Modal Analysis in Virtual Prototyping and Product Validation

March 19th, 2009

Agenda

Modal Analysis in Virtual Prototyping and Product Validation

March 19th, 2009

8am EDT (New York) / 12n GMT (London) / 5:30pm (Bangalore)

- Welcome & Introduction (Overview of NAFEMS Activities)
  - Mr. David Quinn, *NAFEMS Marketing and Communications*
- Modal Analysis in Virtual Prototyping and Product Validation
  - Mr. Dhanushkodi D.M., *TechPassion Technologies Pvt. Ltd.*
- Q&A Session
  - Panel
- Closing

Quinn

Dhanushkodi

NAFEMS

THE INTERNATIONAL ASSOCIATION FOR THE ENGINEERING ANALYSIS COMMUNITY

An Overview of NAFEMS Activities

David Quinn
NAFEMS
Marketing & Communications

Planned Activities

- Webinars
  - New topic each month!
    - March 19th - Modal Analysis in Virtual Prototyping and Product Validation
  - Recent webinars:
    - Pathways to Future CAE Technologies and their Role in Ambient Intelligent Environments
    - Computational Structural Acoustics: Technology, Trends and Challenges
    - FAM: Advances in Research and Industrial Application of Experimental Mechanics
    - CCOPPS: Power Generation: Engineering Challenges of a Low Carbon Future
    - Practical CFD Analysis
    - Complexity Management
    - CCOPPS: Creep Loading of Pressurized Components – Phenomena and Evaluation
    - Multiphysics Simulation using Implicit Sequential Coupling
    - CCOPPS: Fatigue of Welded Pressure Vessels
    - Applied Element Method as a Practical Tool for Progressive Collapse Analysis of Structures
    - AUTOSIM: The Future of Simulation in the Automotive Industry
    - A Common Sense Approach to Stress Analysis and Finite Element Modeling
    - The Interfacing of FEA with Pressure Vessel Design Codes (CCOPPS Project)
    - Multiphysics Simulation using Directly Coupled-Field Element Technology
    - Methods and Technology for the Analysis of Composite Materials
    - Simulation Process Management
    - Simulation-supported Decision Making (Stochastics)
    - Simulation Driven Design (SDD) Findings

To register for upcoming webinars, or to view a past webinar, please visit: www.nafems.org/events/webinars

e-LEARNING NAFEMS

- Established in 2009
- Proposed initial course offerings:
  - Dynamic FE Analysis
  - Stochastics
  - Composites
  - Verification & Validation
- Next course:
  - Topic: Dynamic FE Analysis
  - Start: April 21st, 2009 (six-week course)
- For more information, visit: www.nafems.org/e-learning

NWC 2009
NAFEMS WORLD CONGRESS 09
JUNE 16th - 19th CRETE - GREECE

- When: June 16^{th} – 19^{th}, 2009
- Where: Crete, Greece
- Updates:
  - Over 200 presentations
  - Six Keynote Presentations
  - Additional Workshops and Activities:
    - Mini-symposium: Analysis and Simulation of Composite Structures Including Damage and Failure Prediction
    - Engineering Analysis Quality, Verification & Validation

NAFEMS WORLD CONGRESS 09
JUNE 16th - 19th CRETE - GREECE

- Additional Workshops and Activities (cont.):
  - High Performance Computing in Engineering Simulation
  - Multi-physics Simulation: Advanced Coupling Algorithms and Strategies
  - Crash

- Additional Workshops and Activities (cont.):
  - EC AUTOSIM Project – (one year)
  - EC FENet Project – (four years)
  - EC Multi-Scale Analysis of Large Aerostructures Project
  - NAFEMS Skills Management Initiative
  - Simulation Data Management
  - Material Data
  - Optimization/Robustness/Stochastics
  - Round Table Discussion on Business Drivers

NWC09 Keynotes

- **Erich Schelkle** - Porsche AG and Automotive Simulation Center Stuttgart, Germany

- **Tsuyoshi Yasuki** - Toyota Motor Corporation, Japan

- **Martin Wiedemann** - DLR German Aerospace Center, Germany

- **Jacek Marczyk** - Ontonix, Italy

- **Louis Komzsik** - Siemens PLM Software, USA

- **François Besnier** - Principia RD, France

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- For more information about the NWC09, please visit: www.nafems.org/congress.

- Sponsorship and Exhibition Opportunities Still Available!
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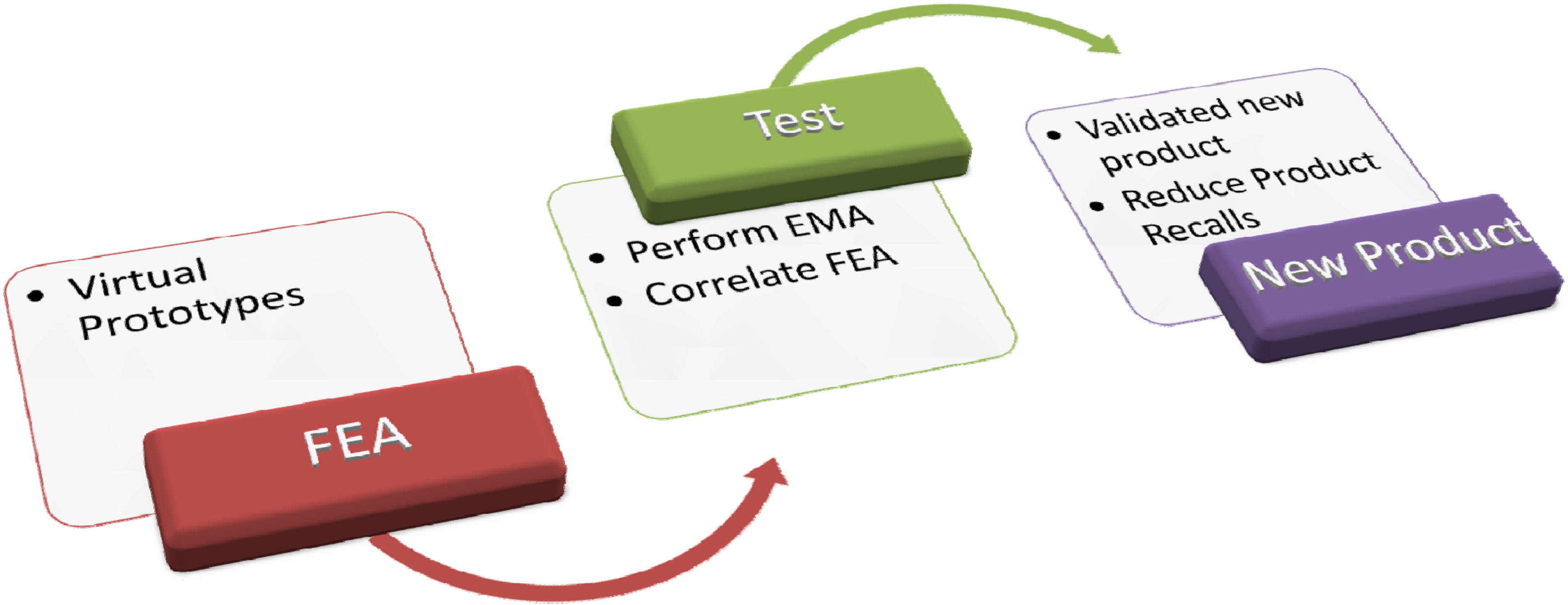
Modal Analysis in Virtual Prototyping and Product Validation

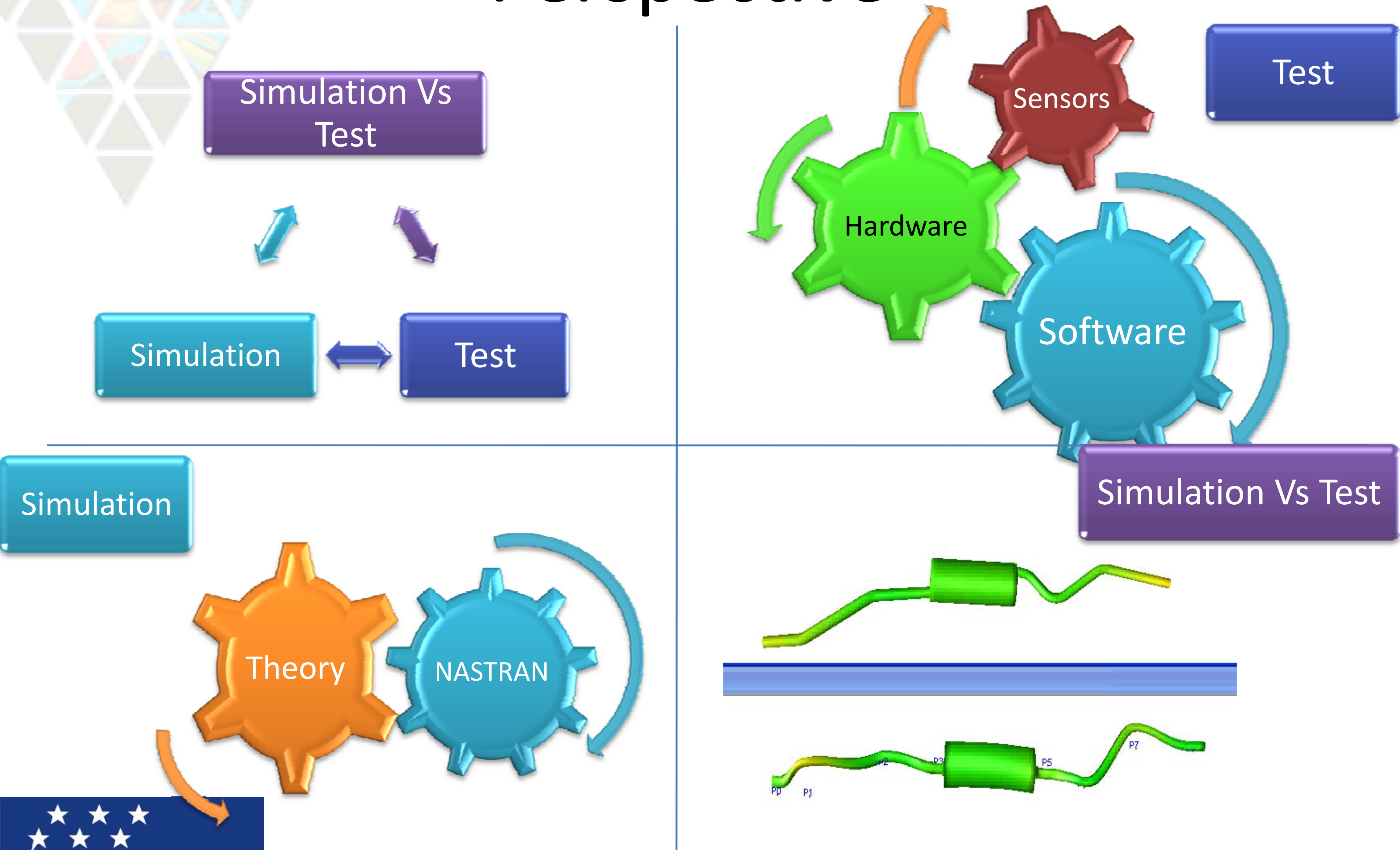
Outline

1. Finite Element Analysis
    1. Modal Parameters
    2. Damping Estimation
2. Experimental Modal Analysis
    1. Input – Output Modal Analysis
    2. Operational Modal Analysis
    3. Experimental Setup
    4. Modal Parameter Extraction
    5. Time Domain Methods
    6. Frequency Domain Methods
3. Correlation
    1. Qualitative : Visual Correlation
    2. Quantitative : Numerical Correlation
4. Case Studies
    1. Exhaust Pipe : Determining parameters using experimental modal analysis
    2. Determination of Damping : Connecting Rod, Exhaust pipe

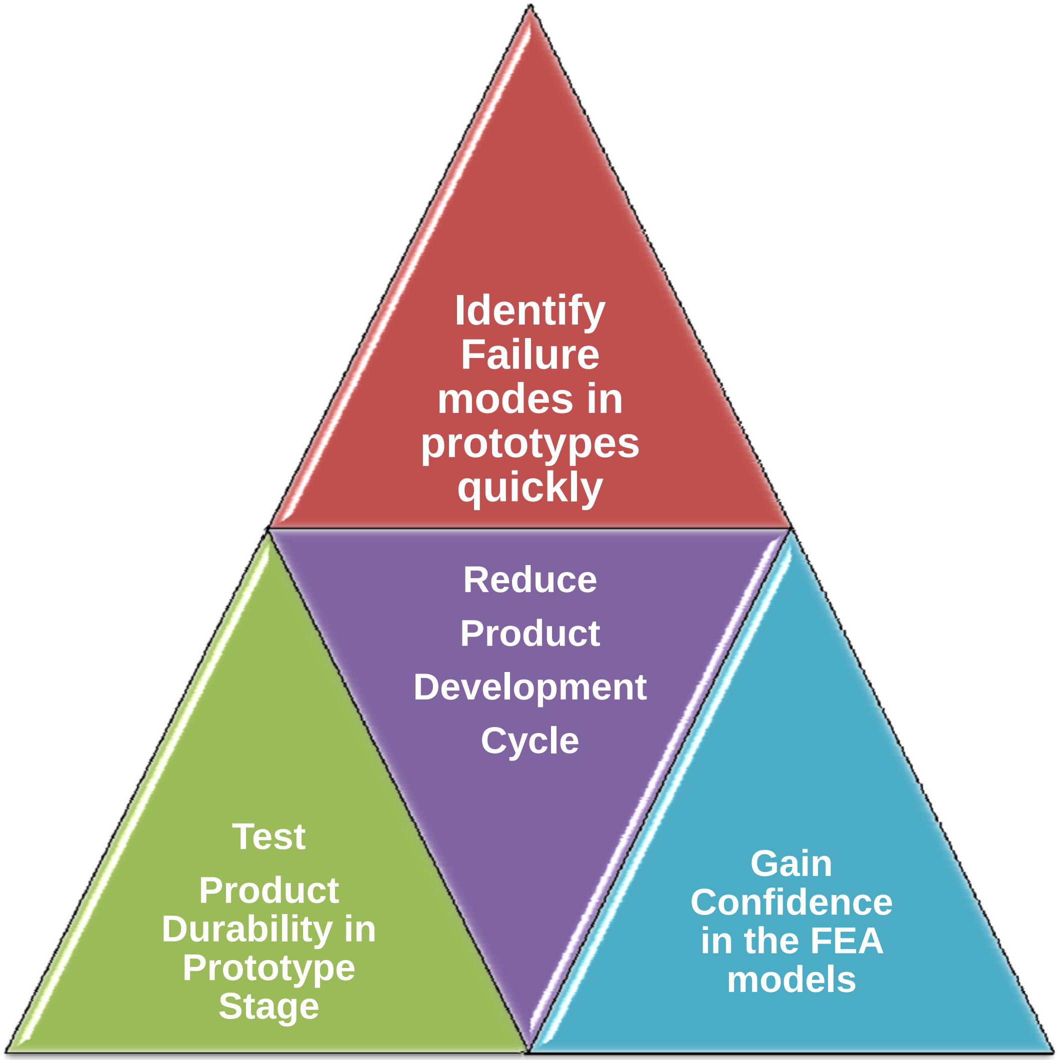
Product Development Stages



Perspective



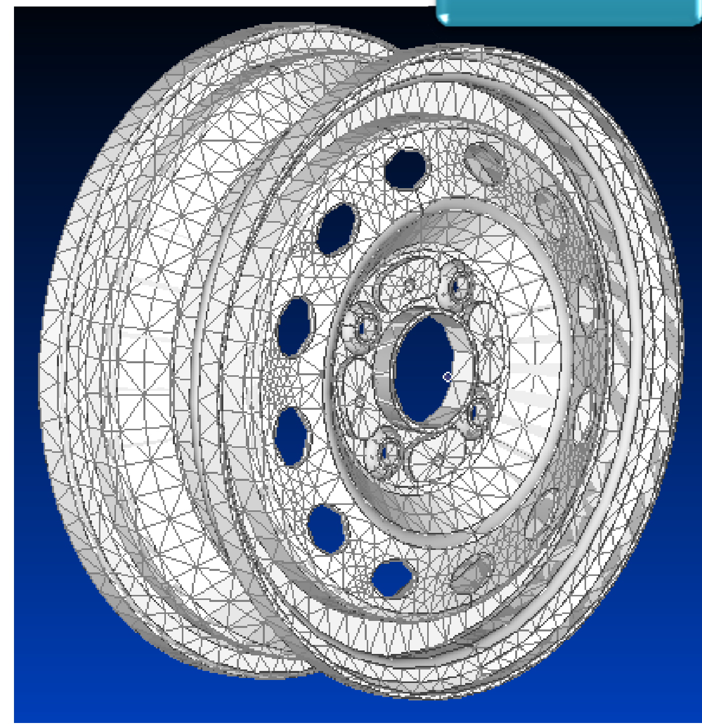
Realizable Benefits



The Finite Element Approach

Finite element methodology
The basic concept

Simulation



CAD → Mesh Model

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Finite element methodology
Steps involved

