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

- Concept
- Detail Drawing
- Prototype
- Production
- Field Failure

Cost of Change

Engineer

Validate

Troubleshoot
Why identify structural resonance?

**Pains**

- **Field failure**
  - Increasing speed causes:
    - Component breakdown
    - Machine failure
    - Poor precision
    - Inconsistent product quality
    ...

- **Noise & Vibration problem**
  - Steering wheel shake
  - Driver seat vibration
  - Noise at Driver’s & Passenger’s Ears
  ...

- **Product Certification**
  - Structural integrity
  - Ground Vibration Testing
  - Reduce vibration dose value
  - Flutter phenomena
  ...

**What?**

**Durability**

**Performance/Perceived Quality**

**Safety**

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.

\[ \omega_n = \sqrt{\frac{k}{m}} = \text{natural frequency (rad/sec)} \]
Natural Frequency
Resonant Frequency

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

\[ \omega_f = 0.4 \quad \omega_f = 1.01 \quad \omega_f = 1.6 \]

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

\[
\text{FRF} = \frac{\text{output}}{\text{input}}
\]
Frequency Response Functions

- Frequency Response Functions (FRFs) measure the system's output in response to known input signals.

\[
\text{FRF} = \frac{\text{output}}{\text{input}}
\]

![Diagram showing force and response]
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 damped.

\[ Q = \frac{1}{2\zeta} \]

**Half Power (3 dB) Method**
Other Damping Terms

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

where:
- \( \eta \) is loss factor
- \( Q \) is amplification factor
- \( \xi \) is damping ratio
- \( \%Cr \) is percent of critical damping
  \( (\%Cr = 100\% \times \xi) \)
- \( \delta \) is the log decrement of a transient response
- \( D \) is the energy dissipation per cycle
- \( U \) is the stored energy during loading
- \( \phi \) is the phase angle between cyclic stress and strain
DEMONSTRATION: Test.Lab Cursor Calculations

FRF (Acceleration/Force)

<table>
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<tr>
<th>Curve</th>
<th>18.44</th>
<th>27.19</th>
<th>49.69</th>
<th>55.63</th>
<th>58.75</th>
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<tr>
<td>ζ (%)</td>
<td>0.10e-3</td>
<td>0.62e-3</td>
<td>0.09e-3</td>
<td>0.16e-3</td>
<td>0.09e-3</td>
</tr>
<tr>
<td>Hz</td>
<td>23.08</td>
<td>0.93</td>
<td>0.93</td>
<td>1.13</td>
<td>5.72</td>
</tr>
</tbody>
</table>

(m/s)/N
FRFs determine mode shapes

1st Bending Mode
FRFs determine mode shapes

1\textsuperscript{st} Torsional Mode
Experimental Modal Analysis

The process of identifying the *dynamic behavior* of a system (structure) in terms of its *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?
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

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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** is a value from 0 to 1 that shows how much of the output is really due to the input.
Coherence differs from 1 in case of:

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

Impact Testing

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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

Burst Random

Random

Amplitude (g/N)

Frequency (Hz)
Understanding leakage and windows
Joseph did help us a lot ...

Joseph Fourier
(1768 - 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 series

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

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

5 V Sine Wave - 3 Hz  

5 V Sine Wave - 2.5 Hz
Non Periodic Signals – DSP Errors (Leakage)

- Smaller amplitude
- Smearing of spectral content
Periodic Signals

$T = N \Delta t$

Are these signals the same?

YES!
Non-Periodic Signals

Are these signals the same?

NO!

\[ T = N \Delta t \]
Finite Observation – Side Effect

No Leakage

Leakage
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

Rectangular, uniform

Hanning

Flat top

Time domain

Freq. domain

AKA No Window

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### Window Types – Specific Characteristics

<table>
<thead>
<tr>
<th>Window type</th>
<th>Highest side lobe (dB)</th>
<th>Sidelobe falloff (dB/decade)</th>
<th>Noise Bandwidth (bins)</th>
<th>Max. Amp error (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>-13</td>
<td>-20</td>
<td>1.00</td>
<td>3.9</td>
</tr>
<tr>
<td>Hanning</td>
<td>-32</td>
<td>-60</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Hamming</td>
<td>-43</td>
<td>-20</td>
<td>1.36</td>
<td>1.8</td>
</tr>
<tr>
<td>Kaiser-Bessel</td>
<td>-69</td>
<td>-20</td>
<td>1.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Blackman</td>
<td>-92</td>
<td>-20</td>
<td>2.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Flattop</td>
<td>-93</td>
<td>0</td>
<td>3.43</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

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: $1.5 \Delta f$
Up to 15% amplitude

Flattop: $3.4 \Delta f$
Up to 0.02% amplitude
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

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?

