Correlation of FE Modal Analysis with Experimental Vibration Data

January 31st, 2011

Agenda

Correlation of FE Modal Analysis with Experimental Vibration Data.

- **Welcome & Introduction**
  - David Quinn, Head of Marketing, NAFEMS
- **Correlation of FE Modal Analysis with Experimental Vibration Data**
  - Dhanushkodi Mariappan, Techpassion
- **Q&A Session**
- **Closing**

An Overview of NAFEMS

David Quinn
NAFEMS

NAFEMS

The International Association for the Engineering Analysis Community

Almost 1000 Corporate Members worldwide

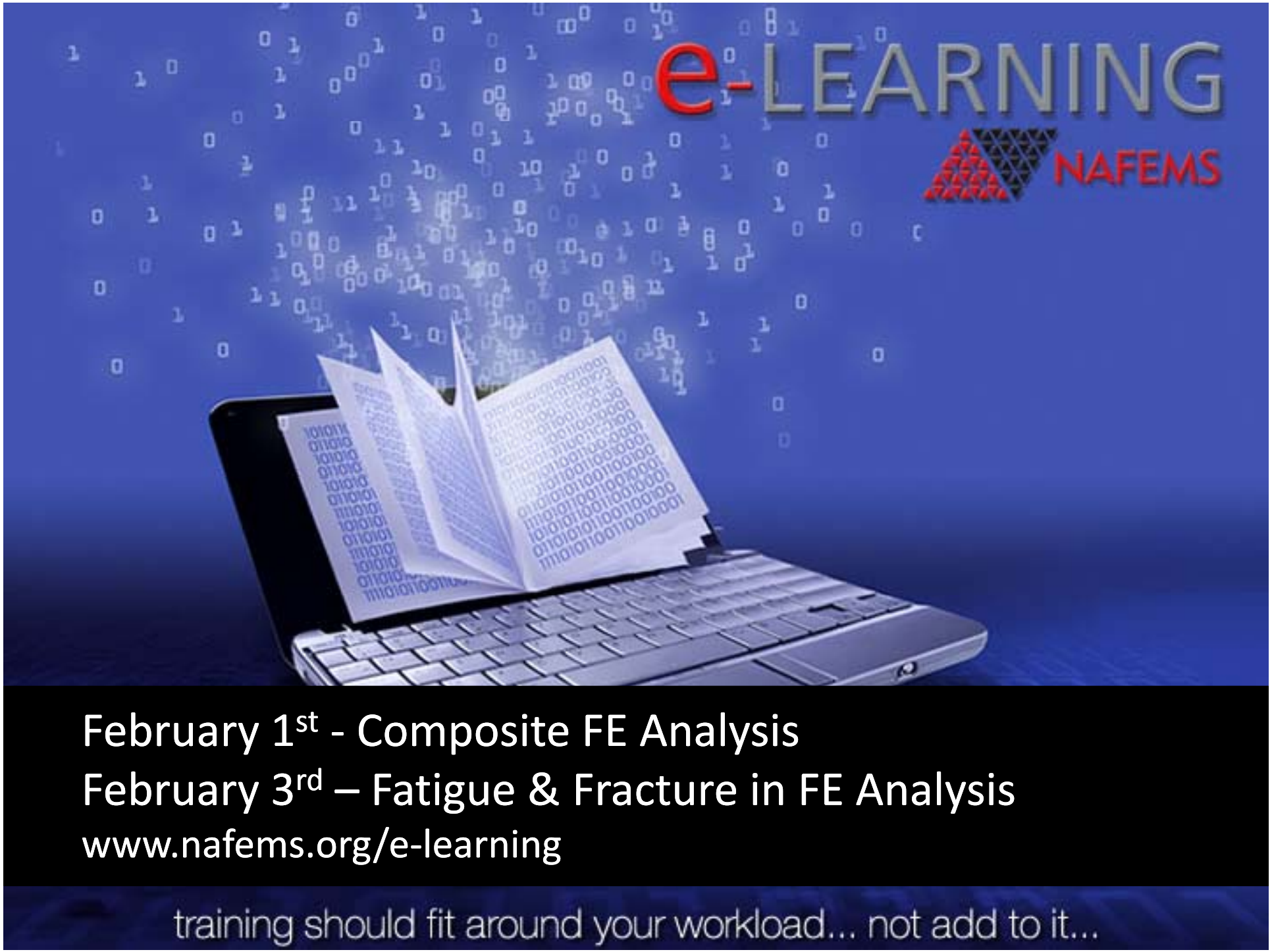
Library of cutting edge publications

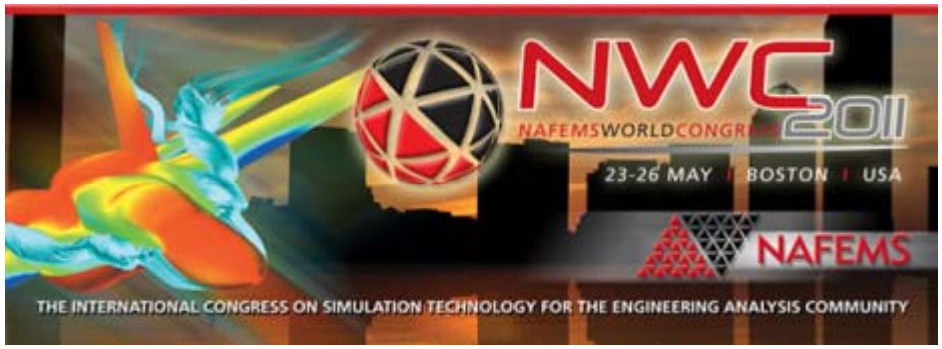
50-60 seminars, courses, conferences, webinars and e-learning events per year

Members get free attendance at seminars, and significant discounts on all other events

Visit www.nafems.org to find out more

Contact Paul Steward, paul.steward@nafems.org , +44(0)1355 225688 for full details


e-LEARNING
NAFEMS
February 1st - Composite FE Analysis
February 3rd – Fatigue & Fracture in FE Analysis
www.nafems.org/e-learning
training should fit around your workload... not add to it...



- Date: May 23-26, 2010
- Location: Boston, MA
- Keynote Speakers Announced
- Principal Sponsor - Simulia
- For more information, visit: www.nafems.org/congress