Simulation

- Step 1
  - Descretization
- Step 2
  - Shape Functions
- Step 3
  - Element Matrices
- Step 4

$$\det\left([K]-\omega^2[M]\right)=0$$

- Step 5
  - Natural Frequencies and Modeshapes

The Modal Problem - Formulation

Simulation

$$[M]\frac{(d^2\vec{Q})}{(dt^2)}+[C]\frac{(d\vec{Q})}{(dt)}+[K]\vec{Q}=\vec{P}$$

$$[M^{(e)}]=[\lambda]^T[m^{(e)}][\lambda]$$

$$[K^{(e)}]=\iiint_{V^{(e)}}[B]^T[D][B].dv$$

$$[m^{(e)}]=\iiint_{V^{(e)}}\rho[N]^T[N].dv$$

$$[C^{(e)}]=\iiint_{V^{(e)}}\mu[N]^T[N].dv$$

$$det[[K]-\omega^2[M]]=0$$

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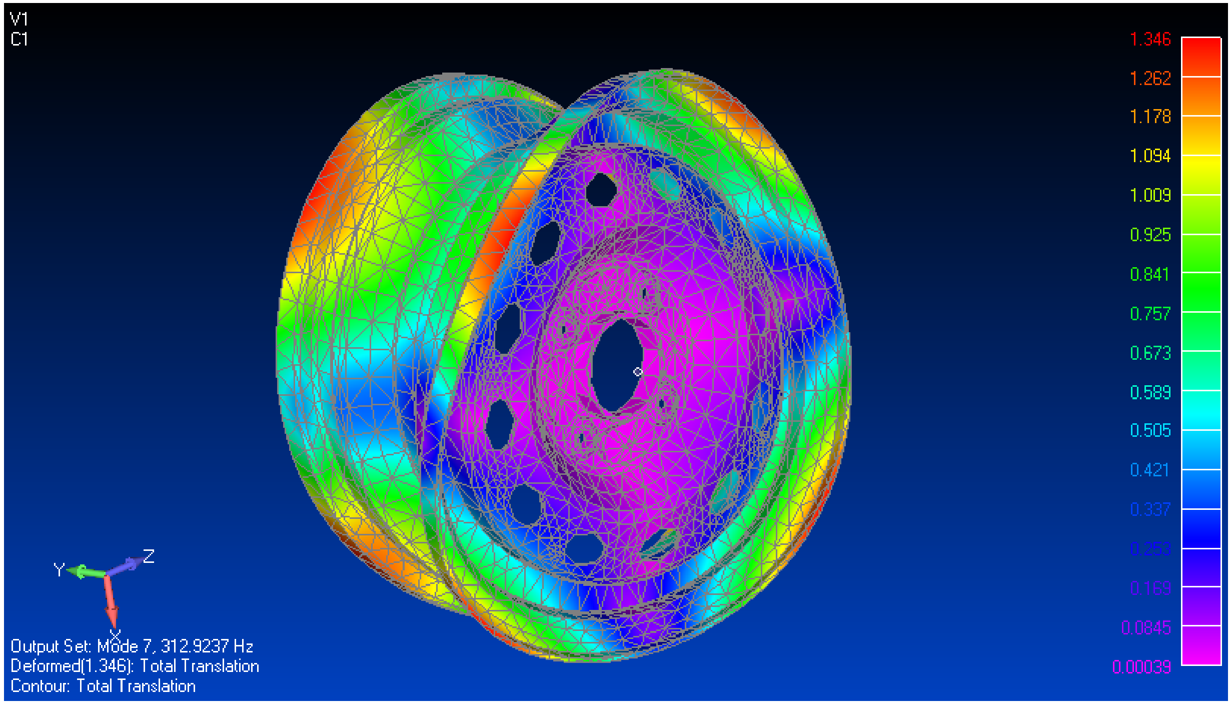
Finite element solving

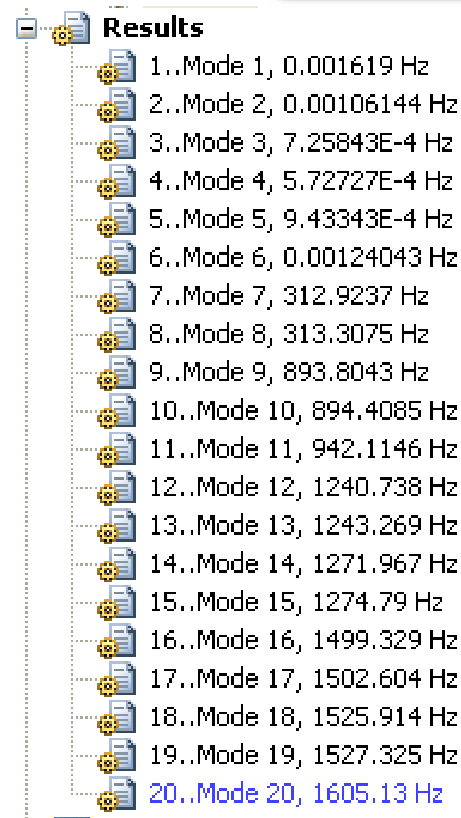
Simulation

Geometry → Material Properties → Elements → Mesh → Boundary Conditions → Solve

Post Processing

Simulation





At each of the mode that is solved for, we can obtain the natural frequency and the respective deflection shape – Mode Shape

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Experimental Modal Analysis

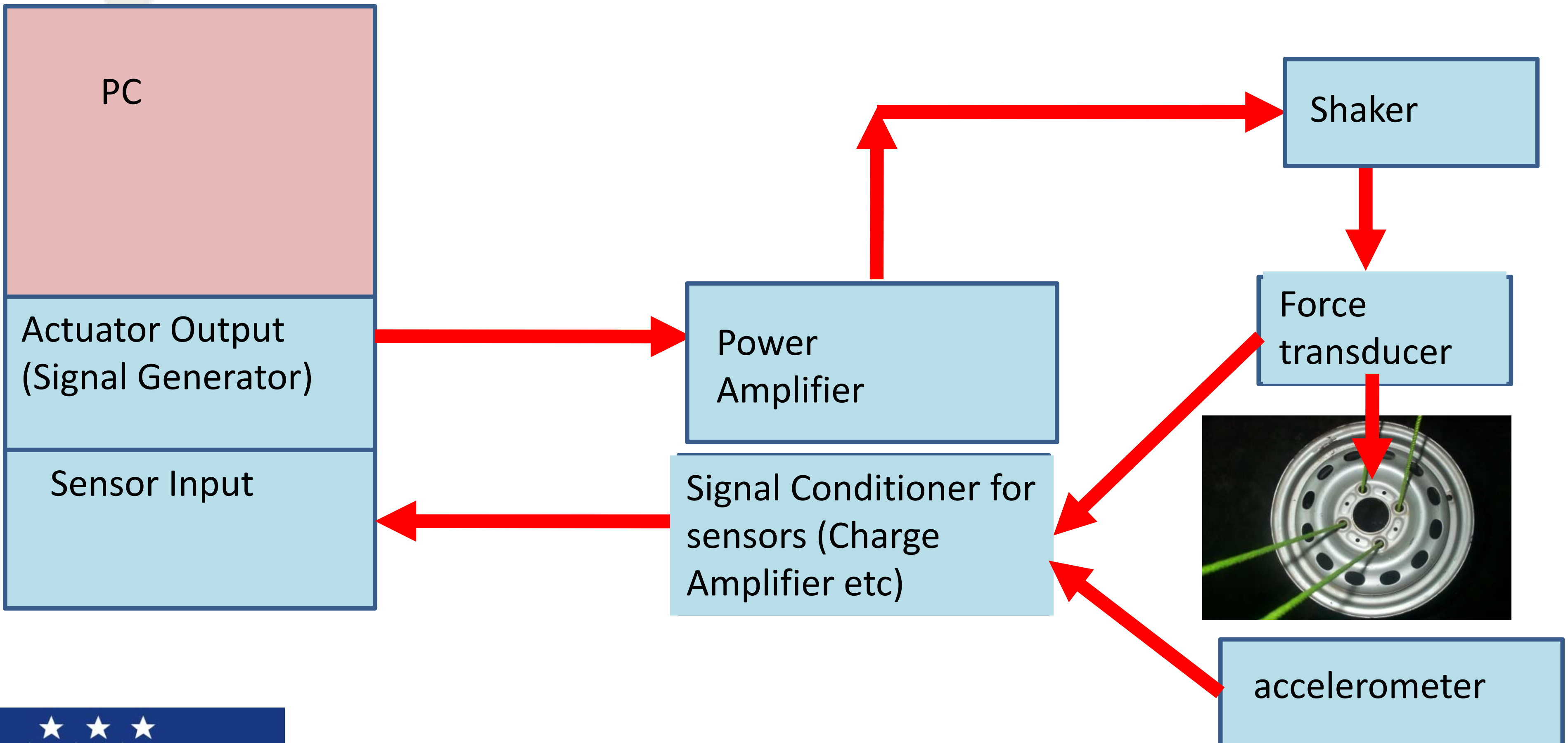
Test

Overview

Excite → Measure → FRF → Modal Parameter Extraction → FEA –Test Correlation → FEA Model Updating

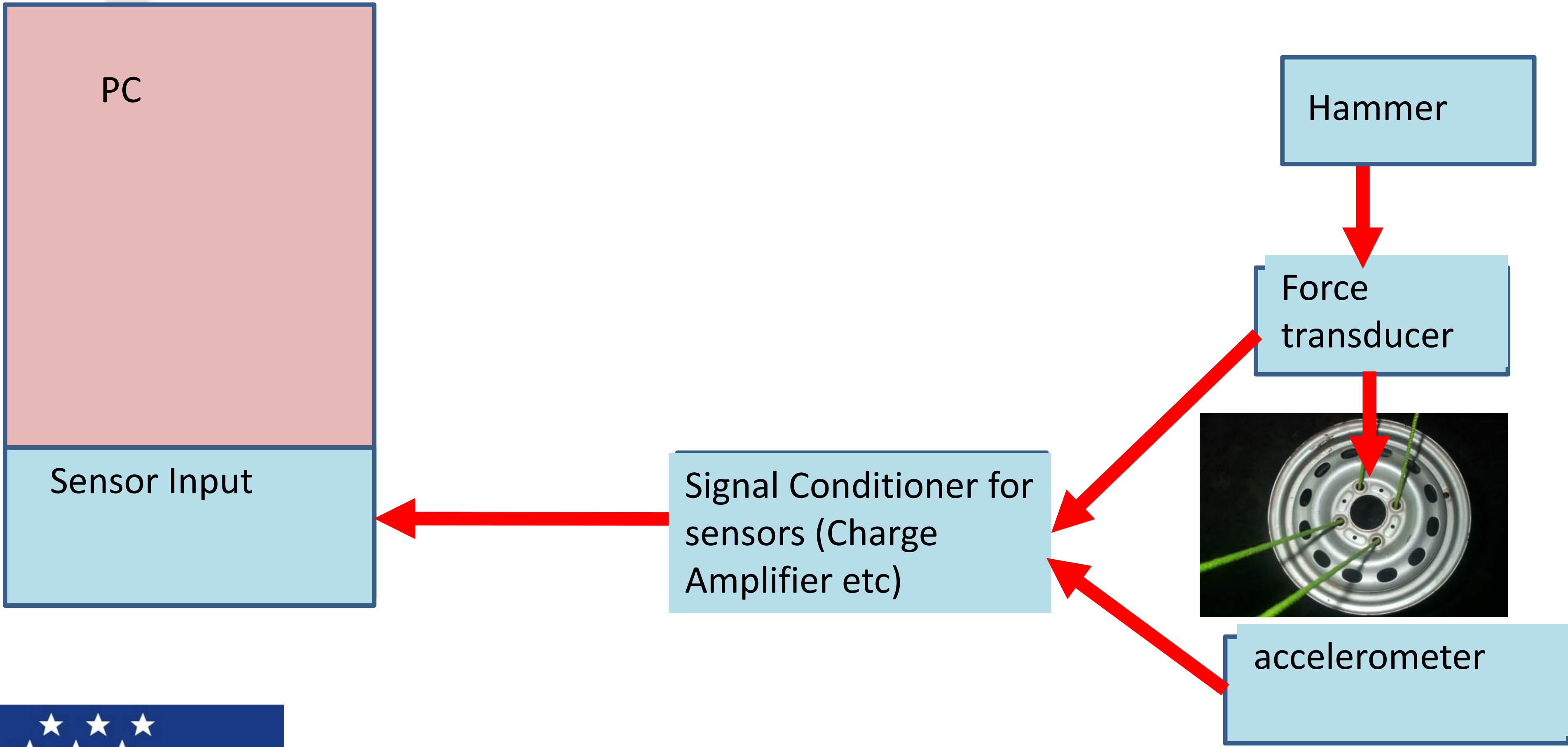
Test

Experimental Setup-1



Experimental Setup-2

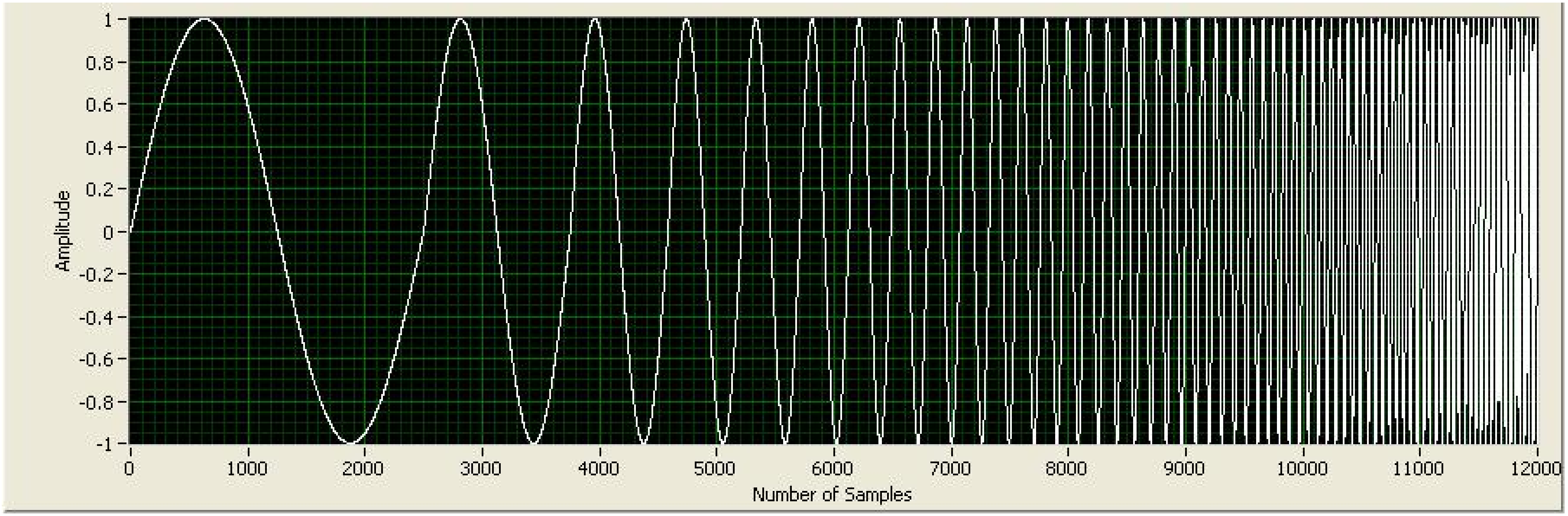
Test



Sinusoidal Excitation

Test

- Sweep from a low frequency to high frequency in steps
- Ideal for structures with non-linearity and are highly damped



