Hybrid Shake Table Testing: Overview, Theory, and Application

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Outline of Presentation

1. Motivation & Overview
2. Theory & Implementation
3. Midlevel Seismic Isolation Application
4. Application with Structural Actuator
5. Tall Building Application
6. Commissioning Test at LHPOST
7. Summary & Conclusions
Motivation & Overview
Motivation

- Many structures exhibit significant rate of loading effects
- Need testing to occur at or near real time
- Large systems such as tall buildings, long-span bridges, or SFSI are difficult to test on shake tables
Motivation

- Enables us to perform dynamic tests of full-scale specimens without exceeding size, strength and weight limitations of shake table.

- With very little effort we can perform a wide range of parameter studies by changing the properties of the analytical portion of the hybrid model.
Hybrid Shake Table Testing

\[ M \ddot{u}_t + C \dot{u}_t + P_r (u_t, \dot{u}_t, \ddot{u}_t) = 0 \]

Dynamic Loading:
- Seismic
- Wind
- Blast/Impact
- Wave
- Traffic

- Inertia
- Energy Dissipation
- Resistance
Hybrid Shake Table Configuration

Tall Building Application

Experimental Portion

Analytical Portion

OpenFresco

3 translational DOF + 3 rotational DOF

Feed motion at top of analytical portion into shake table

Feed forces from load cells back into hybrid model

MTS/PEER Expert Seminar, UCB
Hybrid Shake Table Configuration

1 actuator DOF + 2 table DOF

OpenFresco

Feed motion at top of analytical portion into shake table

Feed forces from load cells back into hybrid model

Bridge Deck

Structural Actuator

Shake Table

Long-Span Bridge Application

Analytical Portion

Experimental Portion
Theory & Implementation

One 6DOF Shake Table
Equations of Motion

1. Slow test
\[
M \dddot{U}_{i+1} + C \dot{U}_{i+1} + P^A \left( U_{i+1}, \ddot{U}_{i+1} \right) + P^E \left( U_{i+1} \right) = P_{i+1} - P_{0,i+1}
\]

2. Rapid test
\[
P^E \left( U_{i+1} \right) = P^E_{r,i+1} - M^E \dddot{U}_{i+1} - C^E \dot{U}_{i+1}
\]

3. Real-time test
\[
M^A \dddot{U}_{i+1} + C^A \dot{U}_{i+1} + P^A \left( U_{i+1}, \ddot{U}_{i+1} \right) + P^E \left( U_{i+1}, \dot{U}_{i+1}, \dddot{U}_{i+1} \right) = P_{i+1} - P_{0,i+1}
\]
\[
P^E \left( U_{i+1}, \dot{U}_{i+1}, \dddot{U}_{i+1} \right) = P^E_{r,i+1} + M^E \dddot{U}_{i+1}
\]

4. Smart shaking table test
\[
P^E \left( U_{t,i+1}, \dot{U}_{t,i+1}, \dddot{U}_{t,i+1} \right) = P^E_{r,i+1} + M^E \dddot{U}_{t,i+1}
\]
Important Analysis Parameters

- OpenSees or Simulink as comp. driver
- Using AlphaOSGGeneralized or KRAlphaExplicit integration method \( (\rho_\infty < 1) \)
- Both integrators require no iterations
- Using MultipleSupport excitation pattern in OpenSees to get absolute response
- Gravity loads on test specimen always present \( \rightarrow \) apply gravity loads to numerical portion before connecting with shake table + apply disp. commands relative to start of test
Connecting to MTS 469D + FlexTest

OpenSees Finite Element Model

OpenFresco Middleware

TCP/IP or SCRAMNetGT

xPC-Target real-time Predictor-Corrector

MTS 469D Controller

MTS FlexTest Controller

Physical Specimen in Laboratory
Improving Stability & Accuracy

- Delay compensation is essential for real-time hybrid simulations (RTHS)
- Use Adaptive Time Series (ATS) delay compensator (by Y. Chae)
- Modify ATS to use target velocities and accelerations computed by predictor-corrector algorithm instead of taking derivatives of target displacements
- Use stabilization and loop-shaping
- Sensor noise reduction by filtering fbk
Three-loop architecture

- ATS delay compensator
- filtering & noise reduction
- TVC or other adv. ctrl. & force balancing
Test Rehearsal