Correlation of FE Modal Analysis with Experimental Vibration Data

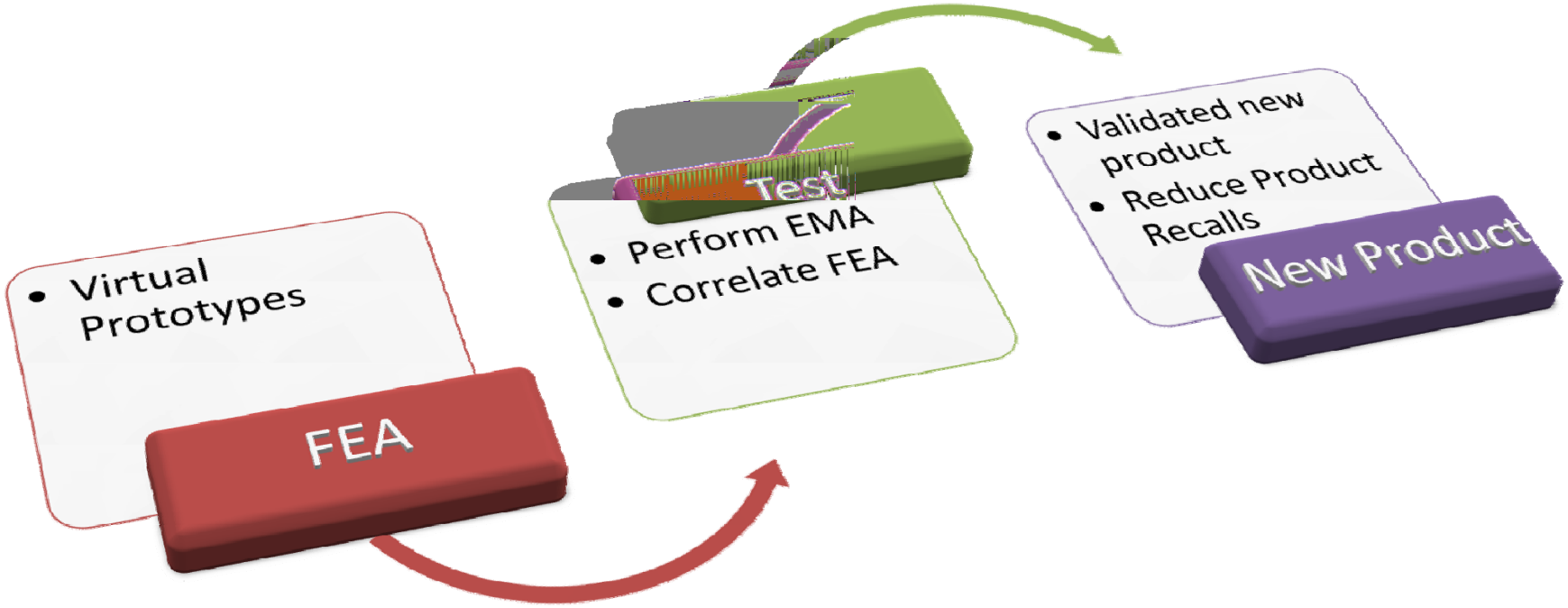
Dhanushkodi Mariappan

Techpassion

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

Simulation Vs Test

Simulation ⟷ Test

Test

Sensors

Hardware

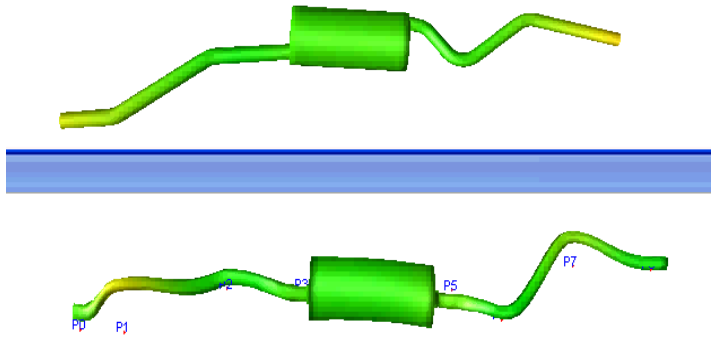
Software

Simulation Vs Test

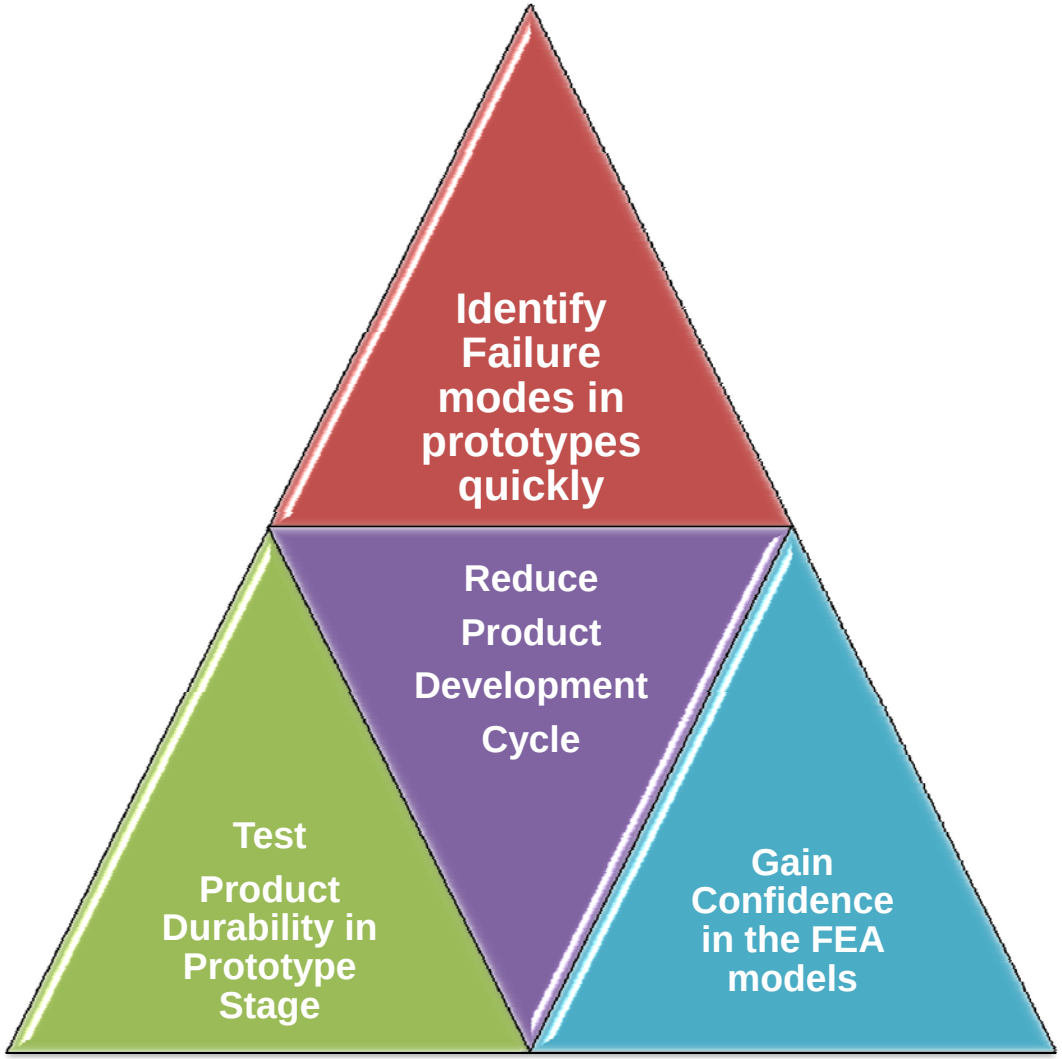
Simulation

Theory

NASTRAN



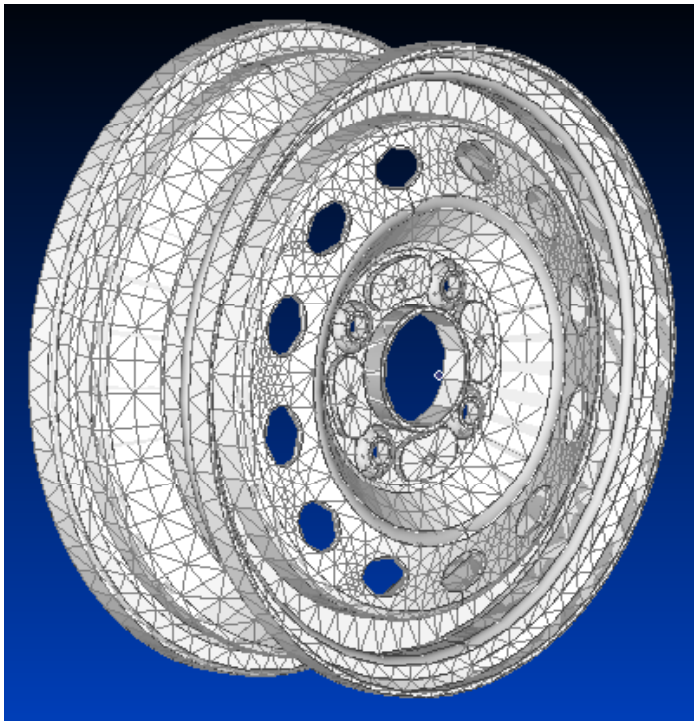
Realizable Benefits



The Finite Element Approach

Finite element methodology
The basic concept

Simulation



CAD → Mesh Model

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

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

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

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

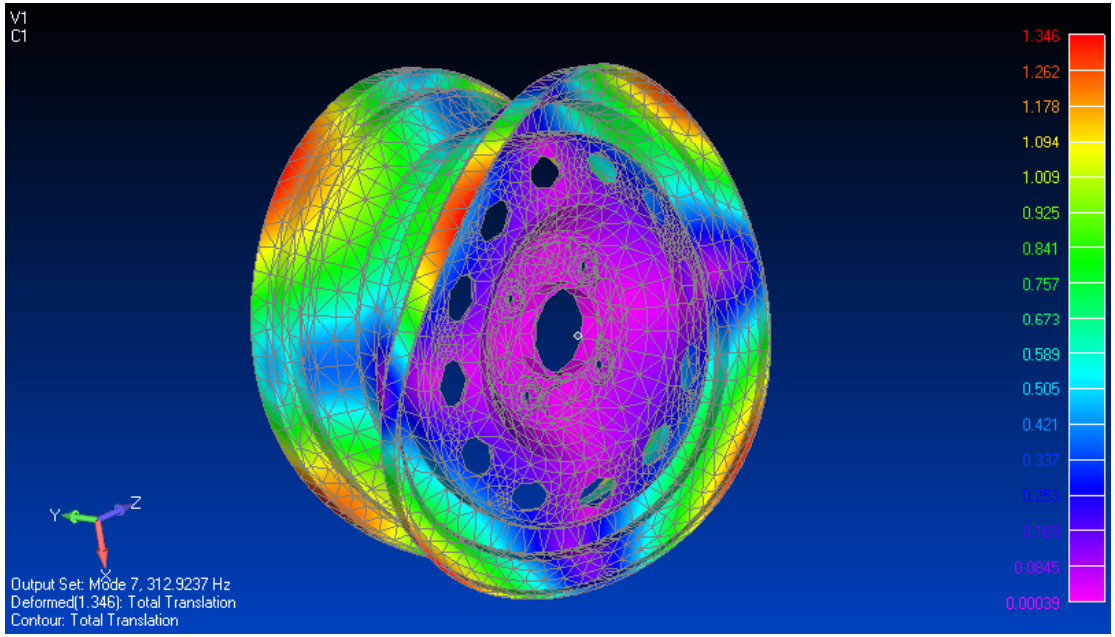
$$det[[K]-\omega^2[M]]=0$$

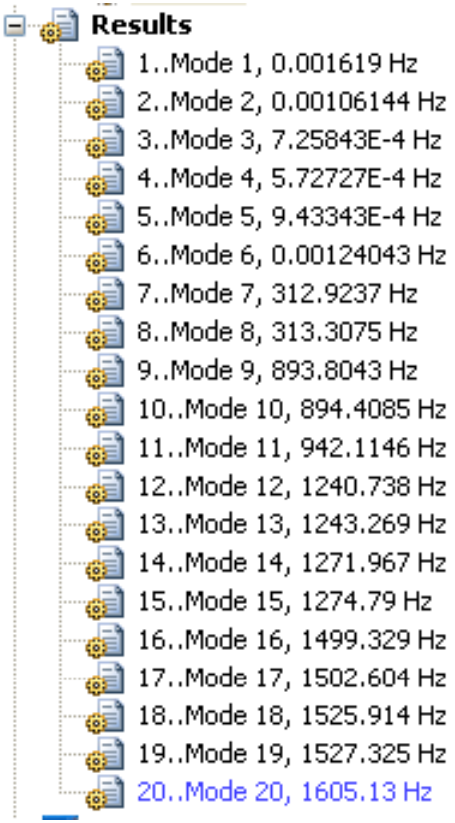
Finite element solving

Simulation

Post Processing

Simulation



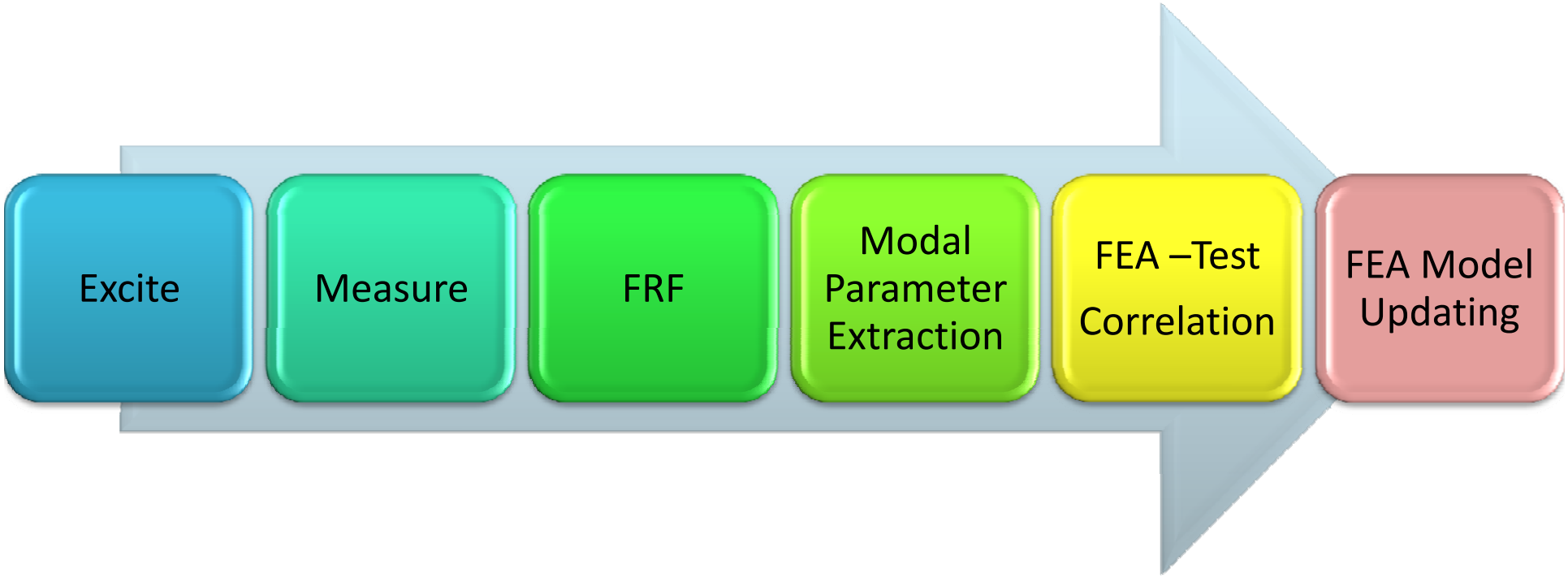


At each of the mode that is solved for, we can obtain the natural frequency and the respective deflection shape – Mode Shape

Experimental Modal Analysis

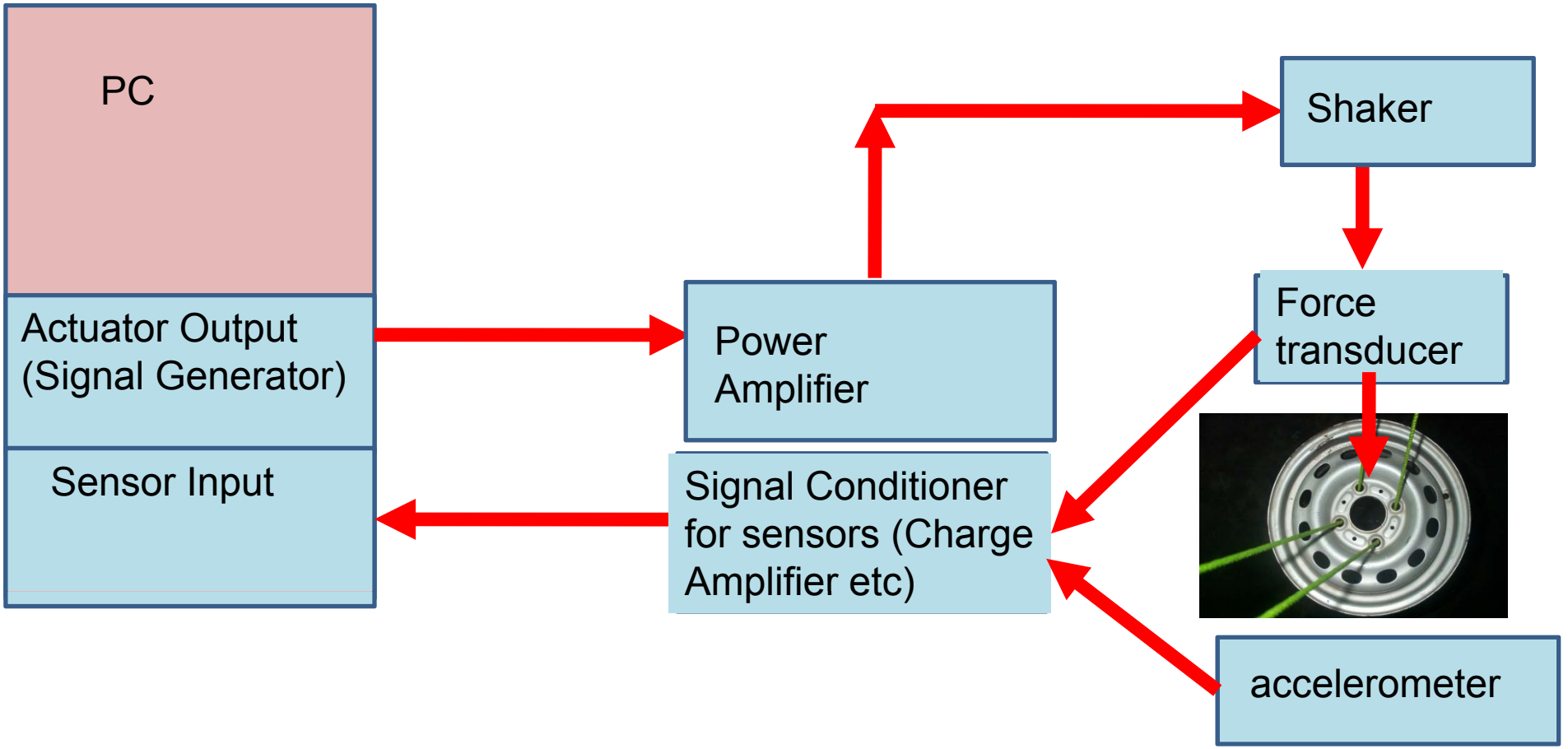
Overview

Test



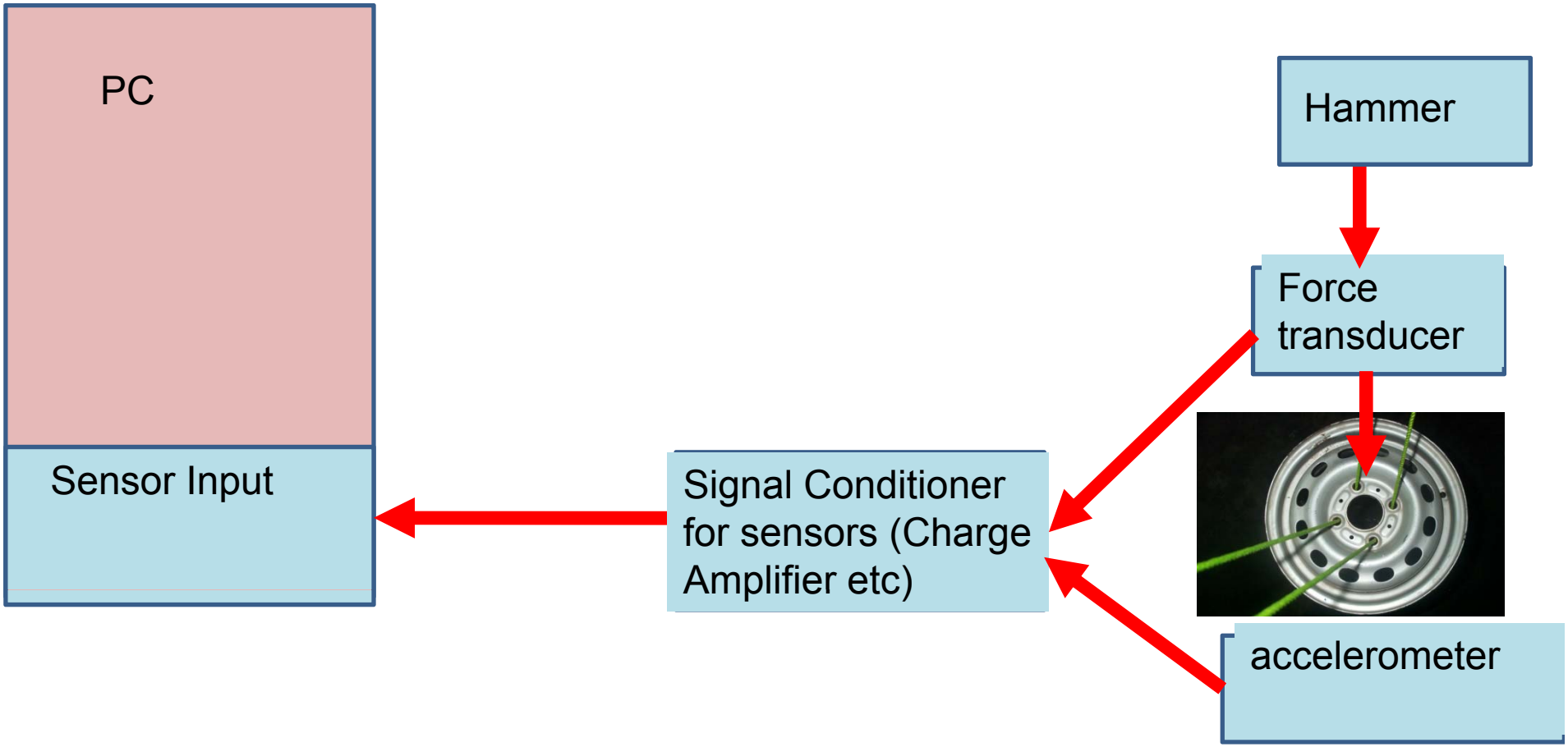
Experimental Setup-1

Test



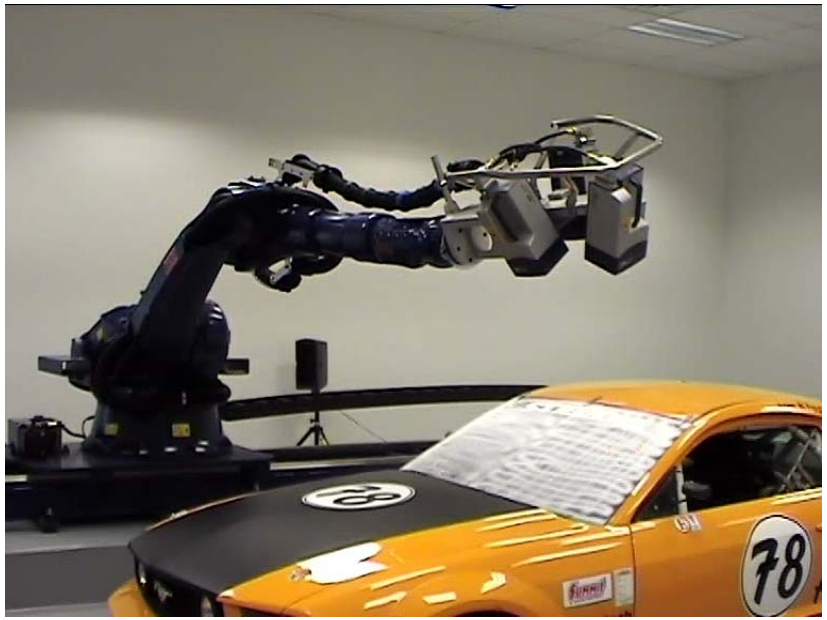
Experimental Setup-2

Test



Non-Contact Vibration Measurement

1. No mass loading
2. Accurate Correlation
3. Accurate Model Updating



MEMS

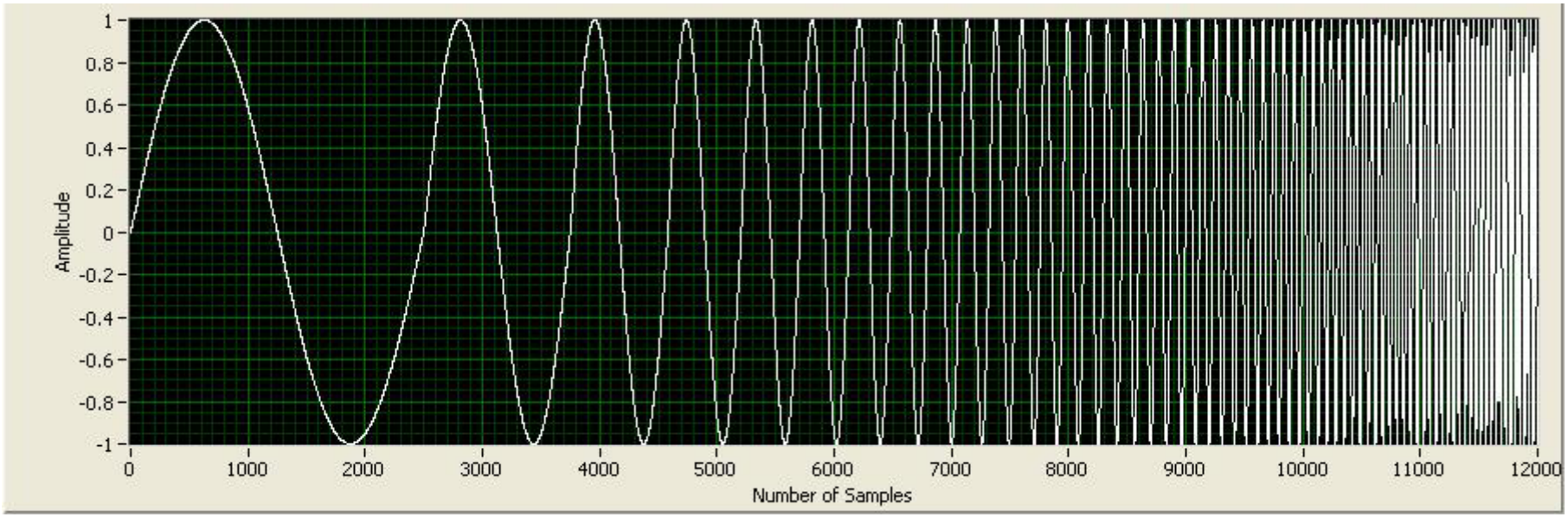
Rotating Machinery

Hot Surfaces

Sinusoidal Excitation

Test

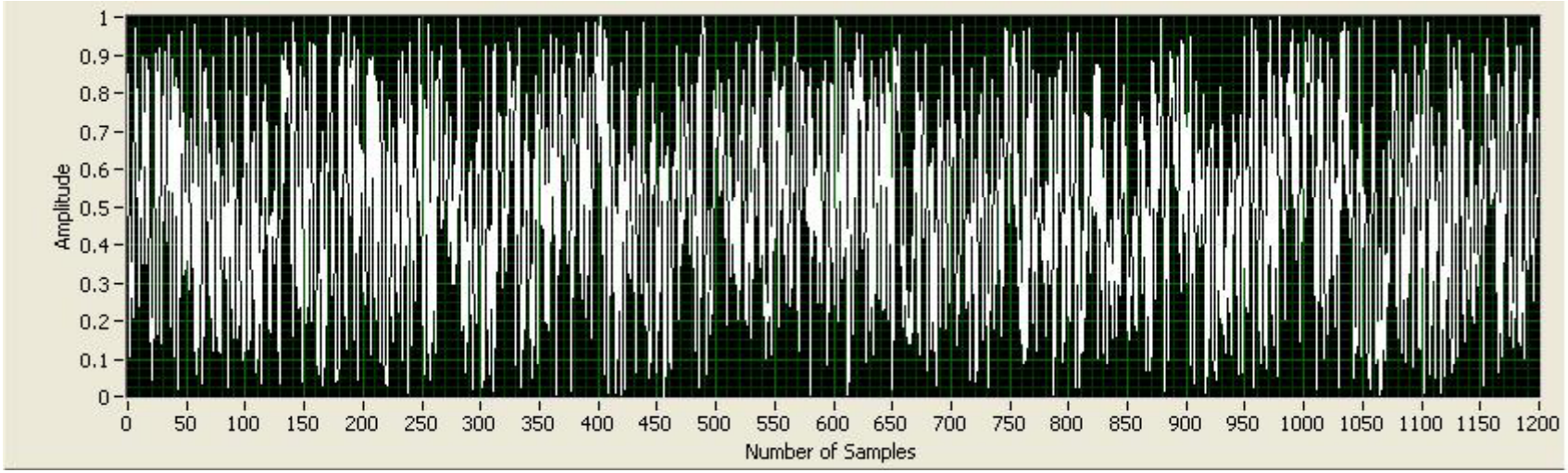
- Sweep from a low frequency to high frequency in steps
- Ideal for structures with non-linearity and are highly damped