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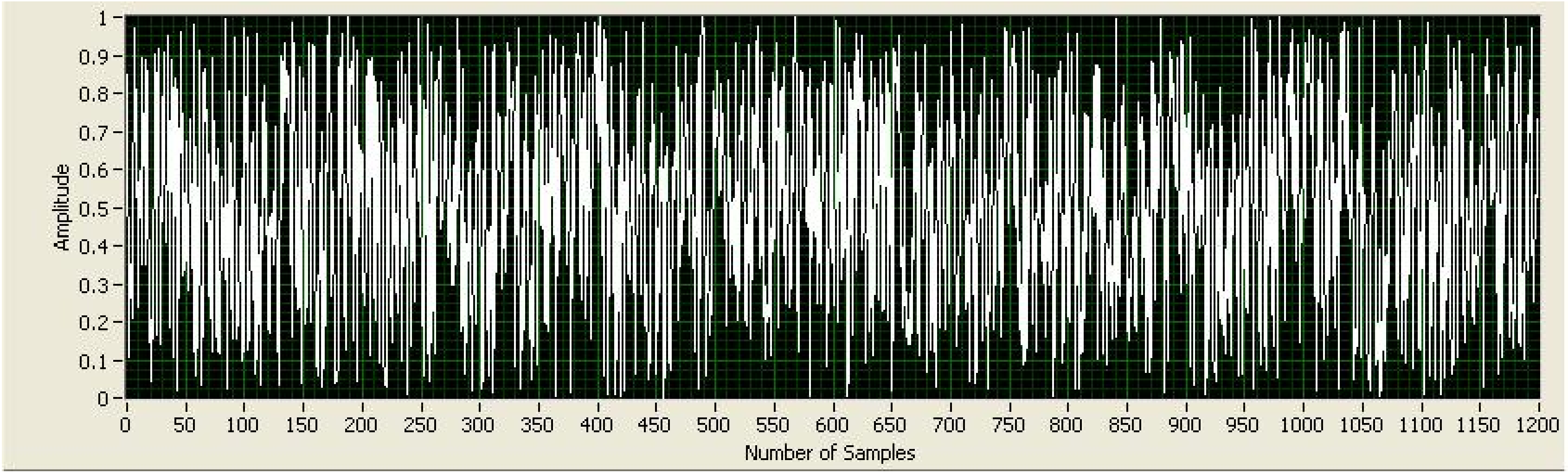
Random Excitation

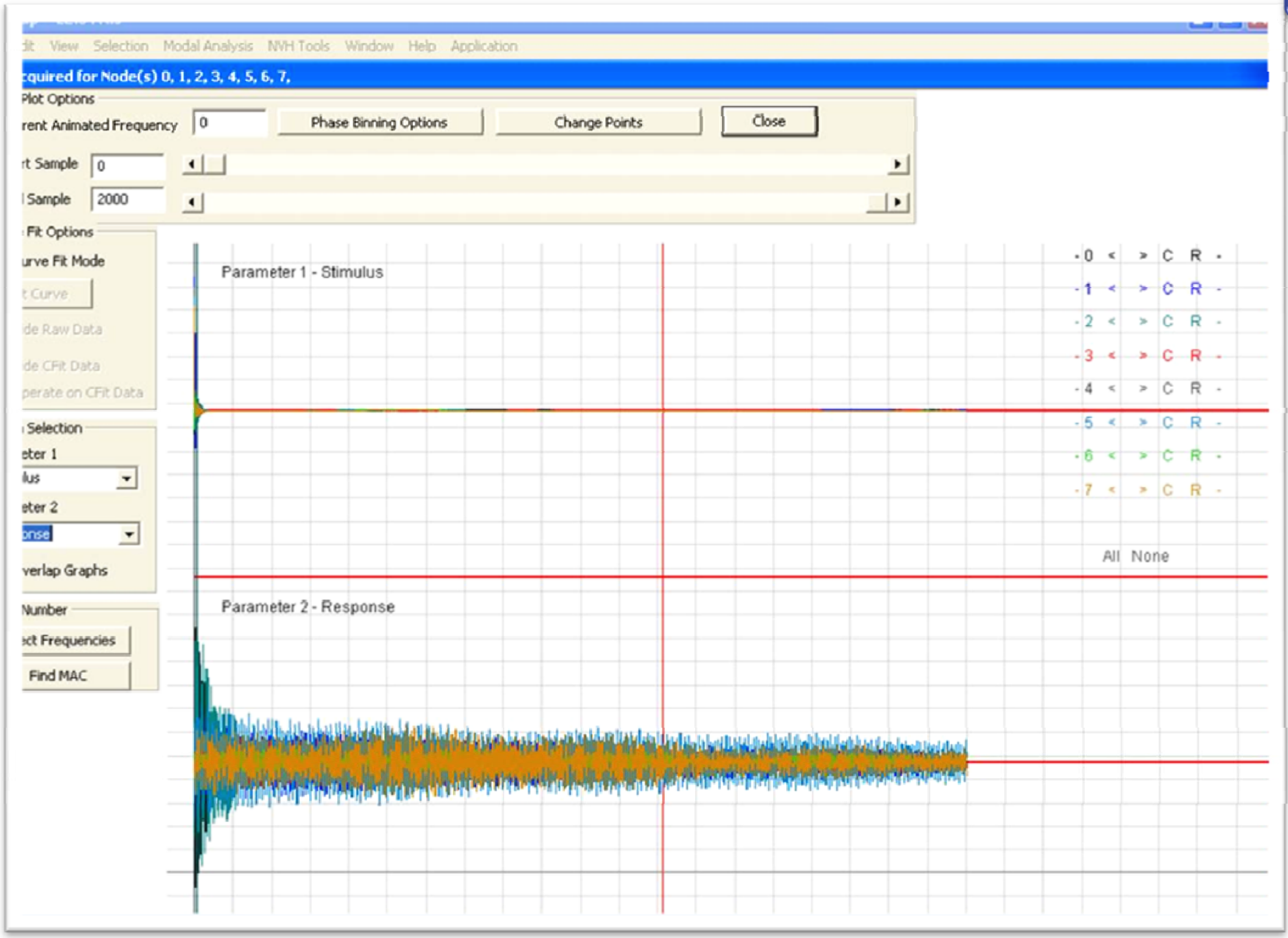
Test

- random signal with Gaussian distribution
- Ideal for structures with non-linearity
- Leakage exists as the force and response signals are non-periodic



Impact Excitation

Test



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Excite - Measure

Test

Frequency Response Function
FRF

Test

$$\text{Receptance} = \frac{Displacement}{Force}$$

$$H(\omega) = \frac{Y(\omega)}{X(\omega)}$$

$$\text{Mobility} = \frac{Velocity}{Force}$$

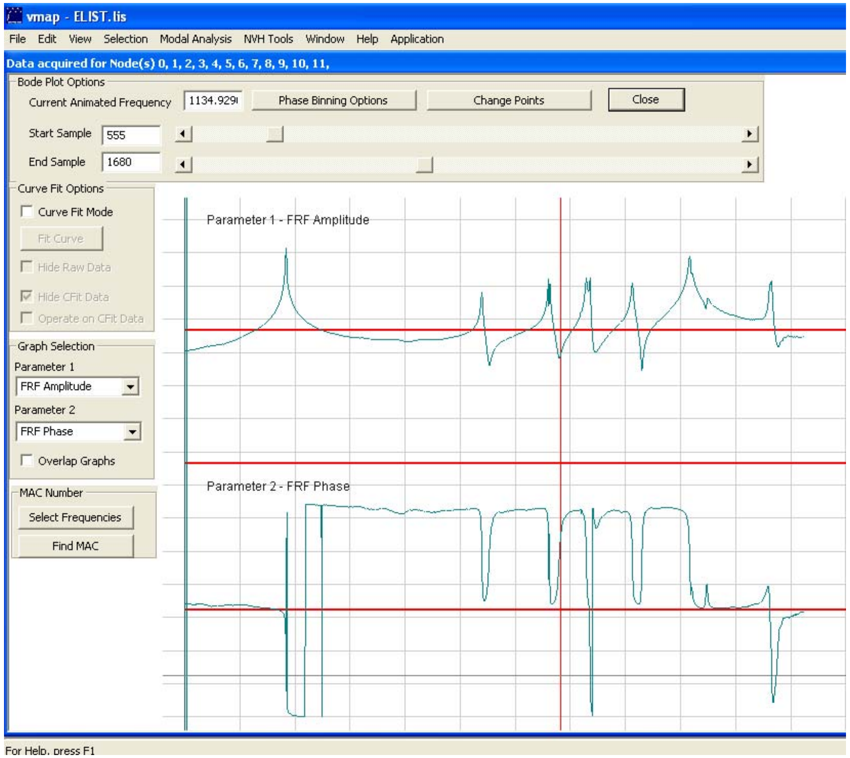
$$\text{Accelerance} = \frac{Acceleration}{Force}$$

FRF Estimators

Test

- Noise level in excitation and response determines the accuracy
- Near resonance, response noise can be ignored
- Near anti-resonance, excitation noise can be ignored

$$H(\omega) = \frac{Y(\omega)}{X(\omega)}$$



One FRF estimator does not fit all situations

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Linearity

Test

- Modal Analysis is meaningless without the assumption of linearity

Linearity Test

FRF must be independent of excitation amplitudes

Reciprocity

A LTI (Linear Time-Invariant) System follows reciprocity

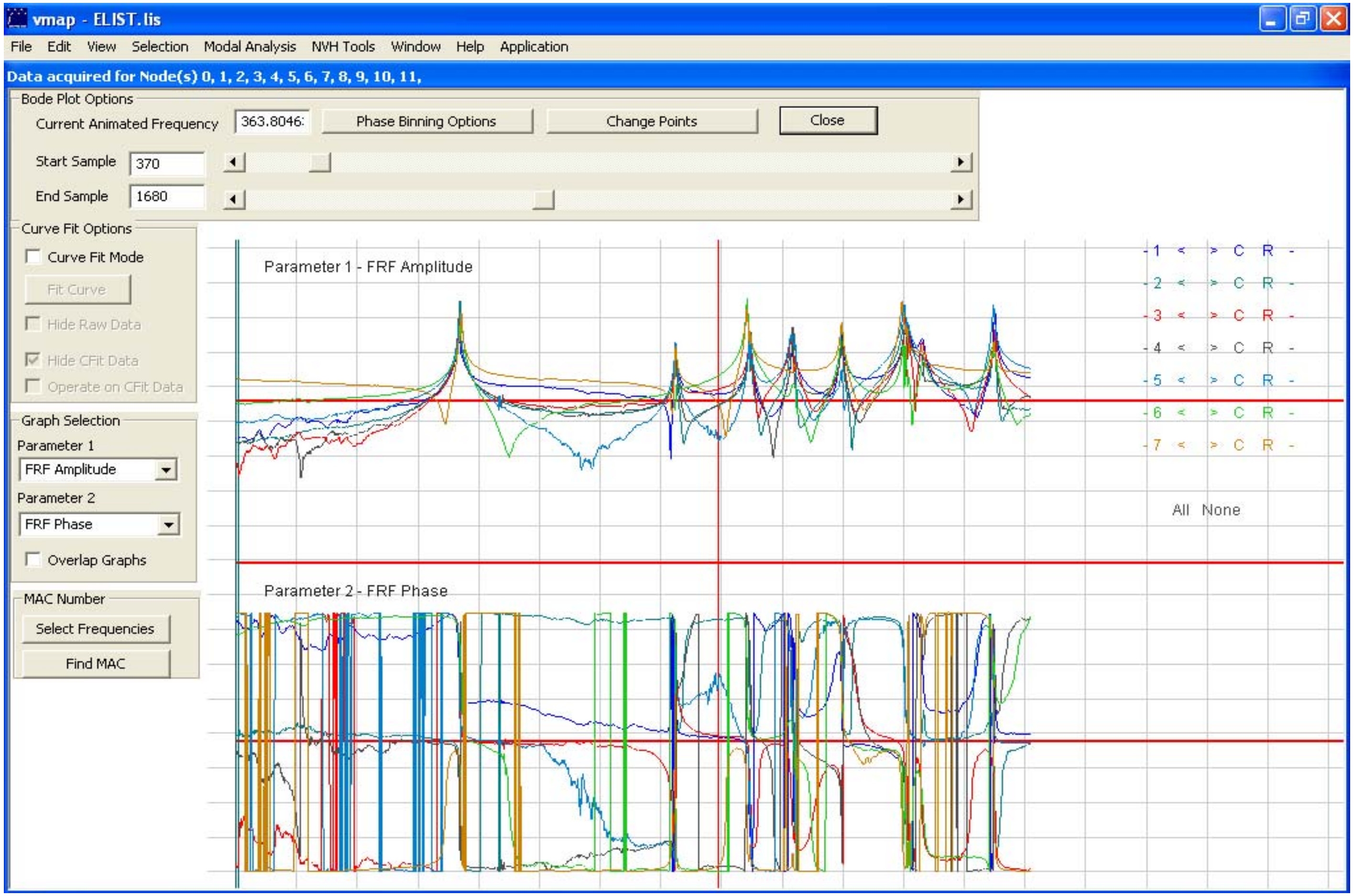
$$H_{12} = H_{21}$$

Repeatability

- To ensure that the whole setup and measurement system is time-invariant
- For a given pair of excitation and measurement locations, an LTI should yield identical FRF for every measurement
- Repeat some FRF measurements at the beginning and end of test

