The impact of uncertainty in operational modal analysis for structural identification of constructed systems

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Ph.D. Thesis Defense Presentation
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Presentation Outline

1. Research motivation, objectives, definitions, past research
2. Research Plan
   i. Physical models
   ii. Analytical models
   iii. Experimental tools
3. Uncertainty assessment study
4. Statistical methods for data quality assessment
5. Conclusions and summary
Motivation for the Research

• The nation’s infrastructure is rapidly deteriorating and objective assessment methods are needed for condition evaluation of constructed systems

• Structural identification is a framework that stems from system identification concept and its utilization on constructed systems has been proposed for objective condition evaluation

• Civil engineers have long been interested in experimental modal analysis as the primary experimentation tool for St-Id

• The uncertainties involved in implementation of modal analysis within the context of St-Id have never been systematically studied

RESULT: St-Id remains to be an active research area and it has only enjoyed sparse implementation on real structures
Research Objectives

• Establish relationships between different uncertainties and identified modal parameters of a structure through operational modal analysis using output-only measurements within the framework of Structural-Identification (St-Id).

• Propose optimum data processing approaches in operational modal analysis

• Investigate different methods for data quality assessment in operational modal analysis
Definition of Structural Identification (St-Id)

The parametric correlation of structural response characteristics predicted by a mathematical model with analogous quantities derived from experimental measurements.
Classification of Analytical Modeling Tools in St-IId

**Physics-Based (PB) Models**

*Laws of Mechanics:*
  - Newton’s Laws of Motion, Hooke’s Law

*Continua Models:*
  - Theory of Elasticity
  - Idealized Differential Equations (e.g. Beam theories of Bernoulli, Timoshenko, Vlasov)

*Discrete Geometric Models:*
  - Idealized macro or element level models (e.g. idealized grillage models)
  - FEM for solids and field problems
  - Modal models:
    * Modal parameters (i.e. natural frequency, mode shape, damping)
    * Ritz vectors

**Non Physics-Based (NPB) Models**

*Semantic Models:*
  - Ontologies
  - Semiotic Models

*Meta Models:*
  - Input-Output models
  - Rule-based meta models
  - Mathematical (e.g. Ramberg-Osgood representation of stress and strain near the yield region)

*Numerical Models:*
  - Statistical Data-Driven Models
    * ARMA modeling, Wavelets, Empirical Mode Decomposition, Artificial Neural Networks
  - Probabilistic Models
    * Histograms, probability and frequency distributions, Markov modeling, Agent-based models
# Classification of Experimental Tools for St-Id

<table>
<thead>
<tr>
<th>Local NDE</th>
<th>Geometry Monitoring</th>
<th>Short-Term Structural Testing</th>
<th>Vibration Analysis (Dynamic Testing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Testing</td>
<td>Surveying</td>
<td>Load Testing (Static or Quasi-Static Testing)</td>
<td>Controlled</td>
</tr>
<tr>
<td>Thermal</td>
<td>GPS</td>
<td>Measure Inputs &amp; Outputs</td>
<td>Measure Outputs Only</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Laser</td>
<td>Static Trucks</td>
<td>Input by Traffic</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>Remote Sensing</td>
<td>Crawling Trucks</td>
<td></td>
</tr>
<tr>
<td>Acoustic</td>
<td>Photo Methods</td>
<td>Special Loading Devices</td>
<td></td>
</tr>
<tr>
<td>Electrical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electro-Chem</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Weigh-in-motion*
Excitation tools for Experimental Modal Analysis

FORCED VIBRATION
- Controlled
- Measured
- Known

AMBIENT VIBRATION
- Not Controlled
- Not Measured
- Not Known
Tools for Experimental Modal Analysis with Forced Excitation

**Impulse Response Functions (IRF)**

**Frequency Response Functions (FRF)**

<table>
<thead>
<tr>
<th>Assumptions:</th>
<th>Modal Parameters:</th>
<th>Algorithms:</th>
<th>Domain:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observability</td>
<td>$\omega_d$</td>
<td>Natural Frequency</td>
<td>PTD</td>
</tr>
<tr>
<td>Linearity</td>
<td>$\psi$</td>
<td>Mode Shapes</td>
<td>ITD</td>
</tr>
<tr>
<td>Stationarity</td>
<td>$\sigma$</td>
<td>Damping</td>
<td>LSCE</td>
</tr>
<tr>
<td></td>
<td>$Q_r$</td>
<td>Scaling Factor</td>
<td>PFD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>CMIF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Others…</td>
</tr>
</tbody>
</table>
Tools for Experimental Modal Analysis with Ambient Excitation

Ambient Vibration Data → Pseudo-Response Functions (P-RF) → Modal Parameters

Assumptions: Observability, Linearity, Stationarity

Modal Parameters: $\omega_d$ (Natural Frequency), $\psi$ (Mode Shapes), $\sigma$ (Damping), $Q_r$ (Scaling Factor)

Algorithms: PTD, ITD, LSCE, PFD, CMIF, Others...

