Hybrid Simulation: Framework, Hardware & Software Capabilities

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NHERI Lehigh Research Scientist
Overall Concept of Real-time Hybrid Simulation (RTHS): Structural System Subject to Predefined Wind Loading

NSF CMMI: Semi-Active Controlled Cladding Panels for Multi-Hazard Resilient Buildings
- S. Laflamme (Iowa State), J. Ricles (Lehigh University), S. Quiel (Lehigh University)

Structural System

40-Story Building with Outriggers and Supplemental Dampers

Wind Loading, F(t)

Hybrid Wind Simulation Experiments

Real-time input (Forcing Function):
Wind Tunnel Data

Cmd Displ
F_{i+1}^a

Cmd Displ
X_{i+1}^a

Integrates Eqns of Motion

Real-time structural response

M\ddot{X}_{i+1} + C\dot{X}_{i+1} + R_{i+1}^a + R_{i+1}^c = F_{i+1}^a

Experimental substructure (dampers)

Restoring Force

Restoring Force

(Owned in lab)

Wind Tunnel Tests NHERI@FIU
Wind Load Determination
Why Real-Time Hybrid Simulation?

- **Enables cost-effective large-scale dynamic tests**
  - Low experimental cost compared to a full shake table test
  - Various analytical substructures can be used for a given experimental substructure, enabling extensive and comprehensive experimental studies
  - Meets the need of the natural hazards engineering community of providing experimental validation of concepts for natural hazards mitigation

- **Accounts for rate-dependency of physical specimens**
  - Rate-dependent structures (frictional devices, dampers, base-isolators, tuned mass damper, etc.) can be investigated with RTHS
    - not possible with conventional, slow hybrid simulation
RTHS: Implementation issues and challenges

Simulation coordinator
- Numerical integration algorithm
  - Accurate
  - Explicit
  - Unconditionally stable
  - Dissipative
- Fast communication

Experimental substructure
- Large capacity hydraulic system and dynamic actuators required
- Actuator kinematic compensation
- Robust control of dynamic actuators for large-scale structures

Analytical substructure
- Fast and accurate state determination procedure for complex, nonlinear structures

Preferred
RTHS Implementation solutions

• Advanced experimental techniques in NHERI Lehigh EF:
  ✓ Unconditionally stable explicit integration algorithms with minimal overshooting
    and controlled numerical damping for HS and RTHS

Velocity update: \[ \dot{X}_{n+1} = \dot{X}_n + \Delta t \alpha_1 \ddot{X}_n \]
Displacement update: \[ X_{n+1} = X_n + \Delta t \dot{X}_n + \Delta t^2 \alpha_2 \ddot{X}_n \]

Weighted equations of motion: \[ M \ddot{X}_{n+1} + C \dot{X}_{n+1-\alpha_f} + K X_{n+1-\alpha_f} = F_{n+1-\alpha_f} \]

MKR-\(\alpha\): One parameter (\(\rho_\infty\)) family of algorithms

• \(\rho_\infty\), Parameter controlling numerical energy dissipation
  ➢ \(\rho_\infty = \) spectral radius when \( \Omega = \omega \Delta t \to \infty \)
  ➢ varies in the range \(0 \leq \rho_\infty \leq 1\)
  ➢ \(\rho_\infty = 1\): No numerical energy dissipation
  ➢ \(\rho_\infty = 0\): Asymptotic annihilation


RTHS Implementation solutions

• Advanced experimental techniques in NHERI Lehigh EF:
  ✓ Unconditionally stable explicit integration algorithms with minimal overshooting and controlled numerical damping for HS and RTHS
  ✓ Explicit force-based nonlinear fiber element for NLTHA, HS and RTHS

RTHS Implementation solutions

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![Analytical Substructure](image1)

![Experimental Substructure](image2)

- Moment $M_z (kN\cdot m)$
- Curvature $f_z (1/m)$
- Moment $M_y (kN\cdot m)$
- Curvature $f_y (1/m)$

3D EQ Real-Time Hybrid Simulation - 2-Story R/C Building
1994 Northridge EQ, RSN960 Canyon Country Station, MCE Level
RTHS Implementation solutions