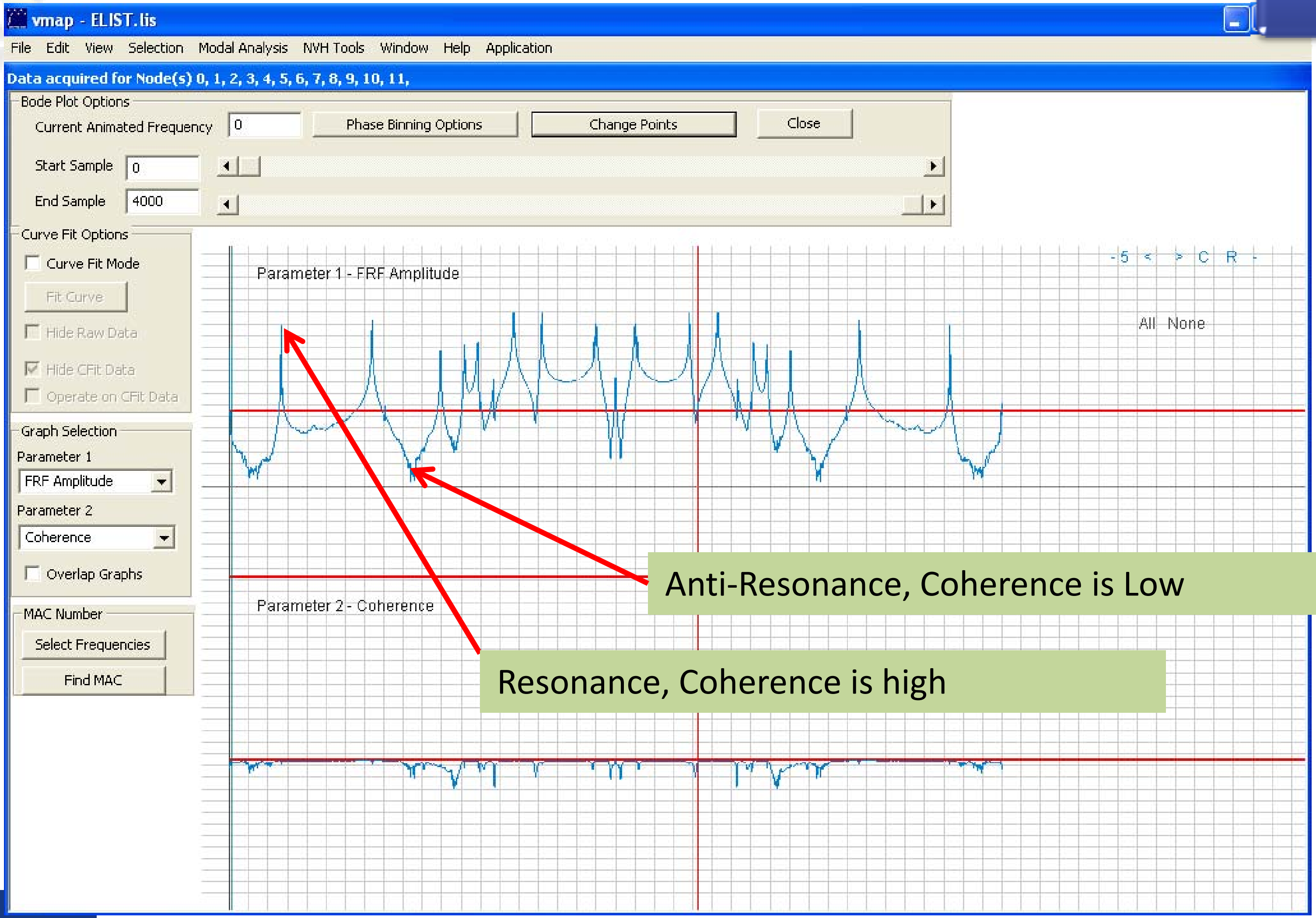
Modal Parameters

Test



Coherence

Test



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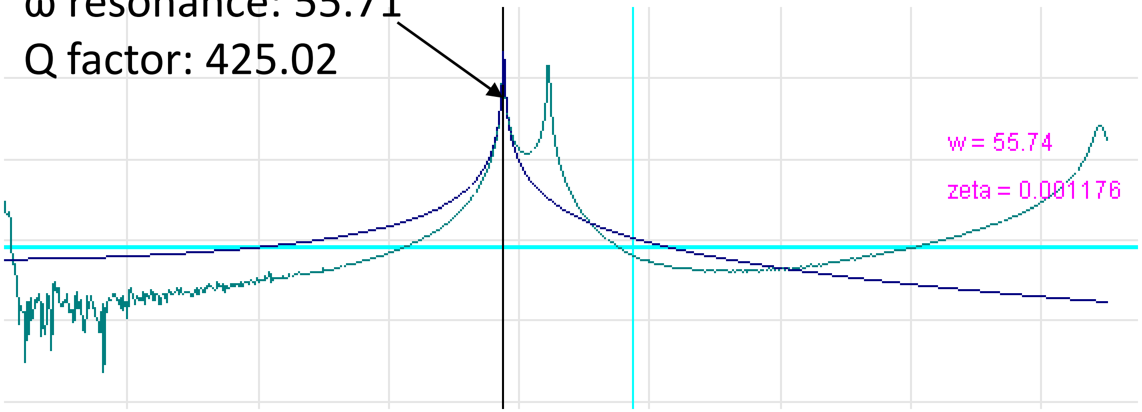
Modal Parameters

Test

- Damping

$$\zeta = \frac{1}{2Q} = \frac{1}{850} = 0.0012$$

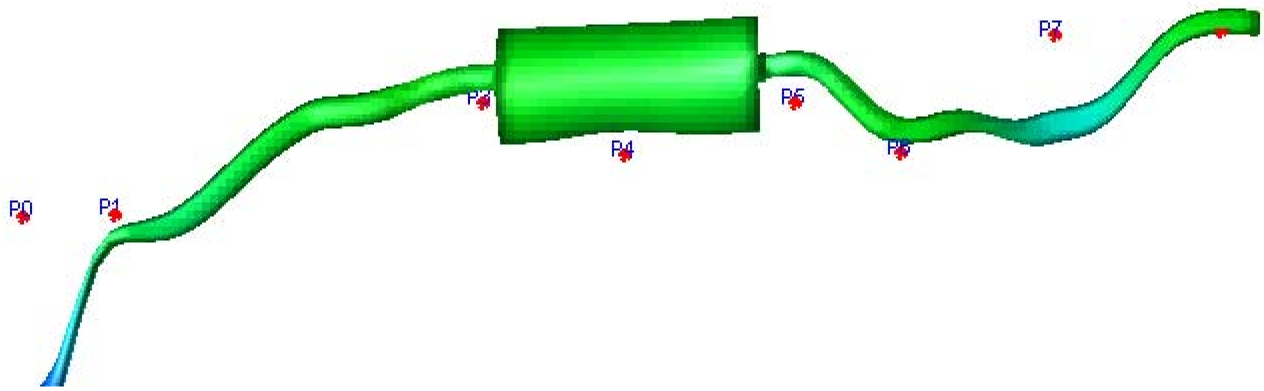
ω resonance: 55.71
Q factor: 425.02



Damping cannot be estimated through FEA – It is estimated only by experimental method

Modeshapes

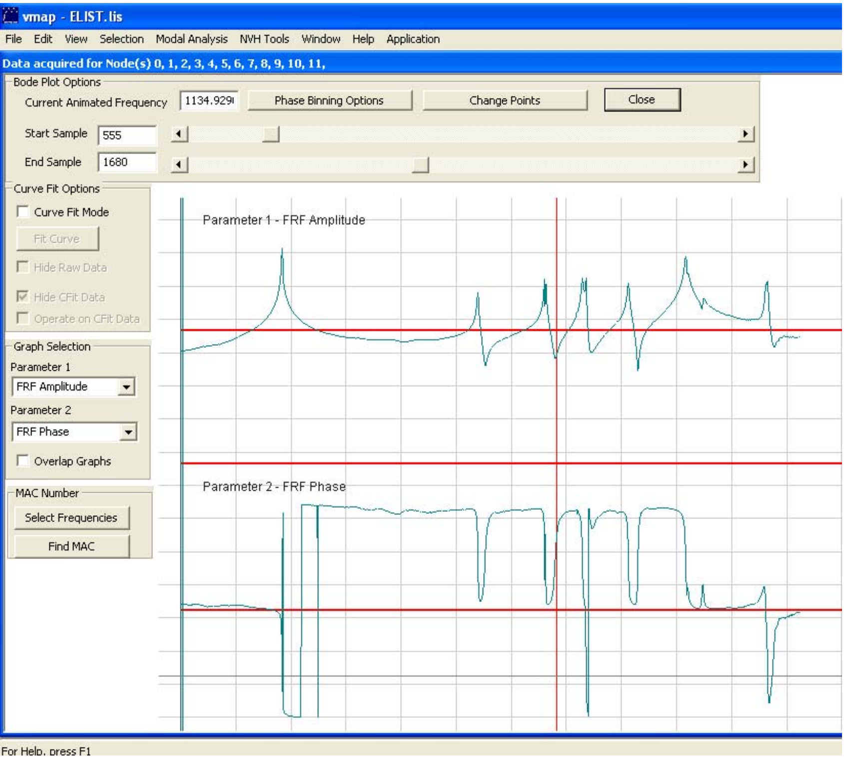
Test



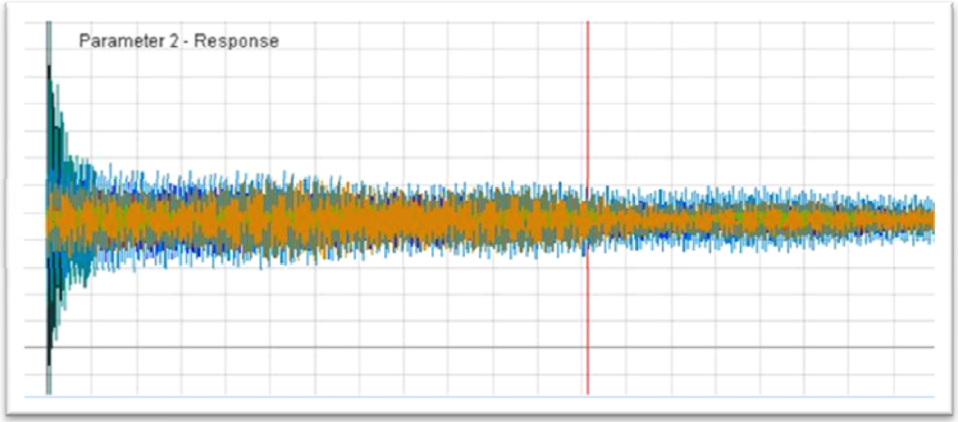
Modal Parameter Extraction

Test

Frequency Domain Analysis



Time Domain Analysis



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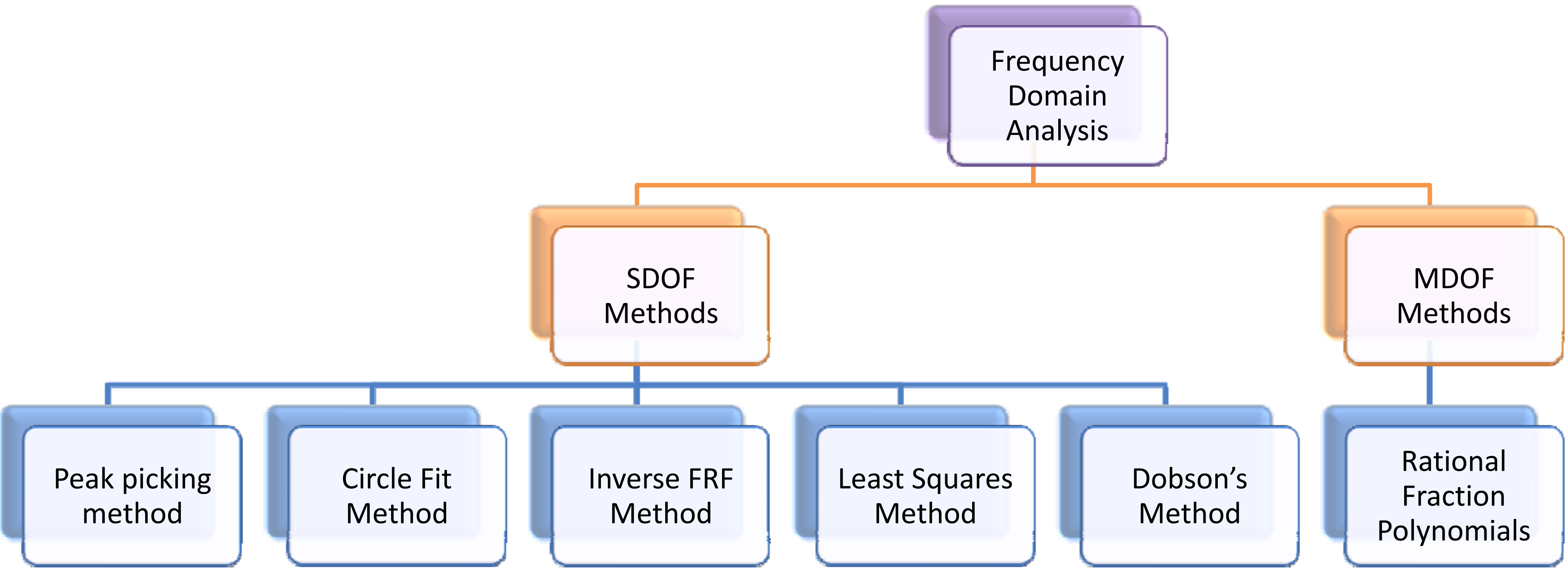
Comparison

Test

Time Domain Analysis	Frequency Domain Analysis
Can be done even with ambient excitation	Needs controlled excitation
Noise affects the predictions significantly	Effect of noise near resonances is small
Needs simultaneous measurement of all channels	Can be done with one measurement point at a time

Frequency Domain Methods

Test



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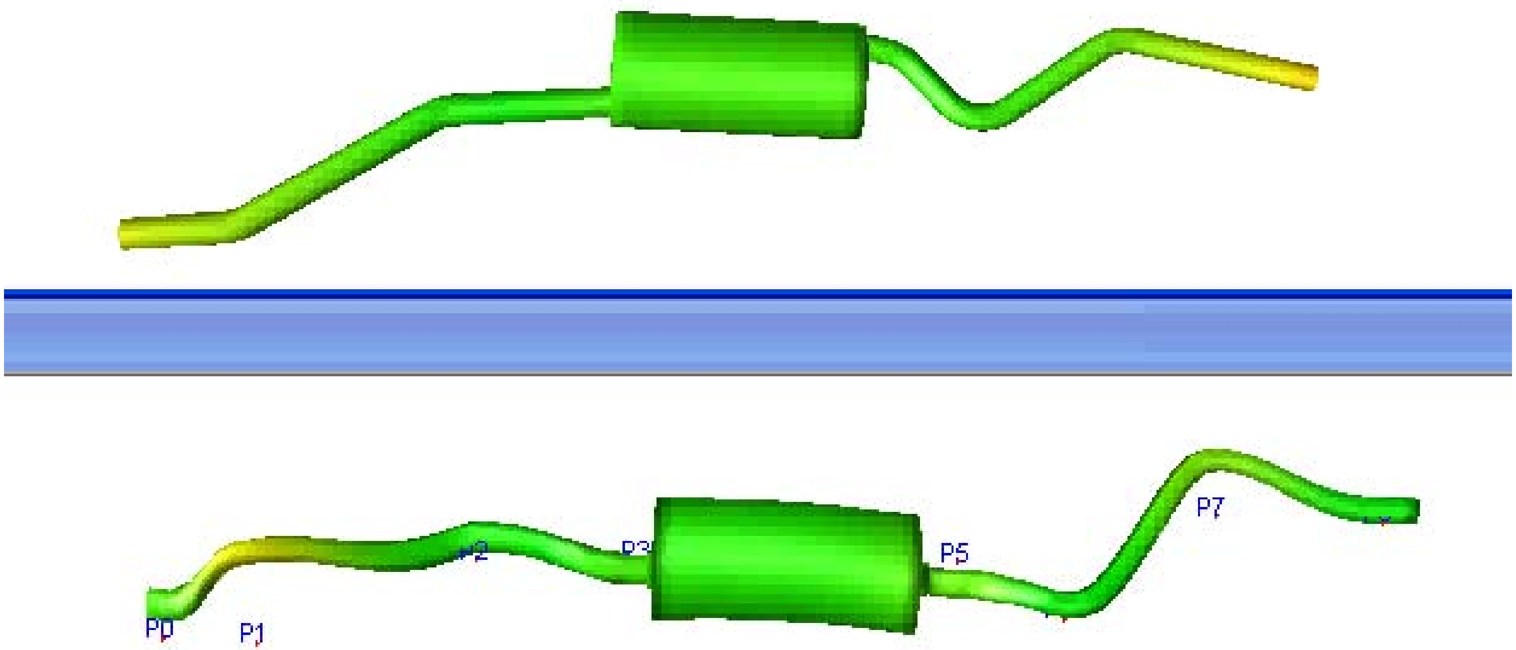
Time Domain Methods