- Use FE-Adapter element method to simultaneously connect hybrid model to a numerically simulated test specimen.
Safety Precautions

- At analysis side
  - Set limit on displacement command (saturation and possibly rate limit)
  - Set limit on actuator force so that once the limit is exceeded, the analysis model sends displacement commands to ramp both table and actuator to starting positions

- At controller side
  - Set both displacement and force limits so that once the limit is exceeded, the actuator pressure is switched to low, therefore, limiting the actuator force that can be applied to the specimen
Applications

One 6DOF Shake Table
A) Midlevel Seismic Isolation Application

- Provide architectural flexibility
  - transitions between different structural systems
- Facilitate addition of new stories
  - minimally increase seismic demands on the existing building
  - exploit untuned mass-damper effect
- Decrease cost of isolation
  - Moat and clearance space
Shake Table

- 5.8m x 2.1m platform
- Linear bearings with $\mu < 10\%$
- Actuator with 667kN, $\pm 0.5m$ and $\pm 1m/sec$ capacity
Specimen

- REACTION WALL
- CONCRETE BLOCKS
- CLEVIS CONNECTION
- JOINT
- COLUMN
- TPS BEARING
- LOAD Cell
- SHAKE TABLE FRAME
- REACTION FLOOR
- HIGH-SPEED ACTUATOR
Triple Friction Pendulum Bearings

\[ T_{\text{eff}} = 1.4 \text{ sec @ 10cm} \]

1/3\textsuperscript{rd} scale

<table>
<thead>
<tr>
<th>PROPERTY</th>
<th>VALUE</th>
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<tbody>
<tr>
<td>R 1</td>
<td>3.00&quot;</td>
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<tr>
<td>R 3</td>
<td>18.64&quot;</td>
</tr>
<tr>
<td>D_IN 1</td>
<td>1.5&quot;</td>
</tr>
<tr>
<td>D_IN 3</td>
<td>3.0&quot;</td>
</tr>
<tr>
<td>D_OUT 1</td>
<td>2.5&quot;</td>
</tr>
<tr>
<td>D_OUT 3</td>
<td>9.0&quot;</td>
</tr>
<tr>
<td>H_0</td>
<td>6.0&quot;</td>
</tr>
<tr>
<td>( \mu _1 )</td>
<td>2%</td>
</tr>
<tr>
<td>( \mu _3 )</td>
<td>9%</td>
</tr>
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</table>
Analytical Substructure Parameters

<table>
<thead>
<tr>
<th>$W_{\text{floor}}$ (kN)</th>
<th>$T_1$</th>
<th>$\zeta_1$</th>
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<tbody>
<tr>
<td>445</td>
<td>1.01</td>
<td>0.03</td>
</tr>
<tr>
<td>445</td>
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<tr>
<td>445</td>
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<td>0.03</td>
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<tr>
<td>445</td>
<td>0.13</td>
<td>0.03</td>
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<table>
<thead>
<tr>
<th>$W_{\text{floor}}$ (kN)</th>
<th>$T_1$</th>
<th>$T_2$</th>
<th>$T_3$</th>
<th>$\zeta_{1,3}$</th>
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<tr>
<td>142</td>
<td>1.02</td>
<td>0.36</td>
<td>0.25</td>
<td>0.03</td>
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<td>0.51</td>
<td>0.18</td>
<td>0.13</td>
<td>0.03</td>
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<tr>
<td>142</td>
<td>0.25</td>
<td>0.09</td>
<td>0.06</td>
<td>0.03</td>
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</table>

