Uncertainty in Field Testing and Monitoring Applications

Kirk A. Grimmelsman & A. Emin Aktan

Drexel University
Contents

- Introduction and definitions
- State of practice: field experiments and monitoring of civil infrastructure
- Types of uncertainty affecting reliability of field measurements
- Ambient vibration testing in laboratory of a cantilever beam
- Ambient vibration testing of the Brooklyn Bridge
- Continuous monitoring of a pin & hanger retrofit
- Conclusions
Health Monitoring Paradigm

- Health Monitoring: track health by data and analytical simulation so current and expected performance can be described in a proactive manner.

- Health Monitoring paradigm offers great advantages:
  - Objective characterization of health
  - Proactive management of maintenance
  - Enabler of performance-based engineering

- Requires integration of experimental, analytical, and information technologies

- System Identification approach offers rational framework for optimum integration of these technologies
# Classification of Experimental Tools I

<table>
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<th>Classification</th>
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<tr>
<td></td>
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<td>(Static or Quasi-Static Testing)</td>
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<td>Measure Inputs &amp; Outputs Only</td>
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## Classification of Experimental Tools II

<table>
<thead>
<tr>
<th>Long-Term Testing with Intermittent or Continuous Monitoring</th>
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<tbody>
<tr>
<td><strong>Low-Bandwidth Measurements</strong></td>
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<tr>
<td>Construction Effects</td>
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<td>Wind/Ambient Weather Conditions</td>
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<tr>
<td>Temperature</td>
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<td>Movements or Displacements</td>
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<tr>
<td>Mechanical Variables (Force, Stress, Strain, etc)</td>
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<tr>
<td>Deterioration/Damage Effects</td>
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<tr>
<td>Changes in: Geometry, Electro-chemical Properties</td>
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<tr>
<td><strong>High-Bandwidth Measurements</strong></td>
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<tr>
<td>Vibrations</td>
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<tr>
<td>Traffic Loads</td>
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<td>Operations</td>
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<td>Incidents or Accidents</td>
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<td>Impacts</td>
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<td>Earthquake</td>
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<tr>
<td>Security Monitoring</td>
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</table>
Cantilever Beam Test
Dynamic Testing of a Cantilever Beam

- **Laboratory Testing:**
  - Simple structure under near ideal conditions
  - Analytical and experimental characterization
  - Excitation: (1) random shaker @ base, (2) random taps on beam (spatially distributed excitation), and (3) multi-reference impact testing

- **Test Objectives:**
  - Calibration of different dynamic test and evaluation methods
  - Identify, characterize, and mitigate sources of uncertainty
Cantilever Beam Setup

Support

Steel Tube Section
3” x 1.5” x 0.125”

5 Spaces @ 23.5” = 117.5”

Instrumented Cantilever Beam
Partial Differential Equation Solution

Classical solution method for cantilever beam with distributed mass and stiffness (ignores shear force and rotary motion)

Natural Frequencies:

\[ f_1 = 4.6933 \text{ Hz} \]
\[ f_2 = 29.4147 \text{ Hz} \]
\[ f_3 = 82.3704 \text{ Hz} \]
\[ f_4 = 161.4167 \text{ Hz} \]
\[ f_5 = 266.8047 \text{ Hz} \]
Laboratory Testing Overview

Experimental Testing

Static Testing
- Controlled Input
  - Static Flexibility

Dynamic Testing

Controlled Input
- Controlled Initial Conditions
- Ambient Vibration
  - Random Taps on Beam
  - Random Base Excitation

Impact
- Pre-Processing
  - Time Domain Algorithms
  - Frequency Domain Algorithms
    - Frequencies, Mode Shapes, Damping & Modal Flexibility

Pull-Release
- Pre-Processing
  - Time Domain Algorithms
  - Frequency Domain Algorithms
    - Frequencies, Mode Shapes & Damping
Cantilever Beam Experimental Setup

