Rapid Impact™ Testing of Any Size Structure

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Topics of this Presentation

- ***Limitations of Single Reference Modal Testing***
- ***Simulated Rapid Impact™ Test***
- ***Modal Residues => Mode Shapes***

- **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***

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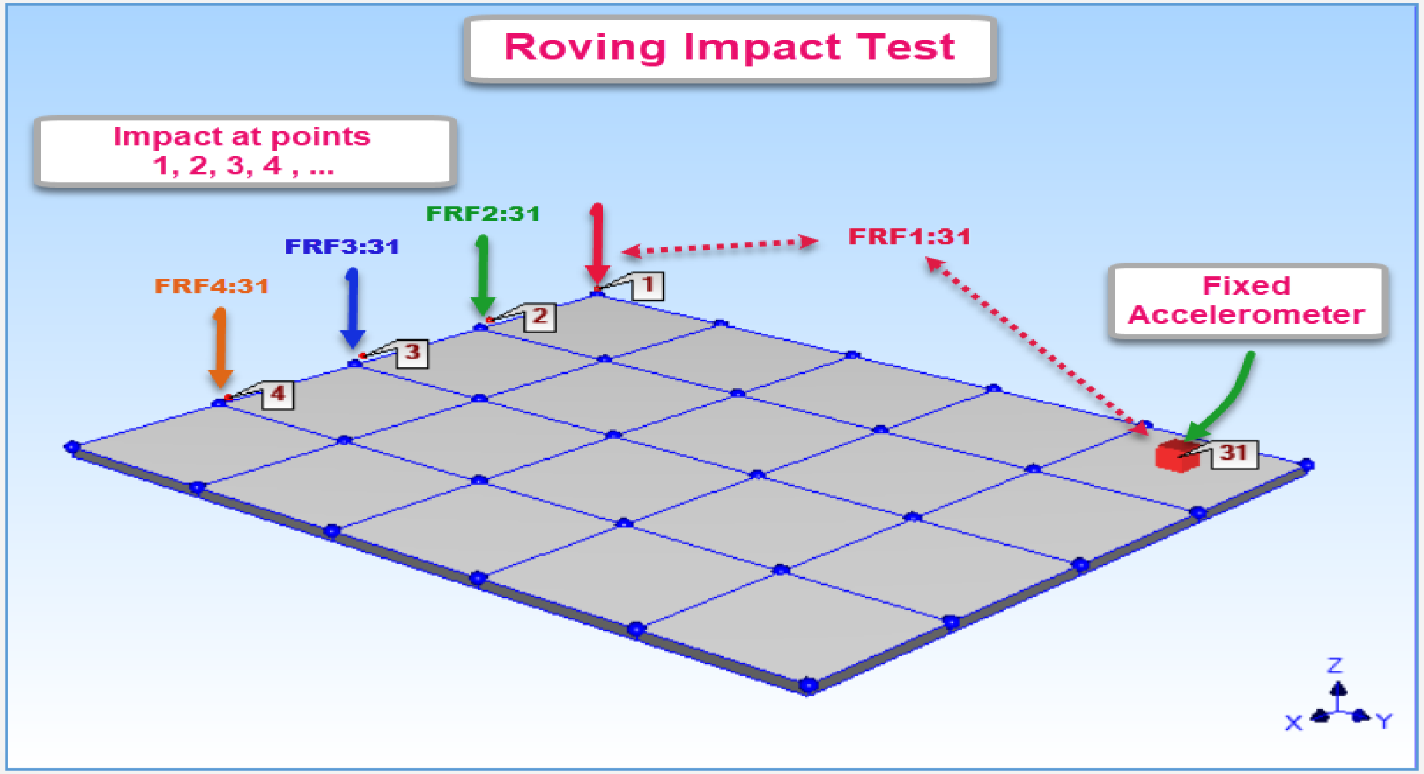
Modal Parameters from a Roving Impact Test

Modal parameters are extracted by *curve fitting a set of FRFs* calculated from a roving impact test

- **Limitation #1:** Mode shape points & directions (DOFs) are defined by the *impact points & directions (DOFs)*
- **Limitation #2:** The response sensor *must remain fixed* throughout the test
- **Limitation #3:** To test a large structure, a *long wire is required* to connect either the response sensor or the instrumented impactor to the acquisition front end
- **Limitation #4:** If an impact is applied *at a long distance* from the response sensor, a *weak or un-useable response might result*



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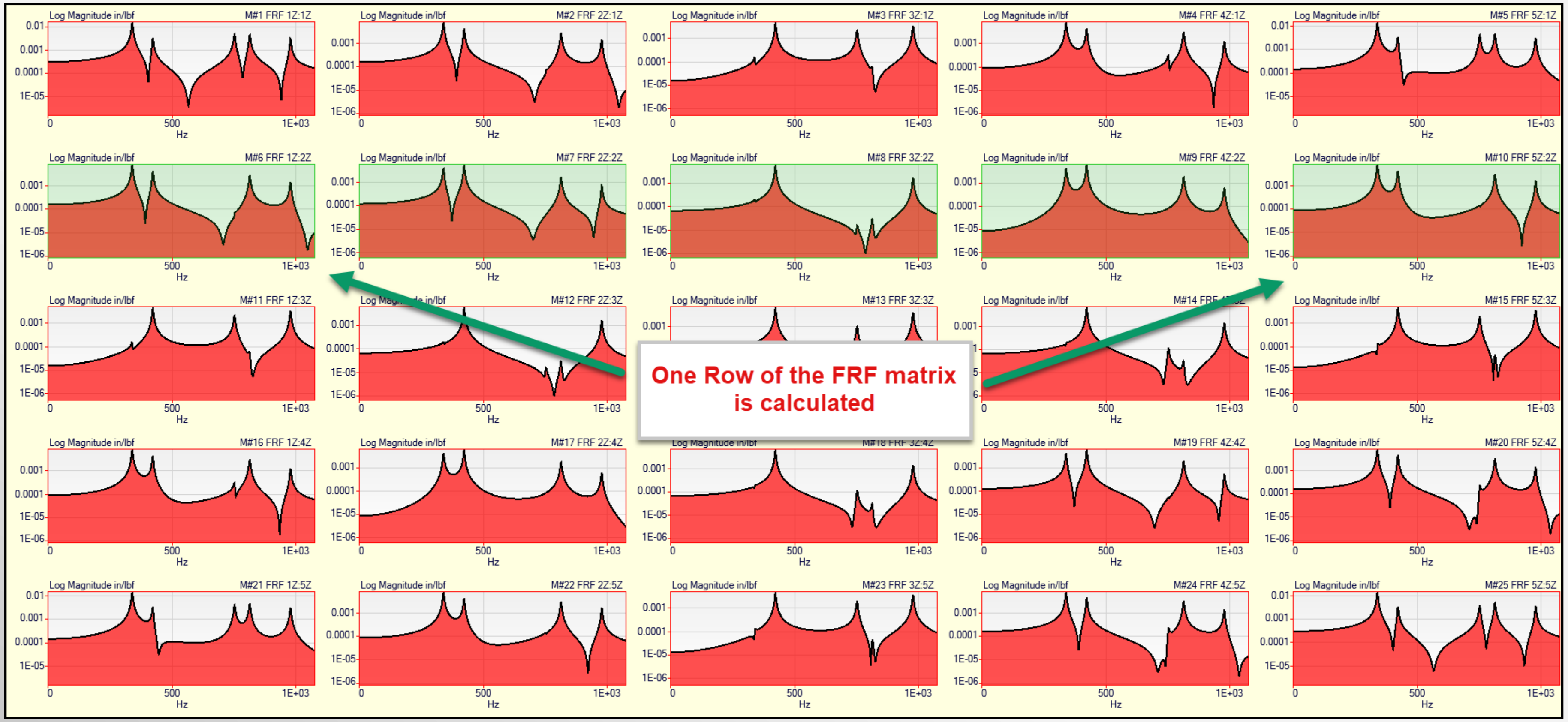
FRFs From a Roving Impact Test

- **Single-reference test:** ***One row*** **of the FRF matrix is calculated from** ***multiple Impact DOFs*** **and** ***one Response DOF***
- **Multi-reference test:** ***Multiple rows*** **of the FRF matrix are calculated from** ***multiple Impact DOFs*** **and** ***multiple Response DOFs***



Single response

Symmetric FRF matrix

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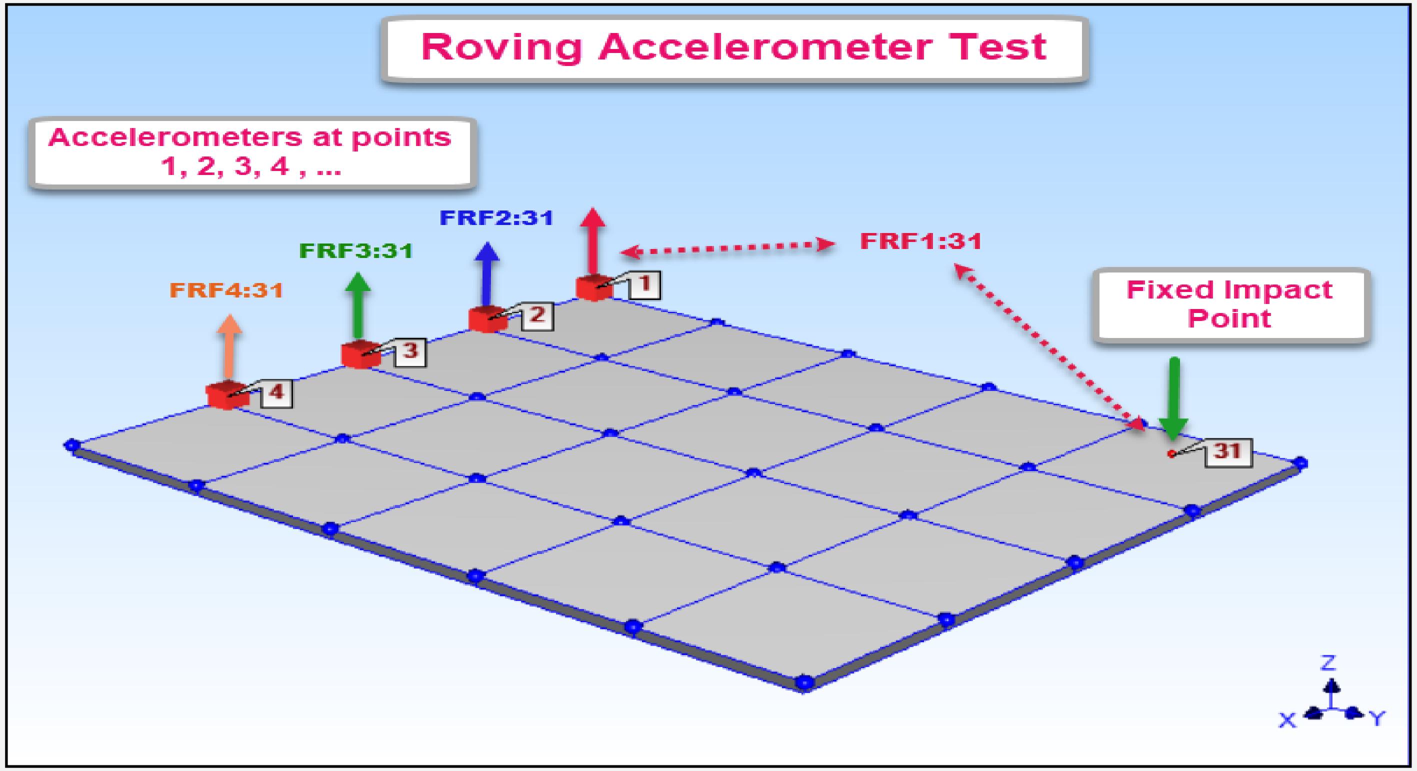
Modal Parameters From a Roving Response Test