Model A

Model B
Shake Table Displacements

Model A

Target Displacements from xPC-Target

Model B

Error between Measured and Target Displacements

Frequency domain
FFTs of acc. histories for $T = 0.25$ sec

**Model A**

- Sub top
- Iso level
- Sup 2nd fl
- Roof

**Model B**

- Sub 1st fl
- Sub 2nd fl
- Sup 2nd fl
- Iso level
- Roof
# Mode shapes and frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td>$k_{iso} = initial$</td>
<td><img src="image1" alt="Mode 1" /></td>
<td><img src="image2" alt="Mode 2" /></td>
<td><img src="image3" alt="Mode 3" /></td>
<td><img src="image4" alt="Mode 4" /></td>
<td><img src="image5" alt="Mode 5" /></td>
<td><img src="image6" alt="Mode 6" /></td>
</tr>
<tr>
<td></td>
<td>1.7 Hz</td>
<td>3.6 Hz</td>
<td>7.0 Hz</td>
<td>9.6 Hz</td>
<td>14.2 Hz</td>
<td>17 Hz</td>
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</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tr>
<td>$k_{iso} = 2nd sliding stage$</td>
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<td><img src="image8" alt="Mode 2" /></td>
<td><img src="image9" alt="Mode 3" /></td>
<td><img src="image10" alt="Mode 4" /></td>
<td><img src="image11" alt="Mode 5" /></td>
<td><img src="image12" alt="Mode 6" /></td>
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<tr>
<td></td>
<td>0.51 Hz</td>
<td>3.4 Hz</td>
<td>4.0 Hz</td>
<td>7.6 Hz</td>
<td>11.0 Hz</td>
<td>15.9 Hz</td>
</tr>
</tbody>
</table>
Movie of Test
Earthquake Exhibit: Life on a Dynamic Planet
B) Application with Structural Actuator

Four 2DOF Shake Tables
Shake Table + Structural Actuator
Hybrid Model Development

Actual Bridge Configuration
(with foundation + soil)

Simplified **Hybrid** OpenSees Model of Bridge (Stage 2)

- Experimental bridge with partial bridge deck weight
- Remaining numerical mass
Experimental Setup

Partial-weight bridge deck

Using table observer to get shear forces at bottom of columns (load cells would be better)
Movie of Test
Displ. Response Comparison

Accuracy is assessed using
- FFTs of tracking error
- Tracking Indicator (by Mercan and Ricles)
- Normalized RMS Error histories
- Comparison with purely numerical simulation
Force Response Comparison

Force-Histories: Run094

- Table daq Sim
- Act daq Sim
- Table daq Test
- Act daq Test

Force Feedback [kN]

Time [sec]
Frequency Domain Assessment

Acceleration FFTs: Frequency domain

- Soil Level
- Table Level Sim
- Bridge Deck Sim
- Table Level Test
- Bridge Deck Test

P(freq) vs. Frequency [Hz]
Delay Assessment

Error between Measured and Target Displacements from xPC-Target: DOF 01

- Target
- Measured
- Measured (shifted by -0 msec)
- Error
C) Tall Building Application

One 6DOF Shake Table
PEER Shake Table Facility

- 20 ft x 20 ft table size
- Still the largest 6 DOF shake table in the US
- Can test structures, weighing 100,000 lbs, to horizontal accelerations of 1.5 g
- +/- 5 in. horizontal displacement capacity
- +/- 2 in. vertical displacement capacity
- +/- 40 in./sec velocity capacity
Triple Friction Pendulum Bearings

\[ \begin{array}{ccc}
L1 \text{ (in.)} & L2 \text{ (in.)} & L3 \text{ (in.)} \\
2.175 & 17.17 & 17.17 \\
T1 \text{ (s)} & T2 \text{ (s)} & T3 \text{ (s)} \\
0.67 & 1.41 & 1.87 \\
\end{array} \]

<table>
<thead>
<tr>
<th>Inner sliding surfaces</th>
<th>Outer sliding surfaces</th>
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<tbody>
<tr>
<td>Dish radius (inch)</td>
<td>3</td>
</tr>
<tr>
<td>Height (inch)</td>
<td>1.65</td>
</tr>
<tr>
<td>Outer diameter (inch)</td>
<td>2.60</td>
</tr>
<tr>
<td>Inner diameter (inch)</td>
<td>1.75</td>
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<tr>
<td></td>
<td>18.64</td>
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<tr>
<td></td>
<td>2.94</td>
</tr>
<tr>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
Analytical Substructure Parameters

15-DOF Shear Building
- $W_{tmd} = 53$ kip
- $W_{bldg} = 450$ kip
- $f_{x1} = 1$ Hz
- $f_{y1} = 1.25$ Hz
- $f_{z1} = 9.8$ Hz

3-DOF Equivalent Model
- $W_{tmd} = 53$ kip
- $W_{bldg} = 0.886 \times 450$ kip
- $f_{x1} = 1$ Hz
- $f_{y1} = 1.25$ Hz
- $f_{z1} = 11$ Hz

Models without rotational DOF

Experimental Superstructure (with TFP bearings)