Random Excitation

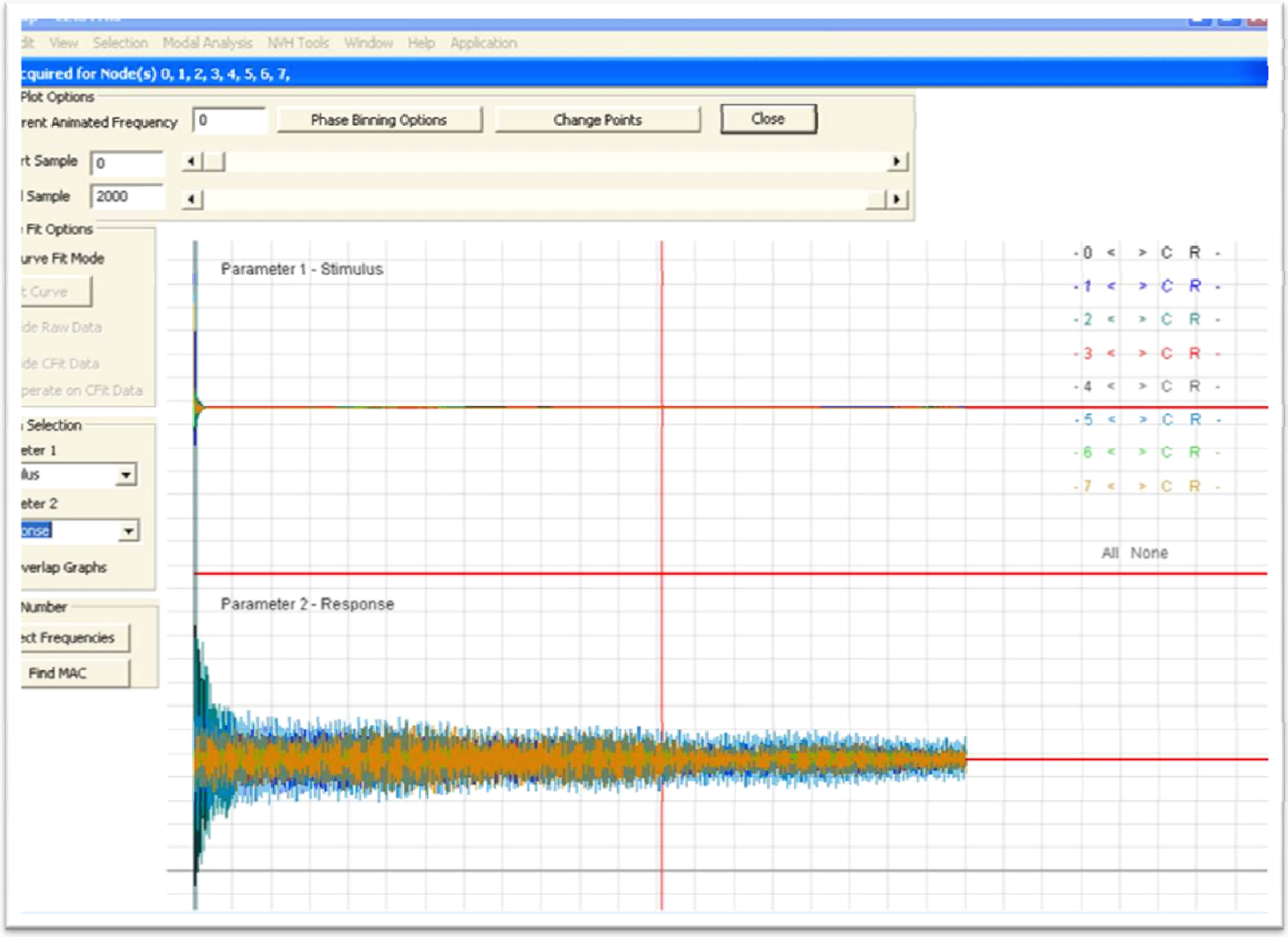
Test

- 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



Excite - Measure

Test

Frequency Response Function
FRF

Test

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

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

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

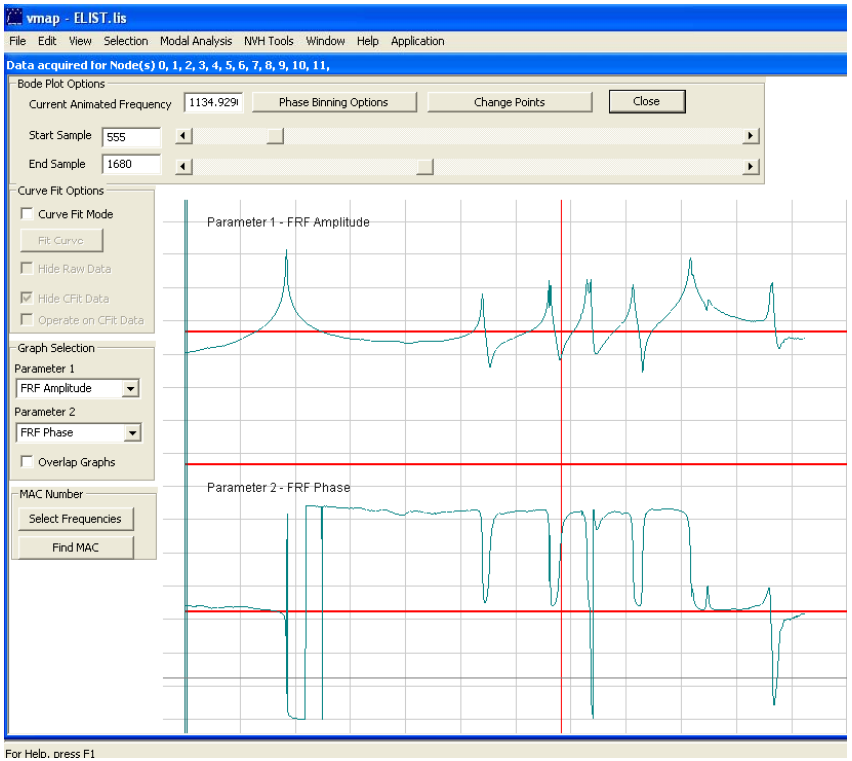
$$\text{Accelerance} = \frac{Acceleration}{Force}$$

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

Linearity

Test

- Modal Analysis is meaningless without the assumption of linearity

Linearity Test

FRF must be independent of excitation amplitudes

Reciprocity

Test

A LTI (Linear Time-Invariant) System follows reciprocity

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

Repeatability

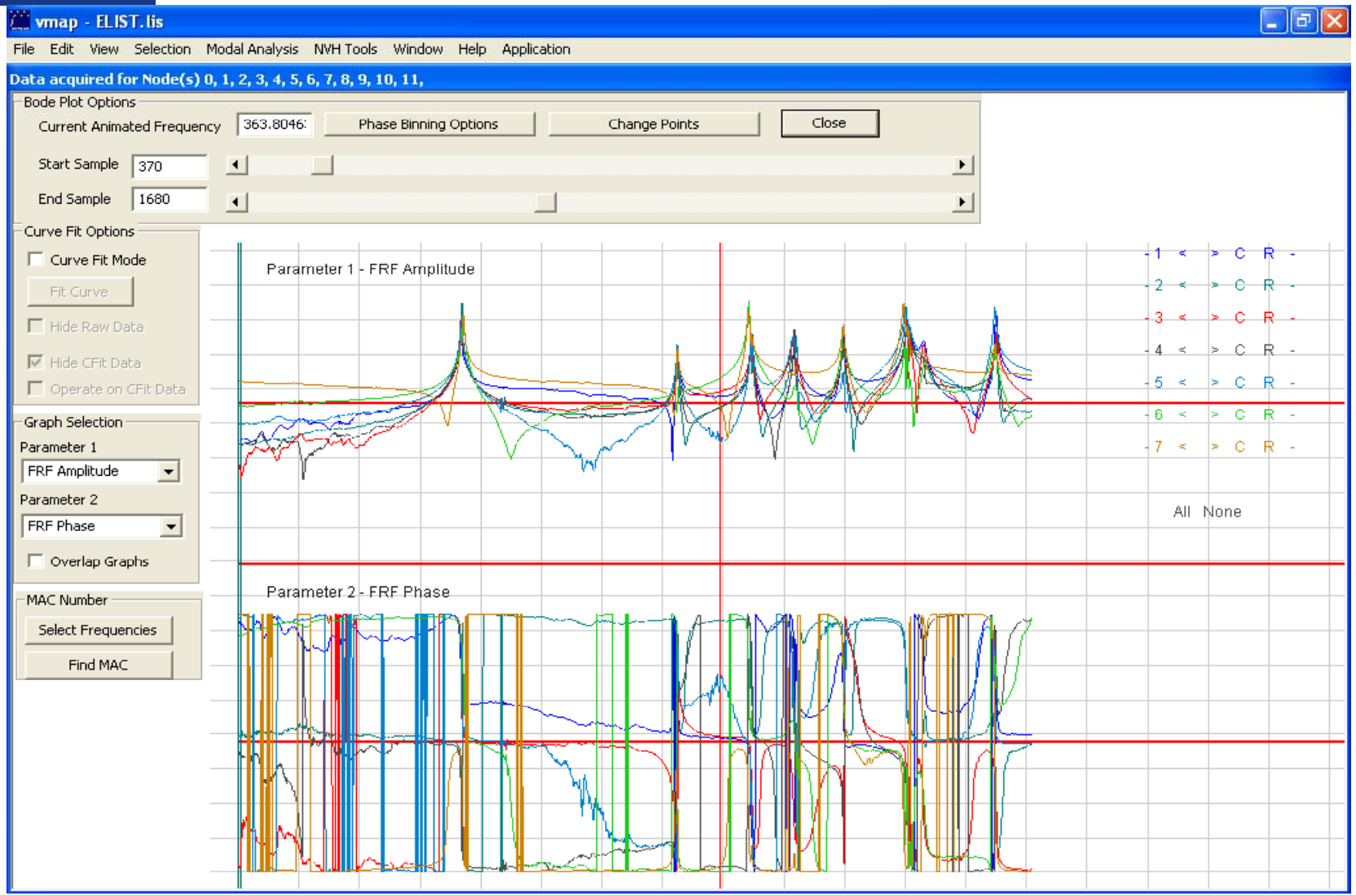
Test

- 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

TechPassion
Engineering the Future

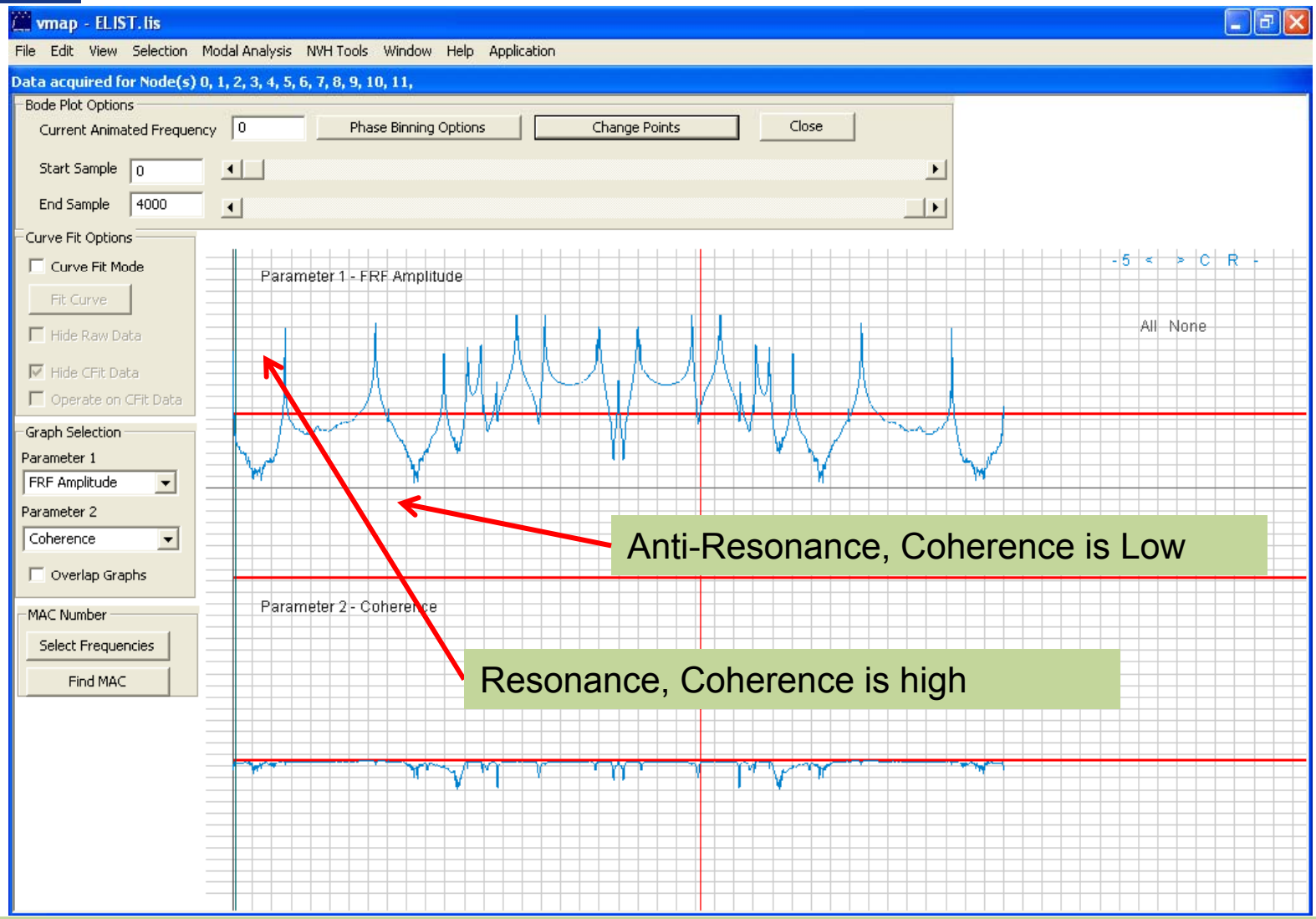
Modal Parameters

Test



Coherence

Test

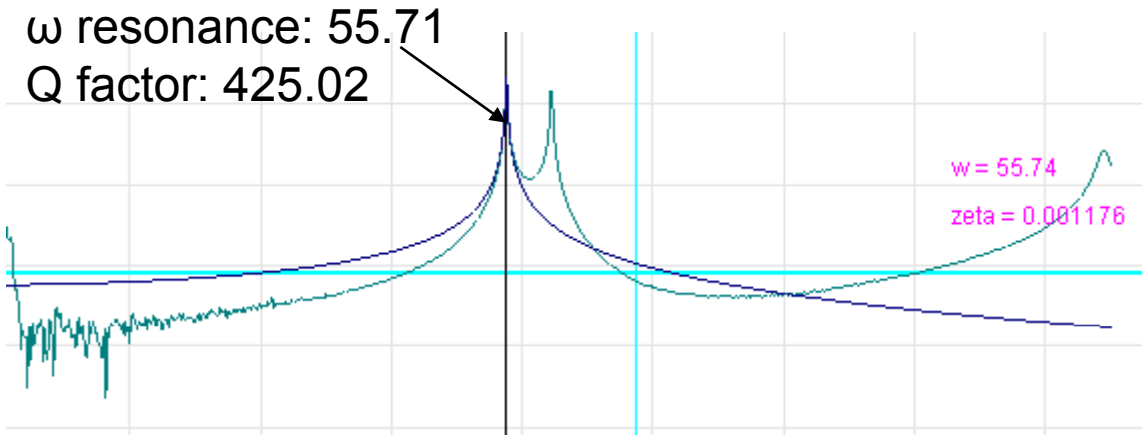


Modal Parameters

Test

- Damping

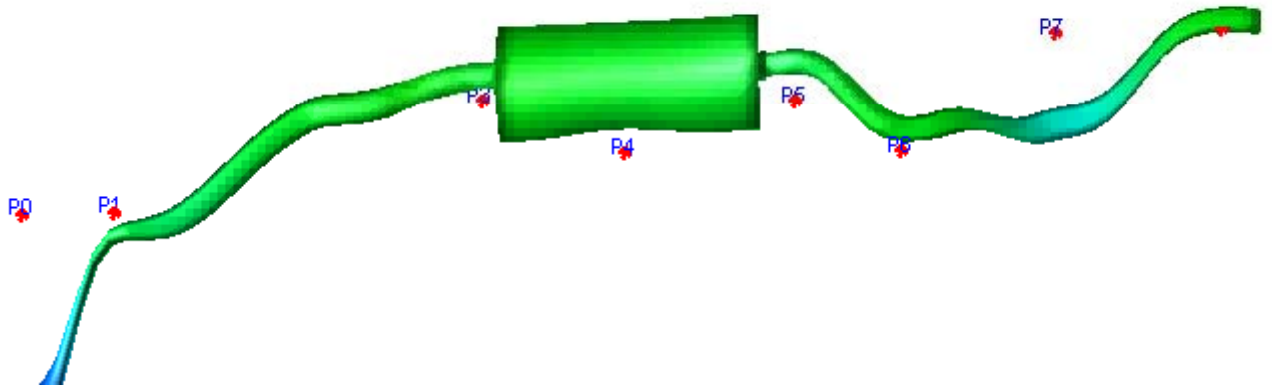
$$\zeta = \frac{1}{2Q} = \frac{1}{850} = 0.0012$$