Modal parameters are extracted by *curve fitting a set of FRFs* calculated from a roving response test

- **Limitation #1:** Mode shape points & directions (DOFs) are defined by the ***response sensor points & directions (DOFs)***
- **Limitation #2:** The impact DOF ***must remain fixed*** throughout the test
- **Limitation #3:** To test a large structure, a ***long wire is required*** to connect either the response sensor or the instrumented impactor to the acquisition front end
- **Limitation #4:** If an impact is applied ***at a long distance*** from the response sensor, a ***weak or un-useable response might result***



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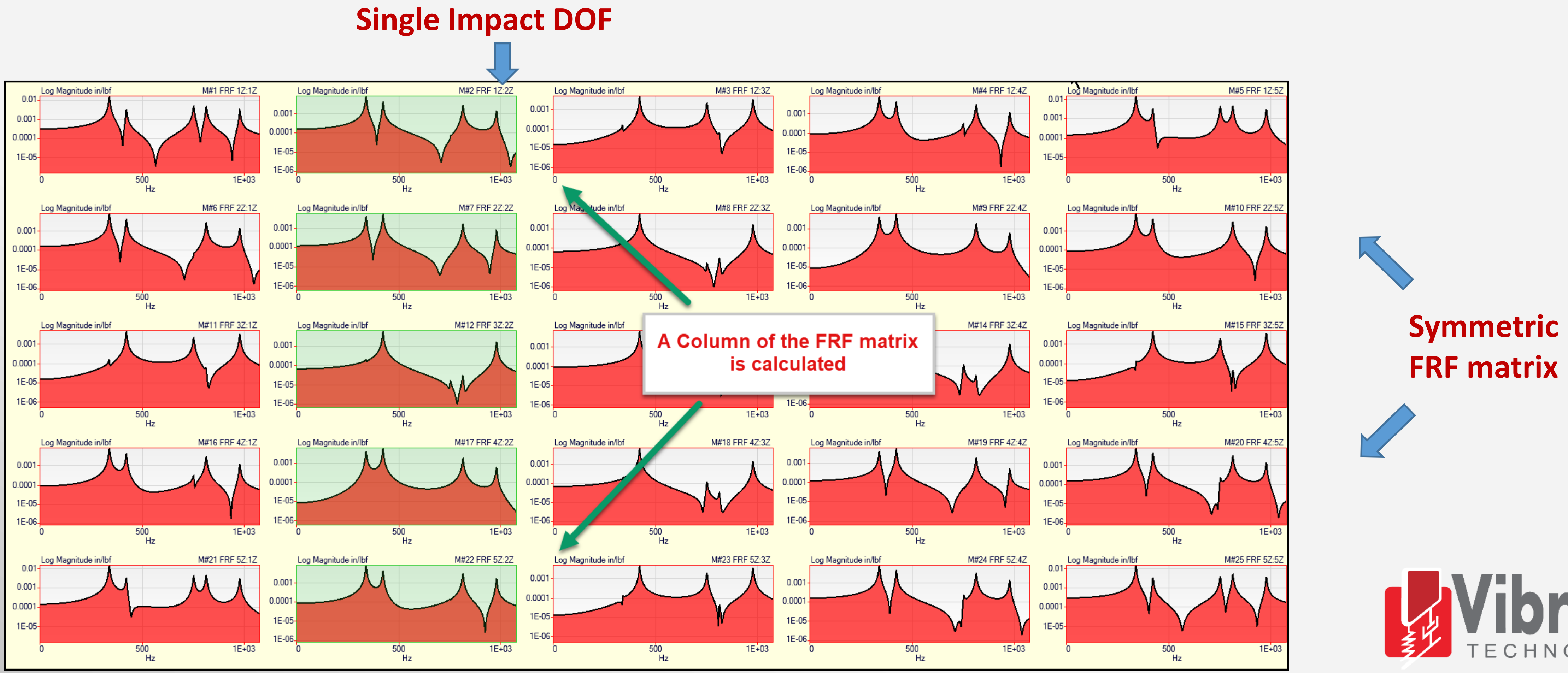
FRFs From a Roving Response Test

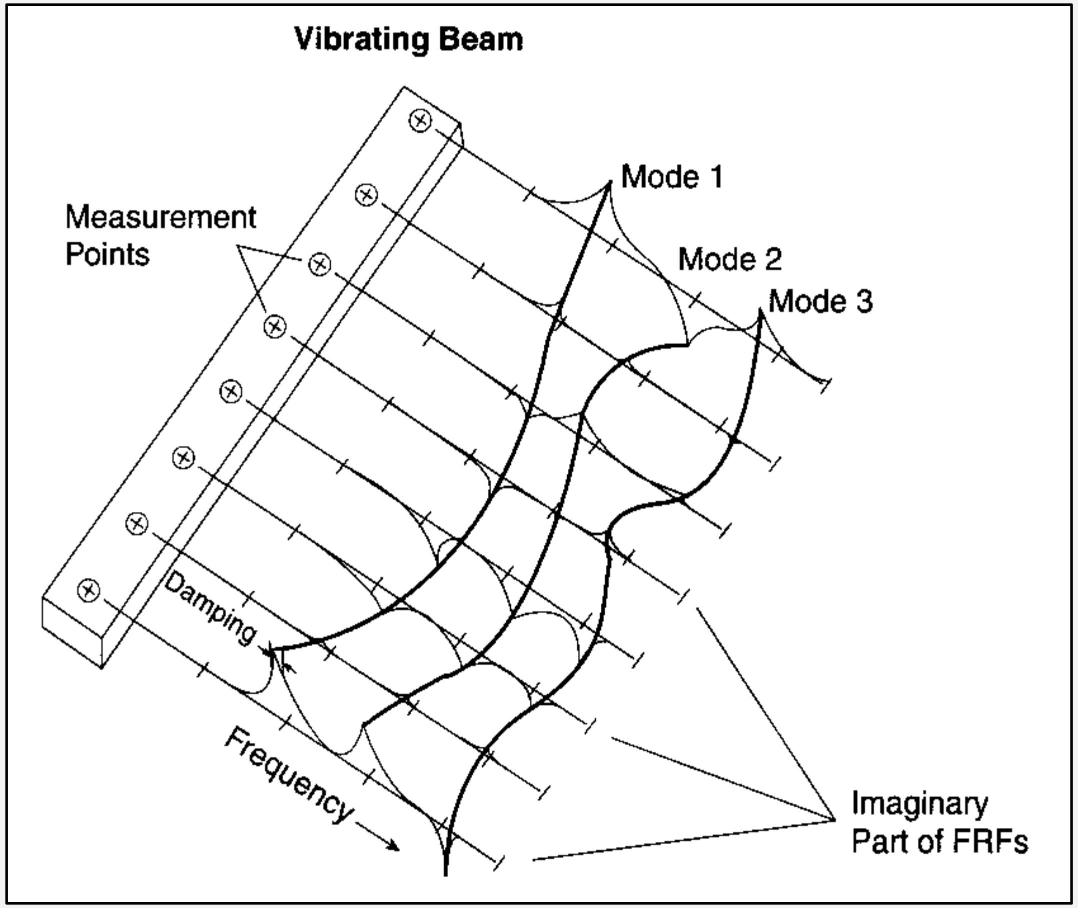
- **Single-reference test: *One column* of the FRF matrix is calculated from *one Impact DOF* and *multiple Response DOFs***
- **Multi-reference test: *Multiple columns* of the FRF matrix are calculated from *multiple Impact DOFs* and *multiple Response DOFs***



Modal Parameters From FRFs

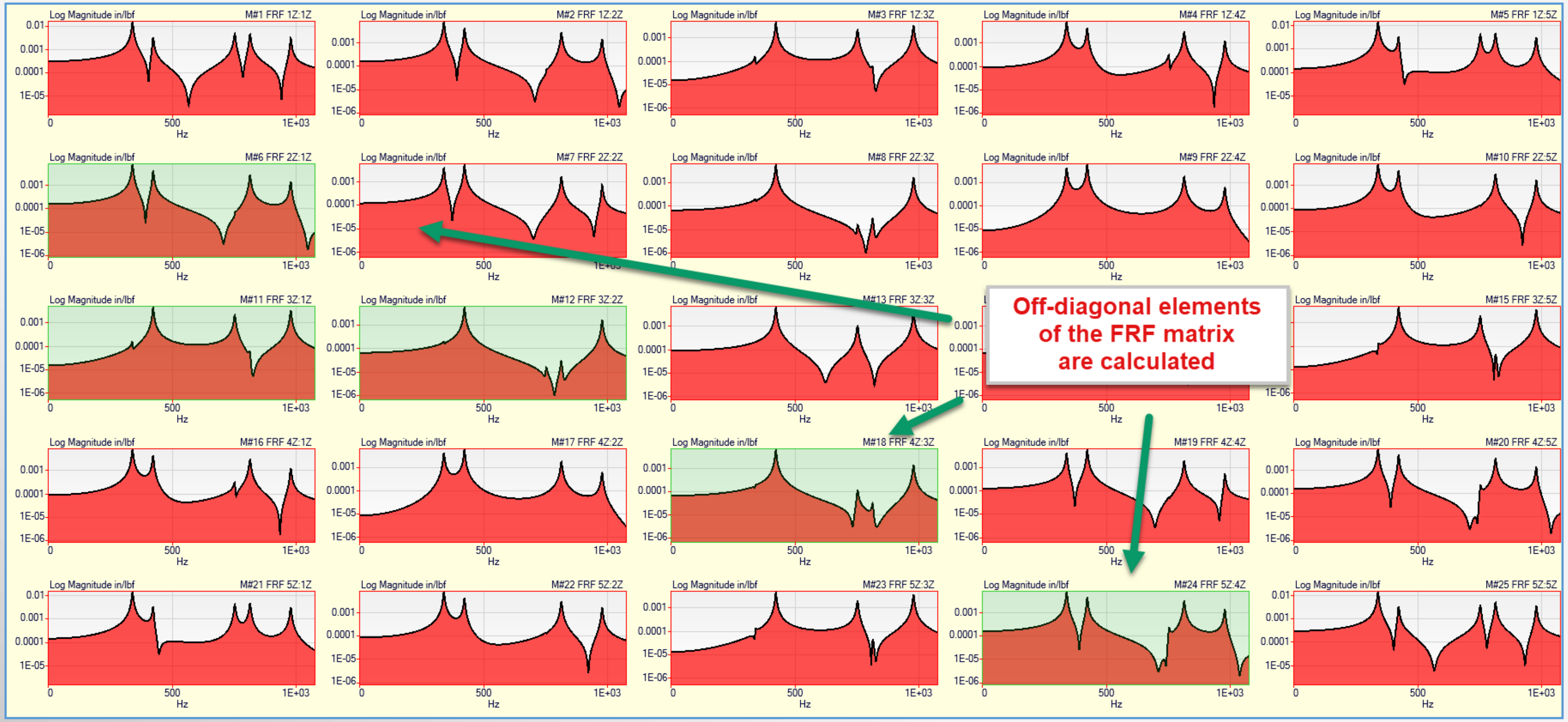
Each mode is *defined with three parameters*

