SIEMENS

Fundamentals of Structural Dynamics

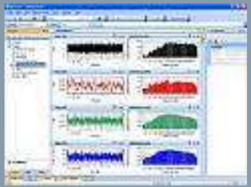
SIEMENS

Structural Dynamics Agenda Topics

How to characterize structural behavior?

Fundamentals

Natural Frequencies, Resonances, Damping



How does my structure naturally want to move?

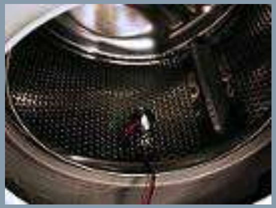
Modal Analysis

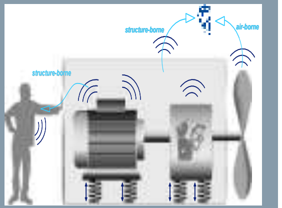
Curve fitting, data quality checks (MAC), mode shapes

How to validate simulation models?

Modal Correlation

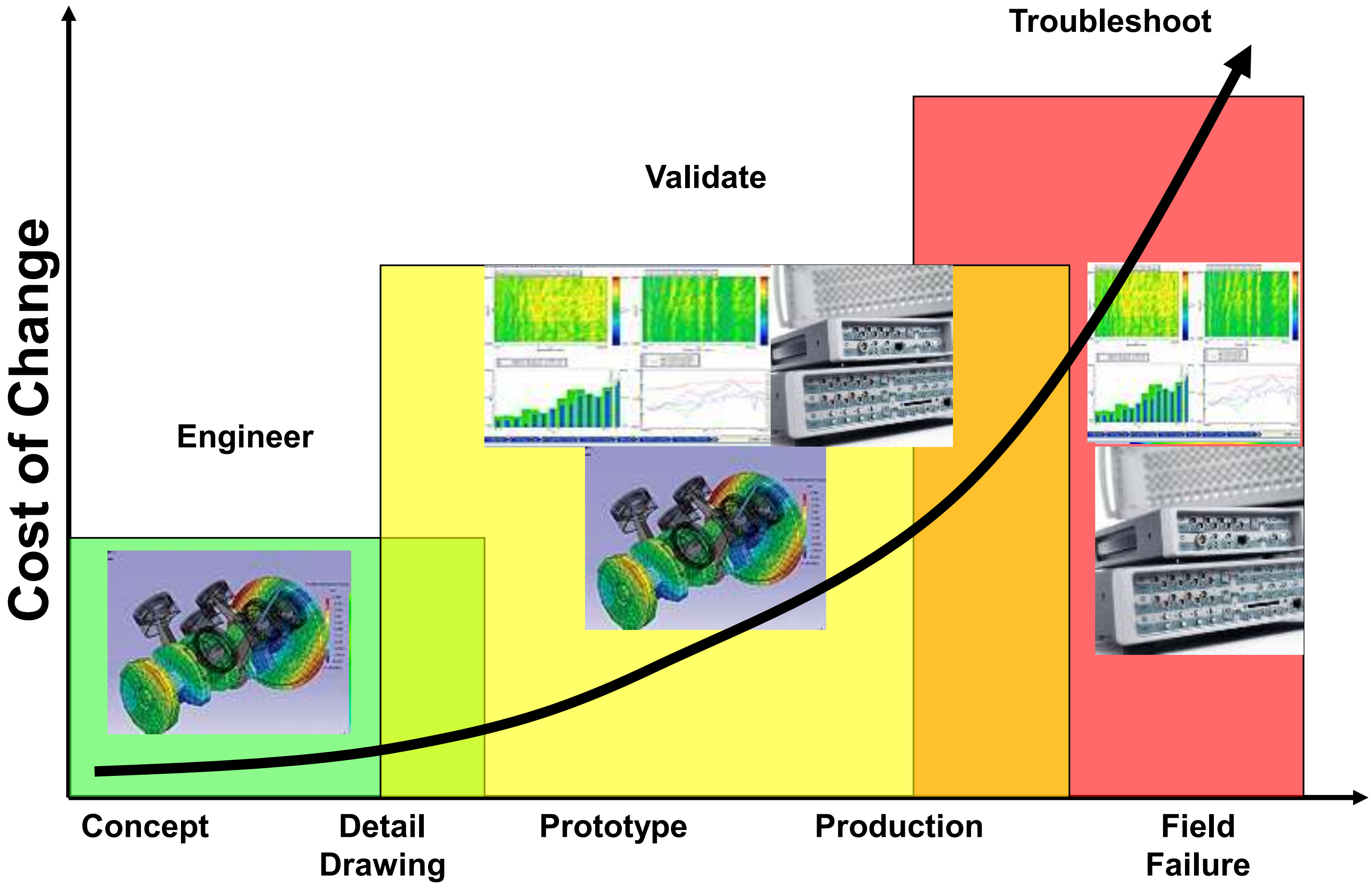
Modal Assurance Criteria, Modal Contribution, Updating





Why are structural dynamics important?

Product Development Process



Why identify structural resonance?




	Durability	Performance/Perceived Quality	Safety
Pains	Field failure	Noise & Vibration problem	Product Certification
What ?	Increasing speed causes: - Component breakdown - Machine failure - Poor precision - Inconsistent product quality …	- Steerling wheel shake - Driver seat vibration - Noise at Driver's & Passenger's Ears …	- Structural integrity - Ground Vibration Testing - Reduce vibration dose value - Flutter phenomena …

Excessive vibration problems

Aircraft Flutter

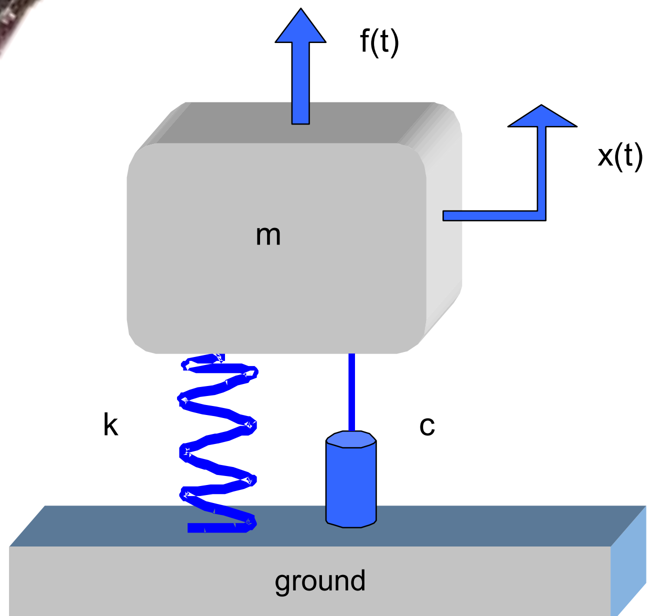
Tacoma Bridge Collapse

Natural frequency of a traffic signal

What is a natural frequency?

Natural Frequency

Natural frequency is the frequency at which a system naturally vibrates once it has been forced into motion



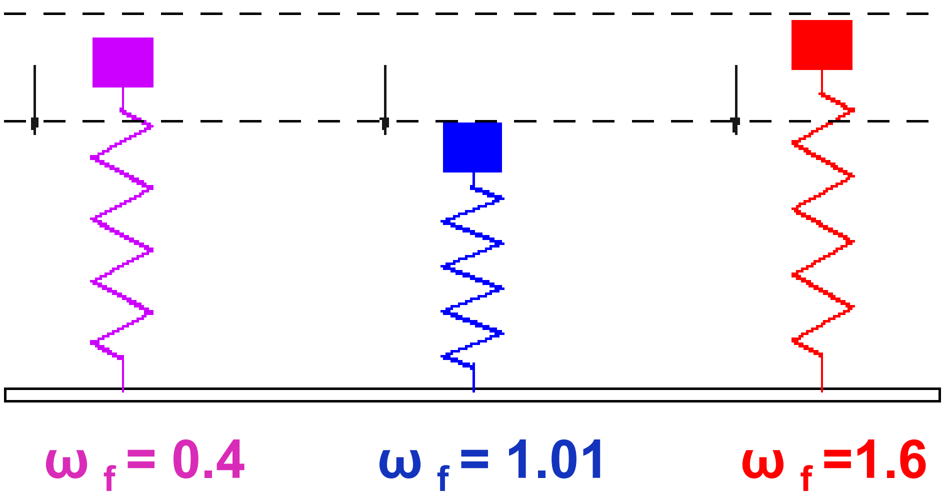
Single Degree of Freedom System

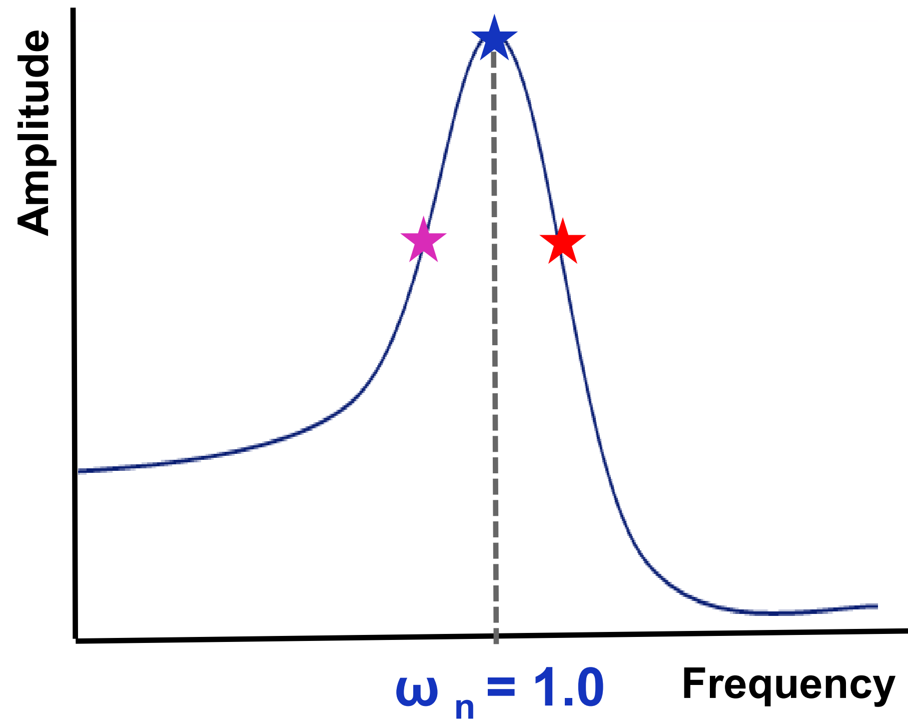
$$\omega_n = \sqrt{\frac{k}{m}} = \text{natural frequency (rad/sec)}$$

Natural Frequency

Resonant Frequency

- **Resonance** is the buildup of large amplitude that occurs when a structure is excited at its natural frequency

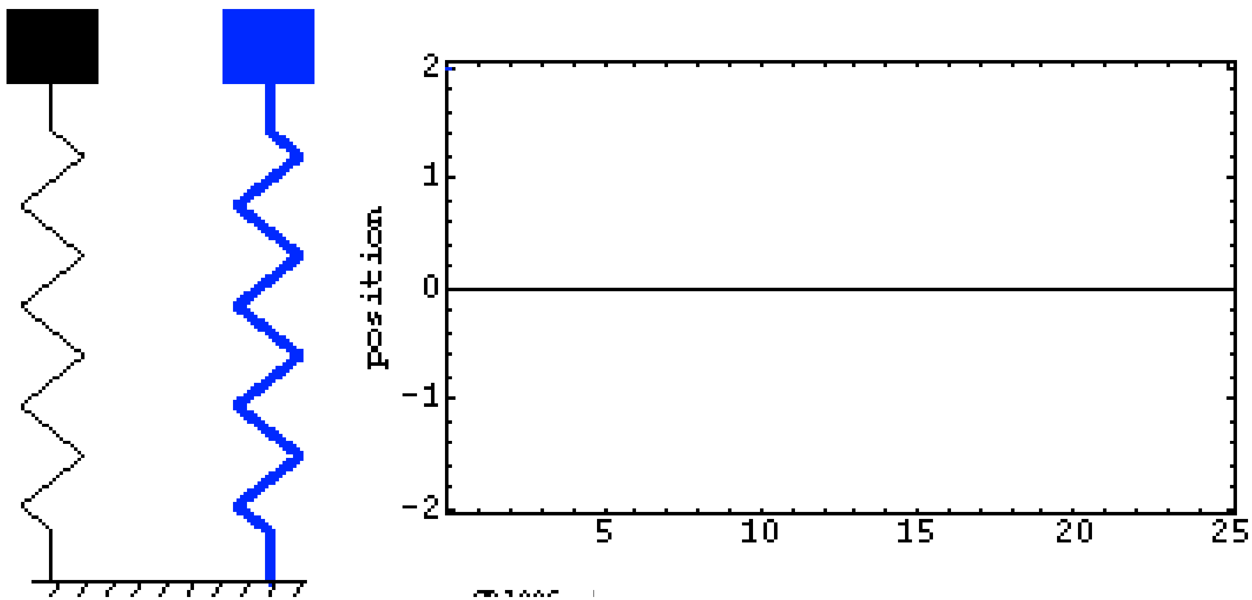




3 Single Degree of Freedom Systems with same mass, stiffness and damping

Structural Damping

- **Damping** is any effect that tends to reduce the oscillations in a system



$$\omega_d = \omega_n \sqrt{1 - \zeta^2}$$

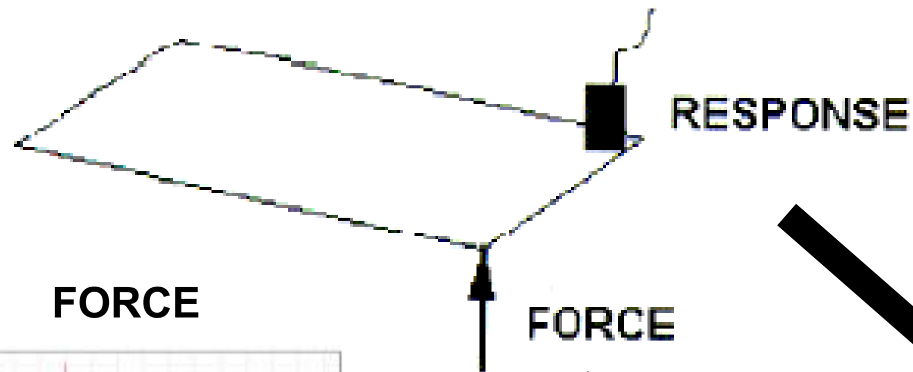
$$\zeta = \frac{c}{2\sqrt{km}}$$

How do we determine the resonant behavior of a structure?

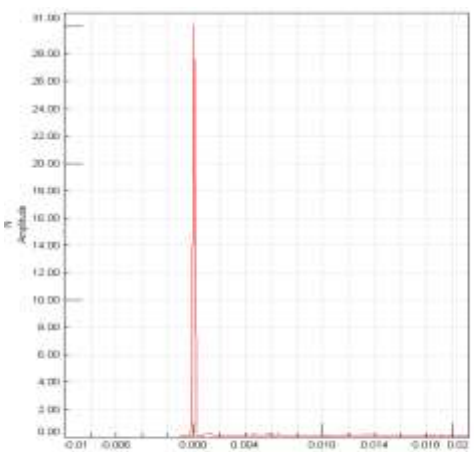
Frequency Response Functions

- **Frequency Response Functions (FRFs)** measure the system's output in response to known an input signal

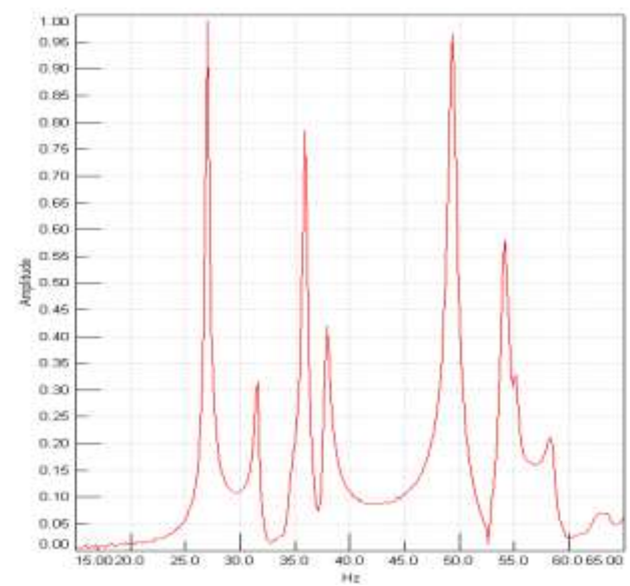
$$\text{FRF} = \frac{\text{output}}{\text{input}}$$



FORCE



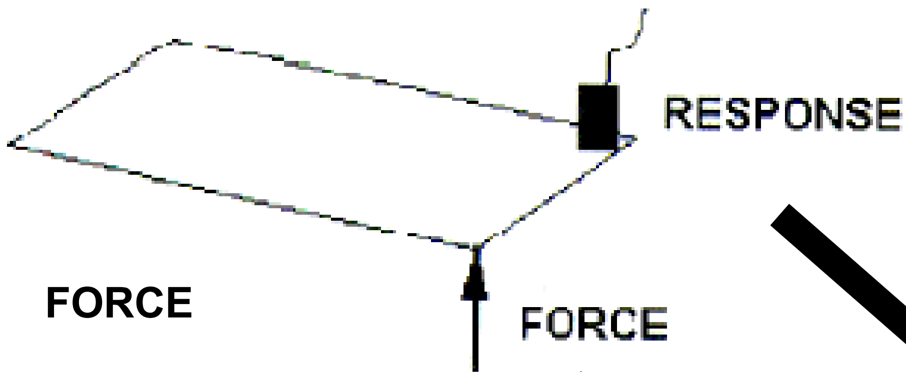
RESPONSE

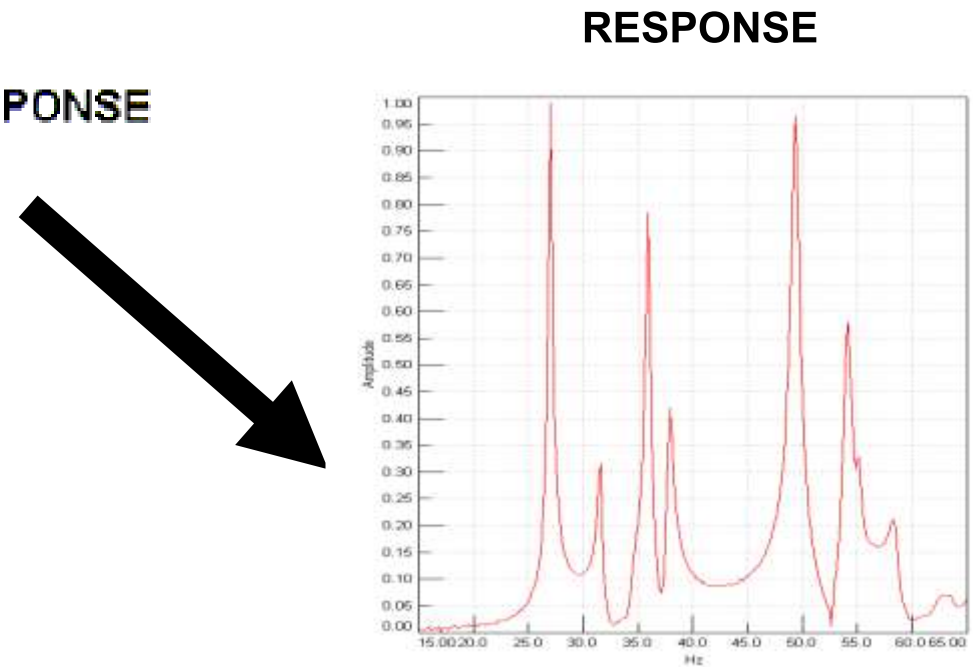


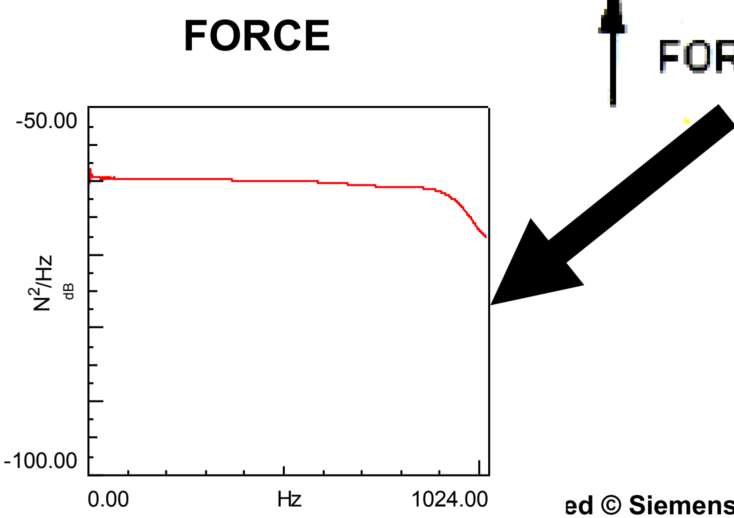
Frequency Response Functions

- **Frequency Response Functions (FRFs)** measure the system's output in response to known an input signal

$$FRF = \frac{\text{output}}{\text{input}}$$







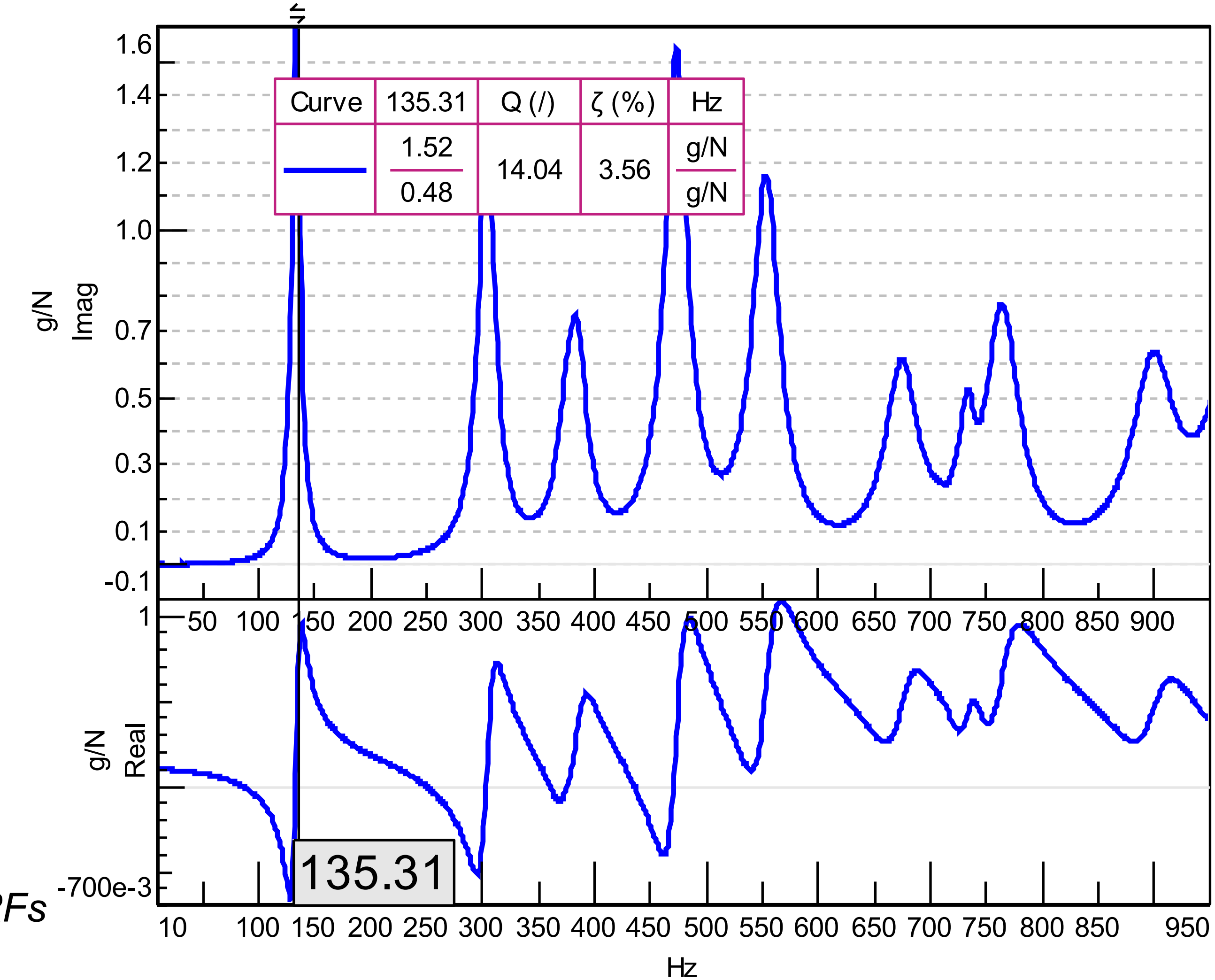
What can an FRF tell you?

Resonant Frequency

- Damping

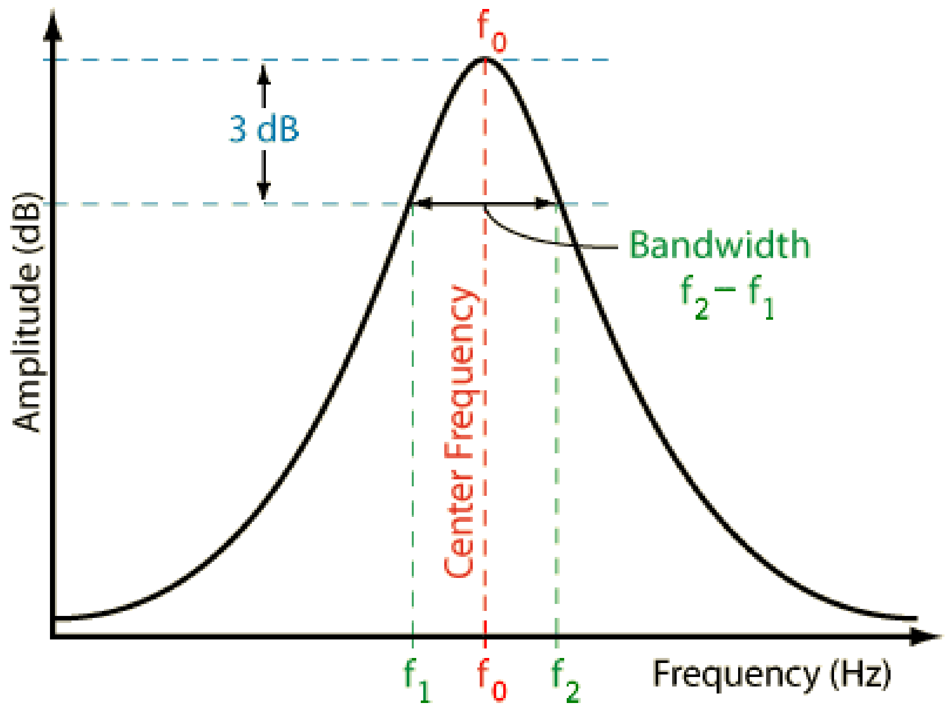
- Mode Shape

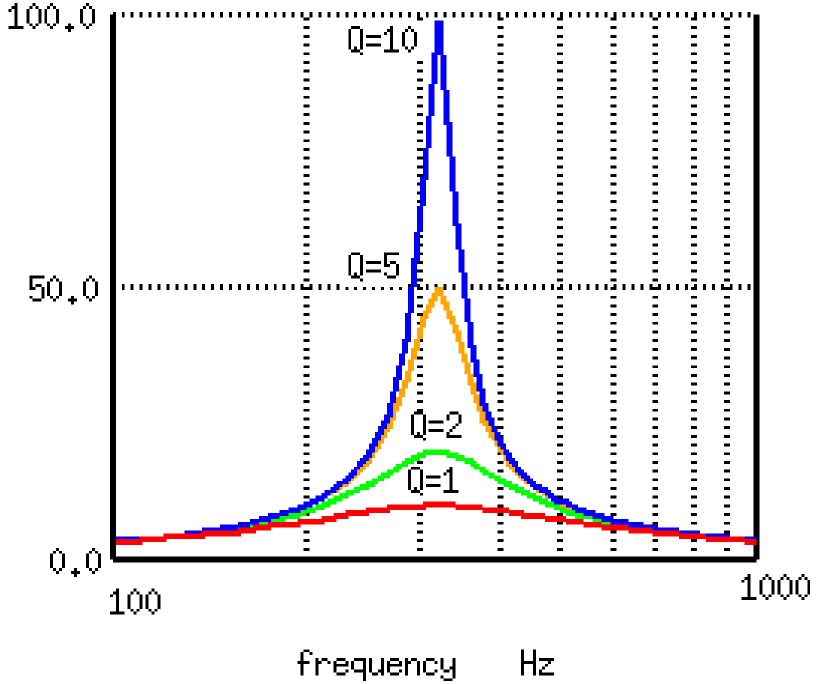
➢ *Requires Multiple FRFs*



Quality Factor

- **Q-factor** describes whether a system is heavily or lightly dan $Q = \frac{1}{2\zeta}$





$$Q = \frac{f_o}{f_2 - f_1}$$

Half Power (3 dB) Method

Other Damping Terms

Relationship Between Measures of Damping

$$\eta = \frac{1}{Q} = 2\xi = \frac{\%Cr}{50} = \tan\phi = \frac{\delta}{\pi} = \frac{D}{2\pi U} = \frac{\Delta\omega_{3dB}}{\omega_0}$$

where:

η is loss factor

Q is amplification factor

ξ is damping ratio

%Cr is percent of critical damping

(%Cr = 100% x ξ)

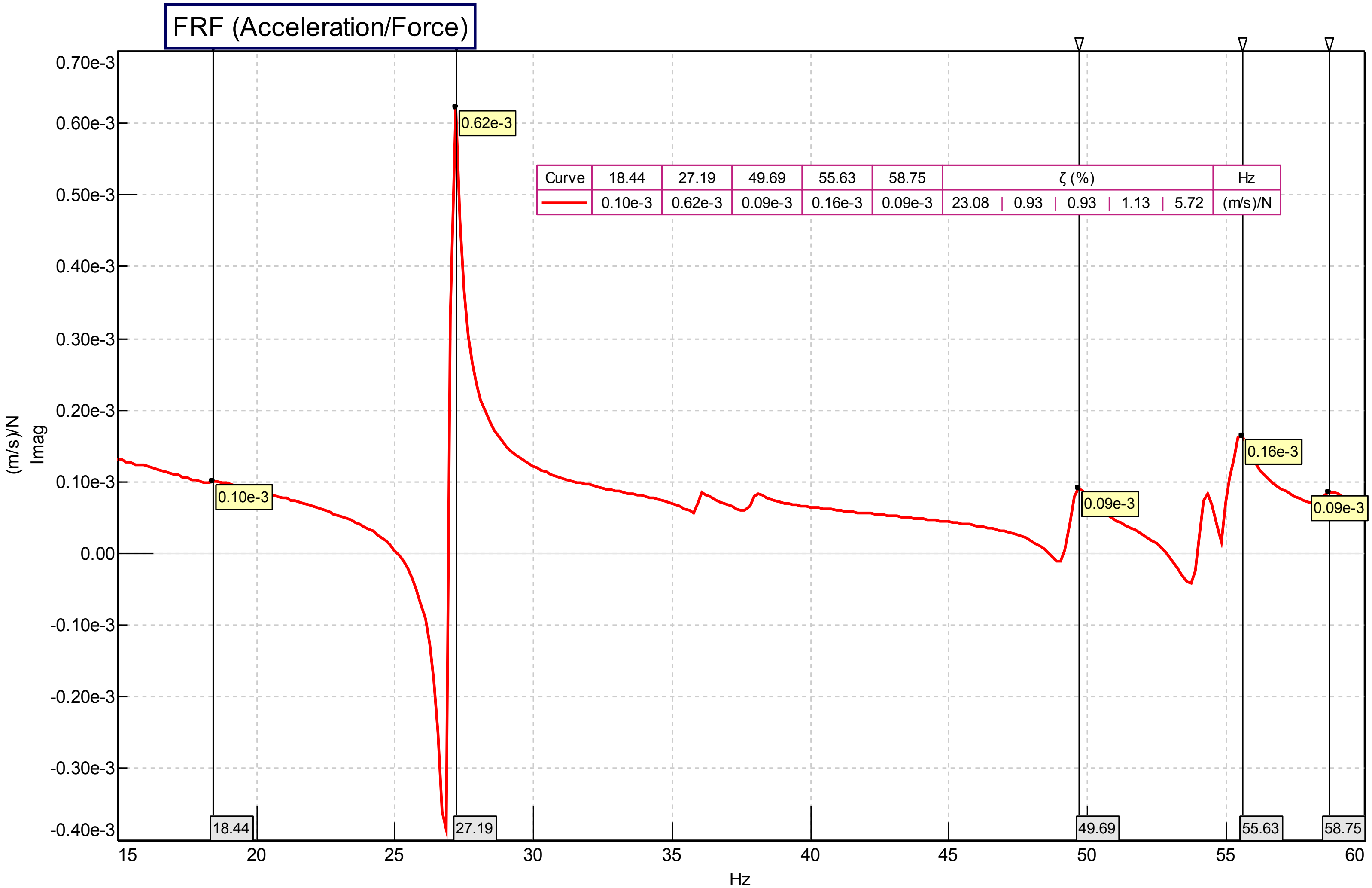
ϕ is the phase angle between cyclic stress and strain

δ is the log decrement of a transient response

D is the energy dissipation per cycle

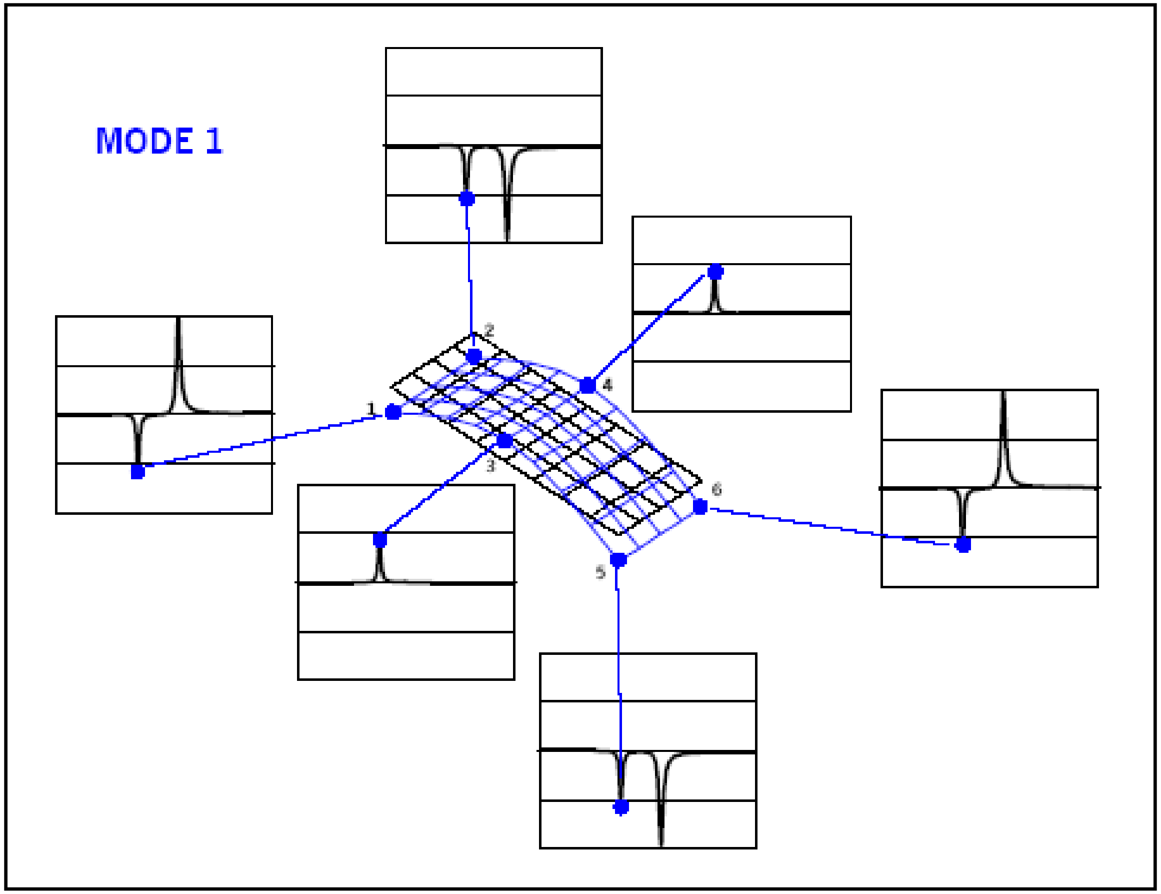
U is the stored energy during loading

DEMONSTRATION: Test.Lab Cursor Calculations



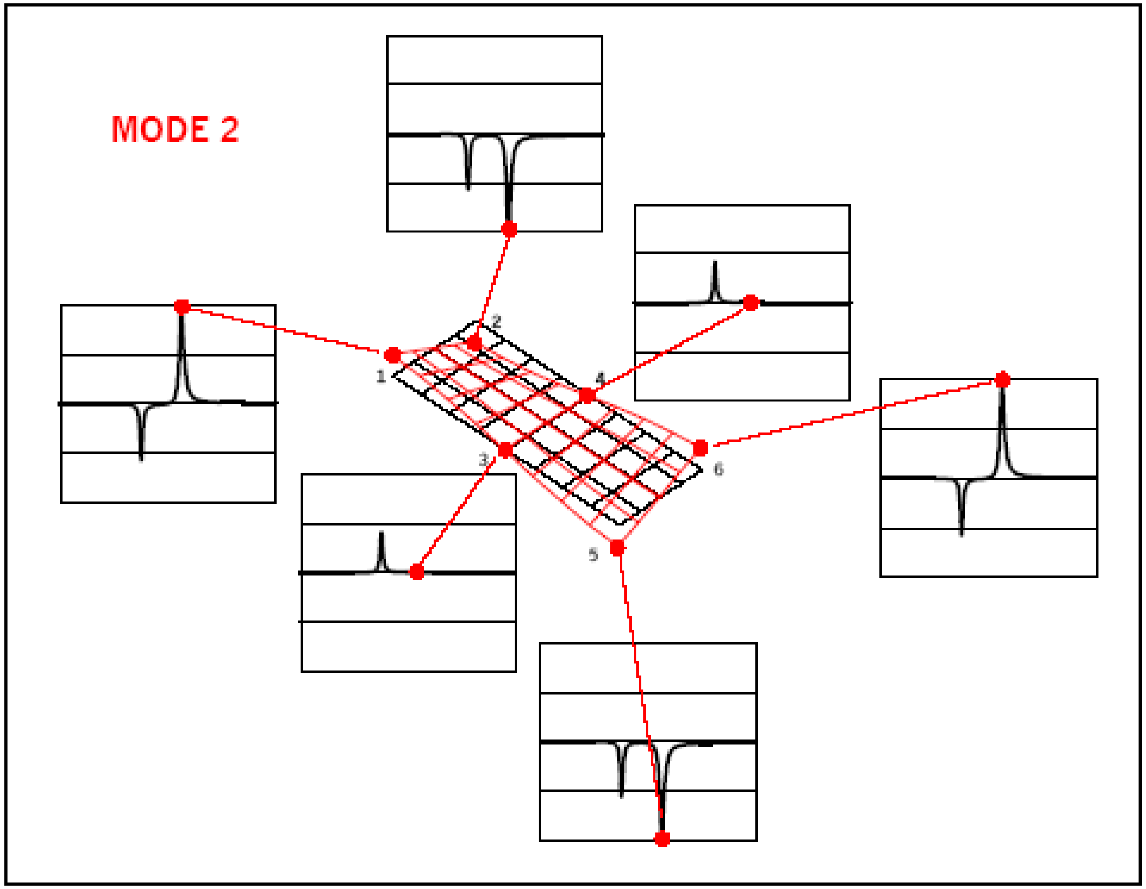
Curve	18.44	27.19	49.69	55.63	58.75	ζ (%)	Hz
	0.10e-3	0.62e-3	0.09e-3	0.16e-3	0.09e-3	23.08 | 0.93 | 0.93 | 1.13 | 5.72	(m/s)/N

FRFs determine mode shapes



1st Bending Mode

FRFs determine mode shapes



1st Torsional Mode

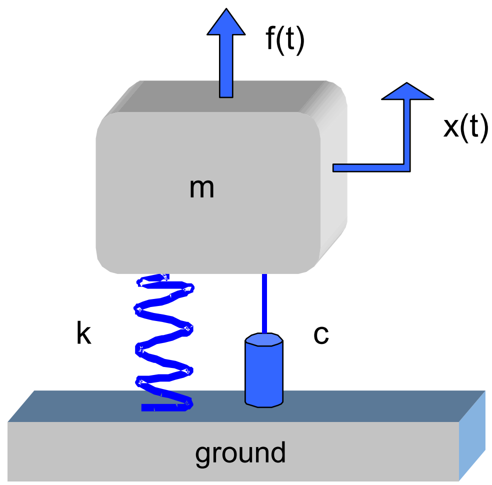
Experimental Modal Analysis

The process of identifying the dynamic behavior of a system (structure) in terms of it's modal parameters

Modal parameters

- *Frequency*
- *Damping*
- *Mode Shape*

- Troubleshooting
- Simulation and prediction
- Optimization
- Diagnostics and health monitoring



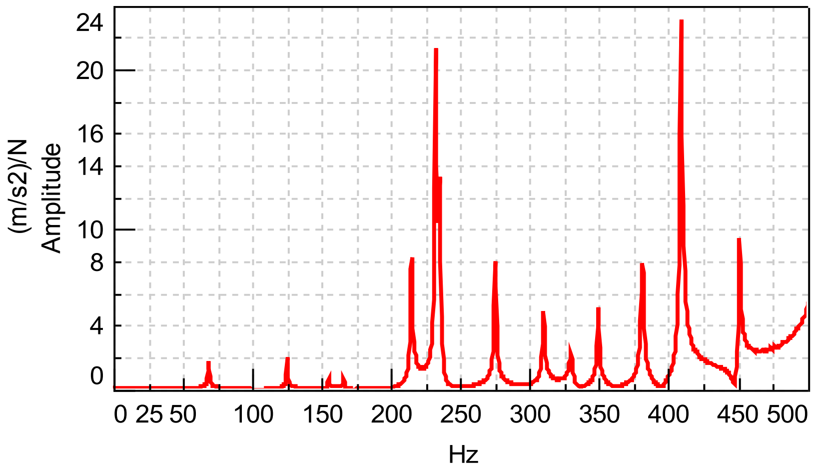
Single Degree of Freedom System

$$\omega_n = \sqrt{\frac{k}{m}}$$

$$\omega_d = \omega_n \sqrt{1-\zeta^2}$$

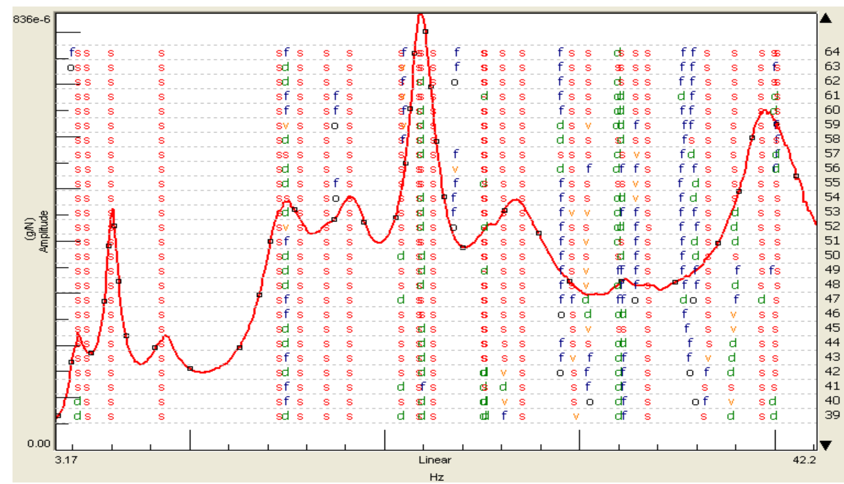
$$\zeta = \frac{c}{2\sqrt{km}}$$

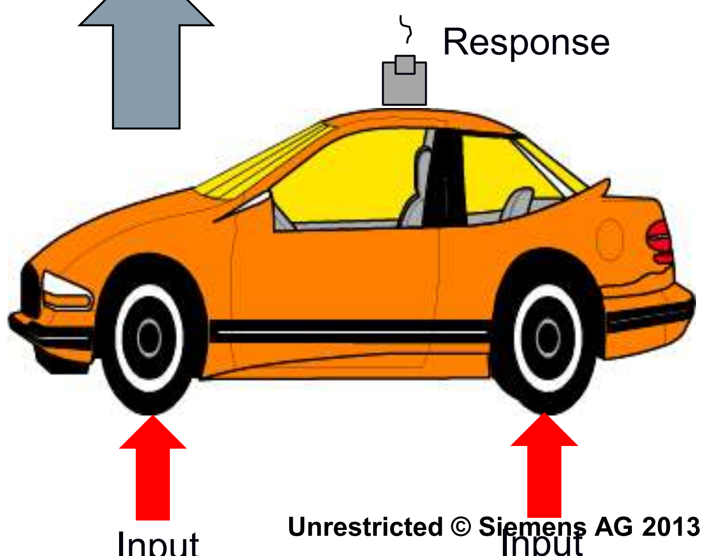
Experimental Modal Analysis Process



Measure the Frequency Response Functions

Curve Fit to Estimate Modal Parameters





Frequency
Damping
Mode Shapes

Fundamentals of structural dynamics review

Why are resonant frequencies important?

How can I get realistic damping values?

What is the significance of Frequency Response Functions and how can they help me?

What can I learn from a mode shape?