- Advanced experimental techniques in NHERI Lehigh EF:
  - Unconditionally stable explicit integration algorithms with minimal overshooting and controlled numerical damping for HS and RTHS
  - Explicit force-based nonlinear fiber element for NLTHA, HS and RTHS
  - Development and implementation of real-time nonlinear model updating for HS and RTHS

\[ f_{d_{i+1}} = f_d + K_d \Delta t \left( \frac{f_d}{C_d} \left| \alpha \right| \text{sign}(f_d) + K_d (u_{d_{i+1}} - u_d) \right) \]

Nonlinear real-time model updating –
Explicit nonlinear viscous damper model

RTHS Implementation solutions

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  - Explicit force-based nonlinear fiber element for NLTHA, HS and RTHS
  - Development and implementation of real-time nonlinear model updating for HS and RTHS
  - Development and implementation of 3-D kinematic compensation actuator control algorithm

\[
(M_{SNxL_{\text{new}}}, M_{SNyL_{\text{new}}}) = (-LM_{a_{\text{inew}}}, \sin(\theta_2 + \phi_i) , LM_{a_{\text{inew}}}, \cos(\theta_2 + \phi_i))
\]

\[
\theta_2 = \arcsin\left(\frac{LM_{b_{\text{inew}}}}{yF_i \cos \phi_i} \sin \theta_3 \right)
\]

\[
\theta_3 = \arccos\left(\frac{LM_{a_{\text{inew}}}^2 + LM_{b_{\text{inew}}}^2 - (yF_i / \cos \phi_i)^2}{2LM_{a_{\text{inew}}} \cdot LM_{b_{\text{inew}}}}\right)
\]

\[
(SP_{N_{x_{\text{new}}}}, SP_{N_{y_{\text{new}}}}) = (M_{1} SN_{m} x_{\text{new}} - VM_1 \cos(\theta M_{1.0} + d^m SP_{N}\theta), M_{1} SN_{m} y_{\text{new}} - VM_1 \sin(\theta M_{1.0} + d^m SP_{N}\theta))
\]

3D Multi-directional loading of CLT Shear Wall-Floor Diaphragm-Gravity Load System Subassembly


RTHS Implementation solutions

- Advanced experimental techniques in NHERI Lehigh EF:
  - Unconditionally stable explicit integration algorithms with minimal overshooting and controlled numerical damping for HS and RTHS
  - Explicit force-based nonlinear fiber element for NLTHA, HS and RTHS
  - Development and implementation of real-time nonlinear model updating for HS and RTHS
  - Development and implementation of 3-D kinematic compensation actuator control algorithm
  - Development and implementation of real-time adaptive servo-hydraulic control for delay compensation

\[ u_k^c = a_0 k x_k^t + a_1 k \dot{x}_k^t + a_2 k \ddot{x}_k^t \]
\[ A = \left( X_m^T X_m \right)^{-1} X_m^T U_c \]

Real-time Adaptive Time Series Delay Compensation

Summary of Advancements in Experimental Methods

3-D large-scale multi-directional RTHS:

- Unconditionally stable explicit integration algorithms
- Explicit force-based nonlinear fiber element
- Real-time nonlinear model updating for HS and RTHS
- 3-D kinematic compensation actuator control
- Real-time adaptive servo-hydraulic control
Example: Multi-hazard RTHS of a Tall Building

- 40-story (+4 basement) BRBF building in Los Angeles designed by SGH\(^{(1)}\) for PEER Tall Building Initiative case studies – BRBFs with Outriggers

- Objectives of study
  - Improve performance using nonlinear fluid viscous dampers with outriggers
  - Assess performance of structure under multi-hazards using RTHS
  - Extend MKR-\(\alpha\) integration algorithm and ATS actuator control to multi-hazards
  - Online model updating – explicit-based NL Maxwell model

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(1) Moehle et al., PEER 2011/05

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Multi-Hazard RTHS of Tall Building – EQ & Wind

- Bidirectional EQ ground motions
  - 1989 Loma Prieta EQ – Saratoga Aloha Ave Station scaled to MCE (2500 year return period) hazard level
- Bidirectional wind loading
  - Wind speed of 110 mph, 700 MRI
  - Exposure B
Wind Loading
Aerodynamic Wind Testing @ FIU WOW

- Aerodynamic wind testing at the NHERI FIU WOW to obtain wind pressure time histories distributed on the building.

