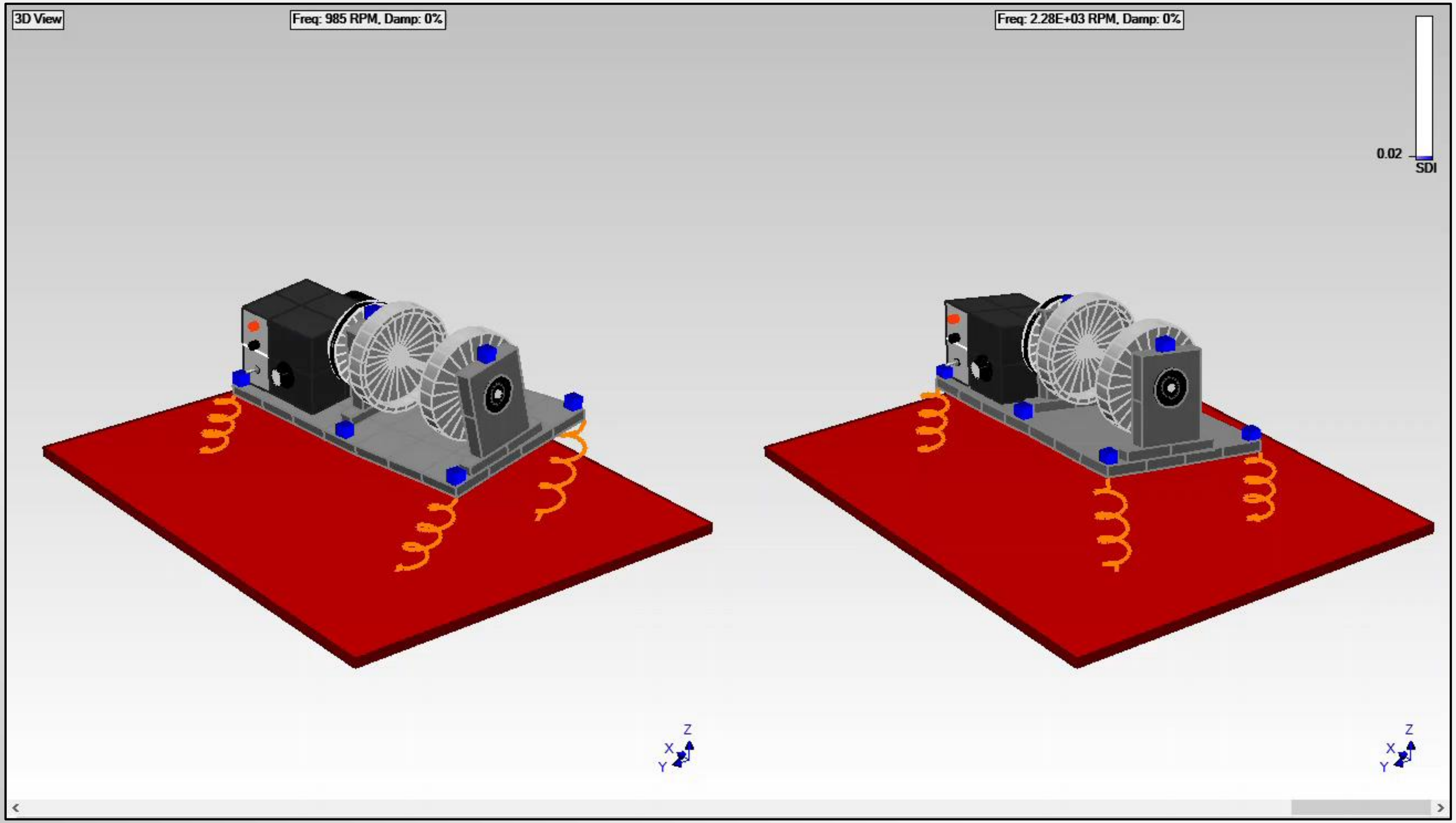
The *low SDI value (0.08)* indicates that these two Deflection Shapes are *very different*



Video

985 RPM & 2280 RPM ODS

The *low SDI value (.02)* indicates that these two Deflection Shapes are *very different*



Video

ODS’s versus Mode Shapes

ODS’s

1. ODS's are *defined at any frequency* or *at any time value*
2. If the *forces or loads change* on a structure, its *ODS’s change*
3. Each ODS is a *summation of mode shapes*

Mode Shapes

1. Mode shapes are *defined at specific natural frequencies*
2. If the *forces or loads change* on a structure, its mode shapes *don’t change*
3. EMA mode shapes are *extracted from ODS data*

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ODS's versus Mode Shapes

ODS's

4. ODS's ***have engineering units***
5. ODS's ***have unique values***
6. An ODS ***defines the actual motion*** of each DOF
7. ODS's change if the ***material properties*** or ***boundary conditions*** or ***excitation forces*** change

Mode Shapes

4. Mode shapes ***don't have engineering units***
5. Mode shapes ***don't have unique values***
6. A mode shape ***defines the relative motion*** between two DOFs
7. Mode shapes change if the ***material properties*** or ***boundary conditions*** change

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Summary

- All vibration is *caused by applied forces*
  - Forces *are measured* during an *impact or shaker modal test*
  - Forces *are not measured* during an *ODS test* of an operating machine
- All modes *participate in all vibration*
  - First Law of Modal Analysis (1st LoMA): *Any object with mass & elasticity will vibrate*
  - Second Law of Modal Analysis (2nd LoMA): *Forces cause vibration*
  - Third Law of Modal Analysis (3rd LoMA): *All vibration* is *a summation of mode shapes*
  - Fourth Law of Modal Analysis (4th LoMA): *All modes* are *excited at all frequencies*