SIEMENS

Experimental Modal Acquisition and Analysis

Measurement Techniques

Measurement Equipment

Excitation

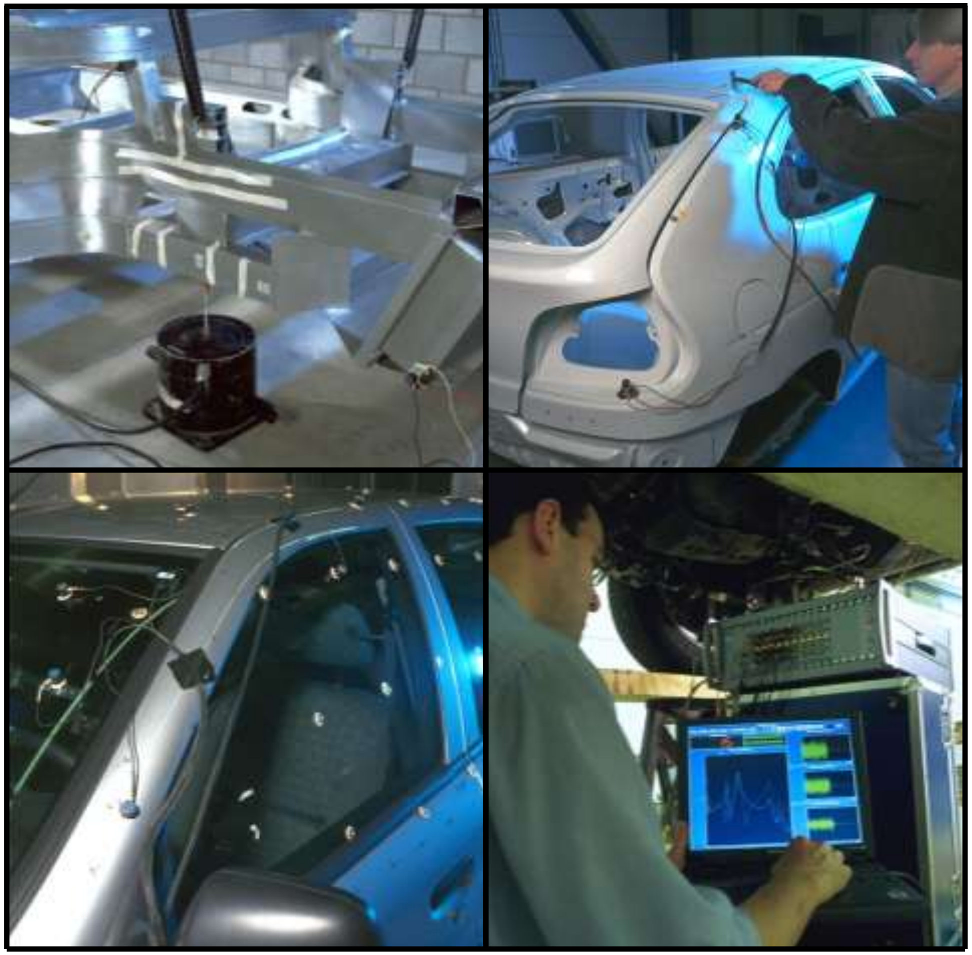
- Laboratory
  (shakers, hammer, force cell, …)
- Operational excitations
  (road simulation, flight simulation, wind excitation, …)
- Unusual excitations
  (loudspeaker, gun shot, explosion, …)

Response

- (Accelerometers, Laser,…)

Measurement system

- FFT analyzer (2-4 channels)
- PC & data-acquisition
  front-end (2-1000 channels)



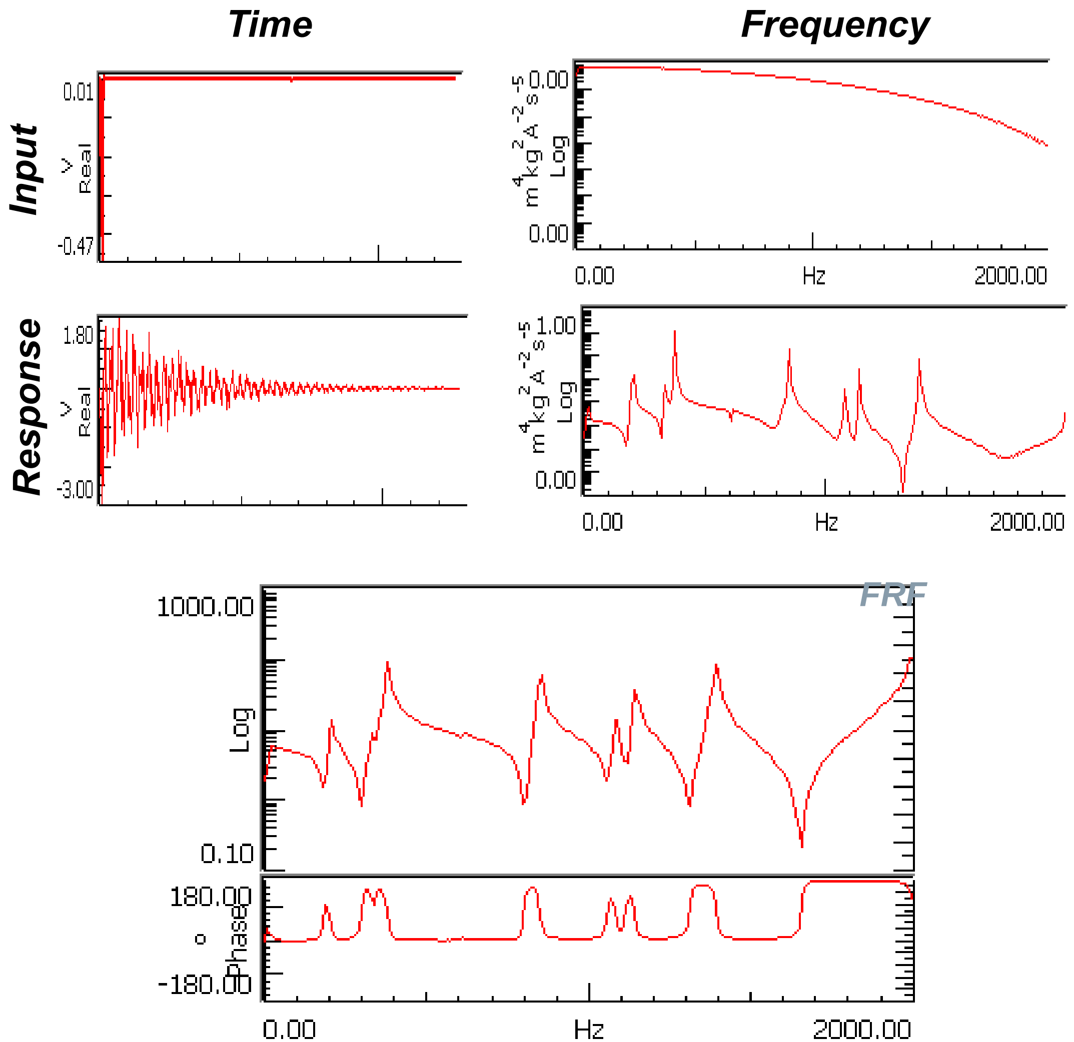
Excitation Techniques

Impact Testing

Shaker Testing

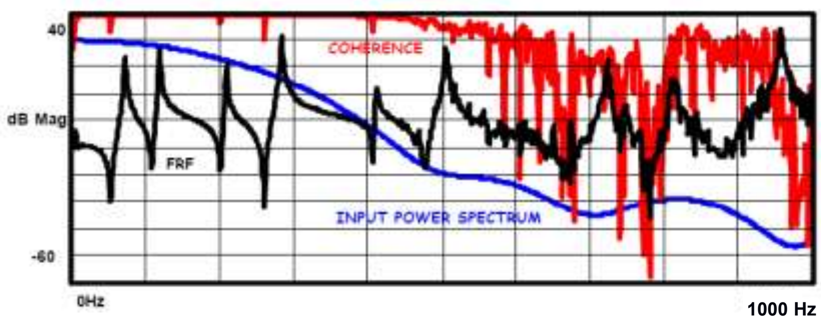
Impact Testing

- Minimal equipment
- Easy and fast
- Good for wide range of structures
- Limited frequency range
- Typically: fixed response accelerations - roving impact location

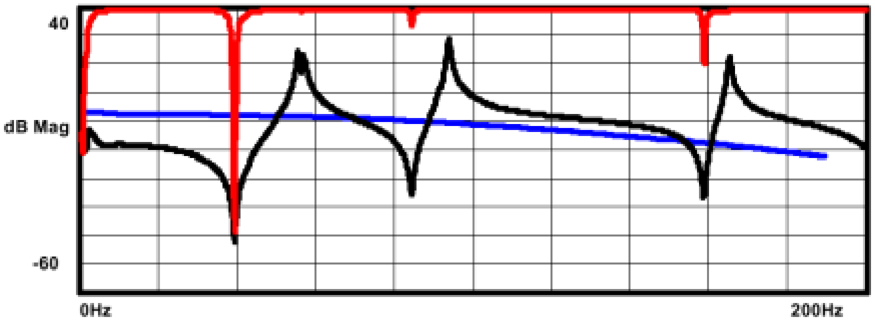


Impact Testing

Shorter impact time → Wider freq range



Soft Tip



Correct Tip

Blue Line – Hammer Input Autopower

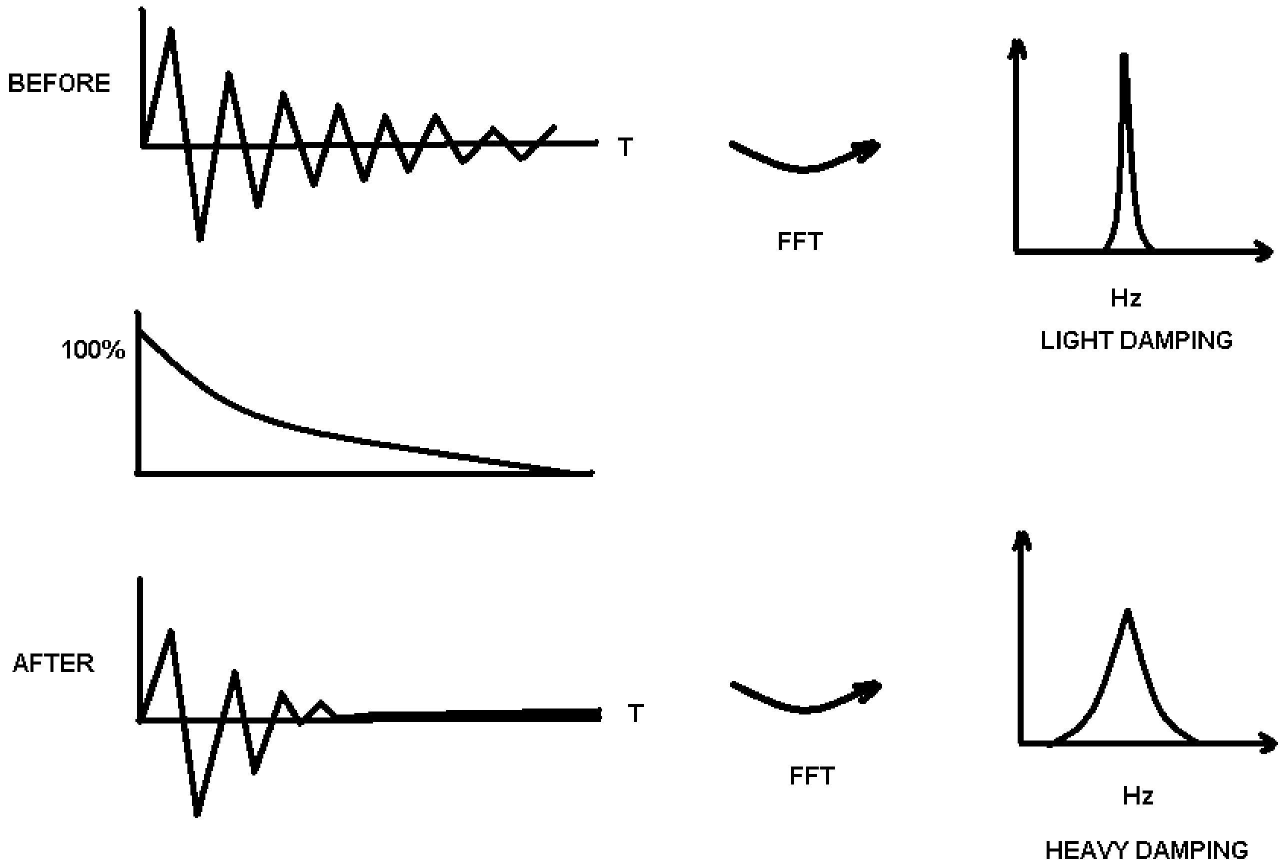
Red – Coherence

Black - FRF

Huge Impact Test

Exponential Window for Response

Exponential Window

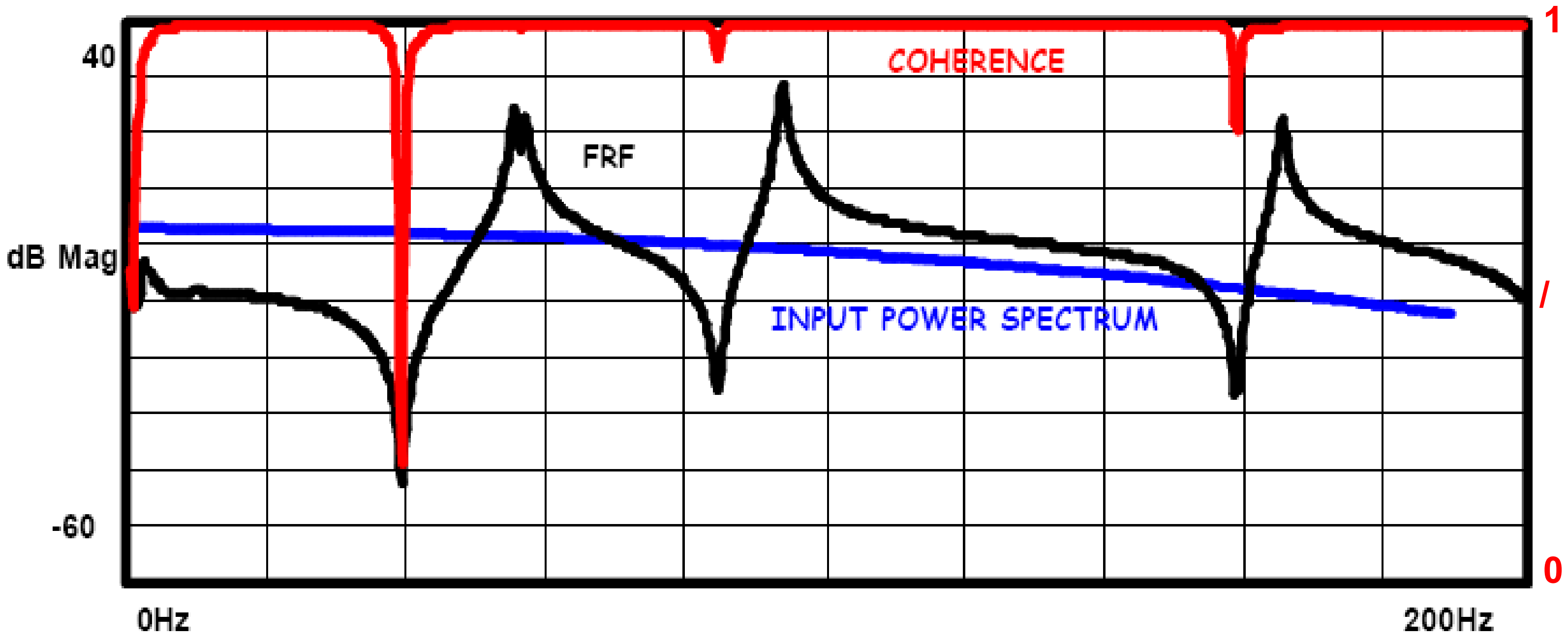


- Exponential Window Increases Apparent Damping Values When Applied.
- Avoid Applying The Exponential Window Unless Absolutely Necessary.

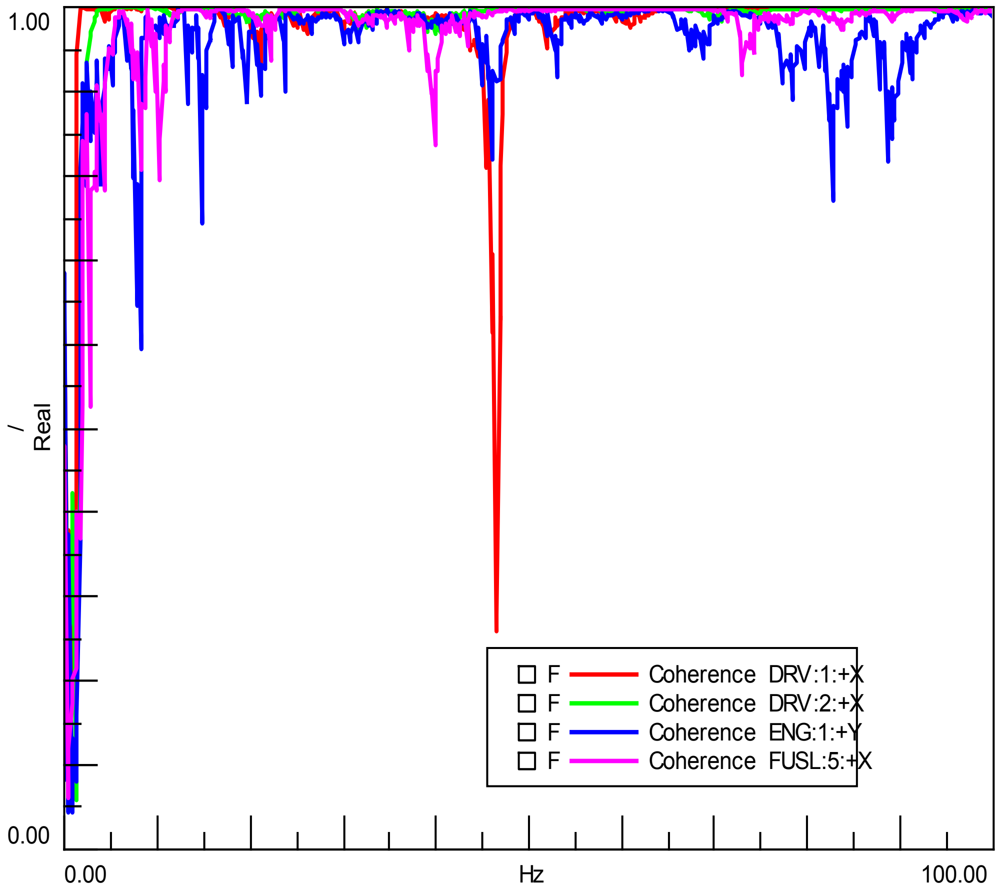
Coherence

Coherence

- **Coherence** is a value from 0 to 1 that shows how much of the output is really due to the input



Coherence



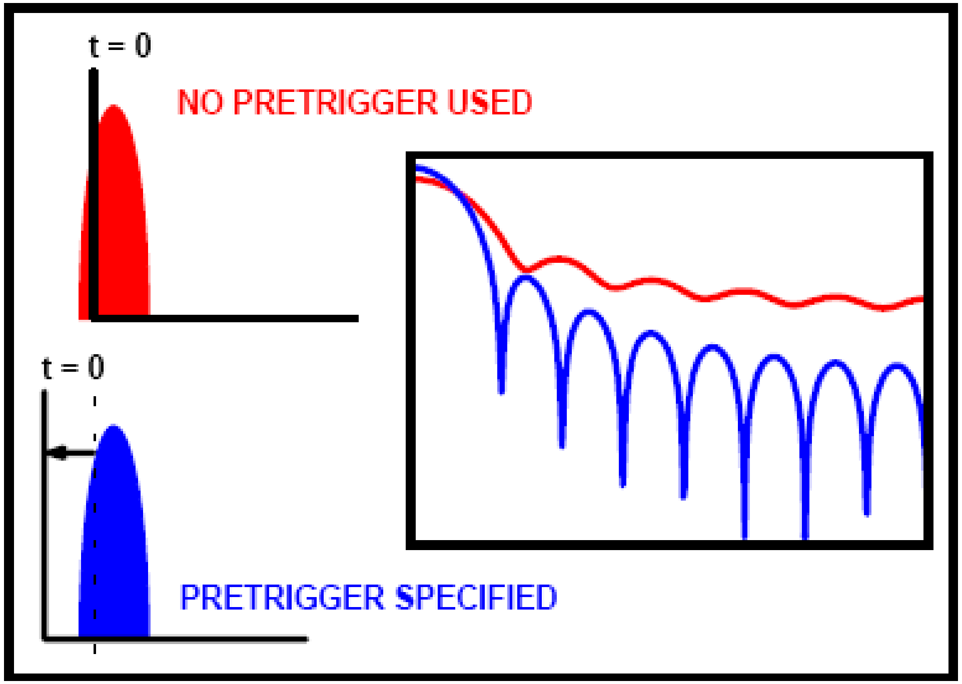
Coherence differs from 1 in case of:

- Non-Linearity
- Unmeasured sources
- Antinodes
- Frequency range of excitation
- Other noise

Pretrigger

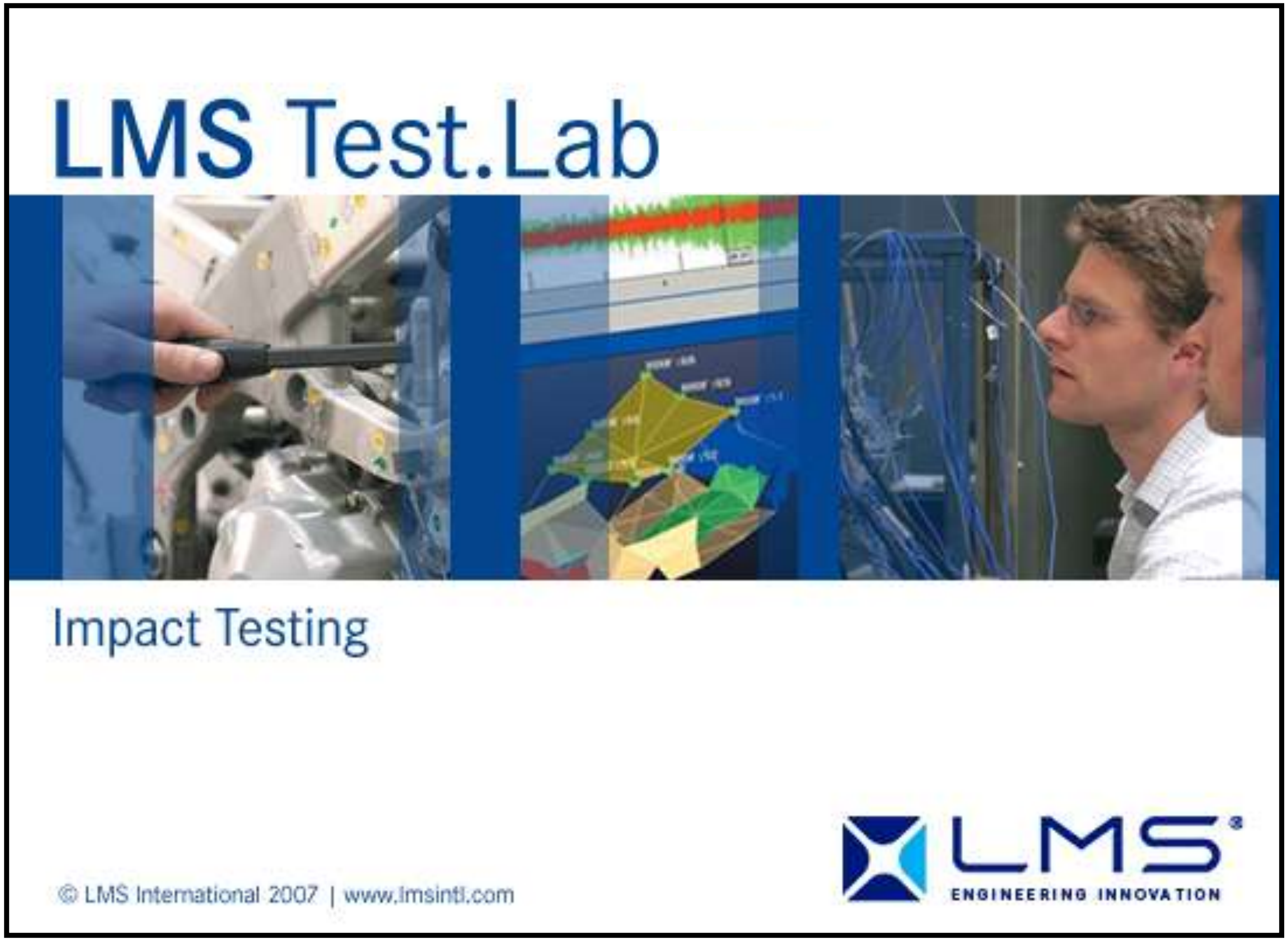
Pretrigger

Pretrigger is the amount of "buffer time" measured before the impulse



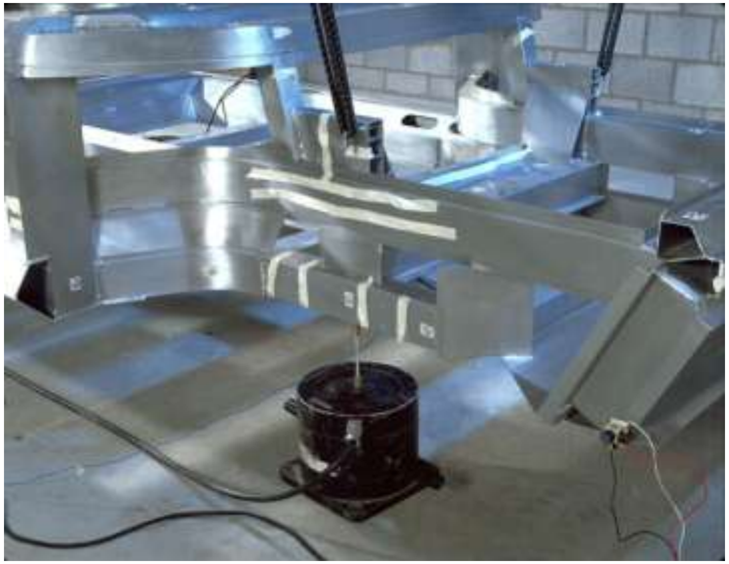
- Lose initial part of the input signal
- Use a pretrigger to avoid distorted FRF

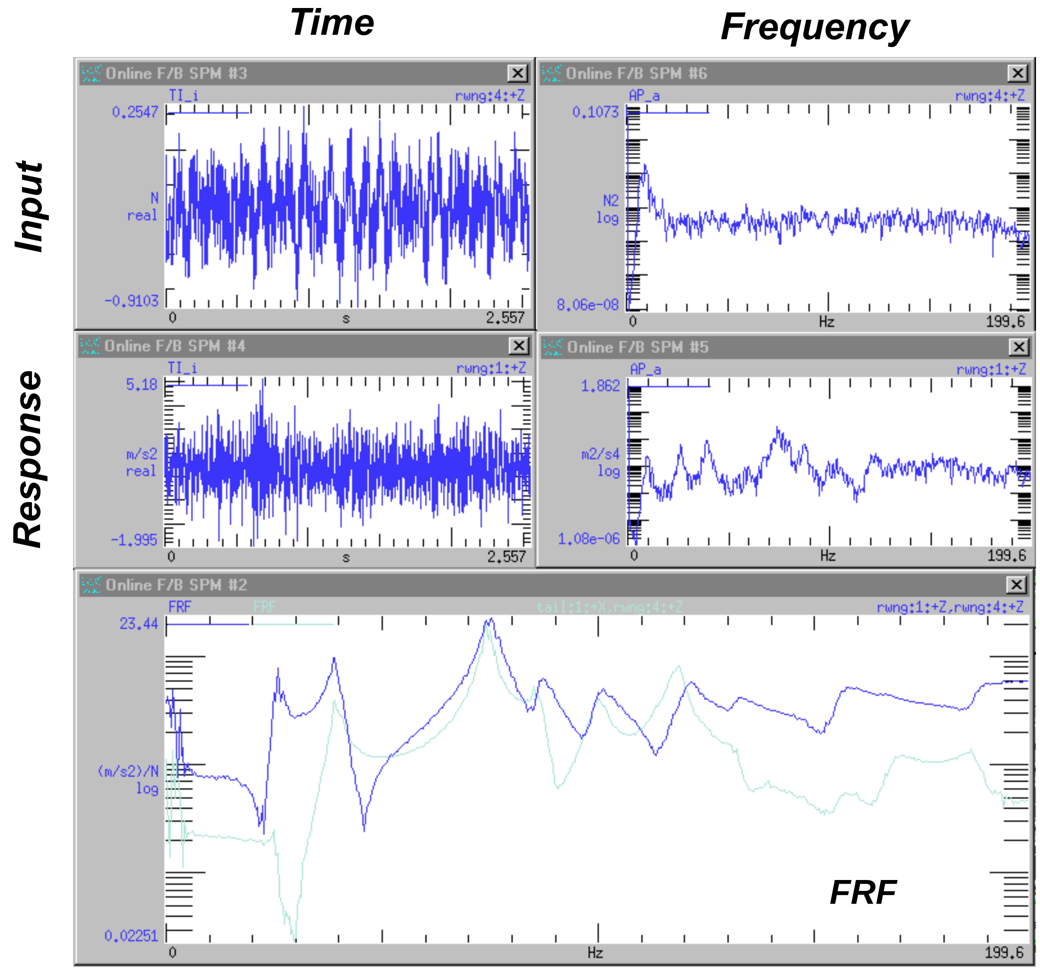
DEMONSTRATION: Modal Impact Test



Shaker Testing

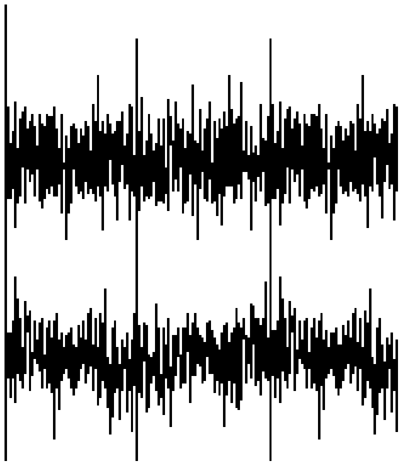
- Time Consuming to setup
- Control frequency range
- Control Force Amplitude
- Better for larger structures
- Typically fixed excitation point, multiple response points - measured in batches





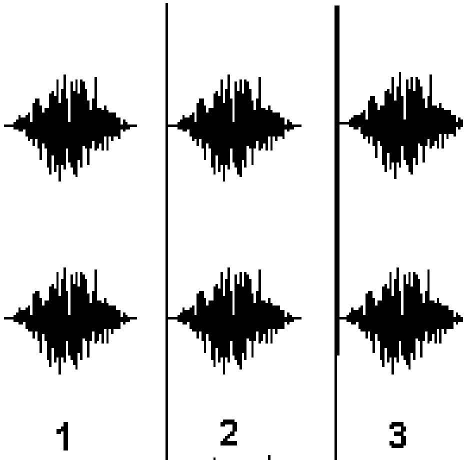
Shaker Testing: Excitation Signals

Random



Window Required

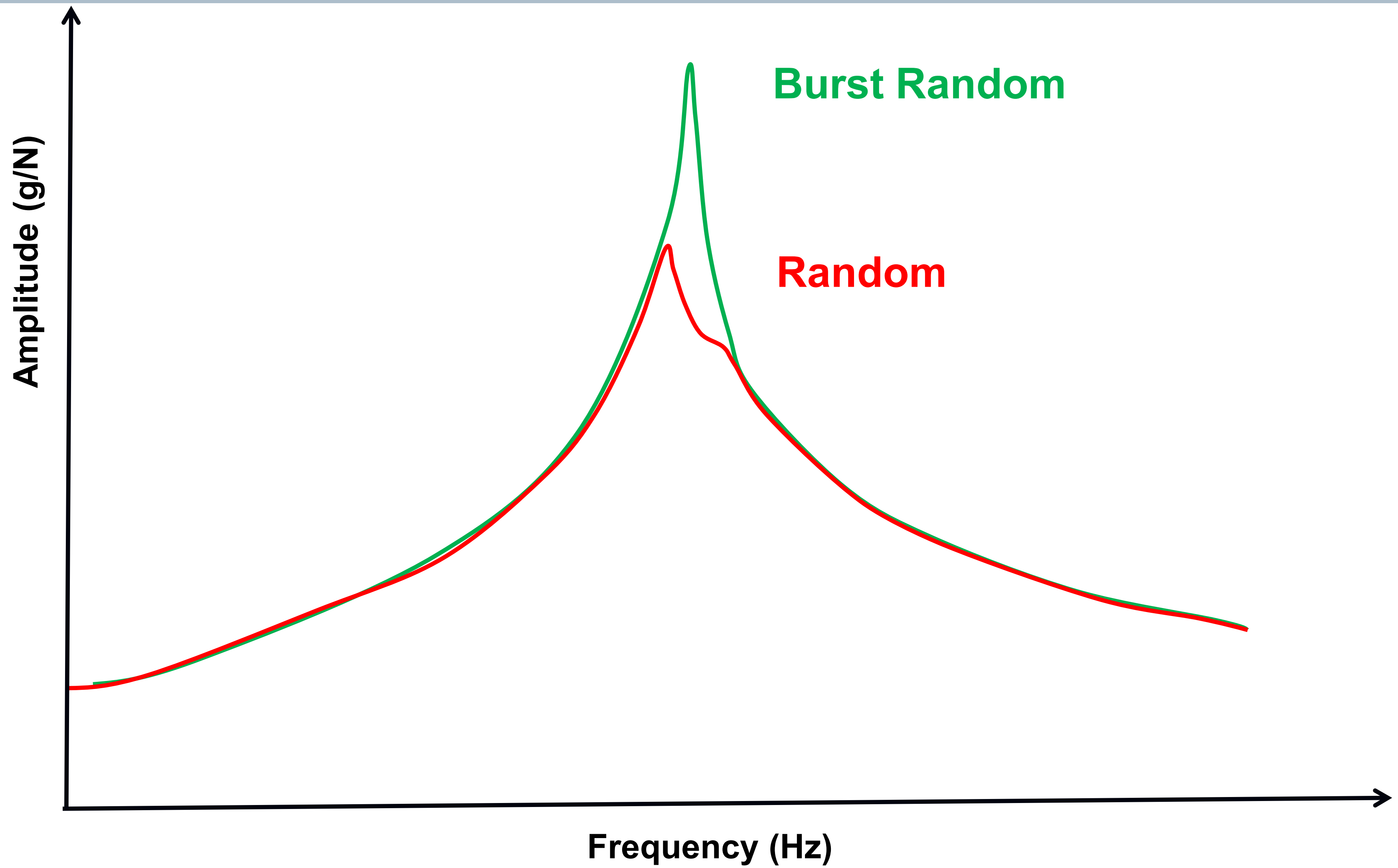
Burst Random



No Window Needed

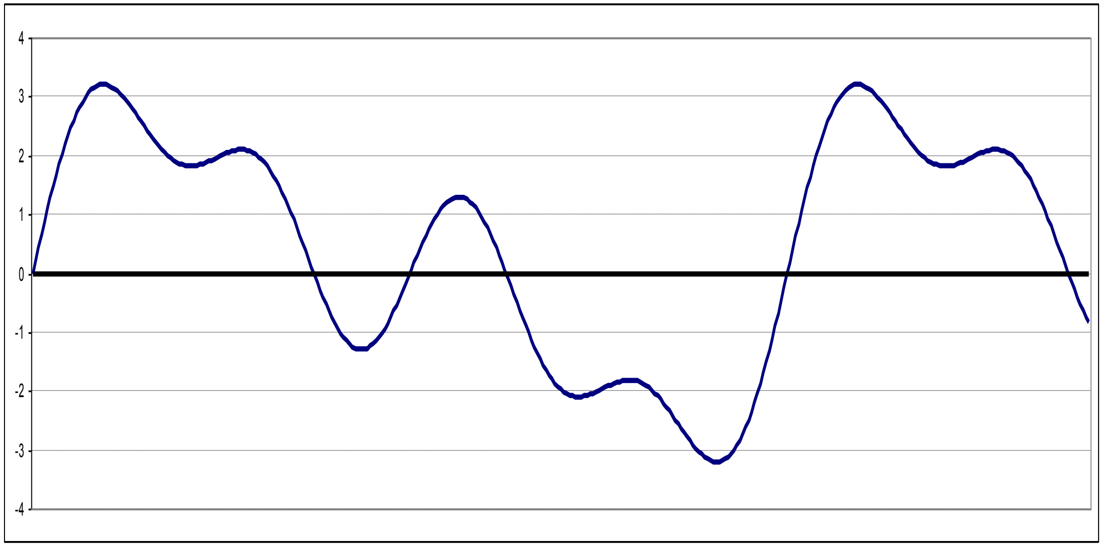
Generally, Burst Random is better

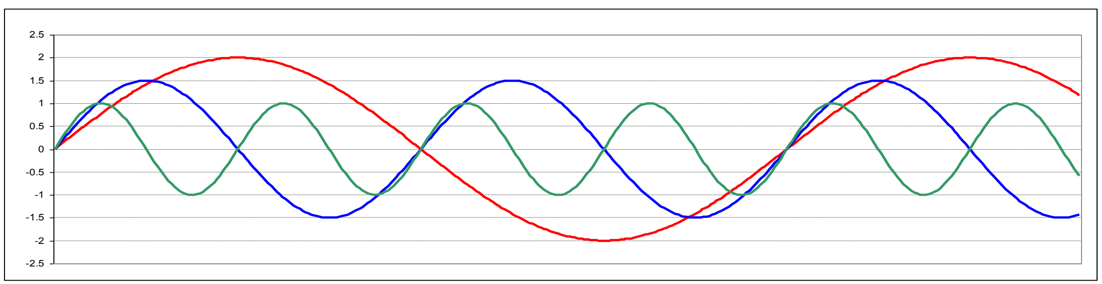
Effect of not using a window on excitation signal



Understanding leakage and windows

Joseph did help us a lot …





Joseph Fourier

(º1768 - †1830)

Théorie analytique de la chaleur (1822)

- Fourier's law of heat conduction

$$\frac{\partial u}{\partial t} = k\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right]$$

- Analyzed in terms of infinite mathematical
es

Any signal can be described as a combination of sine waves of different frequencies

Useful by-product

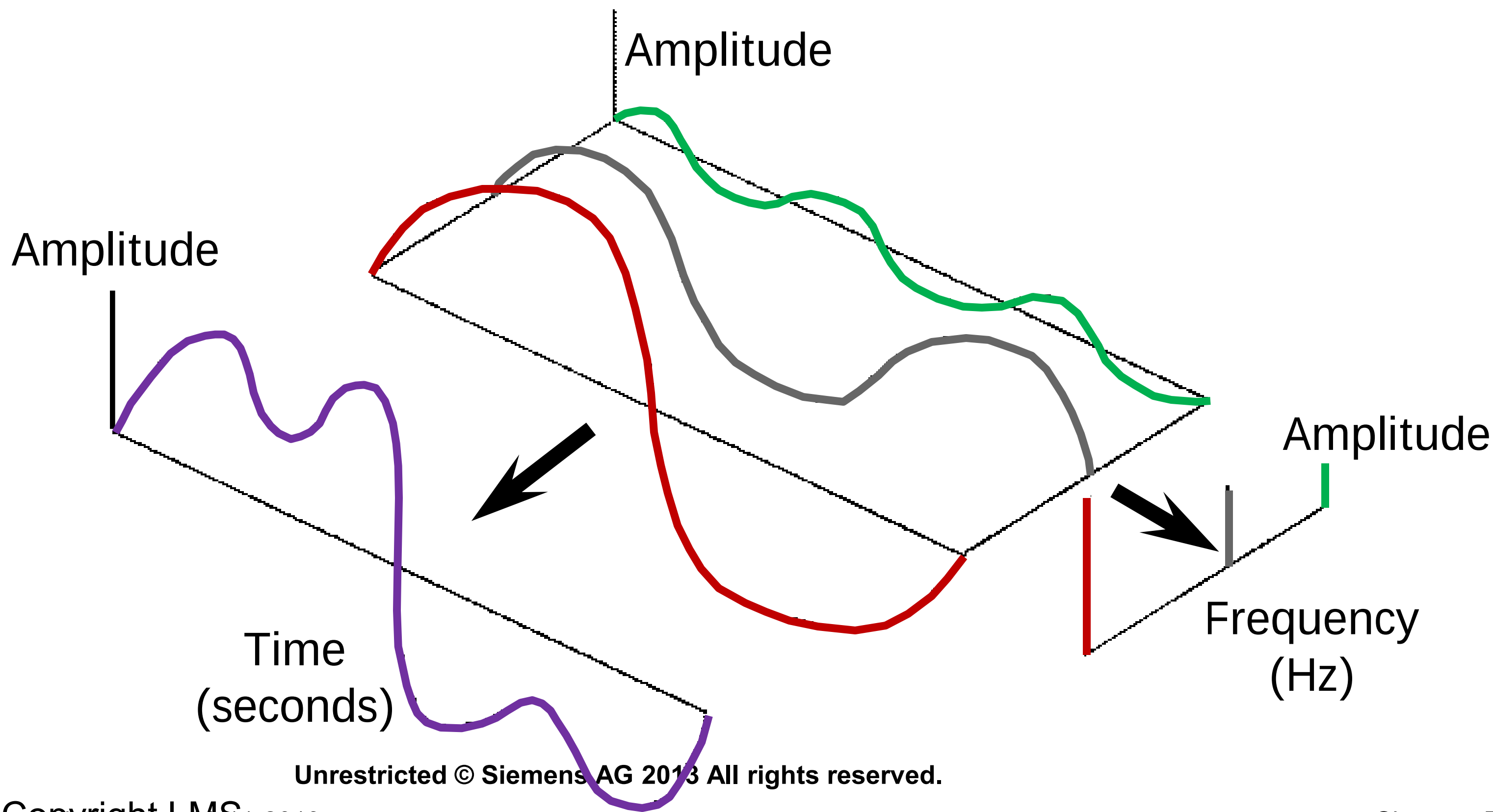
Fourier Transform

Transforms from Time Domain to Frequency Domain

Fourier: "Any signal can be described as a unique combination of sine waves of different frequencies and amplitudes"

Complicated signals become easier to understand

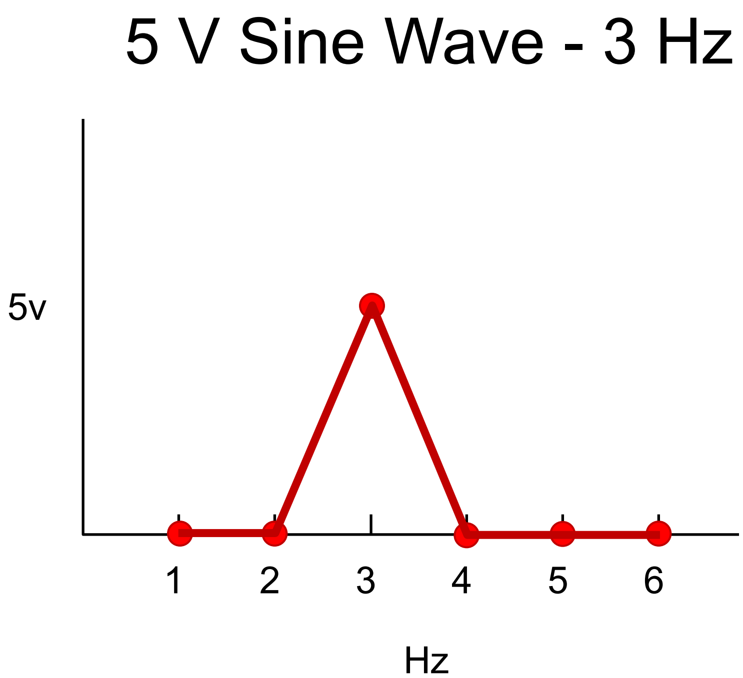
No information is lost when converting!

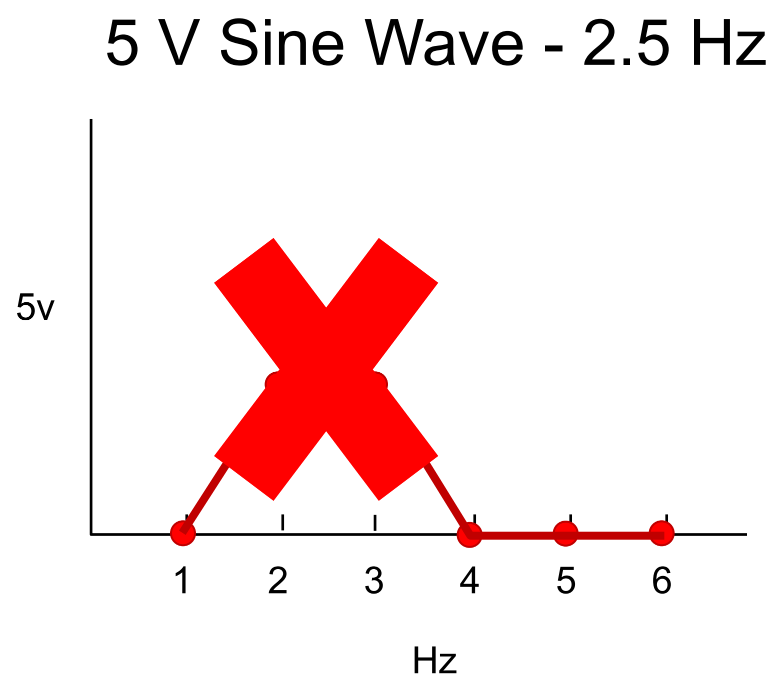


"What is Leakage?"

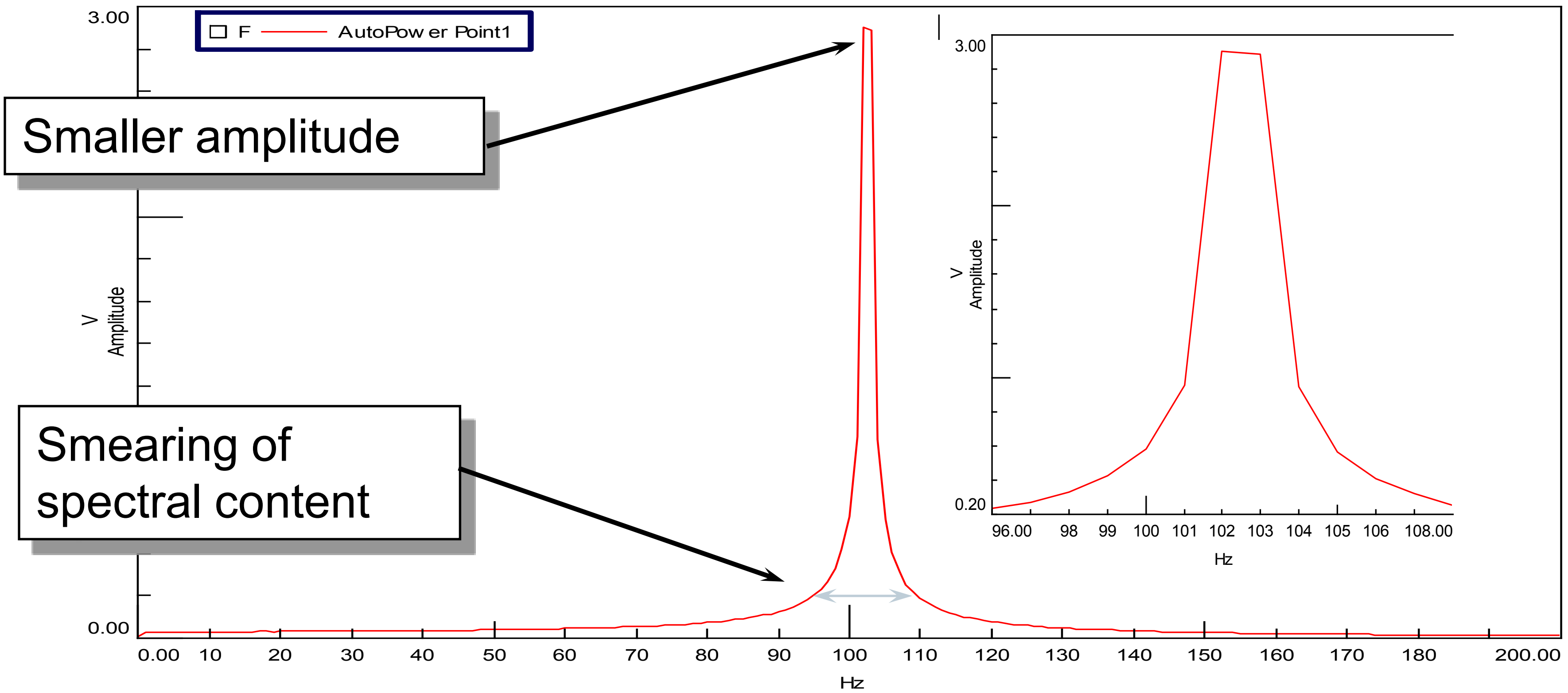
When the spectral content of your signal does not correspond to an available spectral line

$$\Delta f = 1\,\text{Hz}$$

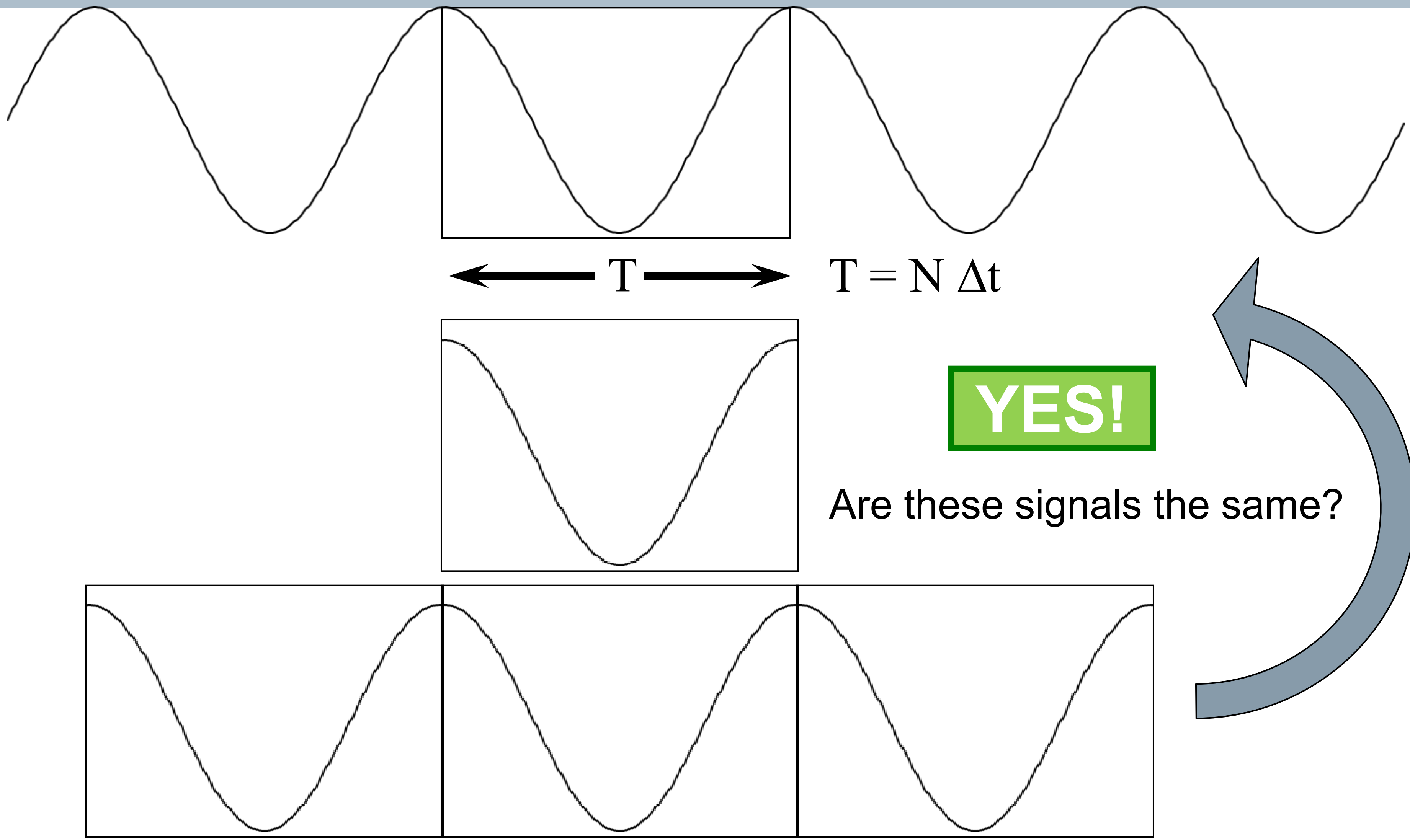




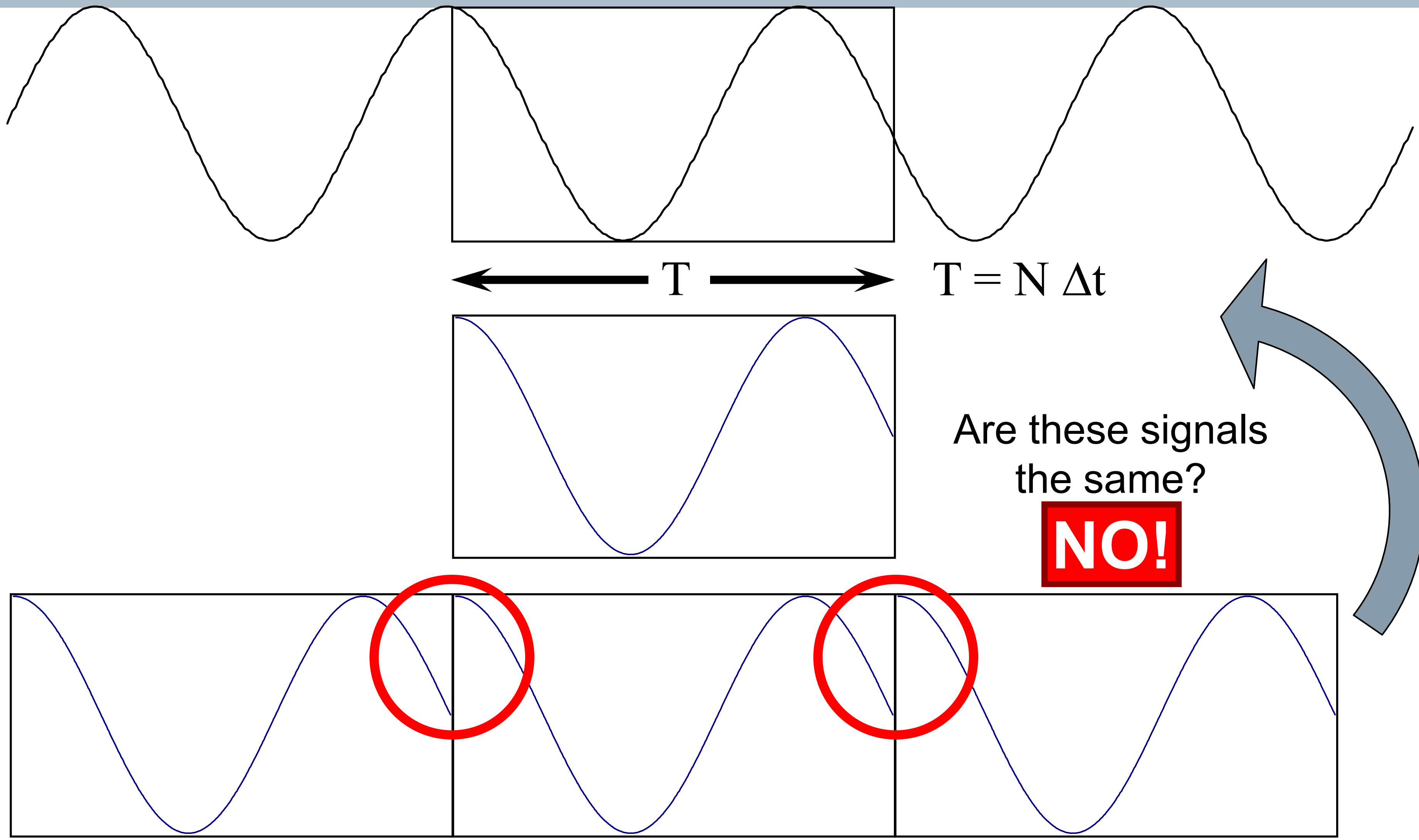
Non Periodic Signals – DSP Errors (Leakage)



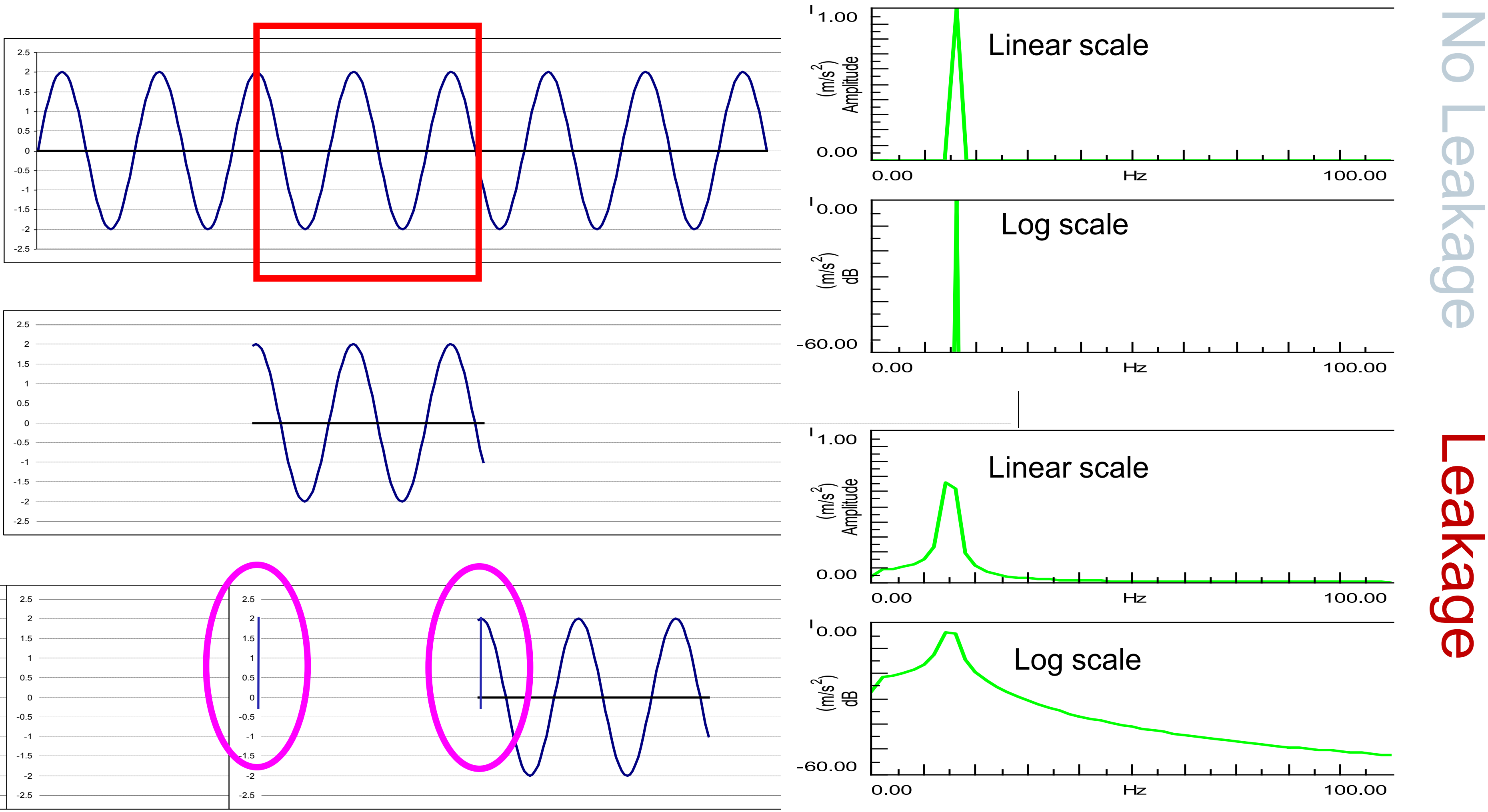
Periodic Signals



Non-Periodic Signals



Finite Observation – Side Effect



Leakage – Amplitude Uncertainty

Periodic observation

100% of amplitude

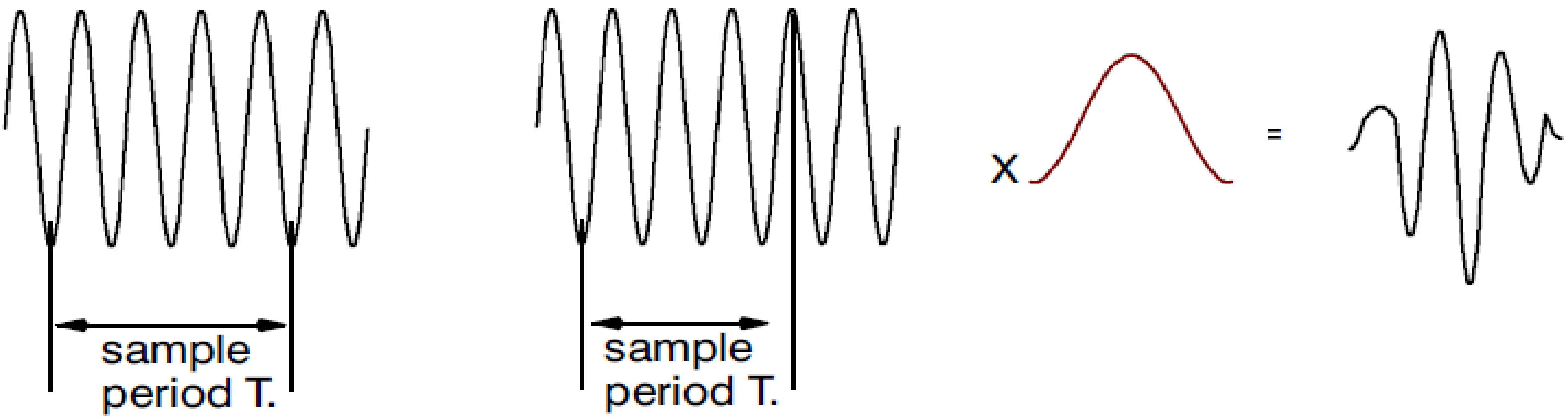
A-periodic observation

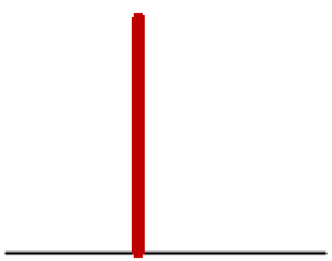
63% of amplitude

" Boss, this system is giving me something between 6 and 10g "

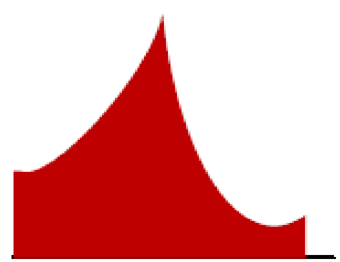
“How can we minimize the effects of leakage?”