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

Modeshapes

Test

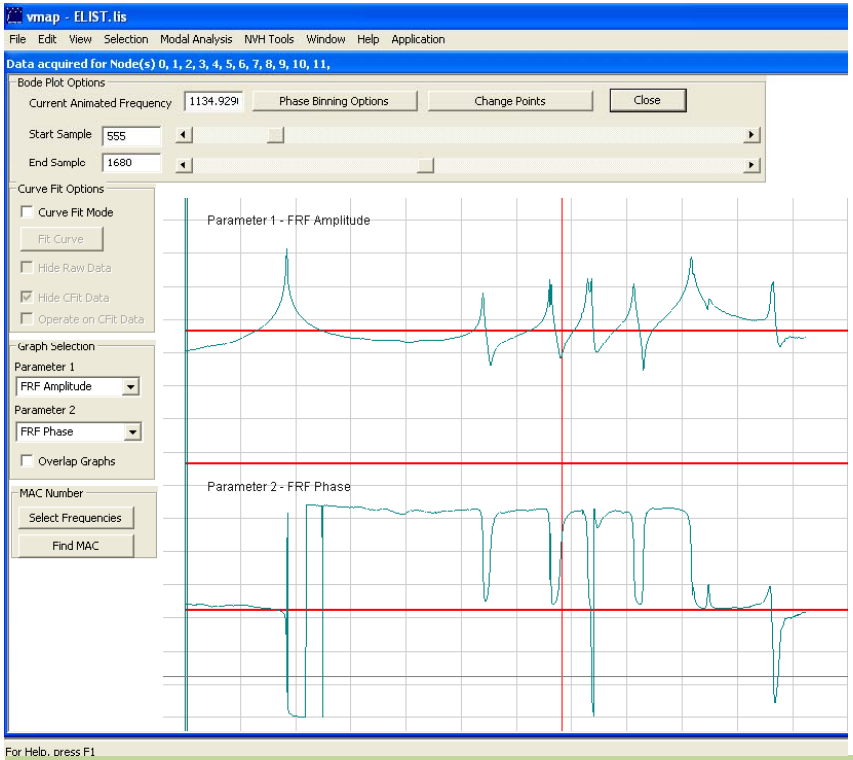


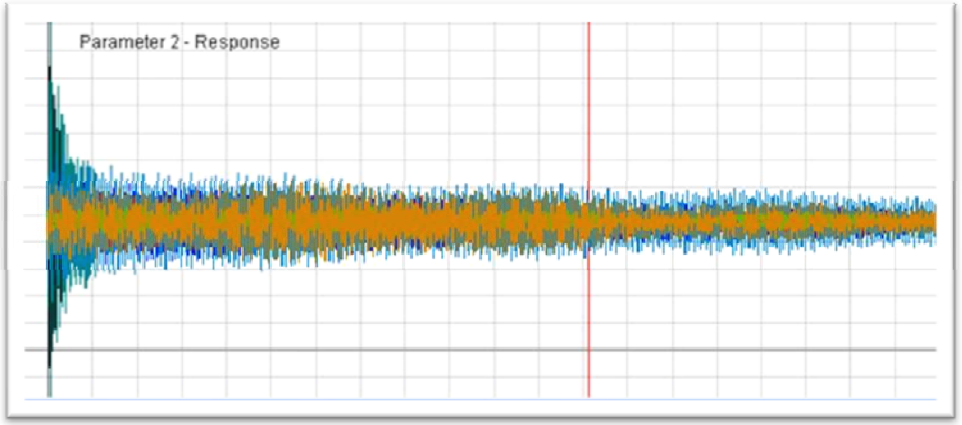
Modal Parameter Extraction

Test

Frequency Domain Analysis

Time Domain Analysis





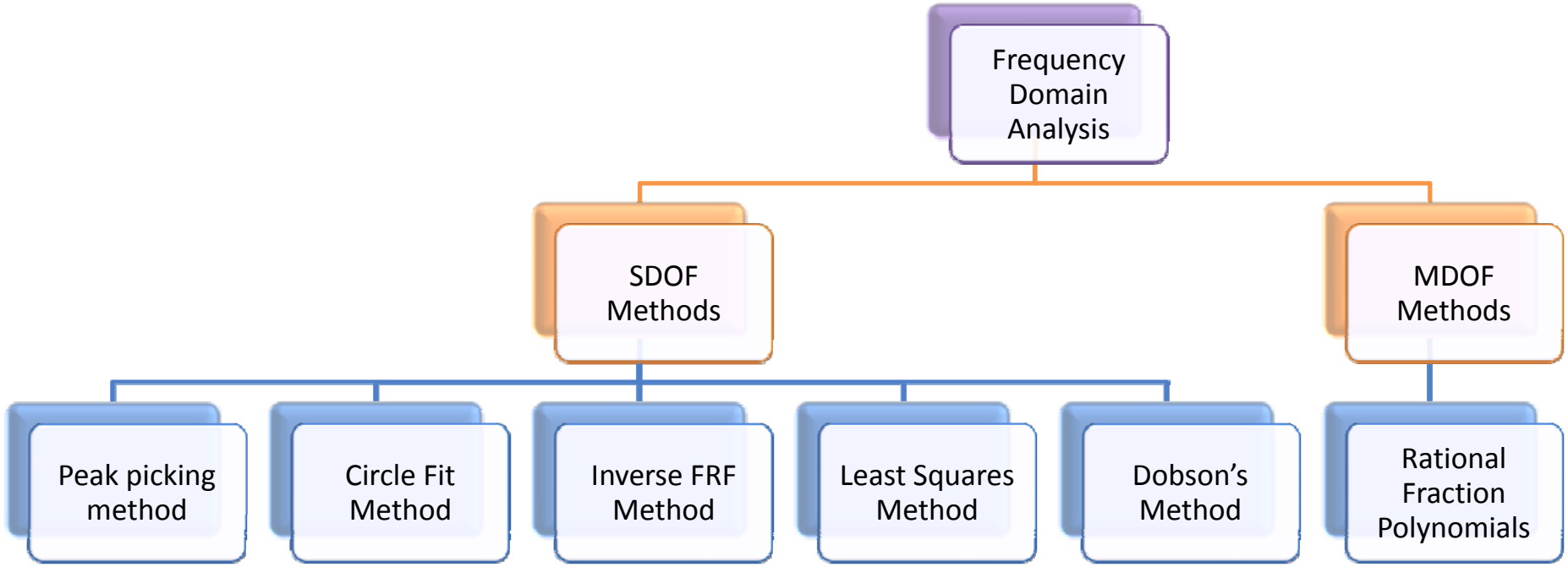
Test

Comparison

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

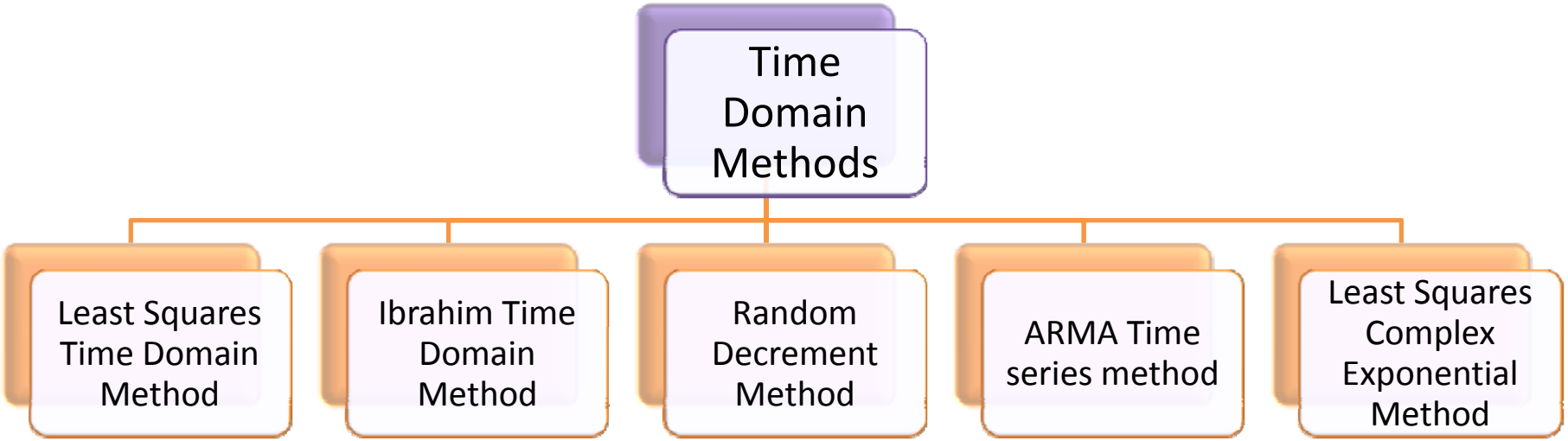
Frequency Domain Methods

Test



Time Domain Methods

Test



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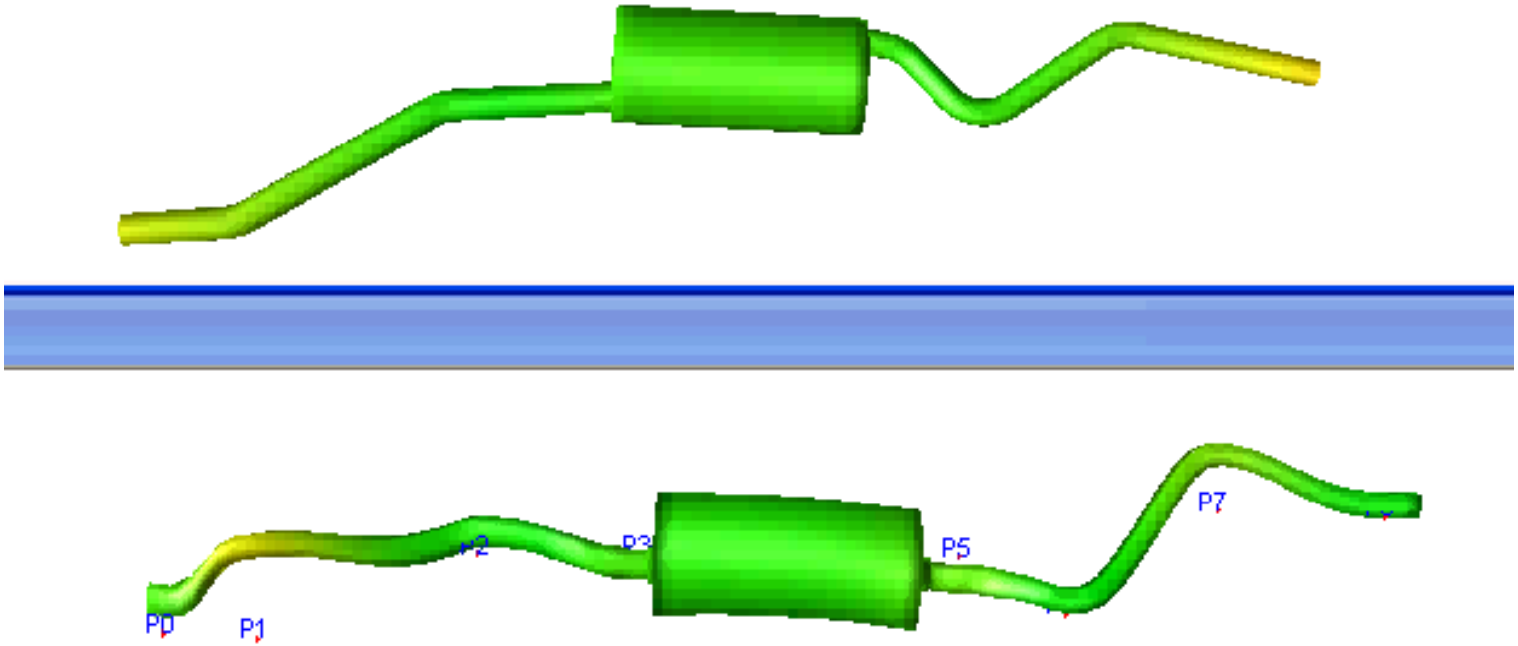
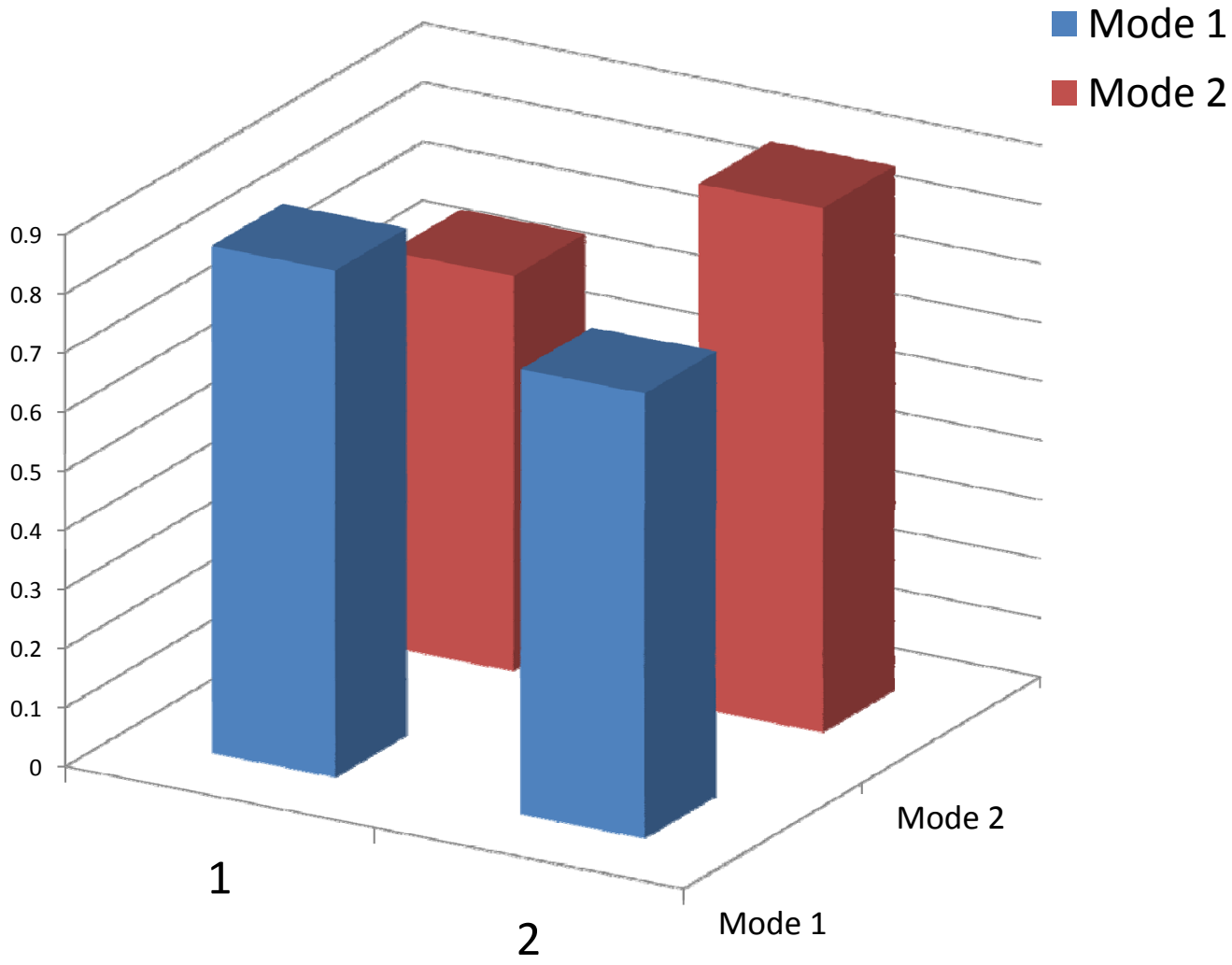
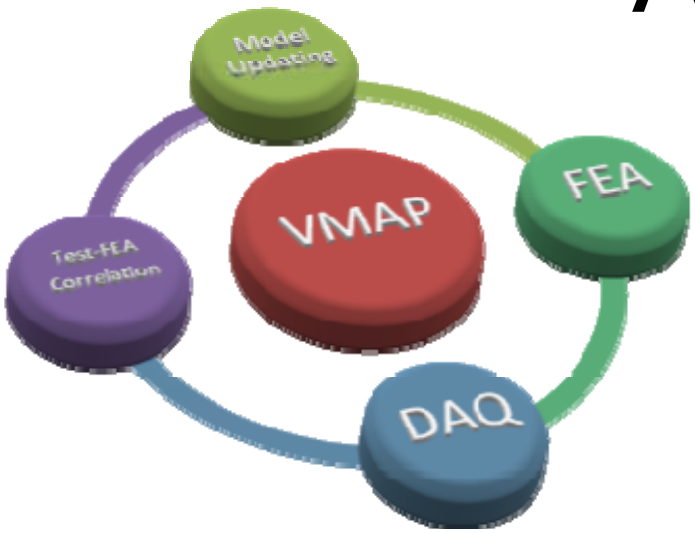
Simulation Vs Test

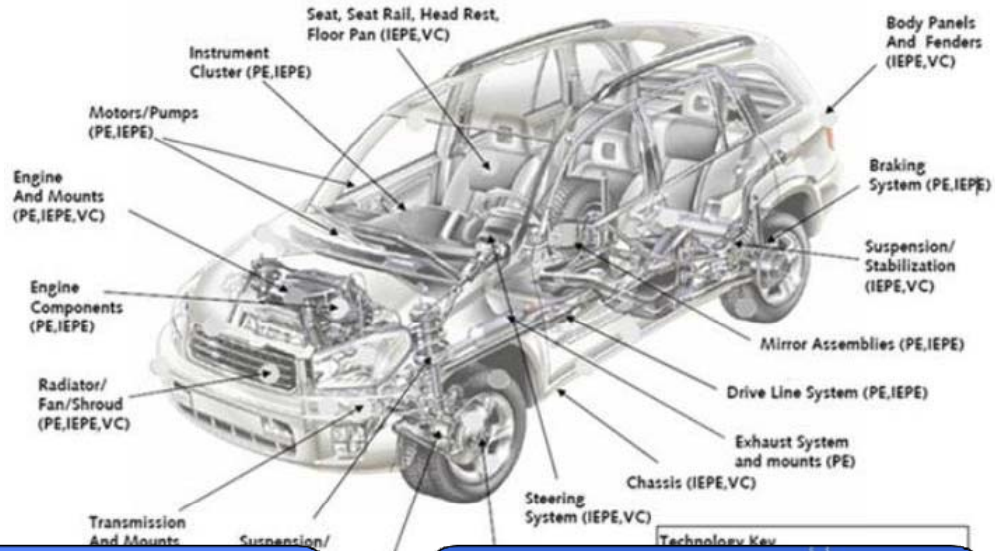


Modal Assurance Criterion



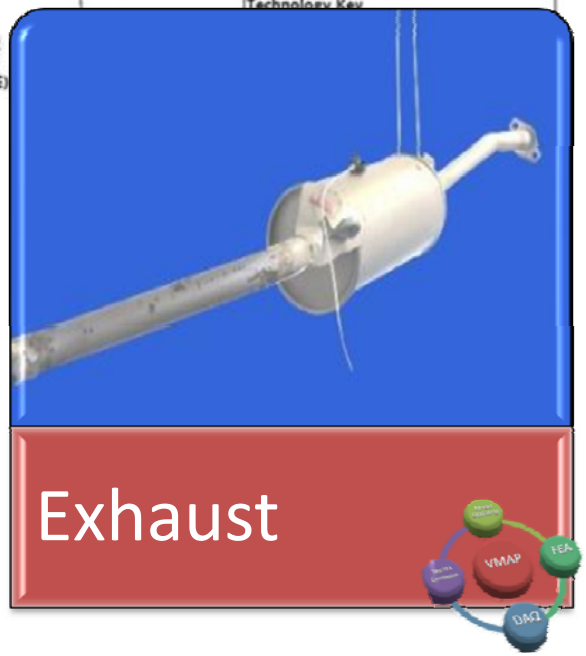
Automotive


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)
Drive Line System (PE,IEPE)
Radiator/ Fan/Shroud (PE,IEPE,VC)
Exhaust System and mounts (PE)
Chassis (IEPE,VC)
Steering System (IEPE,VC)
Transmission And Mounts
Braking System (PE,IEPE)