- **Modal frequency**
  - *frequency* of its resonance peak
- **Modal damping**
  - *width* of its resonance peak
    (half power point, 3dB width)
- **Mode shape**
  - *magnitude & phase* of each resonance
    peak at the same frequency



Rapid Impact™ Test

The *impact DOFs* and *response sensor DOFs* can *change between measurements*



Symmetric FRF matrix

Multi-Reference Roving Response Impact Test

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Multi-Reference Roving Response Impact Test

- The grating was *impacted in the X, Y, Z directions* at one corner (Point 1)
- *Tri-axial accelerometers* were attached to 64 points on the grating
- Data was acquired in *multiple Measurement Sets*

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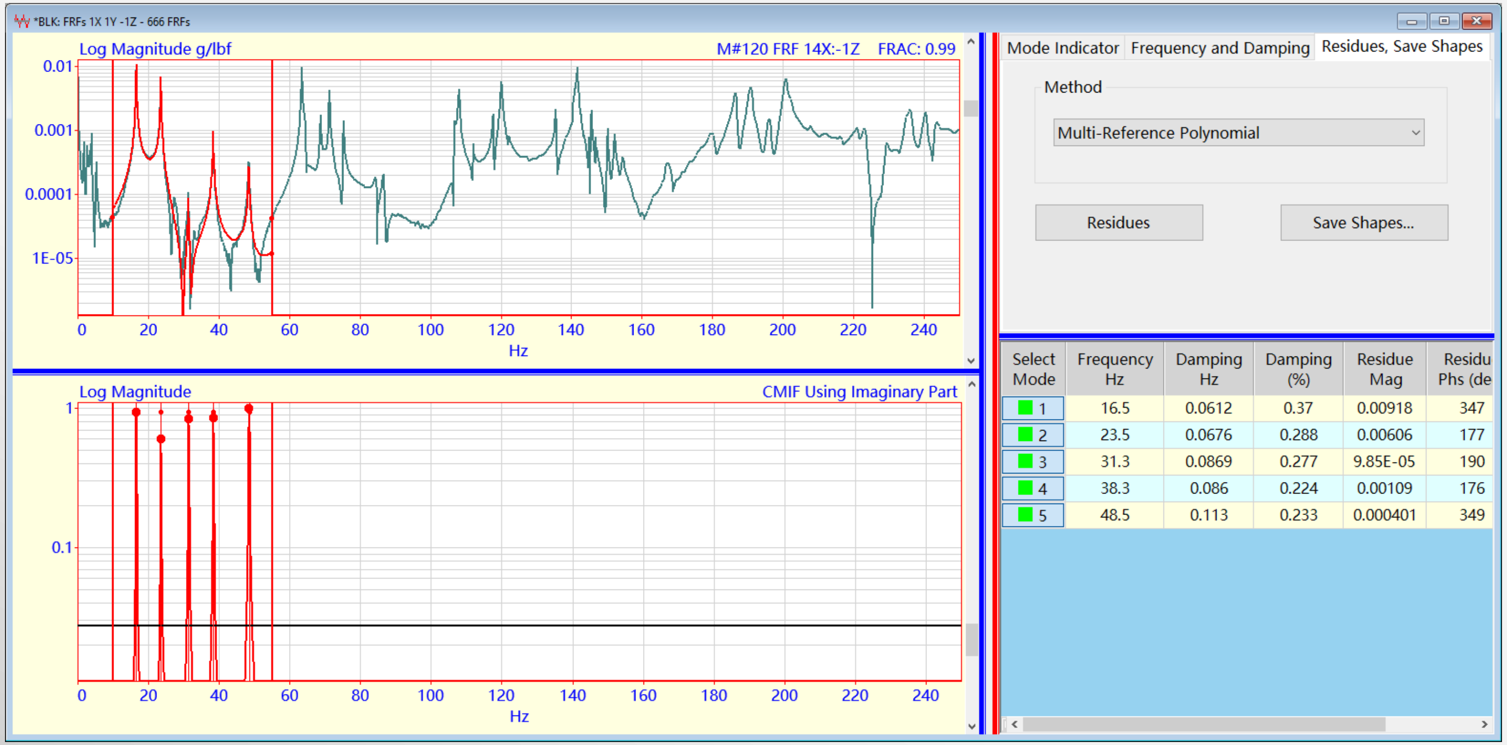
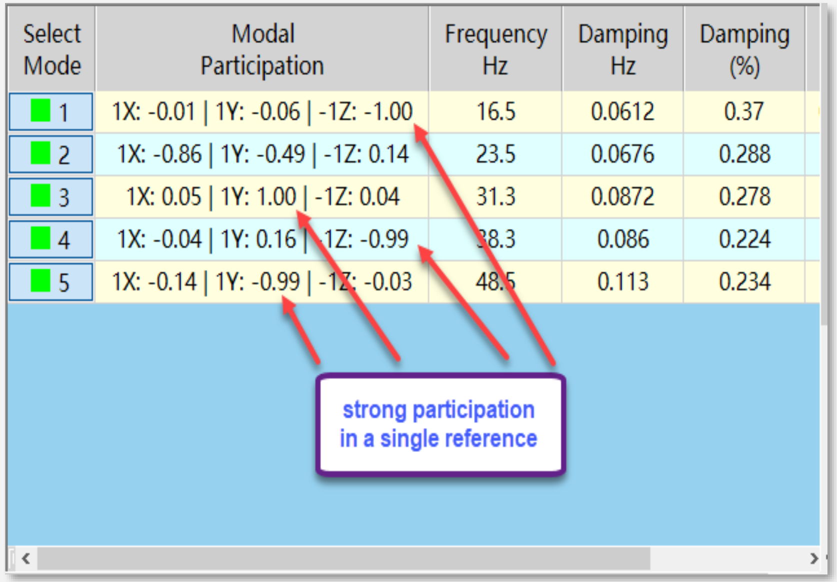
Mode Shapes of the Grating

Five mode shapes were extracted from 576 FRFs ***(64 points x 3 directions x 3 references)*** **using** ***multi-reference curve fitting***



Select Mode	Frequency Hz	Damping Hz	Damping (%)	Residue Mag	Residu Phs (de
1	16.5	0.0612	0.37	0.00918	347
2	23.5	0.0676	0.288	0.00606	177
3	31.3	0.0869	0.277	9.85E-05	190
4	38.3	0.086	0.224	0.00109	176
5	48.5	0.113	0.233	0.000401	349



Select Mode	Modal Participation	Frequency Hz	Damping Hz	Damping (%)
1	1X: -0.01 | 1Y: -0.06 | -1Z: -1.00	16.5	0.0612	0.37
2	1X: -0.86 | 1Y: -0.49 | -1Z: 0.14	23.5	0.0676	0.288
3	1X: 0.05 | 1Y: 1.00 | -1Z: 0.04	31.3	0.0872	0.278
4	1X: -0.04 | 1Y: 0.16 | -1Z: -0.99	38.3	0.086	0.224
5	1X: -0.14 | 1Y: -0.99 | -1Z: -0.03	48.5	0.113	0.234

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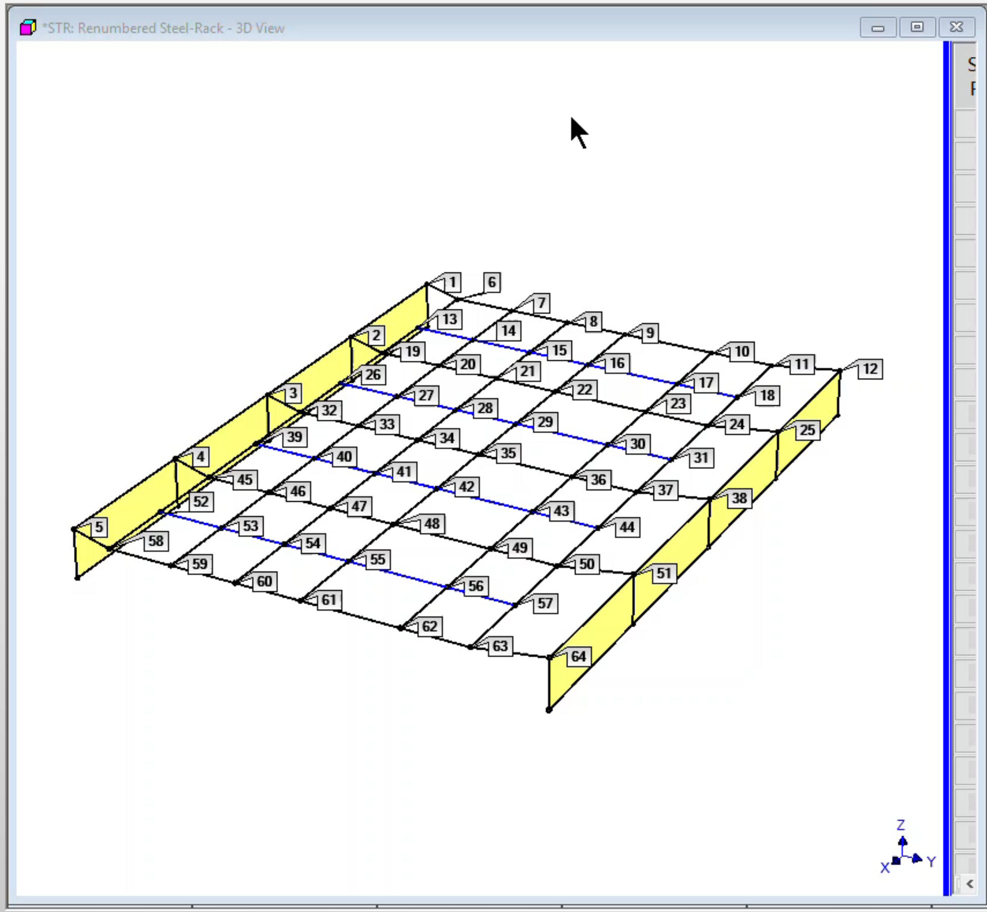
Mode Shapes of the Grating

Each mode shape *participates differently* in each direction of the dynamics



*SHP: Renumbered UMM Mode Shapes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)	Modal Participation
1	16.5	0.061	Hz	0.369	1X: -0.01 | 1Y: -0.06 | -1Z: -1.00
2	23.5	0.0675	Hz	0.287	1X: -0.86 | 1Y: -0.49 | -1Z: 0.14
3	31.3	0.0865	Hz	0.276	1X: 0.05 | 1Y: 1.00 | -1Z: 0.04
4	38.3	0.0858	Hz	0.224	1X: -0.04 | 1Y: 0.16 | -1Z: -0.99
5	48.5	0.113	Hz	0.233	1X: -0.14 | 1Y: -0.99 | -1Z: -0.03