A: Windows

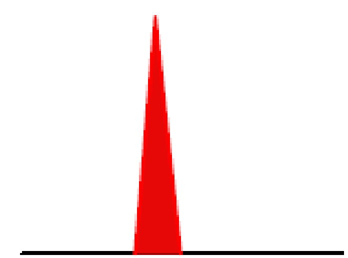




Frequency spectrum of a sine wave, periodic in the sample period T.



Frequency spectrum of a sine wave, not periodic with the sample period without a window.

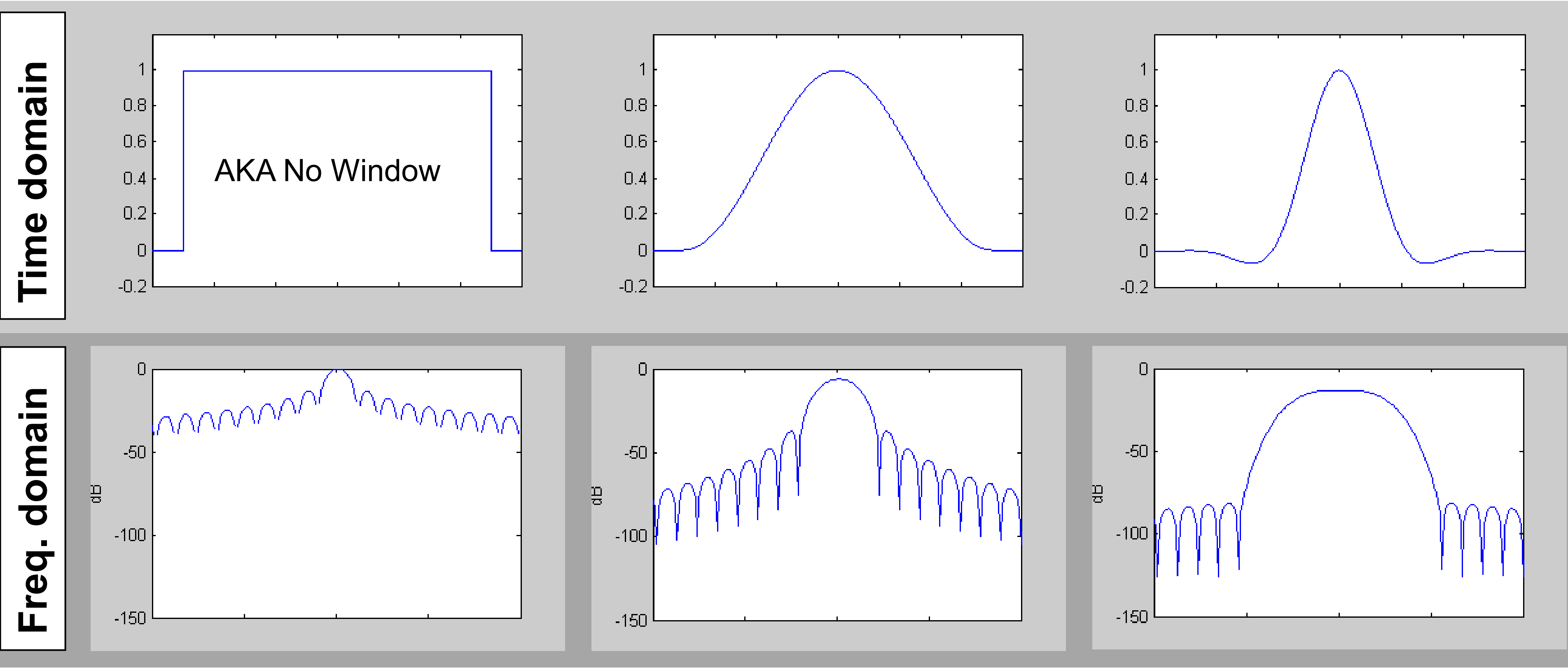


Frequency spectrum of a sine wave that is not periodic with the sample period *with* a window.

Window Types – Specific Characteristics

SIEMENS

Rectangular, uniform | Hanning | Flat top



Window Types – Specific Characteristics

SIEMENS

Window type	Highest side lobe (dB)	Sidelobe falloff (dB/decade)	Noise Band-width (bins)	Max. Amp error (dB)
Uniform	-13	-20	1.00	3.9
Hanning	-32	-60	1.5	1.4
Hamming	-43	-20	1.36	1.8
Kaiser-Bessel	-69	-20	1.8	1.0
Blackman	-92	-20	2.0	1.1
Flattop	-93	0	3.43	<0.01

Table 1.1 Properties of time windows

Windows distort the amplitude and total energy content of the data.

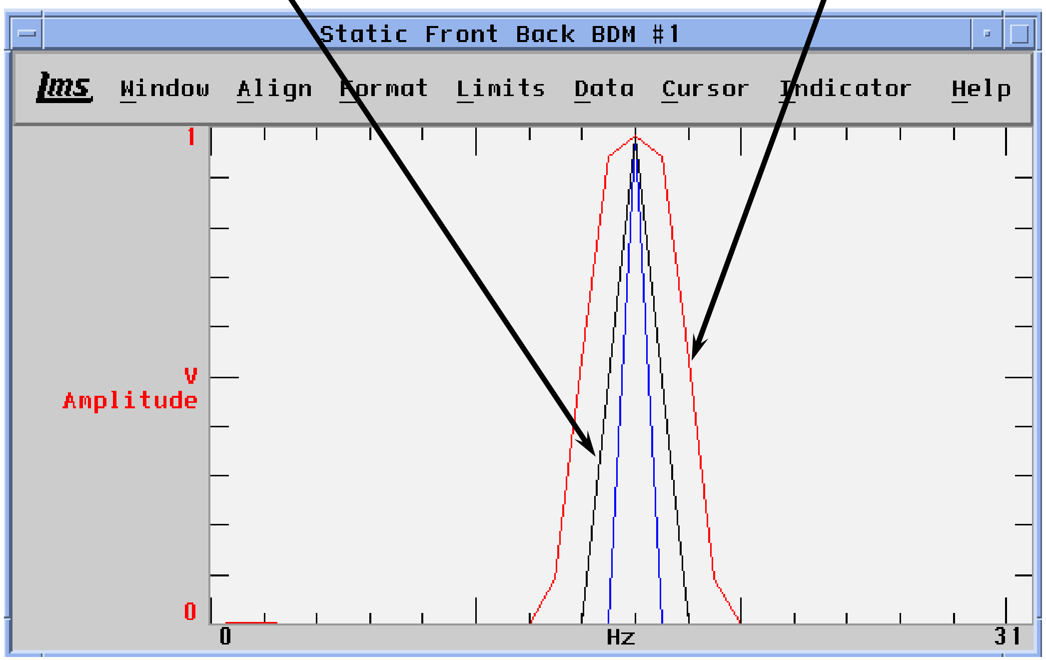
They also smear the frequency content.
This smearing cannot be corrected.

Windows

Windows limit spectral resolution

Hanning: 1.5 Δf
Up to 15% amplitude

Flattop: 3.4 Δf
Up to 0.02% amplitude

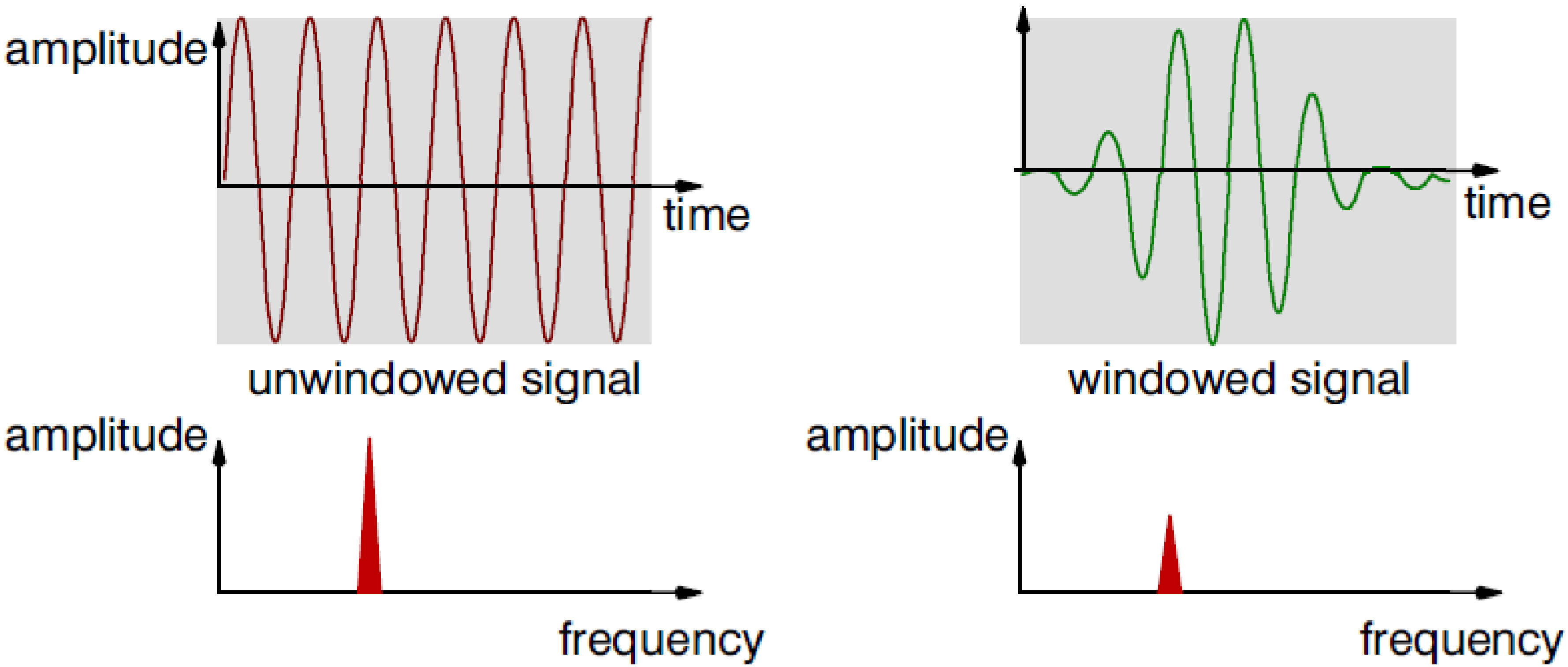


SIEMENS

Amplitude Errors

Amplitude correction

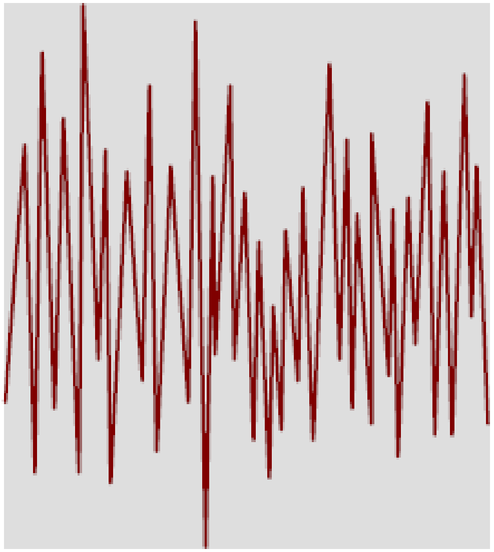
Consider the example of a sine wave signal and a Hanning window.



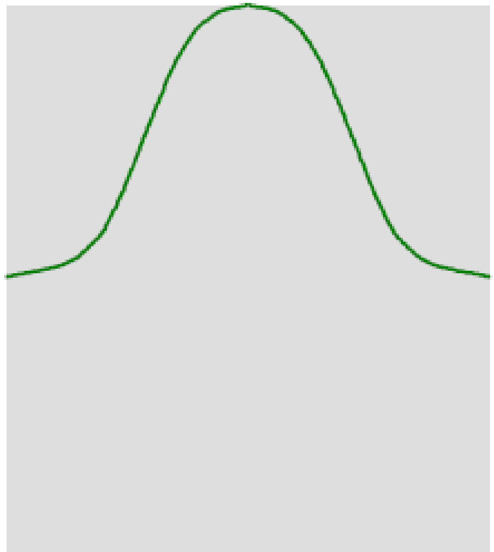
Energy Errors

Energy correction

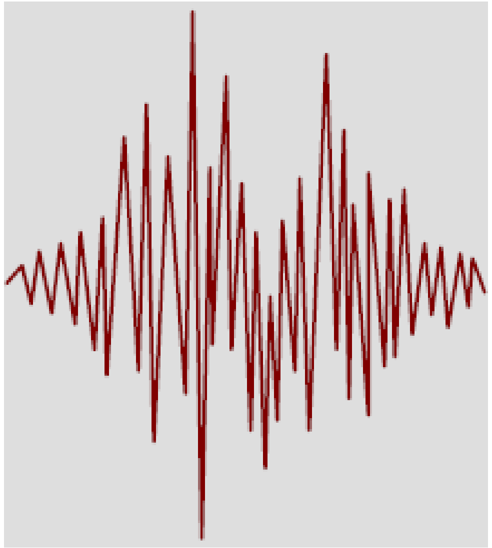
Windowing also affects broadband signals.



original signal



window function



windowed signal

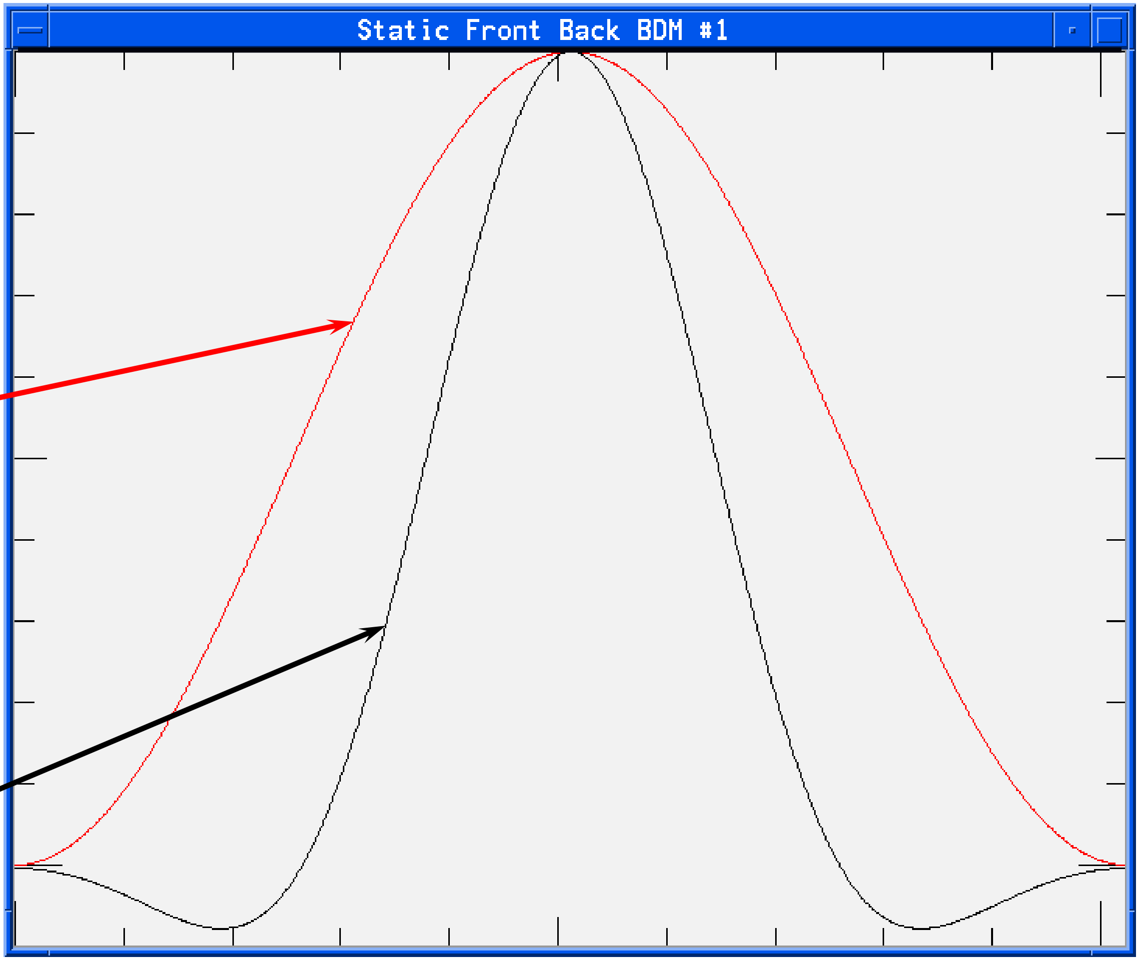
Examples of Windows

SIEMENS

Uniform
"No Window"

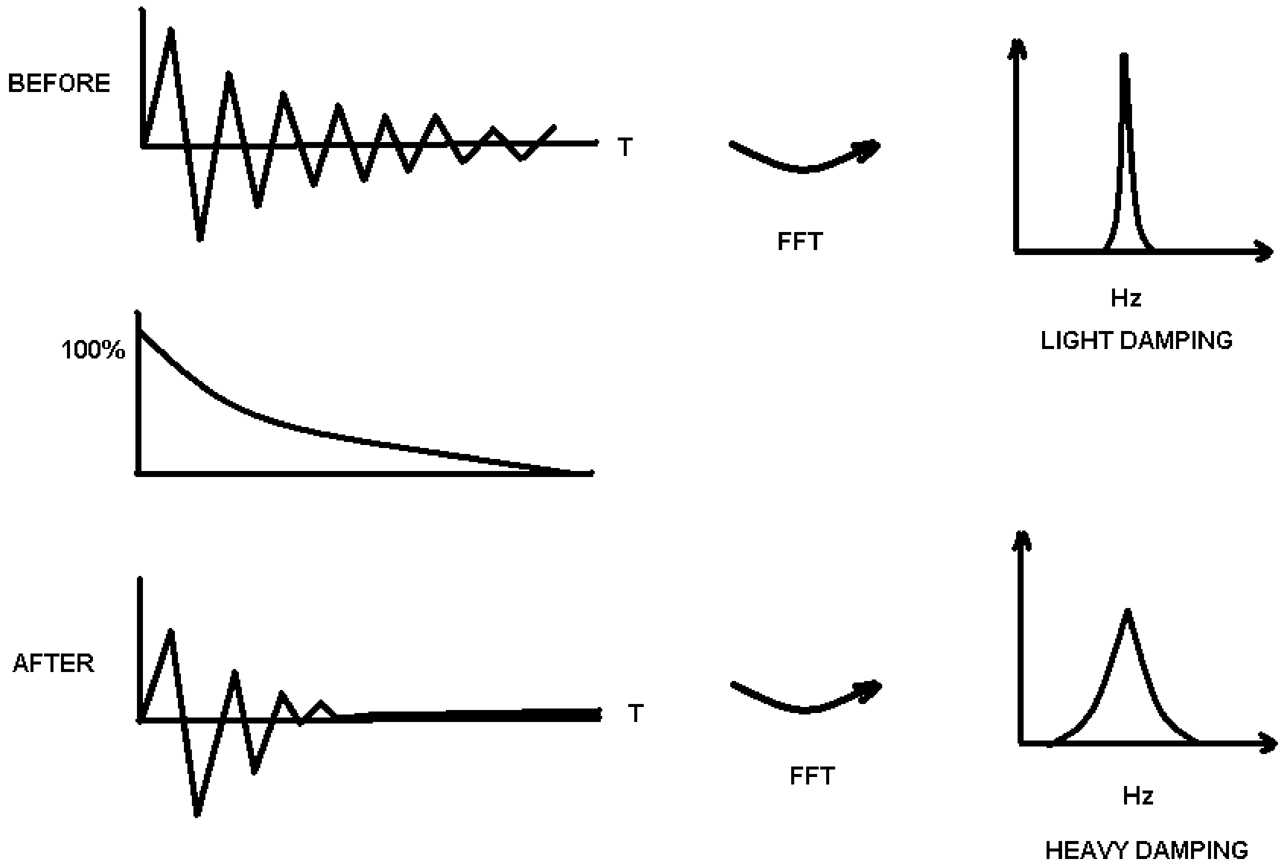
Hanning
"General Purpose"

Flattop
"Single Tone Frequencies"



Exponential Window for Response

Exponential Window



- **Exponential Window Increases Apparent Damping Values When Applied.**
- **Avoid Applying The Exponential Window Unless Absolutely Necessary.**

Tips for modal testing

Boundary Conditions – What are your goals?

SIEMENS

Real boundary conditions

- Flexibility of fixtures
- Added damping, stiffness, mass
- Environmental Conditions

Free-free suspension

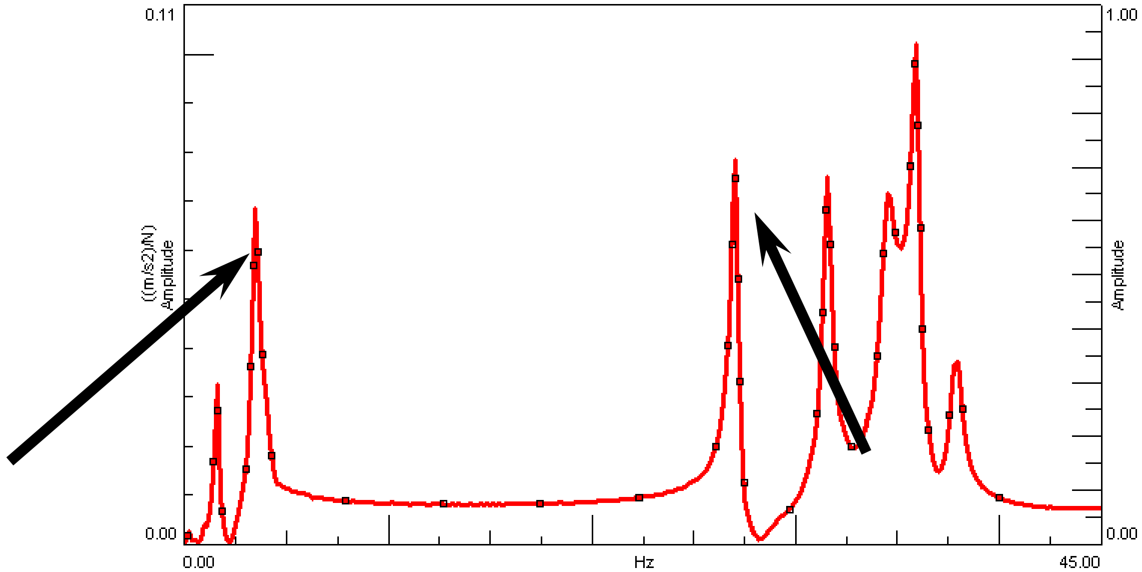
In practice: almost “free-free”

- Soft spring, elastic cord
- Pneumatic suspension
  - Correlation with FEM
  - Can Obtain Rigid Body Modes
  - Verification of Channel Setup (Sensor Direction)

Rigid Body Modes – Rigid Body Properties

<u>Free-Free Boundary Condition</u>

- Approximation of a true "Free System" (FEM)
- Rigid Body Modes Are No Longer Zero – Negligible Effect on Flexible Mode



Rigid body mode frequency < 10 % of first flexible mode

Some Practical Examples – Simulating Free-Free

Elastic cords

Pneumatic suspension

Frequency Response Function - Considerations

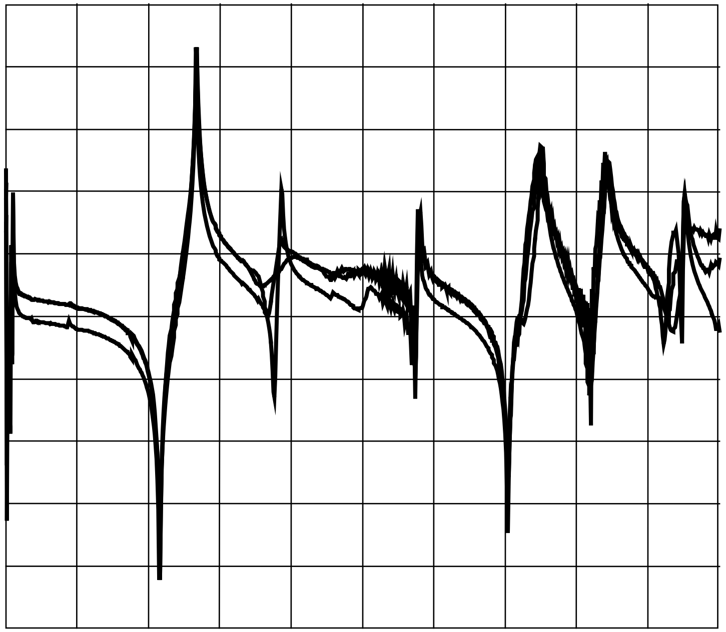
Time invariance…

- Will I get the same measurement tomorrow?
- Is the measurement repeatable?

Is the system linear?

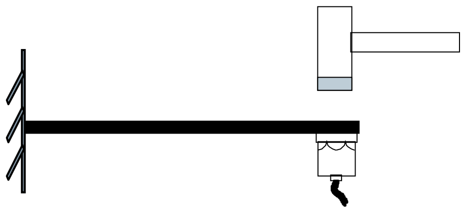
- Different force levels can have an effect (i.e. rubber bushing).

Does reciprocity hold true?



Driving Point FRF

Driving Point FRF is when the excitation point equals the response point



Magnitude

Real

Phase

Imaginary

Anti-resonances occur between every resonance

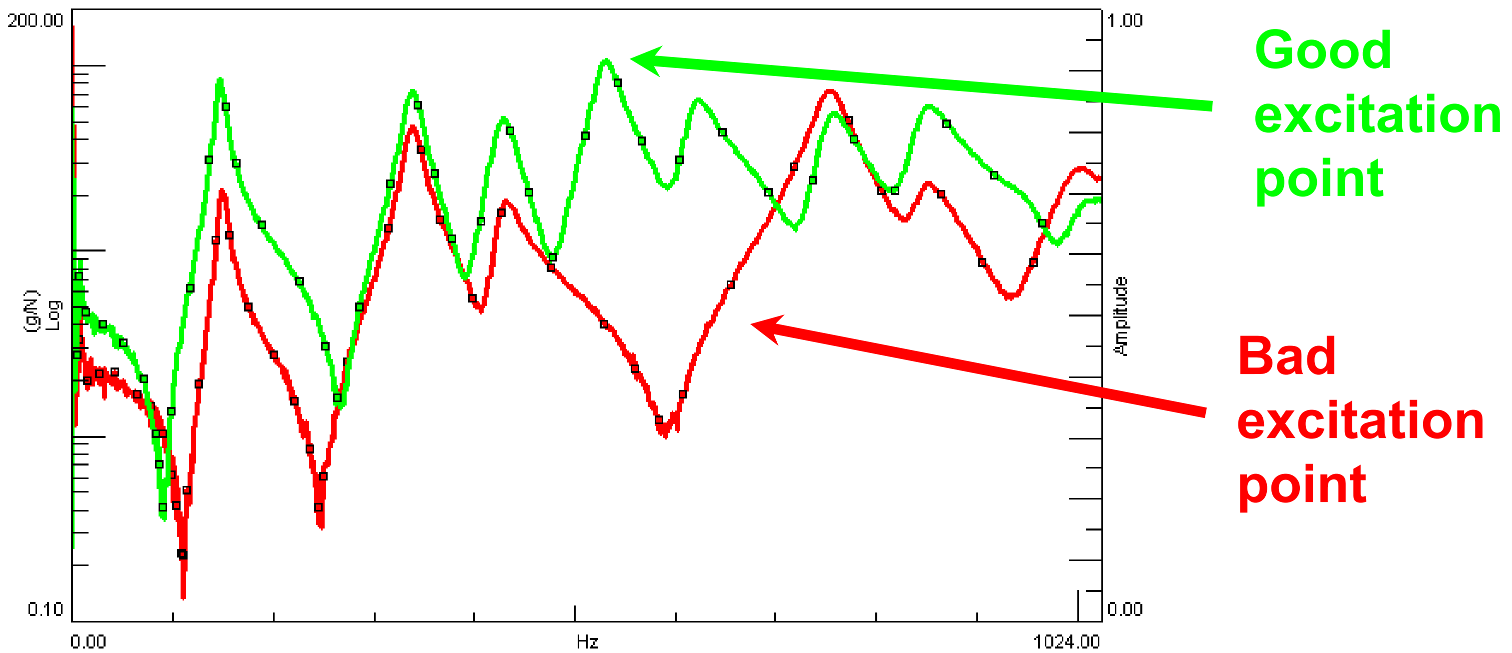
Phase is combination of SDOF systems with phase information pointing in same direction

At least 1 driving point necessary for modal scaling

Driving Point FRF

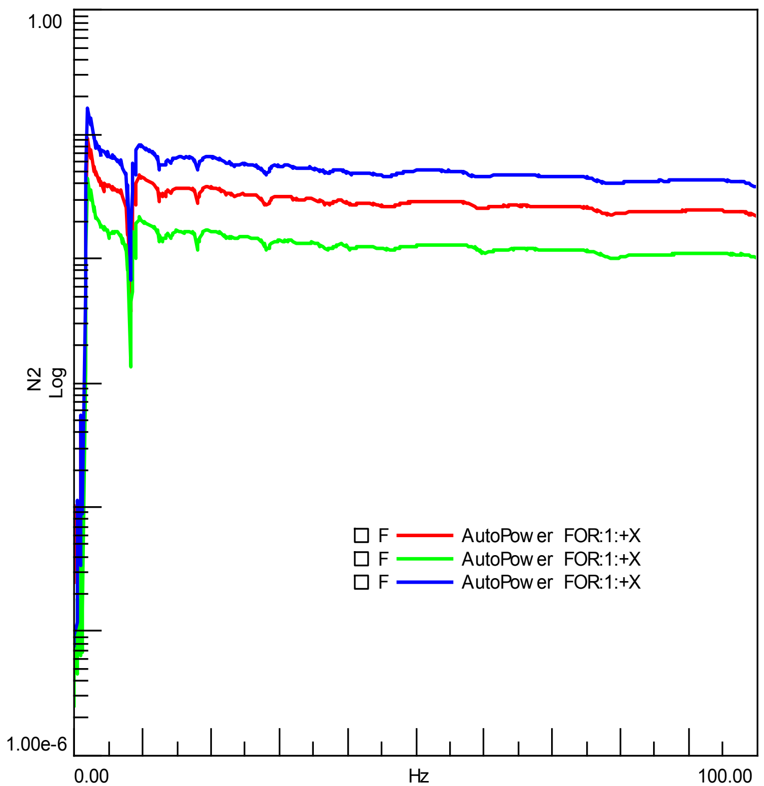
Selection and verification of excitation locations

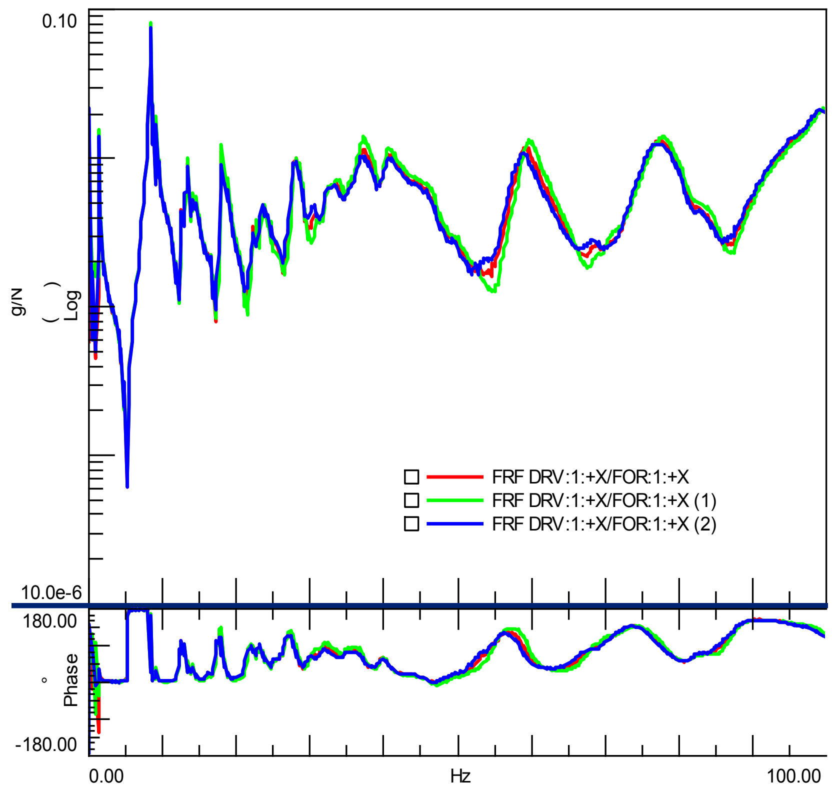
- Are all modes present in driving point FRF ?
- At nodal point: mode is not excited
- Spatially separated



Measure Driving Points for a number of positions and compare FRFs

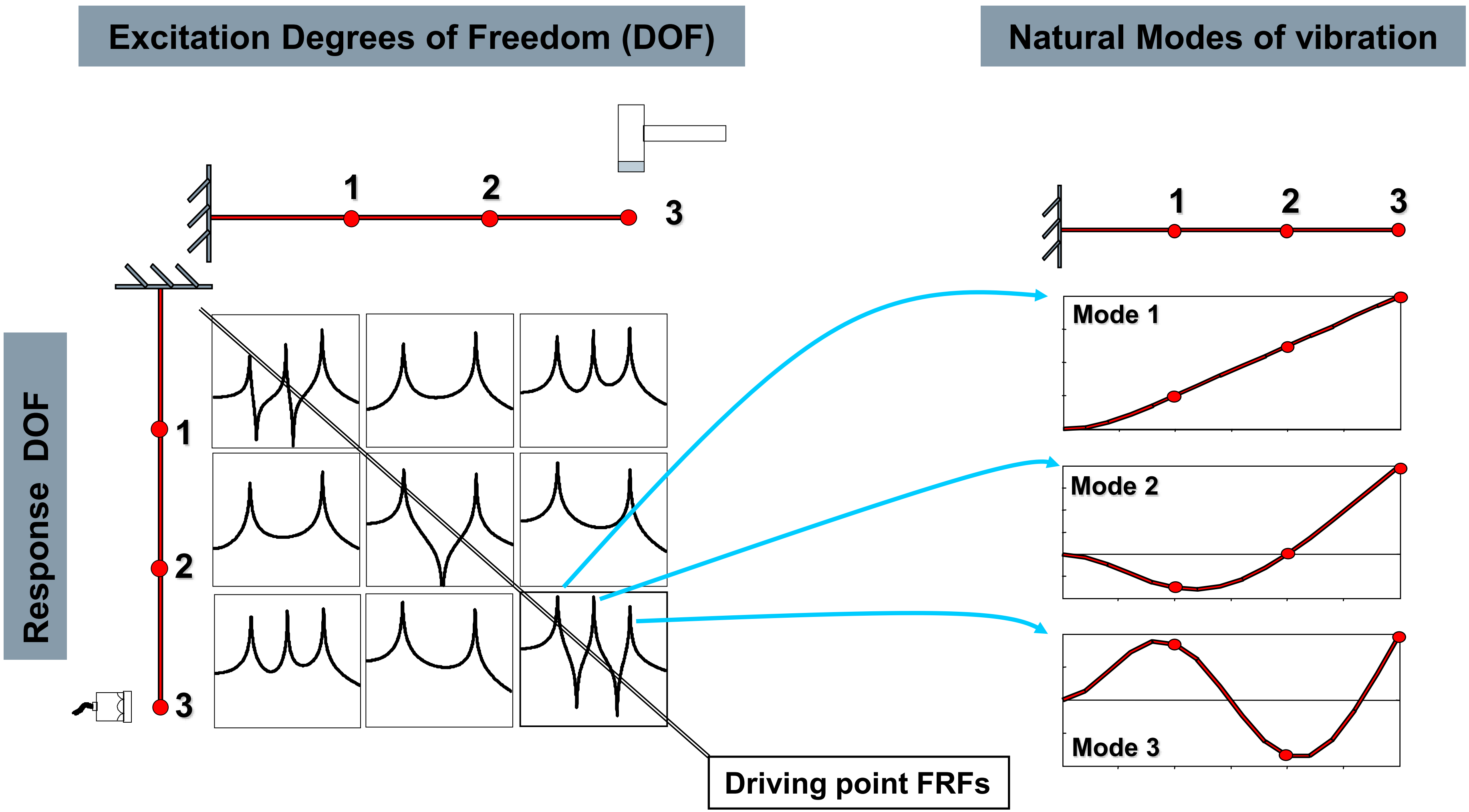
Linearity of the FRF



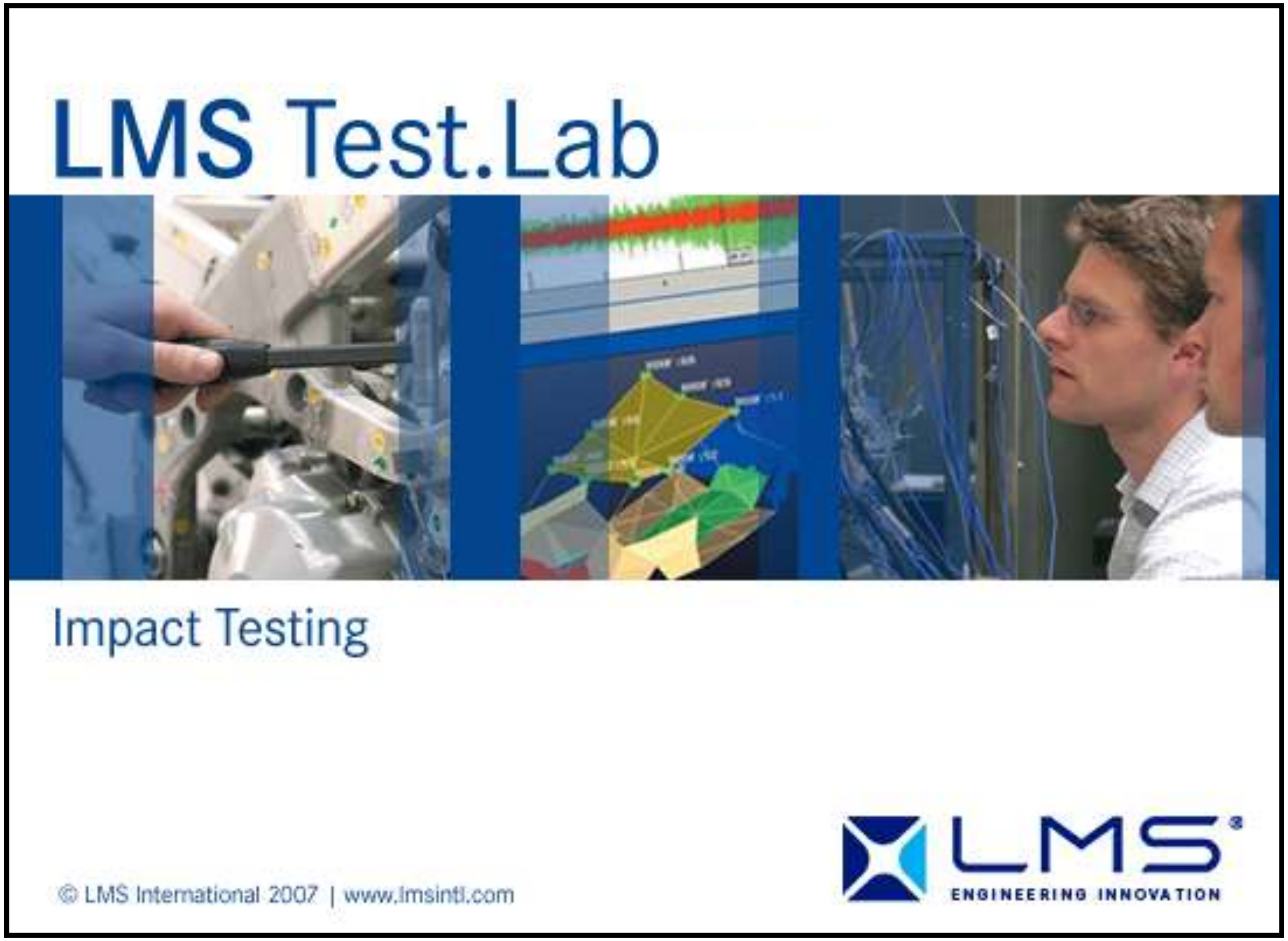


3 different excitation levels

Measuring of Frequency Response Functions

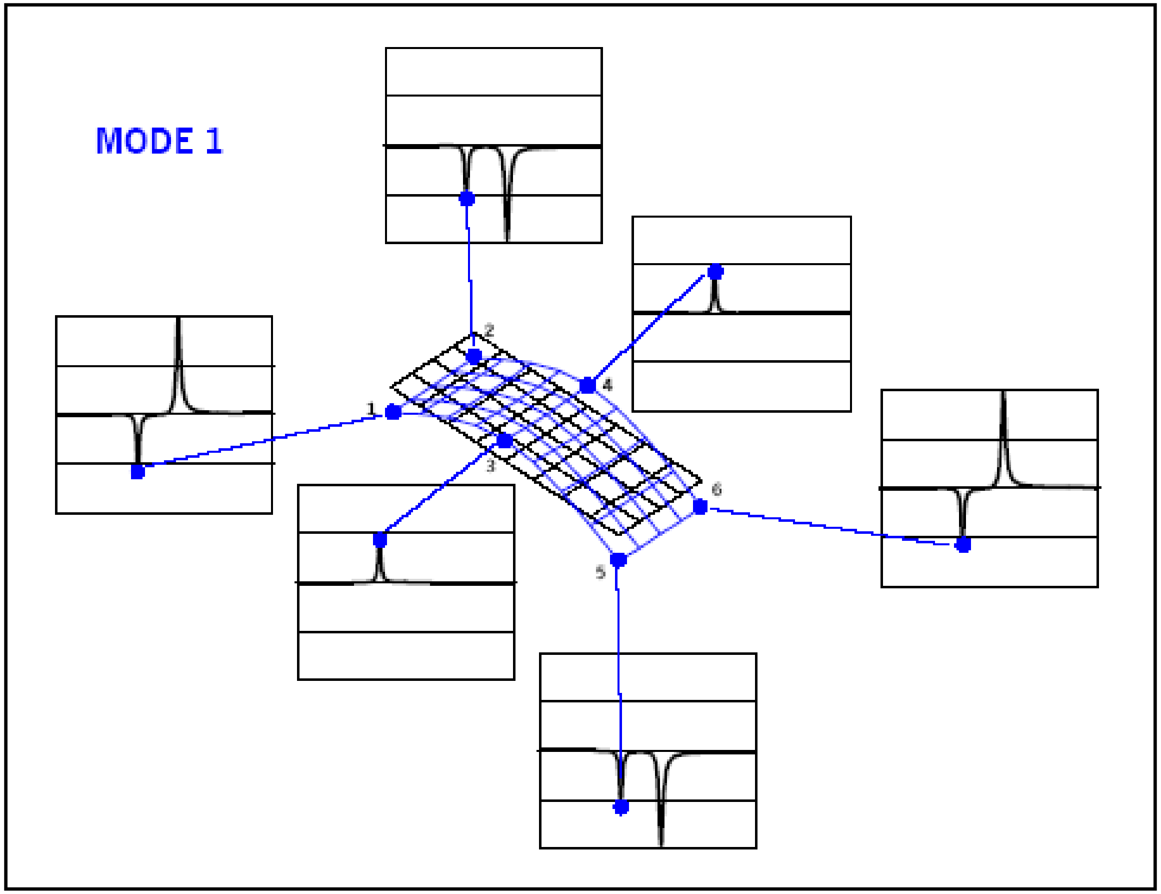


DEMONSTRATION: Modal Impact Test



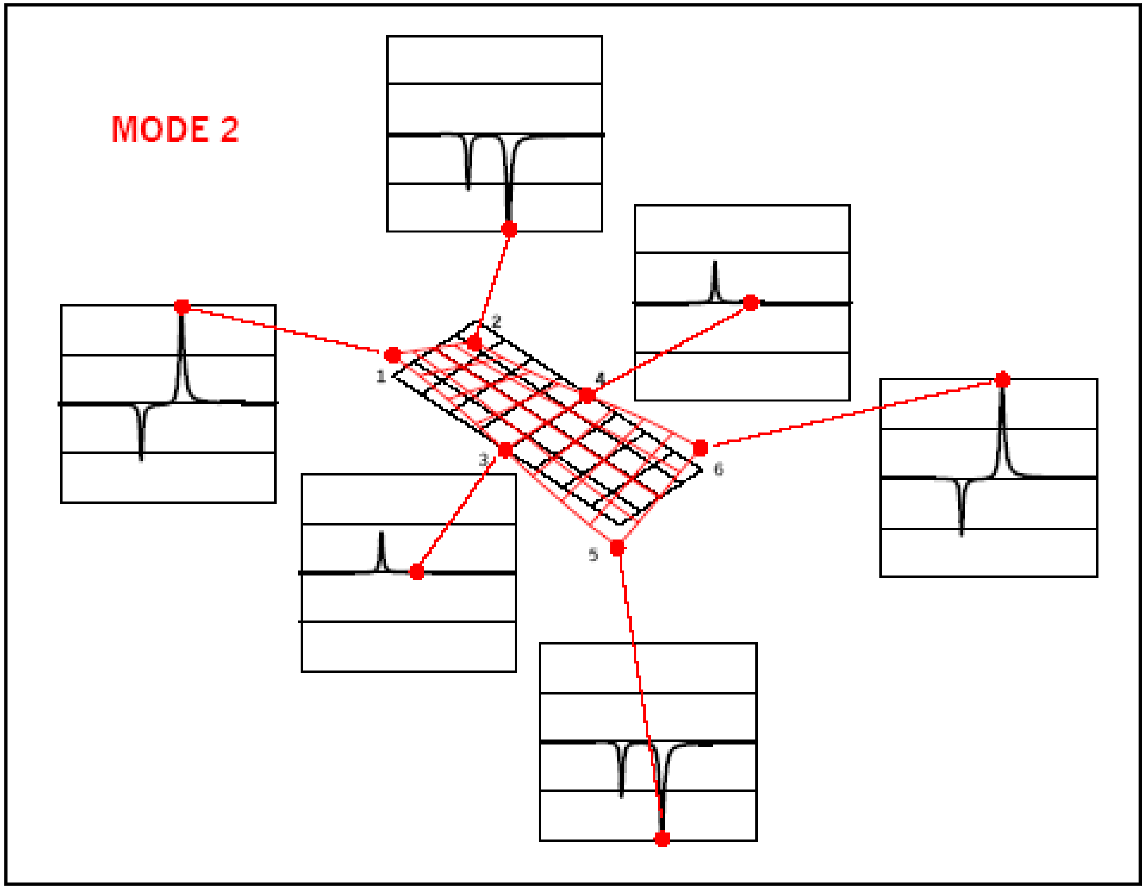
SDOF Peak Picking

Calculation of mode shape



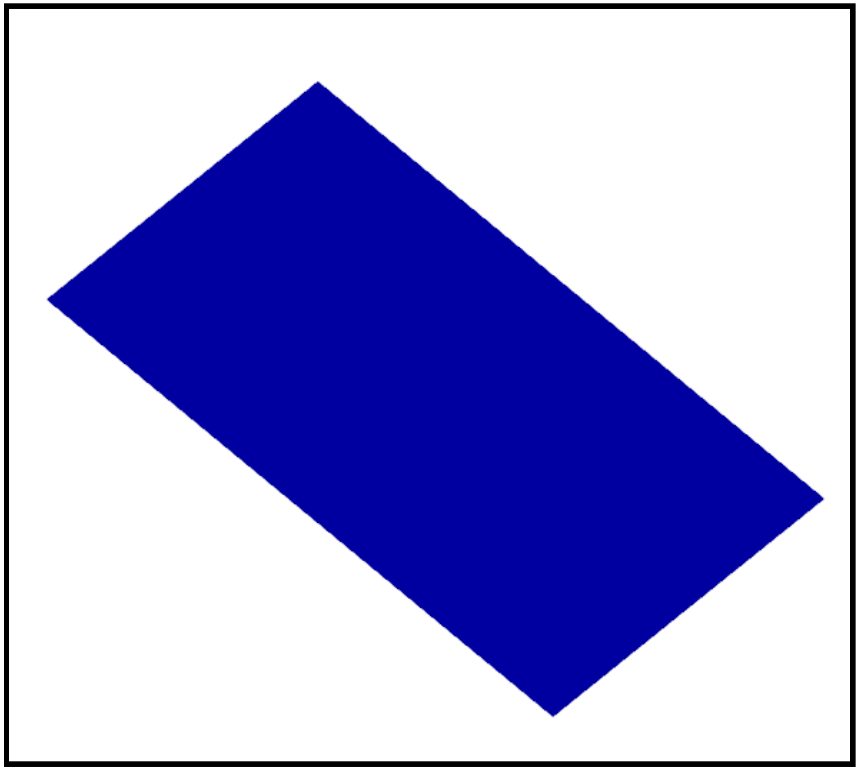
1st Bending Mode

Calculation of mode shape



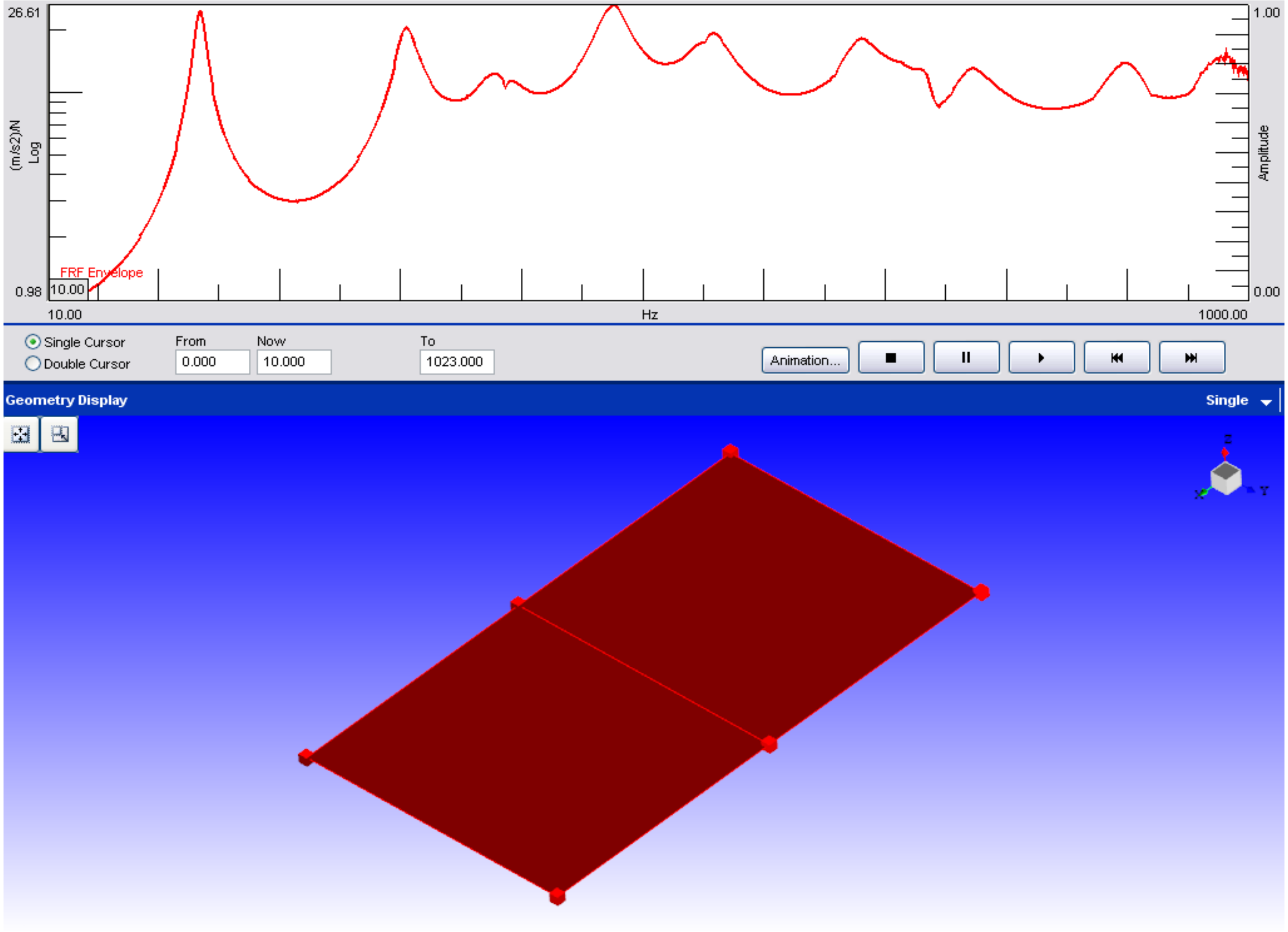
1st Torsional Mode

Experimental Modal Analysis



How do we know we have enough measurement points for our test?

