Introduction to Modal Testing
Introduction to Modal Testing 1

Structural Dynamic Testing
- Term differentiating it from Static Analysis and Testing
- In contemporary language it is Modal Analysis and Modal Testing

Objectives
- What is Modal Testing
- Why do Modal Testing
- How to do Modal Testing
- Brüel & Kjær Solution to Modal Testing
Present day demands
- Increasing speed in transportation
- Higher fuel economy
- Both demands achieved by reducing the mass of structures

Consequences
- Structures become inherently weak
- Resonances move down into frequency regions of excitation forces
- Structures fail because of dynamic loads
- Statics studied for over a century
Modal Testing

What

Why

How

Brüel & Kjær Solution
Definition of Modal Testing

To construct a mathematical model of the vibrational properties and behaviour of a structure by experimental means

Natural Frequency
Modal Damping
Residues
Modal Parameters

<table>
<thead>
<tr>
<th>Theoretician</th>
<th>Experimentalist</th>
</tr>
</thead>
<tbody>
<tr>
<td>● Eigenvalue</td>
<td>● Natural Frequency</td>
</tr>
<tr>
<td>● Percent Damping</td>
<td>● Loss Factor</td>
</tr>
<tr>
<td>● Eigenvector</td>
<td>● Mode Shape</td>
</tr>
</tbody>
</table>

**Frequency**

- **First Mode**
- **Second Mode**
- **Third Mode**

**Distance**

**Amplitude**

**Frequency**

**Modal Domain View**

**Beam**

**Force**
Modal Testing

What

Why

How

Brüel & Kjær Solution
Trouble Shooting

Frequency Response Function

Vibration response during operation

High responses
SDM and FRS (Assumes validated Modal Model)

What if … scenarios

Structural Dynamics Modification

- Mass
- Stiffness
- Tuned absorber
- Move resonance frequency

Forced Response Simulation

- How will a structure behave when one or more forces are applied?
Why do Modal Testing

- **Trouble shooting**
  - To reduce excessive vibration levels

- **FE-modelling**
  - To ensure resonances are away from excitation frequency
  - Validation by testing on prototypes
  - Refinement of the mathematical model through inclusion of damping
  - Prerequisite in aircraft industry
  - Today also commonly used in automotive industry

- **Structural assembly analysis**
  - To predict the dynamic behaviour of assembled sub-components

- **Simulation of “what if” scenarios**
  - Determination of forces
  - Response to complex excitation
Modal Testing

What

Why

How

Brüel & Kjær Solution
How to do Modal Testing

Modeling
- Geometry
- Degree of Freedom definition
- X or XYZ direction

Measurements
- Frequency Response Functions
- Hammer or shaker excitation
- Coherence Function for validation

Curve fitting
- Frequency
- Damping
- Residues

Validation
- MAC (Modal Assurance Criteria)
- Modal Confidence Factor
- Phase Scatter
- ........
Signal Analysis

Determination of the response of a vibration system due to unknown excitation

- Signal Analysis is performed on basis of Time History Recording
- To extract more information Frequency analysis is often used
- Discrete components in the Frequency Spectrum relate to physical phenomena in the device under test
System Analysis

Determination of the inherent properties of the system

- Excitation of the system by a known force
- Measurement of the Output
- Relating the Output to the Input

Frequency Response Function:

\[ H(\omega) = \frac{\text{Output}}{\text{Input}} = \frac{\text{Motion}}{\text{Force}} = \frac{\text{Response}}{\text{Excitation}} \]

- The FRF shows the inherent properties of a dynamic system — independent of the excitation force and type
Frequency Response Function

\[ H(\omega) = \frac{\text{Output}}{\text{Input}} = \frac{\text{Motion}}{\text{Force}} = \frac{\text{Response}}{\text{Excitation}} \]
Modal Model – *Global Parameters*

Natural Frequency and Modal Damping

**Frequency Domain**

3 dB bandwidth  
\[ \omega_0 = 2 \pi f_0 \]

**Time Domain**

Decay Rate  
\[ \sigma = \frac{1}{\tau} \]

Natural Frequency:

- Frequency Domain: \( \omega_0 = 2\pi f_0 \)
- Time Domain: \( f_0 = \frac{1}{T} \)