Select M#	DOFs	Units	Measurement Type	Shape 1 Magnitude	Shape 1 Phase
M#15	5Z	in/lbf-sec	UMM Mode Shape	0.57	174
M#16	6X	in/lbf-sec	UMM Mode Shape	0.0544	172
M#17	6Y	in/lbf-sec	UMM Mode Shape	0.0603	352
M#18	6Z	in/lbf-sec	UMM Mode Shape	0.793	352
M#19	7X	in/lbf-sec	UMM Mode Shape	0.013	355
M#20	7Y	in/lbf-sec	UMM Mode Shape	0.0684	354
M#21	7Z	in/lbf-sec	UMM Mode Shape	0.54	354
M#22	8X	in/lbf-sec	UMM Mode Shape	0.0269	172
M#23	8Y	in/lbf-sec	UMM Mode Shape	0.0647	352
M#24	8Z	in/lbf-sec	UMM Mode Shape	0.259	352
M#25	9X	in/lbf-sec	UMM Mode Shape	0.00015	189
M#26	9Y	in/lbf-sec	UMM Mode Shape	0.0632	1.9
M#27	9Z	in/lbf-sec	UMM Mode Shape	0.0136	2.47
M#28	10X	in/lbf-sec	UMM Mode Shape	0.0301	189
M#29	10Y	in/lbf-sec	UMM Mode Shape	0.0653	9.05

Video

Modal Participation has values between 0 & + or - 1

Participation = + or - 1
➔ *dominant motion*

Participation << + or - 1
➔ *no motion*

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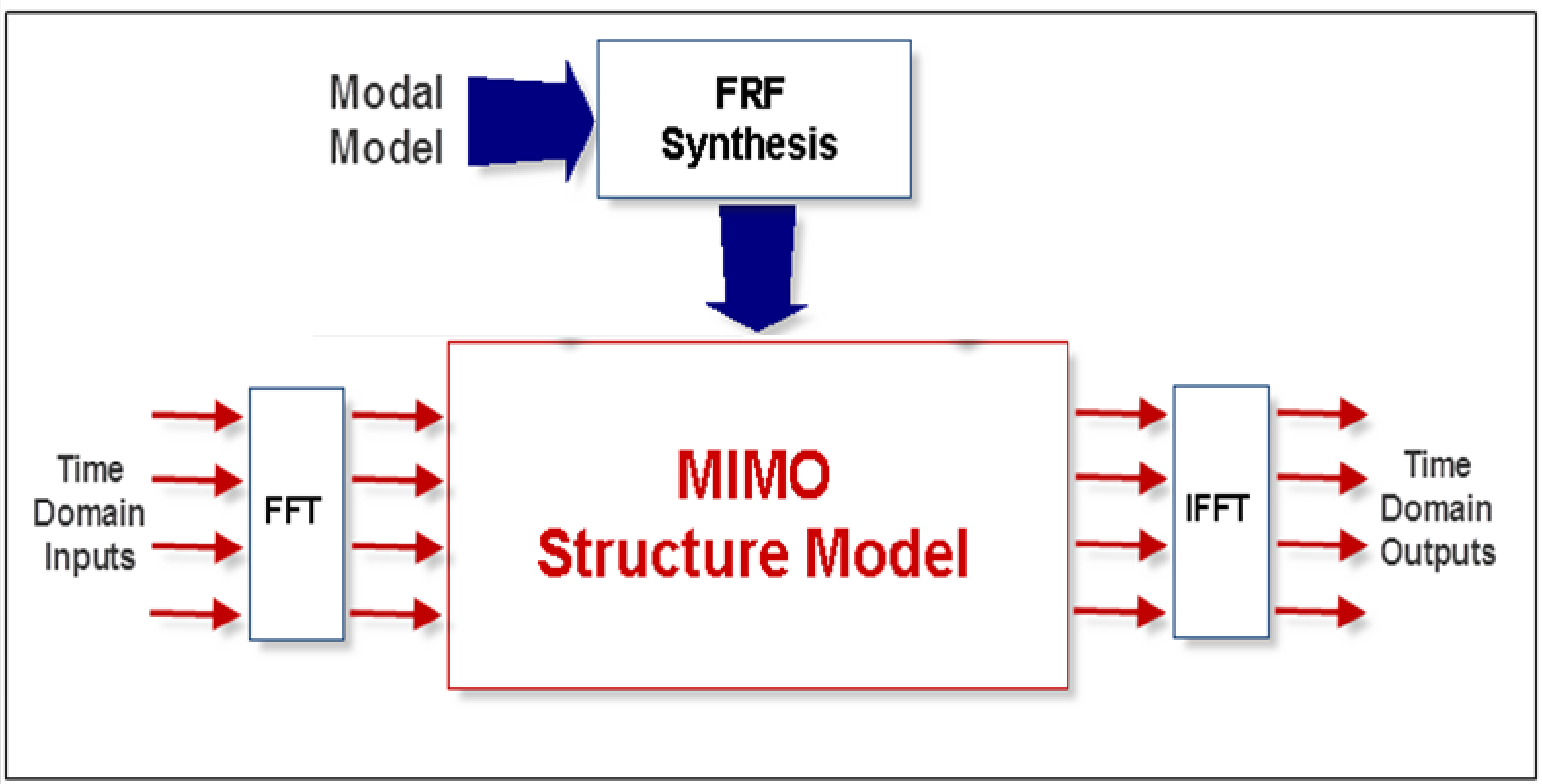
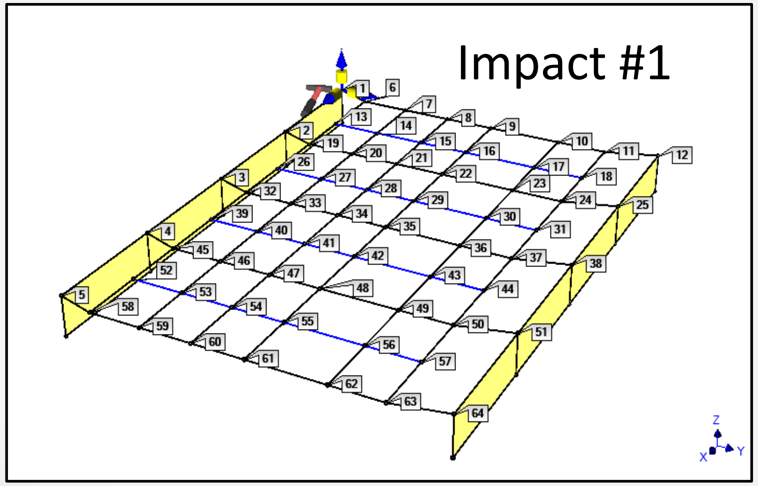
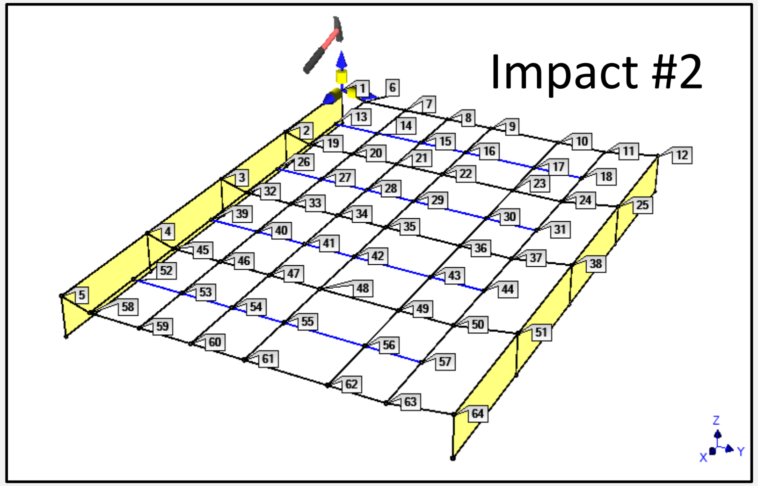
Multi-Input Multi-Output (MIMO) Simulation

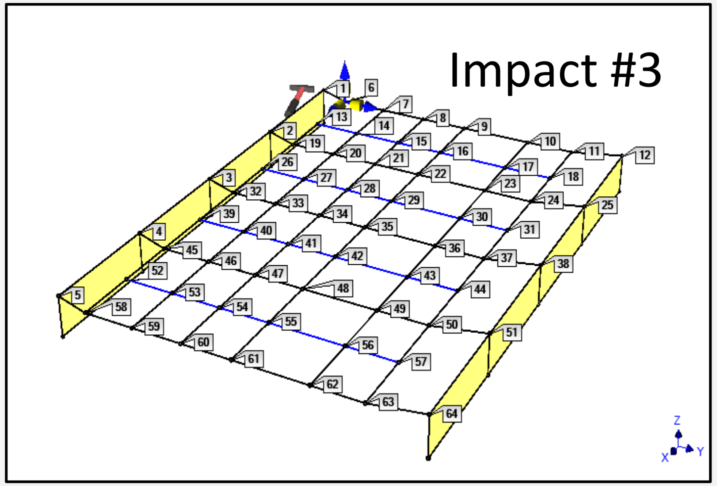
- **Third Law of Modal Analysis (3rd LoMA)**: ***All vibration is a summation of mode shapes***
- ***A modal model* with *five flexible modes* was used to *model the dynamics* of the grating**

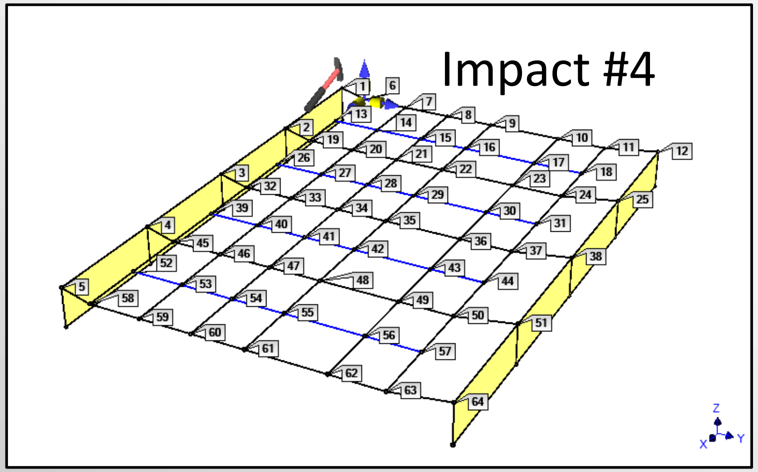


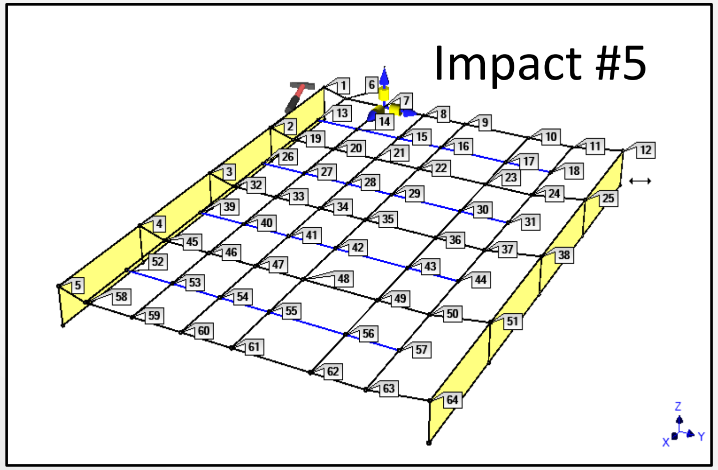
First Six Impacts of Simulated Rapid Impact™