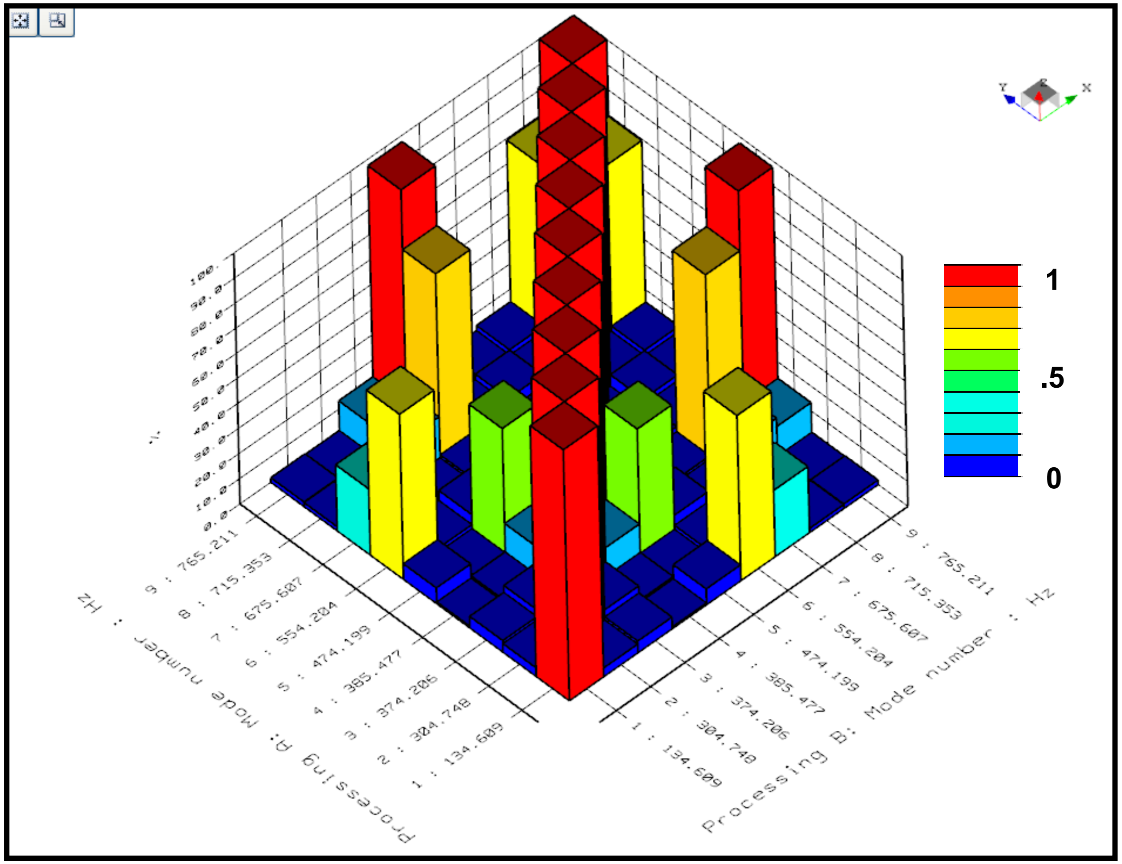
DEMONSTRATION: SDOF Peak Picking on Plate (6 points)



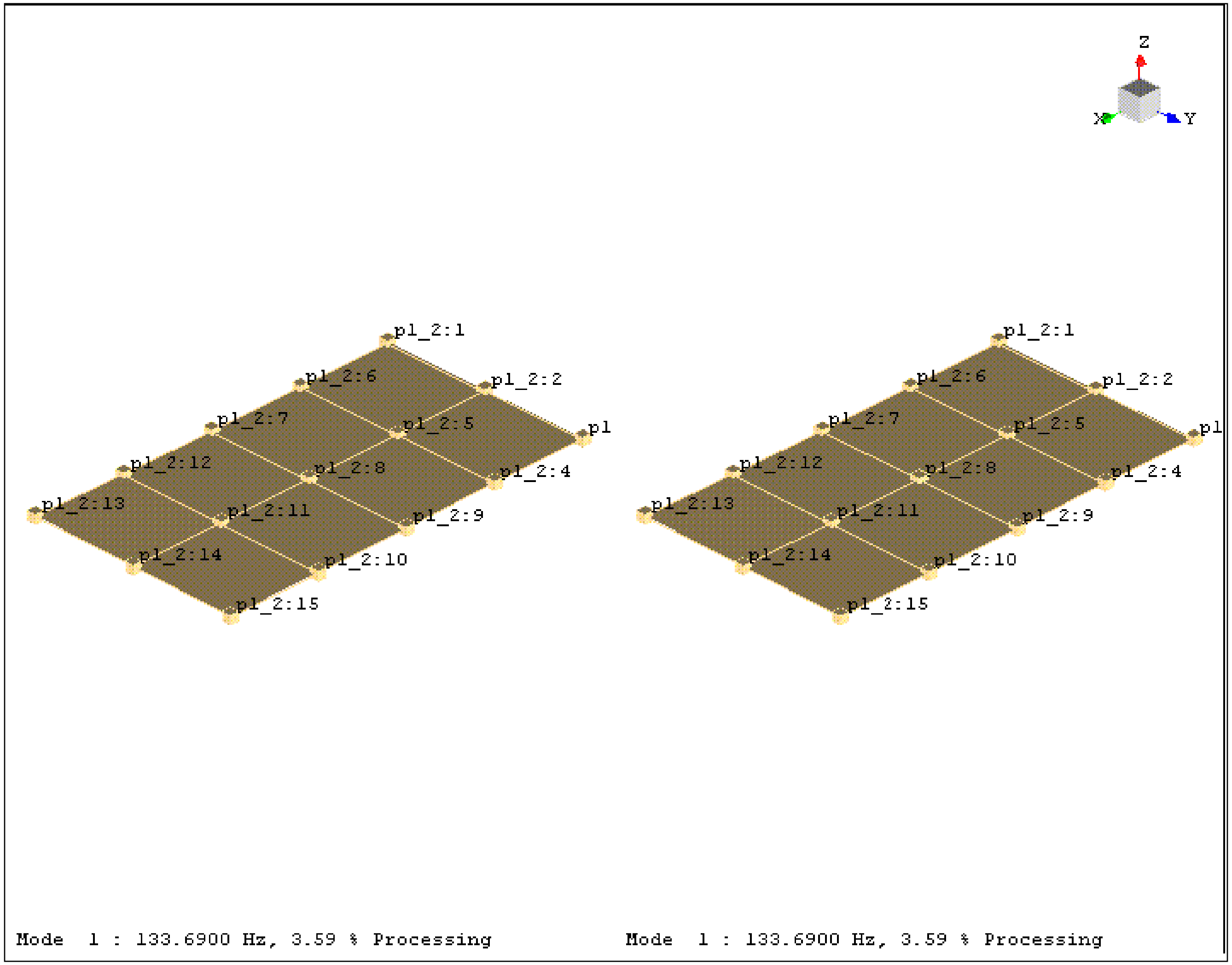
Why are rigid body modes seen at

Modal Assurance Criterion

- **Modal Assurance Criterion (MAC)** describes how similar the shapes are for a given mode pair using a scale of 0 to 1 (e.g. 0% to 100%)

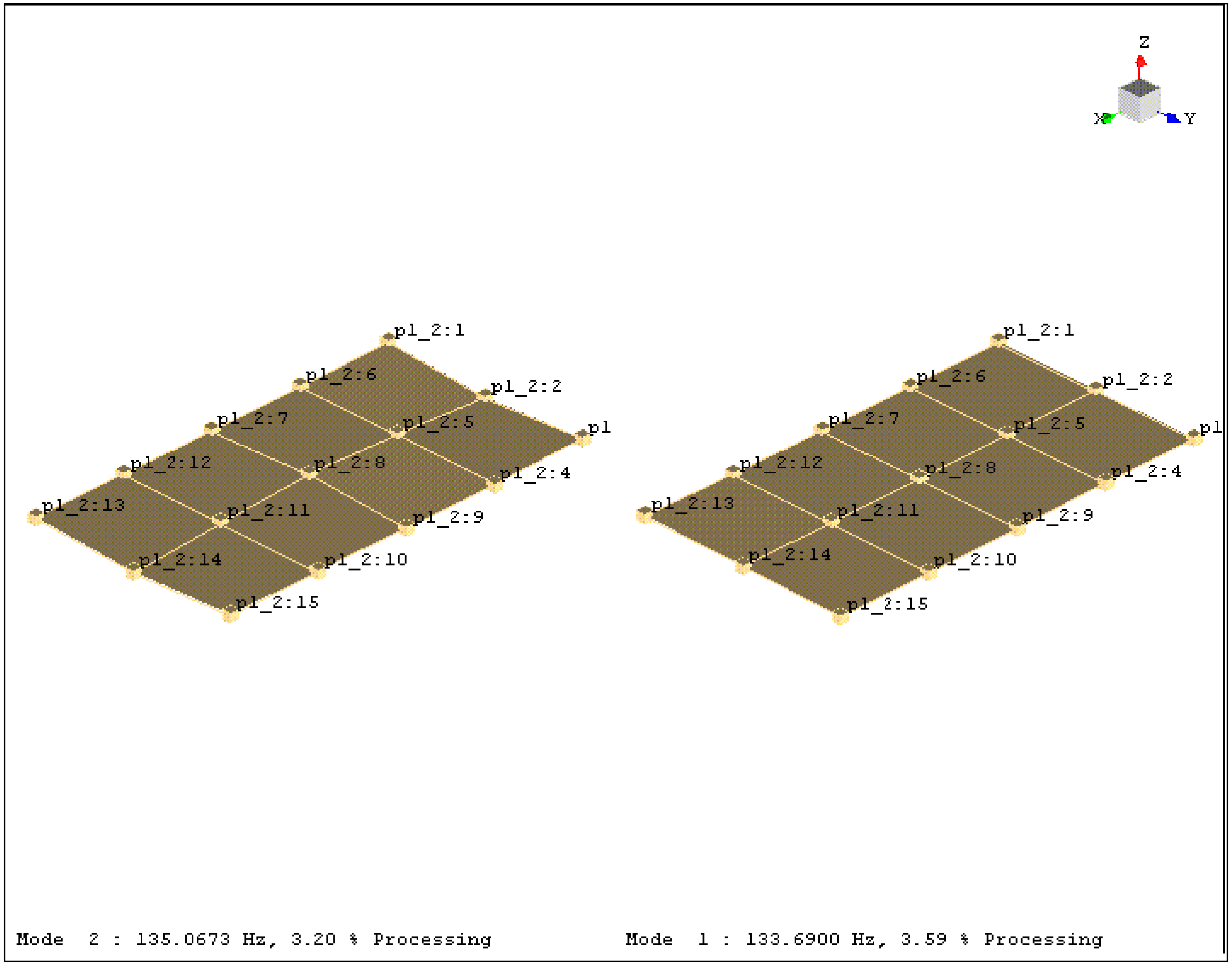


MAC Example



MAC = 100% correlation

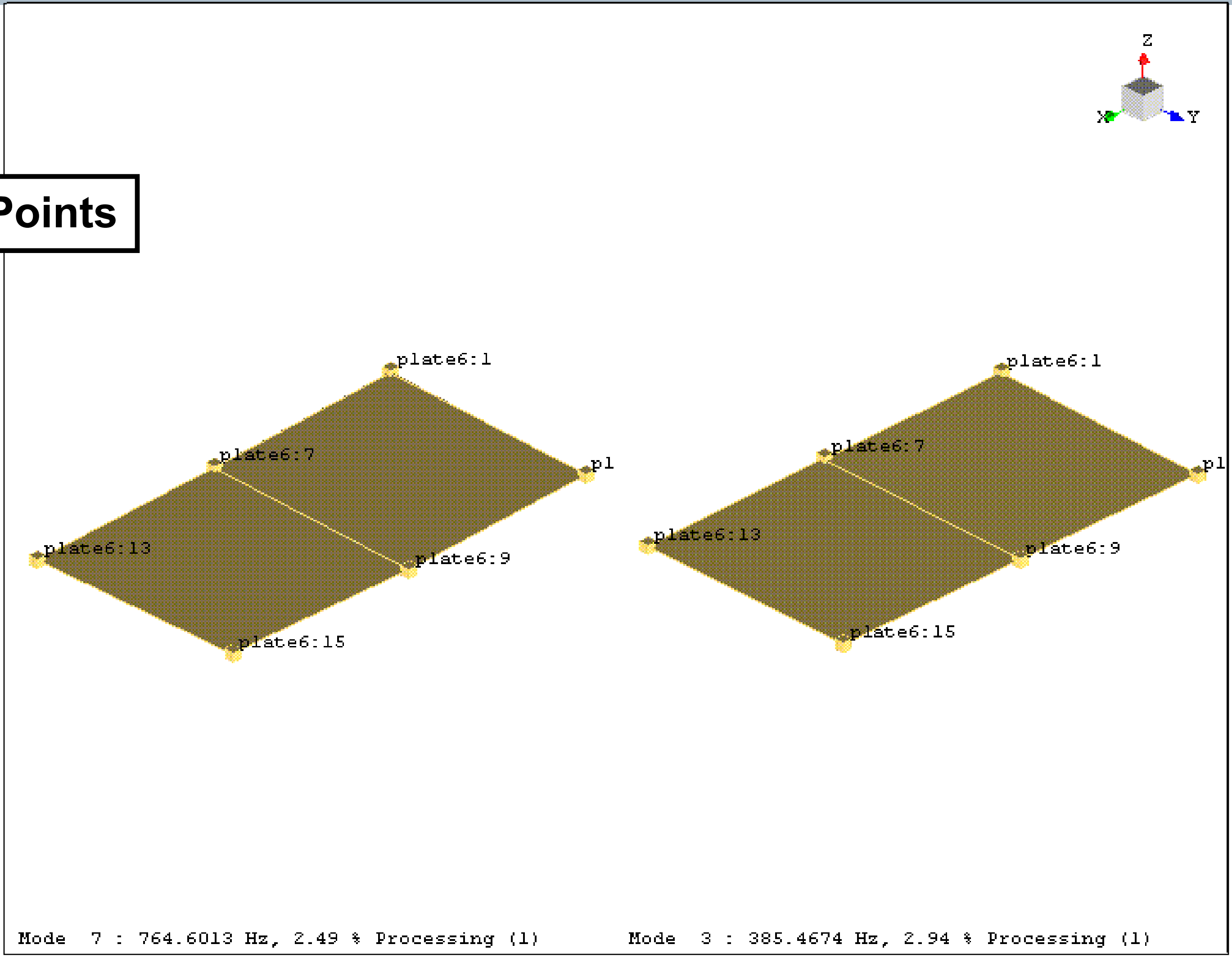
MAC Example



MAC = 0.015 (1.5% correlation)

MAC Example

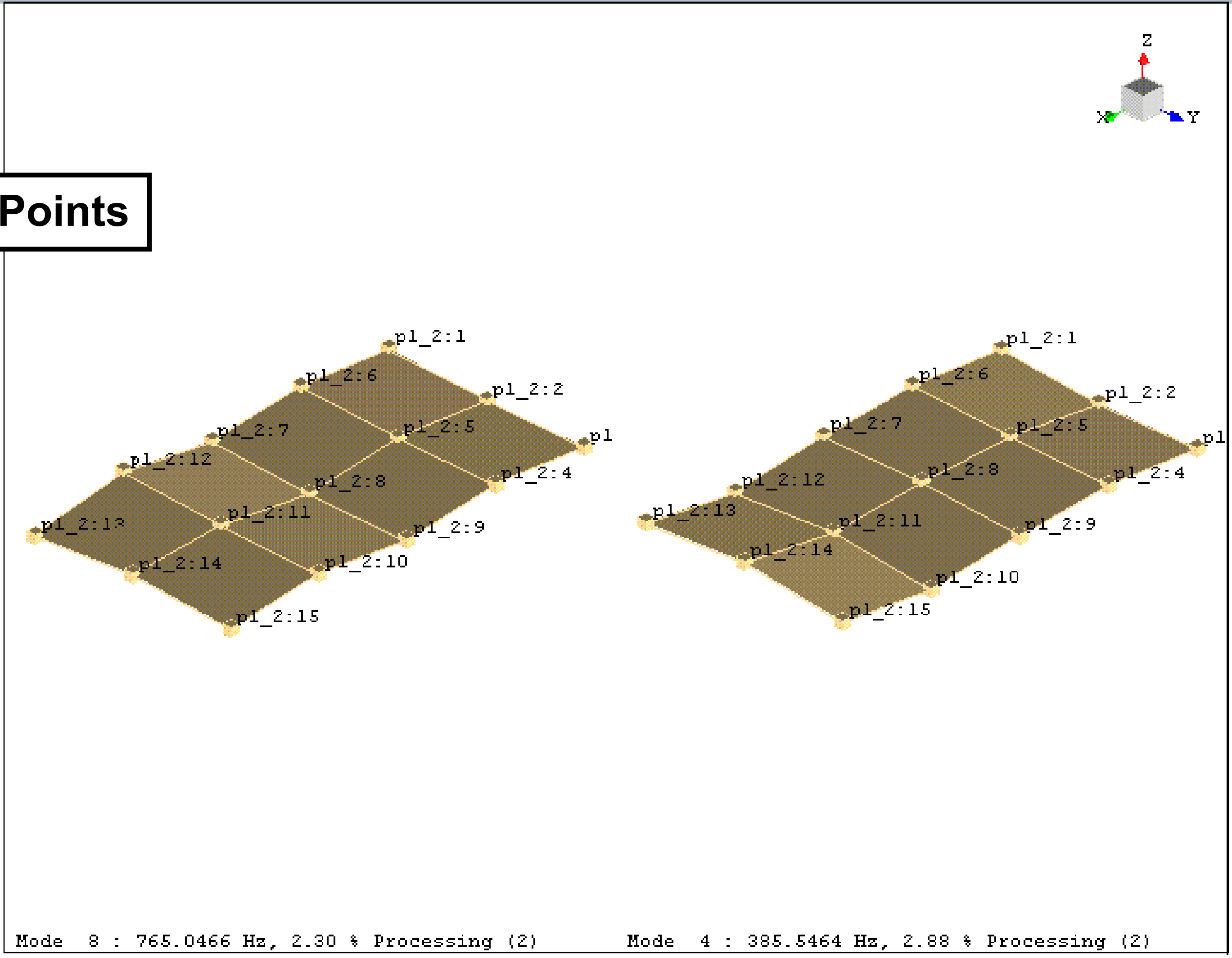
6 Points



764 Hz and 385 Hz - MAC = 0.96 (96% correlation)

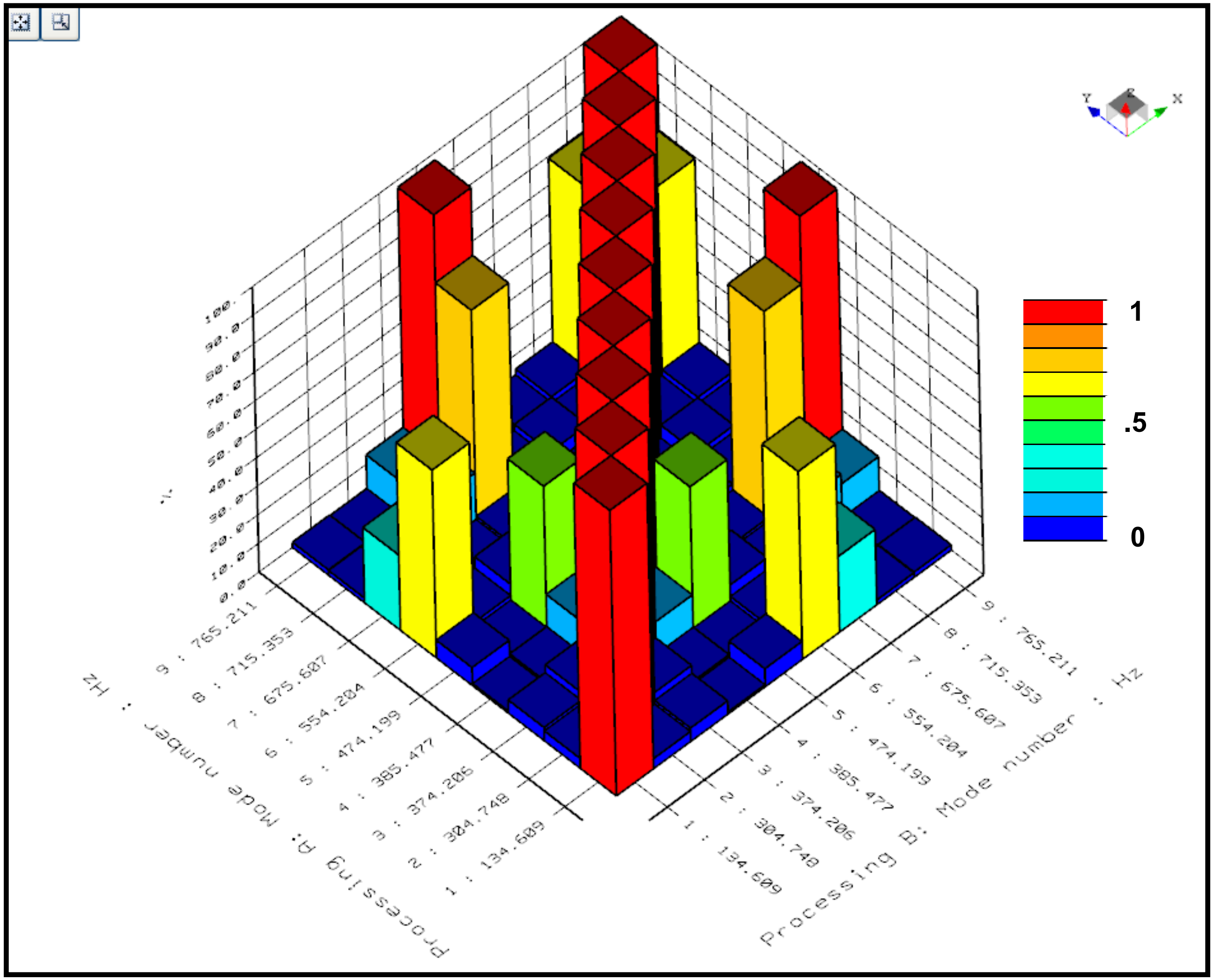
MAC Example

15 Points



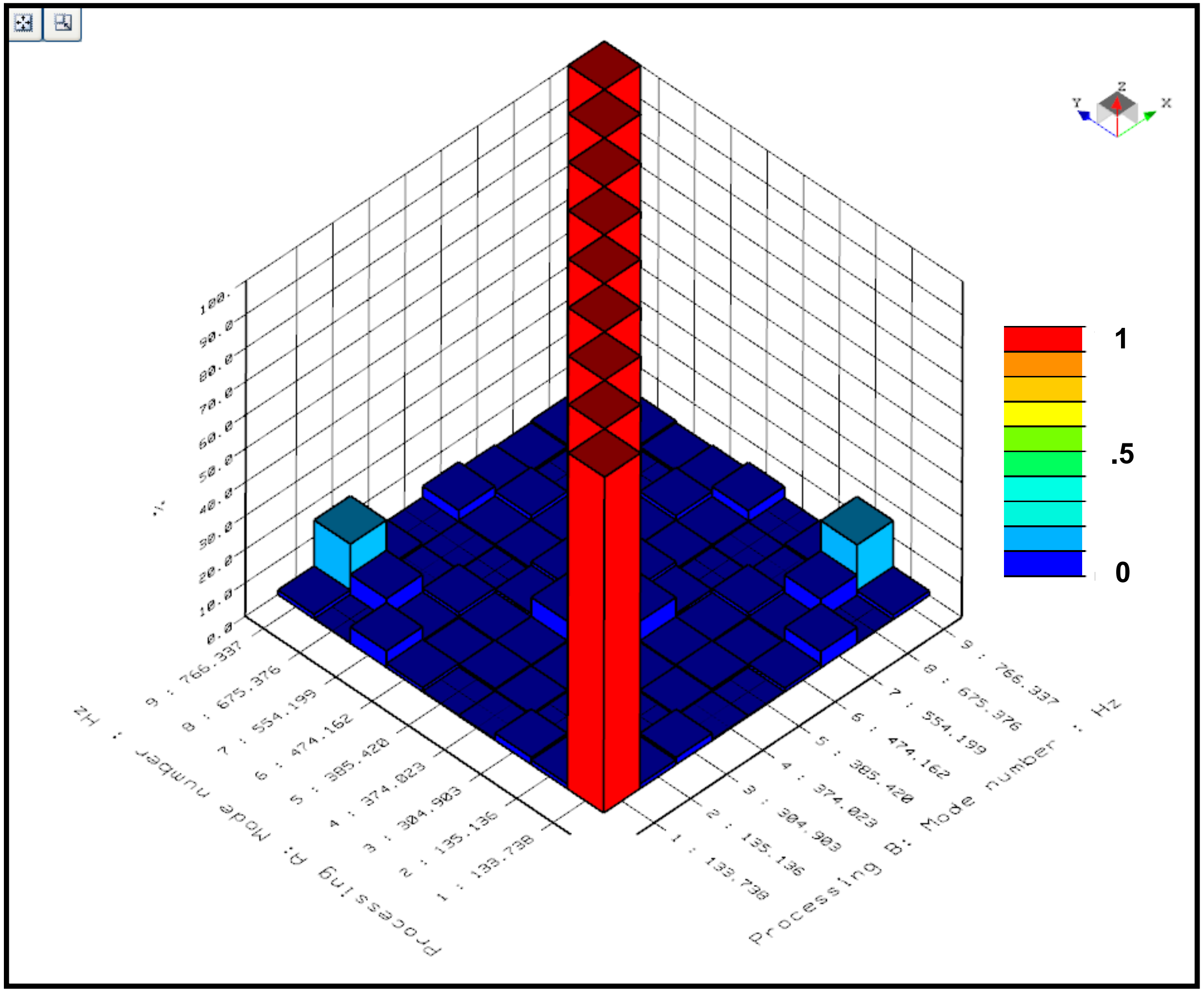
764 Hz and 385 Hz - MAC = 0.03 (3% correlation)

MAC for flat plate with 6 DOFs



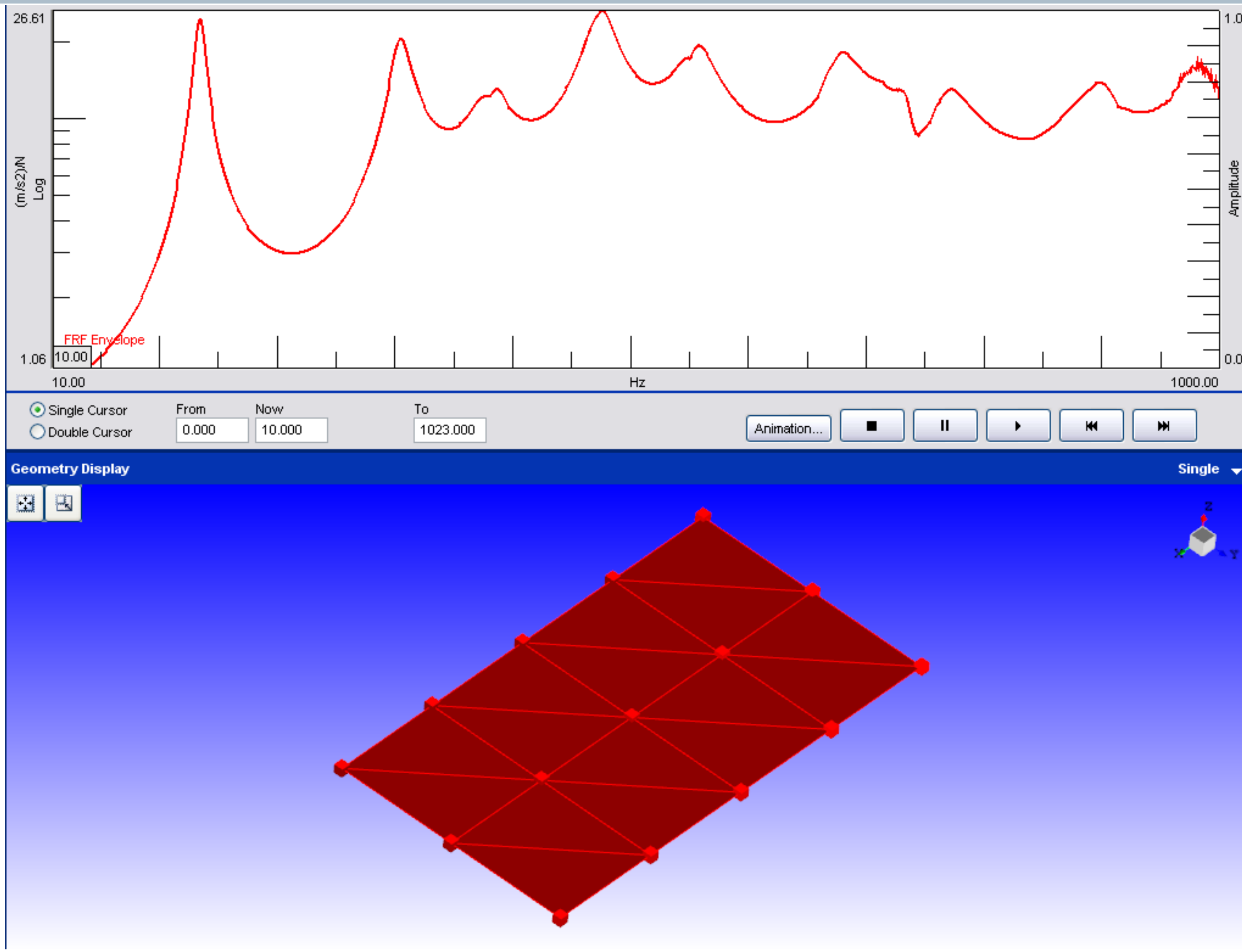
Spatial Aliasing – not enough response points

MAC for flat plate with 15 DOFs



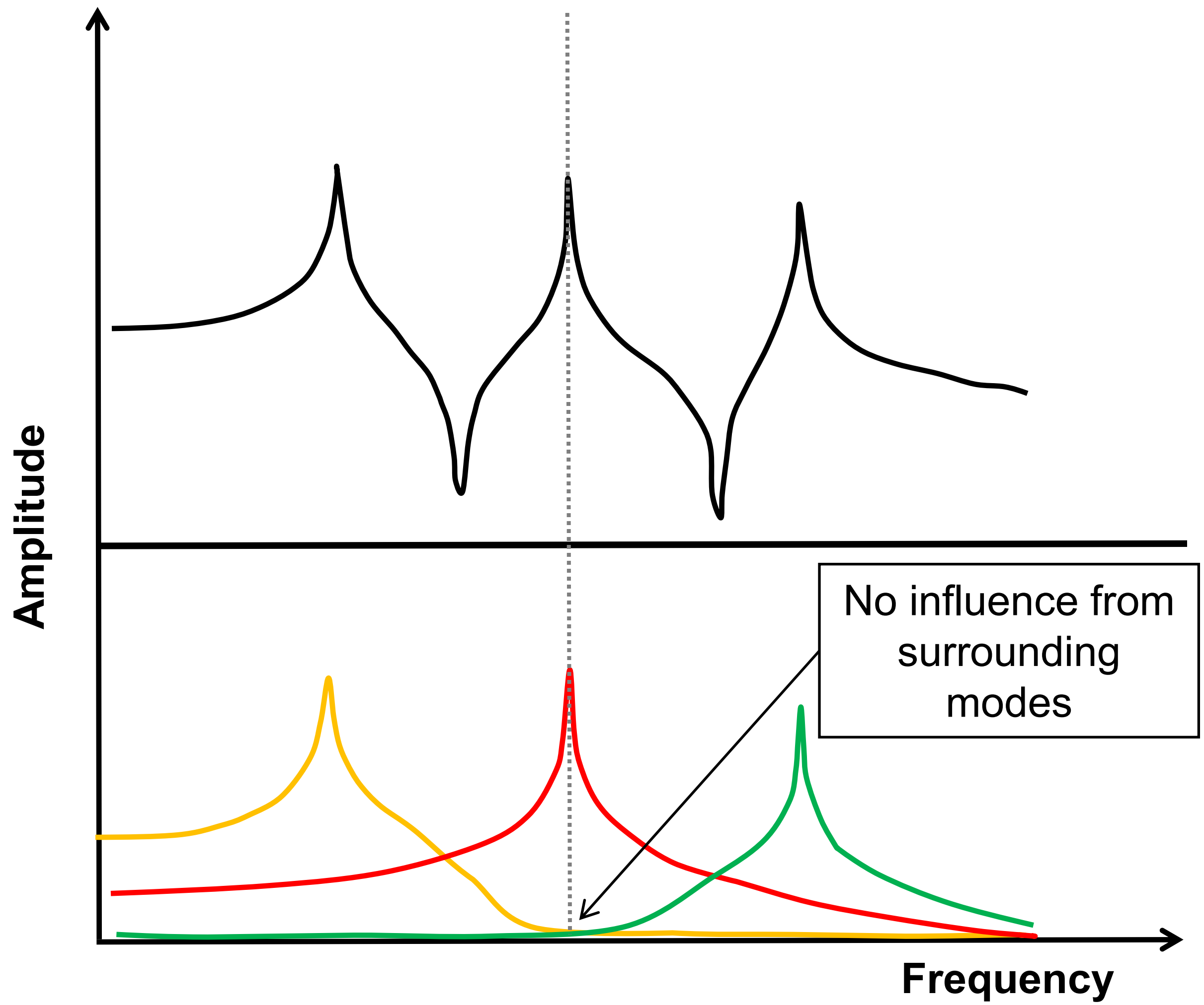
No High Off Diagonal Correlations

DEMONSTRATION: SDOF Peak Picking on Plate (15points)

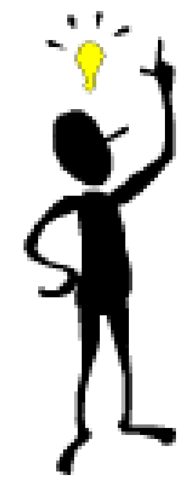


MDOF Curve Fitting

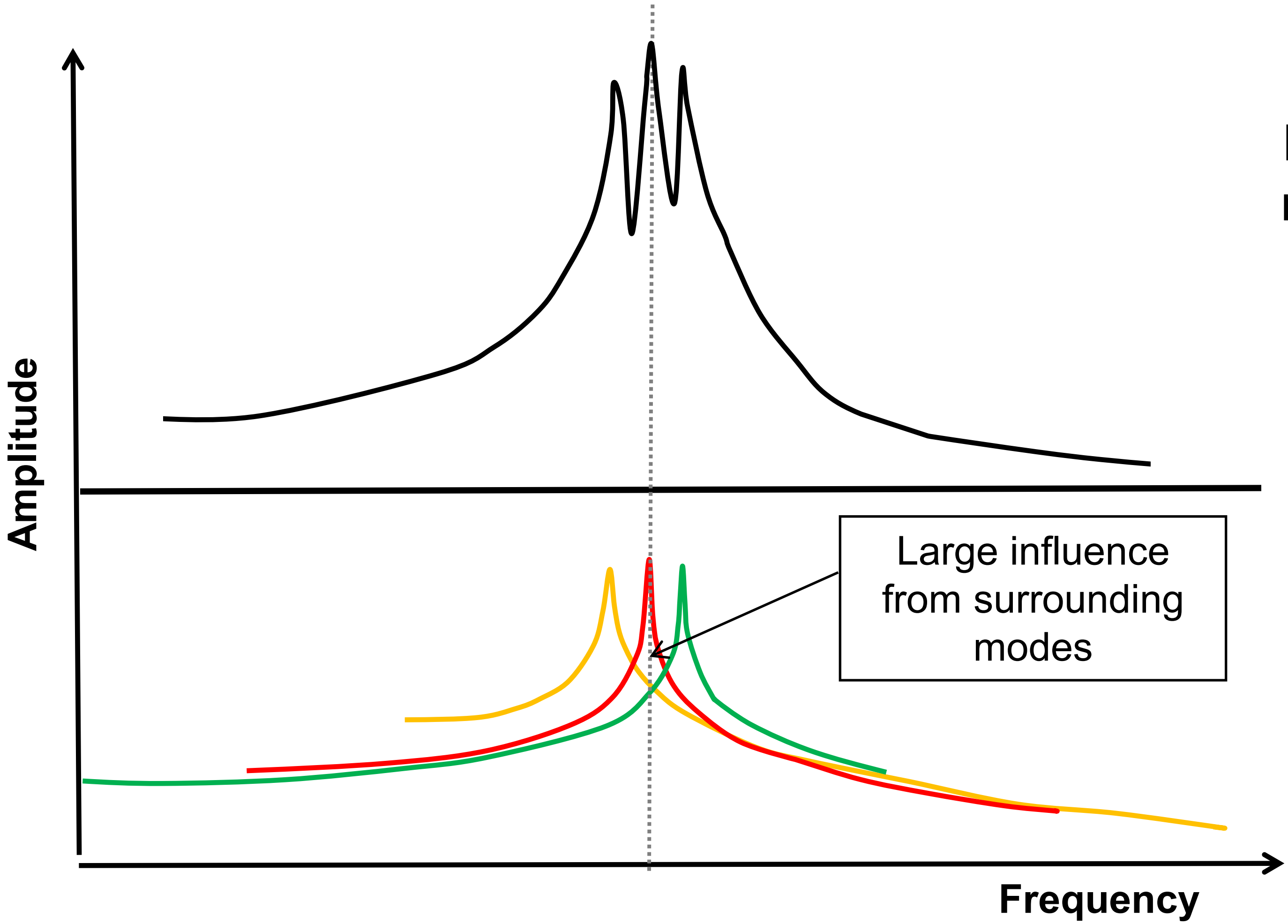
Structure with High Modal Separation



SDOF peak picking is only suitable for data with well-separated modes



Structure with Low Modal Separation



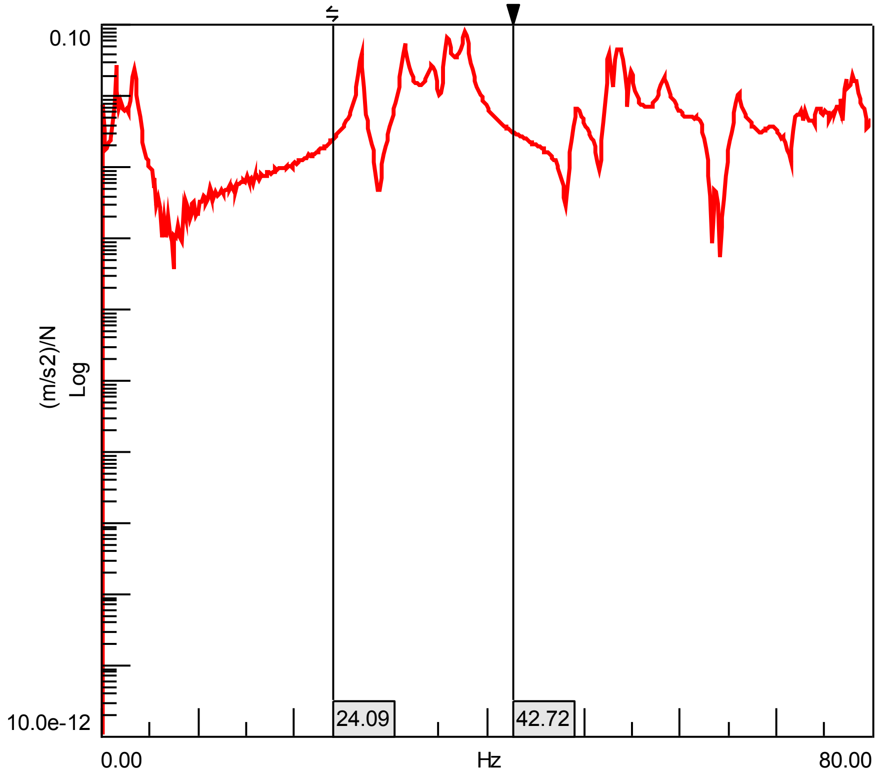
MDOF curve fitter is required to separate closely-spaced modes

Modal Parameter Estimation

Goal of modal parameter estimation

$$[H(\omega)] = \sum_{i=1}^{n} \frac{\{v_i\} < l_i^T >}{j\omega - \lambda_i} + \frac{\{v_i^*\} < l_i^H >}{j\omega - \lambda_i^*}$$

- What is the model order?
- How many modes to curve-fit?



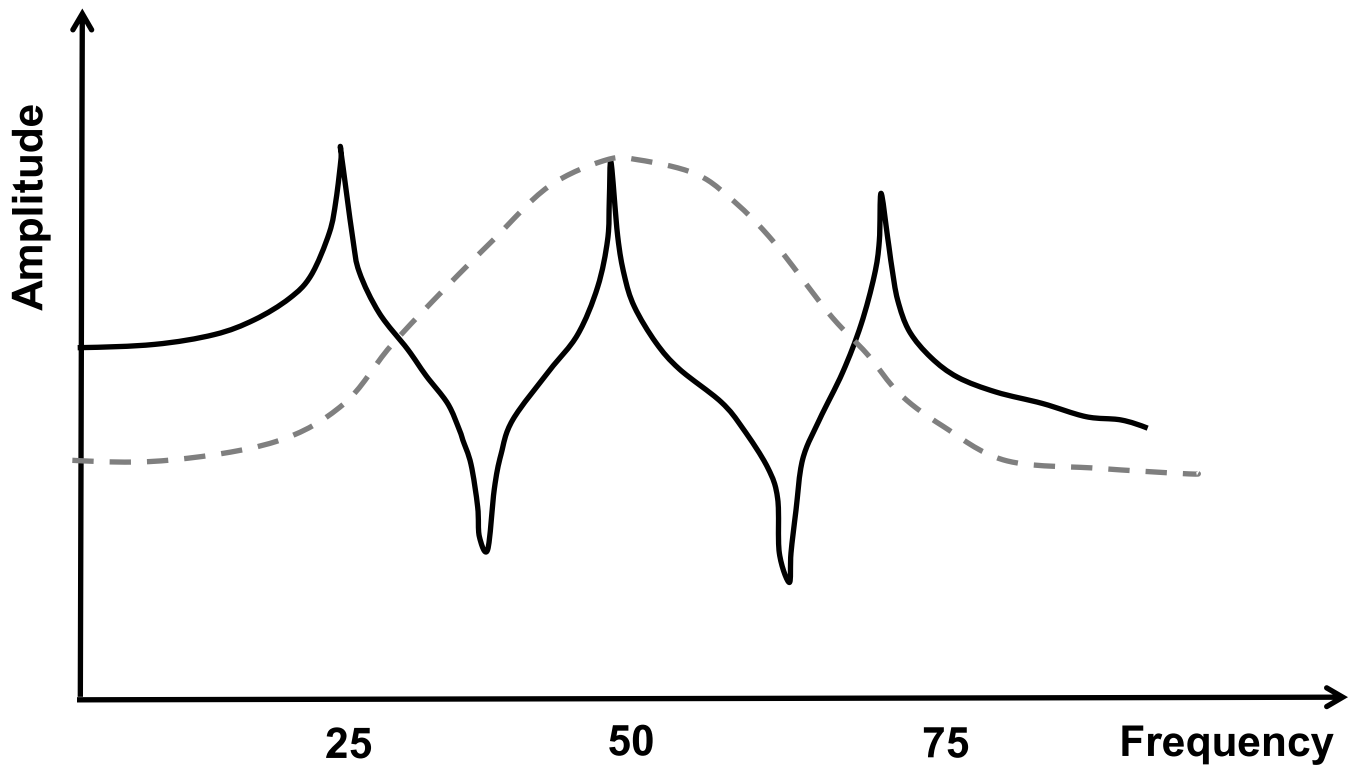
Solutions

- Stabilization diagram
- Mode indicator functions

Modal Parameter Estimation – Assuming 1 Mode

f1 = 50 Hz

d1 = 20 %



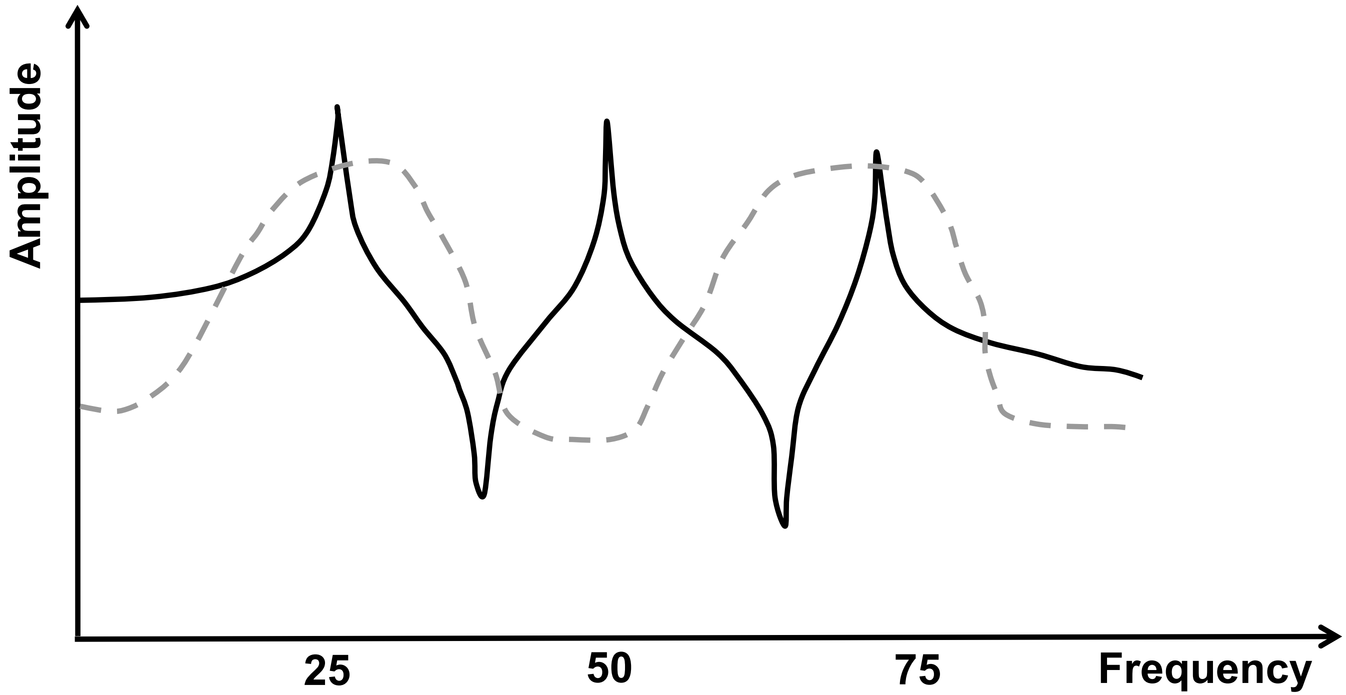
Modal Parameter Estimation – Assuming 2 Modes

f1 = 25 Hz

f2 = 75 Hz

d1 = 10 %

d2 = 10 %



Modal Parameter Estimation – Assuming 3 Modes

f1 = 25 Hz

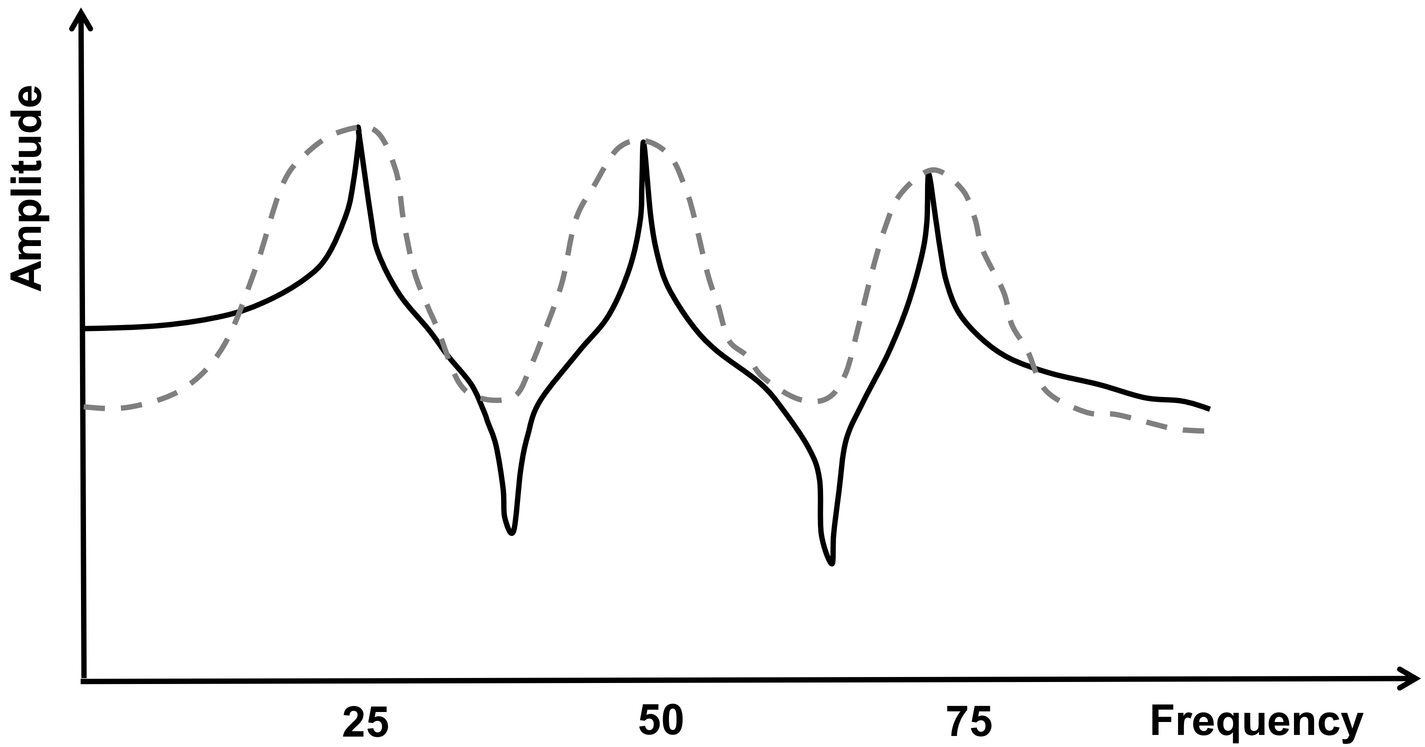
d1 = 5 %

f2 = 50 Hz

d2 = 5 %

f3 = 75 Hz

d3 = 5 %

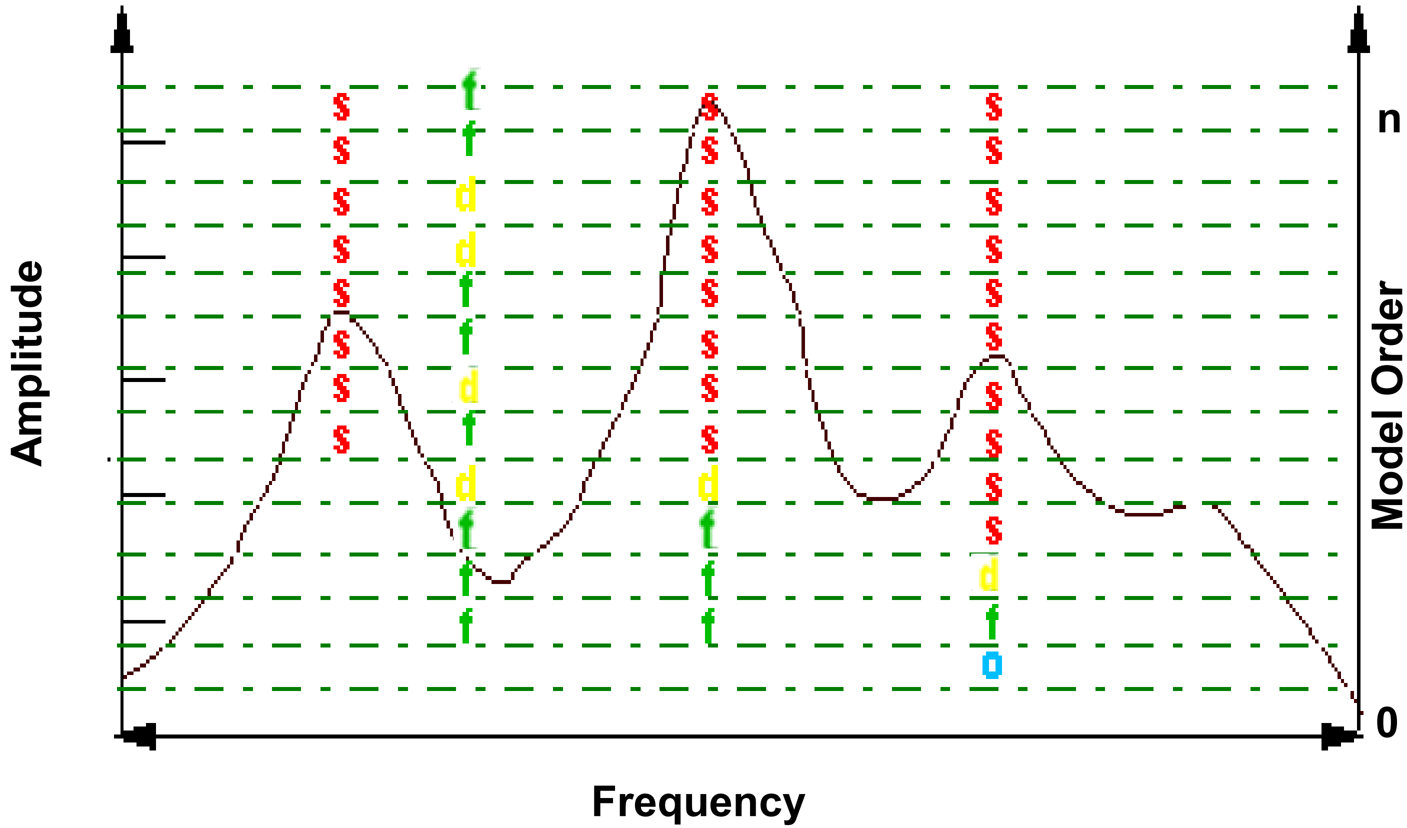


Modal Parameter Estimation - Stabilization Diagram

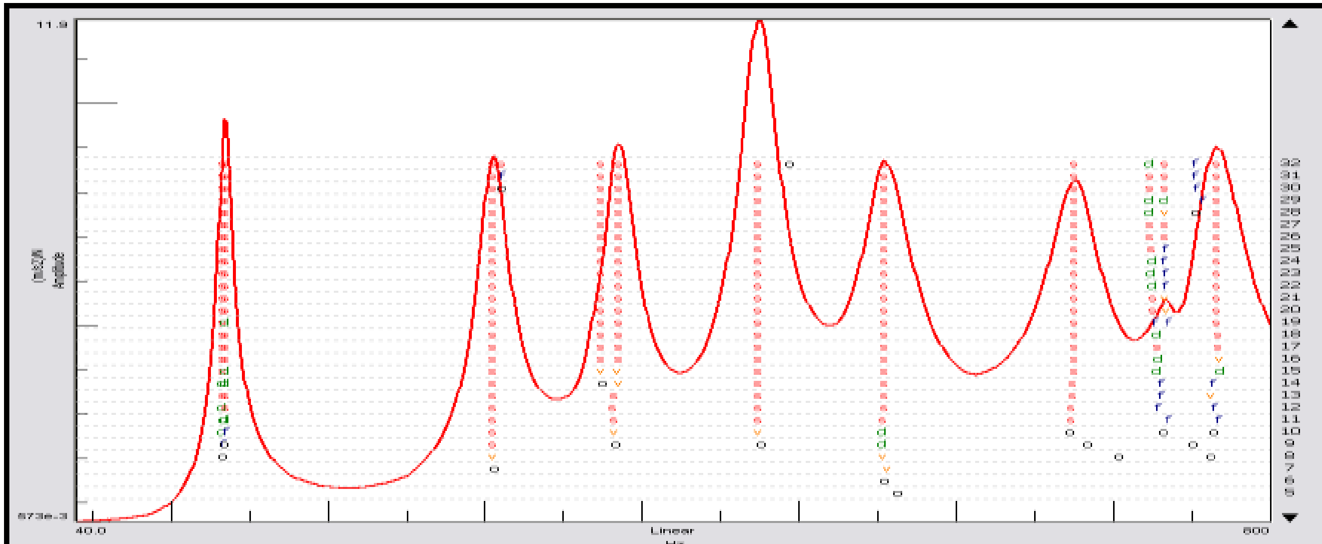
- Compare modal parameters at current order with previous order
- Increase the model order until modes stabilize