Damping Ratio:

- Frequency Domain: \( \zeta = \frac{\sigma}{\omega_0} \)
- Time Domain: \( \zeta = \frac{\sigma}{\omega_0} \)
Modal Model – *Local Parameters*

**Residues**

Residue: The “strength” of the mode

- **Residue:** \( R = H(\omega_0) \cdot \sigma \)
- **Driving point Residue:** \( R_{iir} = a \cdot \psi_{ir}^2 \)
- **General Residue:** \( R_{ijr} = a \cdot \psi_{ir} \cdot \psi_{jr} \)

The Driving point Residue scales the Mode Shape
Excitation Technique

**Hammer excitation**

- Excitation moved
- Small homogenous structures
- Quick Polyreference technique
- Fast method - no fixtures required

\[
[H] = \begin{bmatrix}
H_{11} & H_{12} & \cdots & H_{1n} \\
\vdots & \vdots & \ddots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
\end{bmatrix}
\]

**Shaker excitation**

- Multichannel response or response points may be moved
- Large or complex structures
- Various excitation signals possible
- Time consuming - installation work to be done

\[
[H] = \begin{bmatrix}
H_{11} & \cdots & \cdots & \cdots \\
H_{21} & \cdots & \cdots & \cdots \\
\vdots & \vdots & \ddots & \vdots \\
H_{n1} & \cdots & \cdots & \cdots \\
\end{bmatrix}
\]
Curve Fitting

Single Degree of Freedom (SDOF)
- Simple structure
- Few and widely spaced modes

Multi Degree of Freedom (MDOF)
- Multiple modes
- Many and close modes

Local
- Based upon one single DOF

Global
- Based upon multiple DOF’s

Polyreference
- Symmetric structures exhibit multiple modes at the same frequency
- One single peak does not necessarily mean one mode
How to do Modal Testing

Modeling
- Geometry
- Degree of Freedom definition
- X or XYZ direction

Measurements
- Frequency Response Functions
- Hammer or shaker excitation

Curve fitting
- Frequency
- Damping
- Residues

Validation
- MAC (Modal Assurance Criteria)
- Modal Confidence Factor
- Phase Scatter
- ........
Modal Testing

What

Why

How

Brüel & Kjær Solution
The Brüel & Kjær Solution

Vibration Data → Modal Test Consultant → Modal Software

File Transfer

PULSE inside
Brüel & Kjær Solution

PULSE Software

Predefined projects
- for typical hammer, shaker tests

Contains predefined measurement setup
- trigger conditions, weighting functions, multi-buffer

Easy data display using workbook layouts
- Time, Autospectra, FRF H1, H2, H3, Coherence
- FRF Display of Magnitude and Phase, Real and Imaginary, Nyquist plot
Features and Benefits

- Geometry driven measurement
  - with the option of importing geometry from CAD data
- Intuitive graphic control of analyzer parameters
- Cuts your setup and measurement time in half
- Modal data acquisition your way
  - comprehensive choice of Modal Post-processing packages
PULSE Modal Test Consultant

The Modal Test Consultant based on PULSE gives the user:

- Openness
- Scalability
- Modularity
- Productivity
- Ease of use

OLE Automation

Brüel & Kjær PULSE™
PULSE Modal Test Consultant

Setting up measurements

- Transducer mounting guided by geometry model on screen
- Graphic supported set-up of measurement parameters
- Audio and visual notification of measurement status
- Automatic DOF labeling
  - label while measuring
Easy Scaling and Set-up of Hammer Excitation

- Hit the test object in a number of different places and ..... ① Autorange or select Input Range ② Select Trigger Level

- Hit the test object once and ..... ③ Choose Time Weighting ④ Set Pre-trigger

Hit the test object in a number of different places and ..... ① Autorange or select Input Range ② Select Trigger Level

Hit the test object once and ..... ③ Choose Time Weighting ④ Set Pre-trigger
Create Test Model from geometry

Geometry creation

- Import geometry via DXF and UFF file format
- Easy-to-use geometry drawing tools