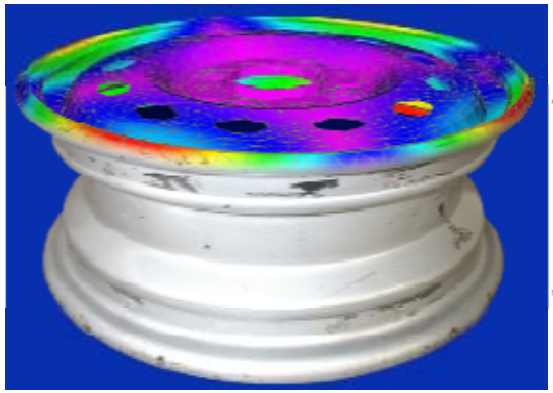

Wheel
VMAP
FEA
DAQ


Suspension
VMAP
FEA
DAQ


Exhaust
VMAP
FEA
DAQ

Case 1: Wheel

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



Finite Element Model

Mesh

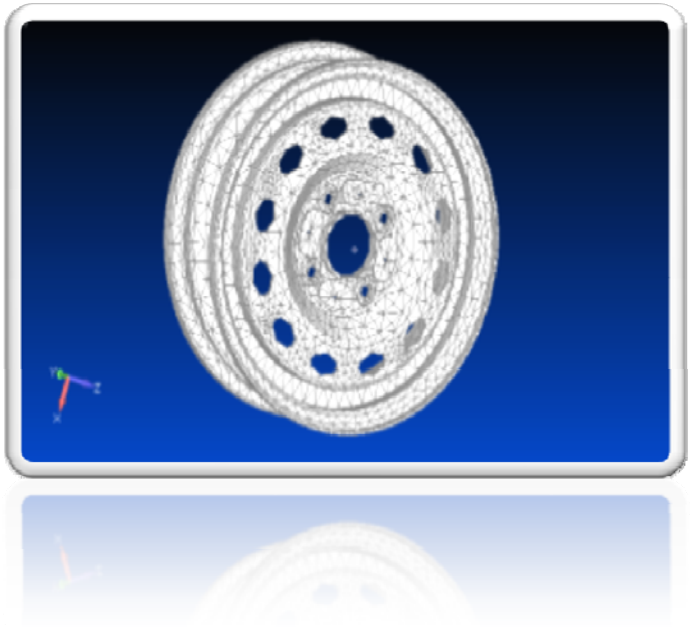
- 10 Node Tetrahedral
- Nodes = 27306
- Elements = 13326

Material

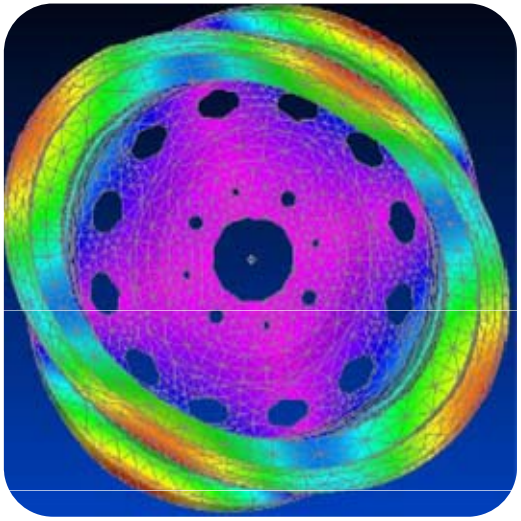
- Aluminum
- Density = 2600 Kg/m3
- Young's Modulus = 70e9 N/m2
- Poisson's Ratio = 0.3

Boundary Conditions

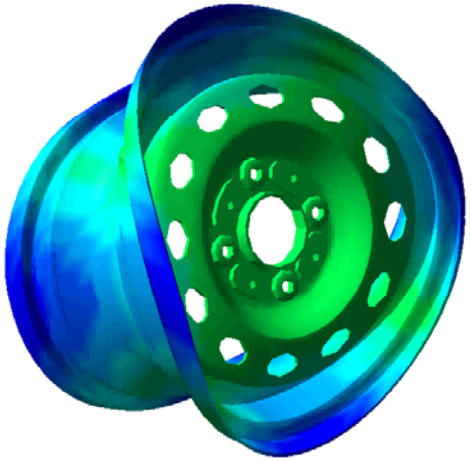
- Free - Free



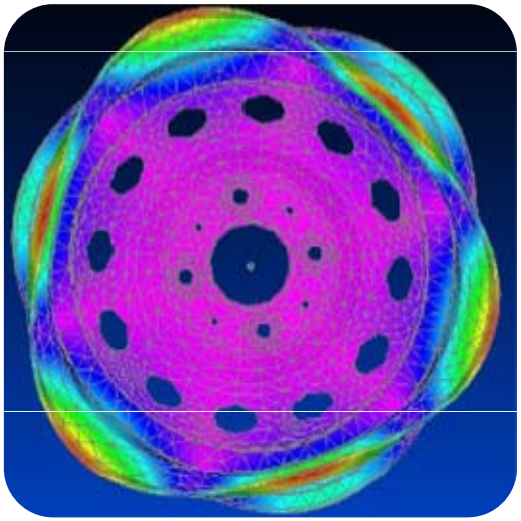
FEA Results



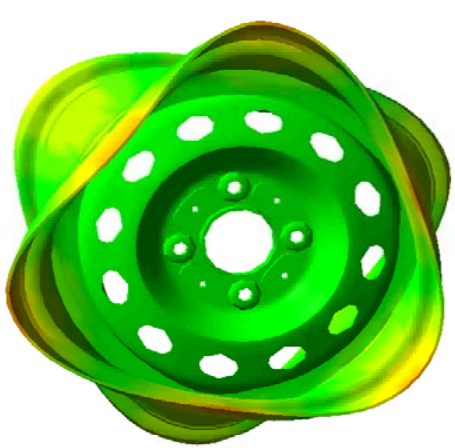
Mode 1 - 311.80 Hz
Mode 2 – 314.74 Hz



Animation of Mode 1



Mode 3 - 893.80 Hz
Mode 4 - 894.41 Hz



Animation of Mode 3

Experimental Setup

Data Acquisition

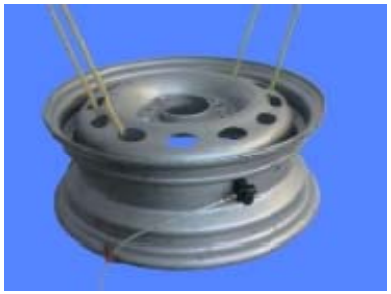
- National Instruments USB 9233
- 50 kS/s
- 4 Channels

Stimulus

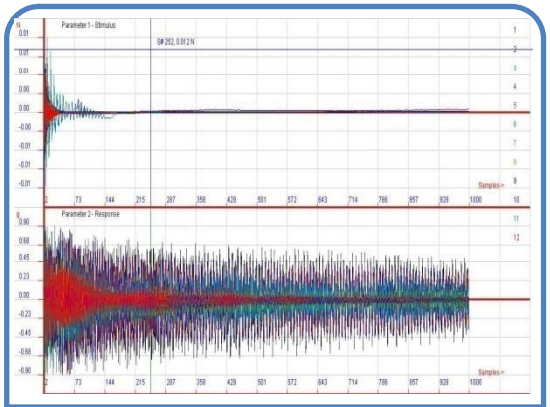
- Impact Hammer
- Range = 500 N
- Sensitivity = 10 mV/N
- Frequency Range < 1200 Hz

Response

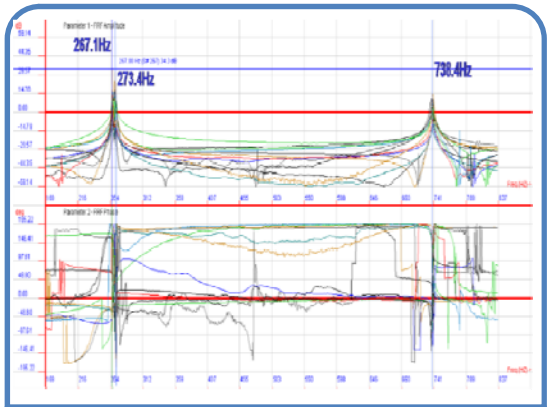
- Accelerometer
- Range : -50g to 50g
- Sensitivity = 100 mV/g