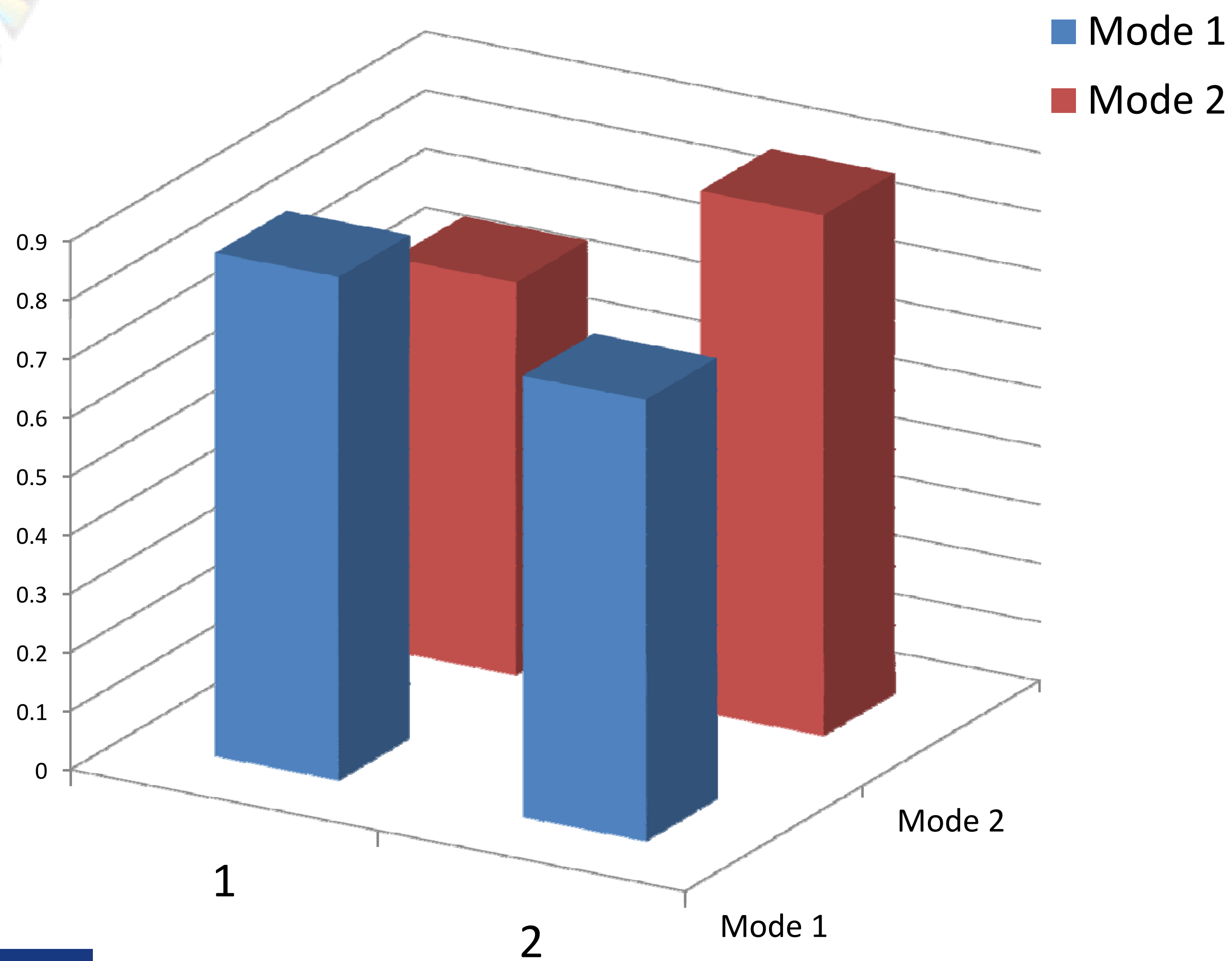
Test

- Time Domain Methods
  - Least Squares Time Domain Method
  - Ibrahim Time Domain Method
  - Random Decrement Method
  - ARMA Time series method
  - Least Squares Complex Exponential Method

Simulation Vs Test

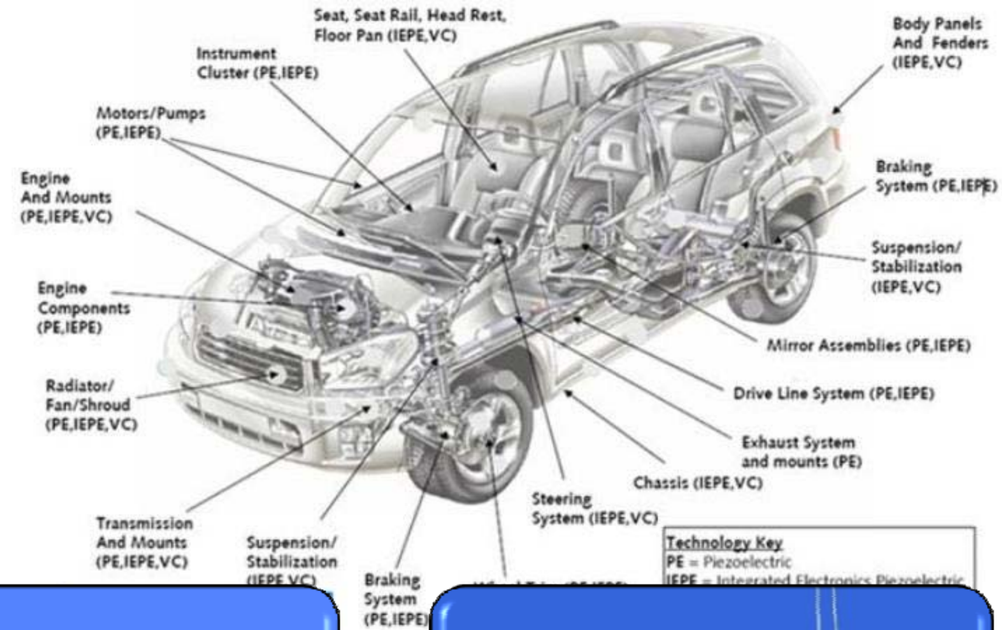


Modal Assurance Criterion



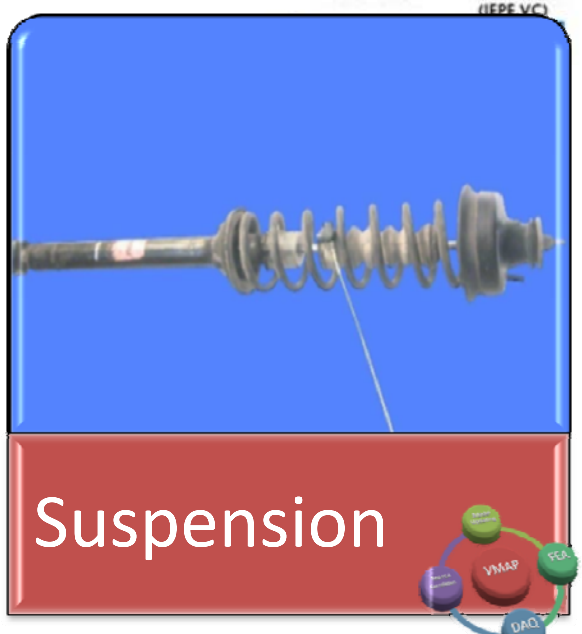
Automotive

Model Updating
FEA
VMAP
Test-FEA Correlation
DAQ

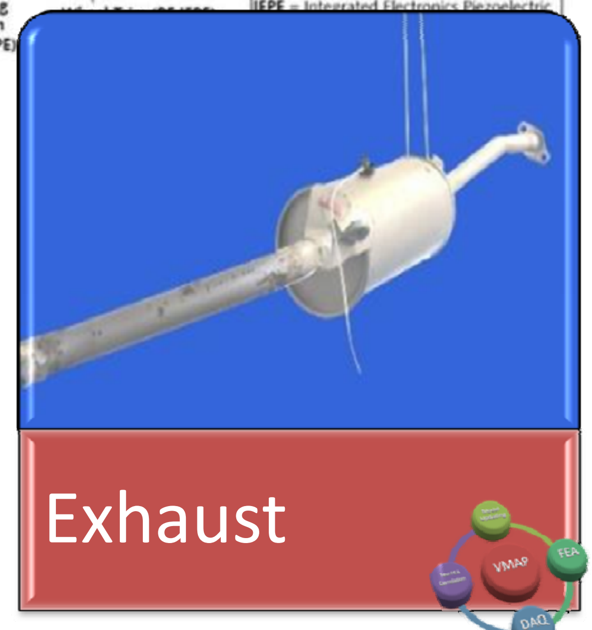


Seat, Seat Rail, Head Rest, Floor Pan (IEPE,VC)
Body Panels And Fenders (IEPE,VC)
Instrument Cluster (PE,IEPE)
Motors/Pumps (PE,IEPE)
Engine And Mounts (PE,IEPE,VC)
Braking System (PE,IEPE)
Suspension/ Stabilization (IEPE,VC)
Engine Components (PE,IEPE)
Mirror Assemblies (PE,IEPE)
Radiator/ Fan/Shroud (PE,IEPE,VC)
Drive Line System (PE,IEPE)
Exhaust System and mounts (PE)
Chassis (IEPE,VC)
Steering System (IEPE,VC)
Transmission And Mounts (PE,IEPE,VC)
Suspension/ Stabilization
Braking System (PE,IEPE)
Technology Key
PE = Piezoelectric

Wheel



Suspension

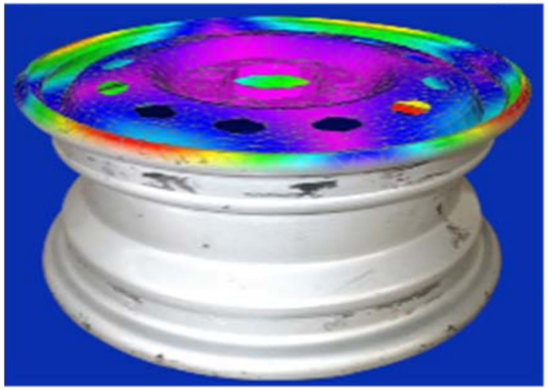


Exhaust

Case 1: Wheel

- Description
- Finite Element Model
- Experiment
- FEA-Test Correlation
  - Modal Parameters
  - MAC

Wheel Dia : 365mm



Rim Width : 140mm

Thickness : 3mm

Finite Element Model

Mesh

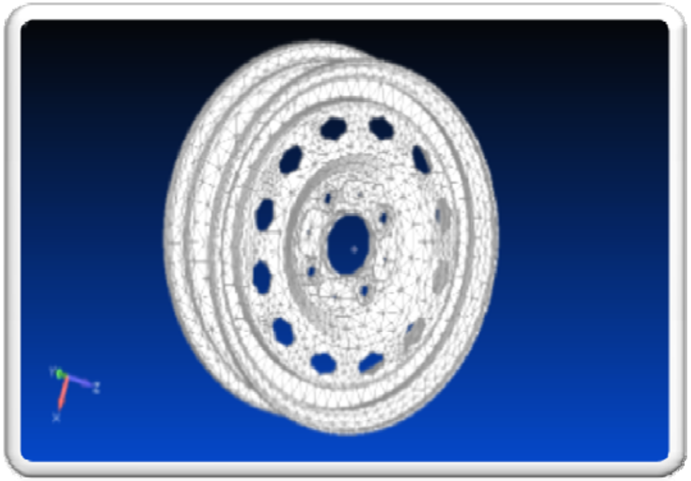
- 10 Node Tetrahedral
- Nodes = 27306
- Elements = 13326

Material

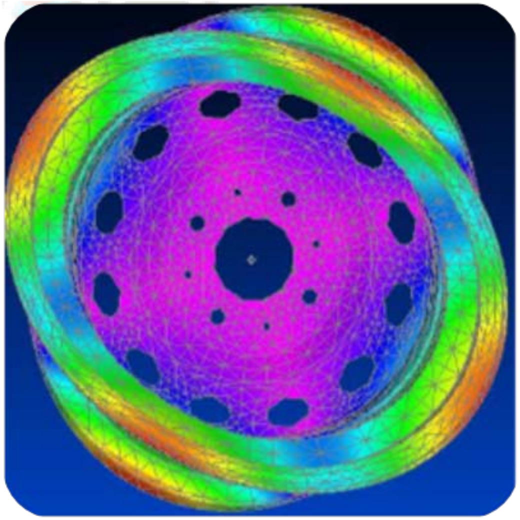
- Aluminum
- Density = 2600 Kg/m3
- Young’s Modulus = 70e9 N/m2
- Poisson’s Ratio = 0.3

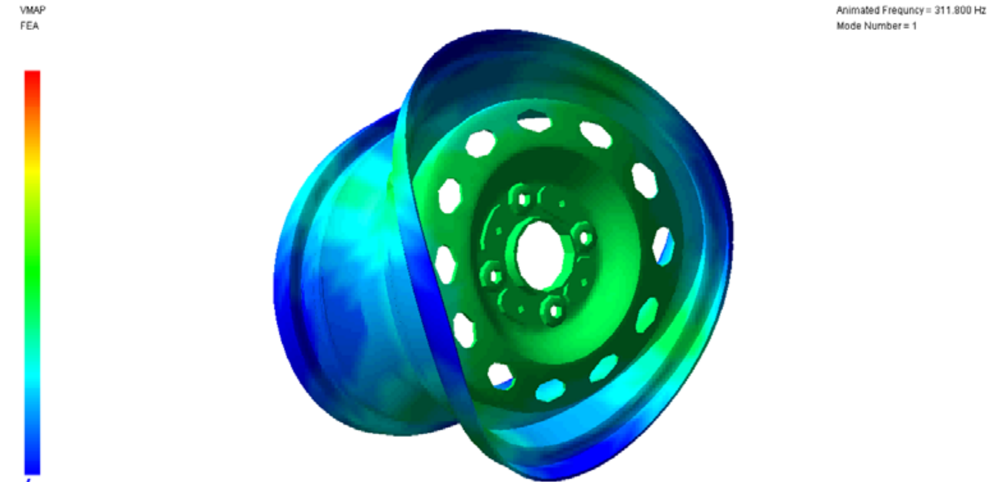
Boundary Conditions

- Free - Free



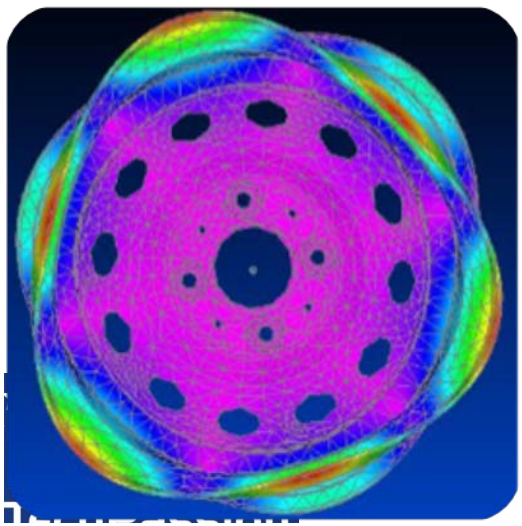
FEA Results

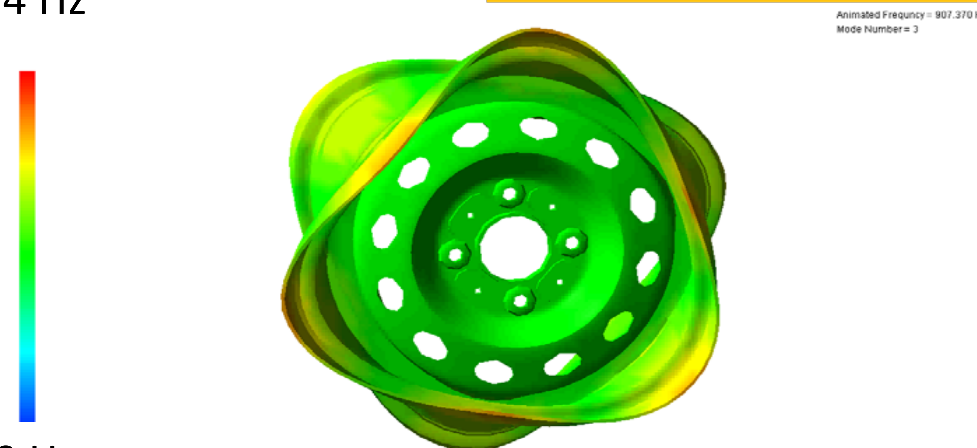




Mode 1 - 311.80 Hz
Mode 2 – 314.74 Hz

Animation of Mode 1





Mode 3 - 893.80 Hz
Mode 4 - 894.41 Hz

Animation of Mode 3

Experimental Setup

Data Acquisition

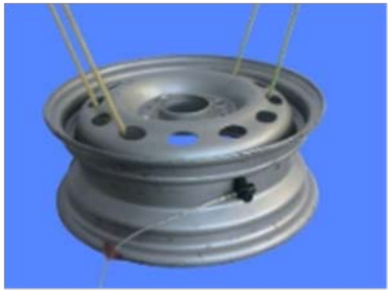
- National Instruments USB 9233
- 50 kS/s
- 4 Channels

