Real-time Hybrid Simulation (RTHS): Background, Theory, and Implementation

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Outline of Presentation

• RTHS Background
• RTHS Developments/Implementation at NHERI Lehigh
• Multi-hazard Example Application
RTHS Background

• Combines experimental and analytical substructures

  ➢ Experimental substructure(s)
    • **Not well understood** and modeled analytically
    • Full scale component can be easily accommodated
    • Rate dependent devices (e.g., dampers, base-isolators) can be tested

  ➢ Analytical substructure(s)
    • **Well understood** and modeled numerically
    • Various substructures possible for a given expt. substructure
    • Damage can accumulate *(not a problem)* provided it can be modeled
Overall Concept of Real-time Hybrid Simulation: Structural System Subject to Multi-Natural Hazards

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

Hybrid Earthquake Simulation Experiments
Real-time input EQ ground acceleration

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

Simulation Coordinator
Integrates Eqs of Motion
Restoring Force

Cmd Displ
\(X^e_{i+1}\)

Experimental substructure
(dampers)

Wind Tunnel Tests NHERI@FIU Wind Load Determination

Task 4: Experimental Validation of Control System Designs (LU)
The objective of Task 4 is to experimentally validate ...
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 structures
RTHS: Implementation issues and challenges

Simulation coordinator

- Numerical integration algorithm
  - Accurate
  - Explicit
  - Unconditionally stable
  - Dissipative

- Fast communication

NHERI Lehigh Solutions

- Various explicit model-based algorithms
- RTMD real-time integrated control architecture
Model-based explicit algorithms for RTHS
NHERI Lehigh Solutions to RTHS Challenges

Model-Based Algorithms

Semi-Explicit-\(\alpha\) (SE-\(\alpha\)) Method

Families of algorithms

Explicit-\(\alpha\) (E-\(\alpha\)) Method

Single-parameter families of Algorithms with numerical dissipation

Single-Parameter Semi-Explicit-\(\alpha\) (SSE-\(\alpha\)) Method

Kolay-Ricles-\(\alpha\) (KR-\(\alpha\)) Method (Kolay & Ricles, 2014)

Modified Kolay-Ricles-\(\alpha\) (MKR-\(\alpha\)) Method (Kolay & Ricles, 2017)

Chen-Ricles (CR) Algorithm (Chen & Ricles, 2008)

Numerical Integration Algorithms

Explicit Modified KR-α (MKR-α) Method

- Explicit Integration of Equations of Motion
- Unconditionally Stable
- One parameter ($\rho_\infty$) algorithm
- Controlled Numerical Damping – eliminate spurious high frequency noise

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: \[ M\ddot{X}_{n+1} + C\dot{X}_{n+1} - \alpha_f \dot{X}_{n+1} + KX_{n+1} - \alpha_f = F_{n+1} - \alpha_f \]

$\alpha_1$, $\alpha_2$, and $\alpha_3$: model-based integration parameters


**KR-α Method: Implementation for RTHS**

Initial calculations: specify $\rho_\infty$, calculate $\alpha_f$, $\gamma$, $K^e$, $C^e$, $A$, $B$, $C$, and $D$

Initial conditions: $X_0$, $\dot{X}_0$, $\ddot{X}_0$, and $R_0$

Set $i = 0$

Excitation forces: $F_{i+1-\alpha_f}$

Responses: $X_i$, $\dot{X}_i$, $\ddot{X}_i$, and $R_i$

Set $i = i + 1$

Optional calculation: $\ddot{X}_{i+1} = D\dddot{X}_{i+1}$

Definitions:
- $A = \Delta t \alpha_1 [M - M\alpha_3]^{-1}$
- $B = \frac{1}{\Delta t} M\alpha_3 \alpha_1^{-1}$
- $D = \frac{1}{\Delta t} \alpha_1^{-1}$
- $\dddot{X}_i = [F_{i+1-\alpha_f} - R_{i+1-\alpha_f} - F_{i+1-\alpha_f}]$
- $\dddot{X}_0 = \Delta t \alpha_1 \dddot{X}_0$

Extrapolation Effects – small
($\delta t = \frac{1}{1024}$ s small)

