Capabilities and Advancements of Hybrid Simulation using LHPOST

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Overview

- Background on Hybrid Simulation
  - Various forms of implementation of hybrid simulation
  - Sources and monitoring of errors
  - Potential Applications of Hybrid Simulation
- Shake Table Substructures
  - Includes restoring forces and inertial forces
- Hardware available at NHERI-UCSD
  - Control system, ScramNet, and Matlab xPC Environment
  - External actuators
- User Requirements and Preparation
- Recent Hybrid Testing Activities at NHERI-UCSD
Experimental Methods

- Experimental Methods for Seismic Performance Evaluation
  - Quasi-Static or Cyclic Loading
  - Shake Table
  - Hybrid Simulation
Hybrid Simulation

• Equation of motion for prototype structure

\[ ma + cv + r = f \]

• Hybrid simulation combines:
  – Physical models of structural resistance
  – Computer models of structural damping and inertia

• Enables seismic testing of large- or full-scale structural models

• Solve equation of motion using numerical integration algorithms
Test Procedure

Time-stepping integration algorithm e.g., Newmark Explicit

\[
ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1}
\]

\[
d_{i+1} = d_i + \Delta t v_i + \frac{1}{2} \Delta t^2 a_i
\]

\[
v_{i+1} = v_i + \frac{1}{2} \Delta t (a_i + a_{i+1})
\]
Implementation Issues

➢ Integration Algorithms
  • Implicit or explicit
  • Integration time step
  • Accuracy and stability

➢ Rate of testing
  • Time scaling
  • Pseudo-dynamic vs. dynamic
  • Material strain rate effects
  • Observation of damage

➢ Experimental Errors
  • Actuator tracking errors
  • Propagation of errors

Central Difference

Newmark’s Method

\[
ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1}
\]

\[
d_{i+1} = d_i + \Delta tv_i + \frac{1}{2} \Delta t^2 a_i
\]

\[
v_{i+1} = v_i + \frac{1}{2} \Delta t \left( a_i + a_{i+1} \right)
\]
Hybrid Structural Model

Modeling

- Selection of experimental substructures
  ✓ components of structure that are difficult to model
- Interface boundary conditions between physical and numerical model
- Size and scale of experimental substructure limited by equipment capabilities
  ✓ substructures can be tested at different scales
Hybrid Structural Model

- **Modeling Assumptions**
  - Assume force release at boundary to simplify experimental setup
  - Consider available equipment in laboratory

![Diagram of Hybrid Structural Model]

Assume pin connection
Various configuration possible

- Substructures at different length scales

Shake table substructure

Reduced scale

Reaction wall

Full scale

Structural Modeling
Errors in Hybrid Simulation

Mitigation of errors key to successful hybrid simulation

Numerical Errors

➢ Similar to numerical simulations, hybrid simulation employs numerical integrators to solve equation of motion

• e.g., Newmark’s Method in explicit form

\[
ma_{i+1} + cv_{i+1} + r_{i+1} = f_{i+1}
\]

\[
d_{i+1} = d_i + \Delta tv_i + \frac{1}{2} \Delta t^2 a_i
\]

\[
v_{i+1} = v_i + \frac{1}{2} \Delta t (a_i + a_{i+1})
\]

➢ Satisfy dynamic equilibrium and kinematics
➢ Selection of integration algorithm and time step critical to stability and accuracy
Errors in Hybrid Simulation

Experimental Errors

- $d_a = \text{actual imposed displacement}$
- $d_c = \text{command displacement}$
- $d_m = \text{measured displacement}$
- $r_m = \text{measured restoring force}$
Errors in Hybrid Simulation

Difference between observed and measured behavior of specimen due to experimental errors can propagate through simulation.
Real-Time Dynamic Hybrid Simulation

- **Real-time Dynamic Hybrid Simulation** combines use of shake tables, actuators and computational models.
- Measured force includes inertia and damping.

**Real Time:** Loading rate is real event rate.

**Dynamic:** Inertia effect is physically realized.

**Hybrid:** Combination of physical test and numerical simulation.

**Simulation:** Replicate structure behavior under earthquake input.

(Reinhorn and Shao)
Real-time Dynamic Hybrid Simulations

- Large scale RTDHS conducted at Tongji University

(Schellenberg et al.)
Hybrid Simulation Control System

- Real time integrated computational capabilities available at NHERI@UCSD

MTS FlexTest Actuator Controller

Windows:
OpenSees/OpenFresco

Simulink Real Time

MTS 469D
Shake Table Controller

ScramNet Ring

Physical Substructure
Structural Actuator
Shake Table
Real-time Hybrid Simulation Control System

- Hardware integrated through ScramNet Reflective Shared Memory for real-time communication between
  - Exchange of data on the order of microseconds
- MTS 469D Shake Table Controller
  - Can be set to take control commands from ScamNet
- Multi-channel MTS FlexTest Actuator Controller
- xPC Target/Simulink Real-Time
  - User programmable environment using Matlab- Simulink that runs in real-time
  - Send commands and receive feedback from actuator controllers through ScramNet
- 50-ton dynamic actuator
Application of Hybrid Simulation

- Simulate large and complex structures that exceed capabilities of the shake table such as long span bridges and tall buildings
  - Test a critical part of the structure at large scale
  - Numerically capture system level response
- Some type of structures exhibit rate dependent effects and distributed inertial forces requiring dynamic testing
Real-time Hybrid Simulation Control System

➢ For hard real-time, users can program numerical structural model in Simulink

➢ Potential to interface with real time programs in other operating systems and program for structural analysis through ScramNet
  • Applications with OpenSees/OpenFresco have been verified

➢ Structural analysis software provides the advantage of access to libraries of integrators, elements etc.