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

Free-Free Boundary Condition
• 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
Boundary Conditions

Some Practical Examples – Simulating Free-Free

Elastic cords

Pneumatic suspension
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 is when the excitation point equals the response point.

Anti-resonances occur between every resonance.

Phase is combination of SDOF systems with phase information pointing in the 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

Excitation Degrees of Freedom (DOF)

Response DOF

Natural Modes of vibration

Driving point FRFs
DEMONSTRATION: Modal Impact Test

LMS Test.Lab

Impact Testing

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Calculation of mode shape

MODE 1

1st Bending Mode
Calculation of mode shape

1st Torsional Mode
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 (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

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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)
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.

Large influence from surrounding modes.

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Modal Parameter Estimation

Goal of modal parameter estimation

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

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

Solutions
- Stabilization diagram
- Mode indicator functions
Modal Parameter Estimation – Assuming 1 Mode

\[ f_1 = 50 \text{ Hz} \]

\[ d_1 = 20 \% \]
Modal Parameter Estimation – Assuming 2 Modes

- $f_1 = 25 \text{ Hz}$
- $d_1 = 10\%$
- $f_2 = 75 \text{ Hz}$
- $d_2 = 10\%$
Modal Parameter Estimation – Assuming 3 Modes

- $f_1 = 25$ Hz
- $f_2 = 50$ Hz
- $f_3 = 75$ Hz
- $d_1 = 5\%$
- $d_2 = 5\%$
- $d_3 = 5\%$
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

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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

Double “dip” indicates two modes at same frequency
Polymax MDOF Curve Fitting
## LSCE versus LMS PolyMAX

<table>
<thead>
<tr>
<th>LSCE</th>
<th>LMS PolyMAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>-For smaller models</td>
<td>+Large number of responses</td>
</tr>
<tr>
<td>-High computational load</td>
<td>+Fast, efficient computation</td>
</tr>
<tr>
<td>-High damping is a problem</td>
<td>+High damping no problem</td>
</tr>
<tr>
<td>-High modal density</td>
<td>+High modal density</td>
</tr>
<tr>
<td>-Not for broadband analysis</td>
<td>+Broadband analysis</td>
</tr>
<tr>
<td>-Unclear stabilization diagram</td>
<td>+Crystal-clear stabilization diagram</td>
</tr>
</tbody>
</table>

Not all MDOF curve fitters are created equal!
DEMONSTRATION: PolyMAX Modal Analysis
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
PolyMAX Validation
“Noisy” FRFs

LMS PolyMAX
PolyMAX Validation
FRF Synthesis with PolyMAX

Left wing

Back of the plane
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

LMS Test.Lab

Modal Analysis

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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
What is MAC abbreviation for?

Modal Assurance Criterion
IS THIS A “GOOD” MAC?
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

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
Importance of Correlation

Evaluate Design

Finite Element Simulation

Vibration

Loads

Durability

Design Refinement

Acoustics
“Old” Product Design Cycle

Product Design Process

Initiate Concept → Build Hardware → Validate Design → Build Hardware → Validate Design → Build Hardware

Validate Design → Release Design

Functional Activities

CAD Modeling → Prototype → Test → Prototype → Test → Prototype → Test → Production
“Modern” Product Design Process Goal

Product Design Process

Evaluate Design

Build Hardware

Validate Design

Release Design

Initiate Concept

CAD Modeling

Finite Element Simulation

Prototype

Test

Production

TIME

Functional Activities

- Simulate product performance before prototypes are available
- Use single prototype & testing for validation
Pretest & Correlation: Process Improvement

Product 1
- Initiate Concept
- Evaluate Design
- Build Hardware
- Validate Design
- Release Design

Product 2
- Initiate Concept
- Evaluate Design
- Build Hardware
- Validate Design
- Release Design

TIME

Correlation

Pretest Analysis

FE Modeling

Process Improvement

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Virtual.Lab Pretest & Correlation: Motivation

**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
PreTest

How many points?
6 or more?
Correlation

Viewing mode shapes side-by-side?
Correlation

MAC
But is there something else…?
Why the frequency difference?

All test modes higher frequency than FE
Need to raise frequency of FE modes
What to change…?
Application Case: Exhaust System
Exhaust Mode at 15 Hz
Exhaust Mode at 15 Hz
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

**Step 1:** 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

**Step 2:** 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

Step 3: 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.
Application Case: Pretest Analysis

**Step 4:** 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

**Step 5:** 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

Step 1: 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

**Step 2:** 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

**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%)
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**
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)
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

**Sensitivity:** Ranks the contribution of various parameters of the FE model to its modal behavior.

**Updating:** Changing the FE model to improve its 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
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
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.)
Virtual.Lab Pretest & Correlation: Conclusions

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