Analytical Substructure

Set $j = n - 1$

$D^c(j) = X_i^e + \frac{j}{n} (X_{i+1}^e - X_i^e)$

Analytical Substructure

$X^a_{i+1}$ and $\dot{X}^a_{i+1}$

$R^e_{i+1} = R^m_{i+1} + K^e [X^e_{i+1} - D^c_{i+1}]$

$+ C^e [\dot{X}^e_{i+1} - V^c_{i+1}]$

$R^a_{i+1}$

$R_{i+1} = R^e_{i+1} + R^a_{i+1}$

$R_{i+1-\alpha_f} = (1 - \alpha_f) R_{i+1} + \alpha_f R_i$

RTMD Real-time Integrated Control Architecture

NHERI Lehigh Solutions to RTHS Challenges

- Multiple real-time workstations with real-time communication (SCRAMNet)
- Synchronized control commands with simulation data, DAQ, and camera triggers to enable real-time simulations and telepresence
RTHS: Implementation issues and challenges

Analytical substructure

- Fast and accurate state determination procedure

NHERI Lehigh Solutions

- Explicit force-based fiber elements
- HybridFEM
Fiber Element State Determination

**Displacement-based fiber elements**

- Curvature varies linearly
  - Requires many elements per structural member to model nonlinear response
  - Increases number of DOFs
- State determination is straightforward

**Force-based fiber elements**

- Equilibrium is strictly enforced
  - Material nonlinearity can be modeled using a single element per structural member
  - Reduces number of DOFs
- Requires iterations at the element level

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Section deformations:

\[ d = [d_1, d_2]^T \]

Section forces:

\[ D = [D_1, D_2]^T \]

Nodal (elem) deformations:

\[ v = [v_1, v_2, v_3]^T \]

Nodal (elem) forces:

\[ s = [s_1, s_2, s_3]^T \]
Explicit-formulated Force-Based Fiber Element

- Used with explicit integration algorithm
- Material nonlinearity
- Reduced DOFs in system modeling
- Fixed number of iterations during state determination with carry-over and correction of unbalanced section forces in next time step

Fiber element

RTHS of RC Structure: Fiber Element Real-time State-Determination

Real-time hybrid simulation using improved explicit unconditionally stable parametrically dissipative MKR-α method

Ground motion: LOS270 component of '94 Northridge EQ Canyon Country
Hazard level: Maximum considered earthquake (MCE)
Algorithmic parameter: $\rho_\infty = 0.50$
Explicit-formulated Force-Based Fiber Element

• Results

Energy Increment (EI) Error

Moment Curvature Response – 1st story RC column
(CO: Carry over unbalanced section forces)

Note: Reference = Newmark Constant Acceleration Method

Lehigh HybridFEM
NHERI Lehigh Solutions to RTHS Challenges

• MATLAB and SIMULINK based computational modeling and simulation coordinator software for dynamic time history analysis and real-time hybrid simulation of inelastic-framed structures

• Run Modes
  - MATLAB script for numerical simulation
  - SIMULINK modeling for Real-Time Hybrid simulation with experimental elements via xPCs, and hydraulics-off for training and validation of user algorithms.

• User’s Manual for training

Configuration Options:
• Coordinate system of nodes
• Boundary, constraint and restraint conditions
• Elements
  • Elastic beam-column
  • Elastic spring
  • Inelastic beam-column stress resultant element
  • Non-linear spring
  • Non-linear truss element
  • Displacement-based NL beam-column fiber element
  • Force-based NL beam-column fiber element
• Zero-length
• 2D NL planar panel zone
• Elastic beam-column element with geometric stiffness
• Geometric nonlinearities
• Steel wide flange sections (link to AISC shapes Database)
• Reinforced concrete sections
• Structural mass & inherent damping properties
• Adaptable integration methods

Materials
• Elastic
• Bilinear elasto-plastic
• Hysteretic
• Bouc-Wen
• Trilinear
• Stiffness degrading
• Concrete
• Steel
RTHS: Implementation issues and challenges

Experimental substructure

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

NHERI Lehigh Solutions

- Large hydraulic power supply system
- 5 large capacity dynamic actuators
- Development of actuator kinematic compensation
- Servo hydraulic actuator control: Adaptive Time Series Compensator (ATS)
Lehigh has unique equipment with large hydraulic power, facilitating large-scale real-time hybrid simulation.

**Large Force Capacity Dynamic Actuators**

- **Maximum load capacity**
  - 2 actuators: 517 kips (2,300kN)
  - 3 actuators: 382 kips (1,700kN)

- **Stroke**
  - +/- 20 in (+/- 500mm)

- **Maximum velocity**
  - 45 in/s (1,140mm/sec) for 382 kip actuators
  - 33 in/s (840mm/sec) for 517 kip actuators
Large Capacity Hydraulic System and Dynamic Actuators

NHERI Lehigh Solutions to RTHS Challenges

- Lehigh has unique equipment with large hydraulic power, facilitating large-scale real-time hybrid simulation

- Enables a large-scale RTHS of a structure under strong ground motions (i.e., Kobe earthquake, Japan)