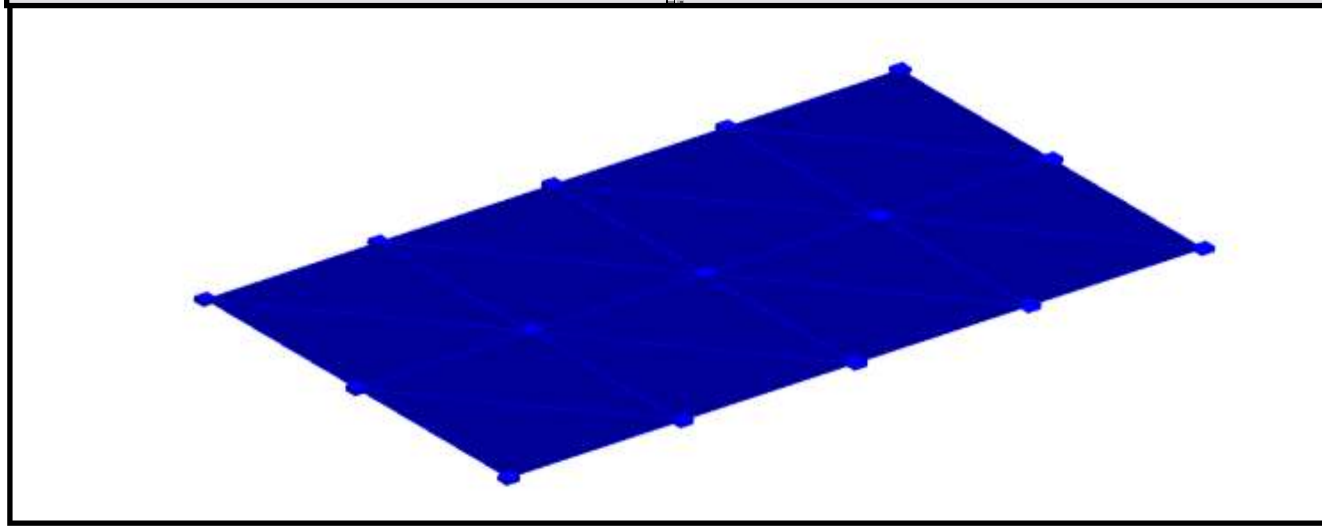
Stability

o : new pole
f : frequency
d : damping
s : all



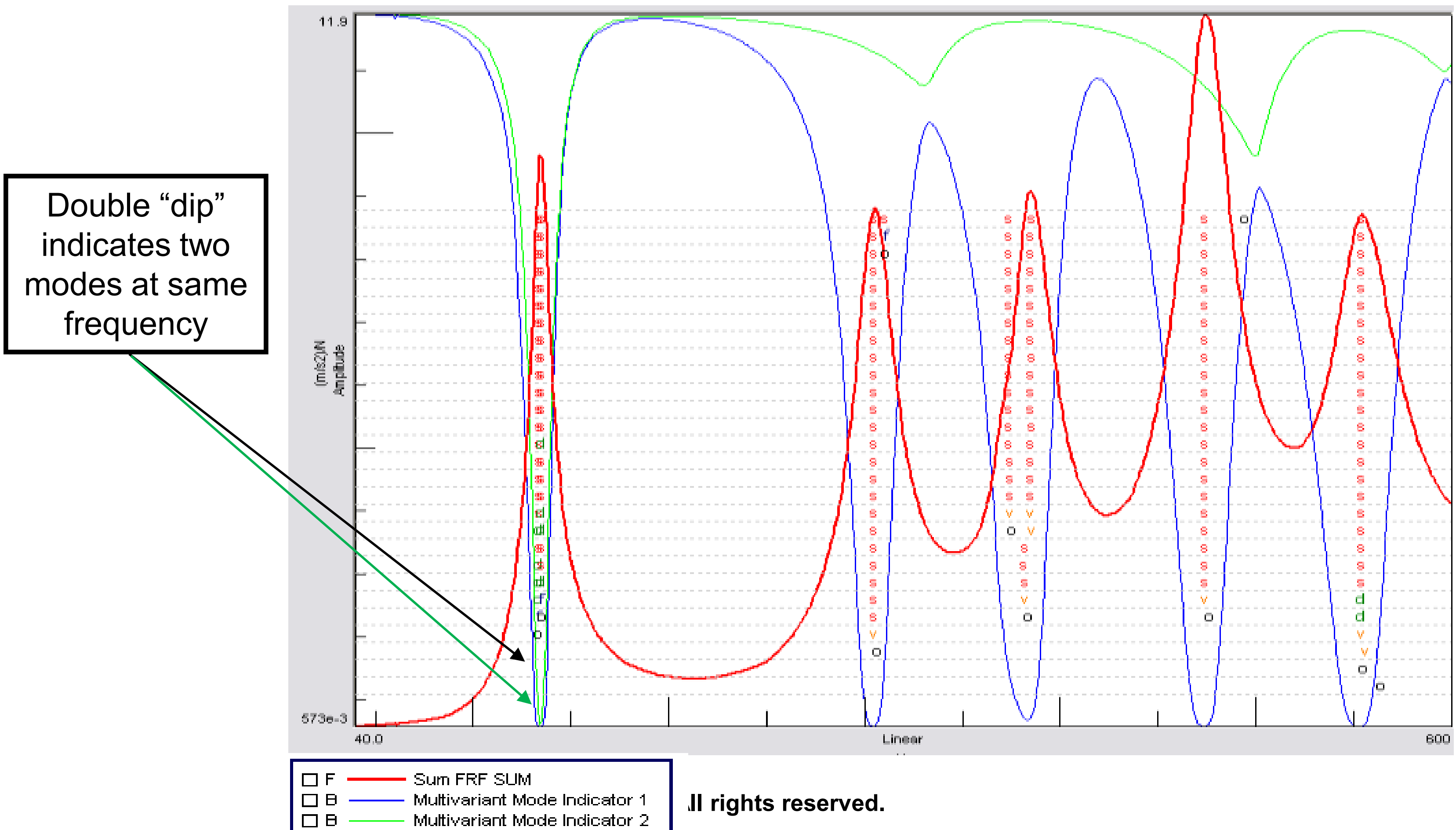
DEMONSTRATION: MDOF Curve Fitting on Flat Plate





Mode Indicator Function

- **Mode Indicator Function (MIF)** helps identify the modes for a system where multiple reference FRFs were measured
  - commonly used to detect the presence of repeated roots



Polymax MDOF Curve Fitting

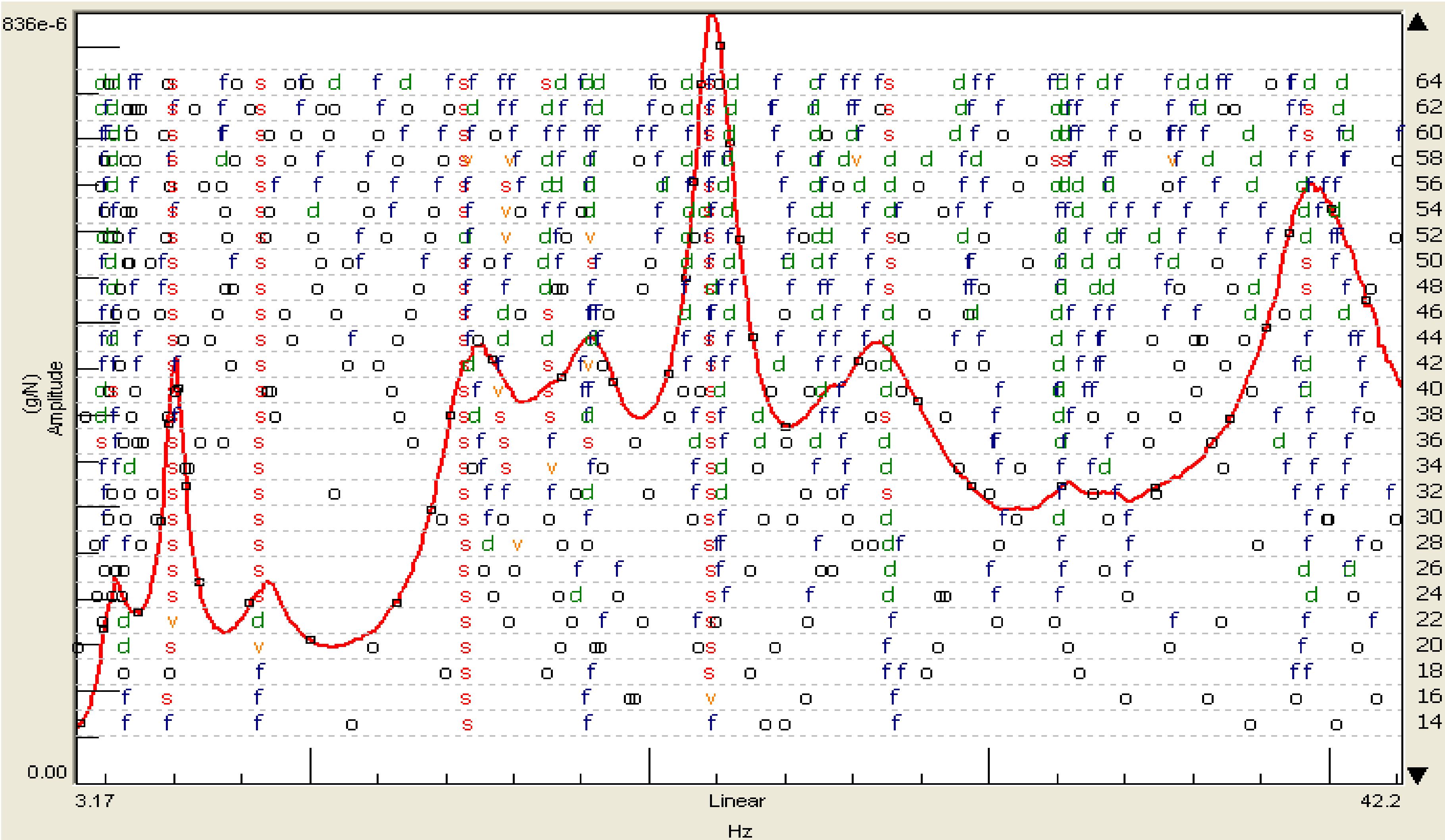
LSCE versus LMS PolyMAX

LSCE	**LMS PolyMAX**
-For smaller models	+Large number of responses
-High computational load	+Fast, efficient computation
-High damping is a problem	+High damping no problem
-High modal density	+High modal density
-Not for broadband analysis	+Broadband analysis
-Unclear stabilization diagram	+Crystal-clear stabilization diagram

Not all MDOF curve fitters are created equal !

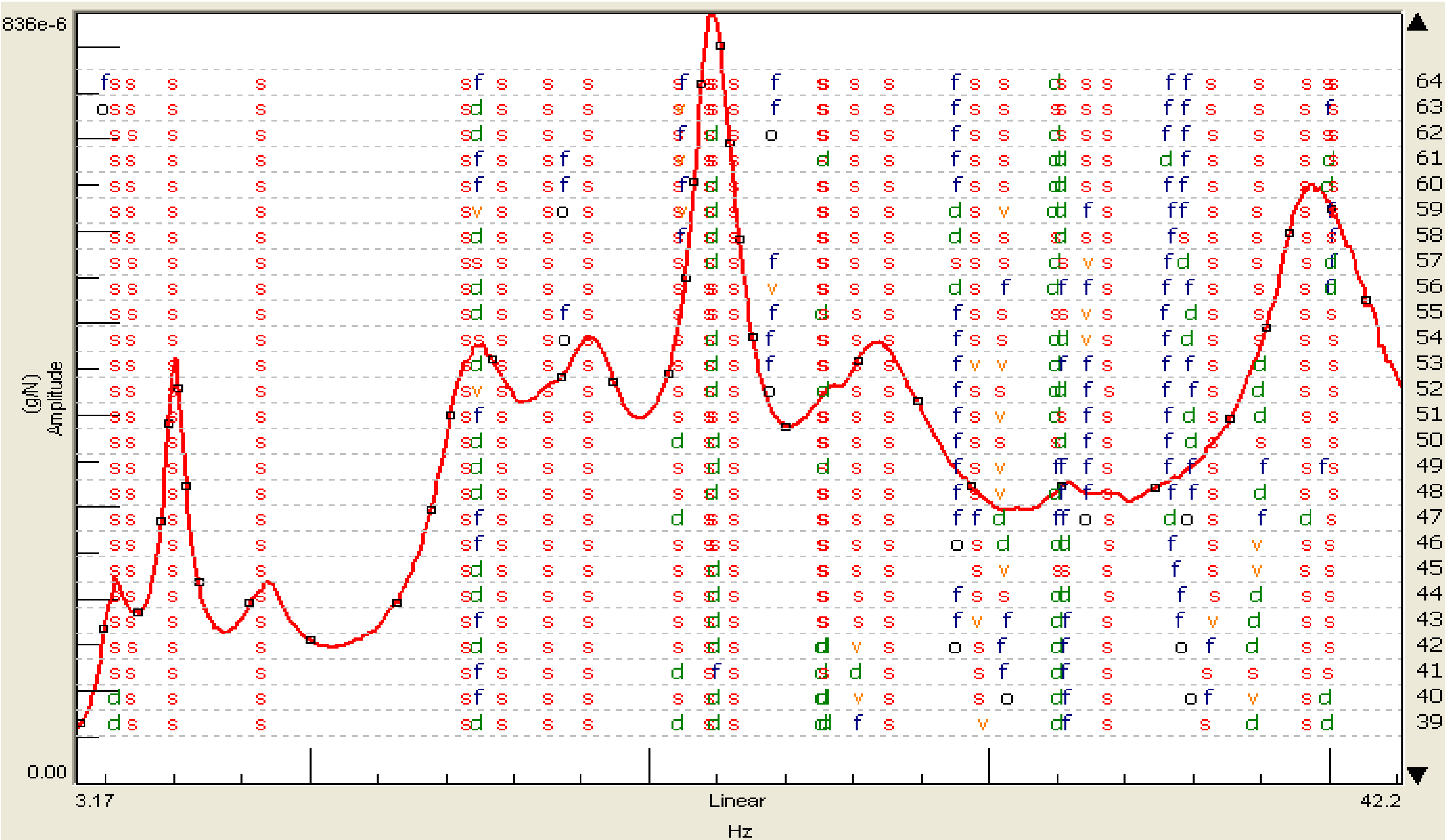
Modal Parameter Estimation – LSCE

SIEMENS

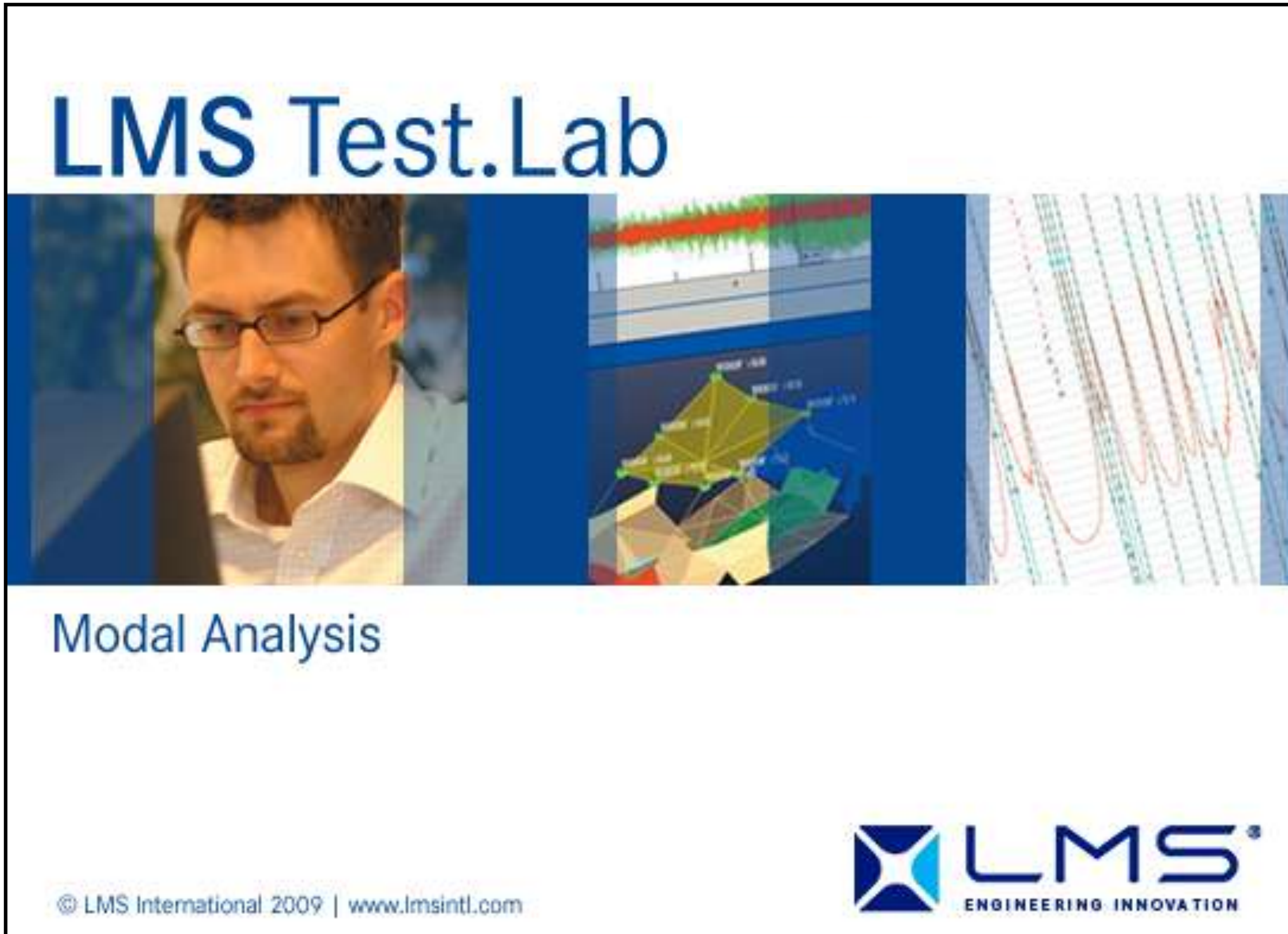


Modal Parameter Estimation – LMS PolyMAX

SIEMENS



DEMONSTRATION: PolyMAX Modal Analysis



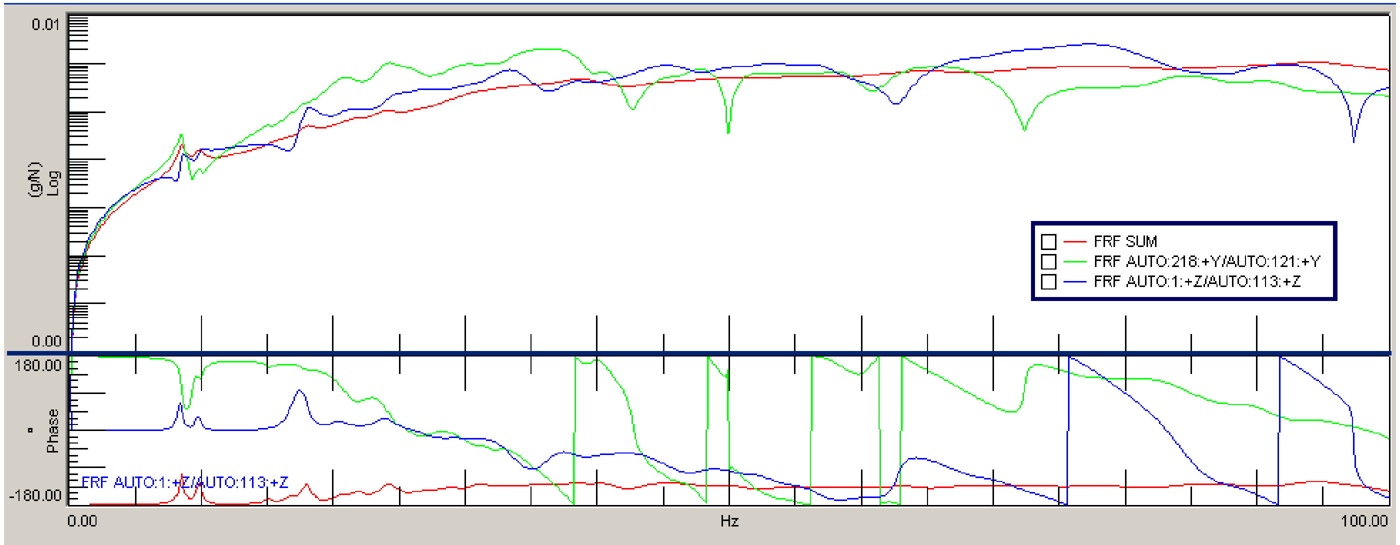
PolyMAX Validation Studies

Validation Study of PolyMAX Algorithm

SIEMENS

FE model of a full trimmed car body

- Synthesized a set of FRFs to use for curve fitting
- FRFs generated for 780 DOF / 2 references
- 0.125 Hz frequency resolution
- 300 modes in 0-100 Hz band, including local modes



PolyMAX Validation
Identifying Modes

Number of modes found

- PolyMAX: **189/300** modes
- LSCE(Time MDOF): **101/300** modes

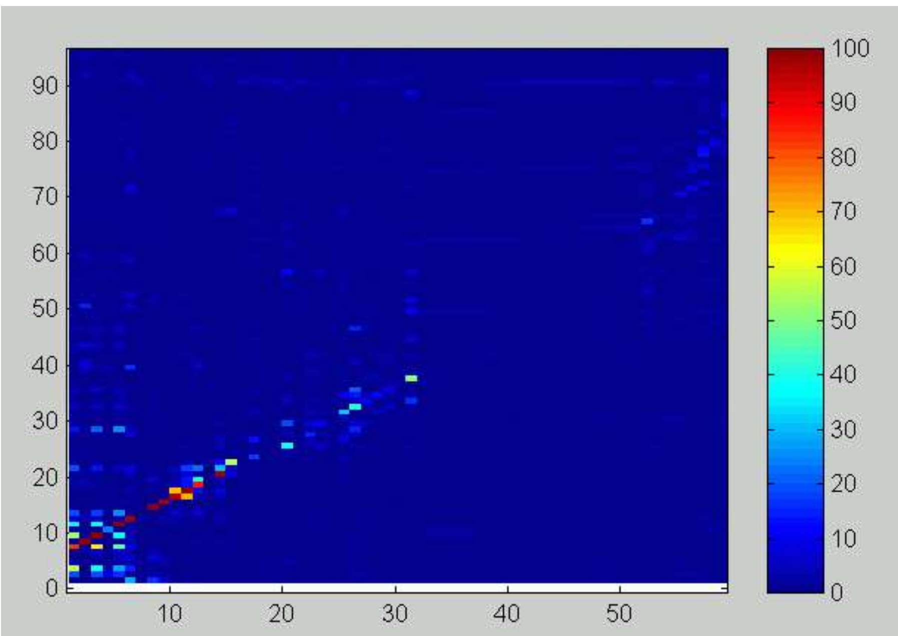
- 0 – 60 Hz band
- PolyMAX: 90/105 modes
- LSCE: 70/105 modes

Possibly more modes found if more FRFs used (local modes)

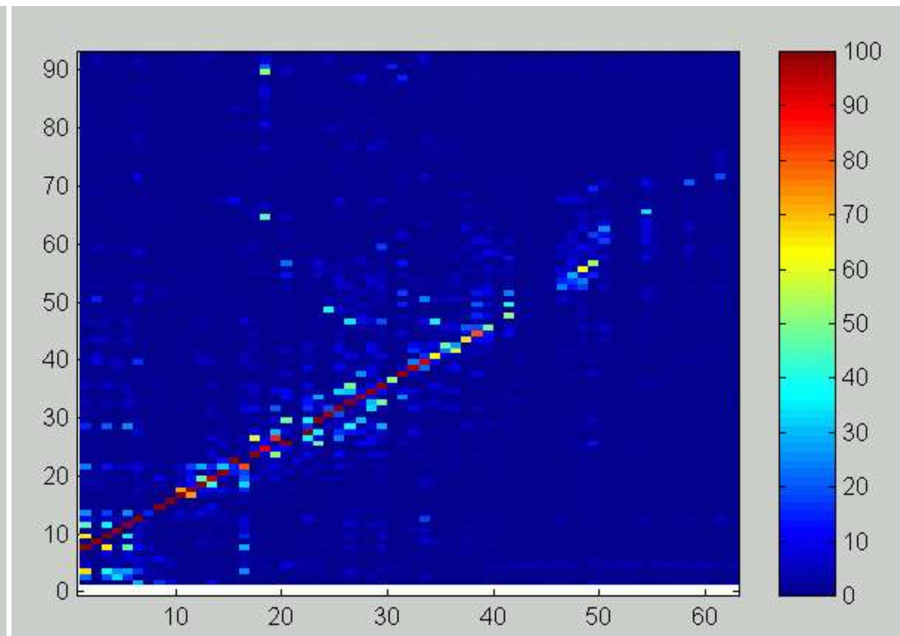
PolyMAX Validation
Mode Shapes Comparison

MAC matrix

LSCE (X) – FE (Y)

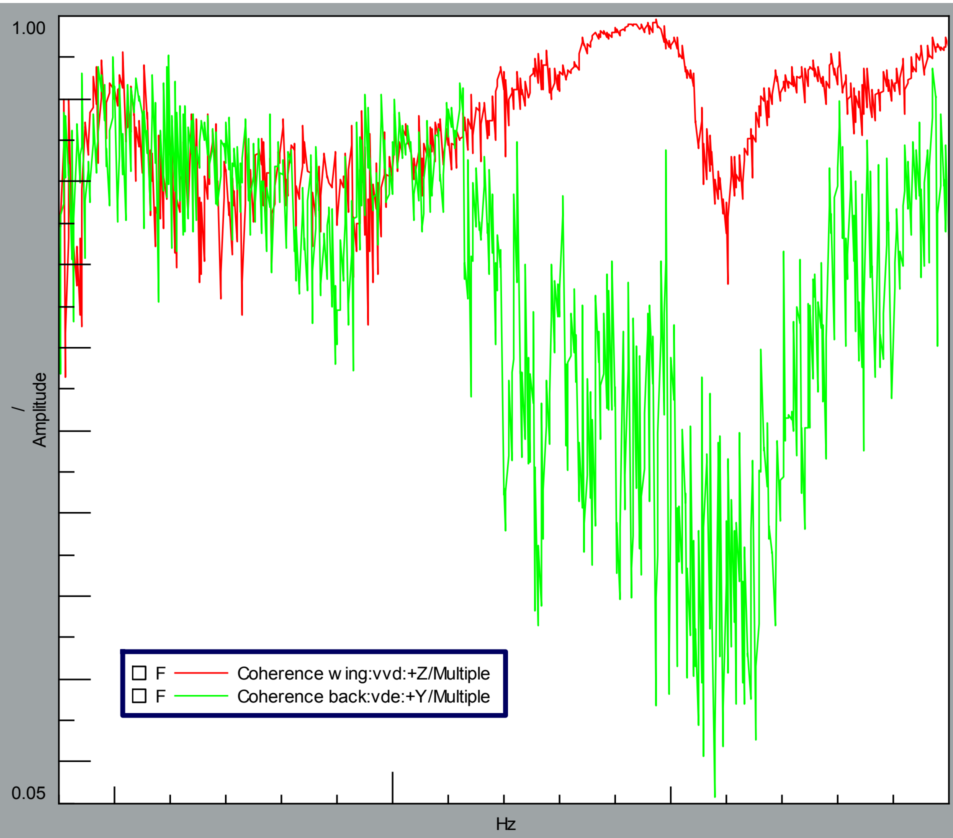


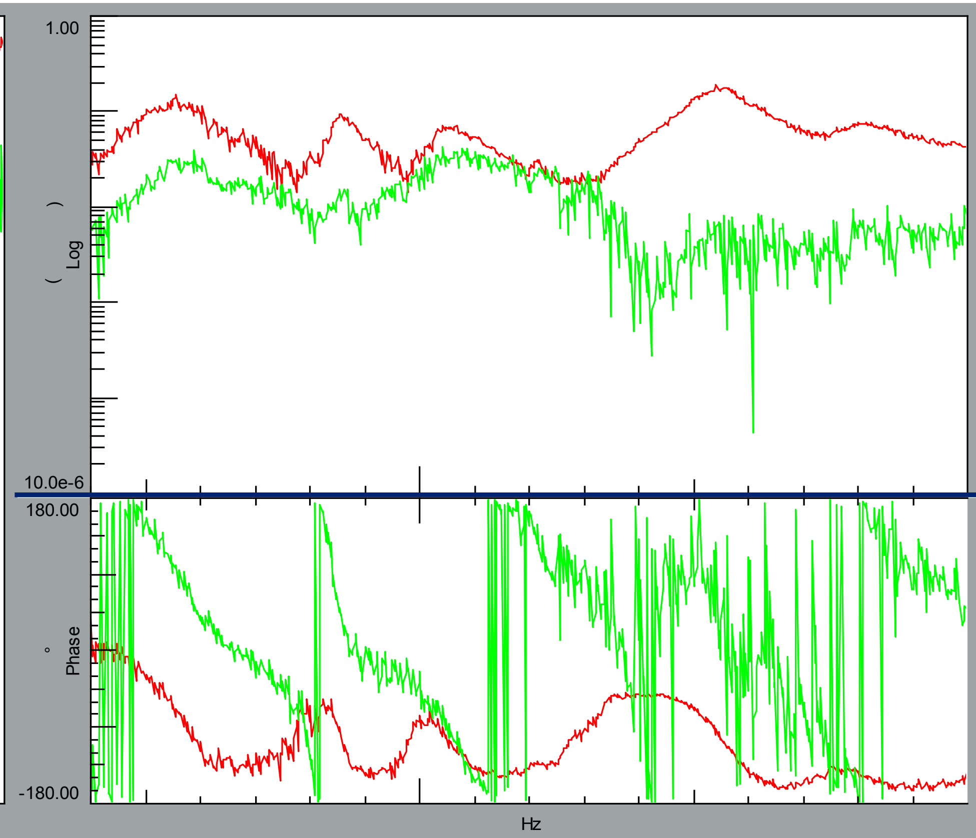
- MAC matrix
- PolyMAX (X) – FE (Y)



PolyMAX yields good correlation to higher frequency

PolyMAX Validation
“Noisy” FRFs

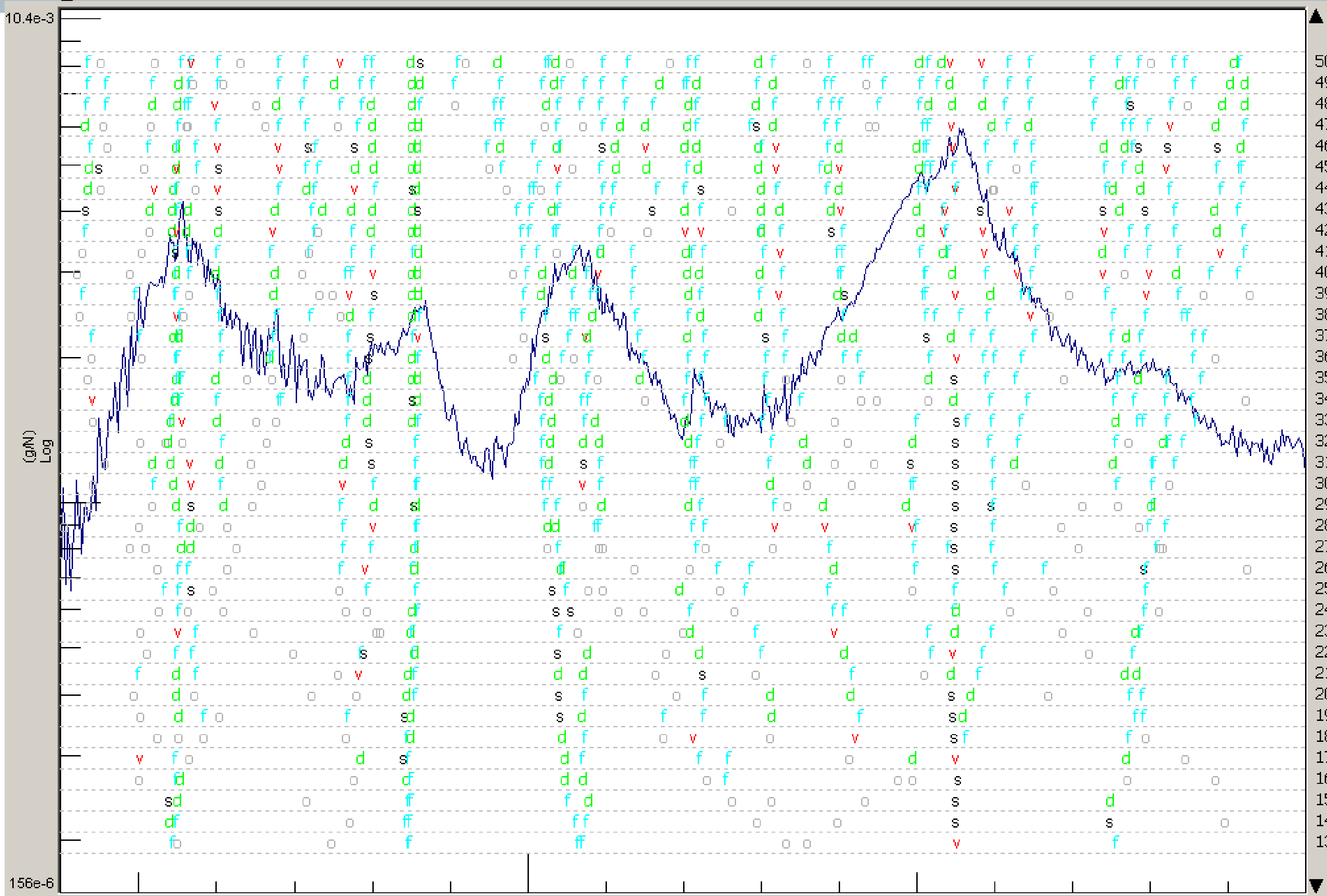




Multiple Coherence

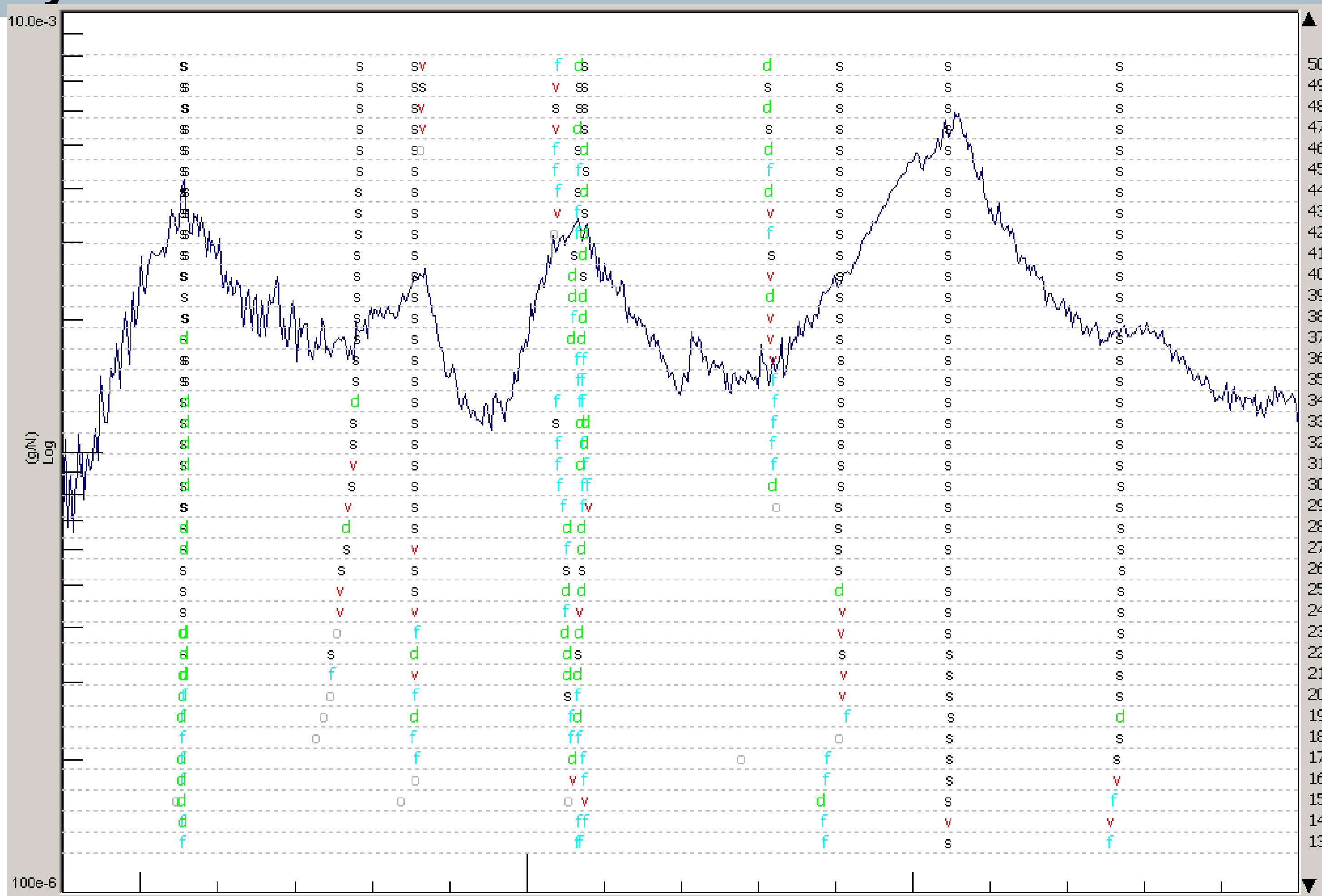
FRFs

PolyMAX Validation
"Noisy" FRFs



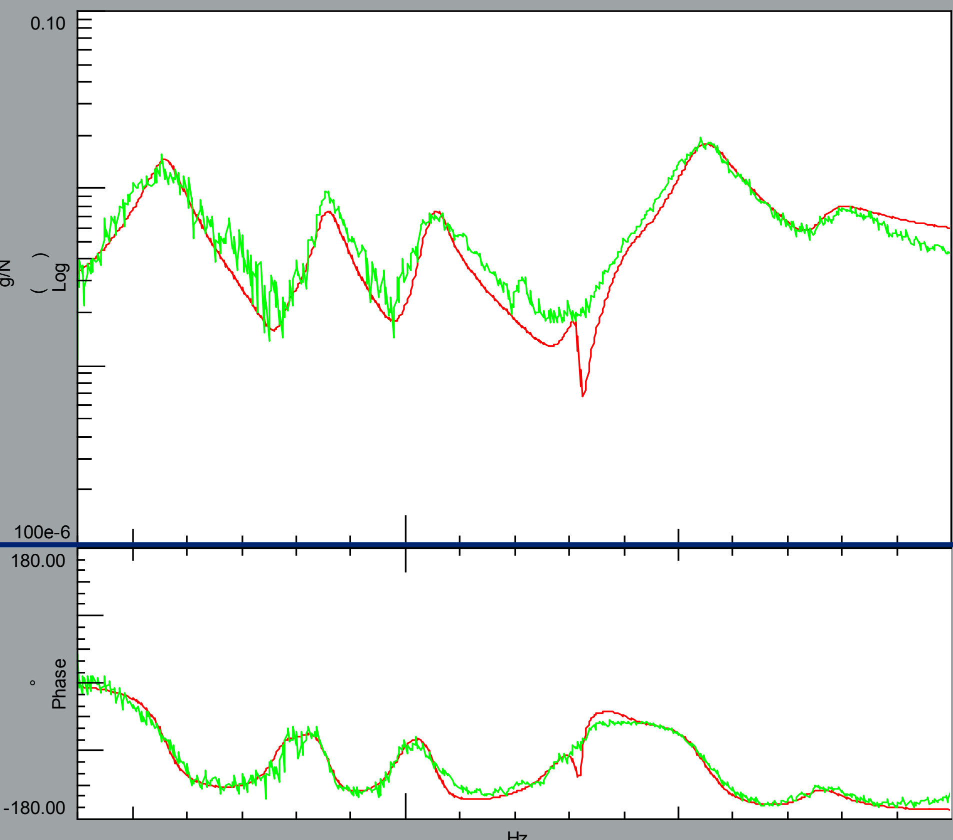
LSCE

PolyMAX Validation
“Noisy” FRFs

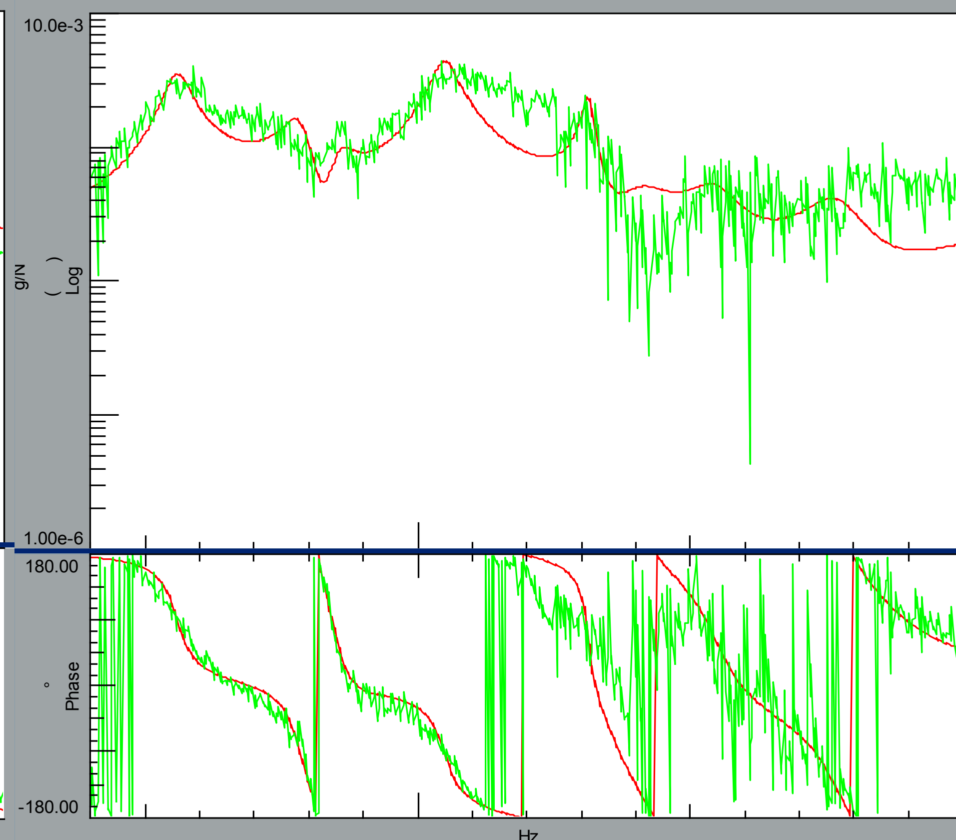


LMS PolyMAX

PolyMAX Validation
FRF Synthesis with PolyMAX



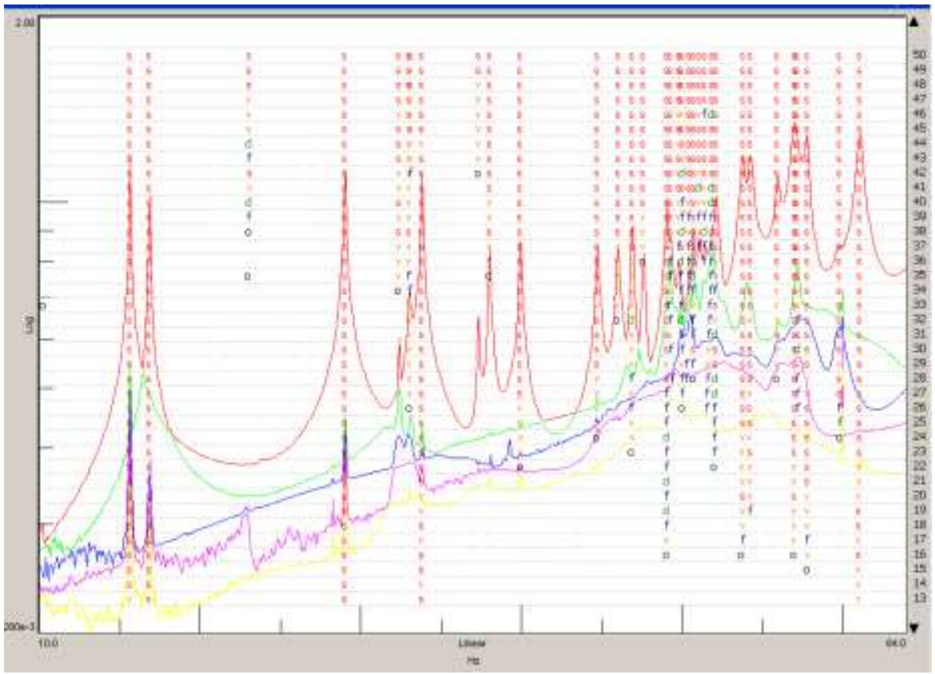
Left wing



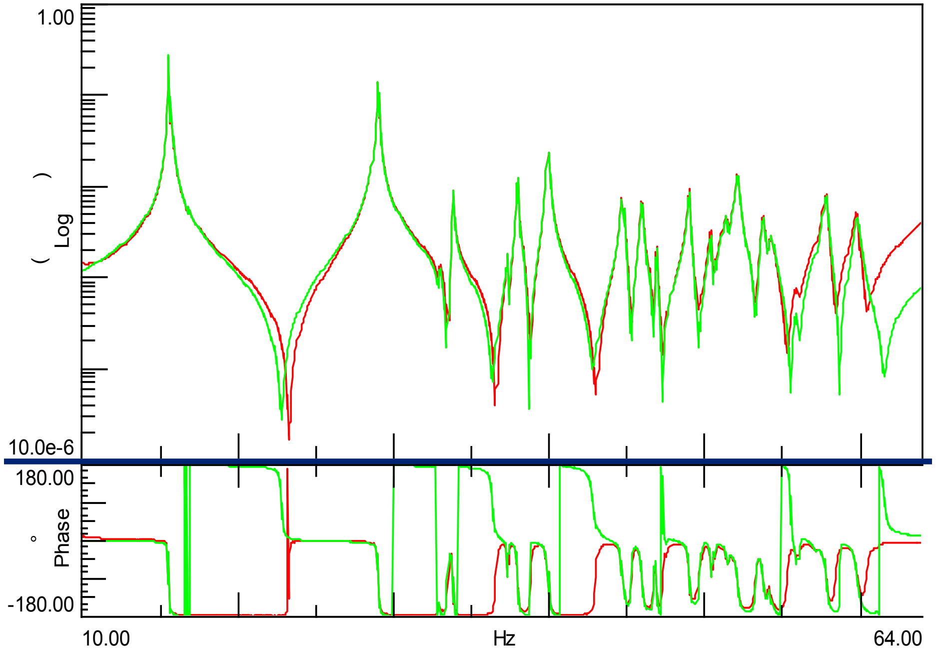
Back of the plane

PolyMAX Validation
Lightly-damped structures

Stabilization

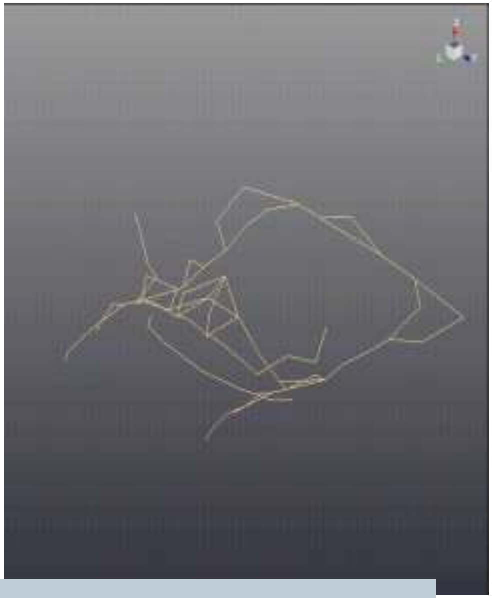


FRF synthesis



PolyMAX alleviates the need to use a different curve fitter algorithm for heavy and lightly damped structures