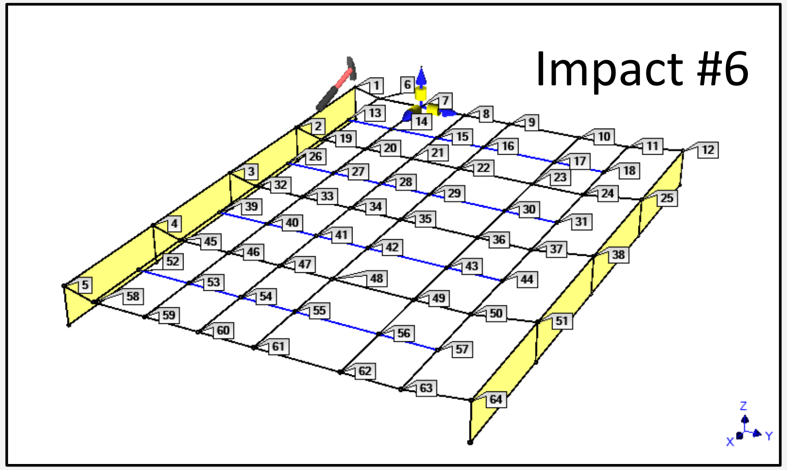




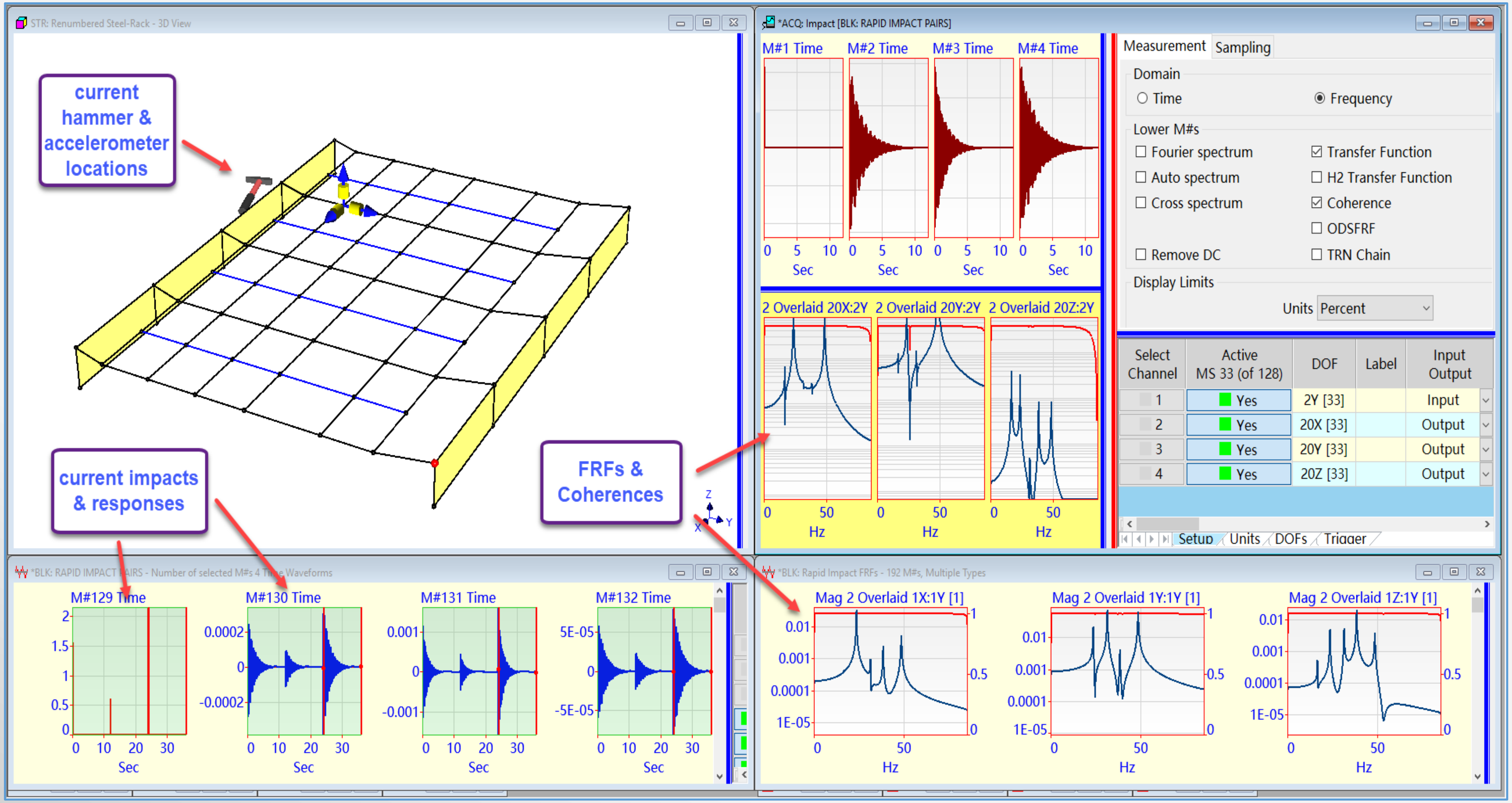








Rapid Impact™ Test FRF & Coherence Calculation



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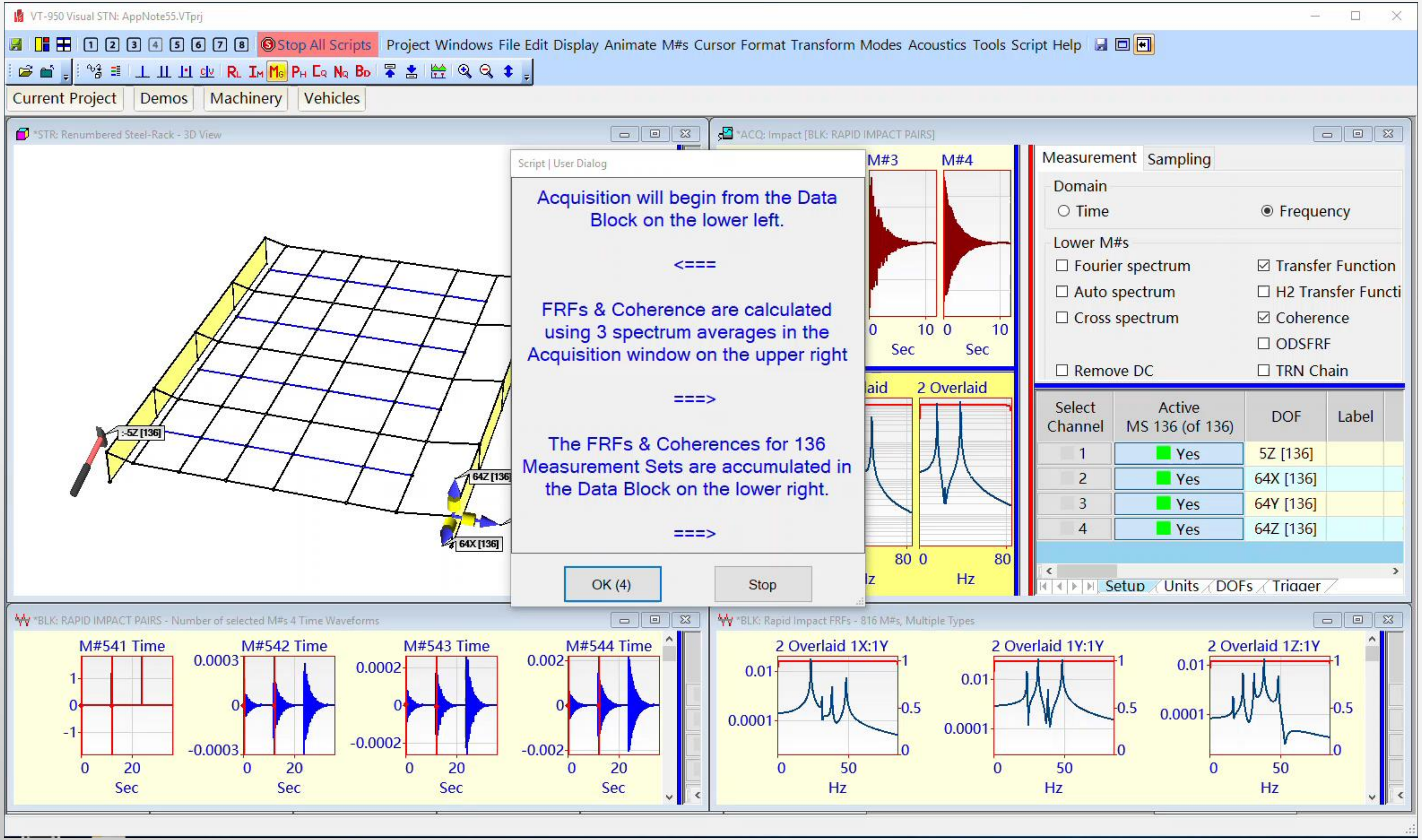
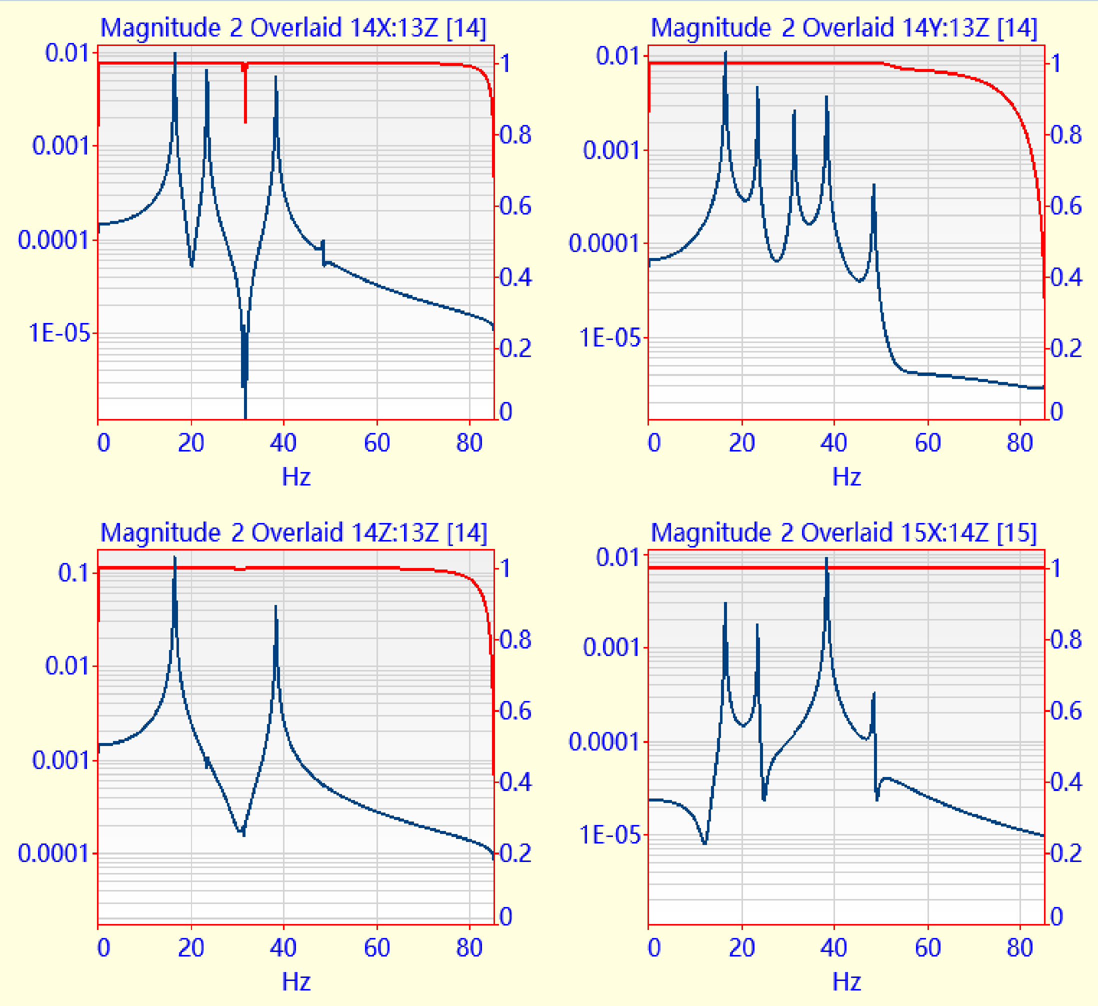
Rapid Impact™ Test FRF & Coherence Calculation