Domain: Time, Frequency
Operational Modal Analysis as a Primary Experimentation Tool

• Operational modal analysis is known as output-only modal analysis or ambient vibration testing

• Suitable for modal parameter identification of large structures

• Unmeasured and uncontrolled input drawback

• Great amount of information available from DSP community for signal treatment

• Civil/Mechanical engineers have to face with uncertainty in two different layers: Epistemic (related to imperfect knowledge), Aleatory (related to natural randomness)
Introduction to Uncertainty in St-Id Framework

Epistemic Type: Uncertainty related to imperfect knowledge

Aleatory Type: Uncertainty related to natural randomness

Hardware/Human Related:
- DAQ/Sensor related electrical noise
- Improper test setup/execution

Input

Structural System

Output

Excitation Related:
- Amplitude
- Localization
- Frequency Content
- Temperature & environmental effects

Structural Complexity:
- Nonlinearity
- Nonstationarity
- Initial/intrinsic stresses
- Lack of observability

DSP/Modal ID:
- Windowing
- Averaging
- Signal Modeling
- Modal Parameter ID
### Uncertainties associated with St-ID of constructed systems

#### (3) Controlled Experimentation

<table>
<thead>
<tr>
<th>STRUCTURAL COMPLEXITY</th>
<th>FORCE AND EXCITATION:</th>
<th>DATA ACQUISITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Vagueness and/or non-stationarity of boundary and continuity conditions</td>
<td>• Amplitude</td>
<td>• Interferences and Spurious Energy Input</td>
</tr>
<tr>
<td>• Intrinsic stresses, redundancy, local deterioration</td>
<td>• Spectral distribution</td>
<td>• Spatial Aliasing</td>
</tr>
<tr>
<td>• Nonlinearity, material, contact and uplift</td>
<td>• Spatial Distribution and transmissibility</td>
<td>• Synchronization of channels</td>
</tr>
<tr>
<td></td>
<td>• Directionality</td>
<td>• Hardware filtering options</td>
</tr>
<tr>
<td></td>
<td>• Dimensionality (1D, 2D or 3D)</td>
<td>• Noise &amp; bias buried in signal</td>
</tr>
<tr>
<td></td>
<td>• Duration and Non-stationarity</td>
<td>• Measurement Bandwidth</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cabling and installation effects</td>
</tr>
</tbody>
</table>

#### (2) A Priori Model(s)

- Completeness of 3D geometry
- Discretization and analytical representation of members, joints and connections
- Soil-foundation stiffness, kinematics
- Nonlinearity, non-stationarity

#### (4) Data Processing

- Data quality measures
- Error identification/Cleaning
- Different filtering, averaging, windowing options
- Post-processing algorithms

#### (1) Conceptualization

- Heuristics
- Archival of structural drawings/design calculations, inspection reports
- Site visits, geometry measurements, photogrammetry
- Material Sampling, testing, NDE
- Virtual Reconstruction in 3D CAD

#### (6) Utilization

- Health/Performance Monitoring
- Damage detection, Prognosis
- Scenario Analysis and Vulnerability Assessment
- Performance-based Engineering
- Guidelines and Codes

#### (5) Model Calibration, Parameter ID

- Parameter grouping
- Sensitivity, Bandwidth
- Modality
- Objective Functions, constraints
- Optimization
- Physical interpretation of results
Literature Review – OMA Examples on Bridges

• Abdel-Ghaaffar and Housner (1978) investigated damping values of Vincent-Thomas Suspension by OMA

• Several researchers investigated dynamic characteristics of the Golden Gate Bridge in mid-eighties

• Brownjohn et. al. (1989, 1992) reported OMA studies on first and second Bosphorus bridges in Turkey

• Aktan et. al. reported OMA results on Commodore Barry Bridge, NJ

• Z-24 Bridge in Switzerland was monitored under different ambient conditions and damage cases in early 2000’s. Bridge data was distributed among researchers.