Support Stand @ Fixed End

Shaker @ Base of Stand
Mechanisms Contributing to Uncertainty in Lab Test

- Signal-to-noise ratio for accelerometers on beam near support location
- Excitation quality: base excitation at single point versus spatially distributed taps on beam
- Transmission of excitation to beam through support during shaker test
- Relative vibration of floor during shaker test
- Data processing approach
Modal Parameter Estimation by Peak-Picking as a Conceptual Check of Behavior

- Time domain signal divided into overlapping segments of fixed size
- Hanning window applied to each segment to reduce leakage
- Adjacent segments overlapped by 50% to capture info at tails of the windowed segments and increase number of averages (smoother spectrum)
- Frequencies identified from peaks in PSD spectra
- Amplitude and sign of each mode shape from DFT (computed using FFT algorithm)
PSD: Random Shaker Input @ Base

PSD for Cantilever, Record Length = 10 minutes

Sampling Rate = 800 Hz
Test Duration = 10 minutes
Segment Size = 8192 points
Frequency Resolution = 0.0977 Hz
# Natural Frequencies for Cantilever Beam from PSD

<table>
<thead>
<tr>
<th>Mode</th>
<th>Classical Solution Frequencies (Hz)</th>
<th>Random Shaker Input @ Base Frequencies (Hz)</th>
<th>% Difference from Classical Solution</th>
<th>Random Tapping on Beam Frequencies (Hz)</th>
<th>% Difference from Classical Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.6933</td>
<td>4.7852</td>
<td>1.96</td>
<td>4.7852</td>
<td>1.96</td>
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<td>2</td>
<td>29.4147</td>
<td>29.6875</td>
<td>0.93</td>
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<td>0.60</td>
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<td>3</td>
<td>82.3704</td>
<td>83.3984</td>
<td>1.25</td>
<td>83.3008</td>
<td>1.13</td>
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<tr>
<td>4</td>
<td>161.4167</td>
<td>162.0117</td>
<td>0.37</td>
<td>162.1094</td>
<td>0.43</td>
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<td>5</td>
<td>266.8047</td>
<td>263.6719</td>
<td>-1.17</td>
<td>263.1836</td>
<td>-1.36</td>
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</tbody>
</table>
FRFs for Different Excitation
Modal Shape Estimation - DFT

Time Domain Segments

FFT 1
FFT 2
FFT 3
FFT 4
FFT n

Magnitude
Magnitude
Magnitude
Magnitude
Magnitude

Phase
Phase
Phase
Phase
Phase

Average Magnitude
Average Phase

FFT MAGNITUDE - RMS, Record Length = 10 minutes

No. of Averages = 118

FFT PHASE, Record Length = 10 minutes

Phase Information is Poor

RMS Average:

Magnitude & phase calculated for FFT of each segment.
Magnitude and phase results are averaged for all segments.

Sensor channels

1
6
Modal Shape Estimation - DFT

Time Domain Segments

alendar

gneral

gneral

gneral

gneral

FFT 1
FFT 2
FFT 3
FFT 4
FFT n

Real Part
Real Part
Real Part
Real Part
Real Part

Imag. Part
Imag. Part
Imag. Part
Imag. Part
Imag. Part

Avg. Real Parts
Avg. Imaginary Parts

Magnitude & Phase

FFT MAGNITUDE - VECTOR AVG, Record Length = 10 minutes

No. of Averages = 118

Magnitude Spectra are Noisy

FFT PHASE - VECTOR AVG, Record Length = 10 minutes

Phase Information is Good

Vector Average:

Real and imaginary parts of each FFT segment are averaged separately.

Sensor channels
Modal Shape Estimation - DFT

FFT MAGNITUDE - RMS, Record Length = 10 minutes

FFT PHASE - VECTOR AVG, Record Length = 10 minutes

Hybrid Approach:
RMS Avg. of FFT for Amplitude and Vector Avg. of FFT for Phase

No. of Averages = 118
“White Washing” to Obtain Normal Modes

Regions of Uncertainty

In-Phase with Reference DOF

Out-of-Phase with Reference DOF

+90 deg

+180 deg

+270 deg

0 deg

In-Phase with Reference DOF

Out-of-Phase with Reference DOF

In-Phase with Reference DOF

Out-of-Phase with Reference DOF
Comparison of Mode Shapes

Random Shaker Excitation @ Base and Random Taps on Beam

S/N ratio is low for support accelerometer
### Some Sources of Uncertainty in Vibration Testing