Video

Rapid Impact™ Test FRFs & Coherence

*BLK: Rapid Test FRFs - 384 M#s, Multiple Types



Select M#	Visible	DOFs	Units	Measurement Type
M#22	Yes	4X:3Z [4]		Coherence
M#23	Yes	4Y:3Z [4]		Coherence
M#24	Yes	4Z:3Z [4]		Coherence
M#25	Yes	5X:4Z [5]	g/lbf	FRF
M#26	Yes	5Y:4Z [5]	g/lbf	FRF
M#27	Yes	5Z:4Z [5]	g/lbf	FRF
M#28	Yes	5X:4Z [5]		Coherence
M#29	Yes	5Y:4Z [5]		Coherence
M#30	Yes	5Z:4Z [5]		Coherence
M#31	Yes	6X:5Z [6]	g/lbf	FRF
M#32	Yes	6Y:5Z [6]	g/lbf	FRF
M#33	Yes	6Z:5Z [6]	g/lbf	FRF
M#34	Yes	6X:5Z [6]		Coherence
M#35	Yes	6Y:5Z [6]		Coherence
M#36	Yes	6Z:5Z [6]		Coherence
M#37	Yes	7X:6Z [7]	g/lbf	FRF
M#38	Yes	7Y:6Z [7]	g/lbf	FRF
M#39	Yes	7Z:6Z [7]	g/lbf	FRF
M#40	Yes	7X:6Z [7]		Coherence
M#41	Yes	7Y:6Z [7]		Coherence
M#42	Yes	7Z:6Z [7]		Coherence

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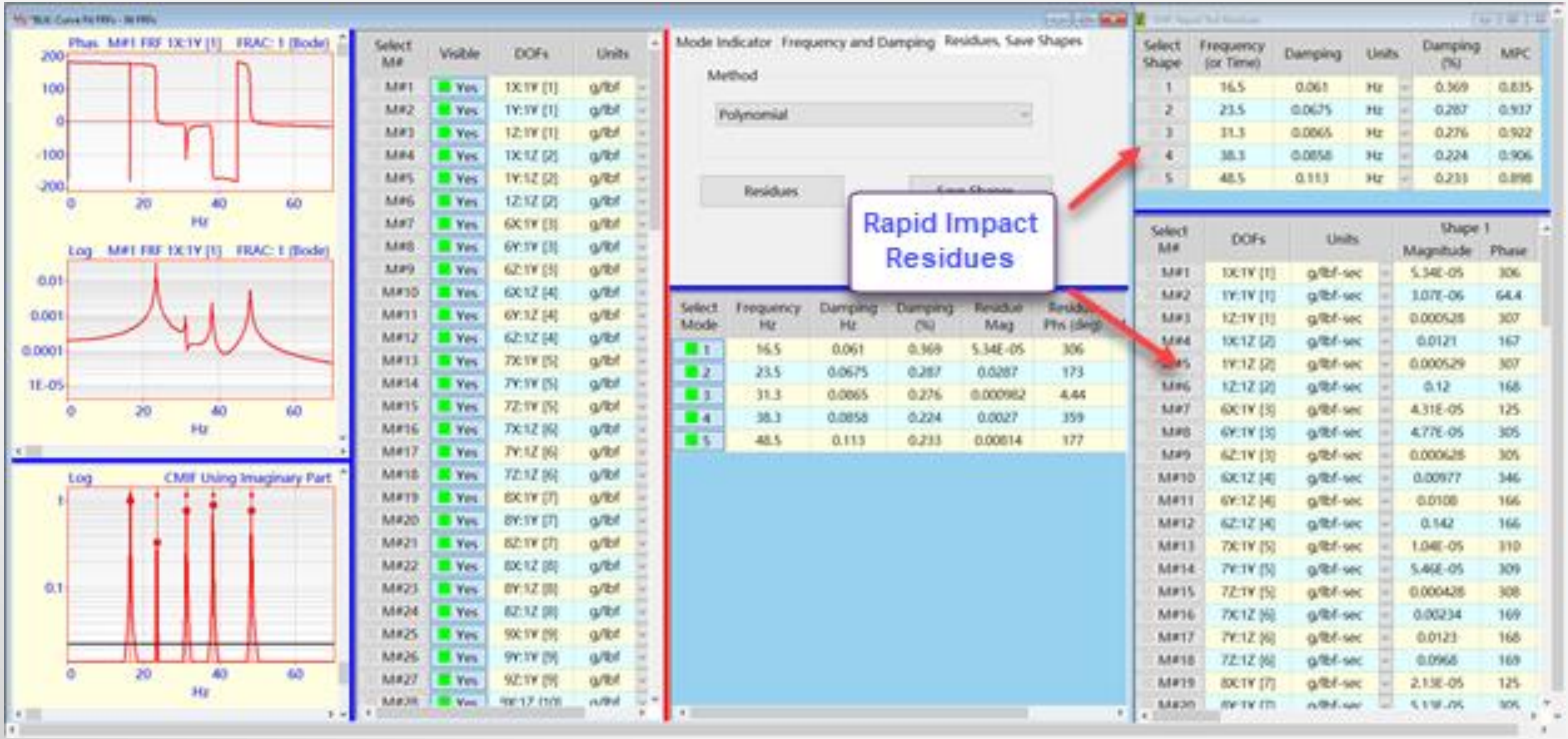
Quick Fit of Rapid Impact™ FRFs



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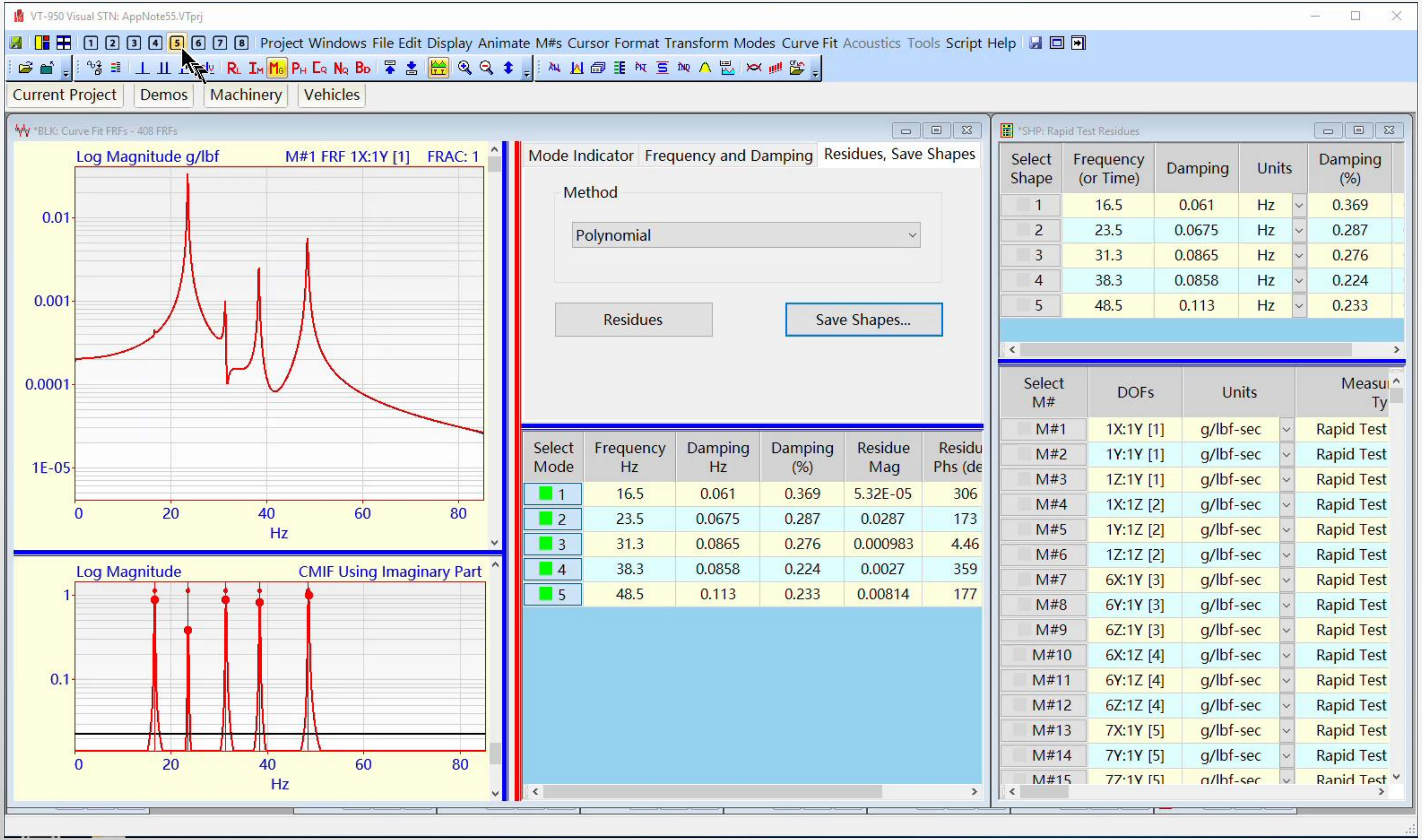
Quick Fit of Rapid Impact™ FRFs



Video

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Modal Residues ➔ Mode Shape

Each modal residue is the *product of two mode shape components*

Residues versus Mode Shape Components

$$\text{Residues} = \begin{Bmatrix} RES(1:2) \\ RES(1:3) \\ RES(2:3) \end{Bmatrix} \qquad \text{Mode Shape} = \begin{Bmatrix} MSC(1) \\ MSC(2) \\ MSC(3) \end{Bmatrix}$$

RES(1:1) = MSC(1) x MSC(1)

RES(1:2) = MSC(1) x MSC(2)

RES(1:3) = MSC(1) x MSC(3)

RES(2:3) = MSC(2) x MSC(3)

Single-Reference Modal Test

$$\text{Residue Mode Shape} = \begin{Bmatrix} RES(1:1) \\ RES(2:1) \\ RES(3:1) \end{Bmatrix} = \begin{Bmatrix} MSC(1) \text{ x } MSC(1) \\ MSC(2) \text{ x } MSC(1) \\ MSC(3) \text{ x } MSC(1) \end{Bmatrix}$$