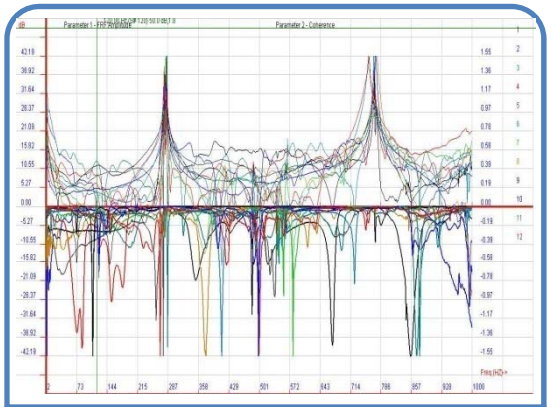
Test Results



Stimulus and response

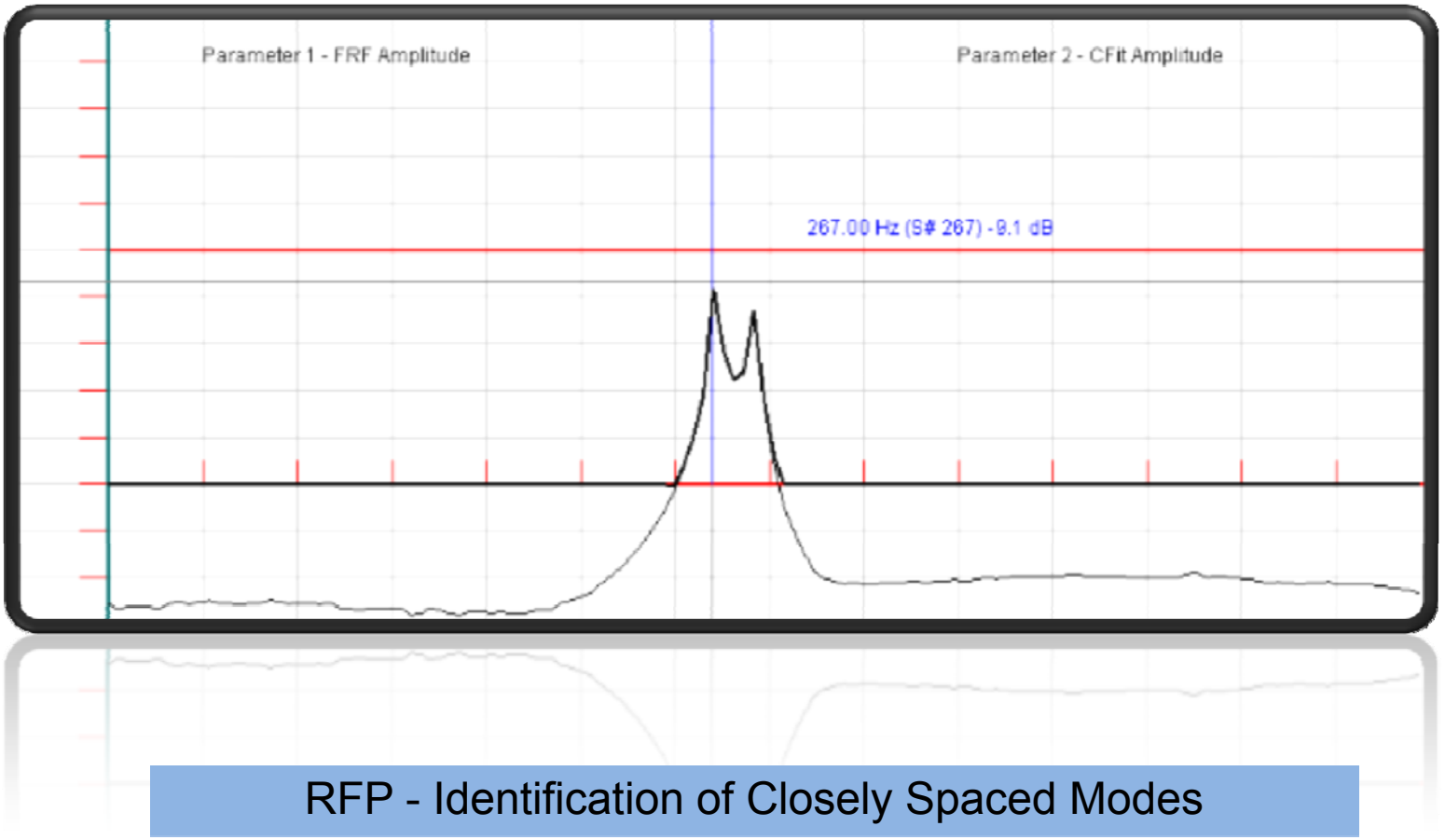


FRF



Coherence

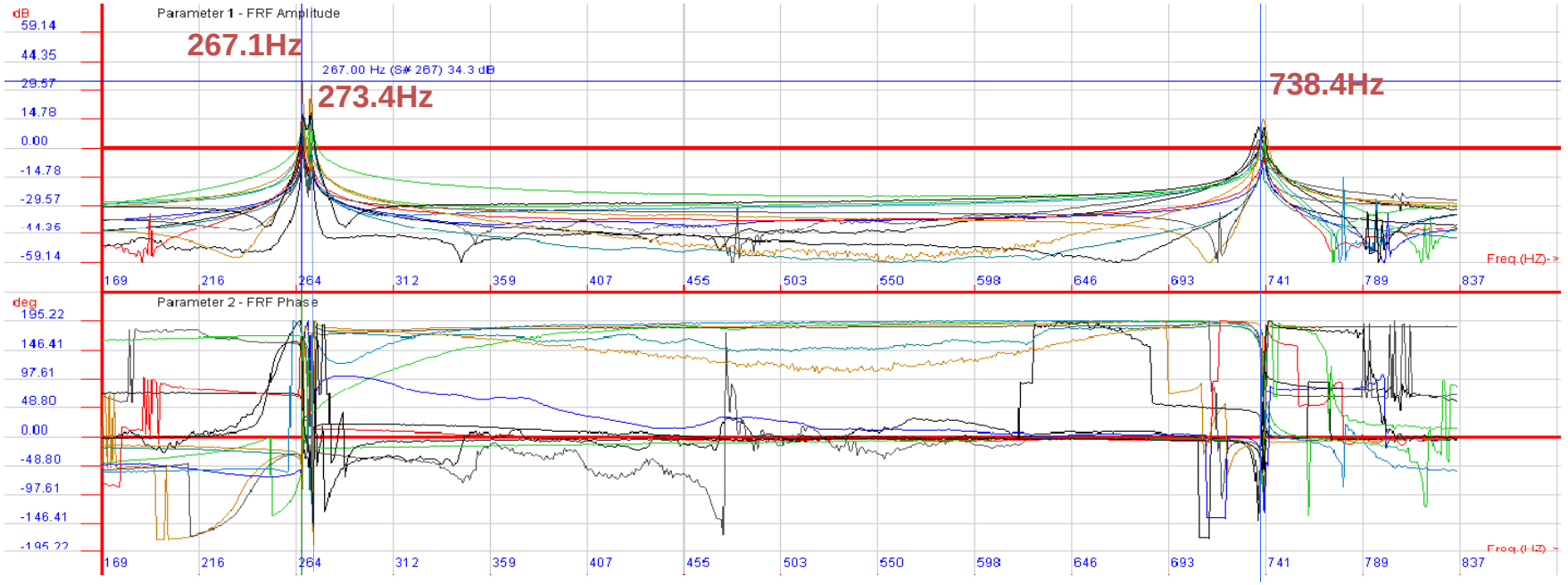
Curve Fitting



RFP - Identification of Closely Spaced Modes

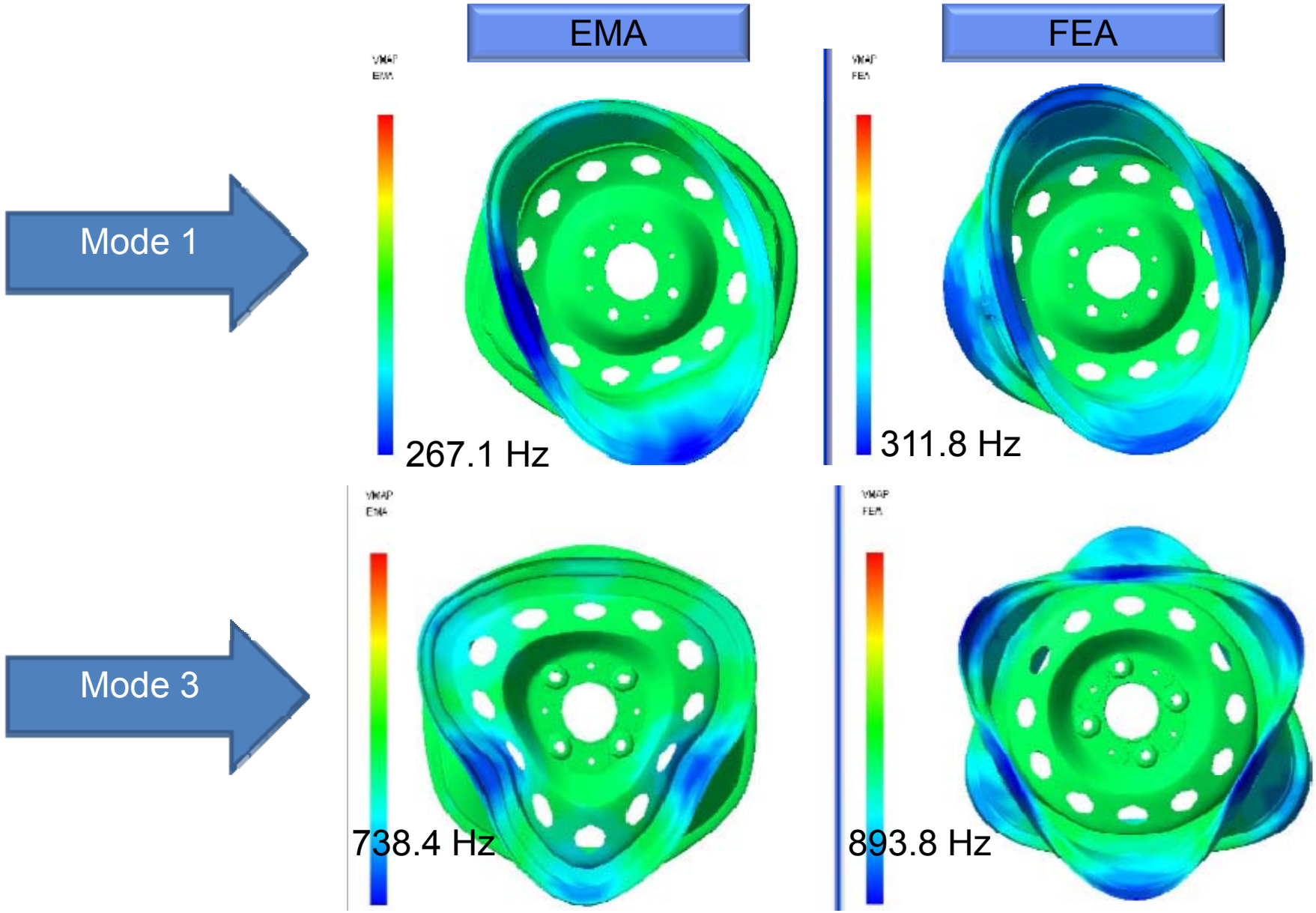
Modal Parameters

	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

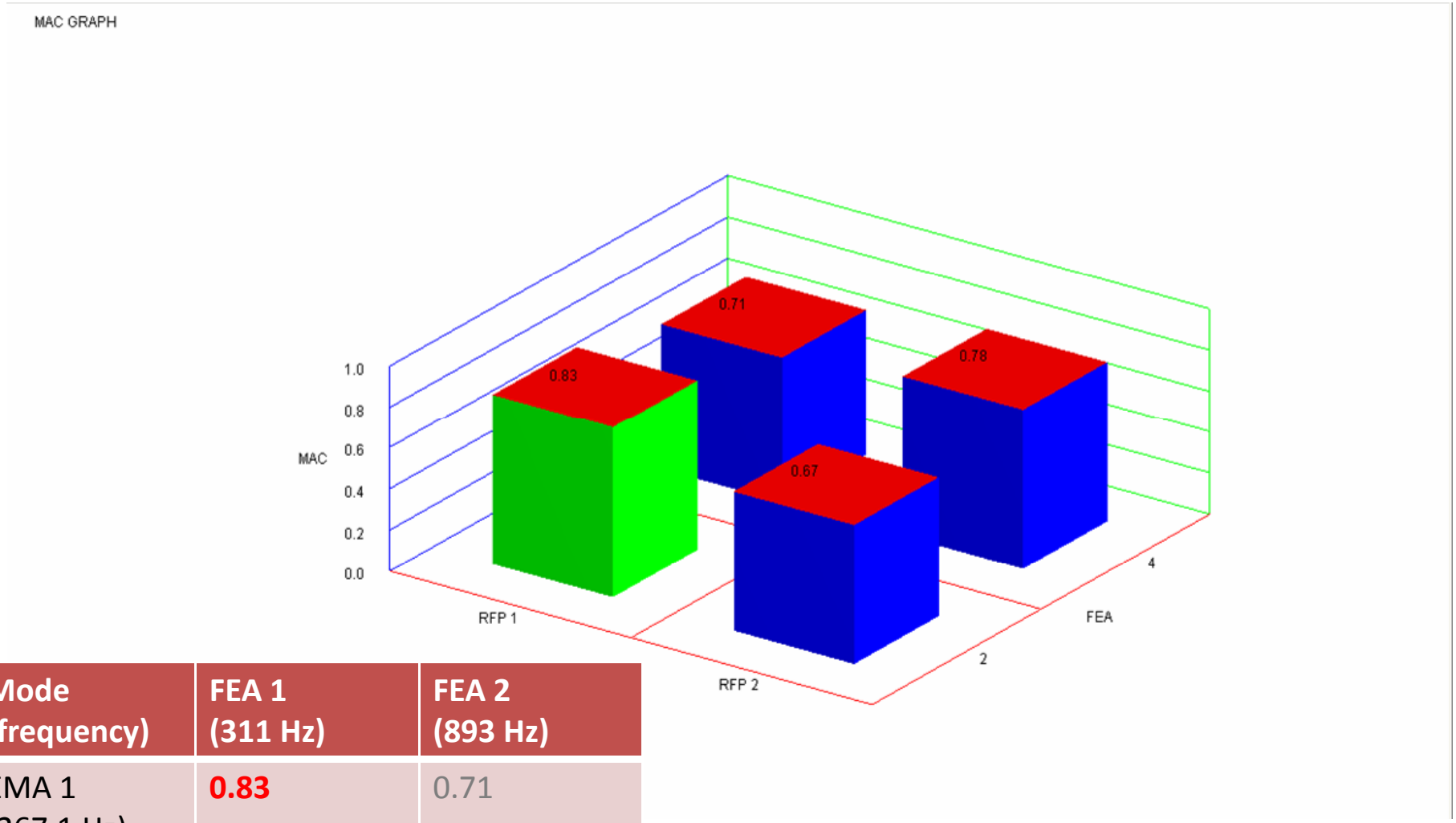


Frequency Response Functions

FEA-Test Correlation



MAC

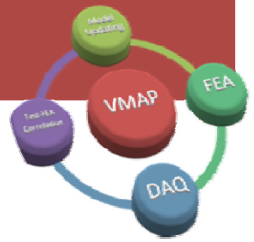


Mode (frequency)	FEA 1 (311 Hz)	FEA 2 (893 Hz)
EMA 1 (267.1 Hz)	**0.83**	0.71
EMA 3 (738.4 Hz)	0.67	**0.78**

Case 2: Gear Box Cover

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

Gear Box Cover



Finite Element Model

Mesh

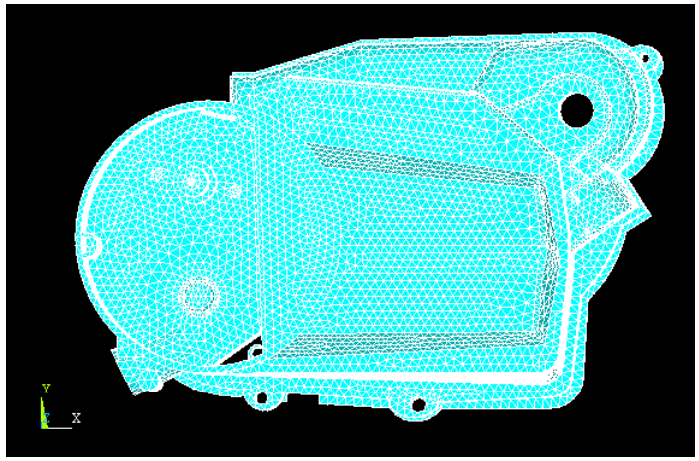
- 10 Node Tetrahedral
- Nodes = 19994
- Elements = 69019

Material

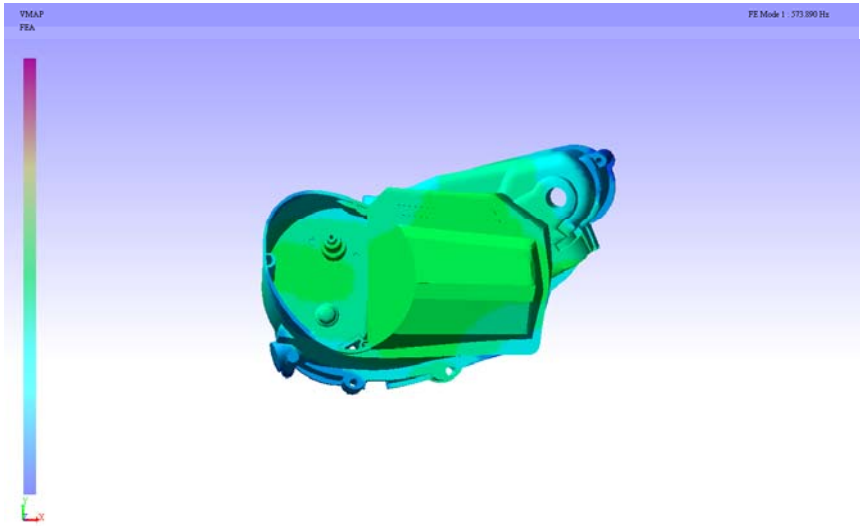
- Aluminum cast alloy
- Density = 4000 Kg/m3
- Young's Modulus = 51e9 N/m2
- Poisson's Ratio = 0.33

Boundary Conditions

- Free - Free

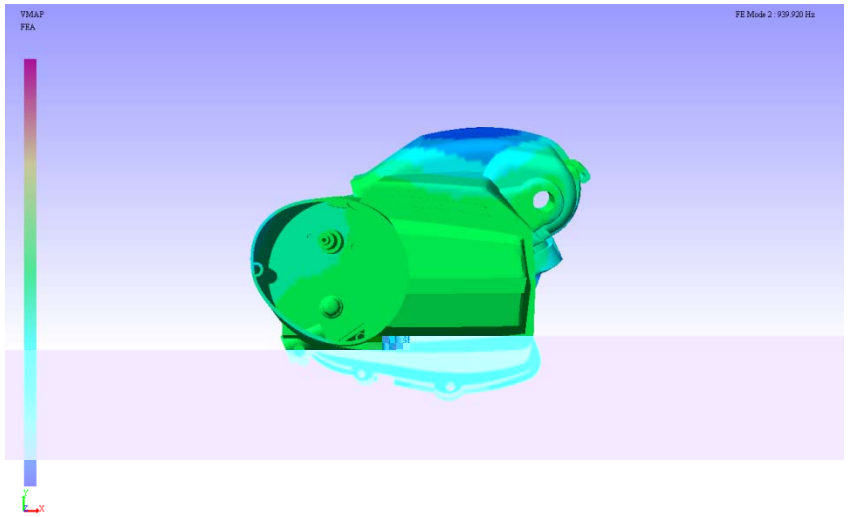


FEA Results



Mode 1 – 573.89 Hz

Animation of Mode 1

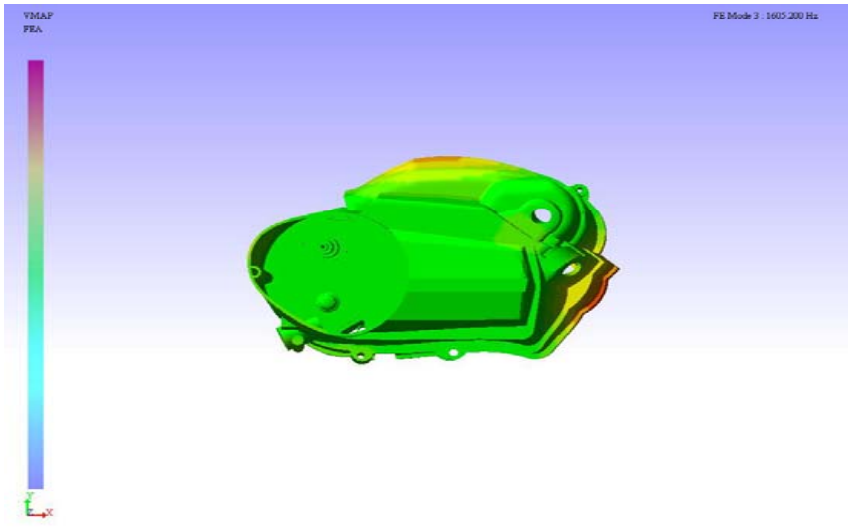


Mode 2 – 939.92 Hz

Animation of Mode 2

FEA Results

Mode 3 – 1605.20 Hz



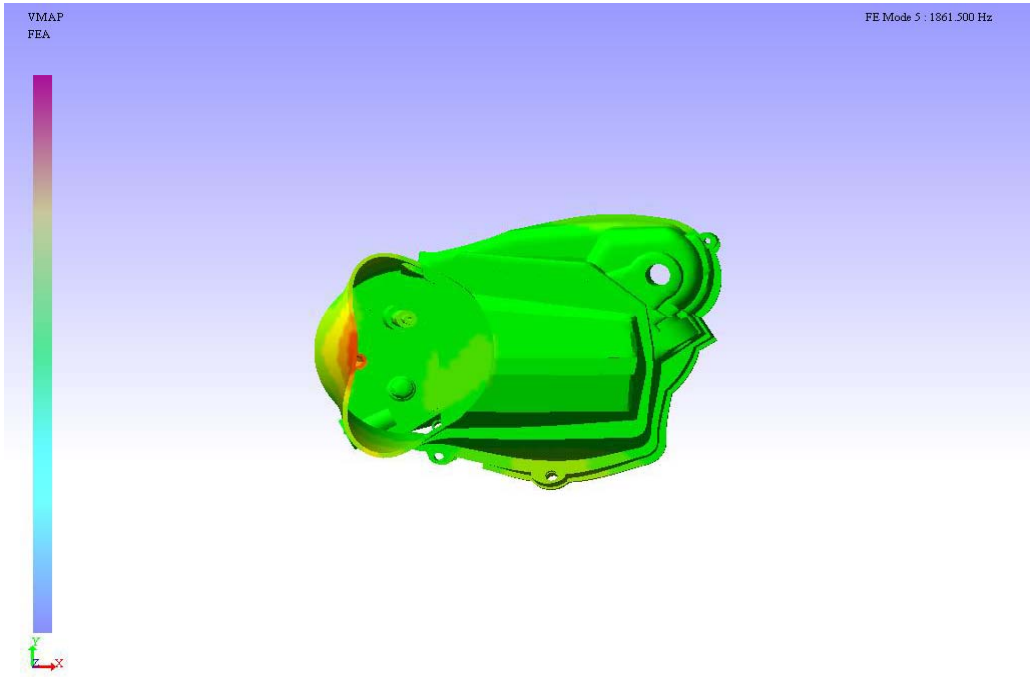
Animation of Mode 3

Mode 4 – 1714.200 Hz

Animation of Mode 4

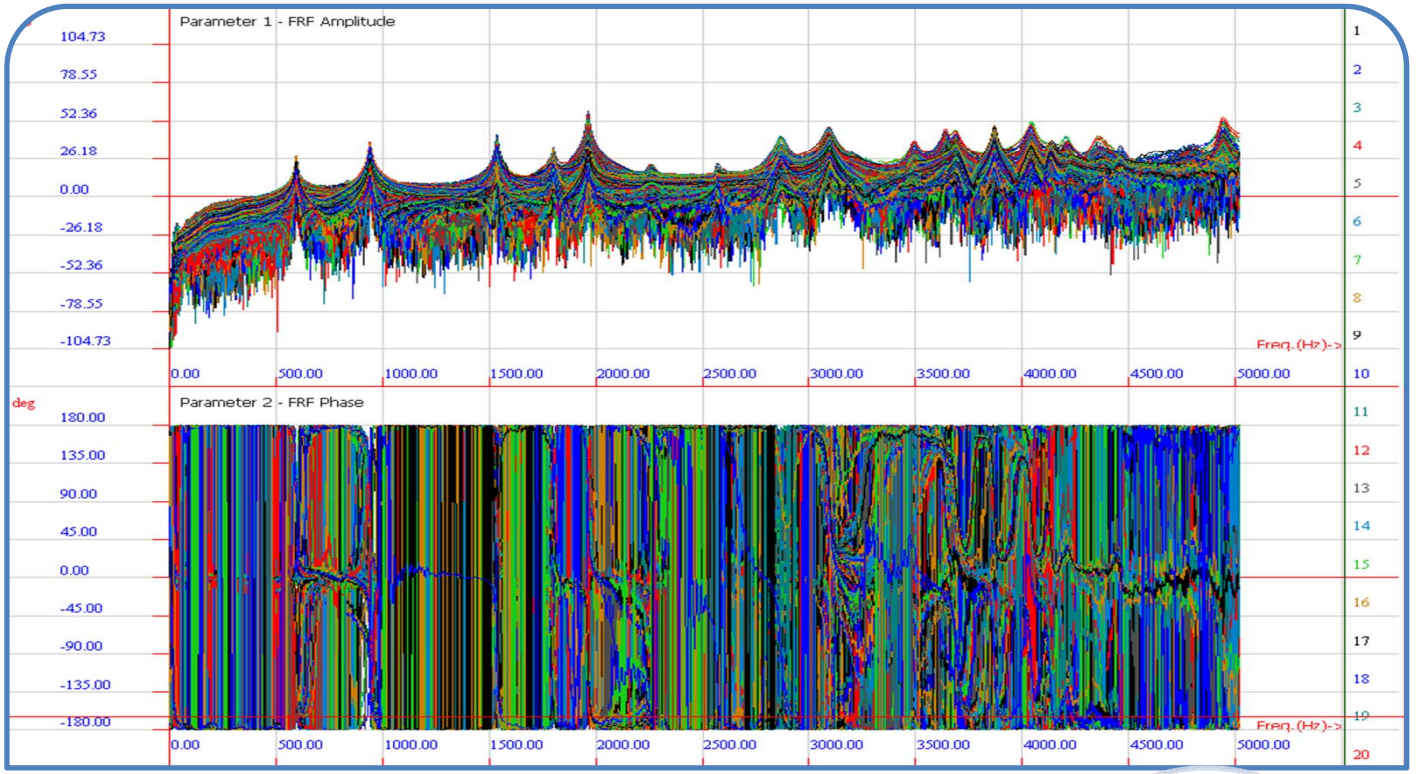
FEA Results

Mode 5 – 1861.50 Hz



Animation of Mode 5

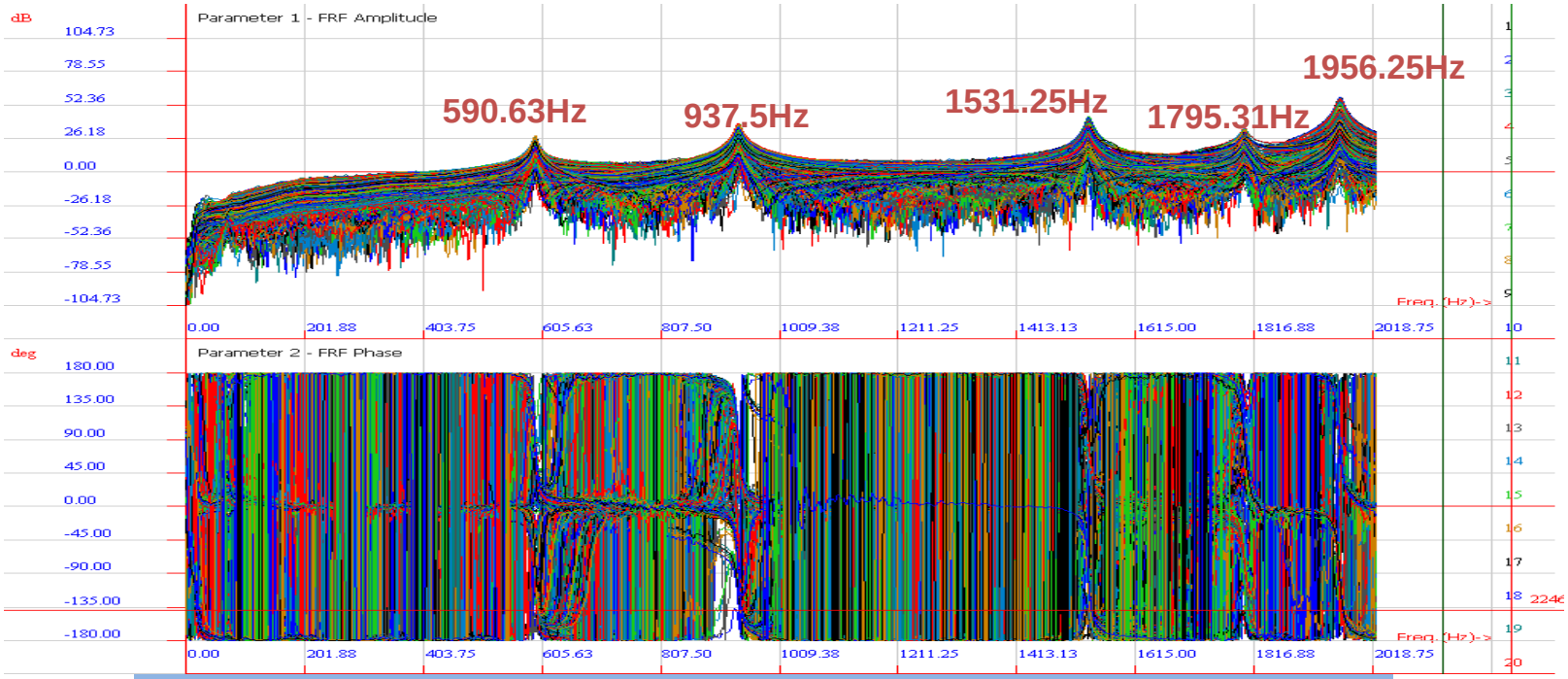
Test Results



FRF and Phase

Modal Parameters

	Rational Fraction Polynomials	
	ω_n (Hz)	Q Factor
Mode 1	590.63	91.45
Mode 2	937.5	105.89
Mode 3	1531.25	183.25
Mode 4	1795.31	167.92
Mode 5	1956.25	193.31