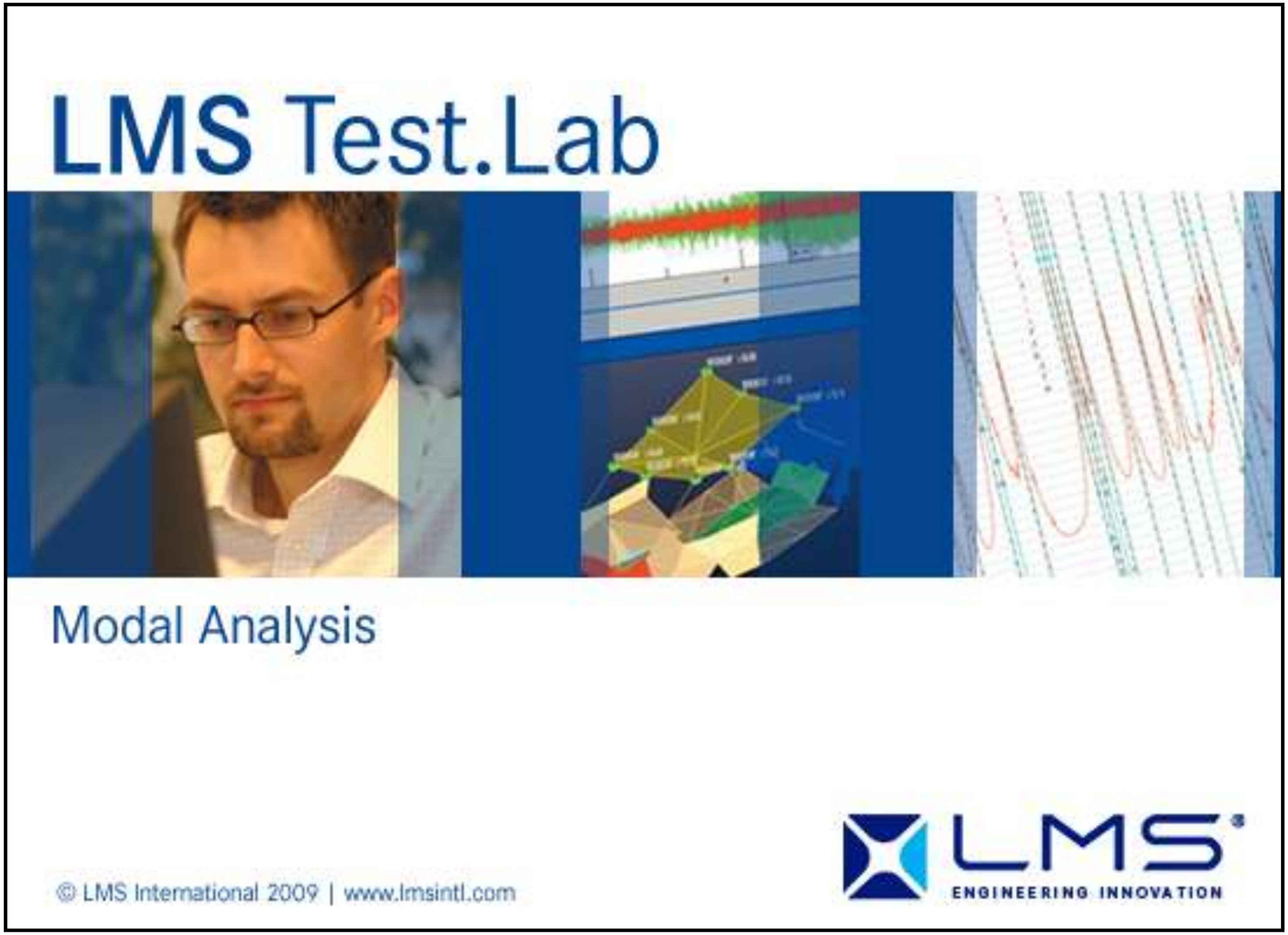
#1 – Automatic Mode Expansion



Test Mesh

STL File

DEMONSTRATION: Modal Expansion

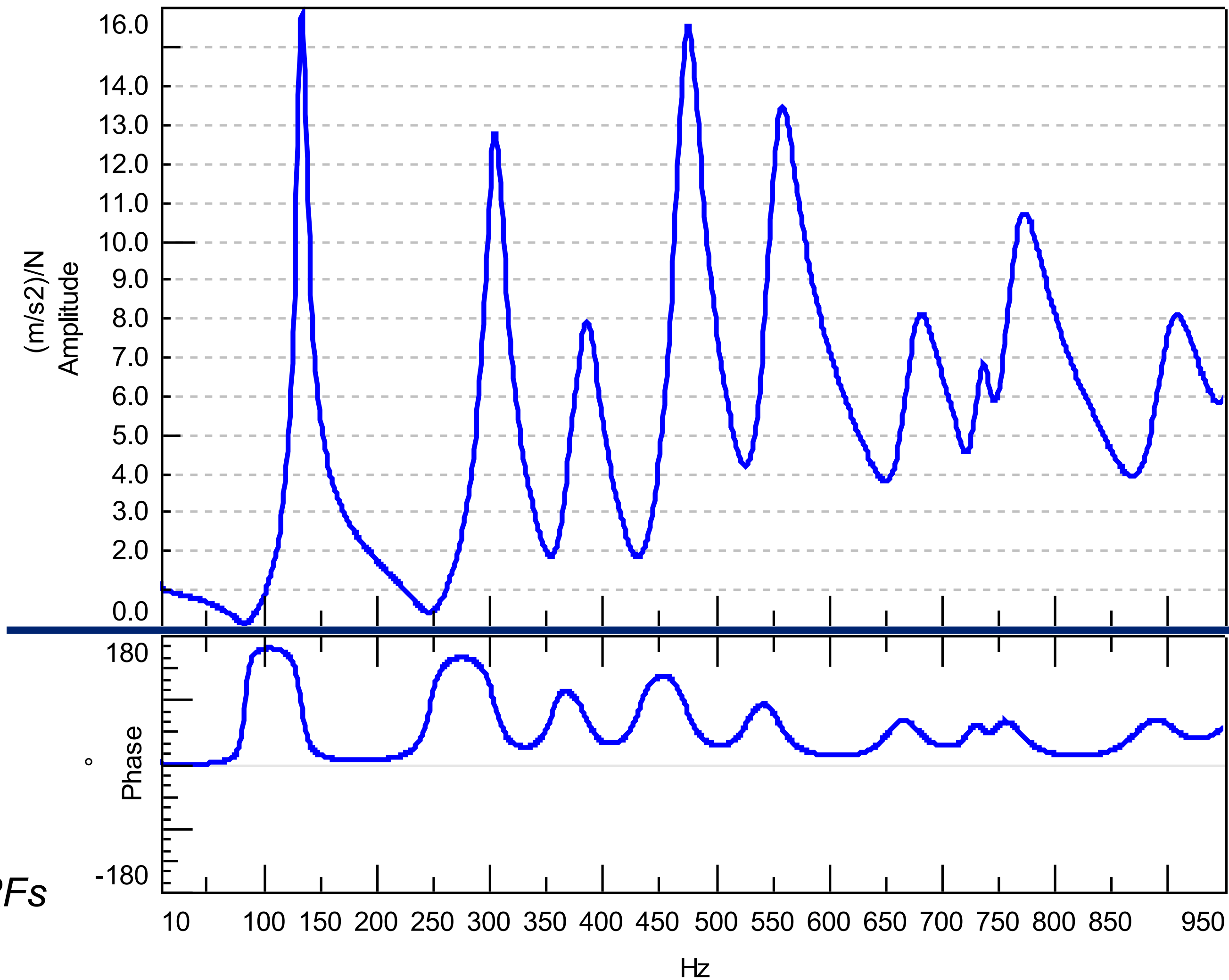


Quiz

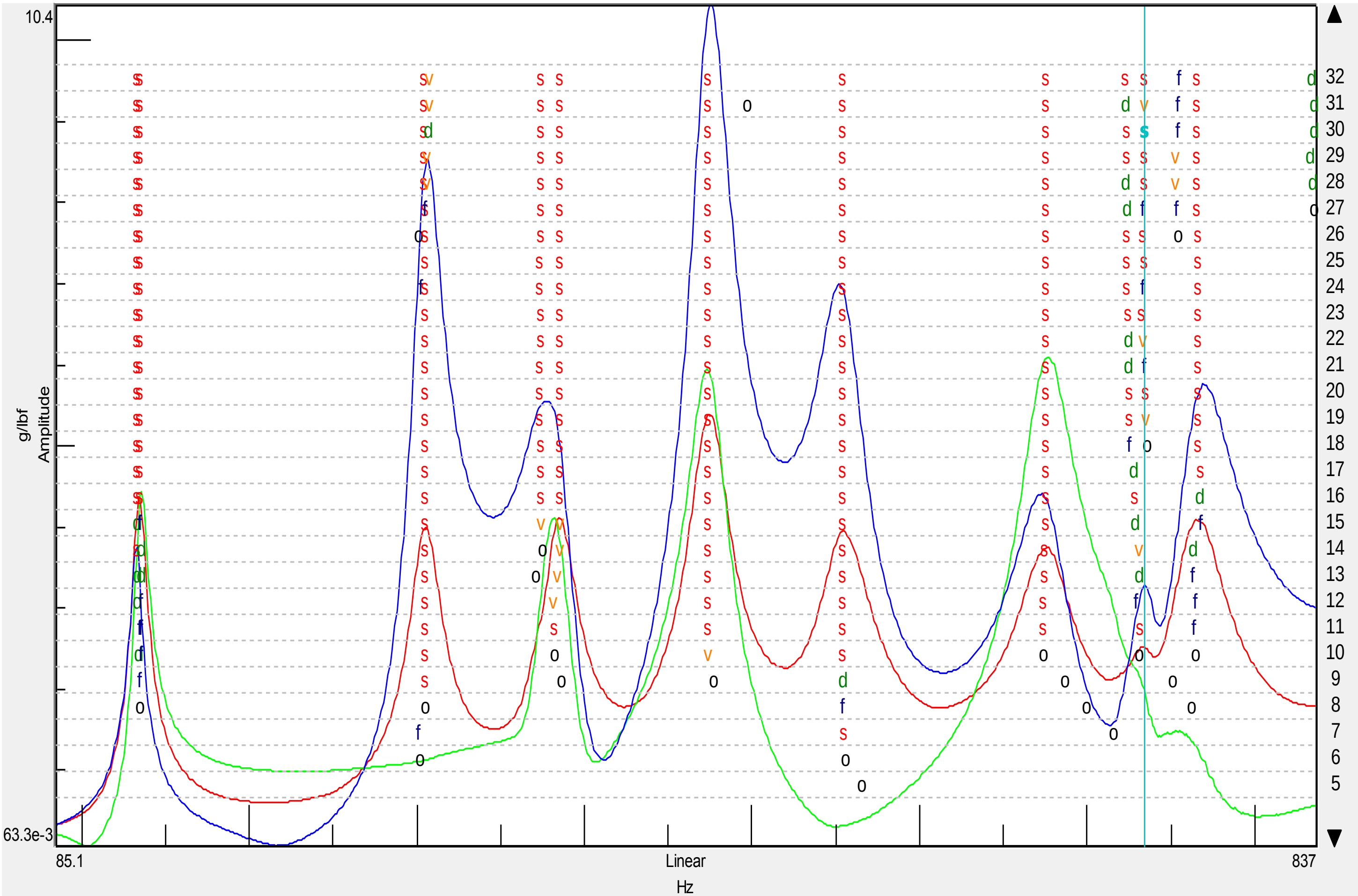
What can an FRF tell you?

Resonant Frequency

- Damping
- Mode Shape
  - *Requires Multiple FRFs*



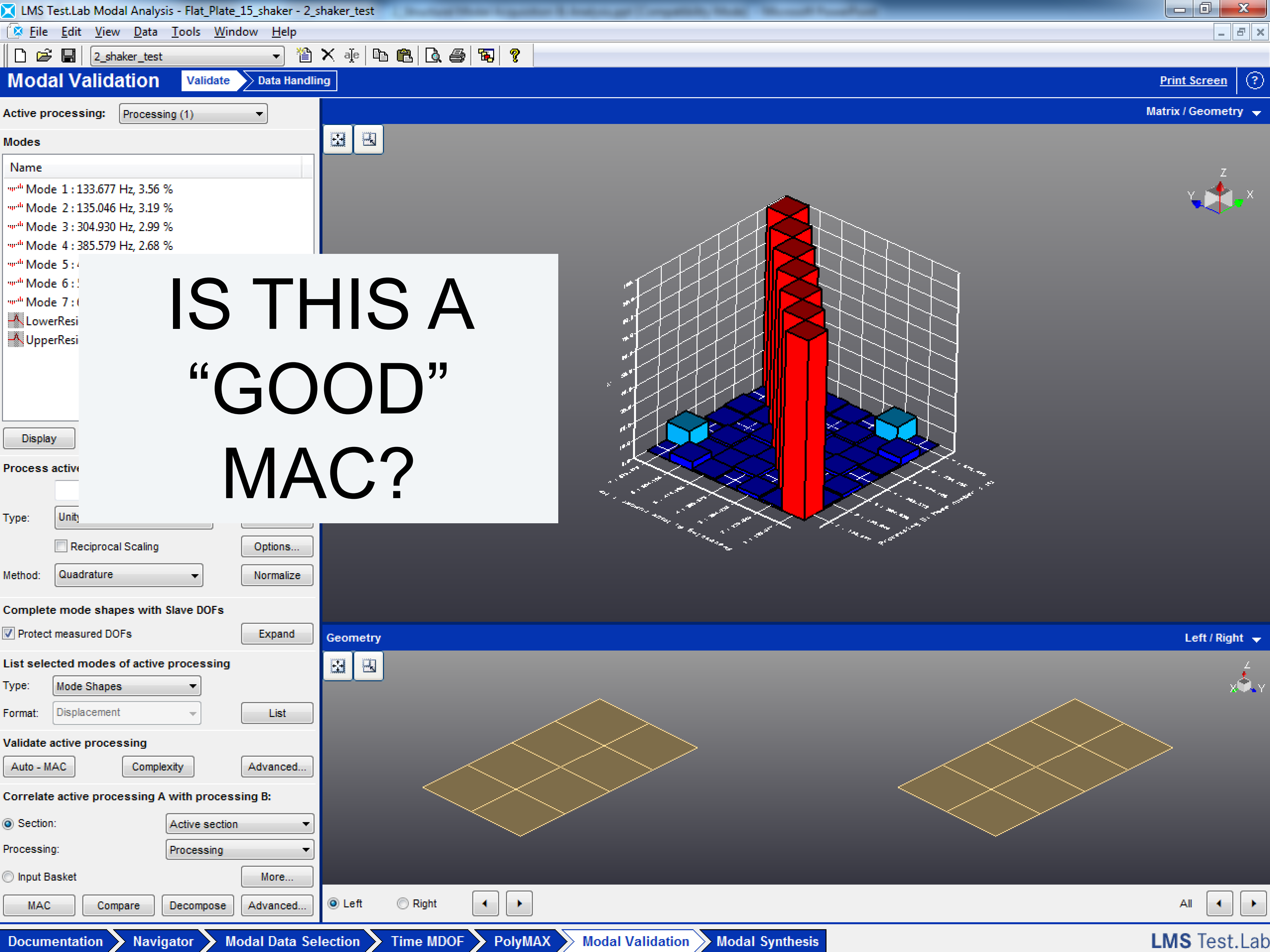
What is this?



What is MAC abbreviation for?

What is MAC abbreviation for?

Modal Assurance Criterion


IS THIS A "GOOD" MAC?
LMS Test.Lab Modal Analysis - Flat_Plate_15_shaker - 2_shaker_test
File Edit View Data Tools Window Help
2_shaker_test
Modal Validation
Validate
Data Handling
Print Screen
Active processing:
Processing (1)
Modes
Name
Mode 1 : 133.677 Hz, 3.56 %
Mode 2 : 135.046 Hz, 3.19 %
Mode 3 : 304.930 Hz, 2.99 %
Mode 4 : 385.579 Hz, 2.68 %
Display
Type:
Reciprocal Scaling
Options...
Method:
Quadrature
Normalize
Complete mode shapes with Slave DOFs
Protect measured DOFs
Expand
List selected modes of active processing
Type:
Mode Shapes
Format:
Displacement
List
Validate active processing
Auto - MAC
Complexity
Advanced...
Correlate active processing A with processing B:
Section:
Active section
Processing:
Processing
Input Basket
More...
MAC
Compare
Decompose
Advanced...
Matrix / Geometry
Geometry
Left / Right
Left
Right
All
Documentation
Navigator
Modal Data Selection
Time MDOF
PolyMAX
Modal Validation
Modal Synthesis
LMS Test.Lab

Advanced Processing and Analysis Techniques

How to ensure consistency when picking modes?

Automatic Modal Parameter Selection

Observe several experienced engineers

↓

Knowledge and skills of experts

↓

Rules of Automatic Modal Parameter Selection

↓

Validated rules with benchmark study

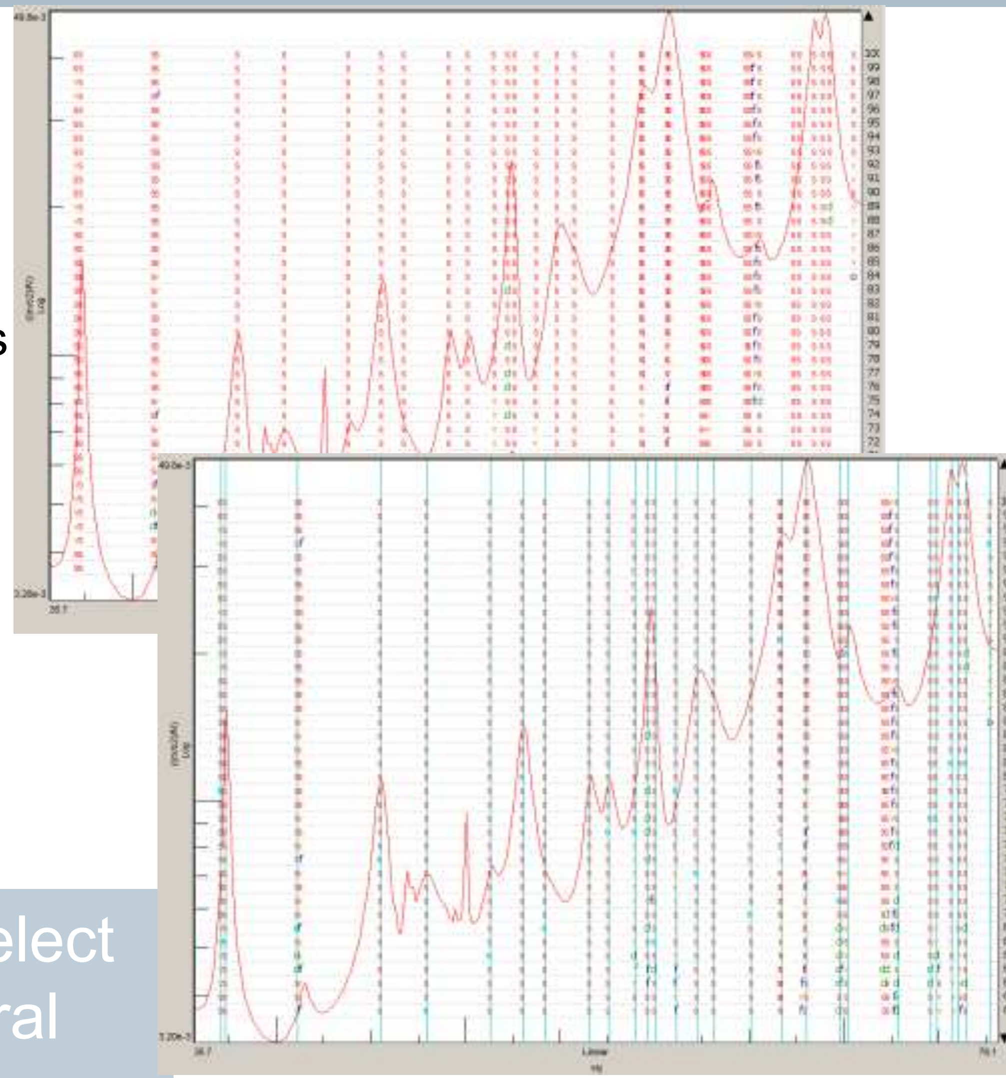
Automatic Modal Parameter Selection

SIEMENS

Vehicle body-in-white
2 inputs and 2005 DOFs

Experienced modal analysts

- Analyze in many small bands
- Found 233 modes
- Took a couple hours



- **AMPS**
  - Analyze in 4 bands
  - Model size = 100
  - Found 173 modes
  - Less than a minute

"LMS PolyMAX & AMPS select 173 of 233 poles in several seconds !"

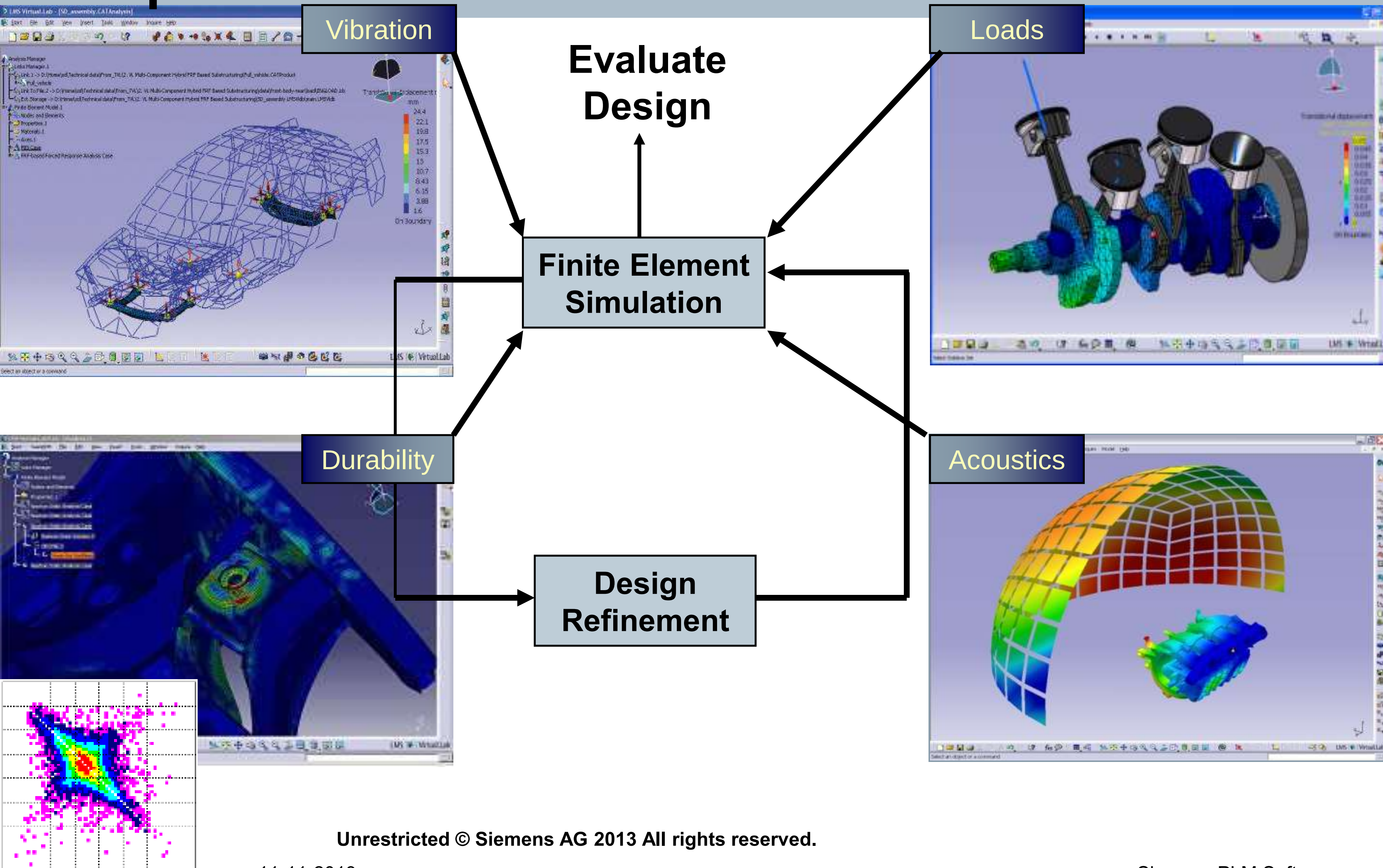
Experimental Modal Analysis

The benefits of modal analysis are:

- Identify structural dynamics properties
- Visualize how a system naturally wants to respond
- Provide insight for root-cause analysis of vibration or fatigue problems
- Determine if natural frequencies are in-line with operational frequencies

SIEMENS

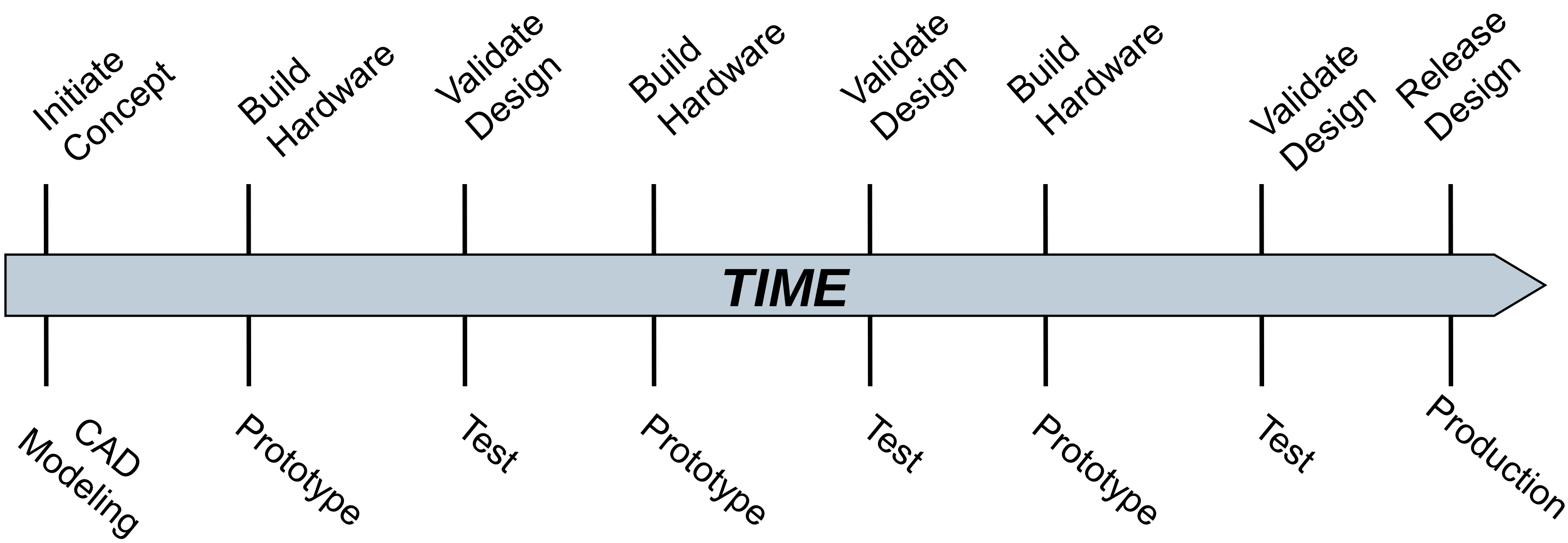
Importance of Correlation



“Old” Product Design Cycle

SIEMENS

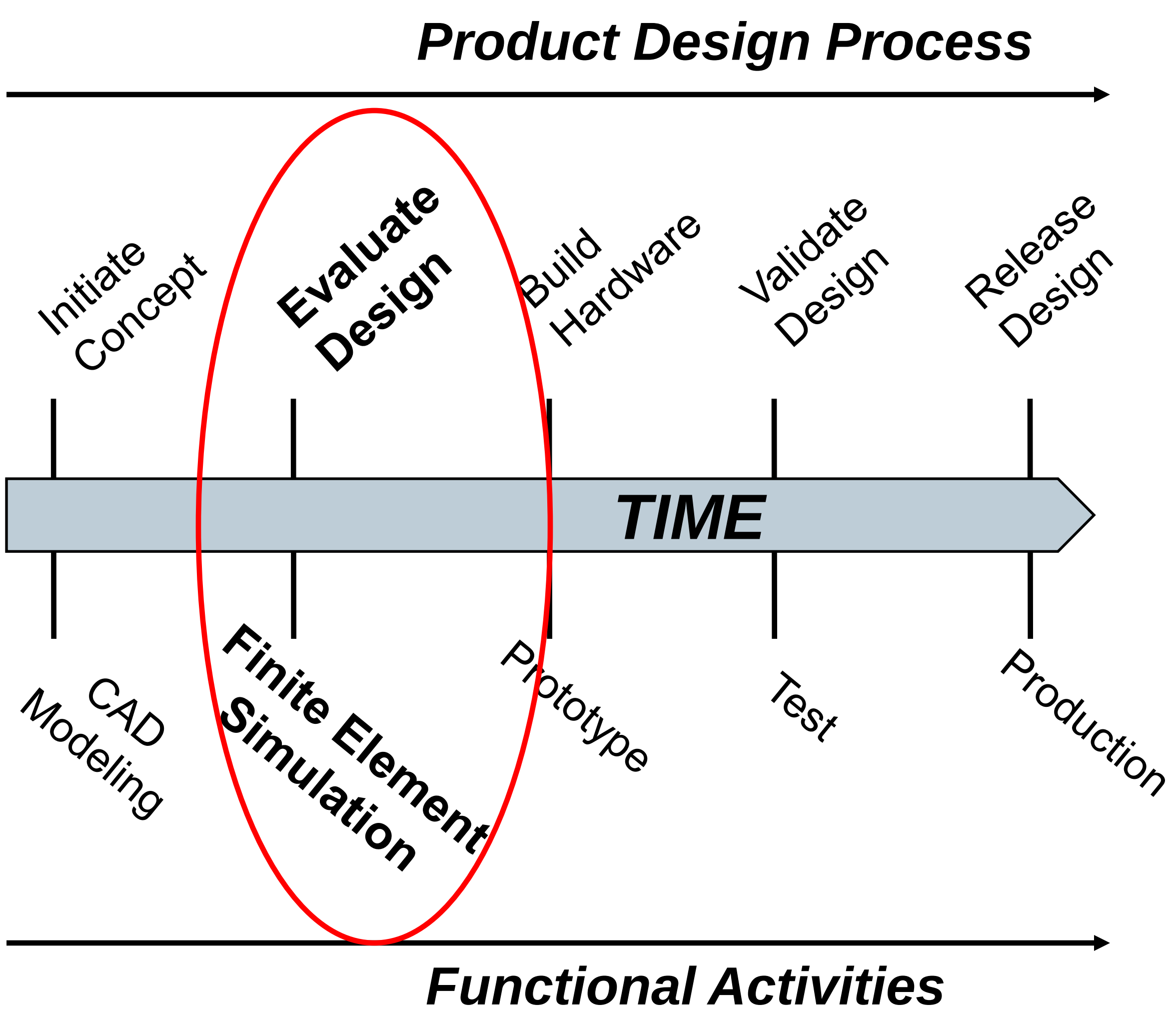
Product Design Process



Functional Activities

"Modern" Product Design Process Goal

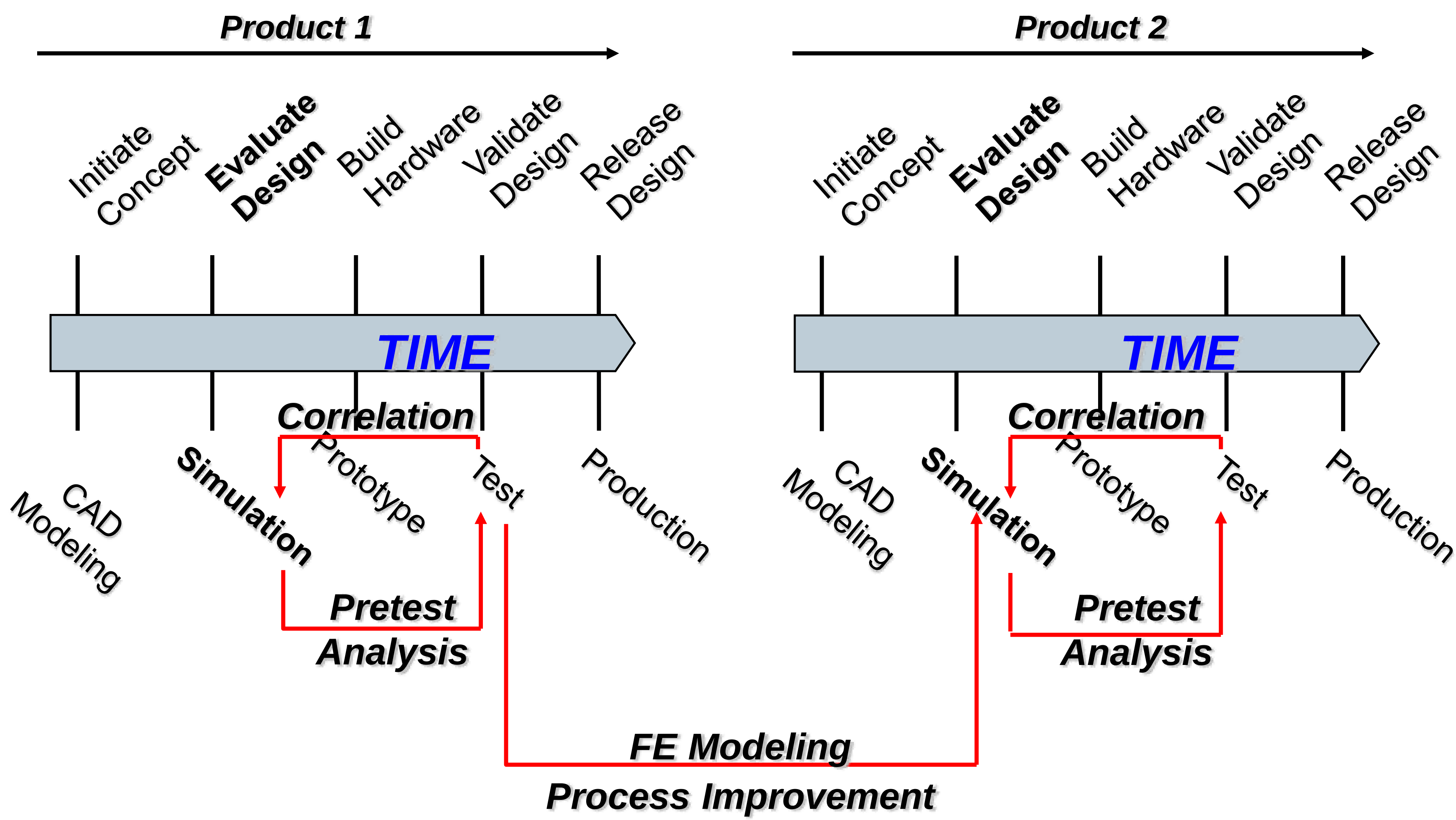
SIEMENS



- ***Simulate product performance <u>before</u> prototypes are available***
- ***Use <u>single</u> prototype & testing for validation***

Pretest & Correlation: Process Improvement

SIEMENS



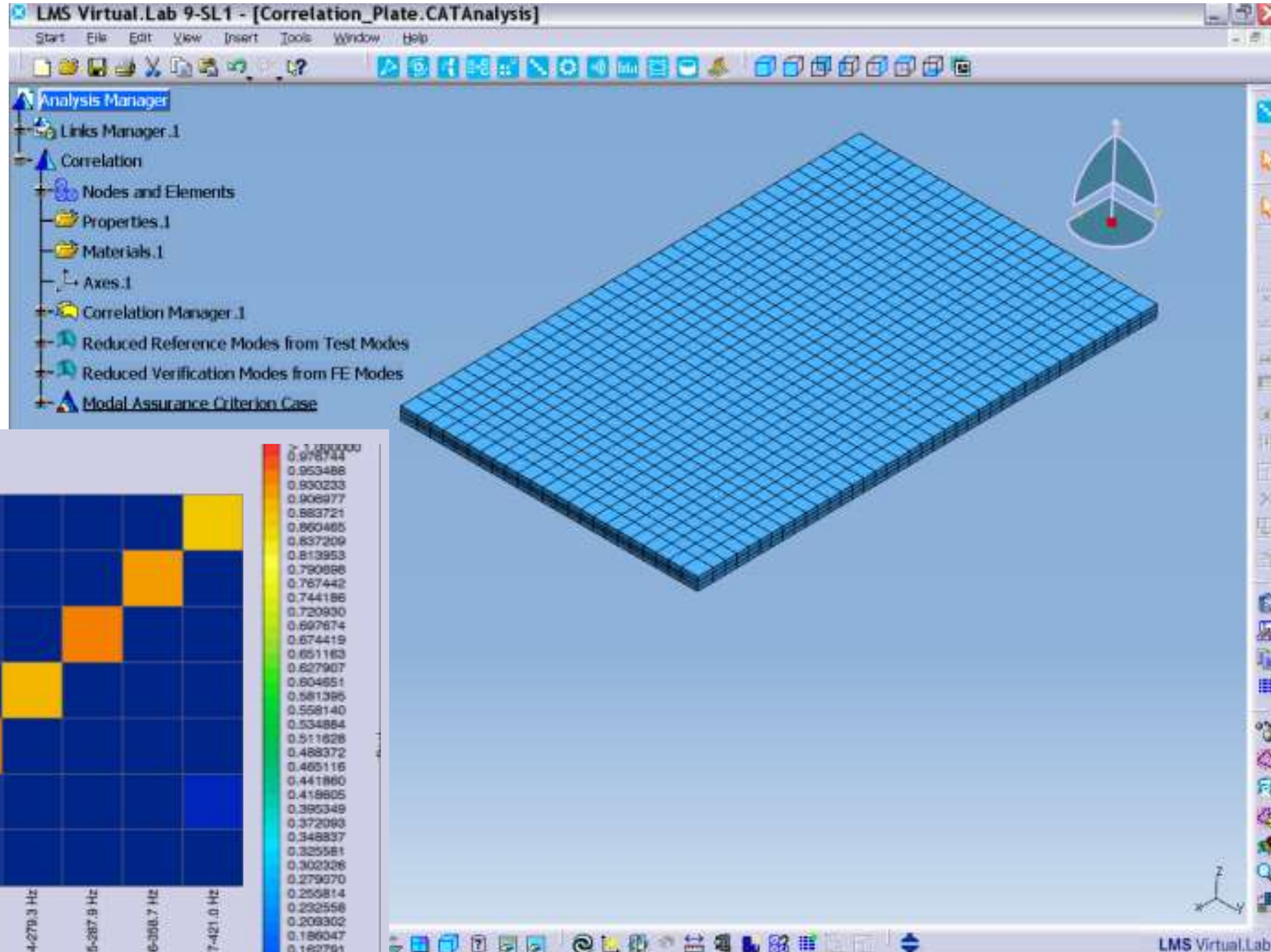
Virtual.Lab Pretest & Correlation: Motivation

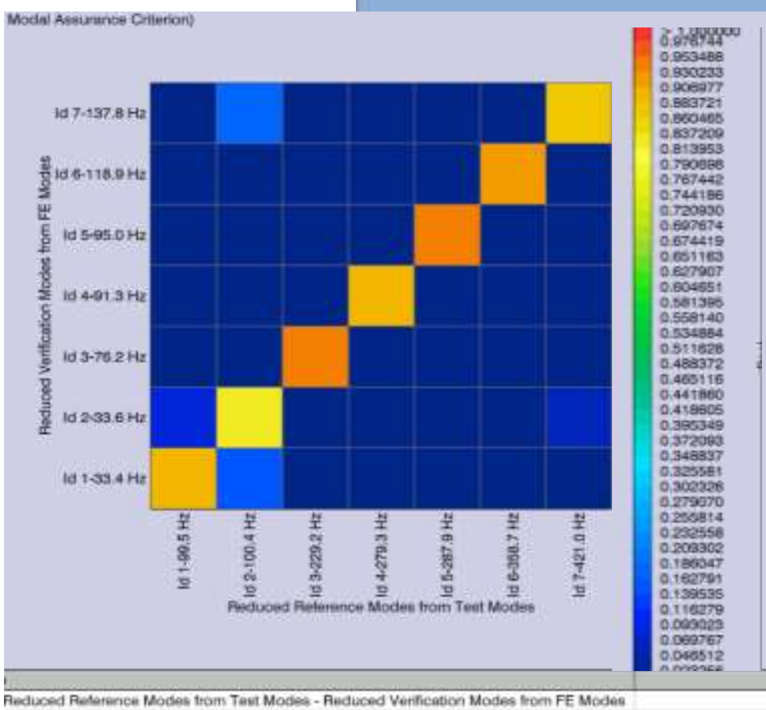
SIEMENS

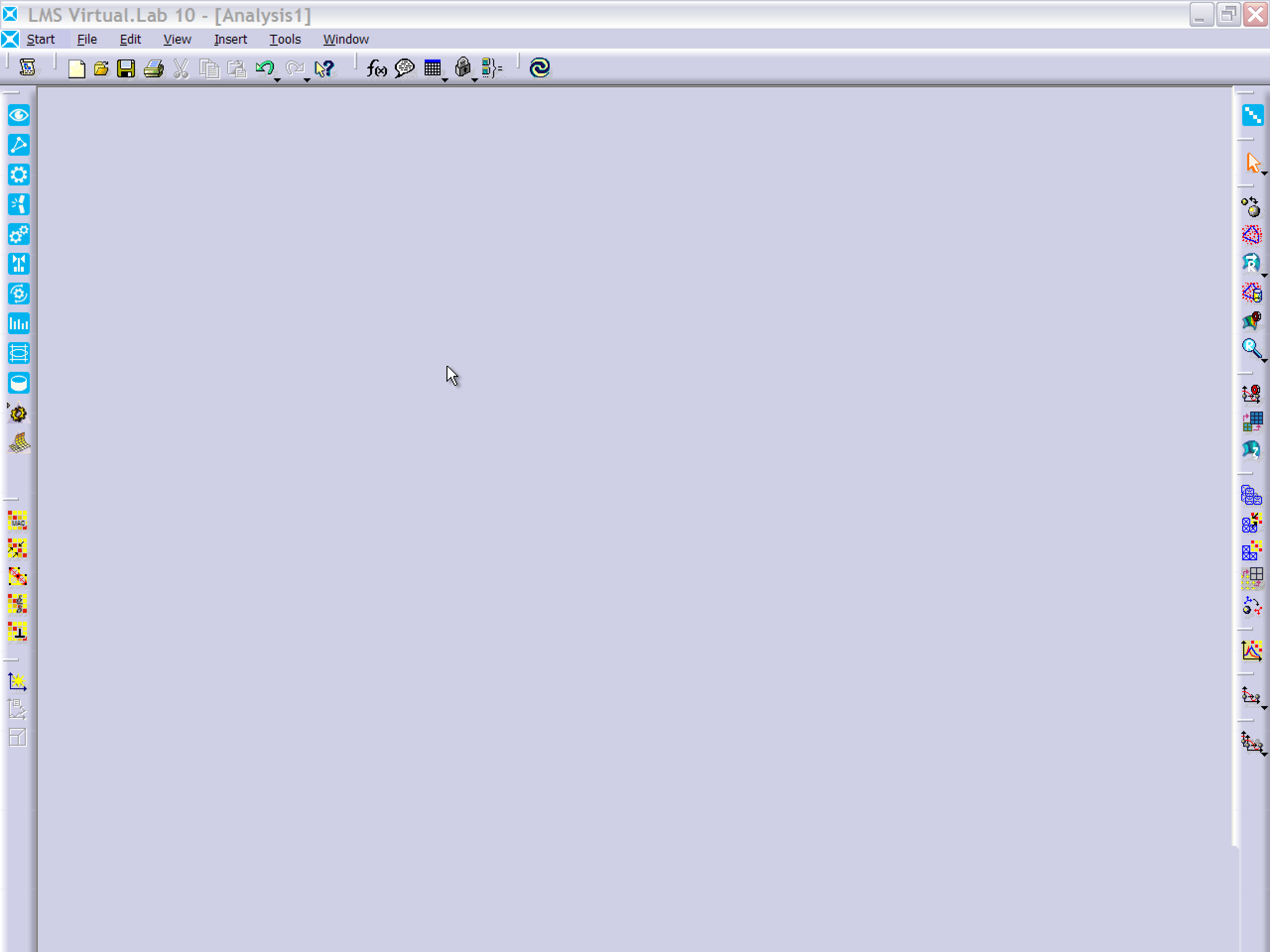
COST !

- **Minimize Failures**
  - FEA accuracy degrades as mode order increases
  - Simulation results are used for design decisions in Acoustics, NVH, Durability, Loads, etc…
- **Reduce Warranty Issues**
  - Improve customer satisfaction
- **Shorten Product Design Cycle**
  - Single prototype for validation
- **Achieve "Design Right First Time"**

DEMONSTRATION: Flat Plate





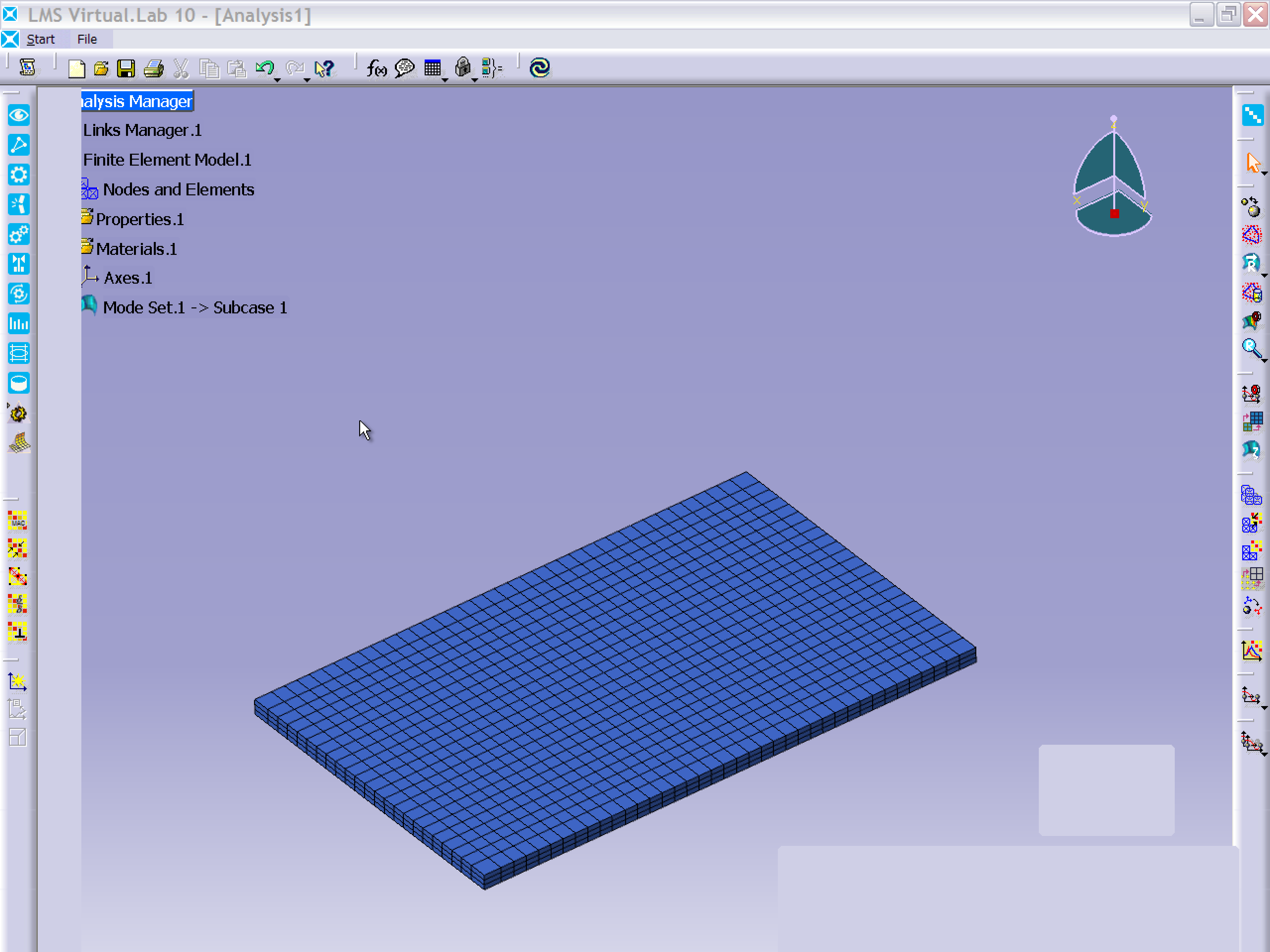

LMS Virtual.Lab 10 - [Analysis1]
Start
File
Edit
View
Insert
Tools
Window

SIEMENS

PreTest

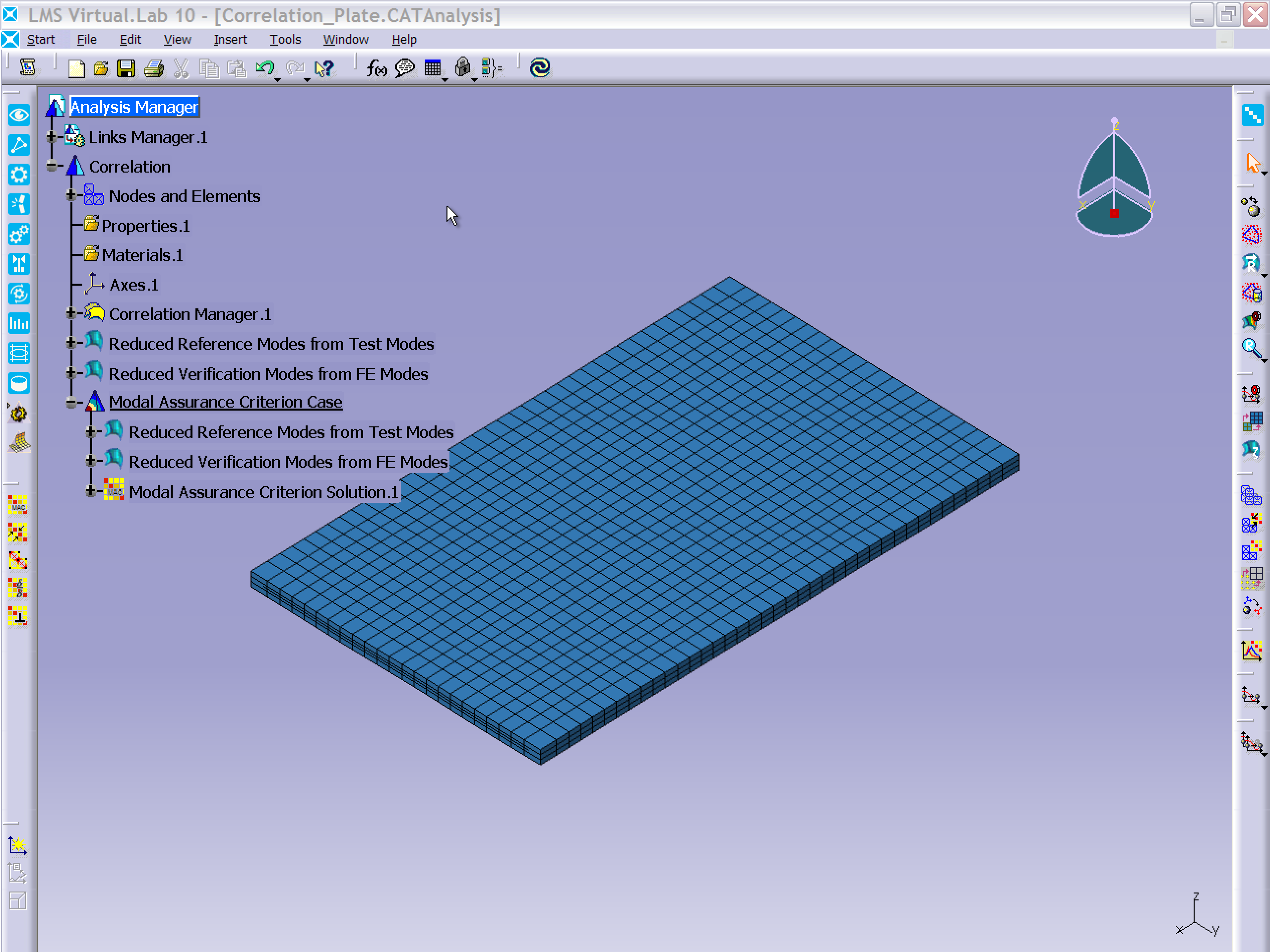
How many points?

6 or more?


LMS Virtual.Lab 10 - [Analysis1]
Start
File
alysis Manager
Links Manager.1
Finite Element Model.1
Nodes and Elements
Properties.1
Materials.1
Axes.1
Mode Set.1 -> Subcase 1

Correlation

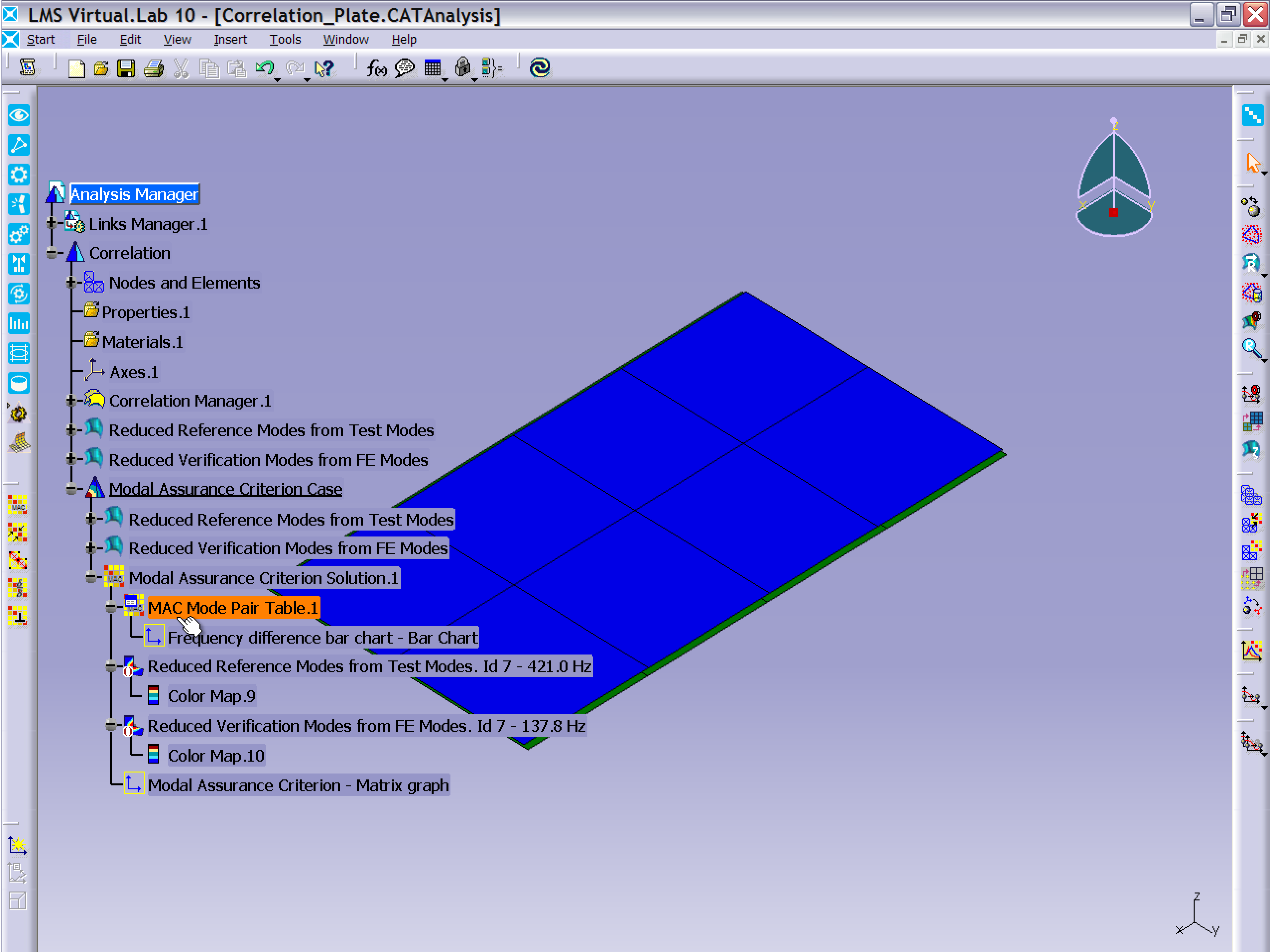
Viewing mode shapes side-by-side?