**INPUT**
- Non-stationary
- Echoes/Reflections
- Bandwidth
- Directionality
- Select Harmonics
- Interference/Noise

**STRUCTURAL SYSTEM**
- Non-stationarity due to changes in environment
- Nonlinearity
- Incomplete free body/Appendage tests
- Lack of observability due to insufficient sensor density
- Scale-induced complexity

**OUTPUT (DATA)**
- Asynchronous
- Filters
- Sensor calibration
- Noise & bias
- Spurious pulses
- Bandwidth
- Window length
- Freq. resolution

**DATA PROCESSING**
- Data quality measures
- Error ID/Cleaning
- Filtering, averaging, and windowing
- Post-processing

**TEST DESIGN**
- Access
- Excitation
- Sensor density and modality
- Diagnose/Mitigate malfunctions

**PARAMETER ID**
- Parameter grouping
- Sensitivity
- Bandwidth
- Modality
- Objective Function
- Optimization

**ANALYTICAL MODEL**
- Completeness
- Material variability
- Geometry
- BC & CC
- Temporal/spatial Nonlinearity & non-stationarity

**MECH PROPERTIES**
- Frequency band
- Modal order
- Spatial adequacy
- 3D vs. idealized
- Separation
- Amplitude & phase
- Damping

---

**Some Sources of Uncertainty in Vibration Testing**

#### INPUT
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#### MECH PROPERTIES
- Frequency band
- Modal order
- Spatial adequacy
- 3D vs. idealized
- Separation
- Amplitude & phase
- Damping
Types of Uncertainty Affecting Reliability of Field Measurements

- **Human Errors (HE)**
  - Inattention/Thoughtlessness
  - Inexperience
  - Omission (Forgetfulness)
  - Commission (Bad Design)

- **Random Phenomena (RP)**

- **Epistemic Uncertainty (EU)**
  - Less Understood Phenomena (LUP)
  - Unknown Phenomena (UP)
Conclusions

- Input, structure, output, experimental setup, data processing, and other systems such as environment act as one interconnected system in an experiment.
- Each element above contributes many components of uncertainty to the experiment.
- Even when we experiment in laboratory with idealized physical model, we observe some mechanisms of uncertainty that impact the reliability of the results obtained by different input/post-processing combinations.
- In spite of the uncertainty in the laboratory, we are still able to identify all 5 frequencies and mode shapes with reasonable accuracy; however, when we go to field with real structures, this may not be the case.
- Uncertainty was greatest near support.
Performance of Infrastructure

What is so different about civil infrastructure systems?

- Fabricated/constructed nature
- Variations in geometric and material properties, environment, site conditions, usage, age, condition, etc.
- Lack of objective data = significant epistemic uncertainty = greater cost & less than optimal performance

Performance limit states for constructed systems

- Codes consider only a few of many possible limit states (Functionality, Serviceability & Durability, Safety & Stability of Failure, Safety at Conditional Limit States)
- Performance Based Engineering: expected performance criteria for the full spectrum of limit states in the life cycle of a bridge

Why is state of practice so deficient? Lack of objective data

Health index Beta – different for different limit states
Current State of Practice: Field Testing and Monitoring

- Practical objectives are primary motivation:
  - Reduce or quantify the uncertainty related to some observed behavior, performance or mechanism (Reactive)
  - Improve the reliability of traditional design or analysis approaches
  - Proactive structural health monitoring rarely considered

- Lack of knowledge regarding capabilities/limitations of experiments – education emphasis is design instead of maintenance or renewal

- Lack of standards or guidelines for field experiments (need is recognized, question is how to get there)
  - Limited or no scientific characterization of how the parameters in stages of experiment affect the quality and reliability of the result
  - Design, execution, and interpretation rely significantly on heuristics
Dynamic Testing of Bridges

- Typical applications:
  - System identification for FE model calibration
    (i.e. seismic retrofits, baseline for HM)
  - Damage detection/diagnosis

- Two possible implementations: (1) Forced-Excitation Test and (2) Ambient Vibration Test

- Forced-vibration testing is not always feasible

- Fundamental assumptions regarding structure under test: (1) linear, (2) stationary, and (3) observable
Ambient Vibration Test of the Henry Hudson Bridge
Objective: Extract modal parameters (frequencies, mode shapes, and damping) from structure subject to random dynamic excitation.