Stimulus

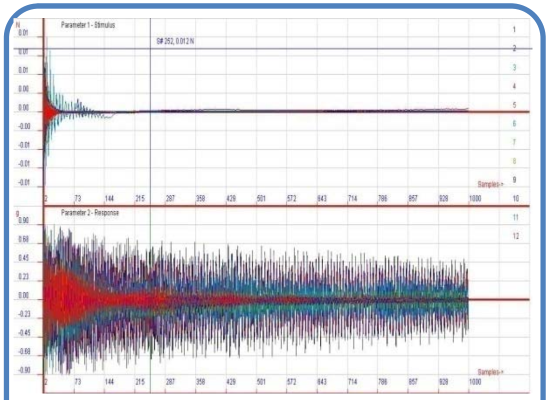
- Impact Hammer
- Range = 500 N
- Sensitivity = 10 mV/N
- Frequency Range < 1200 Hz

Response

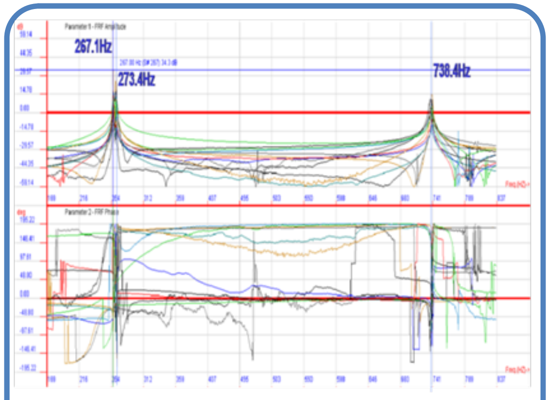
- Accelerometer
- Range : -50g to 50g
- Sensitivity = 100 mV/g



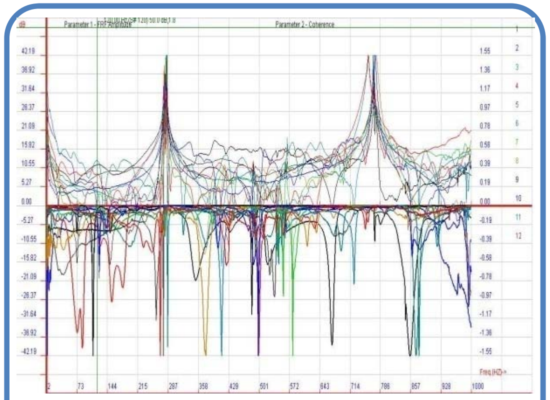
Test Results



Stimulus and response

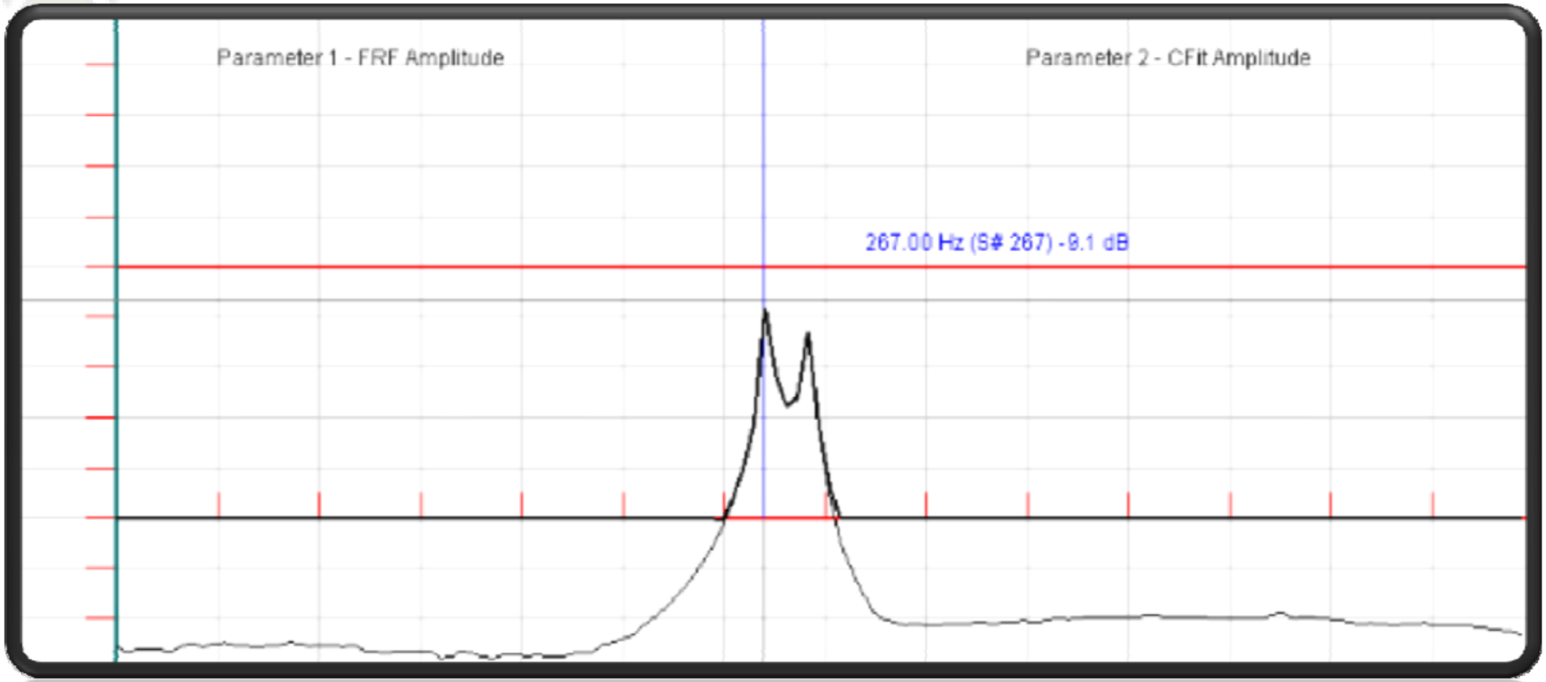


FRF



Coherence

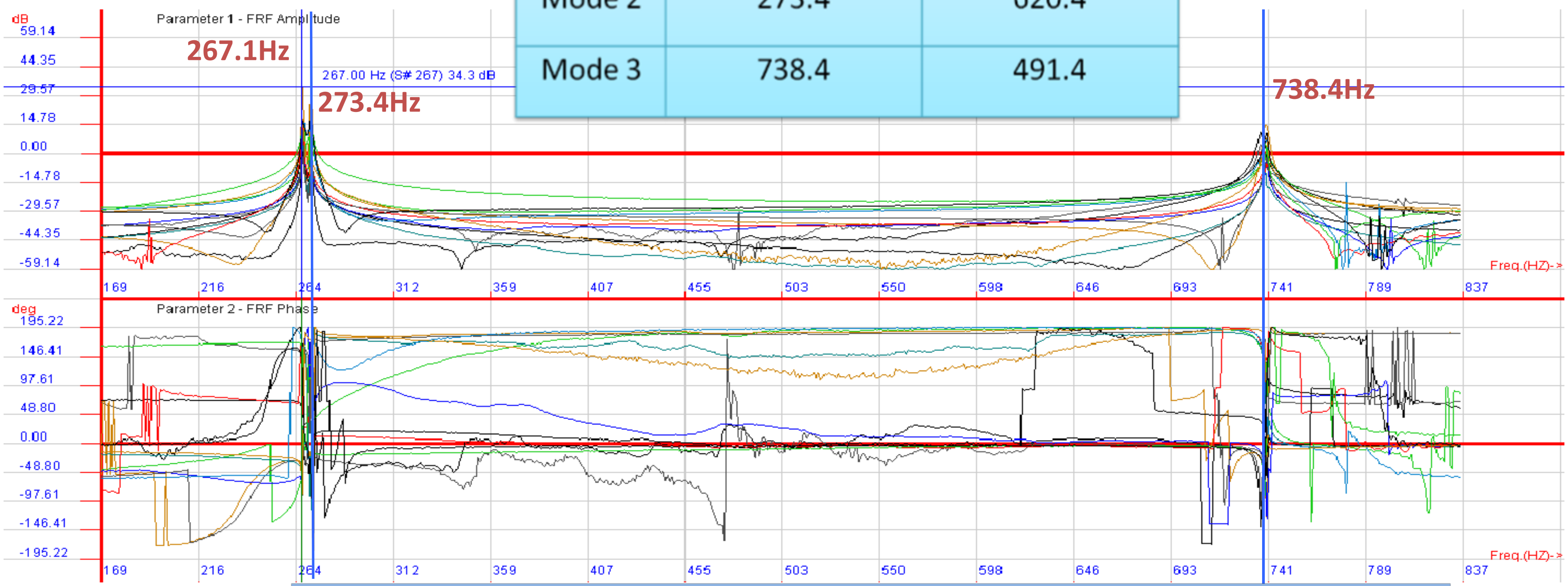
Curve Fitting



RFP - Identification of Closely Spaced Modes

Modal Parameters

	Rational Fraction Polynomials	
	ω_n (Hz)	Q Factor
Mode 1	267.1	898.1
Mode 2	273.4	620.4
Mode 3	738.4	491.4



Frequency Response Functions

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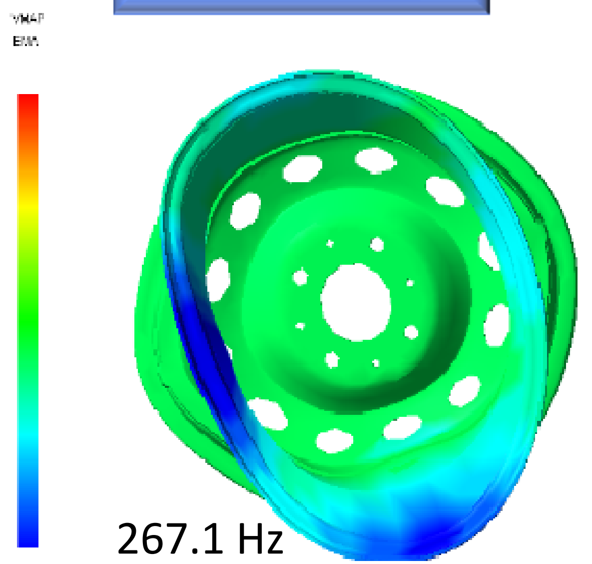
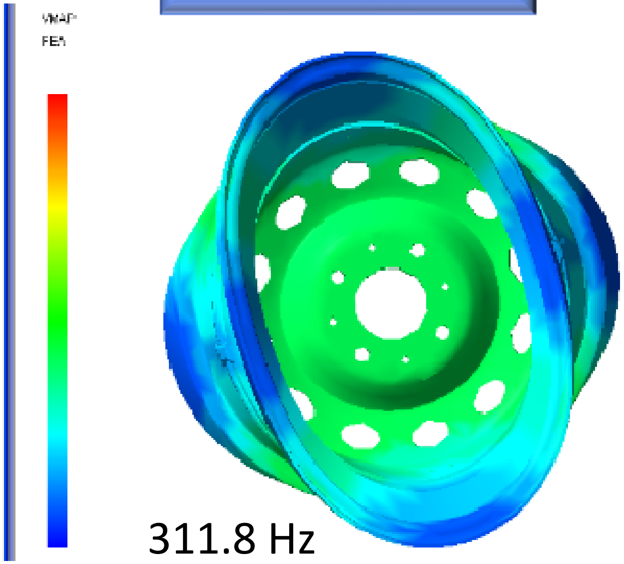
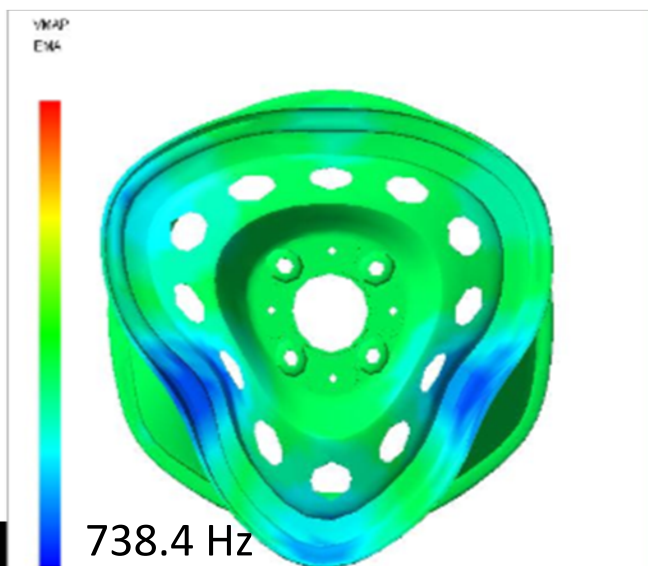
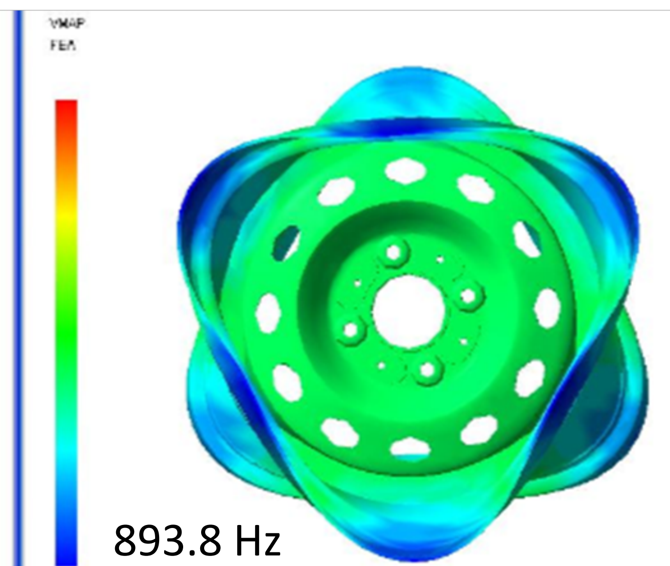
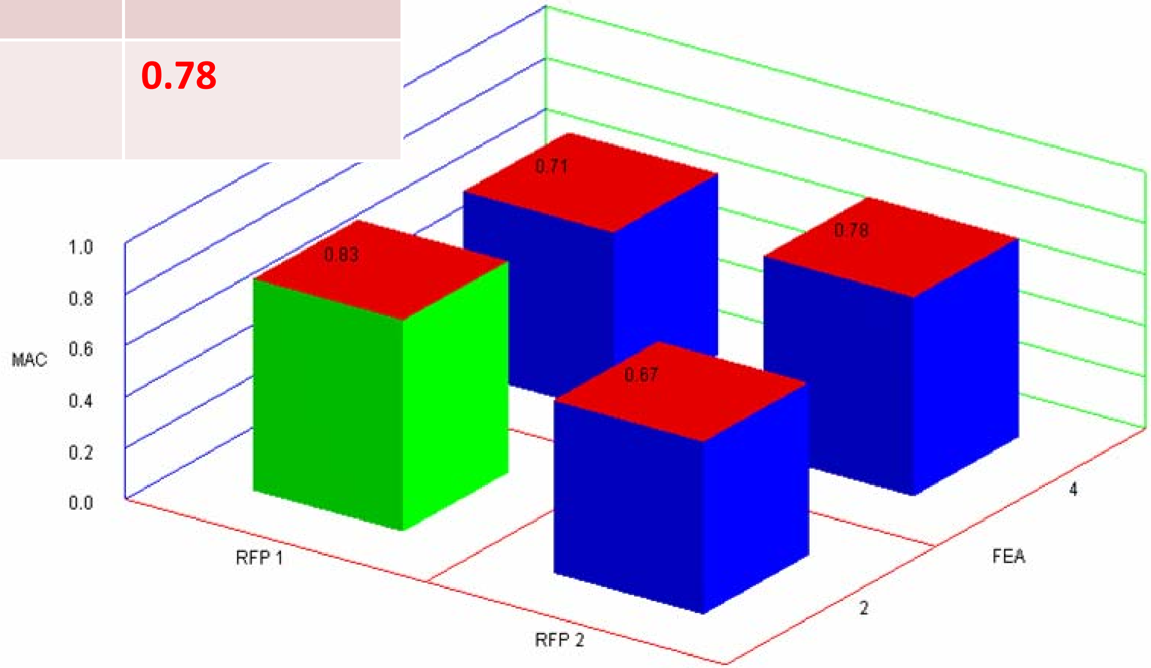
FEA-Test Correlation

