Modal Excitation

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Introduction

• The presentation is concerned with a short tutorial on modal excitation. It will cover:
  – Types of Methods
    • Force Appropriation Methods (Normal Mode)
    • Frequency Response Methods
      – Excitation Signals Types
      – Exciters
        • Impactors
        • Hydraulic and Electro-mechanical
      – Measurement and Signal Processing Considerations
Testing Methods

• Force Appropriation – Is a historical sine testing methods where an array of exciters is tuned to excite single system eigenvector. This methods is used primarily as a method for testing aircraft or space craft and is used by a very small segment of the modal testing community and will not be cover in this talk.

• Frequency Response Functions – In the early sixties estimating modal parameters from FRF measurements became a practical method for determining modal parameters. However, it was the development of FFT which made the method popular. This talk will concentrate upon the excitation methods and equipment for measuring FRF’s.
Dynamic Modal Model

\[ F(\omega) \rightarrow H(\omega) \rightarrow X(\omega) \]

\[
\{X\} = [H] \{F\}
\]
Excitation Signals

- The type of excitation signal used to estimate frequency response functions depends upon several factors. Generally, the excitation signal is chosen in order to minimize noise while estimating the most accurate frequency response function in the least amount of time. With the advent of the FFT, excitation signals are most often contain broadband frequency information and are limited by the requirements of the FFT (totally observed transients or periodic functions with respect to the observation window).
Noise Reduction

• Types of noise:
  – Non-Coherent
  – Signal processing (Leakage)
  – Non-Linear

Noise is reduced by averaging in the non-coherent case, by signal processing and excitation type for the leakage case, and by randomizing and averaging for the non-linear case.
Excitation Types

- Steady State
  - Slow Sine Sweep
  - Stepped Sine

- Random
  - True Random

- Periodic
  - Fast Sine Sweep (Chirp)
  - Pseudo Random
  - Periodic Random

- Transient
  - Burst Random
  - Impact
  - Step Relaxation

- Operating
Excitation Signal Characteristics

- RMS to Peak
- Signal to Noise
- Distortion
- Test Time
- Controlled Frequency Content
- Controlled Amplitude Content
- Removes Distortion Content
- Characterizes Non Linearities
## Summary Excitation Signal Characteristics

<table>
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<tbody>
<tr>
<td>Minimize Leakage</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Signal-to-Noise Ratio</td>
<td>Very High</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
<td>High</td>
<td>Low</td>
<td>Fair</td>
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<tr>
<td>RMS-to-Peak Ratio</td>
<td>High</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
<td>High</td>
<td>Low</td>
<td>Fair</td>
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<tr>
<td>Test Measurement Time</td>
<td>Very Long</td>
<td>Good</td>
<td>Very Short</td>
<td>Fair</td>
<td>Fair</td>
<td>Very Short</td>
<td>Very Short</td>
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<tr>
<td>Controlled Frequency Content</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Controlled Amplitude Content</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
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<tr>
<td>Removes Distortion</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Characterize Nonlinearity</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

* Special Hardware Required
Modal Testing Set Up

• What’s the purpose of the test?
• Application
• Accuracy needs
• Non-linearities
• Testing time
• Expected utilization of the data
• Testing cost
• Equipment availability
Typical modal test configuration: Impact

Signal conditioning

FFT analyzer

Hammer

Transducers

Structure

Modal Excitation
Input Spectrum

• Factors controlling the frequency span of the input spectrum
  – Stiffness of the impact tip
  – Compliance of the impacted surface
  – Mass of the impactor
  – Impact velocity

• The input spectrum should roll-off between 10 and 20 dB over the frequency range of interest
  – At least 10 dB so that modes above the frequency range of interest are not excited
  – No more than 20 dB so that the modes in the frequency range of interest are adequately excited
The load cell of the impactor should be calibrated in its testing configuration since its sensitivity is altered when it used as part of an impactor.

\[ F_{\text{measured}} < F_{\text{input}} \]

The difference of the measured force and the input force depends on the effective mass of the impactor and the impact tip.
Ratio Calibration

\[ H \left[ \frac{g}{lb} \right] = \frac{C_a \left[ \frac{g}{V} \right] * V_a[V]}{C_f \left[ \frac{lb}{V} \right] * V_f[V]} \]

Determine ratio of \( Ca/Cf \) from \( Va/Vf \) for calibration mass.

\[ \frac{C_a}{C_f} = \frac{1}{mH_m} \]

Where: \( H_m = \frac{V_a}{V_f} \)
Hammer Calibration Pictures
Modal Excitation Techniques

• Impact Hammers

• Shakers
Impact Testing

- Easy to use in the field
- No elaborate fixturing
- Fast

Modal Punch
Electric Hammer
Manual Hammers
Impactors
Lightly Damped Systems

- The exponential window reduces leakage in the response signals.
Use of the Force Window

- Defining the force window
  - length in seconds
  - length as $%T$

- The "length" of the force window = the duration of the leading unity portion
Exception to the Rule

• To improve impact testing FRF measurements, the force and exponential windows should *almost always* be applied to the time signals.

• The *exception* to this rule is when the measured signals contain significant components of periodic noise.

• Because of the frequency domain effects of the windows, the periodic noise must be removed from the data before applying the windows in the time domain.