- Damping estimates not very reliable
- Dynamic excitation is not measurable
- Typical sources of excitation for bridges include traffic, wind, pedestrians and micro-tremors (ground motions)
- Excitation is assumed to be stationary and broad-band, Gaussian white noise
Henry Hudson Bridge

<table>
<thead>
<tr>
<th>South Approach</th>
<th>South Viaduct</th>
<th>South Tower</th>
<th>Arch Span</th>
<th>North Tower</th>
<th>North Viaduct</th>
<th>North Approach</th>
</tr>
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<tbody>
<tr>
<td>94 m</td>
<td>91 m</td>
<td></td>
<td>256 m</td>
<td></td>
<td></td>
<td>82 m</td>
</tr>
</tbody>
</table>

Manhattan

The Bronx

EAST ELEVATION
Henry Hudson Bridge
Description of Experiment

- Ambient vibration testing of arch and viaduct spans conducted in two stages
- Fixed array of accelerometers used for both stages
- 36 accelerometers used for Stage 1 and 40 accelerometers used for Stage 2
- 9 accelerometer locations common to both stages
- Mix of ICP and capacitive accelerometers used
- Data sampled primarily at 200 Hz in 15 minute records
- Monitor for 1 week during each test stage
## Accelerometer Calibration

<table>
<thead>
<tr>
<th>Serial #</th>
<th>Mass Calibration (mV/g)</th>
<th>Shaker Calibration @100 Hz (mV/g)</th>
<th>Factory Calibration (mV/g)</th>
<th>Shaker Calibration @1 Hz (mV/g)</th>
<th>Deviation between Shaker Calibration at 1 Hz and 100 Hz (%)</th>
<th>Deviation of Shaker Calibration from Factory Calibration (100Hz) (%)</th>
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<tbody>
<tr>
<td>ICP-1255</td>
<td>1146</td>
<td>1144</td>
<td>1155</td>
<td>1122</td>
<td>1.92</td>
<td>0.95</td>
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<td>1158</td>
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<td>1113</td>
<td>1105</td>
<td>0.80</td>
<td>-0.09</td>
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<td>ICP-8678</td>
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<td>1096</td>
<td>1092</td>
<td>1162</td>
<td><strong>-6.00</strong></td>
<td>-0.37</td>
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<td>ICP-8680</td>
<td>1053</td>
<td>1058</td>
<td>1052</td>
<td>1060</td>
<td>-0.21</td>
<td>-0.57</td>
</tr>
</tbody>
</table>
Sensors and Data Acquisition
Raw Data with Noise