LMS Virtual.Lab 10 - [Correlation_Plate.CATAnalysis]
Start
File
Edit
View
Insert
Tools
Window
Help
Analysis Manager
Links Manager.1
Correlation
Nodes and Elements
Properties.1
Materials.1
Axes.1
Correlation Manager.1
Reduced Reference Modes from Test Modes
Reduced Verification Modes from FE Modes
Modal Assurance Criterion Case
Reduced Reference Modes from Test Modes
Reduced Verification Modes from FE Modes
Modal Assurance Criterion Solution.1

Correlation

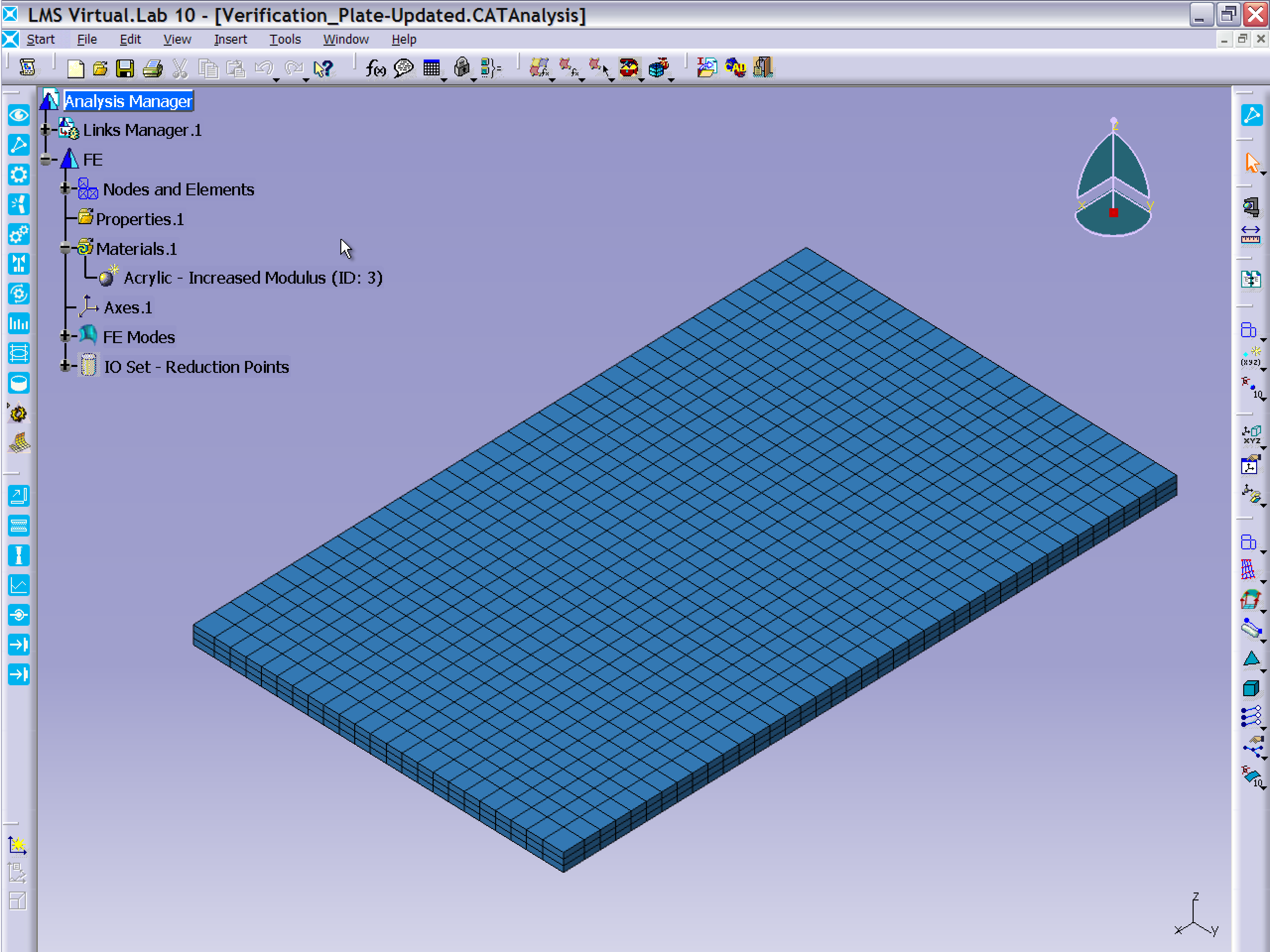
MAC

But is there something else…?

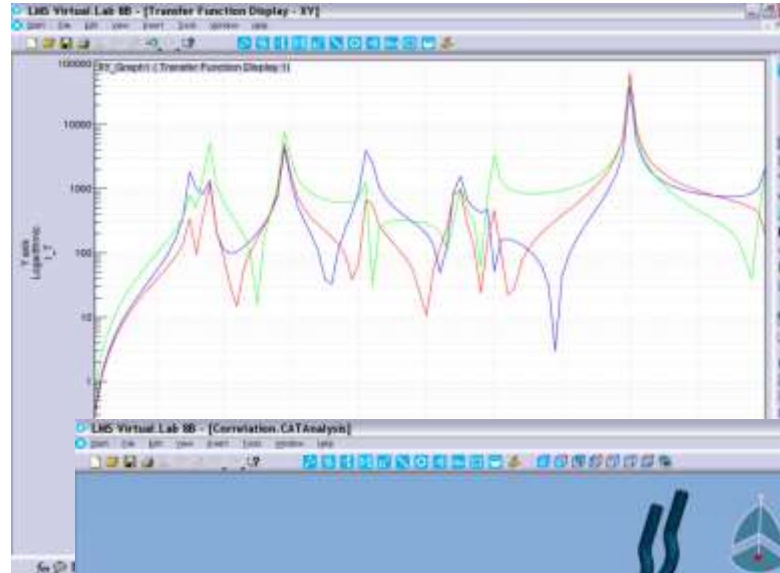

LMS Virtual.Lab 10 - [Correlation_Plate.CATAnalysis]
Start
File
Edit
View
Insert
Tools
Window
Help
Analysis Manager
Links Manager.1
Correlation
Nodes and Elements
Properties.1
Materials.1
Axes.1
Correlation Manager.1
Reduced Reference Modes from Test Modes
Reduced Verification Modes from FE Modes
Modal Assurance Criterion Case
Reduced Reference Modes from Test Modes
Reduced Verification Modes from FE Modes
Modal Assurance Criterion Solution.1
MAC Mode Pair Table.1
Frequency difference bar chart - Bar Chart
Reduced Reference Modes from Test Modes. Id 7 - 421.0 Hz
Color Map.9
Reduced Verification Modes from FE Modes. Id 7 - 137.8 Hz
Color Map.10
Modal Assurance Criterion - Matrix graph

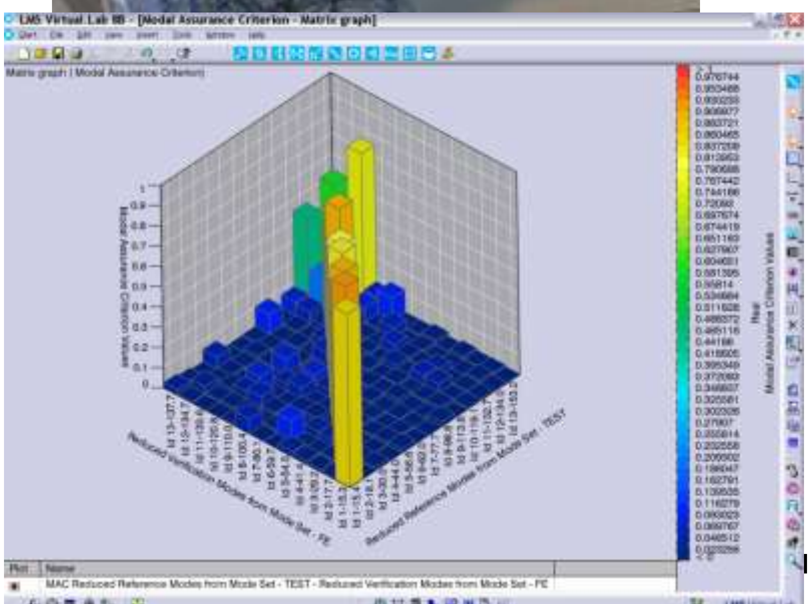
Why the frequency difference?

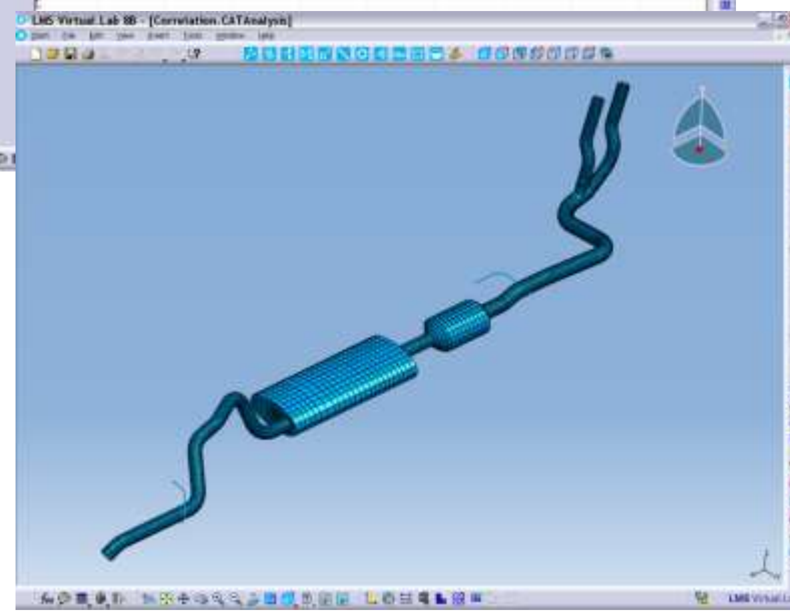
All test modes higher frequency than FE
Need to raise frequency of FE modes
What to change…?


LMS Virtual.Lab 10 - [Verification_Plate-Updated.CATAnalysis]
Start
File
Edit
View
Insert
Tools
Window
Help
Analysis Manager
Links Manager.1
FE
Nodes and Elements
Properties.1
Materials.1
Acrylic - Increased Modulus (ID: 3)
Axes.1
FE Modes
IO Set - Reduction Points

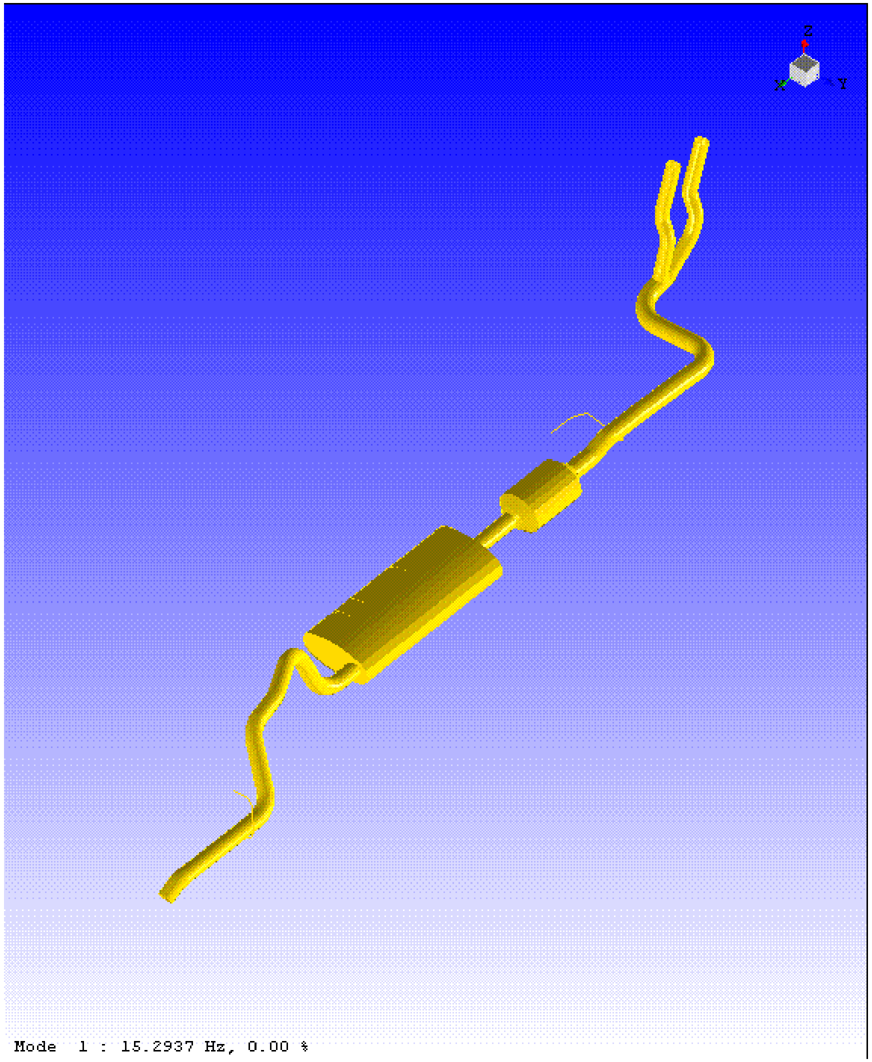
Application Case: Exhaust System



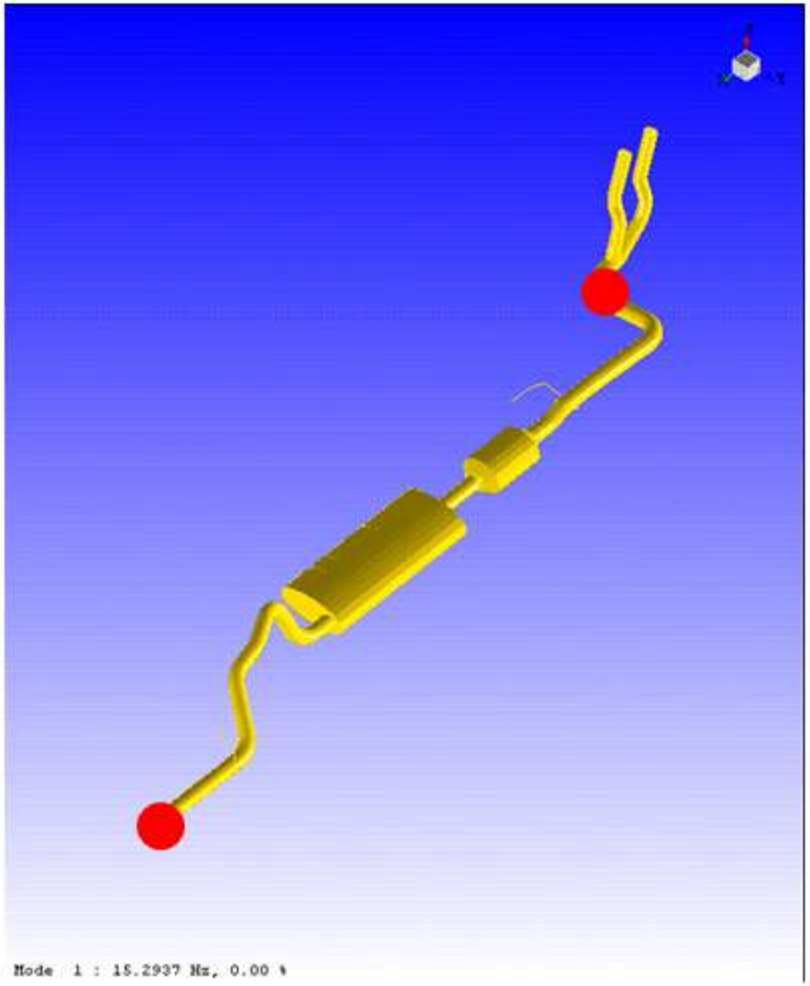




Exhaust Mode at 15 Hz

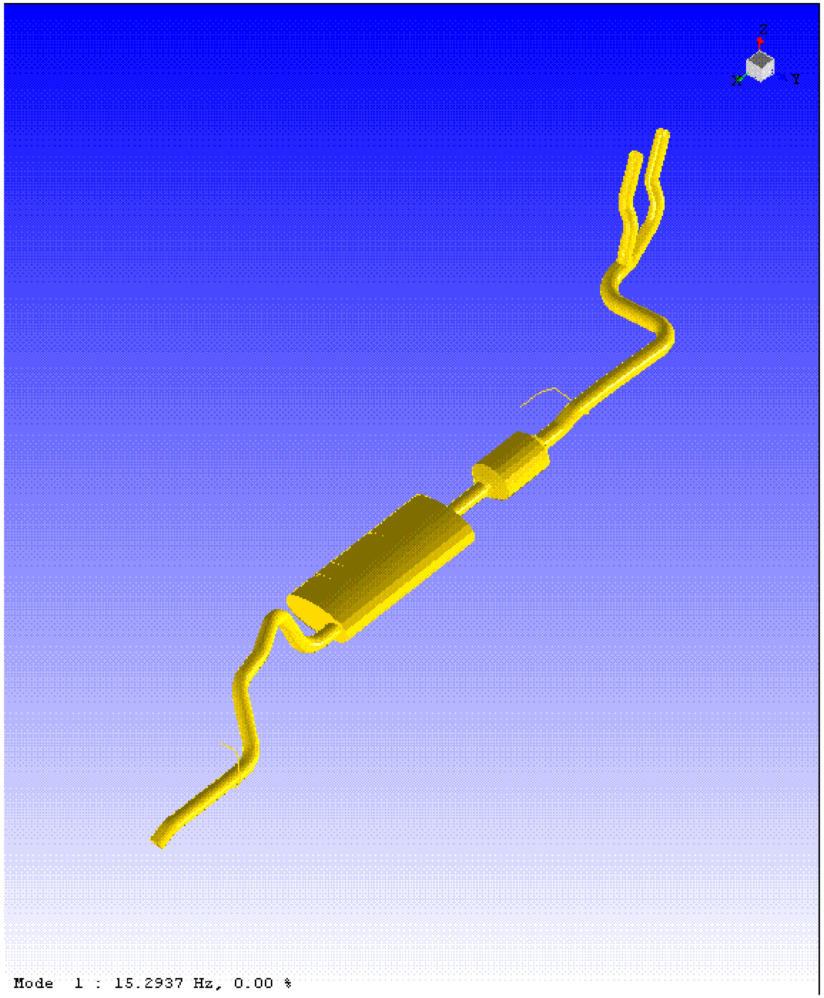


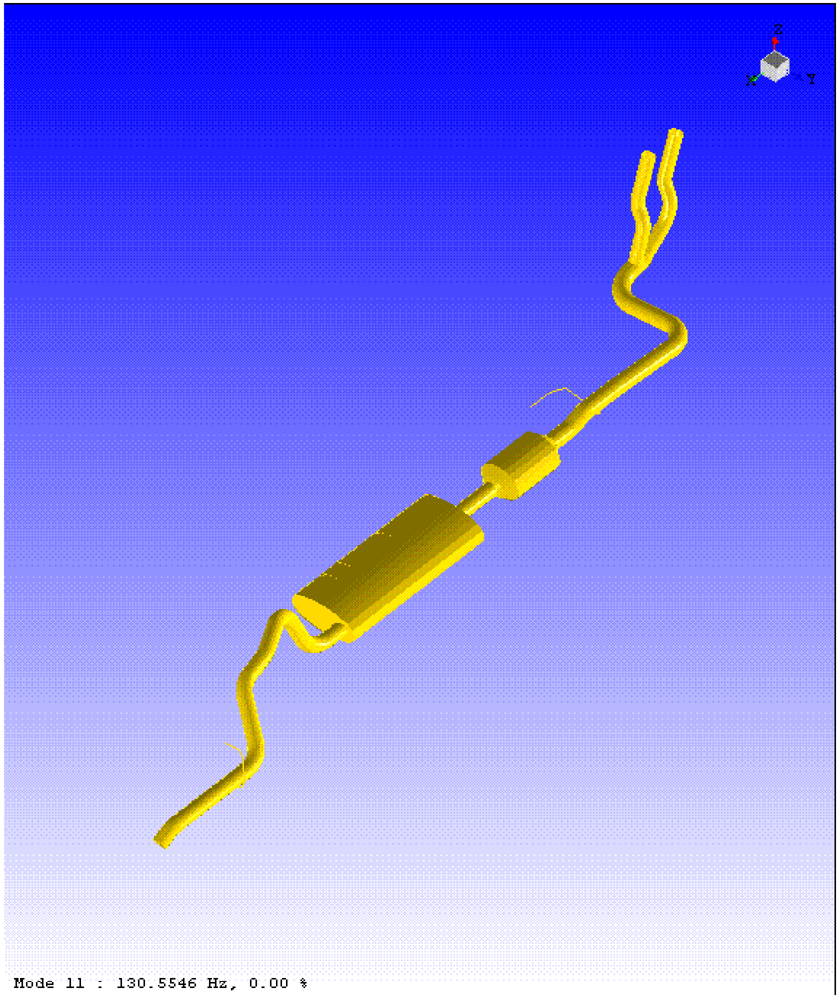
Exhaust Mode at 15 Hz



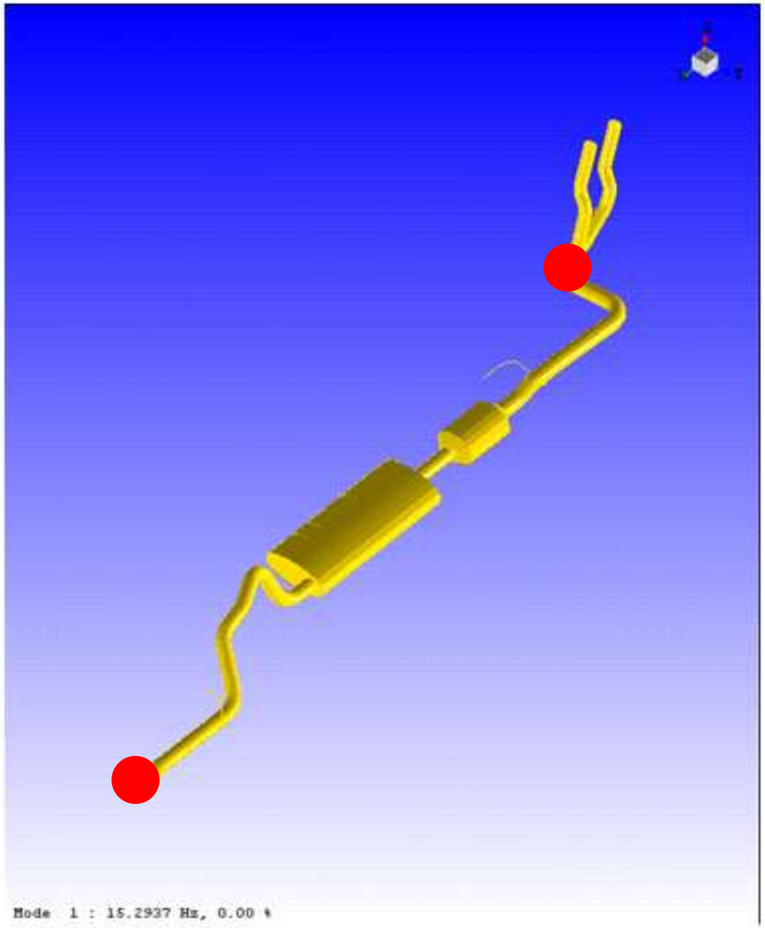
SIEMENS

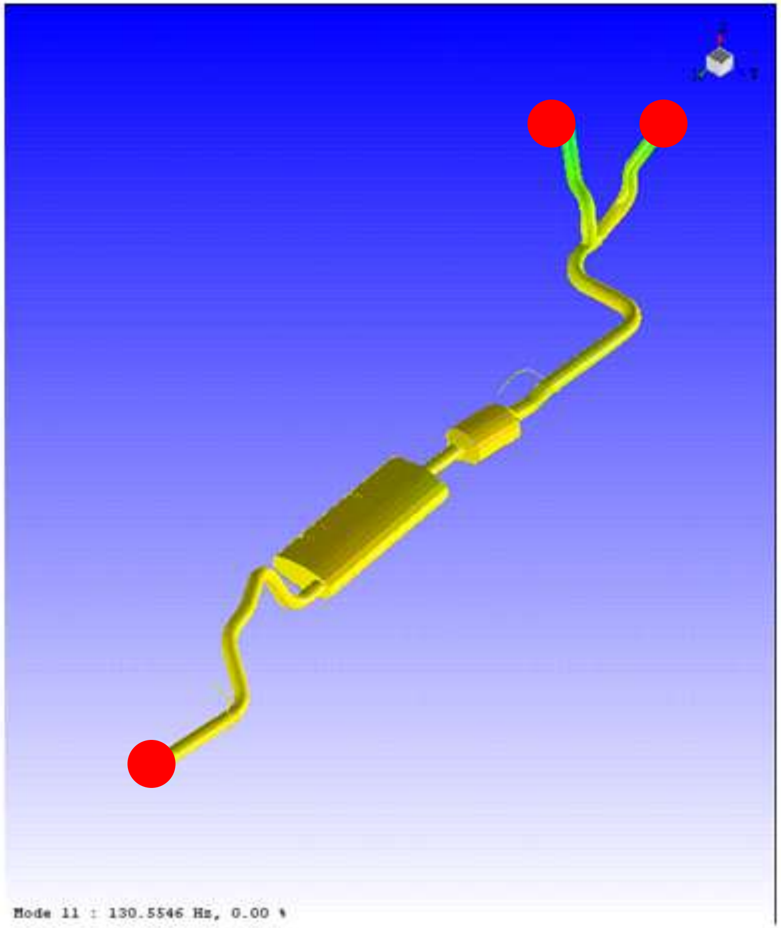
Exhaust Modes at 15 and 130 Hz



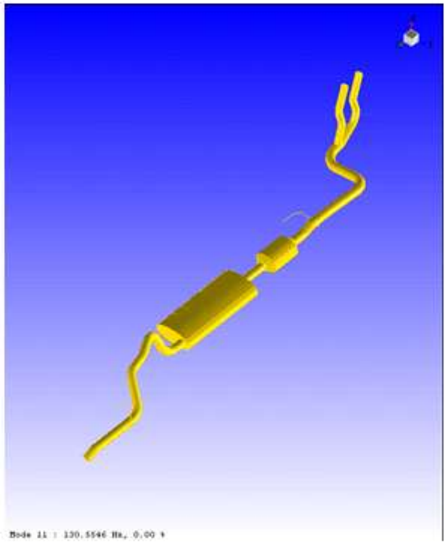


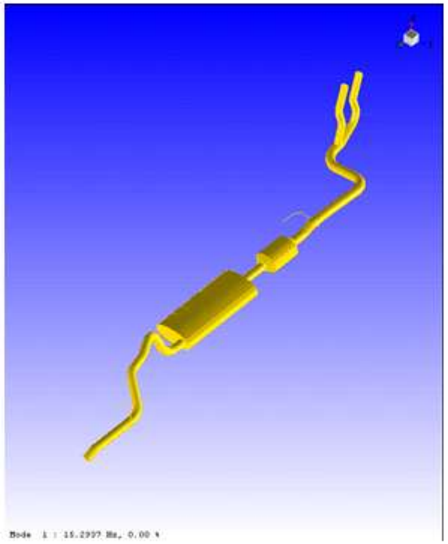
Exhaust Modes at 15 and 130 Hz

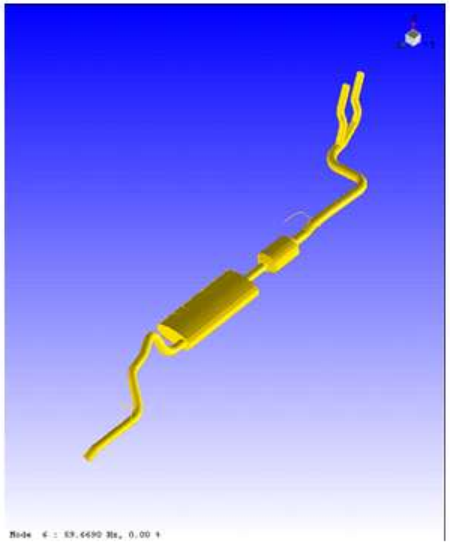


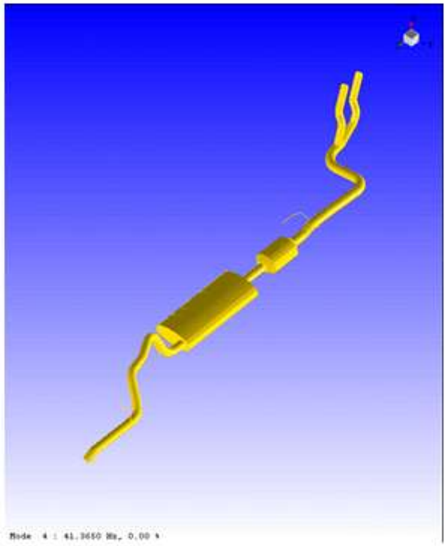


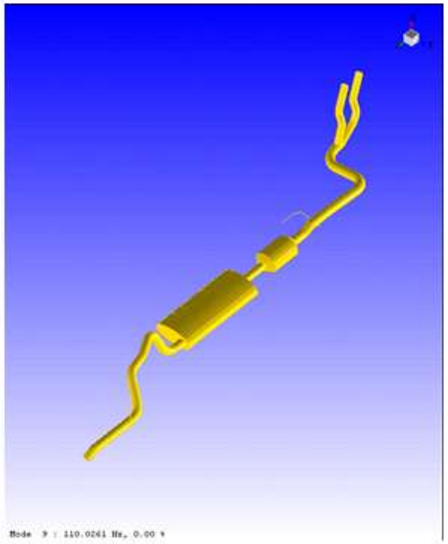
6 Exhaust Modes up to 137 Hz

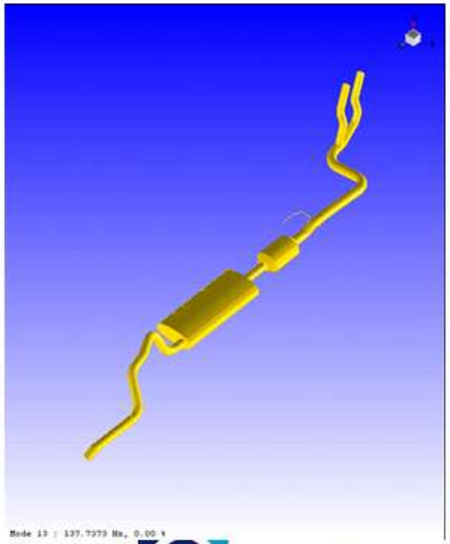




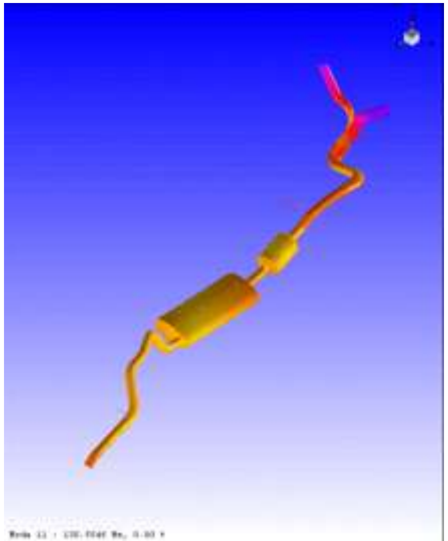


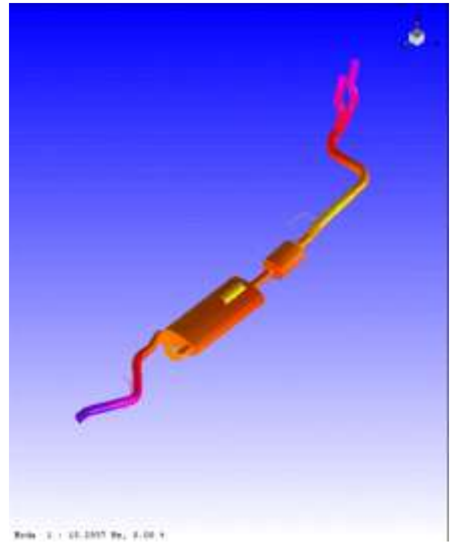


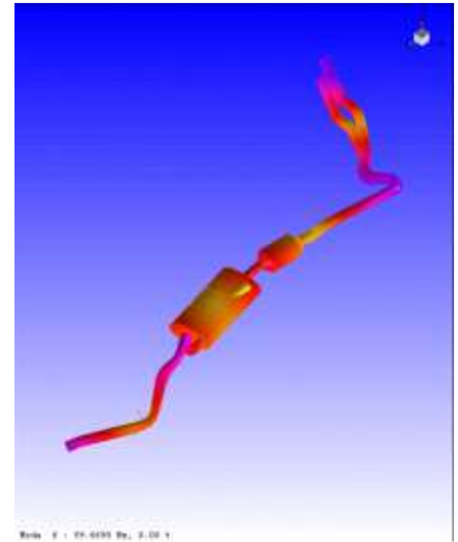


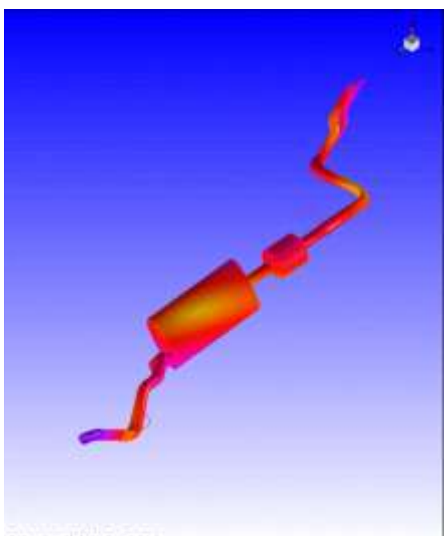


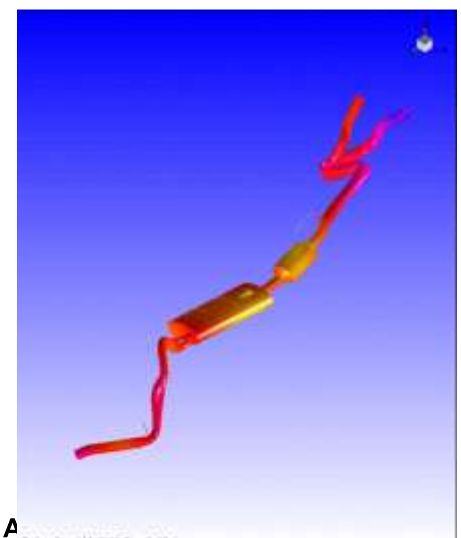
6 Exhaust Modes up to 137 Hz

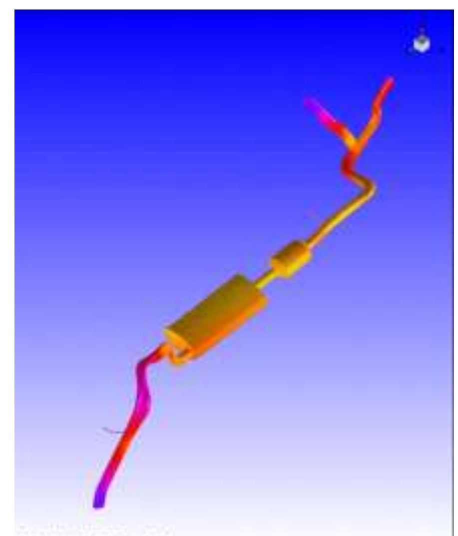










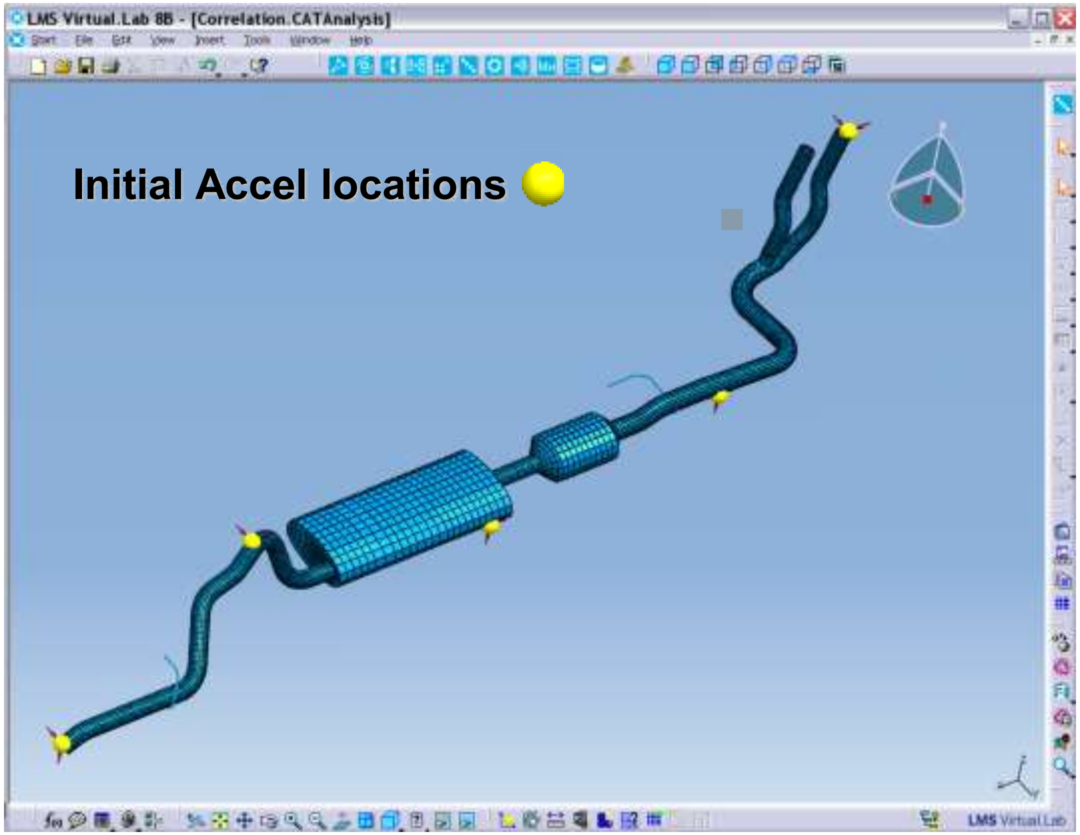


Application Case: Pretest Analysis

<u>Step 1:</u> Use FE model to pick some initial accelerometer locations

Supported FEA Software:

- ***NASTRAN***
- ***ANSYS***
- ***Abaqus***
- ***IDEAS***
- ***Elfini/GPS***
- ***Universal File Format***



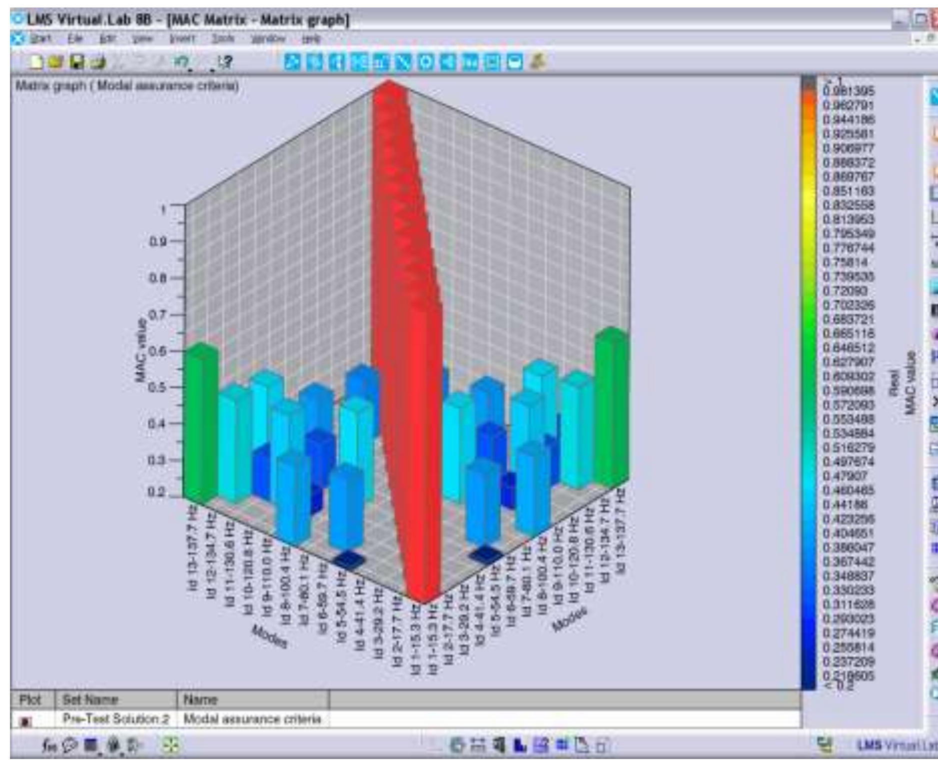
Application Case: Pretest Analysis

<u>Step 2:</u> Use MAC to assure that accelerometer locations are sufficient to uniquely identify all modes from FEM Normal Modes Analysis

MAC: **Modal Assurance Criterion A measure of how well *mode shapes* are correlated.**

In this case, the MAC diagram shows large off-diagonal terms, indicating that several modes are non-uniquely identified.

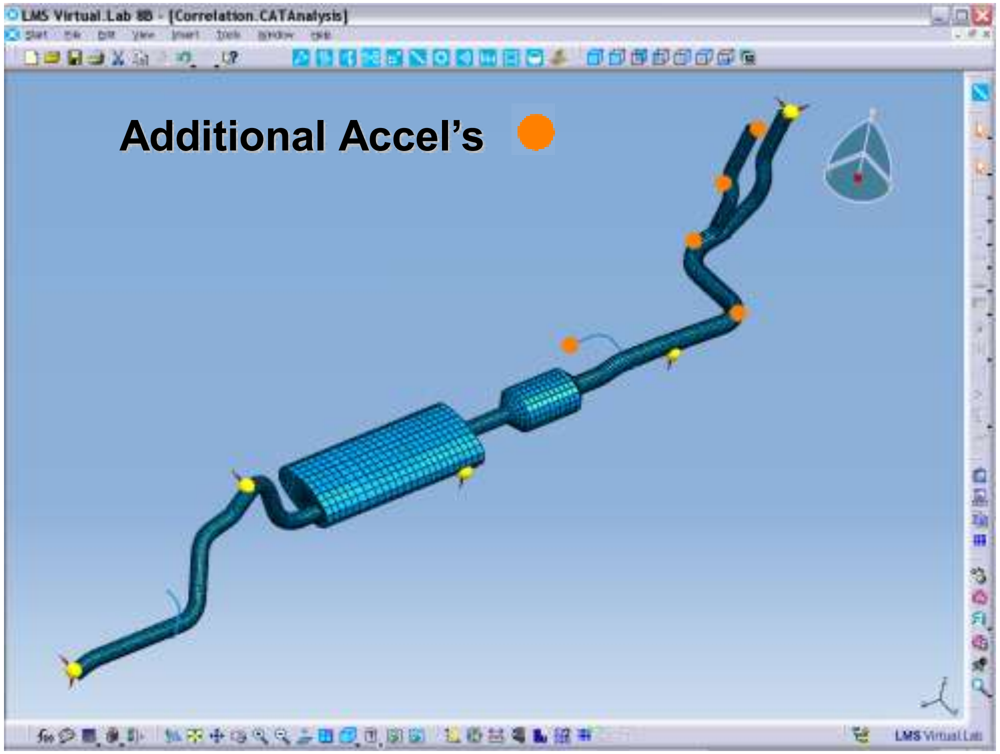
Thus, more accelerometers are required to guarantee a good test.



Application Case: Pretest Analysis

Step 3: Use LMS Pretest to automatically locate additional accelerometers to meet requested MAC criterion.

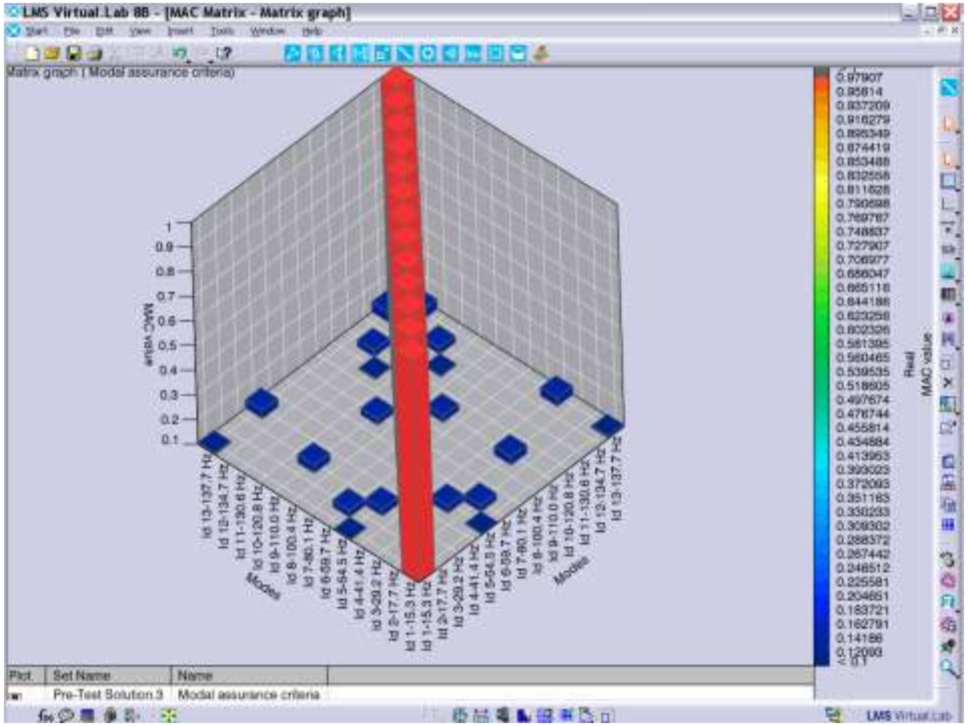
- **5 accelerometers have been added to the exhaust model as shown to reach the target off-diagonal MAC of <0.15**

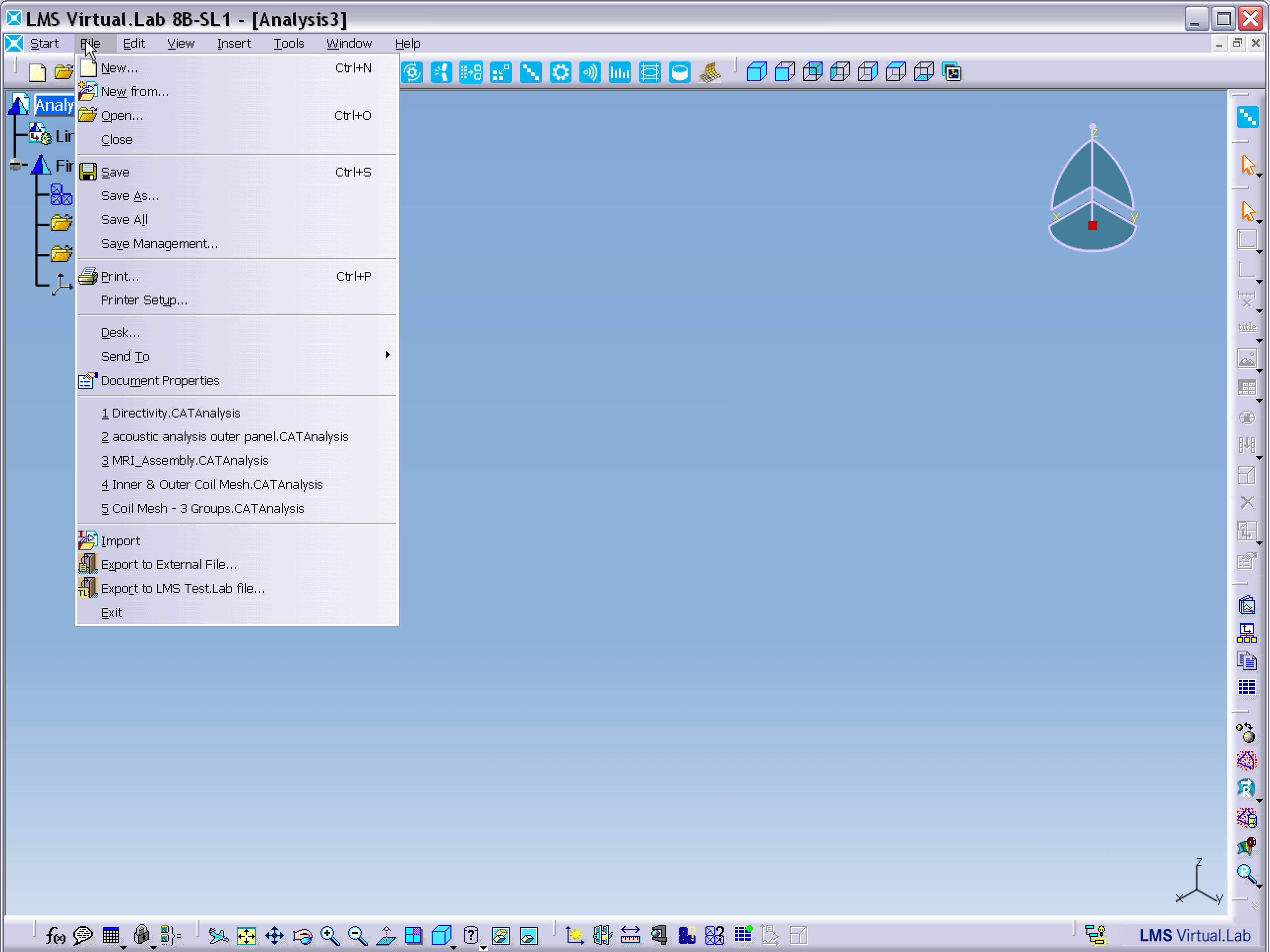


Application Case: Pretest Analysis

<u>Step 3:</u> Use LMS Pretest to automatically locate additional accelerometers to meet requested MAC criterion.

- **New MAC diagram shows all modes uniquely identified. This is indicated by reduction of off-diagonal terms.**



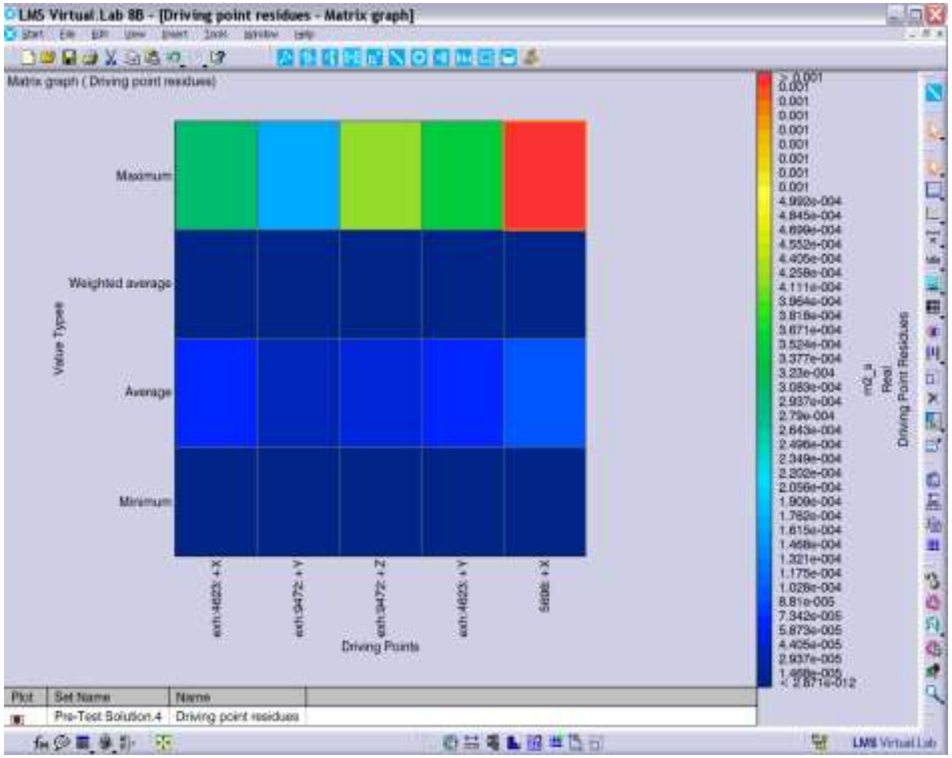

LMS Virtual.Lab 8B-SL1 - [Analysis3]
Start
File
Edit
View
Insert
Tools
Window
Help
New... Ctrl+N
New from...
Open... Ctrl+O
Close
Save Ctrl+S
Save As...
Save All
Save Management...
Print... Ctrl+P
Printer Setup...
Desk...
Send To
Document Properties
1 Directivity.CATAnalysis
2 acoustic analysis outer panel.CATAnalysis
3 MRI_Assembly.CATAnalysis
4 Inner & Outer Coil Mesh.CATAnalysis
5 Coil Mesh - 3 Groups.CATAnalysis
Import
Export to External File...
Export to LMS Test.Lab file...
Exit
LMS Virtual.Lab

Application Case: Pretest Analysis

<u>Step 4:</u> Use LMS Pretest to show optimum locations of shakers or impact to excite all structural modes during the test.