**Exponential Window Line Shape**

- DC-component
- electrical line noise
- periodic excitation sources
Removing Periodic Noise

- A pretrigger delay can be used to measure periodic ambient noise and DC offsets, which should be removed before the windows are applied.
Step Relaxation Excitation
Typical modal test configuration: shaker
Types of Exciters

• Mechanical
  – Out-of-balance rotating masses
• Servo hydraulic
• Electromagnetic or Electrodynamic Shakers
Examples of Infrastructure Excitation

Drop Hammer

32 inch stroke – 1000 lb
Hydraulic vs. Electrodynamic

Useful operating regions of modern hydraulic and electro-dynamic vibration machines (after G.B. Booth)

Modal Excitation
Electrodynamic Shaker System

Test Signal:
- random
- burst Random
- pseudo-random
- periodic-random
- Chirp

Shaker

Power Amplifier

Stinger

force sensor

structure

Modal Excitation
Typical Electrodynamic Shaker

\[ F = l \cdot B \cdot i \]
Typical modal shaker design

- Through hole armature
- Power cable
- Cooling (optional)
- Trunnion
- Handles
Important Shaker Considerations

• Excitation Point
• Boundary Conditions
• Fixturing
  – Exciter support systems
  – Alignment
  – Attachment to the structure: stingers
Excitation Points

• must be able to excite all modes of interest
  – node points of node lines
    • not good points if you want to suppress all modes
    • Good points if you want to suppress modes you are not interested on

• Pre-testing with impact hammer
  – Helps determine the best excitation point

• FEM (Finite Element Model)
  – Helps determine best excitation point
Boundary Conditions

Free condition: highest rigid body mode frequency is 10-20% of the lowest bending mode

Drawing from: Ewins, D. J., Modal Testing: Theory and Practice
Boundary Conditions

Inertial masses

Suspended shaker

Modal Excitation

Drawing adapted from: Ewins, D. J., Modal Testing: Theory and Practice, pp.101
Boundary Conditions

Unsatisfactory configuration

Compromise configuration


Drawings from: Ewins, D. J., Modal Testing: Theory and Practice
Boundary Conditions

Compromise configuration
Boundary Conditions

• Free-free (impedance is zero)
Examples of Exciter Mounting

Dedicated Exciter Support

Hot Glue and Duct Tape Required

“Make Shift” Exciter Support
Typical Installation

Modal Exciter

2-part chuck assembly

collet

armature

stinger

Force sensor

Test Structure

Through hole armature design

Modal Excitation
Shaker Alignment

- Fundamental to avoid side loads and measurement errors
- Through hole design and stingers facilitate alignment
- Floor mounting
  - Trunnion angle adjustment
  - Rubber/Dead blow hammer minor adjusts
  - Hot glue or bolt to the floor
- Suspended Mounting
  - Shaker Stands
    - Special fixturings for major height adjustment
    - Turnbuckles, bungee cords
    - Inertial masses to minimize shaker displacements
Shaker Alignment
Laser Alignment Tools
Final Shaker Set Up
Installation Example

Click on the picture to start the movie
Stingers

• Link between the shaker and the structure
• stinger, quill, rods, push-pull rods, etc.
• Stiff in the direction of Excitation
• Weak in the transverse directions
  – No moments or side loads on force transducer
  – No moments or side loads on shakers
Stinger Types

- Piano wire
- Modal stinger
- Threaded metal rod
- Threaded nylon rod
Stinger Installation

RIGHT

WRONG
Stinger Considerations

• Rigid on excitation direction, weak on transverse direction
• Lightweight
• Buckling & alignment
Stinger Considerations

• Piano Wire: pre-tension
Sensor Considerations

- Normally piezoelectric (PE) force sensors are used for measuring excitation and PE accelerometers structure response
  - broad frequency and dynamic range
- Avoid bottoming mounting studs or stinger to the internal preload stud of the sensor
- Impedance head is a nice option for measuring drive point FRF
Sensor Installation

• Force Sensor or Impedance Head

Dental cement, hot glue

Superglue, stud, etc
Sensor Installation

• Force Sensor or Impedance Head
Shaker Amplifiers Features

• Match excitation device: shaker impedance
• Frequency range
  – Response down to DC
• Interlocks and protection
  – detects shaker over-travel and provides over current protection
• Voltage mode
  – Output proportional to signal input
  – Necessary for Burst Random Excitation Method
• Current mode
  – Compensates for shaker back EMF
  – Normal Mode testing
• Voltage / current monitoring outputs
Exciter Characterization

- Measuring Impedance Model of shaker using second shaker as boundary condition for first shaker and vice versa.

\[
\begin{pmatrix}
F \\
A
\end{pmatrix} = \begin{bmatrix}
H_{Fi} & H_{FV} \\
H_{Ai} & H_{AV}
\end{bmatrix} \begin{pmatrix}
I \\
V
\end{pmatrix}
\]
Testing Configurations

- SISO (Single Input Single Output)
- SIMO (Single Input Multiple Output)
- MISO (Multiple Input Single Output)
- MIMO (Multiple Input Multiple Output)
During the measurement phase it is important to monitor the performance of the exciter. The force and/or reference accelerometers (impact testing) are common to the complete set of measurements. If these references are faulty then the complete set of measurements are compromised.

- Force single input cases, the quality of the force measurement is important. Power Spectrums of the force are measured in real time and the driving point FRF are recorded for each response sensor configuration.
- For the MIMO case the power spectrum for each input, the principle components of the inputs and set of reference FRF’s are monitored in real time.
Example MIMO Force Monitoring
Before Release of Test Item

• At the conclusion of data acquisition phase a quick reduction of the data using a simple modal parameter estimation process should be performed.