• Brooklyn Bridge was tested and monitored by different researchers in the last few years.
Literature Review – Reported Uncertainty Cases

• Ward (1984) reported ambient vibration tests on bridges result in modes that do not relate to physical mode shapes and addressed structural non-stationarity

• Farrar et. al. (1994) reported 5-10% difference in modal frequencies and mode shapes over a 24 hour period due to temperature effects on a bridge in New Mexico

• DeRoeck et. al. reported bilinear relationship between the ambient temperature and modal frequencies on bridge in Switzerland.

• Aktan and Grimmelsman (2005) reported results of ambient monitoring study of Brooklyn Bridge towers and addressed the impact of sub-structural components’ interaction on the identified modes

• Brownjohn reported the impact of uncertainty on the modal properties of bridges in many studies (1989, 1992, 2003)
Literature Review – Laboratory Benchmark Models

STEEL QUAKE
Ispra, Italy

Univ.of Cinn. Grid
OH, USA

Univ. of British C.
IASC-ASCE SHM
Task Group
Benchmark Model
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Parameter Study for Operational Modal Analysis

Major Sources of Uncertainty

- Excitation
- Boundary Conditions
- Data Preprocessing
- Data Postprocessing

Implementation on a physical model

Relationship between uncertainty and identified modal parameters

Identified modal parameters
Overview of the Research Plan

Physical Modeling → Simple Model → Complex Model

Correlation

Good → Impact Test Results

Bad

A Priori FE MODEL

Correlation

Check, modify

Bad

Check

Ctrl. Load Testing

Good → Determine The Critical Bandwidth

Impact Test

Change Uncertainty (n=n+1)

True → Ambient Study Case n

Ambient Vibration Test Results for Case n

False

REPORT CORRELATION
Laboratory Physical Modeling

Two Physical Benchmarks:
1. Simple System (Cantilever)
2. Complex System (Deck/Grid Assembly)
## Physical Laboratory Model

<table>
<thead>
<tr>
<th>Sources of Uncertainty</th>
<th>Mechanisms and Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td>Boundary and Continuity Conditions</td>
</tr>
<tr>
<td></td>
<td>Connectivity Material Prop. Aging, Deterioration, Damage Failure Modes</td>
</tr>
<tr>
<td>Analytical</td>
<td>FE Modeling (Geometric Modeling)</td>
</tr>
<tr>
<td></td>
<td>Sensing Data Acquisition (DAQ) Test Design DAQ Regimes</td>
</tr>
<tr>
<td>Experimental</td>
<td>Parameter Estimation (Modal Modeling)</td>
</tr>
</tbody>
</table>

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![Physical Laboratory Model Image](image)
Physical Laboratory Model - Components

**COMPOSITE DECK**
- E-Glass
- Balsa

**STEEL GRID**
- 3x2x3/16" Steel Tubing
- 3/16" Gusset Plate
- 1/4" Dia. Steel Bolt
- 2x2x1/4" Steel Angle

**CONNECTIVITY**
- 1 ¼" Composite Deck

**BOUNDARY CONDITIONS**
- 3x2x3/16" Steel Tubing
- 4X1/4" Steel Plate
- 4x3/4x1/4" Steel Plate
- 3/8" Dia. Steel Bolt
Physical Model Dynamic Test Setup

Output: Accelerometer (Model: PCB 393C) on the deck and support plates

Output: Accelerometer (Model: PCB 393C) under the grid

Input & Output: Instrumented impact hammer (Model: PCB 086C20), Accelerometer (Model: PCB 393C)
Dynamic Test System Chart

HP VXI

Shaker

Breakout box

Co-ax cable
Microdot cable
Accelerometers

Ch1
Ch2
Ch3
Ch4
Ch5
Ch6
Ch7
Ch8
Ch9
Ch10
Ch11
Ch12
Ch13
Ch14
Ch15
Ch16
Ch17
Ch18
Ch19
Ch20
Ch21

Impact Hammer

Windows

HP DAC Express Software

Agilent IO Lib Control

DAQ PC

DAQ PC
Beam Study – Demonstration of Experimental Modal Analysis

Physical Model and Instrumentation Plan

Accel: 1 2 3 4 5 6

5 Spaces @ 23.5” = 117.5”

Support

Steel Tube Section
3” x 1.5” x 0.125”
Overview of Analytical and Experimental Modal Analysis using Frequency Response Functions

Experimental Approach

- Determine Output/Input DOF
- Collect Data
- Preprocess (filter/window)
- FRF Generation by FFT