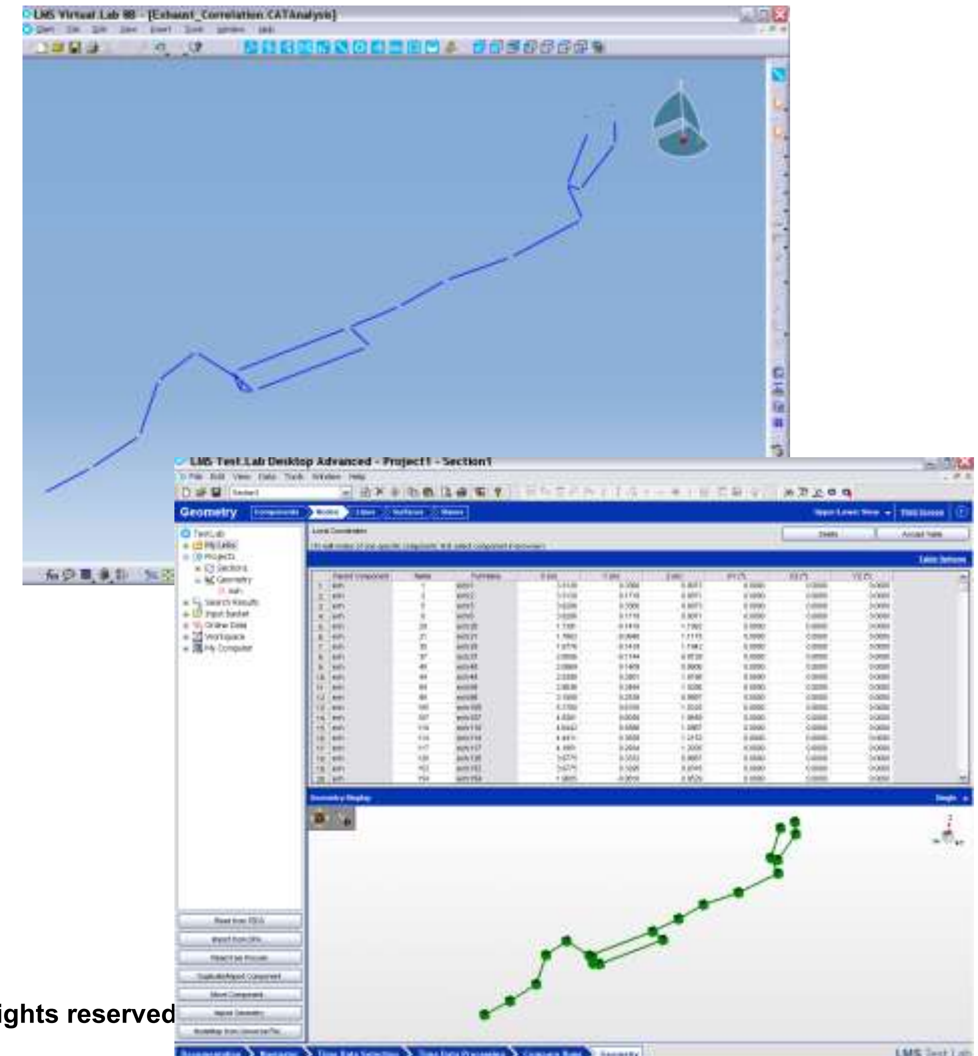
- **DPR (Driving Point Residue) algorithm is used to locate optimum shaker location and orientation. DPR indicates how well *all* modes are excited by a potential reference location.**

- **Practical considerations sometimes lead to selecting excitation locations other than the most optimum. In this case, several points can excite the structure sufficiently.**



Application Case: Pretest Analysis

<u>Step 5:</u> Create wireframe geometry for Modal Test and export to LMS Test.Lab software.



- **A Test.Lab project file is created containing the exhaust geometry, as well as the FE mode shapes & frequencies.**

- **Reduced FE modes provide the test engineer with the ability to visually check the shapes.**

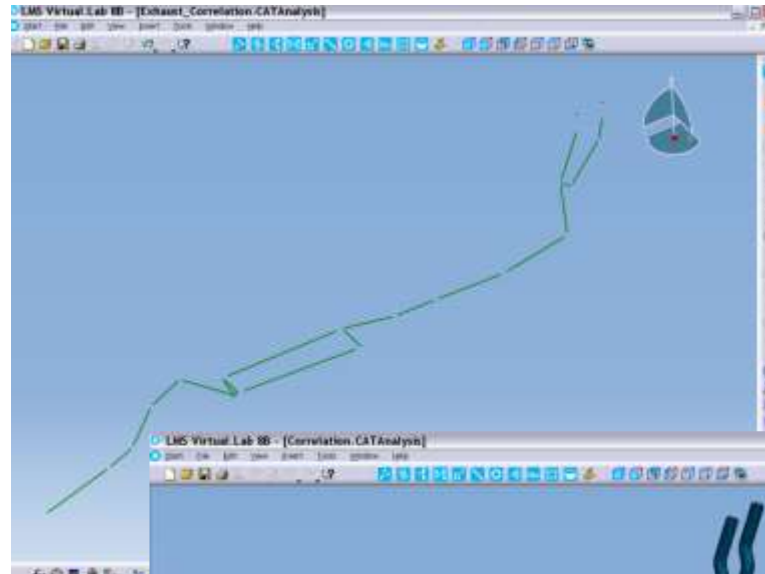
Application Case: Modal Test

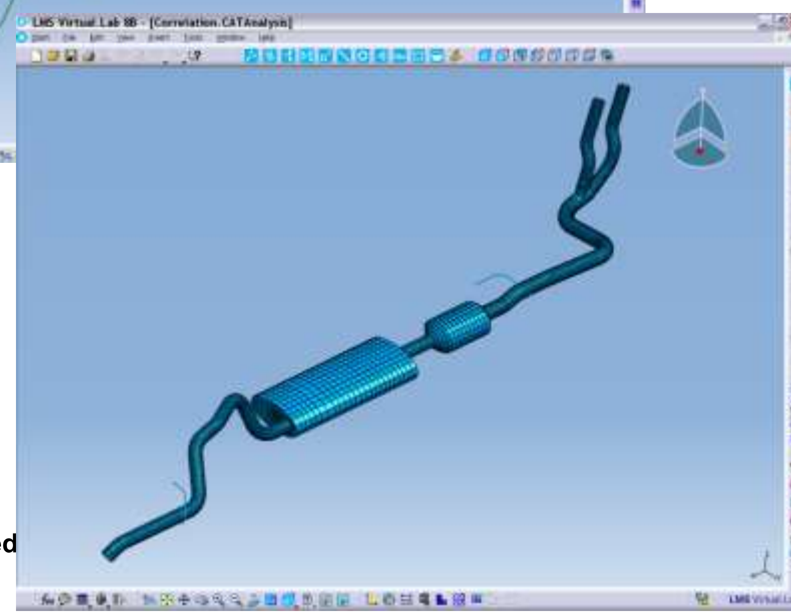
Perform the modal test on the physical structure.

- **The test engineer mounts accelerometers, and collects modal data by exciting the structure with shakers or an impact hammer in the locations as indicated by Pretest.**

Application Case: Correlation

<u>Step 1:</u> Use the LMS Correlation Manager to import the Test and FE Models, and define correlation parameters.





Parameters:

- **MAC threshold value for matching of FE/Test mode pairs**
- **Coordinate system translations and rotations**
- **Frequency range for both FE and Test**

Application Case: Correlation

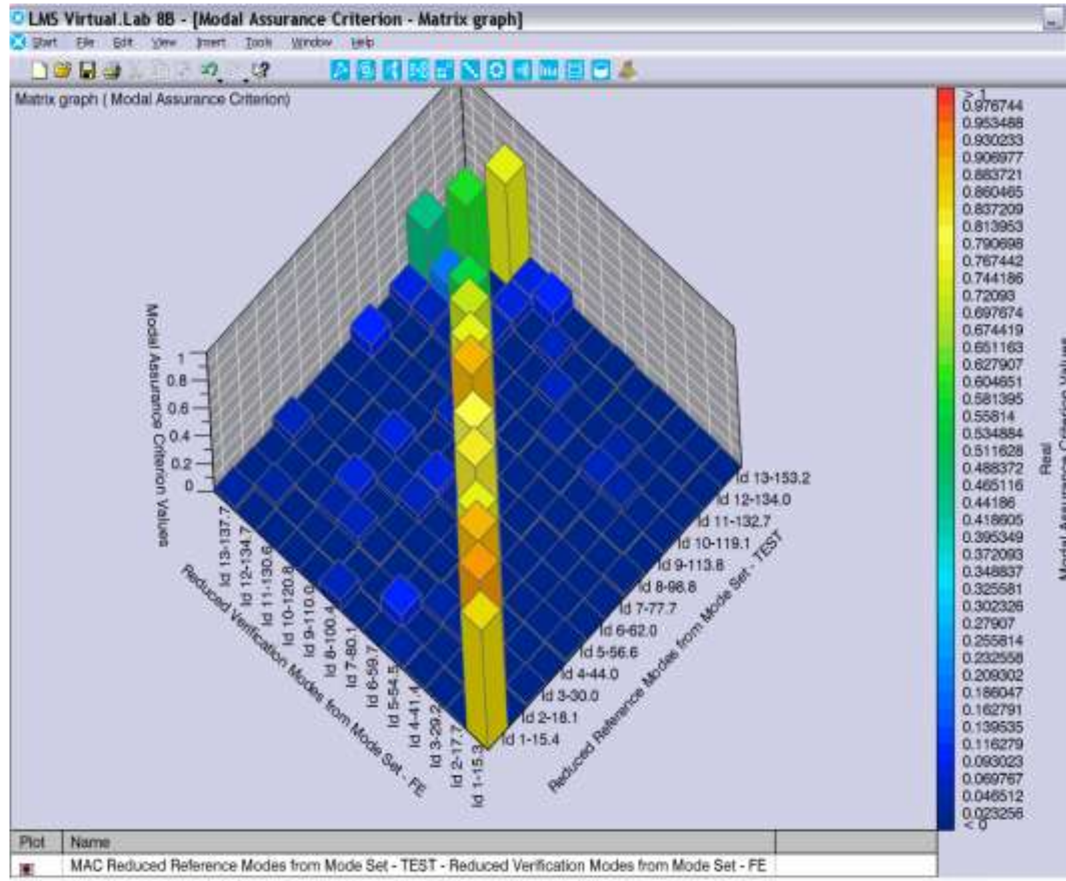
<u>Step 2:</u> Use Correlation Tools to evaluate how well FE and Test models correlate.

Global MAC plot shows:

- **Good *mode shape:* correlation of modes 1-8**

- **Mode swapping between modes 11 and 13 for FE and Test models**

- **MAC <0.75 for modes 9-13**

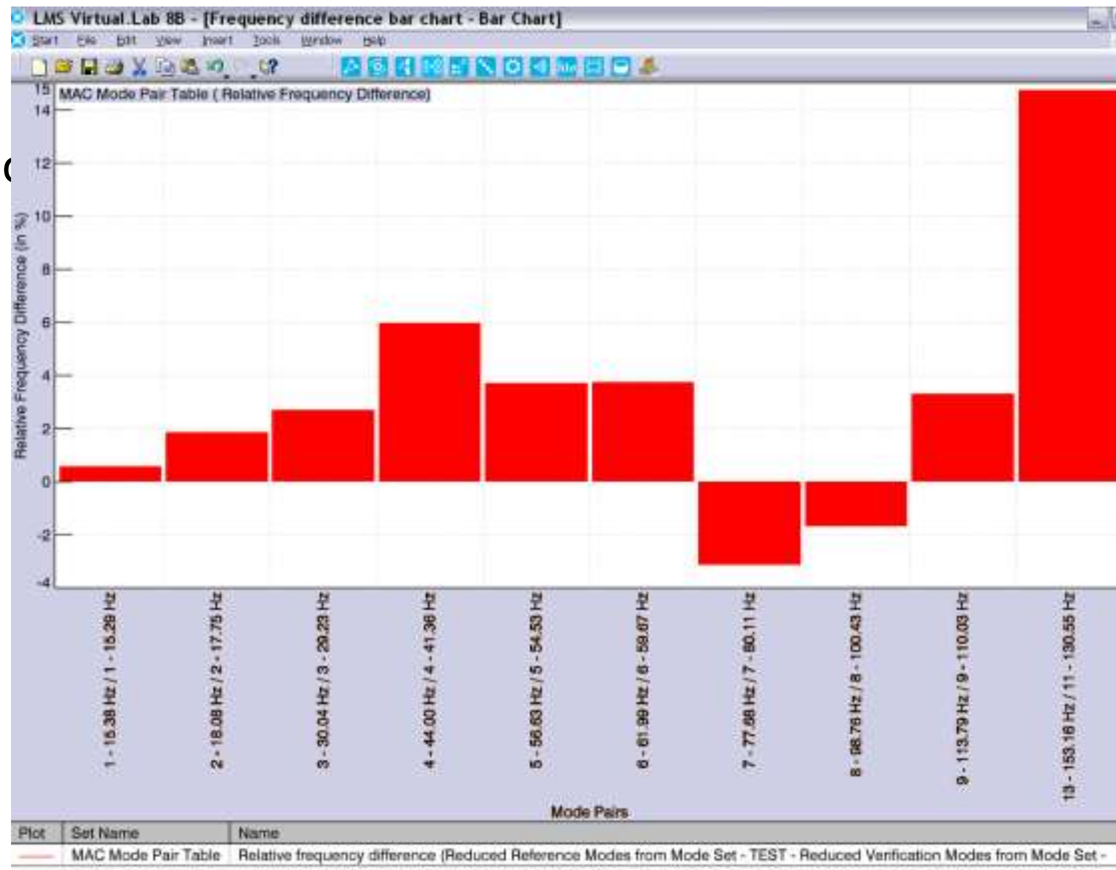


Application Case: Correlation

Step 2: Use Correlation Tools to evaluate how well FE and Test models correlate.

Relative Frequency Difference plot shows:

- **Small *frequency differences***
- **< 6% for modes 1-9**



Application Case: Correlation

SIEMENS

Step 2: Use Correlation Tools to evaluate how well FE and Test models correlate.

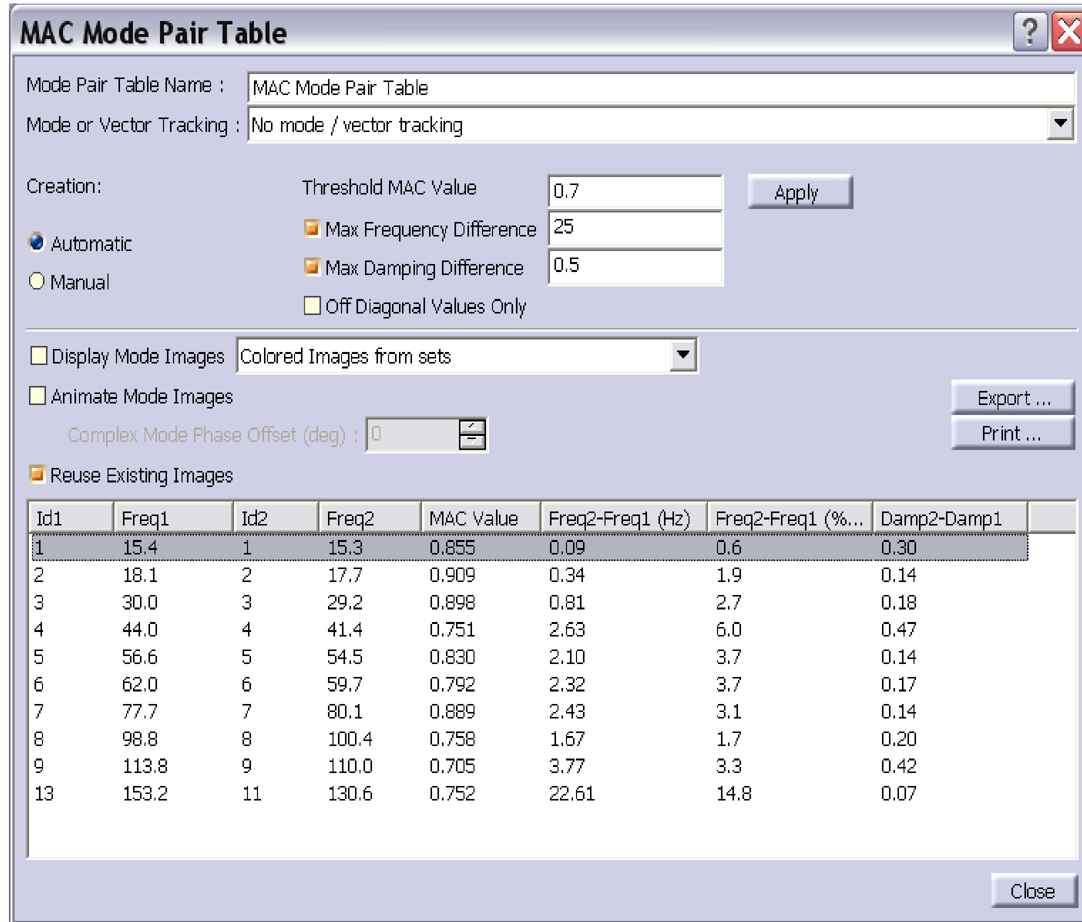
Mode Pair Table:

- **Shows absolute frequency/damping differences for matching FE/Test modes**

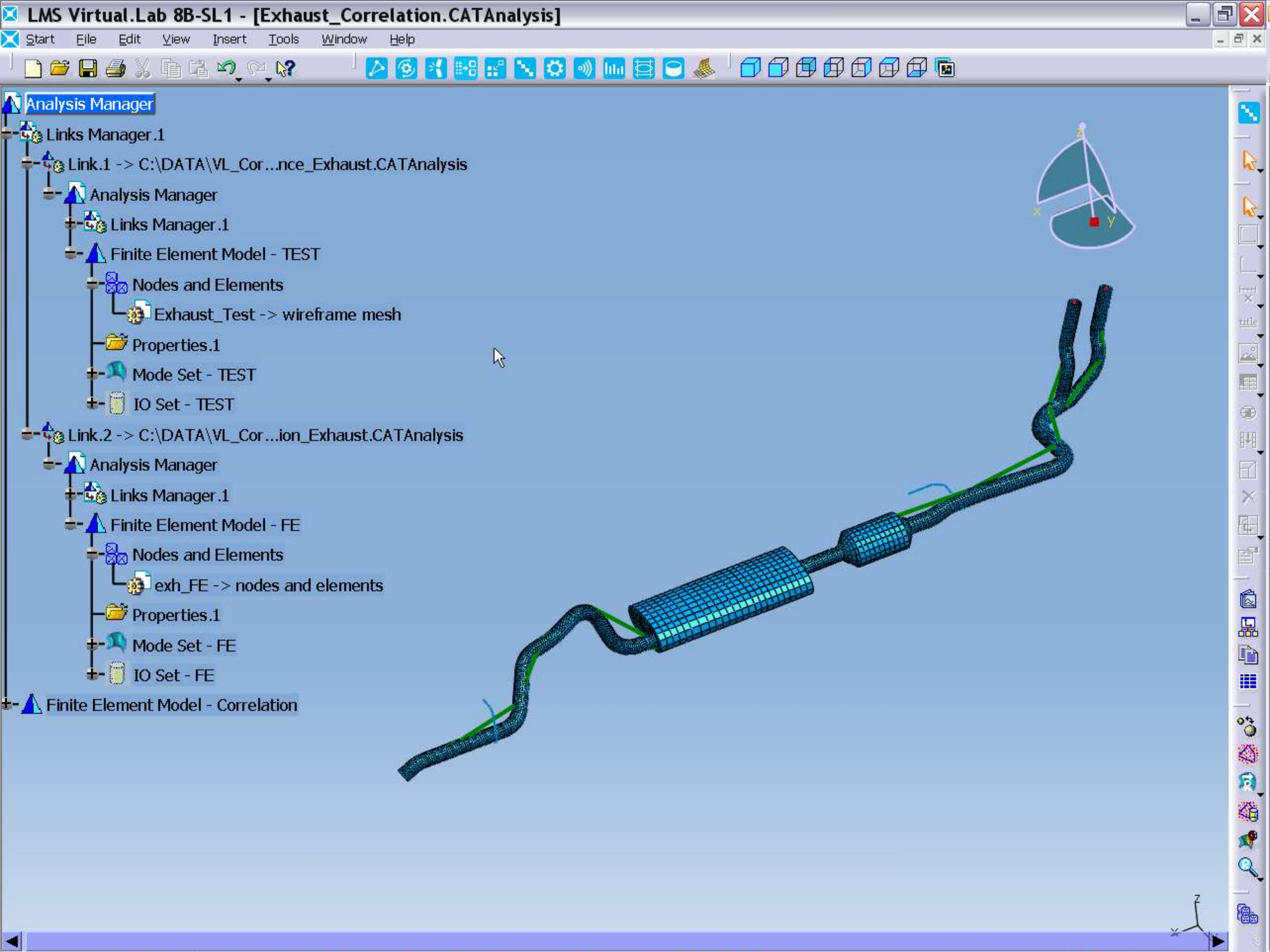
In this case:

- **Good frequency correlation of modes 1-9**

- **Large frequency difference for mode pair 13, 11 (>14%)**



Id1	Freq1	Id2	Freq2	MAC Value	Freq2-Freq1 (Hz)	Freq2-Freq1 (%...	Damp2-Damp1
1	15.4	1	15.3	0.855	0.09	0.6	0.30
2	18.1	2	17.7	0.909	0.34	1.9	0.14
3	30.0	3	29.2	0.898	0.81	2.7	0.18
4	44.0	4	41.4	0.751	2.63	6.0	0.47
5	56.6	5	54.5	0.830	2.10	3.7	0.14
6	62.0	6	59.7	0.792	2.32	3.7	0.17
7	77.7	7	80.1	0.889	2.43	3.1	0.14
8	98.8	8	100.4	0.758	1.67	1.7	0.20
9	113.8	9	110.0	0.705	3.77	3.3	0.42
13	153.2	11	130.6	0.752	22.61	14.8	0.07


LMS Virtual.Lab 8B-SL1 - [Exhaust_Correlation.CATAnalysis]
Start File Edit View Insert Tools Window Help
Analysis Manager
Links Manager.1
Link.1 -> C:\DATA\VL_Cor...nce_Exhaust.CATAnalysis
Analysis Manager
Links Manager.1
Finite Element Model - TEST
Nodes and Elements
Exhaust_Test -> wireframe mesh
Properties.1
Mode Set - TEST
IO Set - TEST
Link.2 -> C:\DATA\VL_Cor...ion_Exhaust.CATAnalysis
Analysis Manager
Links Manager.1
Finite Element Model - FE
Nodes and Elements
exh_FE -> nodes and elements
Properties.1
Mode Set - FE
IO Set - FE
Finite Element Model - Correlation

SIEMENS

Are results close enough?

Although initial inspection might lead us to assume this is good correlation, further analysis yields a different conclusion…

- **Correlation of fundamental modes does not guarantee correlation throughout operating frequency band**

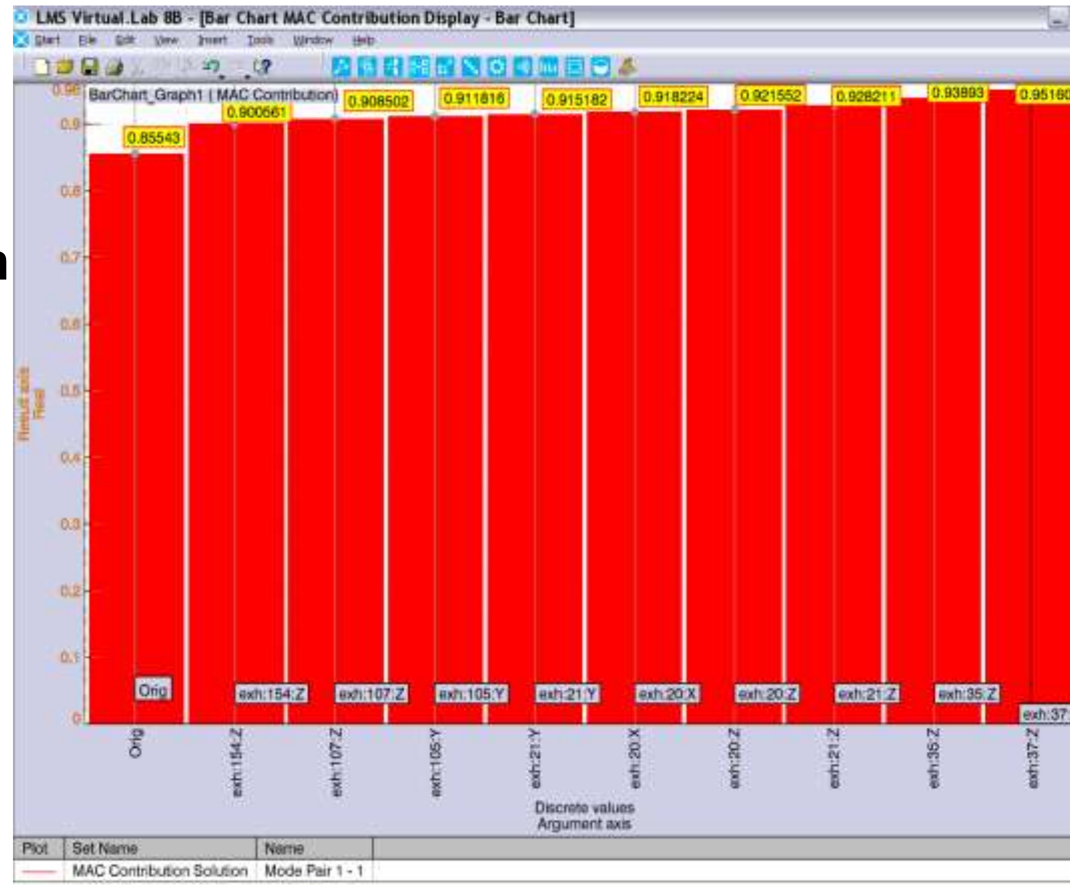
- **Higher order modes are relevant to acoustic, vibration, and durability performance – they are well within the operating frequency range**

- **Ignoring higher order mode correlation could lead to bad engineering decisions, for example:**
  - **- Poor Exhaust Hangar locations leading to Noise and Vibration Issues**
  - **- Vibration fatigue due to Engine or Road excitation at resonant frequencies**

CONCLUSION: *All modes in operating frequency band should be correlated!*

Application Case: Correlation

Step 2: Use Correlation Tools to evaluate how well FE and Test models correlate.



MAC Contribution Display:

- **Shows DOFs making most negative contribution to MAC**

In this case:

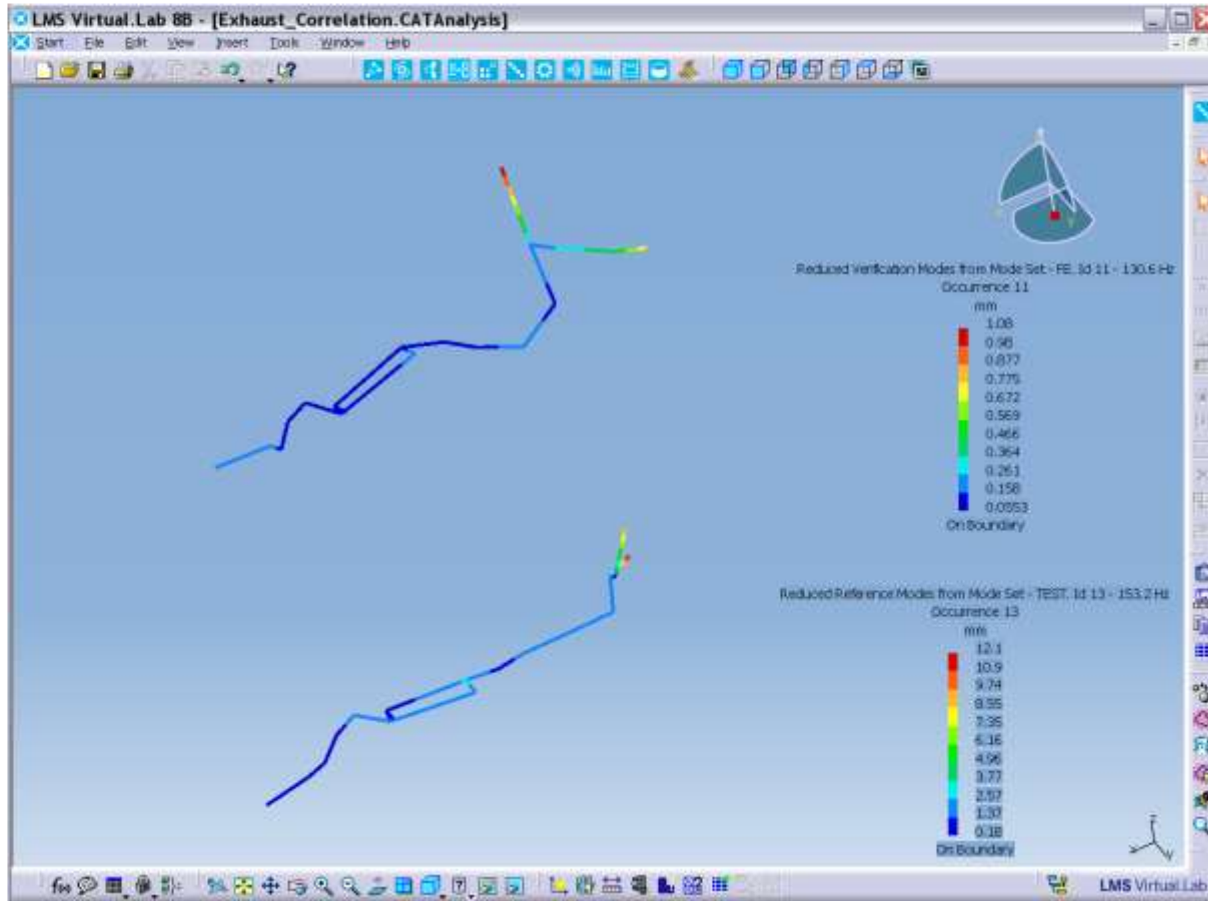
- **9 DOFs can be removed to improve MAC from 85% to 95% for Mode Pair 1, 1**

Application Case: Correlation

Step 3: Use LMS post processing tools to identify physical causes for poor correlation.

Post Processing Tools:

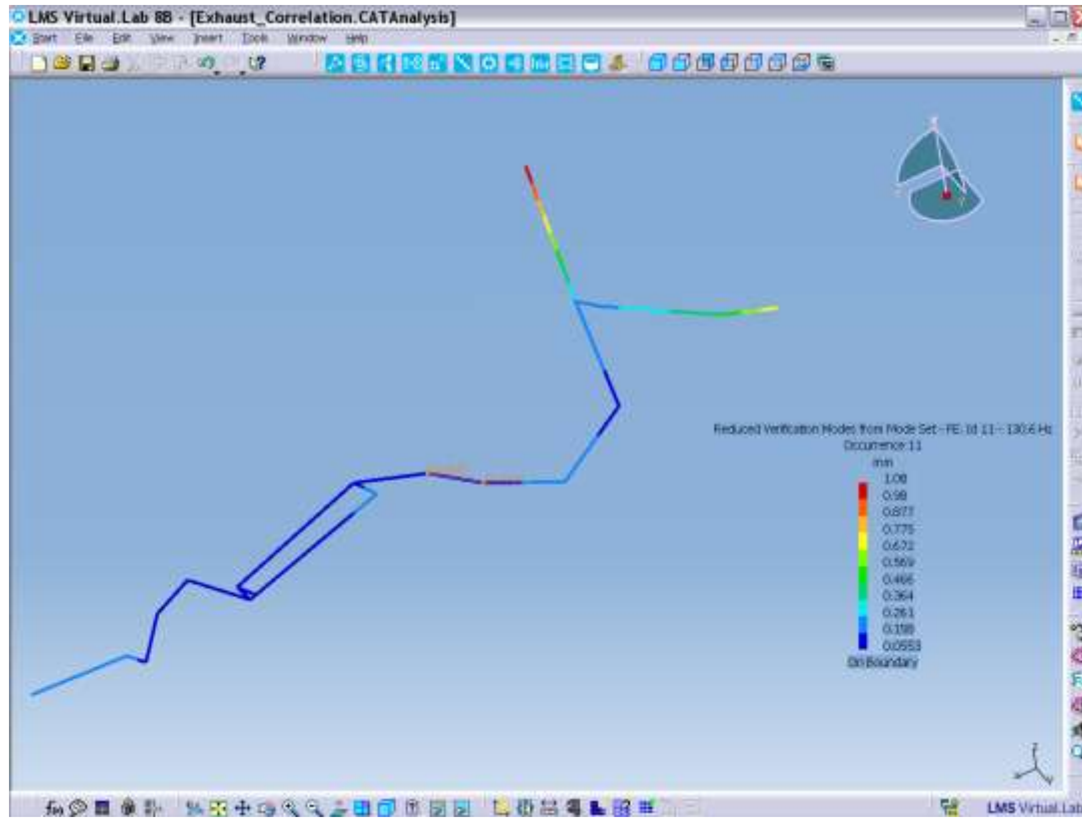
- **Side by side FE/Test animation**
- **MAC Contribution Plots**
- **FRAC Plots**
- **CoMAC Plots**



Application Case: Correlation

Step 3: Use LMS post processing tools to identify physical causes for poor correlation.

- **Local stiffness differences are indicated by lower frequency of FE model for mode pair 11**
- **Animation provides further evidence of this**
- **Consideration of physical exhaust system leads engineer to consider effect of weld on this junction (ignored in the FE model)**



Updating

SIEMENS

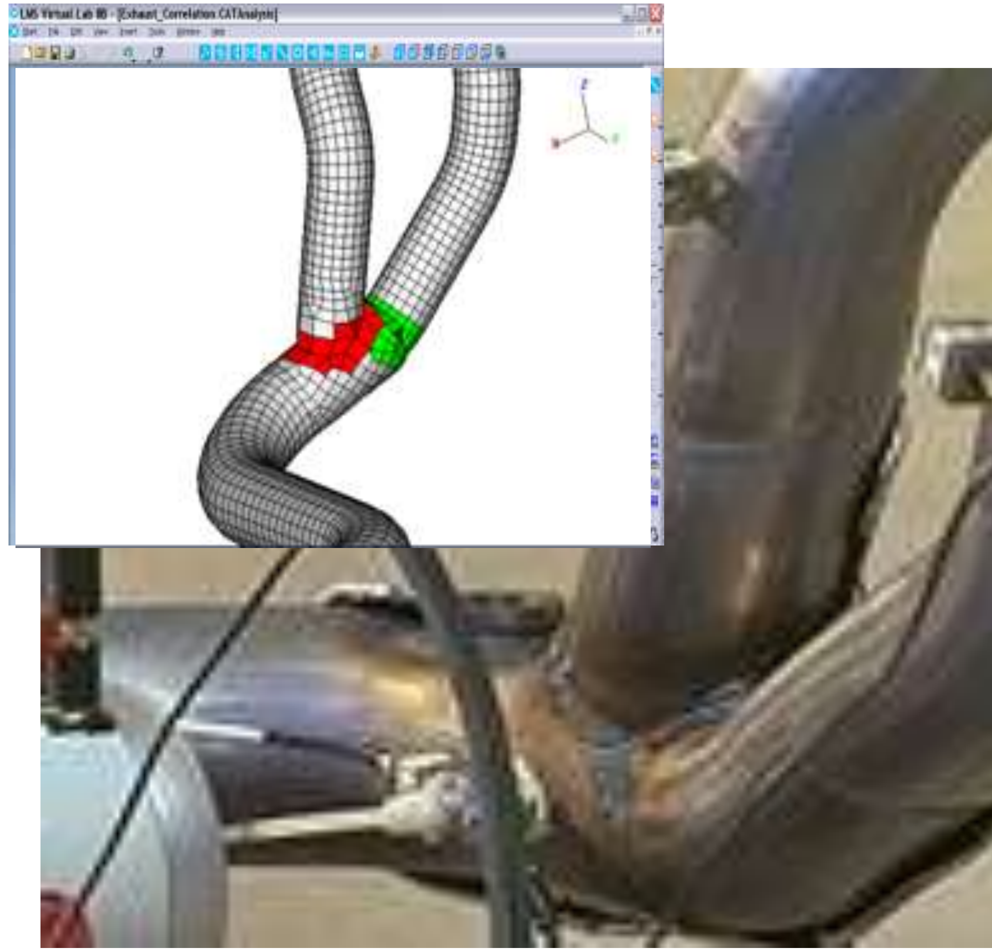
Step 4: Sensitivity Analysis and FE Model Updating

Sensitivity Analysis:

- **Sensitivity Analysis within LMS Virtual.Lab verifies that outlet junction area has dominant influence for mode pair 11**

FE Model Updating:

- **Manual updating**
- **Element thickness increased locally in weld location**
- **Amount of thickness increase guided by MAC and Frequency correlation**



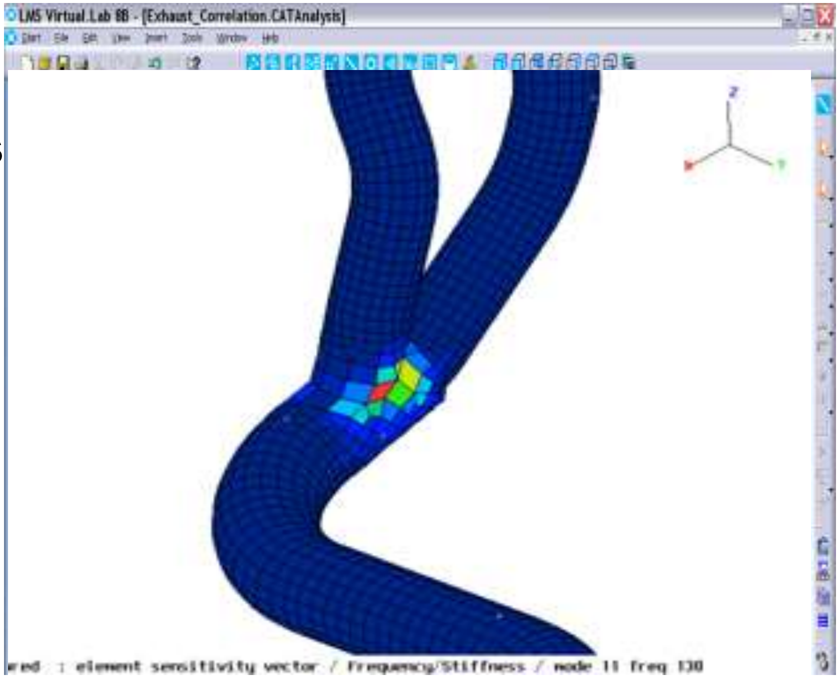
Application Case: Sensitivity & Updating

SIEMENS

Sensitivity: Ranks the contribution of various parameters of the FE model to its modal behavior.
Updating: Changing the FE model to improve it's correlation to Test results.

Sensitivity & Updating Options:

- **Manual inspection & manual updating using correlation indicators**
- **VL Design Sensitivity Analysis & Nastran SOL200 FE Model updating**
- **Optimus Sensitivity Analysis and Updating with ANY FE Solver**

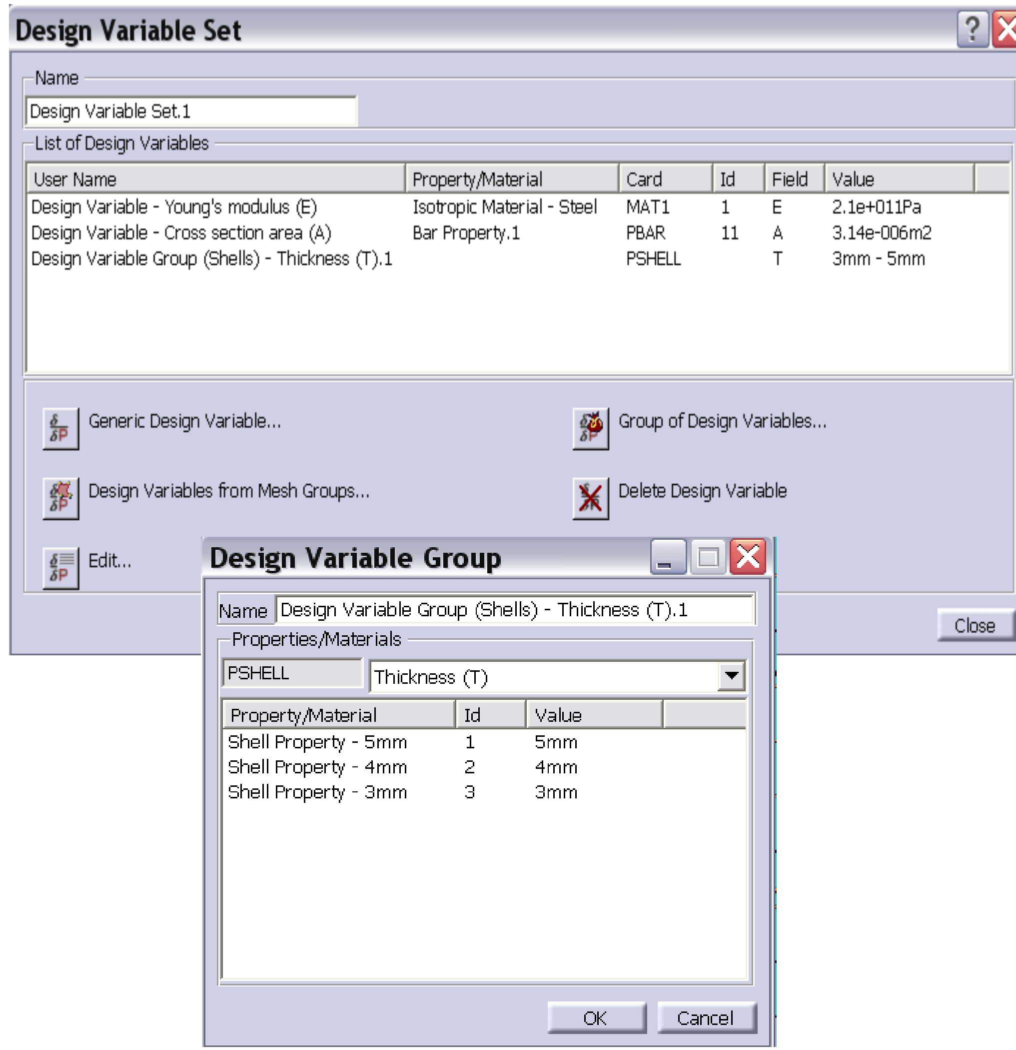


Application Case: Updating

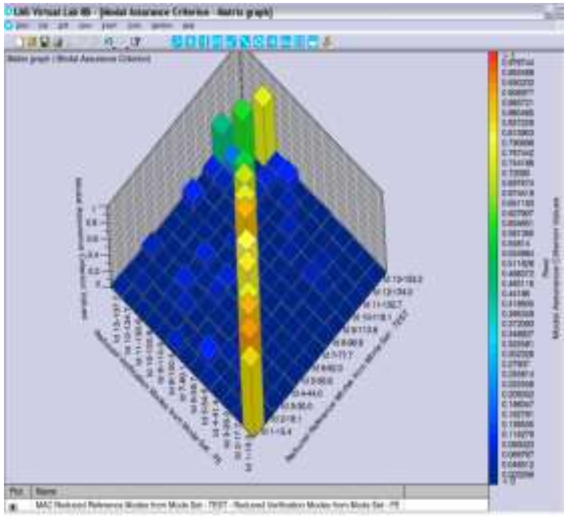
SIEMENS

Step 5: Updating

- **Design variables are selected from the Nastran bulk data deck.**
- **Shell thickness' for the muffler, catalytic converter, pipe, and welds were selected as design variables.**
- **Constraints and design variables selected to avoid unrealistic changes**
- **Optimizer only changed the welds significantly (other parameters changed by < 1%).**

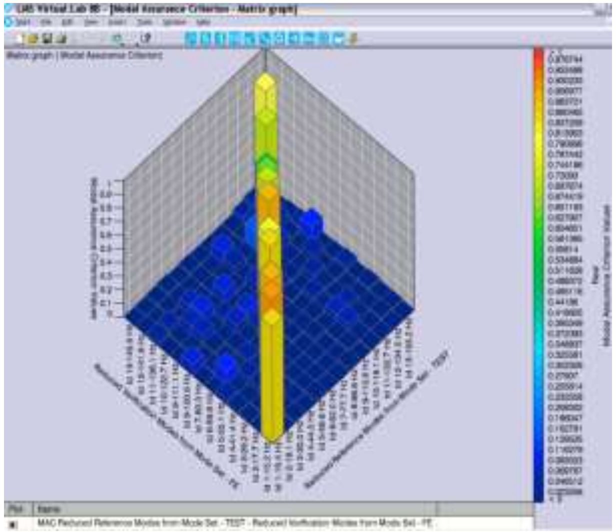


Application Case: Results



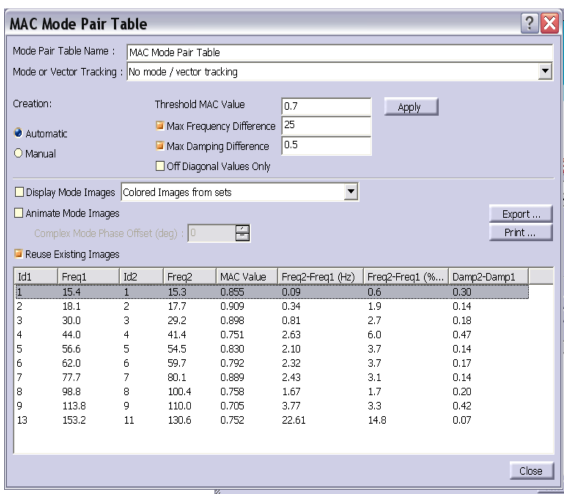
MAC Correlation

- Improved from 0.69 to 0.8
- Mode swapping eliminated



Frequency Correlation

- Improved from max 15% error to 6%
- Improved from max 23 Hz error to only 8 Hz

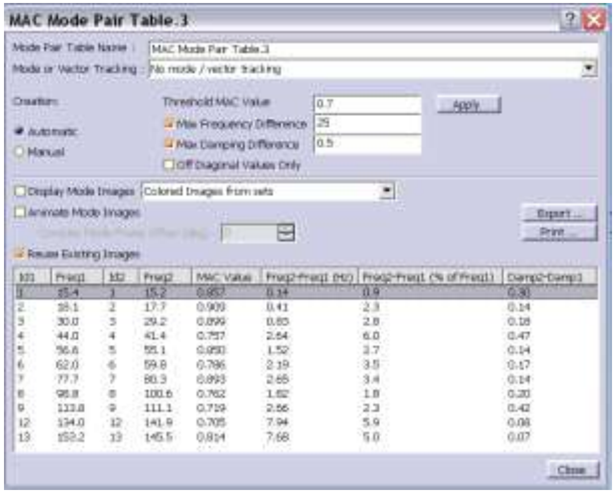


MAC Mode Pair Table

Mode Pair Table Name : MAC Mode Pair Table
Mode or Vector Tracking : No mode / vector tracking
Creation: Threshold MAC Value 0.7 Apply
Automatic / Manual
Max Frequency Difference 25
Max Damping Difference 0.5
Off Diagonal Values Only
Display Mode Images: Colored Images from sets
Animate Mode Images
Complex Mode Phase Offset (deg) : 0
Reuse Existing Images
Export ... Print ...

Id1	Freq1	Id2	Freq2	MAC Value	Freq2-Freq1 (Hz)	Freq2-Freq1 (%...	Damp2-Damp1
1	15.4	1	15.3	0.855	0.09	0.6	0.30
2	18.1	2	17.7	0.909	0.34	1.9	0.14
3	30.0	3	29.2	0.898	0.81	2.7	0.18
4	44.0	4	41.4	0.751	2.63	6.0	0.47
5	56.6	5	54.5	0.830	2.10	3.7	0.14
6	62.0	6	59.7	0.792	2.32	3.7	0.17
7	77.7	7	80.1	0.889	2.43	3.1	0.14
8	98.8	8	100.4	0.758	1.67	1.7	0.20
9	113.8	9	110.0	0.705	3.77	3.3	0.42
13	153.2	11	130.6	0.752	22.61	14.8	0.07

Close



MAC Mode Pair Table.3

Mode Pair Table Name : MAC Mode Pair Table.3
Mode or Vector Tracking : No mode / vector tracking
Creation: Threshold MAC Value 0.7 Apply
Automatic / Manual
Max Frequency Difference 25
Max Damping Difference 0.5
Off Diagonal Values Only
Display Mode Images: Colored Images from sets
Animate Mode Images
Reuse Existing Images
Export ... Print ...

Id1	Freq1	Id2	Freq2	MAC Value	Freq2-Freq1 (Hz)	Freq2-Freq1 (% of Freq1)	Damp2-Damp1
1	15.4	1	15.2	0.857	0.14	0.9	0.30
2	18.1	2	17.7	0.909	0.41	2.3	0.14
3	30.0	3	29.2	0.899	0.85	2.8	0.18
4	44.0	4	41.4	0.757	2.64	6.0	0.47
5	56.6	5	55.1	0.850	1.52	3.7	0.14
6	62.0	6	59.8	0.786	2.19	3.5	0.17
7	77.7	7	80.3	0.893	2.65	3.4	0.14
8	98.8	8	100.6	0.762	1.82	1.8	0.20
9	113.8	9	111.1	0.719	2.56	2.3	0.42
12	134.0	12	141.9	0.705	7.94	5.9	0.08
13	152.2	13	145.5	0.814	7.68	5.0	0.07

Close

SIEMENS

Application Case: Summary

Pretest Analysis was used to ensure reliable Modal Test results:

- Automated wireframe creation
- Optimized accelerometer/exciter locations
- FE mode visualization

Correlation Analysis leveraged Modal Test results to obtain a reliable Finite Element Model

- Full frequency and mode shape correlation
- Insight was provided into physical parameters of model causing correlation issues
- FE Model was Updated to improve reliability
- Critical Design decisions (exhaust hangar location, fatigue life estimation, etc.) were made based on complete and correct information

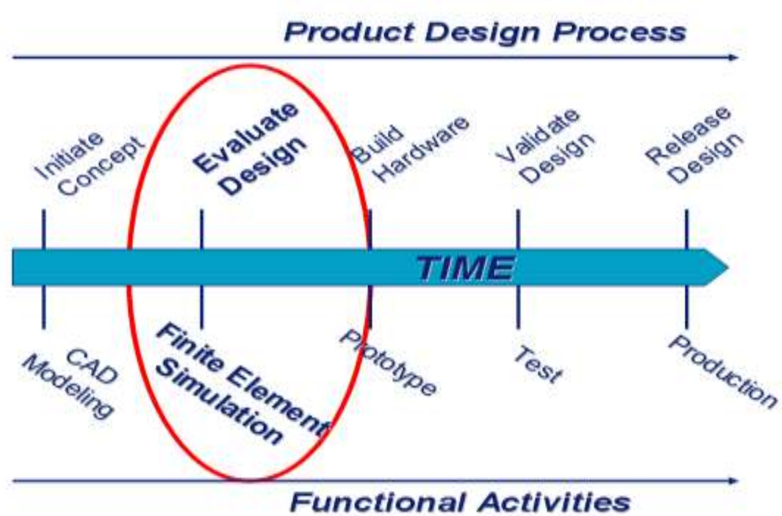
Virtual.Lab Pretest & Correlation: Conclusions

"Design Right First Time" is critical in competitive markets

- Time to Market must be accelerated
- Product failure, warranty costs must be eliminated

Finite Element Models must guide product design

- Performance simulation for Acoustics, Vibration, Durability eliminates expensive, time-consuming prototypes
- Reliability of FE Models depends on modeling assumptions (weld representation, boundary conditions, etc.)



Unrest

Virtual.Lab Pretest & Correlation: Conclusions

SIEMENS

Modal Tests must validate product designs

- Reliability of test results depend upon accelerometer and shaker/impact placement

FE/Test Correlation is Key to “Design Right First Time”

- Fundamental mode correlation is not enough
- Higher order modes are most difficult to correlate

LMS Virtual.Lab Pretest & Correlation Increases Reliability of FE Models and Test Results

- FE Models accurate over entire operating frequency range
- Test results capturing all modes uniquely
- Design decisions based on the complete and correct information