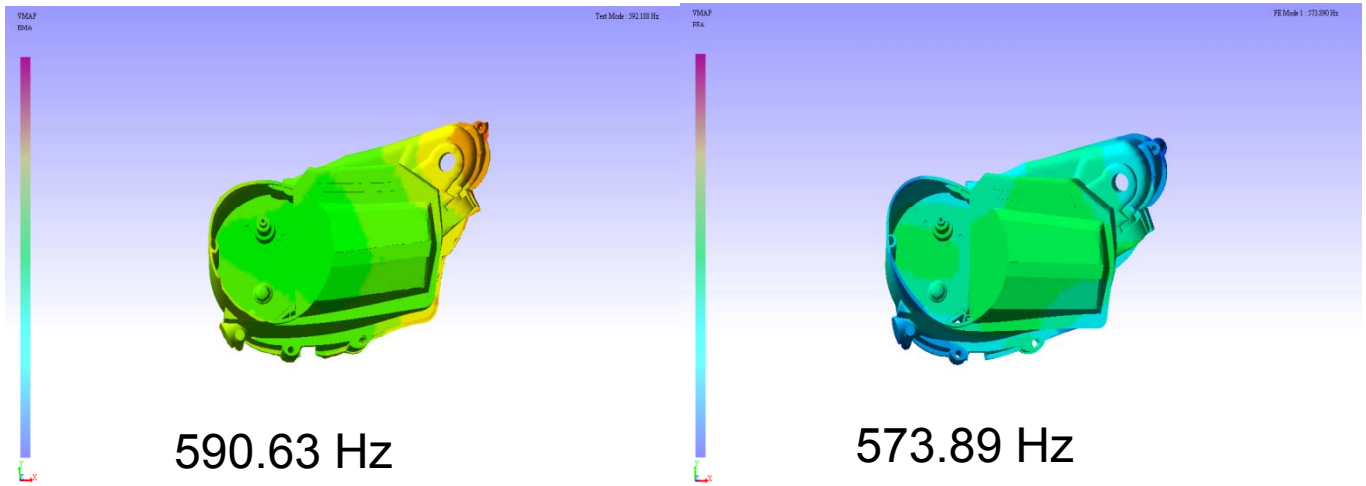
Frequency Response Functions

FEA-Test Correlation

EMA

FEA

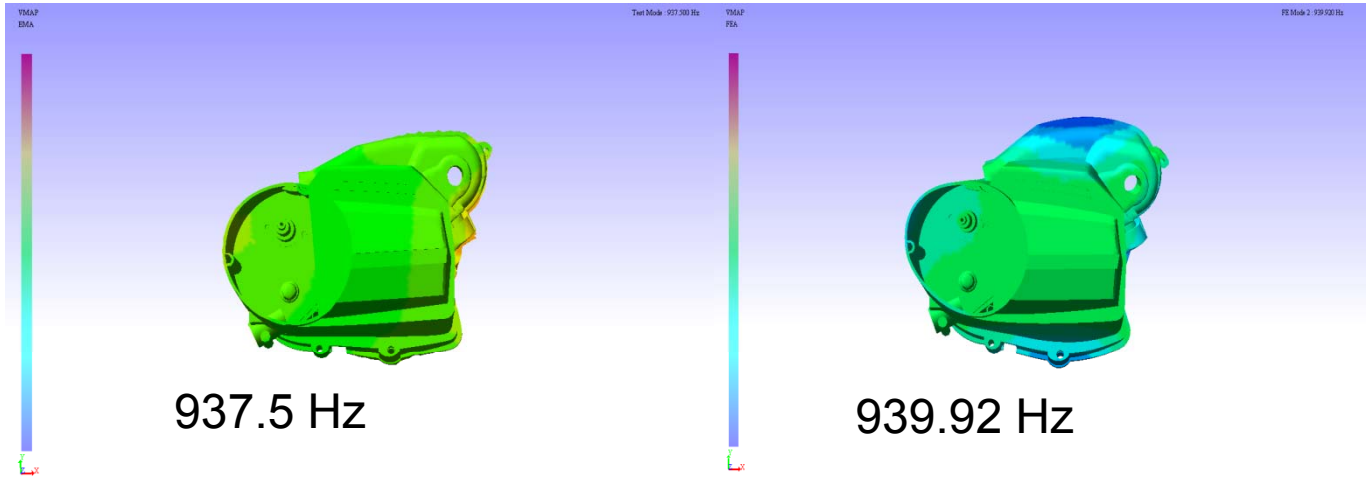
Mode 1



590.63 Hz

573.89 Hz

Mode 2



937.5 Hz

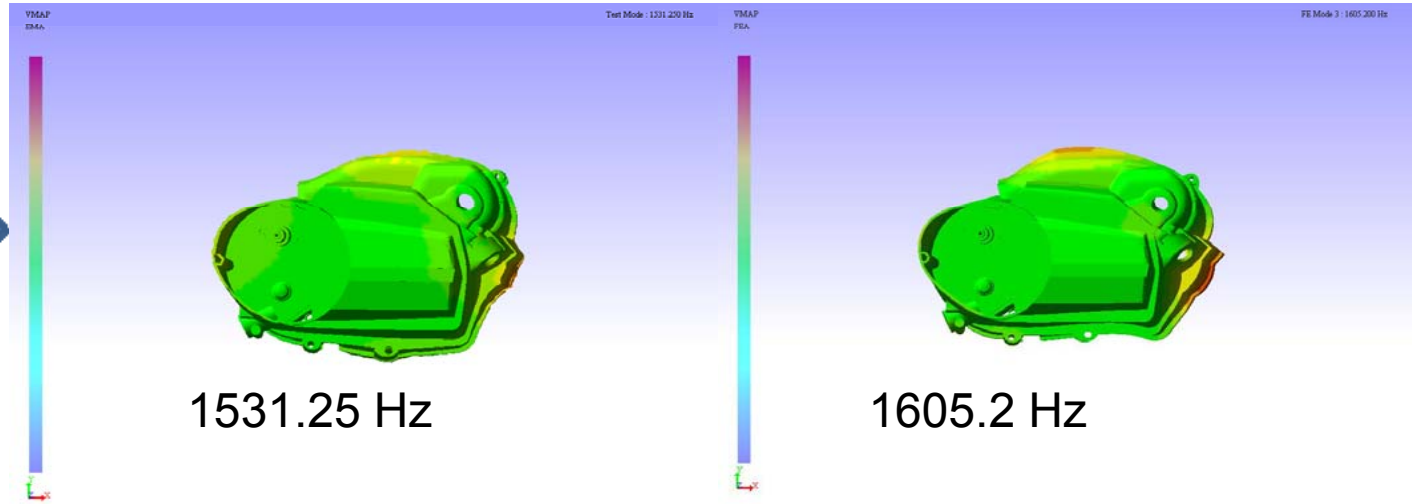
939.92 Hz

FEA-Test Correlation

EMA

FEA

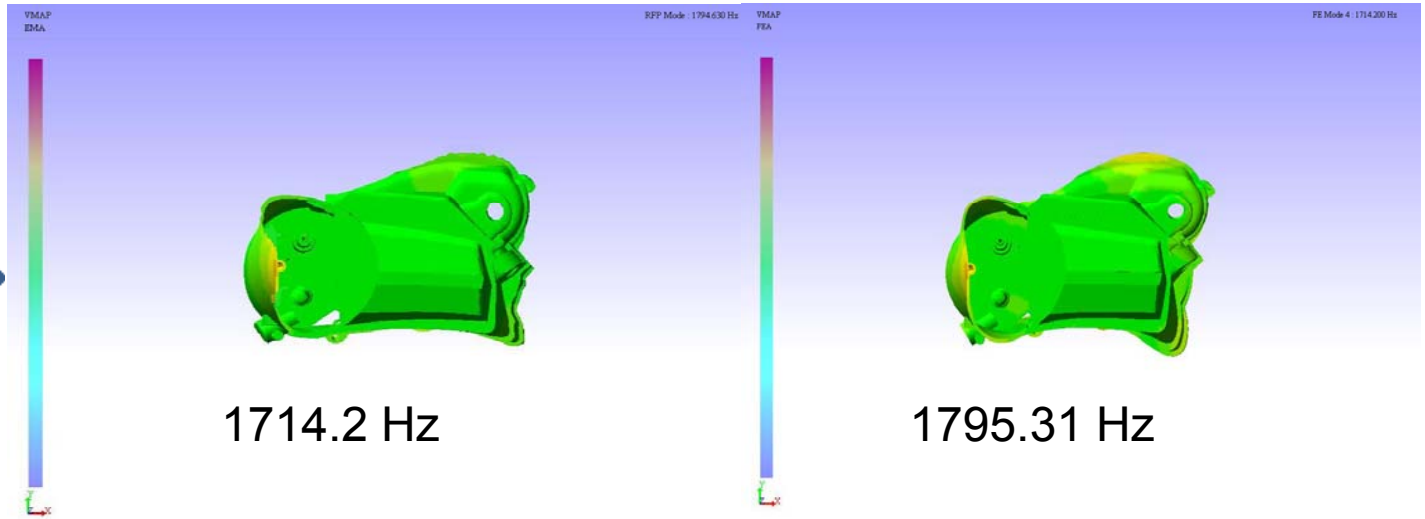
Mode 3



1531.25 Hz

1605.2 Hz

Mode 4



1714.2 Hz

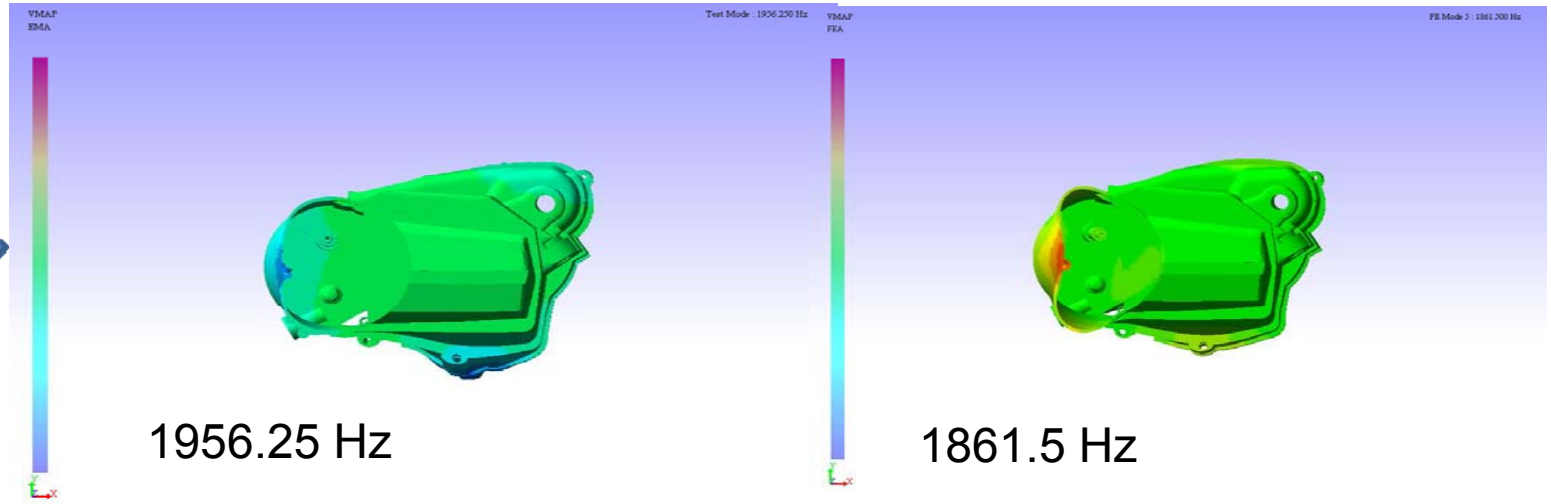
1795.31 Hz

FEA-Test Correlation

EMA

FEA

Mode 5

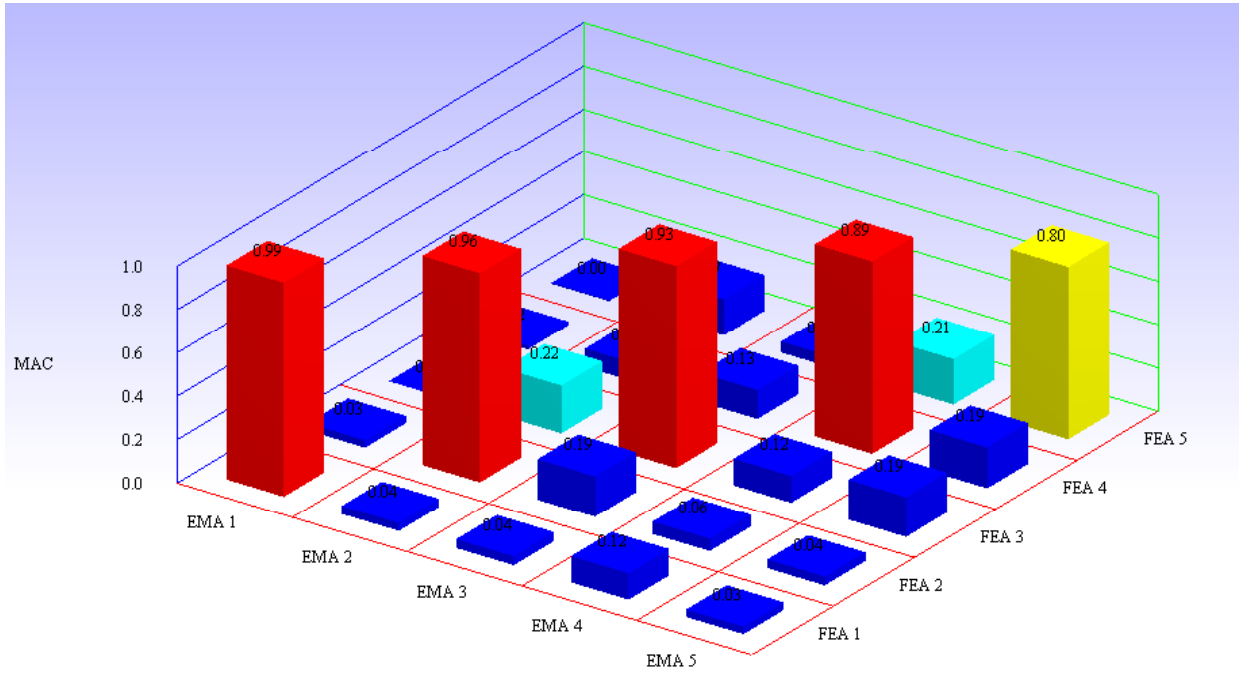


1956.25 Hz

1861.5 Hz

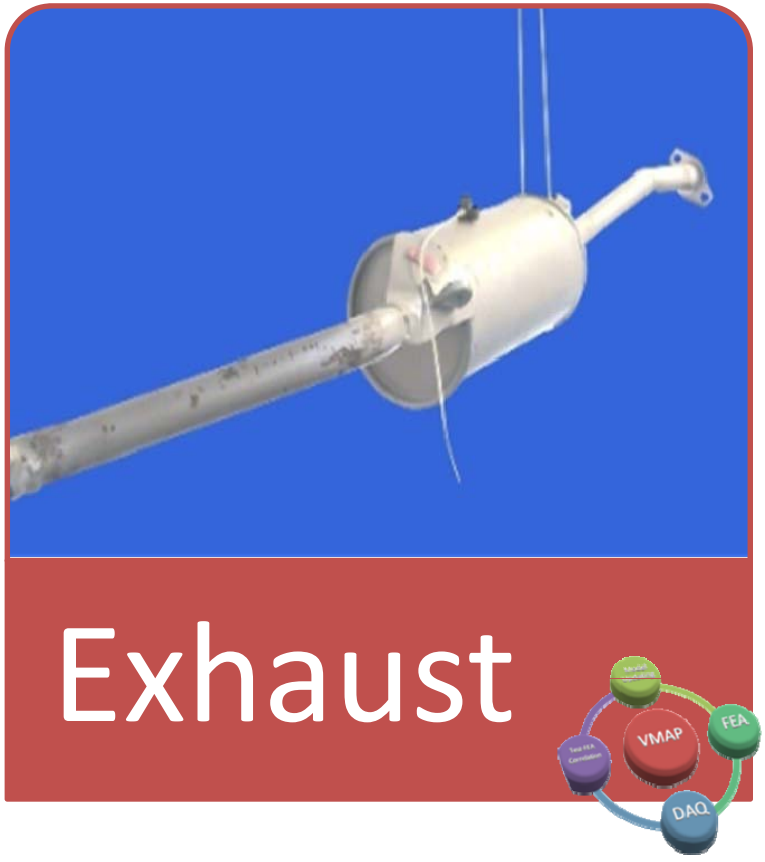
MAC

Mode (frequency)	FEA 1 (573.89 Hz)	FEA 2 (939.92 Hz)	FEA 3 (1605.2 Hz)	FEA 4 (1714.2 Hz)	FEA 5 (1861.5 Hz)
EMA 1 (590.63 Hz)	**0.99**	0.03	0.00	0.01	0.00
EMA 2 (937.5 Hz)	0.04	**0.96**	0.22	0.09	0.17
EMA 3 (1531.25 Hz)	0.04	0.19	**0.93**	0.13	0.05
EMA 4 (1795.31 Hz)	0.12	0.06	0.12	**0.89**	0.21
EMA 5 (1956.25 Hz)	0.03	0.04	0.19	0.19	**0.80**