Analytical Approach

- M, K, C
- Determine Output/Input DOF

\[
H(jω) = \frac{A(jω)}{\det[B(jω)]}
\]
Analytical FRF Construction of the Beam

\[ [H(j\omega)] = \sum_{k=1}^{m} \frac{[A_k]}{(j\omega - \lambda_k)} + \frac{[A_k^*]}{(j\omega - \lambda_k^*)} \]
## Analytical Modal Parameter Identification of the Beam

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>$\omega_d$ (Damped Natural Frequency (Hz))</th>
<th>$\psi$ (Mode Shapes)</th>
<th>$M_{A_r}$ (Modal Scaling Factor (s/lbm))</th>
<th>$\sigma$ (Damping (%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.912</td>
<td>-0.86 ± 12.70E-4i</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>30.800</td>
<td>-4.77E-6 ± 2.12E-4i</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>86.485</td>
<td>-3.70E-6 ± 7.46E-5i</td>
<td>2.47</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>170.703</td>
<td>-3.55E-6 ± 3.67E-5i</td>
<td>4.82</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>282.754</td>
<td>-3.78E-6 ± 2.35E-5i</td>
<td>7.98</td>
<td></td>
</tr>
</tbody>
</table>
Comparison of all Test and Simulation Results

Impact Test
- Impact Test (CMIF)
- Impact Test Simulation

Ambient Vibration Test
- Random Shaker
- Manual Taps

4.67 Hz
4.91 Hz
4.78 Hz
4.77 Hz
29.73 Hz
30.80 Hz
29.58 Hz
29.56 Hz
83.43 Hz
86.50 Hz
83.40 Hz
83.49 Hz
162.13 Hz
170.72 Hz
161.98 Hz
162.22 Hz
263.26 Hz
282.78 Hz
263.55 Hz
263.88 Hz
FE Modeling of the Physical Laboratory Model

MODEL STATISTICS
DOF: 8124
FRAME ELEMENTS: 576
SHELL ELEMENTS: 864

Frame element for the top steel plate
Frame element for tube members
Shell element for the deck
Rigid links for the connection between tube & deck
Rigid links for bolt connection between tube & deck
Frame element for the top steel plate

The weight of angles, bolts & nuts are applied as line mass of grid connection elements
- 400 lbs of load was put on each location in 80 lbs increments
- Data was continuously collected during loading and unloading periods of each point
- Deflections are normalized and 9x9 flexibility matrix was generated by $f_{ij} \cdot F_j = u_i$

$$
(f_{ij})_{exp} =
\begin{bmatrix}
0.258 & 0.109 & 0.018 & 0.344 & 0.183 & 0.045 & 0.144 & 0.081 & 0.023 \\
0.114 & 0.151 & 0.126 & 0.181 & 0.189 & 0.182 & 0.079 & 0.080 & 0.082 \\
0.017 & 0.109 & 0.286 & 0.040 & 0.179 & 0.329 & 0.020 & 0.082 & 0.144 \\
0.340 & 0.179 & 0.046 & 0.728 & 0.371 & 0.092 & 0.345 & 0.191 & 0.048 \\
0.179 & 0.188 & 0.193 & 0.371 & 0.412 & 0.369 & 0.182 & 0.197 & 0.193 \\
0.042 & 0.178 & 0.347 & 0.082 & 0.356 & 0.698 & 0.041 & 0.190 & 0.354 \\
0.140 & 0.080 & 0.022 & 0.352 & 0.183 & 0.043 & 0.275 & 0.122 & 0.020 \\
0.079 & 0.080 & 0.084 & 0.187 & 0.196 & 0.184 & 0.119 & 0.182 & 0.133 \\
0.020 & 0.076 & 0.139 & 0.040 & 0.176 & 0.327 & 0.016 & 0.120 & 0.292
\end{bmatrix}
$$
Controlled Load Test and FEM Correlations Under Uniform Load

**Longitudinal Centerline deflection**

Abs. Error = \[ \frac{ (f_{ij})_{fem} - (f_{ij})_{exp} }{ (f_{ij})_{fem} } \]

**Strain Comparisons**

Load: 400 lbs

<table>
<thead>
<tr>
<th>Point</th>
<th>Static Test</th>
<th>FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>69.41 uE</td>
<td>70.04 uE</td>
</tr>
<tr>
<td>10</td>
<td>122.22 uE</td>
<td>102.69 uE</td>
</tr>
<tr>
<td>11</td>
<td>74.87 uE</td>
<td>70.04 uE</td>
</tr>
<tr>
<td>12</td>
<td>147.13 uE</td>
<td>13</td>
</tr>
</tbody>
</table>