➢ Delay and error compensation is critical to hybrid simulation and can be implemented in real-time environment
Real-time Hybrid Simulation Control System

- User defined structural model and boundary conditions can be implemented in Simulink for ‘hard’ real-time.
Advanced Numerical Models using OpenSees/OpenFresco

OpenSees Finite Element Model

OpenFresco Middleware

xPC-Target real-time Predictor-Corrector

MTS 469D real-time Controller

Physical Specimen on Shake Table
User Preparation

• Selection of structural model
  ✓ Computer modeling, substructures and boundary conditions
• Design of experimental setup within capacity of facility
• Selection of integration and error compensation algorithm and their implementation in real-time software
• Communication link between computer model and hardware for custom software applications
• Pre-test simulation with numerical model of test setup
• Low level simulations to verify system performance and feedback loops
  ✓ Include time for development and implementation of algorithms
• Execute test sequence
Recent Applications

➢ Hybrid Simulation Commissioning Tests using LHPOST

- Collaborative development effort with NHERI SimCenter
- Data workflow and curation with NHERI DesignSafe

\[ M^N \ddot{x}(t) + C^N \dot{x}(t) + K^N x(t) = -M^N L \ddot{x}_g(t) + f_s^I \]
\[ M^E \ddot{x}(t) + C^E \dot{x}(t) + K^E x(t) = -M^E L \ddot{x}_T = -M^E L (\ddot{x}_g(t) + \dddot{x}^N,I(t)) \]

where \( f_s^I \) only affects the interface DOF

Assuming no mass in the interface of the experimental
Recent Applications

➢ Hybrid Simulation Commissioning Tests using LHPOST
  • Two different approaches were implemented for the hybrid simulation computational drivers models programmed fully in Simulink RT and using OpenSees/OpenFresco
  • Displacement control of shake table
  • Two different integrator algorithms were used: the generalized Alpha-Operator-Splitting and the explicit KR-alpha (adapted to shake table sub-structuring)
  • Application of adaptive time delay compensation was used (ATS compensator, Chae et al (2013))
  • SDOF and MDOF numerical models were implemented
Hybrid Simulation using LHPOST

➢ Simulink Real-Time as computational driver

Simulink RT (xPC-Target)

MTS 469D Controller

MTS STS Controller

Physical Specimen on LHPOST

from load cells
to servo valve

SCRAMNet+
SCRAMNet+
Hybrid Simulation using LHPOST

➢ Simulink Real-Time as computational driver
Hybrid Simulation using LHPOST

- **OpenSees as computational driver**

  ![Diagram of Hybrid Simulation using LHPOST]

  - **OpenSees Finite Element Model**
  - **OpenFresco Middleware**
  - **xPC-Target real-time Predictor-Corrector**
  - **MTS 469D Controller**
  - **MTS STS Controller**
  - **Physical Specimen on LHPOST**

  ![MTS 469D STS Controller]

  - **469D Controller**
  - **MTS STS Controller**

  ![Physical Specimen on LHPOST]

- OpenSees as the computational driver
- OpenFresco Middleware
- xPC-Target real-time Predictor-Corrector
- MTS 469D Controller
- MTS STS Controller
- Physical Specimen on LHPOST
Hybrid Simulation using LHPOST

➢ Comparison of two configurations
  • Hard Real-Time vs Soft Real-Time
  • OPS-OPF have access to all the library that includes: MDOF systems, different integration algorithms, different material models and other nonlinear effects.
  • OPS-OPF requires the implementation of a predictor corrector algorithm.
Hybrid Simulation using LHPOST

➢ Experimental Setup

- Rigid Mass (56 kip) over four triple friction pendulum bearings

Figure 1: Triple friction pendulum bearing
(a) Three-dimensional view
(b) Section view and basic parameters
Hybrid Simulation using LHPOST

Experimental Results

The time delay (average 34 ms) introduced by the shake table system was alleviated with an ATS compensator.
Experimental Results

The results using OPS-OPF and Simulink Real Time as the computational driver compare well.

![Graph showing comparison of Hysteresis SimulinkRT vs OPS-OPF](image)
Concluding Remarks

- Hybrid simulation can be a cost-effective and reliable approach to expand testing capabilities
- Control of numerical and experimental errors is critical to accuracy and stability of a hybrid test
- NHERI@UCSD can provide expertise to support the implementation of hybrid simulation
- Hybrid Commissioning tests demonstrate new capabilities that can expand the complexity of large-scale geotechnical and structural systems that can be tested on LHPOST.
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