Arch - Transverse

Viaduct - Transverse
Raw Data with Bias Error

Tower Longitudinal

Capacitive Accelerometers
Raw Data with No Errors

Arch - Transverse

Tower Longitudinal

Arch - Vertical

Tower Longitudinal
Data with Different Amplitudes

- **High Amplitude Data**
  - Channel 3
  - Arch - Vertical

- **Low Amplitude Data**
  - Channel 26
  - Arch - Transverse
Filtered Data

channel 3 after band pass filtering

Arch - Vertical

Channel 26 after band pass filtering

Arch - Transverse
Conditioned Data for Vertical Channels

FFT of Data from Vertical Channels

No Window or Averaging

PSD of Data from Vertical Channels after Windowing & Averaging

Hanning Window & Ensemble Averaging
Processed Data for All Channels

FFT of Data from All Channels

No Window or Averaging

PSD of Data from All Channels after Windowing & Averaging

Hanning Window & Ensemble Averaging
## Ambient Test Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Stage 1 Test</th>
<th>Combination of Stage 1 &amp; Stage 2 Tests</th>
<th>Mode Description</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.606 Hz</td>
<td>0.615 Hz</td>
<td>Transverse</td>
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<tr>
<td>2</td>
<td>0.737 Hz</td>
<td>0.742 Hz</td>
<td>Vertical</td>
</tr>
<tr>
<td>3</td>
<td>0.928 Hz</td>
<td>0.957 Hz</td>
<td>Vertical</td>
</tr>
<tr>
<td>4</td>
<td>1.157 Hz</td>
<td>1.191 Hz</td>
<td>Transverse</td>
</tr>
<tr>
<td>5</td>
<td>1.475 Hz</td>
<td>1.504 Hz</td>
<td>Vertical</td>
</tr>
<tr>
<td>6</td>
<td>1.592 Hz</td>
<td></td>
<td>Transverse</td>
</tr>
<tr>
<td>7</td>
<td>1.719 Hz</td>
<td>1.709 Hz</td>
<td>Torsional</td>
</tr>
<tr>
<td>8</td>
<td>1.738 Hz</td>
<td></td>
<td>Vertical</td>
</tr>
<tr>
<td>9</td>
<td>1.914 Hz</td>
<td></td>
<td>Transverse</td>
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<tr>
<td>10</td>
<td>2.363 Hz</td>
<td></td>
<td>Transverse</td>
</tr>
<tr>
<td>11</td>
<td>2.481 Hz</td>
<td></td>
<td>Transverse</td>
</tr>
<tr>
<td>12</td>
<td>2.446 Hz</td>
<td>2.559 Hz</td>
<td>Vertical</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>2.900 Hz</td>
<td>Torsional</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>3.301 Hz</td>
<td>Vertical</td>
</tr>
</tbody>
</table>
FE Model of Bridge in SAP2000
### FEM & Experimental Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Initial FE Model</th>
<th>Calibrated FE Model</th>
<th>Ambient Test</th>
<th>Mode Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.497 Hz</td>
<td>0.588 Hz</td>
<td>0.615 Hz</td>
<td>Transverse</td>
</tr>
<tr>
<td>2</td>
<td>0.516 Hz</td>
<td>0.721 Hz</td>
<td>0.742 Hz</td>
<td>Vertical</td>
</tr>
<tr>
<td>3</td>
<td>0.874 Hz</td>
<td>0.973 Hz</td>
<td>0.957 Hz</td>
<td>Vertical</td>
</tr>
<tr>
<td>4</td>
<td>0.980 Hz</td>
<td>1.054 Hz</td>
<td>1.191 Hz</td>
<td>Transverse</td>
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<td>2.266 Hz</td>
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<td>1.714 Hz</td>
<td>1.738 Hz</td>
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<td>Vertical</td>
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<td>9</td>
<td>1.487 Hz</td>
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</tr>
<tr>
<td>10</td>
<td></td>
<td>-</td>
<td>2.363 Hz</td>
<td>Transverse</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>2.653 Hz</td>
<td>2.481 Hz</td>
<td>Transverse</td>
</tr>
<tr>
<td>12</td>
<td>2.357 Hz</td>
<td>2.505 Hz</td>
<td>2.559 Hz</td>
<td>Vertical</td>
</tr>
<tr>
<td>13</td>
<td>2.901 Hz</td>
<td>2.900 Hz</td>
<td></td>
<td>Torsional</td>
</tr>
<tr>
<td>14</td>
<td>3.276 Hz</td>
<td>3.301 Hz</td>
<td></td>
<td>Vertical</td>
</tr>
</tbody>
</table>
Mode Shape Comparison