**Transverse Centerline deflection**

- Static Test
- FEM
Establishing Critical Bandwidth For Dynamic Testing

\[ LMC = \sqrt{\sum_{i=1}^{N} (u_{i}^m - u_{i}')^2} \]

\[ [F]^m = [\Phi]_{n \times m} [\Omega] [\Phi]^T \]

\( u_{i}^m \): the ith element of deflection under uniform loading calculated from the modal flexibility matrix \([F]^m\);

\( u_{i}' \): the ith element of deflection under uniform loading calculated from the FEM flexibility matrix \([F]\);

\([F]^m\): the modal flexibility matrix computed with m modes,

\([\Phi]_{n \times m}\): Unit mass normalized mode vectors

\([\Omega]\): \(1/\omega^2\), where \(\omega\) is the radian frequency
Impact Test & FEM Correlation

Mode 1
MAC: 1.000

Mode 2
MAC: 0.999

Mode 3
MAC: 0.992

Mode 4
MAC: 0.975

Mode 5
MAC: 0.961

Mode 6
MAC: 0.718

Mode 7
MAC: 0.799

<table>
<thead>
<tr>
<th>Mode</th>
<th>Impact CMIF Frequency (Hz)</th>
<th>A priori FEM Frequency (Hz)</th>
<th>% Diff. Frequency</th>
<th>MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.04</td>
<td>5.02</td>
<td>-0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>7.80</td>
<td>7.88</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>17.84</td>
<td>17.54</td>
<td>-1.63</td>
<td>0.99</td>
</tr>
<tr>
<td>4</td>
<td>22.29</td>
<td>22.25</td>
<td>-0.14</td>
<td>0.98</td>
</tr>
<tr>
<td>5</td>
<td>28.09</td>
<td>27.46</td>
<td>-2.24</td>
<td>0.96</td>
</tr>
<tr>
<td>6</td>
<td>33.11</td>
<td>29.62</td>
<td>-10.54</td>
<td>0.72</td>
</tr>
<tr>
<td>7</td>
<td>36.36</td>
<td>33.46</td>
<td>-7.99</td>
<td>0.80</td>
</tr>
</tbody>
</table>
Modal Flexibility

Modal Flexibility has been proposed as a reliability signature reflecting the existing condition of bridges.

\[
[f_{ij}] = [\Phi][\Omega][\Phi]^T
\]

\[
\begin{bmatrix}
  f_{1,1} & \cdots & f_{1,n} \\
  \vdots & \ddots & \vdots \\
  f_{n,1} & \cdots & f_{n,n}
\end{bmatrix}_{n \times n}
\]

Modal Flexibility Coefficients

\[
\begin{bmatrix}
  \phi^1(1) & \cdots & \phi^m(1) \\
  \vdots & \ddots & \vdots \\
  \phi^1(n) & \cdots & \phi^m(n)
\end{bmatrix}_{n \times m}
\]

Mass normalized mode vector

\[
\begin{bmatrix}
  \frac{1}{\omega_1^2} & 0 & 0 \\
  0 & \ddots & \vdots \\
  0 & \cdots & \frac{1}{\omega_m^2}
\end{bmatrix}
\]

Frequency (rad/sec)

\[
\begin{bmatrix}
  \phi^1(1) & \cdots & \phi^m(1) \\
  \vdots & \ddots & \vdots \\
  \phi^1(n) & \cdots & \phi^m(n)
\end{bmatrix}_{m \times n}
\]

Transpose of the mass normalized mode vector

\[
f_{ij} = \sum_{k=1}^{m} \frac{\phi^k(i) \phi^k(j)}{\omega_k^2}
\]

Therefore, modal flexibility coefficient of each node is a function of the number modes included in the calculation.
Impact Test Modal Flexibility – Uniformly Dist. Load Case

Deflection Profiles from Flexibilities:

- Modal (SSI Alg.)
- FEM
- Static Test

Girder 1
- FEM
- Modal Flex w/ 1st Mode
- Modal Flex w/ all Modes (13)
- Modal Flex w/ Modes b/w 1 & 13

Girder 2
- Static Test

Girder 3
Impact Test Modal Flexibility – Girder Loading Case

Deflection Profiles from Flexibilities:
• Modal (SSI Alg.)
• FEM

Girder 1
P P P P P P P
Girder 2
Girder 3

P : 1 kip.