- Collapse simulation of a building structure was conducted under extreme earthquake ground motions (beyond MCE level)
Actuator Kinematic Compensation

- Develop **kinematic compensation scheme** and implementation for RTHS (Mercan et al. 2009)
  - Kinematic correction of command displacements for multi-directional actuator motions
  - Robust, avoiding accumulation of error over multiple time steps; suited for RTHS
  - Exact solution for planar motions

\[
(M_1SN_{x new}, M_1SN_{y new}) = (-LM_{a_{new}}sin(\Theta_2 + \Phi_1), LM_{a_{new}}cos(\Theta_2 + \Phi_1))
\]

\[
\Theta_2 = \arcsin\left(\frac{LM_{b_{new}}\sin \Phi_1}{yF/cos\Phi_1}\right)
\]

\[
\Theta_3 = \arccos\left(\frac{LM_{a_{new}}^2 + LM_{b_{new}}^2 - (yF/cos\Phi_1)^2}{2LM_{a_{new}}LM_{b_{new}}}ight)
\]

\[
(SPN_m^{x_{new}}, SPN_m^{y_{new}}) = (M_1SN_{m}^{x_{new}} - \sqrt{VM_1}cos(\Theta M_{1,0} + d^mSPN\Theta), M_1SN_{m}^{y_{new}} - \sqrt{VM_1}sin(\Theta M_{1,0} + d^mSPN\Theta))
\]

Servo Hydraulic Actuator Control

Sources of Nonlinearity in Real-Time Hybrid Simulation

- Nonlinear servo-valve dynamics
- Nonlinear actuator fluid dynamics
- Test specimen material and geometric nonlinearities
- Slop, misalignment, deformations in test setup

Effect of time delay on real-time hybrid simulation

Can lead to variable amplitude error and time delay in servo-hydraulic system that does not enable the target displacement of the experimental substructure to be achieved

- Inaccurate structural response
- Delayed restoring force adds energy into the system (negative damping)
- Can cause the instability of simulation

➤ Important to negate the time delay effect in real-time hybrid simulation
Adaptive Time Series (ATS) Compensator

2nd order ATS compensator

\[ u_k^c = a_{0k} x_k^t + a_{jk} x_k^t + a_{2k} \dot{x}_k^t \]

- \( u_k^c \): compensated input displacement into actuator
- \( x_k^t \): target specimen displacement
- \( a_{jk} \): adaptive coefficients

Adaptive coefficients are optimally updated to minimize the error between the specimen target and measured displacements using the least squares method.

\[
A = \left( X_m^T X_m \right)^{-1} X_m^T U_c
\]

\[
A = \begin{bmatrix} a_{0k} & a_{1k} & \cdots & a_{nk} \end{bmatrix}^T
\]

\[
X_m = x_m^m \dot{x}_m^m \cdots \frac{d^n}{dt^n} \left( x_m^m \right)^T
\]

\[
x_m^m = x_{k_1}^m x_{k_2}^m \cdots x_{k_q}^m
\]

\[
U_c = u_k^c_1 u_k^c_2 \cdots u_k^c_q
\]

(Output (measured) specimen displacement history)

Adaptive Time Series (ATS) Compensator

Unique features of ATS compensator

• No user-defined adaptive gains ➞ applicable for large-scale structures susceptible to damage (i.e., concrete structures)

• Negates both variable time delay and variable amplitude error response

• Time delay and amplitude response factor can be easily estimated from the identified values of the coefficients

• Use specimen feedback

Amplitude error: \[ A = \frac{1}{a_{0k}} \]

Time delay: \[ t = \frac{a_{1k}}{a_{0k}} \]
Adaptive Time Series (ATS) Compensator
- Performance of ATS compensator -

Predefined EQ displacement test (maximum amplitude=40mm)

Slide courtesy of Yunbyeong Chae
Adaptive Time Series (ATS) Compensator
- Performance of ATS compensator -

Predefined EQ displacement test (maximum amplitude=40mm)

\[
\tau = 21 \text{ msec}
\]

Target displacement

Measured (No compensation)

Measured (ATS compensator)
Adaptive Time Series (ATS) Compensator
- Performance of ATS compensator -

Predefined EQ displacement test (maximum amplitude=40mm)

Displacement (mm) vs. Time (sec)

- Target
- Measured (No compensation)
- Measured (ATS compensator)

\( \tau = 21 \text{ msec} \)

Slide courtesy of Yunbyeong Chae
Applications of RTHS to Multi-Hazards
**RTHS of a Tall Building**