Converting Rapid Test Residues to a Mode Shape

Starting with a Driving Point Residue

$$MSC(1) = \sqrt{RES(1:1)} = \sqrt{MSC(1) \text{ x } MSC(1)}$$

MSC(2) = RES(1:2) / MSC(1)

MSC(3) = RES(1:3) / MSC(1)

MSC(3) = RES(2:3) / MSC(2)

MSC(4) = RES(3:4) / MSC(3) = RES(4:3) / MSC(3)

Starting with Triangle Point Residues

$$MSC(1) = \sqrt{\frac{RES(1:2) \text{ x } RES(1:3)}{RES(2:3)}}$$

$$= \sqrt{\frac{MSC(1) \text{ x } MSC(2) \text{ x } MSC(1) \text{ x } MSC(3)}{MSC(2) \text{ x } MSC(3)}}$$

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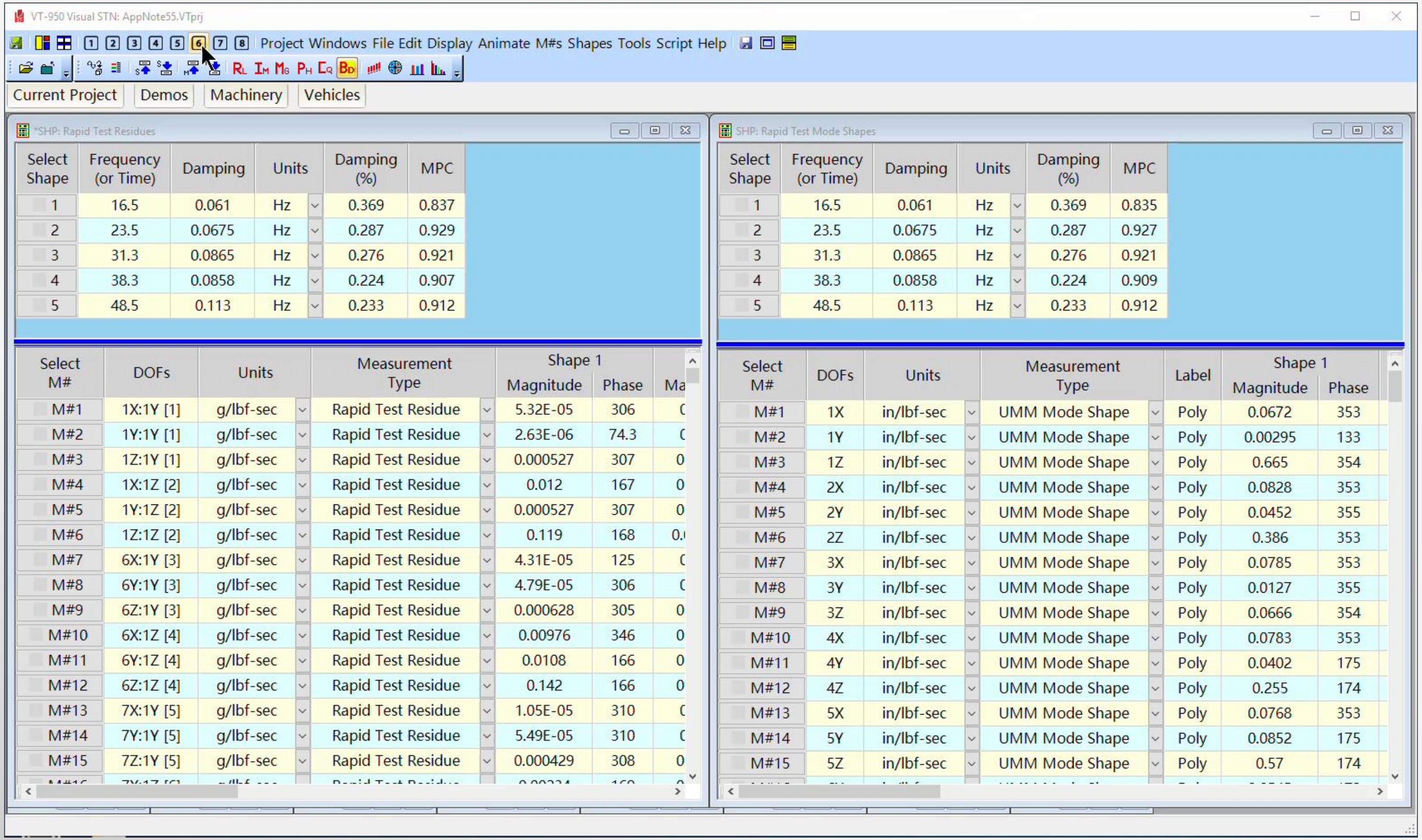
Modal Residues ➔ Mode Shape

Each modal residue is the *product of two mode shape components*



*SHP: Rapid Test Residues

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)	MPC
1	16.5	0.061	Hz	0.369	0.837
2	23.5	0.0675	Hz	0.287	0.929
3	31.3	0.0865	Hz	0.276	0.921
4	38.3	0.0858	Hz	0.224	0.907
5	48.5	0.113	Hz	0.233	0.912

Select M#	DOFs	Units	Measurement Type	Shape 1 Magnitude	Shape 1 Phase
M#1	1X:1Y [1]	g/lbf-sec	Rapid Test Residue	5.32E-05	306
M#2	1Y:1Y [1]	g/lbf-sec	Rapid Test Residue	2.63E-06	74.3
M#3	1Z:1Y [1]	g/lbf-sec	Rapid Test Residue	0.000527	307
M#4	1X:1Z [2]	g/lbf-sec	Rapid Test Residue	0.012	167
M#5	1Y:1Z [2]	g/lbf-sec	Rapid Test Residue	0.000527	307
M#6	1Z:1Z [2]	g/lbf-sec	Rapid Test Residue	0.119	168
M#7	6X:1Y [3]	g/lbf-sec	Rapid Test Residue	4.31E-05	125
M#8	6Y:1Y [3]	g/lbf-sec	Rapid Test Residue	4.79E-05	306
M#9	6Z:1Y [3]	g/lbf-sec	Rapid Test Residue	0.000628	305
M#10	6X:1Z [4]	g/lbf-sec	Rapid Test Residue	0.00976	346
M#11	6Y:1Z [4]	g/lbf-sec	Rapid Test Residue	0.0108	166
M#12	6Z:1Z [4]	g/lbf-sec	Rapid Test Residue	0.142	166
M#13	7X:1Y [5]	g/lbf-sec	Rapid Test Residue	1.05E-05	310
M#14	7Y:1Y [5]	g/lbf-sec	Rapid Test Residue	5.49E-05	310
M#15	7Z:1Y [5]	g/lbf-sec	Rapid Test Residue	0.000429	308

SHP: Rapid Test Mode Shapes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)	MPC
1	16.5	0.061	Hz	0.369	0.835
2	23.5	0.0675	Hz	0.287	0.927
3	31.3	0.0865	Hz	0.276	0.921
4	38.3	0.0858	Hz	0.224	0.909
5	48.5	0.113	Hz	0.233	0.912

Select M#	DOFs	Units	Measurement Type	Label	Shape 1 Magnitude	Shape 1 Phase
M#1	1X	in/lbf-sec	UMM Mode Shape	Poly	0.0672	353
M#2	1Y	in/lbf-sec	UMM Mode Shape	Poly	0.00295	133
M#3	1Z	in/lbf-sec	UMM Mode Shape	Poly	0.665	354
M#4	2X	in/lbf-sec	UMM Mode Shape	Poly	0.0828	353
M#5	2Y	in/lbf-sec	UMM Mode Shape	Poly	0.0452	355
M#6	2Z	in/lbf-sec	UMM Mode Shape	Poly	0.386	353
M#7	3X	in/lbf-sec	UMM Mode Shape	Poly	0.0785	353
M#8	3Y	in/lbf-sec	UMM Mode Shape	Poly	0.0127	355
M#9	3Z	in/lbf-sec	UMM Mode Shape	Poly	0.0666	354
M#10	4X	in/lbf-sec	UMM Mode Shape	Poly	0.0783	353
M#11	4Y	in/lbf-sec	UMM Mode Shape	Poly	0.0402	175
M#12	4Z	in/lbf-sec	UMM Mode Shape	Poly	0.255	174
M#13	5X	in/lbf-sec	UMM Mode Shape	Poly	0.0768	353
M#14	5Y	in/lbf-sec	UMM Mode Shape	Poly	0.0852	175
M#15	5Z	in/lbf-sec	UMM Mode Shape	Poly	0.57	174

Video

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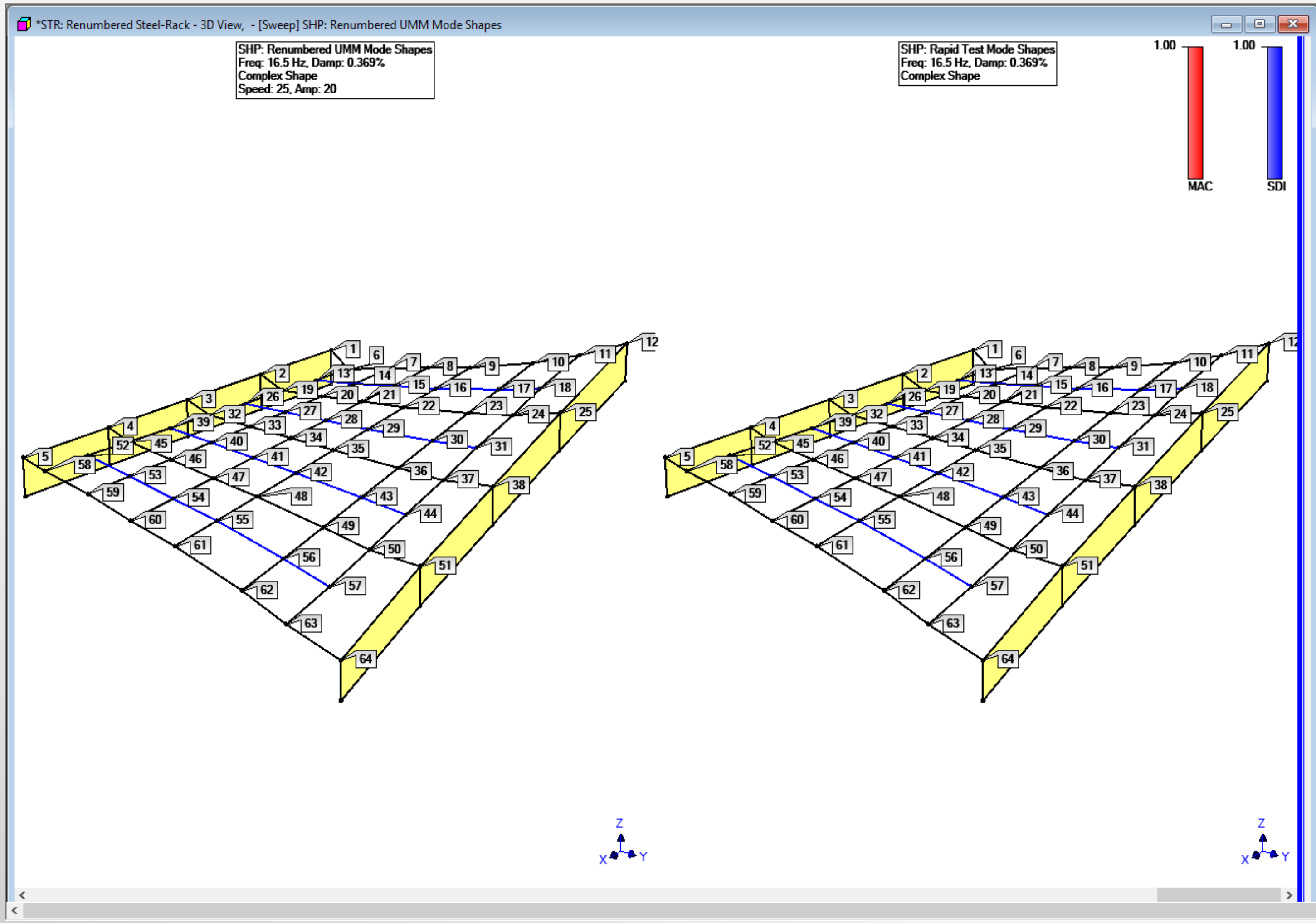
Comparison of Rapid Impact™ & Original Mode Shapes