Courtesy: Amal Elawady and Arindam Chowdhury, FIU
RTHS Configuration

- Use of:
  - Explicit MKR-\(\alpha\) Integration Algorithm
  - Explicit Force-based Nonlinear Fiber Element – Analytical Substructure
  - Adaptive Time Series Compensator for Actuator Control
  - Online Model Updating (OMU) – explicit-based NL Maxwell model

### MKR-\(\alpha\) parameter and ATS coefficients

<table>
<thead>
<tr>
<th>Natural Hazard</th>
<th>Time Step, (\Delta t) (sec)</th>
<th>(\rho_\infty)</th>
<th>ATS Coefficients</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>(\frac{6}{1024})</td>
<td>0.866</td>
<td>(a_{0k}) Fixed</td>
<td>Adaptive Fixed</td>
</tr>
<tr>
<td>EQ</td>
<td>(\frac{6}{1024})</td>
<td>0.50</td>
<td>Adaptive</td>
<td>Adaptive Adaptive Adaptive</td>
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</table>
RTHS Substructures

Experimental Substructure – NL Fluid Viscous Damper

Analytical Substructure

Analytical Sub. Key features:

- 1317 Nodes
- 2974 Elements
  - 2411 Nonlinear Explicit Force-based fiber elements
  - 11 Nonlinear Explicit Maxwell Elements\(^{(1)}\) with real-time model updating (dampers placed in each outrigger at 20\(^{th}\), 30\(^{th}\), & 40\(^{th}\) floors)
  - 552 Nonlinear truss elements
- Reduced Order Modeling
- Geometric nonlinearities
- Mass
- Inherent damping of building

Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)

- Real-time Model Updating
  - 40th story @ S-E corner: damper modeled physically
  - Remaining 11 dampers at 20th, 30th, and 40th stories modeled numerically with real-time model updating
    - Use real-time model updating via Unscented Kalman Filter (UKF) to numerically model the 11 dampers
    - Development of explicit, non-iterative Nonlinear Maxwell Damper Model for real-time hybrid simulation
    - Development of methodology to tune and implement the UKF for real-time identification of nonlinear viscous dampers

Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)

Real-time input EQ ground acceleration

Simulation Coordinator

\[ M\ddot{x}_{i+1} + C\dot{x}_{i+1} + R^a_{i+1} + R^e_{i+1} = F^a_{i+1} \]

Real-time structural response

Updated model parameters \( \bar{x}_{i+1} \)

\[ \bar{x}_{i+1} = \{Kd_{i+1}, Cd_{i+1}, \alpha_{i+1}\}^T \]

Real-time system identification using Unscented Kalman Filter (UKF)

3-D Real-time Hybrid Simulation
1989 Loma Prieta EQ Bidirectional Ground Motions Scaled to MCE

Motions scaled by factor of 5 in animation

3-D Real-time Hybrid Simulation
110 mph, 700 MRI Wind Storm (EW Windward Direction)

Motions scaled by factor of 20 in animation

### 3-D RTHS Results: BRB Maximum Ductility

1989 Loma Prieta EQ Scaled to MCE

<table>
<thead>
<tr>
<th>Story</th>
<th>No Dampers</th>
<th>With Dampers</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>EW</td>
<td>NS</td>
</tr>
<tr>
<td>1</td>
<td>3.2</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Dampers added to outriggers at 20\textsuperscript{th}, 30\textsuperscript{th}, and 40th stories:
- **BRB ductility demand**: Minimal reduction in EW, 30% reduction in NS

Note: Outrigger frames are in NS direction
3-D RTHS Results: Roof RMS Lateral Accelerations
East to West 110 mph, 700 Year MRI Wind

<table>
<thead>
<tr>
<th>Floor</th>
<th>No Dampers</th>
<th>With Dampers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EW</td>
<td>NS</td>
</tr>
<tr>
<td>40</td>
<td>7.0</td>
<td>31.5</td>
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Peak Roof Accelerations (mG)

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<th>No Dampers</th>
<th>With Dampers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EW</td>
<td>NS</td>
</tr>
<tr>
<td>40</td>
<td>28.8</td>
<td>90.3</td>
</tr>
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</table>

Dampers added to outriggers at 20th, 30th, and 40th stories:
- RMS Acceleration: 2% reduction in EW, 49% reduction in NS
- Peak Acceleration: 10% reduction in EW, 35% reduction in NS

Note: Outrigger frames are in NS direction.