The use of exotic multisines in MIMO structural dynamics and acoustic applications

Introduction

Context
- VLAIO post-doc project (PhD technology transfer to industry): "Development of an advanced time-varying and nonlinear nonparametric estimation framework for industrial measurements"
  - Grant holder: Péter Csurcsia
  - Promotors: Johan Schoukens (VUB), Bart Peeters (Siemens PLM Software)

Target applications
- Structural Dynamics Testing & Modal Analysis
- Vibration and acoustic control

Content of presentation:
- Special multisines for multiple-input excitation
- GVT of the eFusion Magnus Aircraft
- Link to non-linear Finite Element Modelling
- MacPherson suspension: indirect force measurements
- Direct Field Acoustic Control
Structural Dynamics Testing & Experimental Modal Analysis
Ground Vibration Testing

Input

System

Output

Modal parameter estimation

Measurement data (FRFs)

Finding 5 resonances

There is a 6th resonance in the data

Sum of all resonances compares very well with the measured data -> Successful modal parameter estimation
Structural Testing – Overview of excitation methods

- Impact
- (burst) Random
- Periodic Random
- Swept Sine
- Stepped Sine
- Normal Modes

Phase Separation or Frequency Response Function (FRF) based methods

- Measure FRF
- Modal Parameter Estimator
- Experimental Modal Model \( \{ \omega, \zeta, \psi \} \)

Phase Resonance / Mode Appropriation

Special odd multisine source signal looks random …
... but has a well-defined amplitude spectrum ...

... and it is periodically repeated.
“Robust method” (can be combined with fast method)

Special measurement sequence of pseudo random signals
- Flat multisine
- Random phases

Scheme can be extended for multiple-input cases

Multiple-input multisine generation and analysis tools

- Easy generation of multisines
- Automated processing
- Compatible with Simcenter Testlab
eFusion Magnus aircraft:
Test program

Test equipment
- 2 shakers;
- 2 force cells;
- 91 acceleration channels: mono-axial accelerometers;
  1 tri-axial accelerometer on each aerodynamic surface;
  1 tri-axial accelerometer on the fuselage nose;
  YZ accelerometer on fuselage node 5.

Test settings
- Frequency range: 7-50 Hz;
- Sweep rates: 0.6 oct/min, 1.2 oct/min, 2.4 oct/min.

Driving points FRFs at different force levels
Test – FE correlation in a non-linear world

Testing as part of a product development process: How to model non-linearities (physical modelling)? How to update the model based on measurements?

Indirect measurement of wheel forces
Case study: MacPherson suspension – tire assembly

Virtual sensing techniques are used to provide feasible and economical alternatives to costly or unpractical physical measurement instrument. A virtual sensing system uses information available from other measurements and process parameters to calculate an estimate of the quantity of interest.

Two major categories:
• Analytical techniques
• Empirical techniques
Indirect measurement of wheel forces
Case study: MacPherson suspension – tire assembly

• "Road B", 0-30 Hz, 30 km/h
• Cube controller: Single-axis TWR (Time Waveform Replication)

SIMO model:
• Input: road displacement
• Outputs: 3 wheel hub forces and 3 moments
Indirect measurement of wheel forces
Case study: MacPherson suspension – tire assembly

Volterra series estimate
- A branch of the SIMO block is estimated by a second order regularized Volterra series.
- If the system is weakly nonlinear (still linear dominancy) then low order Volterra series usually gives acceptable results.
- In Volterra series, nonparametric time domain estimates are considered (impulse response functions of higher orders)

\[ F_{z,\text{measured}} = g_0 + g_1 \cdot D_3 + g_2 \cdot D_3 \cdot D_3 + e \]
Wheel force prediction – Validation data
Linear model vs. Volterra series

- Model built using training dataset
- Model validated using validation dataset
- Error index calculated

![Validation output graph](image)

Wheel force prediction – Validation data
Linear model vs. Volterra series

Zoom

![Zoomed validation output graph](image)
Indirect measurement of wheel forces
Case study: MacPherson suspension – tire assembly

<table>
<thead>
<tr>
<th></th>
<th>A linear FIR model</th>
<th>2nd degree Volterra series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error index</td>
<td>8.9 ... 20.6</td>
<td>4.4</td>
</tr>
<tr>
<td>Computational time</td>
<td>Seconds</td>
<td>1-3 minutes / channel</td>
</tr>
<tr>
<td>Complexity of method</td>
<td>1 parameter to choose</td>
<td>2 parameters to choose</td>
</tr>
</tbody>
</table>

- 2nd degree Volterra series outperforms linear model
- Limited gain using 3rd degree Volterra series
- Easy to compute and to analyze the results when nonparametric estimates are needed
- Use of Volterra series model in virtual sensing context possible
  - Identification takes time, but is done in preparation phase
  - Use of model for prediction is very fast

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Spacecraft flight environments and dynamic loads

Flight environments:
- Low-frequency dynamic response (typically 0-100 Hz), of the launch vehicle/payload system to transient flight events
- High-frequency random vibration environment (20-2000 Hz) transmitted from the launch vehicle to the payload at the launch vehicle/payload interfaces
- High frequency acoustic pressure environment (20-8000 Hz), inside the payload compartment
- Shock events (concentrated at or above 500 Hz, measured in range of 100 Hz – 10 kHz)

On-orbit:
- Micro-vibration environment important for verifying the mission performances (e.g. optical instruments)

ESA spacecraft mechanical loads analysis handbook, 2013.

Spacecraft design and qualification
Sine, Random and (Pyro)shock testing from component tests to full satellite qualification

Courtesy of ESA ESTEC
Spacecraft design and qualification
Replicating launch loads with controlled acoustic excitation in reverberant room

DFAX – Direct Field Acoustic eXcitation
Direct Field Acoustic Control

MIMO System (12 control microphones x 6 independent drives)
- Step 1: System Identification
- Step 2: MIMO Random Control
Direct Field Acoustic Control  
System Identification using special multisines

High-quality multisine excitation signal generation

![Graph showing high-quality multisine excitation signal generation]

Microphone response
- Noise level -40 dB
- Even non-linearities more dominant

Typical Frequency Response Function

Benefits of special multisines:

- **System Identification**
  - High-quality model obtained: BLA (Best Linear Approximation)
  - Nonlinearity assessment

- **Control**
  - A better (linear) model leads to better and faster control: no longer than required exposure to high sound pressure levels
  - In case of severe non-linear behavior: need for more advanced control strategies

![Graph showing typical frequency response function]
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Contact page

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