Numerical Substructure

Model C

Model B
Analytical Substructure Parameters

30-DOF Flexural Building

- $W_{tmd} = 53 \text{ kip}$
- $W_{bldg} = 450 \text{ kip}$
- $f_{x1} = 1 \text{ Hz}$
- $f_{y1} = 1.25 \text{ Hz}$
- $f_{z1} = 9.8 \text{ Hz}$

5-DOF Equivalent Model

- $W_{tmd} = 53 \text{ kip}$
- $W_{bldg} = 0.849 \times 450 \text{ kip}$
- $f_{x1} = 1 \text{ Hz}$
- $f_{y1} = 1.25 \text{ Hz}$
- $f_{z1} = 11 \text{ Hz}$
Analytical Substructure Parameters

30-DOF Shear Building

- $W_{tmd} = 53$ kip
- $W_{bldg} = 63000$ kip
- $SF = 120$
- $SL = \sqrt{SF}$
- $SI = SL^4$
- $ST = \sqrt{SL}$
- $SV = SL/ST$
- $f_{x1} = 0.27$ Hz
- $T_{x1} = 3.7$ sec
Movie of Test
Delay Assessment

Error between Measured and Target Displacements from xPC-Target: DOF 01

- blue: target
- red: measured
- magenta: measured (shifted by 0 msec)
- green: error

- Y-axis: Displacement [mm]
- X-axis: Time [sec]
Delay Assessment

**Error between Measured and Target Displacements from xPC-Target: DOF 02**

- Blue: target
- Red: measured
- Pink dashed: measured (shifted by 0 msec)
- Green: error

**Graph Details:**
- **Y-axis:** Displacement [mm]
- **X-axis:** Time [sec]
Delay Assessment

Error between Measured and Target Displacements from xPC-Target: DOF 03

- **target**
- **measured**
- **measured (shifted by -2 msec)**
- **error**

- **Time [sec]**
- **Displacement [mm]**

Graph showing the comparison between measured and target displacements over time.
Tracking Indicator & NRMSE [%]

<table>
<thead>
<tr>
<th>Model</th>
<th>H1</th>
<th>H2</th>
<th>V</th>
<th>R1</th>
<th>R2</th>
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<tbody>
<tr>
<td>B</td>
<td>0.08</td>
<td>0.05</td>
<td>0.26</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>0.09</td>
<td>0.06</td>
<td>0.79</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>0.09</td>
<td>0.05</td>
<td>-</td>
<td>0.80</td>
<td>1.64</td>
</tr>
<tr>
<td>E</td>
<td>0.11</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Filtering of Force Feedback

![Graph 1](image1)

![Graph 2](image2)
Building Response Modification

![Diagram showing comparison of displacement and pseudo acceleration for different levels with and without TMD.]
D) Commissioning Test at LHPOST

NHERI @ UCSD

OpenSees Finite Element Model

OpenFresco Middleware

xPC-Target real-time Predictor-Corrector

MTS 469D Controller

MTS STS Controller

Physical Specimen on LHPOST

to servo valve

from load cells
Connecting to MTS 469D + MTS STS

OpenSees Finite Element Model

OpenFresco Middleware

xPC-Target real-time Predictor-Corrector

MTS 469D Controller

MTS STS Controller

Physical Specimen on LHPOST

or

MTS/PEER Expert Seminar, UCB
Control Room Layout
Comparison of Results

Comparison Hysteresis SimulinkRT vs OPS-OPF

- Force [kip]
- Displacement [in]

- Blue line: OPS-OPF (Load Cells)
- Red line: Simulink (Load Cells)
Comparison of Results

Displacement Time History in the Table (System delay = 0.034668 sec)
Summary & Conclusions

- Ability to drive large scale shake tables through a finite element model in real-time
- Shake table platform can thus represent a floor or the roof of a building, the motion on top of a bridge column, or the ground surface on top of a soil domain
- Ability to perform parameter studies
- ATS delay compensator works very well
Summary & Conclusions

- Use whenever the dynamics of the test specimen significantly affects the response of the supporting structure or soil and, therefore, alters the required input to the shake table as testing progresses.

- Need to further investigate sensor noise reduction methods to improve feedback signals (look into Kalman filters).
Questions?
Thank you!

http://openfresco.berkeley.edu/

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