SHP: Renumbered UMM Mode Shapes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)	M Part
1	16.5	0.061	Hz	0.369	1X: -0.01 | 1Y
2	23.5	0.0675	Hz	0.287	1X: -0.86 | 1Y
3	31.3	0.0865	Hz	0.276	1X: 0.05 | 1Y
4	38.3	0.0858	Hz	0.224	1X: -0.04 | 1Y
5	48.5	0.113	Hz	0.233	1X: -0.14 | 1Y

Select M#	DOFs	Units	Measurement Type	Ma
M#1	1X	in/lbf-sec	UMM Mode Shape	0
M#2	1Y	in/lbf-sec	UMM Mode Shape	0.
M#3	1Z	in/lbf-sec	UMM Mode Shape	(
M#4	2X	in/lbf-sec	UMM Mode Shape	0

SHP: Rapid Test Mode Shapes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)
1	16.5	0.061	Hz	0.369
2	23.5	0.0675	Hz	0.287
3	31.3	0.0865	Hz	0.276
4	38.3	0.0858	Hz	0.224
5	48.5	0.113	Hz	0.233

Select M#	DOFs	Units	Measurement Type	Lab
M#1	1X	in/lbf-sec	UMM Mode Shape	Pol
M#2	1Y	in/lbf-sec	UMM Mode Shape	Pol
M#3	1Z	in/lbf-sec	UMM Mode Shape	Pol
M#4	2X	in/lbf-sec	UMM Mode Shape	Pol

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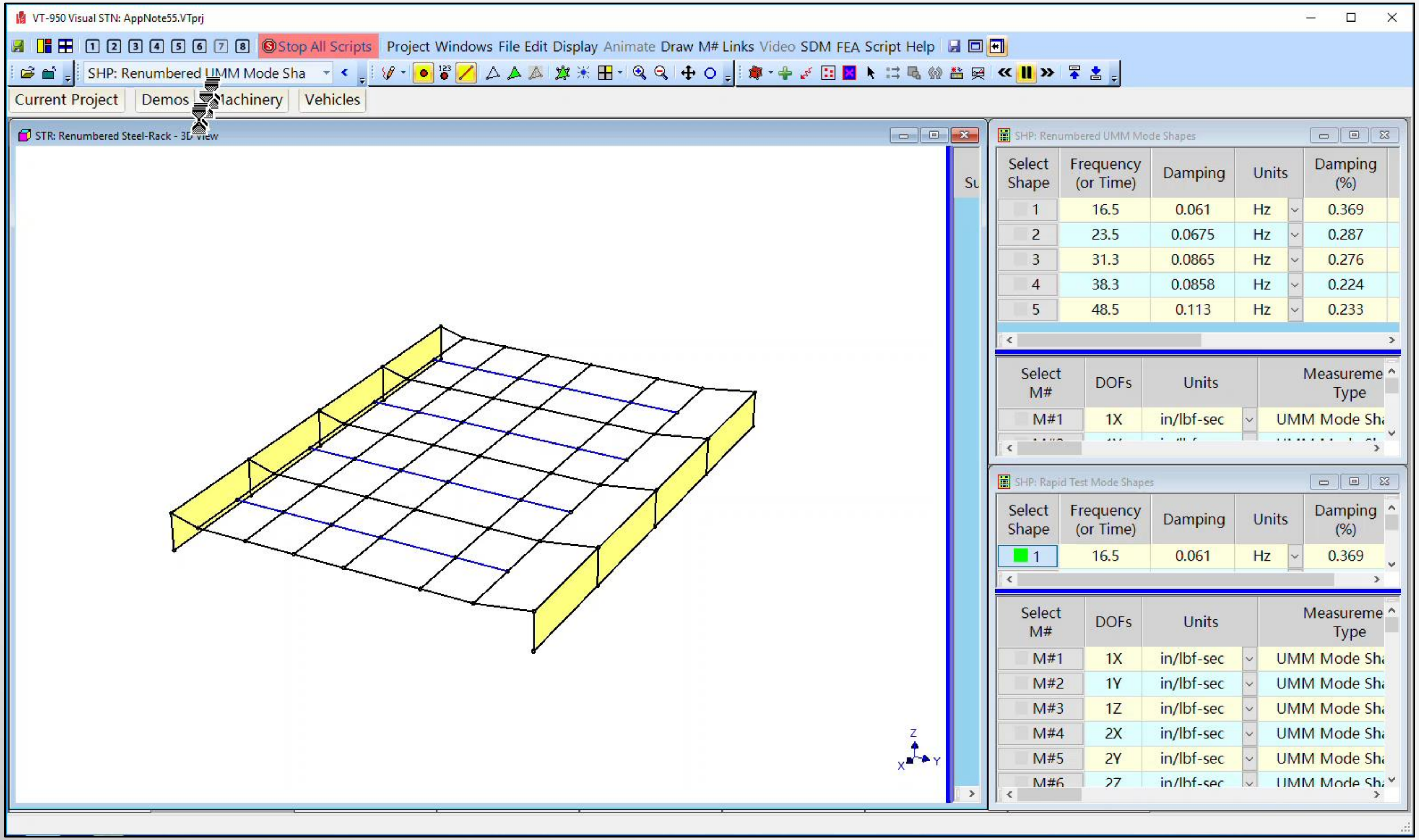
Comparison of Rapid Impact™ & Original Mode Shapes



Video

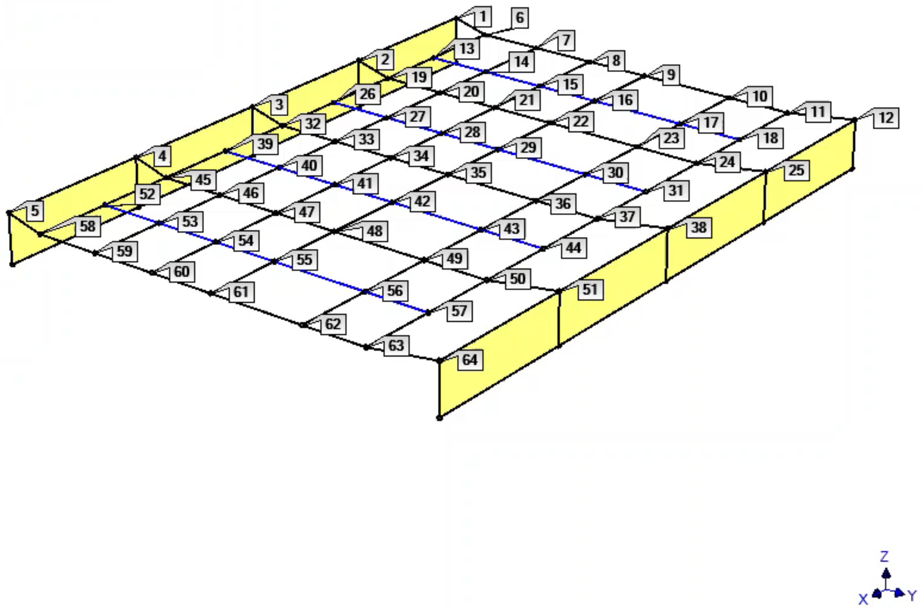
Rapid Impact™ Test Summary

VT-950 Visual STN: AppNote55.VTprj

Project Windows File Edit Display Animate M#s Shapes Tools Script Help

Current Project | Demos | Machinery | Vehicles

*STR: Renumbered Steel-Rack - 3D View



*SHP: Renumbered UMM Mode Shapes

Select Shape	Frequency (or Time)	Damping	Units	Damping (%)	Modal Participation
1	16.5	0.061	Hz	0.369	1X: -0.01 | 1Y: -0.06 | -1Z: -1.00
2	23.5	0.0675	Hz	0.287	1X: -0.86 | 1Y: -0.49 | -1Z: 0.14
3	31.3	0.0865	Hz	0.276	1X: 0.05 | 1Y: 1.00 | -1Z: 0.04
4	38.3	0.0858	Hz	0.224	1X: -0.04 | 1Y: 0.16 | -1Z: -0.99
5	48.5	0.113	Hz	0.233	1X: -0.14 | 1Y: -0.99 | -1Z: -0.03

Select M#	DOFs	Units	Measurement Type	Shape 1	
				Magnitude	Phase
M#8	3Y	in/lbf-sec	UMM Mode Shape	0.0126	355
M#9	3Z	in/lbf-sec	UMM Mode Shape	0.0664	354
M#10	4X	in/lbf-sec	UMM Mode Shape	0.0781	353
M#11	4Y	in/lbf-sec	UMM Mode Shape	0.0401	175
M#12	4Z	in/lbf-sec	UMM Mode Shape	0.254	173
M#13	5X	in/lbf-sec	UMM Mode Shape	0.0768	353
M#14	5Y	in/lbf-sec	UMM Mode Shape	0.085	175
M#15	5Z	in/lbf-sec	UMM Mode Shape	0.57	174
M#16	6X	in/lbf-sec	UMM Mode Shape	0.0544	172
M#17	6Y	in/lbf-sec	UMM Mode Shape	0.0603	352
M#18	6Z	in/lbf-sec	UMM Mode Shape	0.793	352
M#19	7X	in/lbf-sec	UMM Mode Shape	0.013	355
M#20	7Y	in/lbf-sec	UMM Mode Shape	0.0684	354

Video

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Conclusions

- In a conventional impact test, the *reference sensor* (either the impact DOF or the accelerometer location) *must remain fixed throughout the test*. Since the reference sensor must be connected by a wire to the data acquisition system, a *very long wires might be required* when testing a large structure

- *Better quality signals are possible if each impact force is applied closer to the response sensor*

- In a Rapid Impact™ test, *either the impact hammer or the accelerometer can be moved* to a different DOF between acquisitions

- In a Rapid Impact™ test, a *chain of acquisitions* (based on Input & Output DOFs) *is required*.
  A *chain* is formed when the *Input & Output DOF of each acquisition has the same DOF as another acquisition in the chain*

- An *FRF chain* is calculated from *chain of acquisitions*

- After the Rapid Impact™ FRFs are curve fit, modal residues are converted to mode shapes using the relationship between residues and mode shapes. *Each modal residue is the product of two mode shape components*

- A Rapid Impact™ test is *faster and more convenient* for testing *any size structure*

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