Test Model

- Assign DOFs to geometry

Export

- Geometry model
- DOF information
PULSE Modal Test Consultant

Measurements are guided by a geometrical model
PULSE Test Consultant for Modal

Set up of signal parameters using tables*

* The tables can be customized to suit individual needs

<table>
<thead>
<tr>
<th>Transducer family</th>
<th>Transducer type</th>
<th>Input type</th>
<th>Input sensitivity</th>
<th>Input gain adjust</th>
<th>Max peak input</th>
<th>Lowpass filter</th>
<th>Highpass filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>8202+2646</td>
<td>CCLD</td>
<td>1</td>
<td>1</td>
<td>100mV</td>
<td>On</td>
<td>0.09 Hz</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>4504x</td>
<td>CCLD</td>
<td>1</td>
<td>1</td>
<td>10 V</td>
<td>On</td>
<td>0.09 Hz</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>4504y</td>
<td>CCLD</td>
<td>1</td>
<td>1</td>
<td>10 V</td>
<td>On</td>
<td>0.09 Hz</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>4504z</td>
<td>CCLD</td>
<td>1</td>
<td>1</td>
<td>10 V</td>
<td>On</td>
<td>0.09 Hz</td>
</tr>
</tbody>
</table>
PULSE Test Consultant for Modal

Set up Measurement conditions

Auto-ranging signals
- using graphic support

Trigger conditions
- Trigger level (impact test)
- Pre-trigger

Time weighting
- Transient
- Exponential
- Hanning, ...

Automated Transducer Calibration
Data transfer to modal software

Data transfer of
- geometry model and DOF information
- measurement data

Via file transfer
- Universal File ASCII
- Universal File Binary
- Star Binary
- SDF

Via OLE automation
- Automatic transfer to ME´scope
PULSE Modal Test Consultant

- Automatic Data Transfer to modal software
PULSE Modal Test Consultant

The Modal Test Consultant link PULSE to major modal analysis post processing tools

- Reuse of existing software
- Post-processing of modal data as an integral part of Modal Testing
Geometry driven reliable Modal Testing results

- Create test model from geometry
- Set up measurement conditions
- Perform measurements
- Transfer data to modal software
PULSE Bridge to ME’scope

Brüel & Kjær PULSE™

ME’scope™
Automatic Measurement Data Transfer

PULSE
Project for Modal Test using a Hammer

ME'scopeMODAL™

Load PULSE Project

Export to MEScope
Modal Software

Available through Brüel & Kjær:

STAR (Spectral Dynamics)
- The STAR System™ Modal and Structural Analysis - Type 7750

ME’scope™ (Vibrant Technology, Inc)
- Brüel & Kjær ME’scope - Type 7754

I-DEAS™ Master Series (MTS)
- I-DEAS Test

Openness to other software:

ICATS (Imperial College, London)
LMS
Modal Analysis software

Beyond Modal Testing

**Obtain modal parameters**
- Natural Frequency
- Modal Damping
- Residues (Mode shape)

**Validate modal parameters**
- Phase Scatter
- MAC
- Modal Confidence Factor

**Simulations**
- Add mass
- Change stiffness
- Tuned absorbers

**Validate FEM Models**
Conclusion to Modal Testing

What
- Obtain Modal Model

Why
- Trouble shooting, FE Modeling, Structural assembly analysis, SDM and FRS

How
- Modeling, System Analysis Measurements, Curve fitting, Validation of Modal Model

Brüel & Kjær Solution
- PULSE Modal Bridge to ME’scope
- Modal Test Consultant
Literature for Further Reading

- **Frequency Analysis** by R.B. Randall
  (Brüel & Kjær Theory and Application Handbook BT 0007-11)

- **Modal Analysis of Large Structures - Multiple Exciter Systems** by K. Zaveri
  (Brüel & Kjær Theory and Application Handbook BT 0001-12)

- **Modal Testing: Theory and Practice** by D.J. Ewins
  (Brüel & Kjær Theory and Application Handbook BT 0015-12)

- **Dual Channel FFT Analysis** by H. Herlufsen
  (Brüel & Kjær Technical Review No. 1 & 2, 1984)

- **Structural Testing, Part 1: Mechanical Mobility Measurement** by O. Døssing
  (Brüel & Kjær Theory and Application Booklet BR 0458-12)

- **Structural Testing, Part 2: Modal Analysis and Simulation** by O. Døssing
  (Brüel & Kjær Theory and Application Booklet BR 0507-11)