	EMA	FEA
Mode 1		
Mode 3		

MAC

Mode (frequency)	FEA 1 (311 Hz)	FEA 2 (893 Hz)
EMA 1 (267.1 Hz)	**0.83**	0.71
EMA 3 (738.4 Hz)	0.67	**0.78**



Case 2: Suspension

- Description
- Finite Element Model
- Experiment
- FEA-Test Correlation
  - o Modal Parameters
  - o MAC

Suspension

Finite Element Model

Mesh

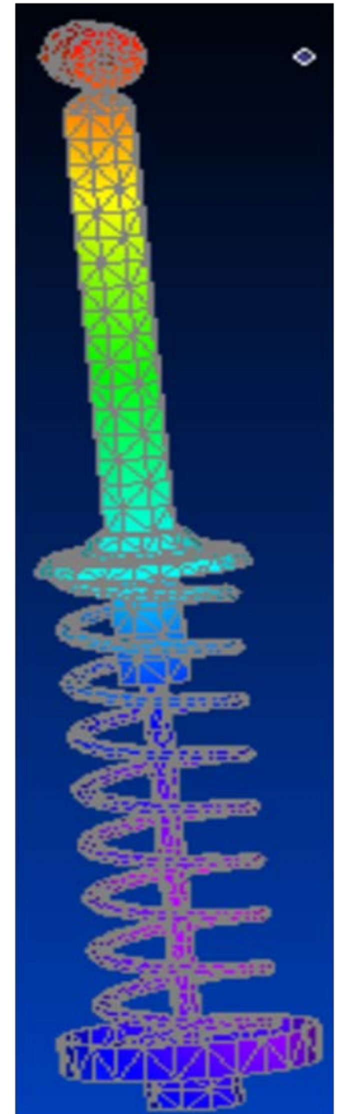
- 10 Node Tetrahedral
- Nodes = 14148
- Elements = 6681

Material

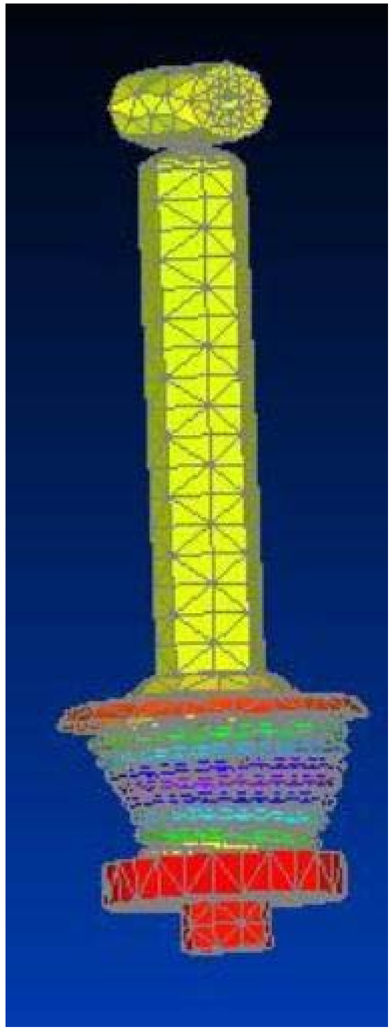
- Steel
- Density = 7800 Kg/m3
- Young’s Modulus = 200e9 N/m2
- Poisson’s Ratio = 0.3

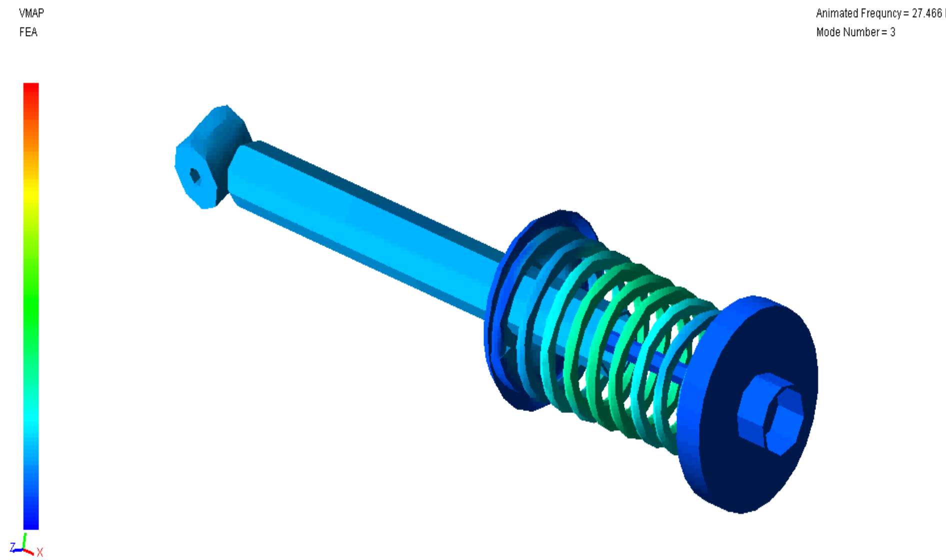
Boundary Conditions

- Free - Free



FEA Results





Animation of Mode 1

Mode 1 - 27 Hz

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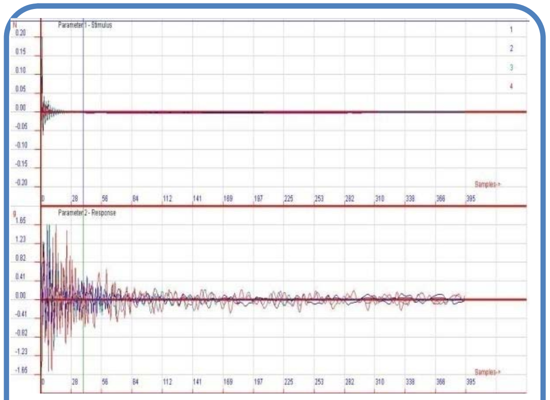
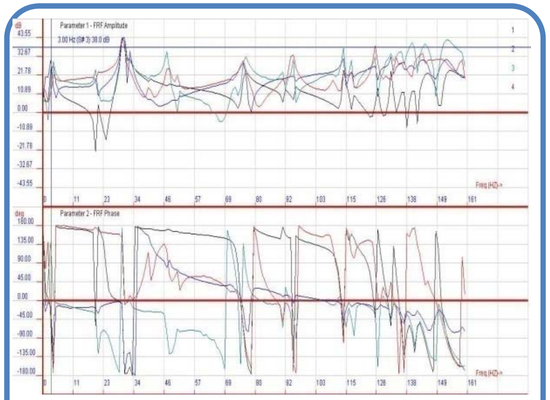
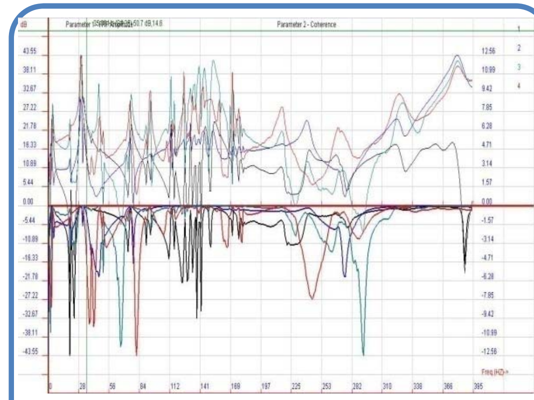
Test Results



Stimulus and response

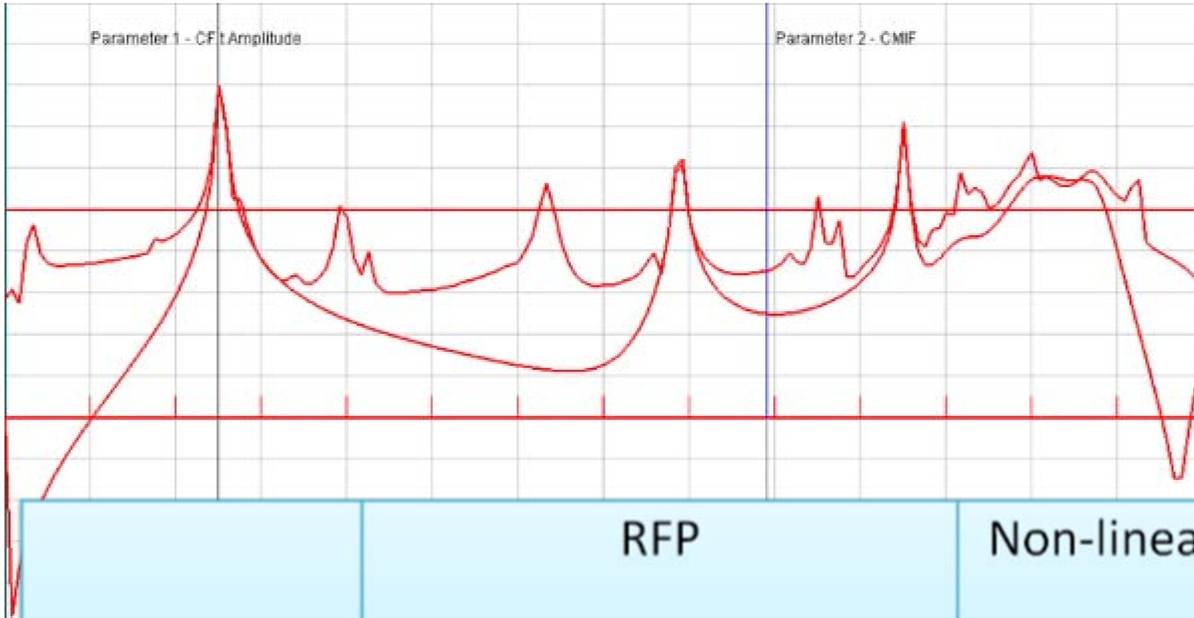


FRF



Coherence

Modal Parameters

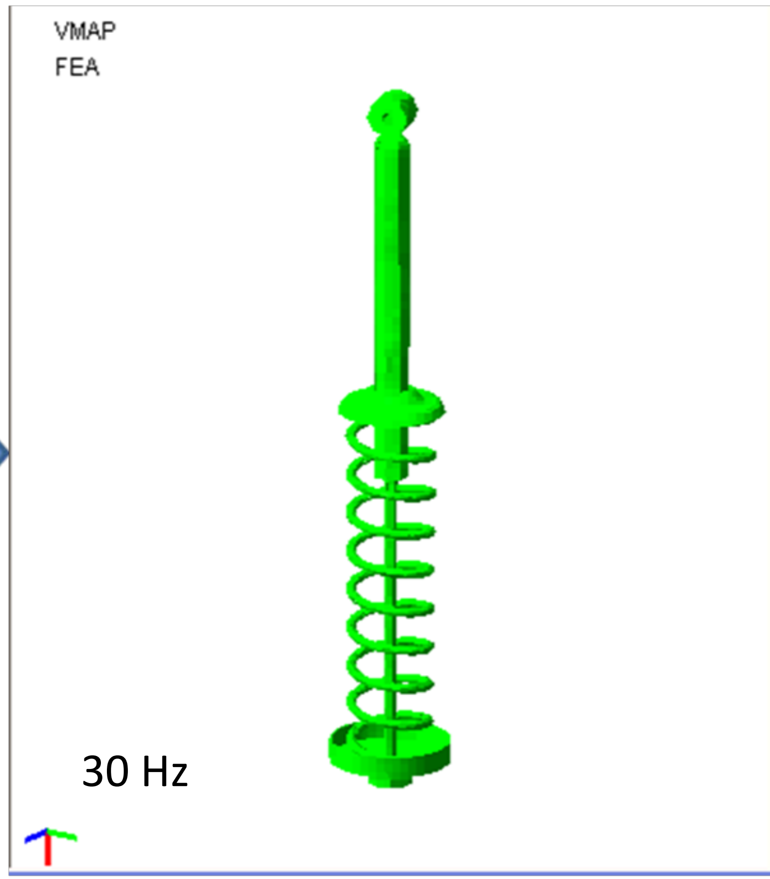


	RFP		Non-linear Least Squares	
	ω_n (Hz)	Q Factor	ω_n (Hz)	Q Factor
Compression Mode	30.4	147.3	30.3	161.9

FEA-Test Correlation

Compression Mode

EMA



FEA

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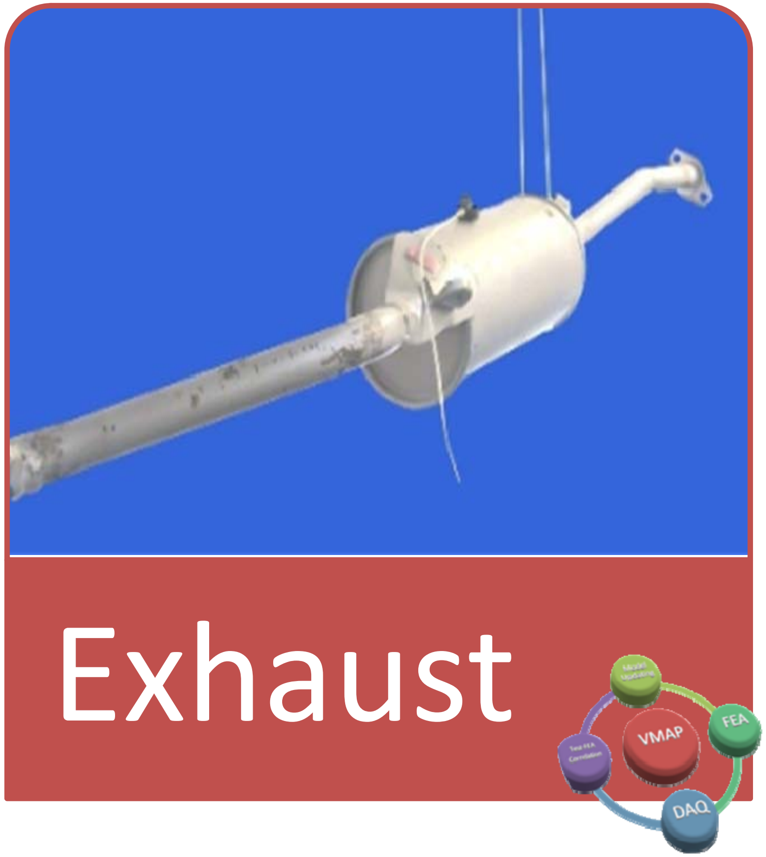
Case 3: Exhaust System

- Description
- Finite Element Model
- Experiment
- FEA-Test Correlation
    - Modal Parameters
    - MAC



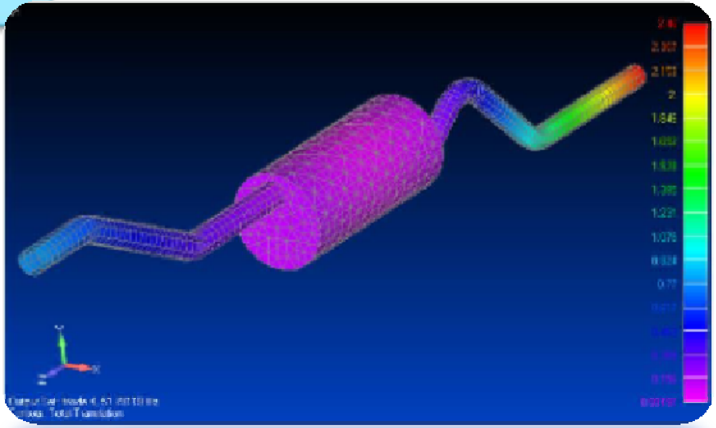
FEA

Mesh → Material → Boundary Conditions

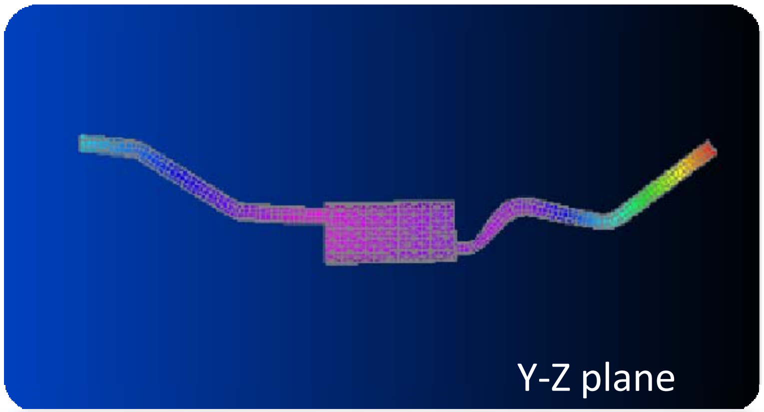
	Type
Engine Manifold	•4 Node, Plate •6 per node
Drum	•10 Node, Solid •3 per node
Exhaust Manifold	•4 Node, Plate •6 per node