Case 3: Exhaust System

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



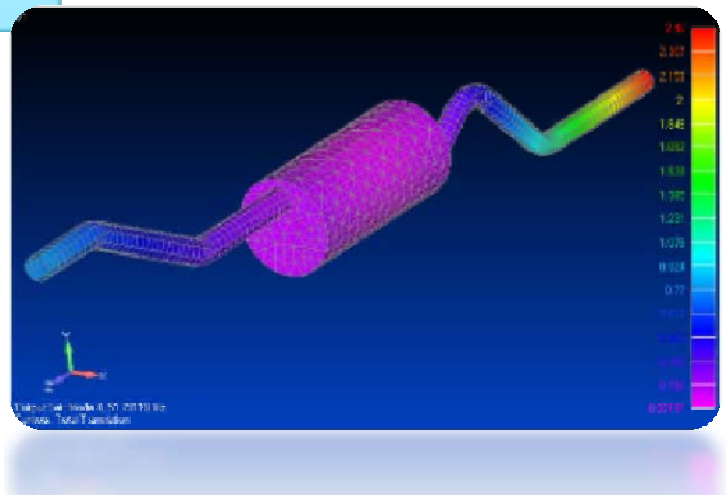
FEA

Mesh → Material → Boundary Conditions

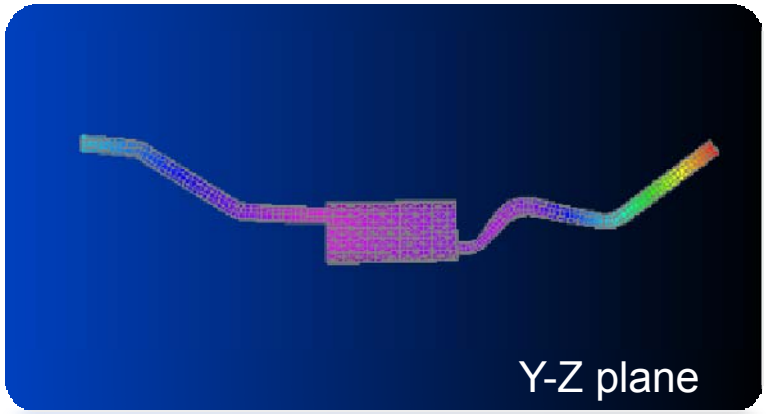
	Type
Engine Manifold	•4 Node, Plate •6 per node
Drum	•10 Node, Solid •3 per node
Exhaust Manifold	•4 Node, Plate •6 per node

	Material
Engine Manifold	E=1.9e11 N/m^2 ρ=8000 Kg/m^3 ν=0.3
Drum	E=2.1e11 N/m^2 ρ=1000 Kg/m^3 ν=0.3
Exhaust Manifold	E=1.9e11 N/m^2 ρ=8000 Kg/m^3 ν=0.3

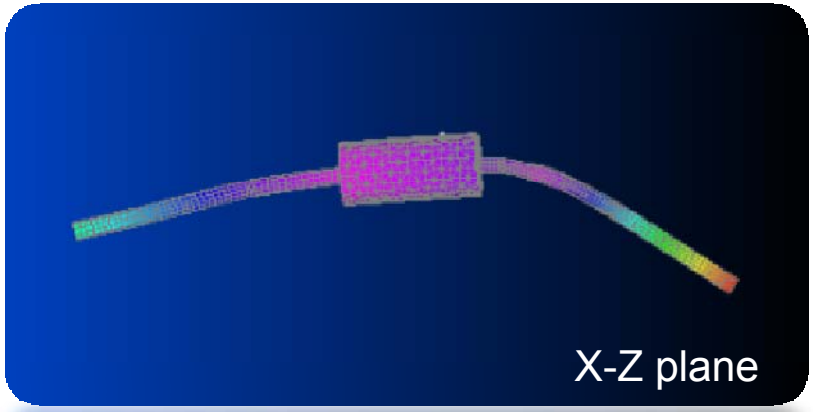
Free - Free



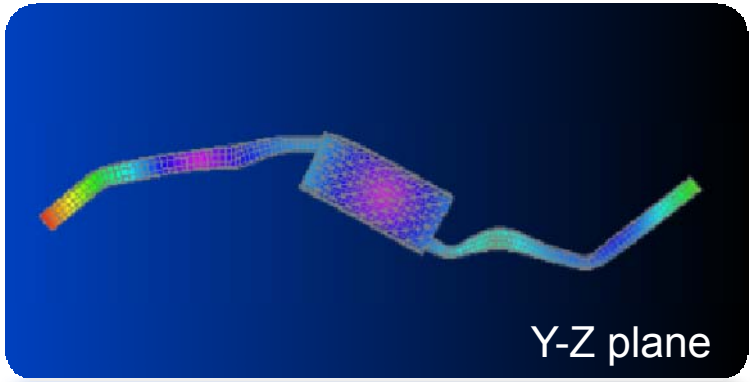
FEA Results



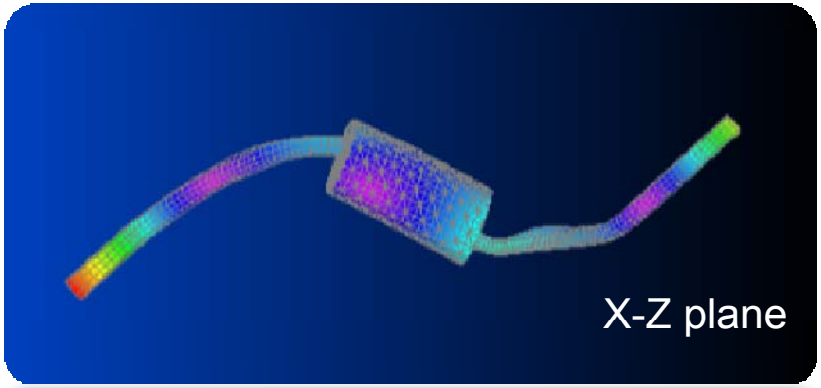
Mode 1 = 58.96 Hz



Mode 2 = 63.18 Hz

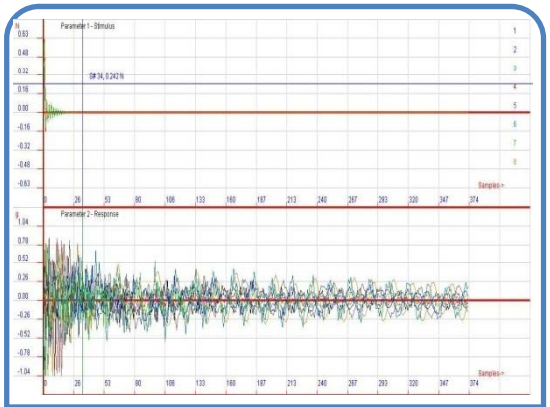


Mode 3 = 142.91 Hz

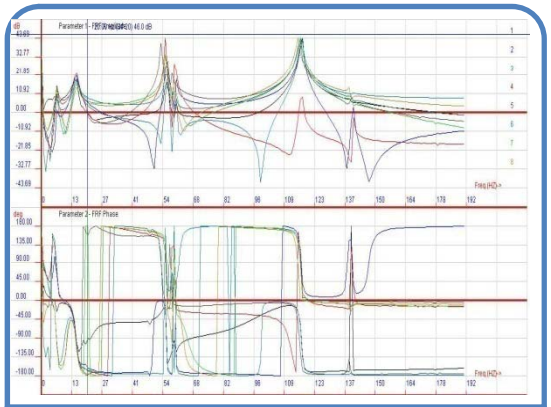


Mode 4 = 162.32 Hz

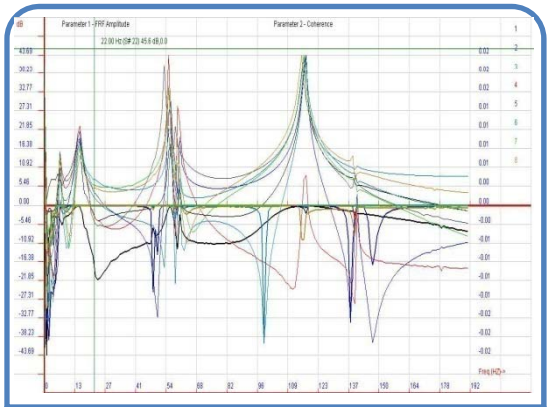
Test Results



Stimulus and response

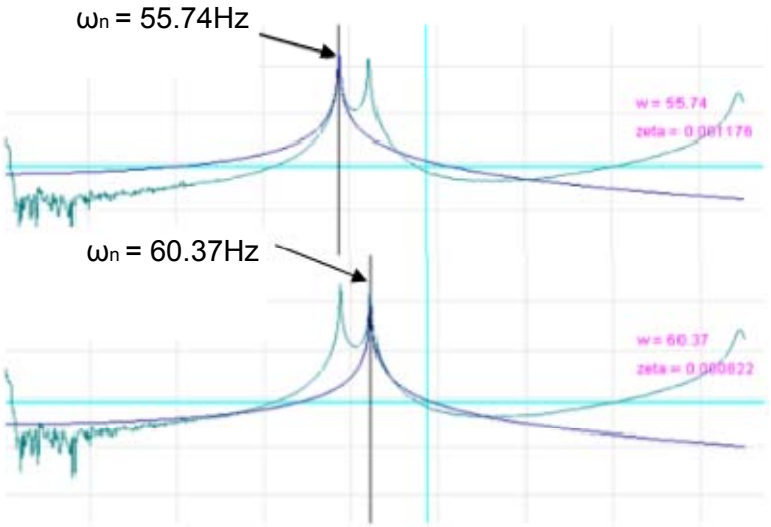


FRF



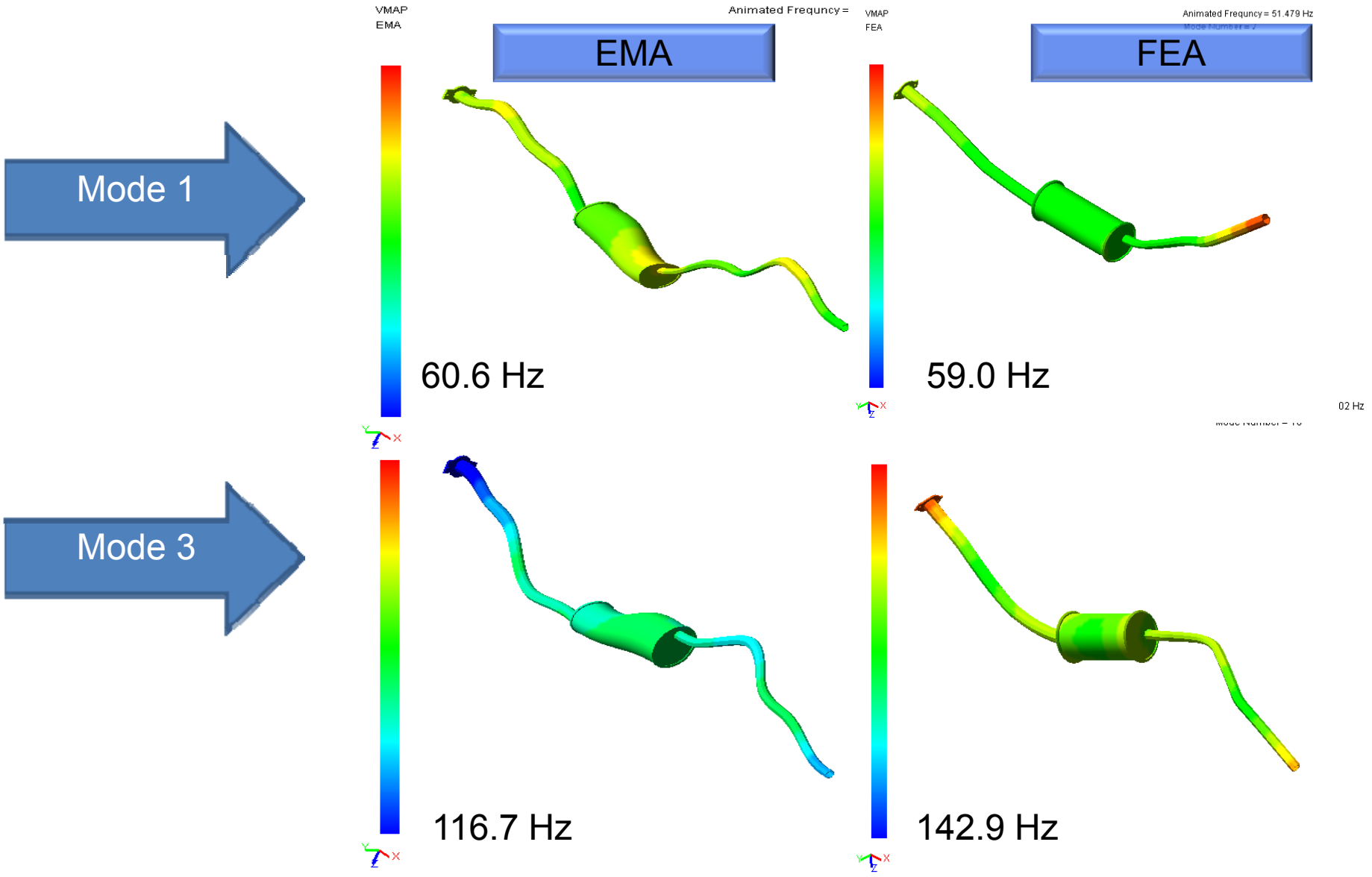
Coherence

Modal Parameters



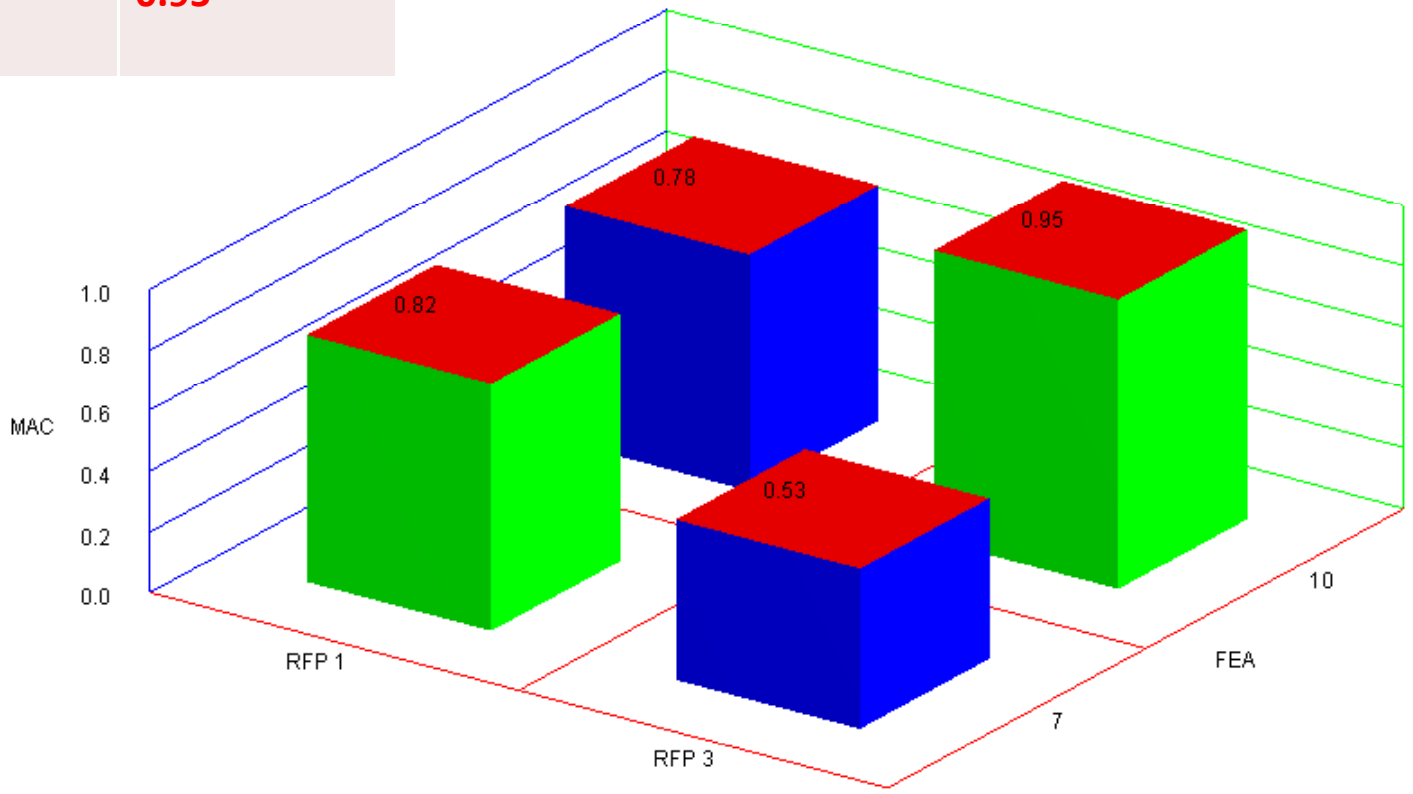
	Circle Fit		RFP	
	ω_n (Hz)	Q Factor	ω_n (Hz)	Q Factor
Mode 2	60.34	608.27	60.61	618.65
Mode 3	116.59	88.21	116.67	86.51

FEA-Test Correlation



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**



Questions

Website: www.nafems.org

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FOR THE ENGINEERING ANALYSIS COMMUNITY

Thank you!