: FEM
: Modal Flex w/ 1\textsuperscript{st} Mode
: Modal Flex w/ all Modes (13)
: Modal Flex w/ Modes b/w 1 & 13

Girder 1
Deflection (in.)

Girder 2

Girder 3
Deflection (in.)

DOF
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Overview of the Research Plan

Physical Modeling → Simple Model → Complex Model → A Priori FE Model → Correlation

- Good: Impact Test Results
  - Change Uncertain Parameter (n=n+1)
    - True: Ambient Study Case n
      - True: Ambient Vibration Test Results for Case n
    - False

- Bad: Ctrl. Load Testing → Correlation
  - Check, modify

REPORT CORRELATION
Outline of the Parameter Study for Operational Modal Analysis

**STRUCTURE**
- Boundary Contact Nonlinearity
- Suppressed Boundary Contact Nonlinearity
- Boundary Material Nonlinearity

**EXCITATION**
- Excitation Through Substructure (spatially distributed, indirect)
- Excitation Through Substructure (non-spatially distributed, indirect)
- Excitation Through Superstructure (spatially distributed, direct)
- Excitation Through Superstructure (non-spatially distributed, direct)

**PREPROCESSING**

**POSTPROCESSING**
- SSI
- PTD
- CMIF
- Data Length Averaging
- Windowing
- Signal Modeling

**IDENTIFIED MODAL PARAMETERS**
Assessment of the Uncertainty

Alternatives

- Qualitative assessment
- Statistical assessment
- Physical assessment

Typical Error function

\[ EF = f(\text{frequency}) + f(MAC) + f(\text{flexibility}) \]

- No more than few percent error was present
- No environmental impact
- Typical term for model updating, but function formulation for uncertainty evaluation is subjective
## Pseudo-Flexibility Concept

### Impact Test Flexibility

\[
[M_A] = [Ψ][M][Ψ]^T
\]

\[
M_{A\mathbf{r}} \{A\}_r = \{Φ\}
\]

\[
[f_{ij}] = [Φ][Ω][Φ]^T
\]

**Φ**: Unit-mass normalized mode shapes

**Ω**: Modal frequency

\[
Ω = \frac{1}{ω^2}
\]

### Ambient Vibration Test Pseudo-flexibility

\[
[M_A] = [Ψ][M][Ψ]^T
\]

\[
M_{A\mathbf{r}} \{A\}_r = \{Φ\}
\]

Incorporate FEM and estimate mass matrix.

Lumped mass matrix case yields

\[
Φ_{ij} = \frac{ψ_{ij}}{\sqrt{\sum_{k=1}^{n} m_k ψ_{kj}^2}}
\]

\[
[f_{ij}^*] = [Φ][Ω][Φ]^T
\]
Comparison of impact and ambient test based deflections

True Deflection
\[ \{ \delta \} = [ f ] \{ F \} \]

Pseudo Deflection
\[ \{ \delta^* \} = [ f^* ] \{ F \} \]

\[ \{ F \} : \text{Unit load at every DOF} \]

Percentage error per DOF
\[ \varepsilon = \frac{\sum_{k=1}^{n} \left[ \frac{\delta^*_k - \delta_k}{\delta_k} \right] \left[ \frac{\delta^*_k + \delta_k}{2 \max(\delta_k)} \right]}{n} \]

Distortions in the unit normalized deflection shapes can be taken as a measure of uncertainty impact.
Different Boundary and Excitation Conditions

Steel Roller

Steel Roller & Additional Mass

Neoprene Roller

- Broadband random shaker excitation at the support
- Broadband random shaker excitation on the laboratory floor
- Narrowband manual excitation on the structure
- Narrowband manual excitation through different points on the structure
Classification of Modal Parameter Identification Algorithms

- Subspace Identification Algorithm
- Eigenvalue Realization Algorithm
- State-Space Modeling of Signal and noise
- High Order ARMA Modeling of signal
- Polyreference Time Domain Algorithm
- Polyreference Freq. Domain Algorithm
- Complex Exponential Algorithm
- Orthogonal Polynomial Algorithm
- SVD
- Modal Parameters
- Zero Order Spatial Modeling of signal
- Complex Mode Indicator Function Algorithm
Modal Parameter Identification Steps using CMIF Algorithm

**Impulse Response Functions**

- CMIF Simulation

**Frequency Response Functions**

- Enhanced FRF
- Curve Fit
- Enhanced Phase

**Singular Value Decomposition**
Flow Chart of Signal Preprocessing Uncertainty Study

Structure

- Steel Roller
- Steel Roller + Weight
- Neoprene Roller

Excitation

- Superstructure Not Distributed
- Superstructure Distributed
- Substructure Not Distributed
- Substructure Distributed