FE Mode 1
f = 0.588 Hz
Mode Shape Comparison

Vertical Mode 1, Test = 0.742 Hz, SAP = 0.721 Hz

FE Mode 2
f = 0.721 Hz

Projection of Mode Shape Points
Mode Shape Comparison

FE Mode 3
f = 0.973 Hz

Vertical Mode 2, Test = 0.957 Hz, SAP = 0.973 Hz

Projection of Mode Shape Points

Vertical Mode 2, Test = 0.957 Hz, SAP = 0.973 Hz

Distance (ft)
Mode Shape Comparison

Mode 4
$f = 1.054$ Hz

Transverse Mode 2, Test = 1.191 Hz, SAP = 1.054 Hz
Conclusions

- Most uncertainty was associated with data errors – a challenge not really faced in laboratory
- Most data errors can be removed by digital signal processing, provided test design is adequate
- Primary excitation was traffic and this was spatially distributed due to type of structure
- Uncertainty due to non-stationary structure – painting equipment removed between stages and temperature effects on structure
Ambient Vibration Testing of the Brooklyn Bridge
Scope and Objectives

- Ambient vibration testing a component of seismic evaluation and retrofit study
- Results used for system identification to improve reliability of FE models
- Focus on towers, but span responses also measured
- Identify frequencies, mode shapes and damping
Description of Experiment

- Fixed array of 43 accelerometers located on towers and spans
- Measure longitudinal, transverse and torsional vibrations of towers
- Measure vertical, transverse and torsional vibrations of main span and side span adjacent to Brooklyn Tower
Description of Experiment

- Wind speed and direction measured
- Ambient temperature measurements
- Vibration data sampled at multiple rates (primarily 20 Hz and 40 Hz)
- Measurements recorded over 1 month period
- Intermittent & continuous operation of data acquisition system
Tower Instrumentation Scheme

Brooklyn Tower Elevation

Level H
Level G
Level F
Level E
Level C
Level B
Level A

Manhattan Tower Elevation

Level D

153'-0"
272'-6"
119'-6"
Accelerometer Layout

Tower Levels Above Deck

Transverse Accelerometer
Longitudinal Accelerometer
Span Instrumentation Scheme

- Side Span: 454'
- Main Span: 240'
- Brooklyn Bound Traffic Lanes: 185'
- Manhattan Bound Traffic Lanes: 393'

Partial Plan

Brooklyn Tower

V T

Clean
Accelerometer Layout for Spans

Pedestrian Walkway

Outer Truss
Inner Truss
Inner Truss
Outer Truss

Roadway

33'-0"
16'-6"
33'-0"

STIFFENING TRUSSES
Cross Section

T Transverse Accelerometer
L Longitudinal Accelerometer
Accelerometer Installation
Uncertainty in Experiment

- Spurious noise spikes in data – remove during preprocessing
- Quality of ambient excitation:
  - Low level excitation
  - Non-stationary excitation
  - Ambient excitation primarily from traffic on spans – transfer to tower only occurs through connections with deck, main cables, and stays
- Identification of critical tower modes
- Damping estimates
Typical Low Level Ambient Excitation

Filtered Time Domain Data for Several Span & Brooklyn Tower Top Sensors

Zoomed View of Filtered Time Domain Data for Several Span & Brooklyn Tower Top Sensors
Effect of Spurious Noise Spikes

Filtered Time Domain Data with Noise for Channel #13

PSD for Channel #13
Non-Stationary Excitation

Frequency Domain – Tower Transverse Acceleration
(22-NOV-04 16:01 – 20:00)

Duration = 4 Hours

Average Normalized PSD

1.587 Hz
2.695 Hz
4.468 Hz, 4.531 Hz
4.639 Hz, 4.668 Hz
5.000 Hz
Non-Stationary Excitation

Time Domain Amplitude – Tower Transverse Acceleration
(22-NOV-04 17:01 – 17:16)

Duration = 15 minutes
Non-Stationary Excitation

Frequency Domain – Tower Transverse Acceleration

(22-NOV-04 17:01 – 17:16)
Non-Stationary Excitation

Time Domain Amplitude - Tower Transverse Acceleration

(22-NOV-04 18:31 – 18:46)

Duration = 15 minutes
Non-Stationary Excitation

Frequency Domain – Tower Transverse Acceleration

(22-NOV-04 18:31 – 18:46)
Cross Spectral Density & Coherence
Top and Bottom Level Transverse Accelerometers
Tower Excitation from Traffic

 Ideal Excitation

 More Probable Excitation
BROOKLYN TOWER TRANSVERSE MODE SHAPES
40 Hz Data Set - Normalized w.r.t. Sensor S51V

- 1.587 Hz
- 2.695 Hz

Levels:
- Level H
- Level G
- Level F
- Level E
- Level C
- Level B

Ground Level
BROOKLYN TOWER TRANSVERSE MODES
40 Hz Data Set - Normalized w.r.t. Sensor S51V

Amplitude vs. Height (ft) graph showing mode shapes at different frequencies for various levels.

