REAL-TIME DYNAMIC HYBRID TESTING OF STRUCTURAL SYSTEMS

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Outline

- Objective of Testing
- Feasibility issues
- Implementations
- Possible Applications
- Remarks

Real-Time Hybrid Seismic Testing System
(Substructure Dynamic Testing)
Real-time dynamic hybrid testing

- Shake Table
- Laminar Soil Box
- Foundation

Well understood

Focus of interest

Structural Actuator
Real-time dynamic hybrid testing

- Shake Table
- Laminar Soil Box
- Foundation
- Structural Actuator
- Distributed mass
- Acceleration input: Table introduces inertia forces
- Response Feedback

Has to operate in Force Control
Real-time dynamic hybrid testing

Combined use of earthquake simulators, actuators and computational engines for simulation
Objectives of Hybrid Testing

- Allow testing of full size structures or substructures
- Allow to test strain rate effects
- Allow to develop inertial effects in distributed mass systems
- Test integrally the computational tools as well as the physical specimens
- Ultimately allow production of computational tools validated by experiments
Relation to state-of-the-art

- Sub-structured pseudo-dynamic testing (Mahin, Shing, Nakashima)
  - Mass simulated computationally
  - Rate-dependent effects simulated predominantly computationally
  - Algorithms and error analysis well-researched
  - Sub-structuring displacement-based (interface displacements applied to specimen)

- Effective-force method (Mahin, Dimig et al.)
  - Ground acceleration applied as equivalent forces using actuators
  - Actuator-structure interaction significant problem (French et al.)

- Shake-table testing (Reinhorn et al.)
  - Table-structure interaction addressed using iterative and adaptive techniques (MTS systems)
Substructure Testing – Unified Approach

Shake table acceleration, $\ddot{u}_t = \alpha_1(s)\ddot{u}_1 - \alpha_3(s)\frac{k_3}{m_2}(x_1 - x_2)$

Actuator Force, $F_a = -\left[1 - \alpha_1(s)\right]m_2\ddot{u}_1 + \left[1 - \alpha_3(s)\right]k_3(x_1 - x_2)$
Unified approach to substructure testing

- If $\alpha_1(s) \neq 0$ and $\alpha_3(s) \neq 0$, then the control requires a shake table and an actuator to implement the substructure testing.

- If $\alpha_1(s) = 0$ and $\alpha_3(s) = 0$, then the controller require just an actuator to implement the substructure testing as pseudo-dynamic testing:

Note:

- In pseudo-dynamic testing, inertia effects are computed while in RTDHT are produced by shaking
- In dynamic hybrid testing ($\alpha_1(s) \neq 0$ or $\alpha_3(s) \neq 0$), the actuator should operate in force control only
Real-time dynamic hybrid testing (RTDHT)

- Unique features
  - Mass in the physical system
  - Distributed inertia and rate-dependent effects
  - Shake-table operated as acceleration device – actuators in dynamic force control
  - Sub-structuring force-based (interface forces applied to specimen)
  - Dynamic test (has to be real-time)

- Challenges
  - Dynamic force control
  - Actuator/table – structure interaction
  - Numerical algorithms – stability, error propagation
  - Flexible hardware/software architecture permitting different other types of tests (eg: pseudo dynamic test with shake-table as a displacement device)
Force control – challenging problem

- Hydraulic actuator fitted with flow-regulating servo-valve
  - Inherently a velocity source
  - Designed to be mechanically stiff for good position control
  - Friction, stick-slip, breakaway forces on seals, backlash cause force noise
  - Stiff oil columns make force control very sensitive to control parameters often leading to instability
Innovative scheme for force control using “Series Elasticity Actuator Approach”

- Target Force
- Command Signal
- Actuator in Displacement Control
- Series Spring, $K_{LC}$
- Structure
- Compensator
- Structure Displacement
- Measured Force

$1 / K_{LC}$
Small-scale test setup

- Load Cell
- Series Spring
- Structure
- Actuator
- Structure Disp. Transducer
Actuator displacement control

- Tuned very well in displacement control
- Standard PIDF controller

- Time-delay = 5.6 ms
Time-delay effect on force transfer function

Need predictive capability in compensator
Control scheme with Smith predictor compensator

Smith Predictive Compensator

\[ T = e^{-st} \]

Model of Structure-Spring System

\[ \frac{1}{\hat{m}s^2 + \hat{c}s + \hat{k} + \hat{K}_{LC}} \]

Corrective Displacement

Predictive Displacement

Delay Model
Force transfer function with predictive compensation

![Graph showing force transfer function with and without compensation](image)
Hybrid Controller Implementation (UB-NEES)

- Flexible architecture using parallel processing (see right side of diagram below)
- Delays of less than 5 milliseconds.
Pilot Test of Real Time Dynamic Hybrid Technique
Pilot Test of Real Time Dynamic Hybrid Technique
Implementation of RTDHT
Substructure response

Second floor
- Calculated

First floor

Hybrid test  Analytical
Hybrid Testing of Electrical Systems

Transformer

Bushing

Bushing Interface

Reduced-Model Representation

Ground Motion

Bushing

Bushing Interface

Dynamically condensed model to simulate the transformer with bushing interface

Shake table

13 WCEE, August 2004
Fast-MOST FAST-PSEUDO-DYNAMIC-HYBRID

- 6-span bridge model – FAST-PSEUDO-DYNAMIC-HYBRID - test in progress
  - Span and one column are numerical models
  - Other 4 columns are experimental models
  - Achieved speeds of 100 milliseconds (based on UB-NEES developments)

Computational Sites:
UIUC/NCSA

Experimental Sites:
Berkeley
Boulder
UIUC
Buffalo
Lehigh

Slide courtesy of
Gilberto Mosqueda
Remarks – Experimental Approaches

- Full scale (or large scale) testing of assemblies can be implemented only as substructure testing in the NEES Collaboratory
- Advanced analytical techniques require validation
- Hybrid testing *may* provide the framework for both of the above
- The current new technology allows for distributed hybrid dynamic testing – although many issues need further solutions
- New experimentation and computing infrastructure in US and networking of such infrastructure allowed the advances necessary for such testing
Thank you!

Questions?