	Material
Engine Manifold	$E=1.9e11\ N/m^2$ $\rho=8000\ Kg/m^3$ v=0.3
Drum	$E=2.1e11\ N/m^2$ $\rho=1000\ Kg/m^3$ v=0.3
Exhaust Manifold	$E=1.9e11\ N/m^2$ $\rho=8000\ Kg/m^3$ v=0.3

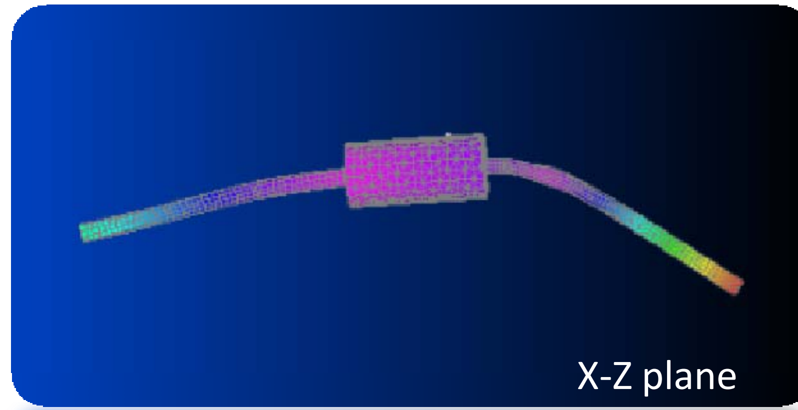
Free - Free



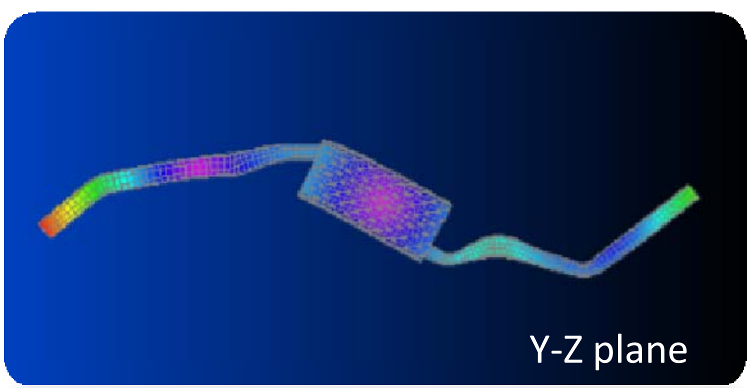
FEA Results



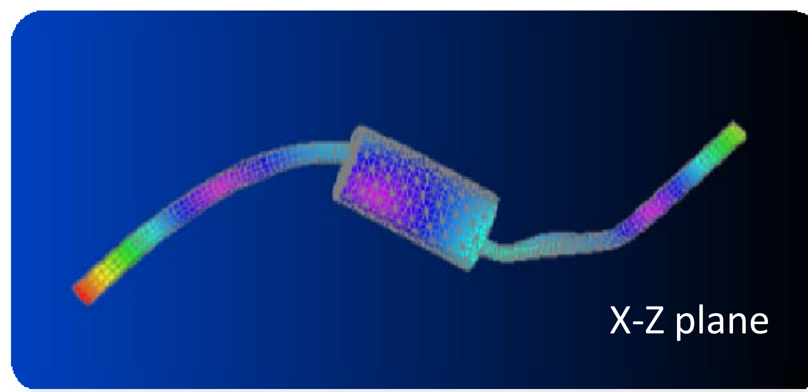
Mode 1 = 58.96 Hz



Mode 2 = 63.18 Hz

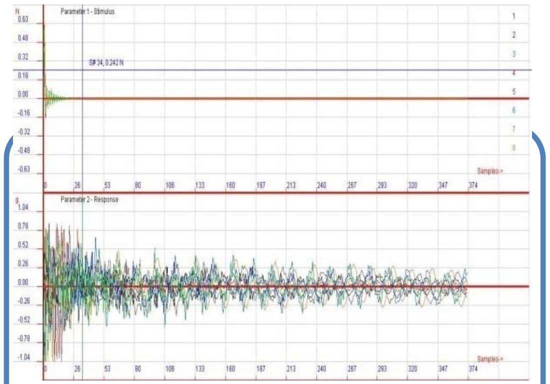


Mode 3 = 142.91 Hz

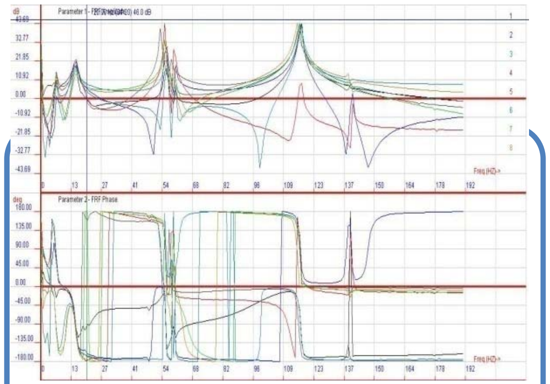


Mode 4 = 162.32 Hz

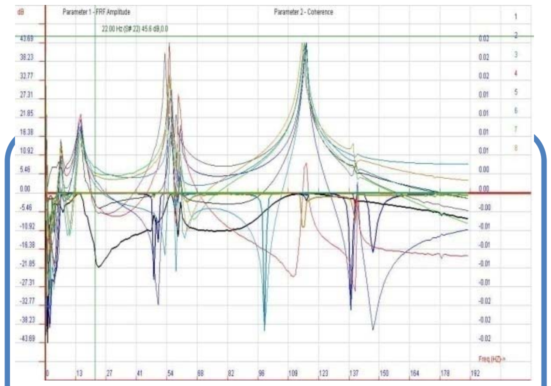
Test Results



Stimulus and response

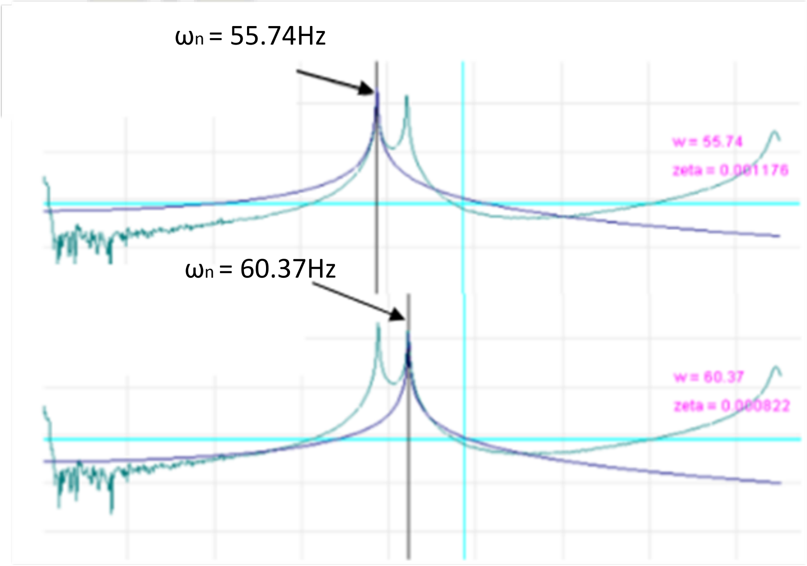


FRF



Coherence

Modal Parameters

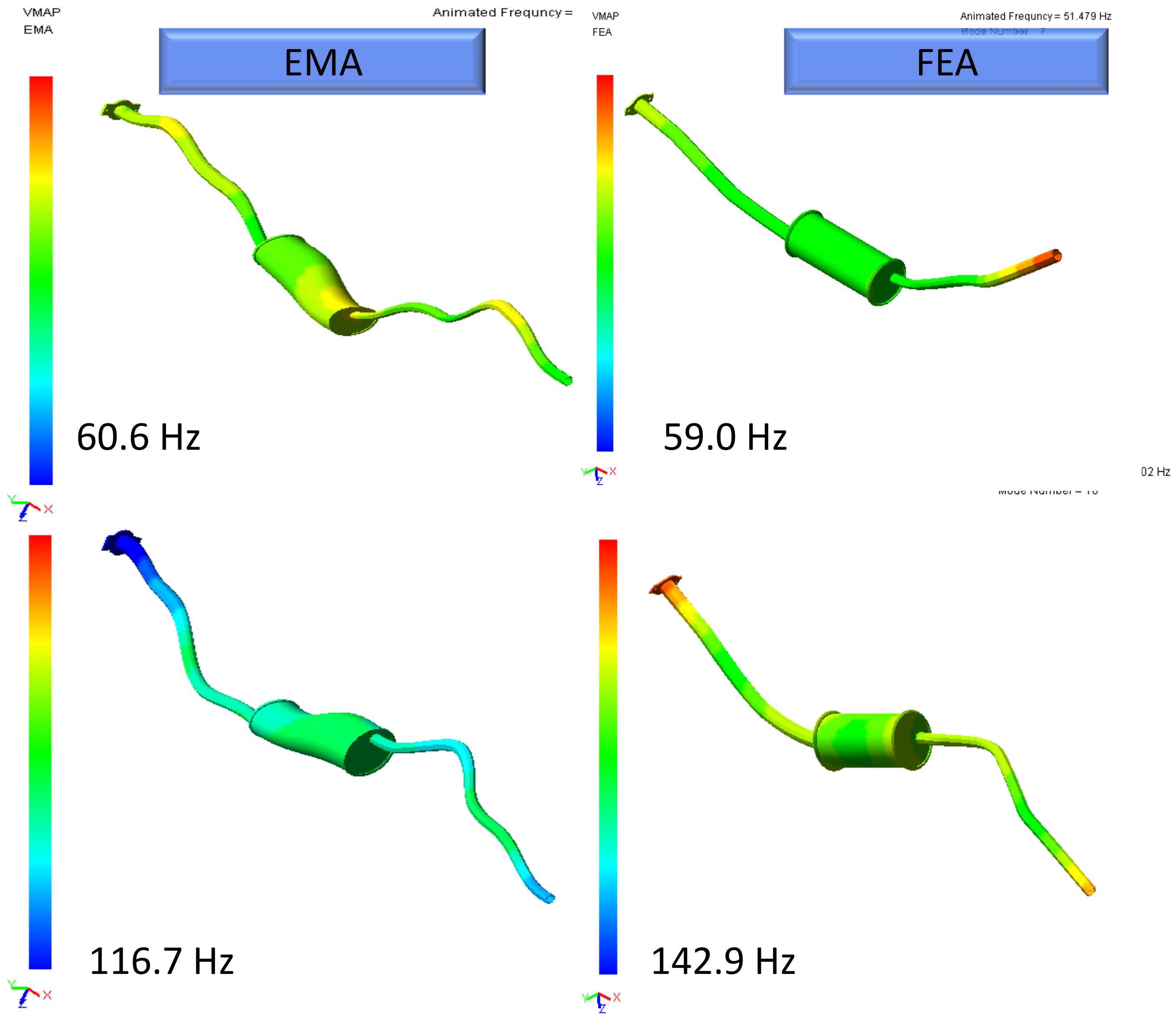


	Circle Fit		RFP	
	ω_n (Hz)	Q Factor	ω_n (Hz)	Q Factor
Mode 2	60.34	608.27	60.61	618.65
Mode 3	116.59	88.21	116.67	86.51

FEA-Test Correlation

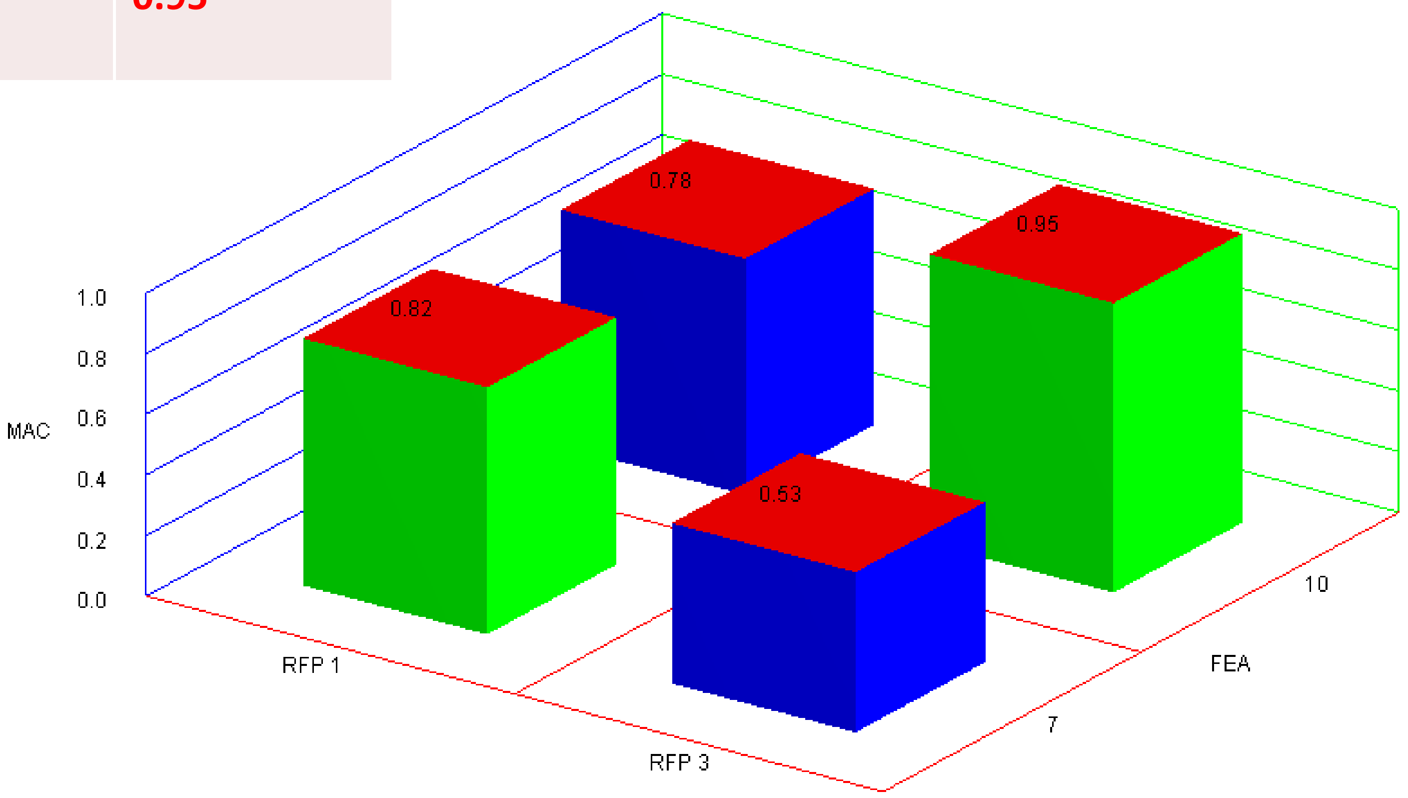
Mode 1

Mode 3



MAC

Mode (frequency)	FEA 1 (51.5 Hz)	FEA 3 (130.7 Hz)
EMA 1 (56.2 Hz)	**0.82**	0.78
EMA 3 (116 Hz)	0.53	**0.95**



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Q&A Session

Using the Q&A tool, please submit any questions you may have for our panel.

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Thank you!

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