- 4.468 Hz
- 4.531 Hz
- 4.639 Hz
- 4.668 Hz
- 5.000 Hz

Levels indicated:
- Level C
- Level E
- Level F
- Level G
- Level H
- Ground
# Identified Tower Modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.387</td>
<td>1\textsuperscript{st} Longitudinal Mode</td>
</tr>
<tr>
<td>2</td>
<td>1.597</td>
<td>1\textsuperscript{st} Lateral Mode</td>
</tr>
<tr>
<td>3</td>
<td>2.705</td>
<td>1\textsuperscript{st} Torsional Mode</td>
</tr>
<tr>
<td>4</td>
<td>3.765</td>
<td>2\textsuperscript{nd} Longitudinal Mode</td>
</tr>
<tr>
<td>5</td>
<td>4.668</td>
<td>2\textsuperscript{nd} Lateral Mode</td>
</tr>
<tr>
<td>6</td>
<td>4.766</td>
<td>Coupled lateral and longitudinal mode</td>
</tr>
</tbody>
</table>
Tower Longitudinal Mode Shapes

BROOKLYN TOWER LONGITUDINAL MODE SHAPES

- **Height Above Base (ft)**
- **Normalized Amplitude**

**Tower Top**

**Tower Base**

- Bold shapes have best coherence & largest peak in frequency spectra.
BROOKLYN TOWER LATERAL MODE SHAPES
Middle Leg Transverse Sensors at Level F and Level G

- Bold shapes have best coherence & largest peak in frequency spectra

- Tower Top
- Tower Base

Height Above Base (ft)

Normalized Amplitude
Tower Lateral Mode Shapes

North Tower Leg Sensors at Level F and Level G

BROOKLYN TOWER LATERAL MODE SHAPES
North Leg Transverse Sensors at Level F and Level G

Bold shapes have best coherence & largest peak in frequency spectra
BROOKLYN TOWER TORSIONAL MODE SHAPES

Tower Torsional Mode Shapes

Tower Top

Tower Base

Bold shapes have best coherence & largest peak in frequency spectra
Analytical Model of Isolated Tower

3D Tower

Cross-Sections of Different Tower Levels
Analytical Model Results for Tower

Mode 1 – 1st Long.
1.201 Hz

Mode 2 – 1st Tran.
1.962 Hz

Mode 3 – 1st Tor.
2.874 Hz

Mode 4 – 2nd Long.
2.975 Hz

Mode 5 – 2nd Tran.
4.541 Hz

Mode 6 – 2nd Tor.
4.921 Hz
Conclusions

- Uncertainty due to data quality and errors (bias, noise spikes) – corrected through digital signal processing and manual removal of spikes
- Uncertain excitation due to transfer of traffic excitation through interfaces with towers
- Non-stationary excitation – sample for longer time
- Pattern recognition approaches can help to identify some sources of uncertainty
- Tower modes coupled with span modes – reflection of motions between the two components
- Uncertainty related to extracting the most critical tower modes from the coupled modes of the spans and towers
Thank You
Tower Mode 2 - 1st Lateral Mode

North Tower Leg

South Tower Leg

Graphs showing amplitude vs. height for different modes:
- PP (1.597 Hz)
- PTD & RD (1.588 Hz)
- PTD & CORR (1.588 Hz)
Tower Mode x – 2nd Lateral Mode

North Tower Leg

South Tower Leg

-1.000 -0.500 0.000 0.500 1.000

-1.000 -0.500 0.000 0.500 1.000

0 50 100 150 200 250 300

HEIGHT

AMPLITUDE

PP (4.668 Hz)
PTD & RD (4.669 Hz)
PTD & CORR (4.667 Hz)