- 40-story (+4 basement) BRBF building in Los Angeles designed by SGH for PEER Tall Building Initiative case studies
- Objectives of study
  - Investigate multi-hazard performance of building outfitted with nonlinear fluid viscous dampers placed in outriggers
  - Assess performance using RTHS
- Extend MKR-\(\alpha\) integration algorithm and ATS actuator control to wind natural hazard

Ref.: Moehle et al., PEER 2011/05

Plan for floors that do not include the outriggers. Image courtesy of Dutta and Hamburger (2010)

3-D view of the building. Image courtesy of Dutta and Hamburger (2010)
Nonlinear Viscous Dampers

Characterization testing

Damper testbed

Loading Protocol

Damper force - deformation

Damper force - velocity
RTHS Configuration

• Use of:
  - Explicit MKR-α Integration Algorithm
  - Explicit Force-based Fiber Element – Analytical Substructure
  - Adaptive Time Series Compensator for Actuator Control

**MKR-α parameter and ATS coefficients**

<table>
<thead>
<tr>
<th>Natural Hazard</th>
<th>Time Step, Δt (sec)</th>
<th>$\rho_\infty$</th>
<th>ATS Coefficients</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>$6 \over 1024$</td>
<td>0.866</td>
<td>Fixed</td>
<td>Adaptive</td>
</tr>
<tr>
<td>EQ</td>
<td>$6 \over 1024$</td>
<td>0.50</td>
<td>Adaptive</td>
<td>Adaptive</td>
</tr>
</tbody>
</table>

Wind: static component with dynamic gusts - 1st mode linear response
EQ: Multi-mode non-linear response
RTHS Configuration

**Wind load:**
- Tokyo Polytechnic University Wind Tunnel Test database
- Normalized pressure coefficient time histories are converted to full scale forces corresponding to Exposure B and wind speed of 110 mph, 700 year MRI

**EQ load:**
- 1989 Loma Prieta EQ – Saratoga Aloha Ave Station scaled to SLE, DBE, and MCE (43, 475, 2475 year return periods, respectively) hazard level

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**Building Floor Plan**

**Test Structure Elevation**
RTHS Test Structure

BRB: nonlinear truss element with isotropic hardening

Beams and columns: beam-column fiber element

Nonlinear fluid viscous dampers: Modeled physically

- Mass & inherent damping of building: modeled analytically
RTHS Substructures

Analytical Substructure

Key features:
- P-Δ effects included
- 780 Nodes
- 996 Elements
- 1590 DOFs
- Mass
- Inherent damping of building

Experimental Substructures

South Side Damper at 30th Story Outrigger

South Side Damper at 20th Story Outrigger
Demonstration of a Typical Wind RTHS

Real-time Hybrid Simulation of a Wind Excited Tall Building
Wind Speed = 110 mph (MRI 700 years)
Demonstration of a Typical EQ RTHS

Real-time Hybrid Simulation of a Seismically Excited Tall Building
1989 Loma Prieta EQ Scaled to MCE Level
RTHS Results: Damper Force-Displacement Response, 700 Year MRI Wind

- Dampers experienced low velocity, with dynamic gust
  - Dampers performed similar to linear viscous dampers
Dampers developed appreciable dynamic response

- Dampers performed as nonlinear dampers, where force is capped
Actuator Control: Typical Wind RTHS

Time History of Adaptive Coefficients

Amplitude Correction

$$A_k^{(j)} \approx \frac{1}{a_{0k}^{(j)}} = 1.0$$

Delay Compensation $$a_1$$

$$\tau_k^{(j)} \approx \frac{a_{1k}^{(j)}}{a_{0k}^{(j)}} = 27 \sim 34 \text{ msec}$$

Time variation of ATS parameters

Measured specimen disp

Target specimen disp

Floor 20 (NRMSE=0.50%)

Floor 30 (NRMSE=0.30%)

Synchronization subspace plot
**Actuator Control: Typical EQ RTHS**

**Time History of Adaptive Coefficients**

**Amplitude Correction**

\[ A_{k}^{(j)} \approx \frac{1}{a_{0k}^{(j)}} = 0.99 \sim 1.01 \]

**Delay Compensation**

\[ \tau_{k}^{(j)} \approx \frac{a_{1k}^{(j)}}{a_{0k}^{(j)}} = 15 \sim 20 \text{ msec} \]

**Time variation of ATS parameters**

**Synchronization subspace plot**
RTHS Analytical Substructure
Buckling Restrained Brace Response

Wind
1st Story

Earthquake
1st Story
Current Research: Multi-Natural Hazard 3-D Hybrid Simulation

Natural Hazards:
- Earthquake
- Wind (FIU WOW)

Analytical Substructure
- 2920 elements
- 4069 degrees of freedom
Thank you