MDOF Hybrid Shake Table Testing of Response Modification Devices

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Outline of Presentation

1. Motivation
2. Hybrid Shake Table Testing
3. Stability and Accuracy Considerations
4. Test Rehearsal and Safety Precautions
5. Bridge Application
6. Building Application
7. Summary & Conclusions
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
Hybrid Shake Table Testing

\[ M \cdot \ddot{u} + C \cdot \dot{u} + P_r(u, \dot{u}, \ddot{u}) = P(t) \]

- Inertia
- Energy Dissipation
- Resistance
Hybrid Shake Table Configuration

Experimental Portion

Analytical Portion

OpenFresco

3 translational DOF + 3 rotational DOF

Feed forces from load cells back into hybrid model

Feed motion at top of analytical portion into shake table

Tall Building Application

3 translational DOF + 3 rotational DOF

NHERI EF Workshop, Lehigh
Hybrid Shake Table Configuration

- 1 actuator DOF + 2 table DOF
- Long-Span Bridge Application

OpenFresco

Feed motion at top of analytical portion into shake table

Feed forces from load cells back into hybrid model

Analytical Portion
Experimental Portion

Structural Actuator
Bridge Deck
Isolators
Shake Table
Equations of Motion

1. Slow test
\[ M \ddot{U}_{i+1} + C \dot{U}_{i+1} + P^A_r (U_{i+1}, \dot{U}_{i+1}) + P^E_r (U_{i+1}) = P_{i+1} - P_{0,i+1} \]

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

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

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

- OpenSees or OpenSees SP as comp. driver
- Using AlphaOSGGeneralized ($\rho_{\text{inf}} = 0$)
- Next time try KRAAlphaExplicit method
- No iterations necessary
- 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**
- **xPC-Target real-time Predictor-Corrector**
- **MTS 469D Controller**
- **MTS FlexTest Controller**
- **Physical Specimen in Laboratory**

Connections:
- TCP/IP or SCRAMNetGT
- Control System in Laboratory
- Connecting to MTS 469D + FlexTest Controller

Diagram showing connections between the mentioned components.
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

ATC 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
Bridge Application

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

**ExpBridge**
Experimental Setup

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)
- 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]
Delay Assessment

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

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

Displacement [mm]

Time [sec]

0  5  10  15  20  25  30  35  40  45

-80  -60  -40  -20   0   20   40   60   80  100  120
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

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Analytical Substructure Parameters

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

3-DOF Equivalent Model
\[ W_{tmd} = 53 \text{ kip} \]
\[ W_{bldg} = 0.886 \times 450 \text{ kip} \]
\[ f_{x1} = 1 \text{ Hz} \]
\[ f_{y1} = 1.25 \text{ Hz} \]
\[ f_{z1} = 11 \text{ Hz} \]
Analytical Substructure Parameters

30-DOF 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

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

Models with rotational DOF

Not tested yet
Analytical Substructure Parameters

Tall Building Model E

30-DOF Shear Building

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

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

- **Target**
- **Measured**
- **Measured (shifted by 0 msec)**
- **Error**
Delay Assessment

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

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

Displacement [mm]

Time [sec]
Delay Assessment

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

- target
- measured
- measured (shifted by -2 msec)
- error
Tracking Indicator & NRMSE[\%]

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Filtering of Force Feedback

- Future work required
- Investigate other filtering techniques
- Investigate Kalman filtering techniques (can this be applied to force feedbacks using an predictive analysis model in parallel?)
Building Response Modification
Summary & Conclusions

- Ability to drive a MDOF shake table through a finite element model
- 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
- Performed large-scale RTHS where a shake table is combined with a dynamic structural actuator applied to a bridge
- Ability to perform parameter studies
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.
- ATS delay compensator worked very well.
- Need to further investigate sensor noise reduction methods to improve feedback signals (look into Kalman filters).
Questions?
Thank you!

http://openfresco.berkeley.edu