Preprocessing

- Random Dec.
- Correlation Func.
- Signal L-1
- Signal L-2
- Signal L-3
- W/ Exp. Window
- W/o Exp. Window
- DFT
- CMIF
- PTD
- SSI

Algorithm

- Signal Modeling
Random Decrement Method

\[
RD_{xx}(\tau) = \frac{1}{N} \sum_{i=1}^{N} x(t_i + \tau) \{a_1 \leq x(t_i) < a_2\}
\]

\[
RD_{yy}(\tau) = \frac{1}{N} \sum_{i=1}^{N} y(t_i + \tau) \{a_1 \leq y(t_i) < a_2\}
\]
Correlation Functions

Direct Method (*Correlogram* Method)

Direct method utilizes of calculation of cross and auto correlation functions and taking the FFT of resultant correlation functions.

\[
R_{XX}(\tau) = \frac{1}{N - \tau} \sum_{i=1}^{N-\tau} x(t_i) x(t_i + \tau)
\]

\[
R_{XY}(\tau) = \frac{1}{N - \tau} \sum_{i=1}^{N-\tau} x(t_i) y(t_i + \tau)
\]

Welch’s Periodogram Method:

The method consists of dividing the time series data into segments, computing a modified periodogram of each segment, and then averaging the PSD estimates.

<table>
<thead>
<tr>
<th></th>
<th>RD</th>
<th>Periodogram</th>
<th>Corrolegram</th>
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<tr>
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## Assessment of Uncertainty due to averaging – Table Format

### Impact Test Results

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<th>Random Shaker Input</th>
<th>% Diff. Frequency</th>
<th>MAC</th>
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### Ambient Test Results

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<th>% Diff. Frequency</th>
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<th>PTD Frequency (Hz)</th>
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### Uncertainty Parameters

- **Random Decrement**
  - Value: 2.27
  - Value: 109.05
  - Value: 2.43

- **Correlogram**
  - Value: 1.70
  - Value: 1.38
  - Value: 1.26
Signal Length

Raw signals → RD averaging → Averaged Signals

N=2048
N=4096
N=8192
Assessment of Uncertainty due Signal Length

Impact Test Results

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<tr>
<th>No.</th>
<th>CMIF Frequency (Hz)</th>
<th>CMIF Frequency (Hz)</th>
<th>% Diff. Frequency</th>
<th>MAC</th>
<th>CMIF Frequency (Hz)</th>
<th>% Diff. Frequency</th>
<th>MAC</th>
<th>CMIF Frequency (Hz)</th>
<th>% Diff. Frequency</th>
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Ambient Test Results

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<td>εεεεεε</td>
<td>εεεεεε</td>
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RANDOM DECREMENT

\( \varepsilon \) 2.43 2.27 2.36
Assessment of Uncertainty due to Exponential window

<table>
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<th>No.</th>
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<th>Ambient Test Results</th>
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Error/DOF (ε)

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<td>CMIF</td>
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<tr>
<td>PTD</td>
</tr>
<tr>
<td>SSI</td>
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</table>
Alternative Parametric Method (Prony’s Method) for Conditioning RD Results

Prony's method is an algorithm for finding an IIR filter with a prescribed time domain impulse response. It has applications in filter design, exponential signal modeling, and system identification (parametric modeling).

\[
H(z) = \frac{B(z)}{A(z)} = \frac{b(1) + b(2)z^{-1} + \cdots + b(n + 1)z^{-n}}{a(1) + a(2)z^{-1} + \cdots + a(m + 1)z^{-m}}
\]

IIR filter coefficients a and b may be calculated by Prony’s method from time domain impulse response i.e. the result of random decrement process.
Comparison of Raw RD & Conditioned RD Results

Standard RD-CMIF Application (nonparametric)

RD IRF. In@11Out@15

Exp. Window Applied

CMIF

Conditioned RD Application (parametric)

RD IRF. In@11Out@15

Prony’s Method

Time Dom. IIR Filter Parameters (a & b)

Back Calculated IRF

CMIF
Assessment of Uncertainty due to Signal Modeling

<table>
<thead>
<tr>
<th>No.</th>
<th>Impact Test Results</th>
<th>Ambient Test Results</th>
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\( \varepsilon \) \hspace{1cm} 2.30 \hspace{1cm} 57.71 \hspace{1cm} 1.96

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\( \varepsilon \) \hspace{1cm} 1.76 \hspace{1cm} 1.50 \hspace{1cm} 1.29
Flow Chart of Excitation Uncertainty Study

Structure
- Steel Roller
  - Superstructure Not Distributed
    - Random Dec.
    - Correlation Func.
    - Signal L-2
    - W/ Exp. Window
    - DFT
    - CMIF
  - Superstructure Distributed
    - W/o Exp. Window
    - SSI
- Steel Roller + Weight
  - Substructure Distributed
  - Signal L-1
- Neoprene Roller
  - Substructure Not Distributed
  - Signal L-3
  - Signal Modeling
  - PTD
  - SSI

Excitation
- Steel Roller
- Superstructure Not Distributed
- Superstructure Distributed
- Substructure Not Distributed

Preprocessing
- Signal L-1
- Signal L-2
- Signal L-3
- W/o Exp. Window
- W/ Exp. Window

Algorithm
CMIF Plots of Different Excitation Cases

Substructure – Broadband – Not Distributed

Substructure – Broadband – Distributed

Superstructure – Narrowband – Not Distributed

Superstructure – Narrowband – Distributed
Assessment of Uncertainty due to Excitation

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Flow Chart of Structural Uncertainty Study

Structure

- Steel Roller
- Steel Roller + Weight
- Neoprene Roller

Excitation

- Superstructure Not Distributed
- Superstructure Distributed

Preprocessing

- Random Dec.
- Correlation Func.
- Signal L-1
- Signal L-2
- Signal L-3
- W/ Exp. Window
- W/o Exp. Window
- Signal Modeling

Algorithm

- DFT
  - CMIF
- PTD
- SSI
Effect of Different Boundary Conditions

Impact Test FRF

Boundary

True Deflection

Pseudo Deflection

Method $\epsilon$

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Method $\epsilon$

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1. Research motivation, objectives, definitions, past research
2. Research Plan
   i. Physical models
   ii. Analytical models
   iii. Experimental tools and parameter id. models
3. Uncertainty assessment study
4. Statistical methods for data quality assessment
5. Conclusions and summary
Data Quality Assessment – Overview

- Separation of good data from bad data is coupled with parameter identification problem
- Several parametric and nonparametric methods may be utilized for investigation (i.e. signal modeling, ICA etc.)
- Descriptive statistics may be useful for detection of clear abnormalities
- Kurtosis has been used in vibration monitoring of machinery to detect alignment and wear problems and it may be useful in data quality assessment

\[
kurt(X) = \frac{E[(X - \mu)^4]}{\sigma^4} - 3
\]

Low Kurtosis

High Kurtosis
Data Quality Assessment – Example

[Graph showing raw data and kurtosis for different channels]
Conclusions

• Evaluation of data in the flexibility domain provides information about the test quality/reliability that cannot be extracted otherwise

• Preprocessing:
  i. Averaging is the most critical step in preprocessing and using correlation function over random decrement consistently provided better results
  ii. Exponential windowing may be detrimental and should be avoided when S/N is low
  iii. Signal modeling may enhance the results quality when S/N ratio is low, but it is not a robust method
  iv. Averaging time window size (frequency resolution) has no significant impact unless there are closely spaced modes
Conclusions

• Postprocessing:
  i. High order model based algorithms i.e. SSI and PTD provide undistorted deflection shapes which indicate improvement in the results
  ii. SSI algorithm performs better correlation than the other algorithm when signals have low S/N ratio in the modal space with impact test
  iii. No algorithm is significantly superior than others

• Excitation:
  i. PTD method resulted in high quality results when the structure was excited through the superstructure

• Boundary conditions:
  i. No preprocessing or parameter id algorithm has been shown to make a difference to mitigate the uncertainty caused by boundary conditions
Research Accomplishments

- Different uncertainty sources in operational modal analysis have studied in detail on a physical model.
- The impact of uncertainty has been assessed by using the impact test results as a reference which was independently verified by static load tests.
- A novel physics-based uncertainty evaluation index using pseudo-flexibility approach has been presented.
- Statistical methods for data quality evaluation have been explored. Kurtosis has been presented as a simple tool to detect noisy channels.
Future work and recommendations

• Transform of information from modal domain to physical domain (flexibility domain) remains to be studied. What is the best scaling method for ambient mode shapes?

• Similitude rules needs to be incorporated and studied for future laboratory studies

• Study of different damage cases is necessary

• Different structure types should be studied

• Uncertainty mitigation should be an inherent component of field research
THANK YOU