Overview of Large-Scale Damper Characterization and RTHS Demonstration

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NHERI Lehigh EF
Outline

- Large-scale nonlinear viscous damper characterization test
- RTHS implementation challenges and NHERI Lehigh solutions
- RTHS of a RC building with nonlinear viscous damper
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1-RED</td>
<td>Control Room</td>
<td>Lab Floor</td>
<td>Lab Tour</td>
<td></td>
</tr>
<tr>
<td>2-BLUE</td>
<td>Lab Floor</td>
<td>Control Room</td>
<td>Lab Tour</td>
<td></td>
</tr>
<tr>
<td>3-GREEN</td>
<td>Lab Tour</td>
<td>Control Room</td>
<td>Lab Floor</td>
<td></td>
</tr>
<tr>
<td>4-YELLOW</td>
<td>Lab Tour</td>
<td>Lab Floor</td>
<td>Control Room</td>
<td></td>
</tr>
</tbody>
</table>

Back of your name tag has a group label and color
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Damper Characterization Test

Nonlinear fluid viscous damper

- Make: Taylor Devices Inc.
- Nominal force capacity 600 kN
- Max stroke \( \pm 125 \) mm
- Theoretical force-velocity:
  \[
  f_D = C_D \text{sgn}(\dot{u}_D) |\dot{u}_D|^\alpha
  \]
- Manufacturer provided
  \[C_D = 773 \text{ kN.} \left( \frac{s}{m} \right)^\alpha \text{ and } \alpha = 0.4 \]
- Operating temperature:
  \(-6.7^\circ C \text{ to } +54.4^\circ C (+20^\circ F \text{ to } +130^\circ F)\)
Procedure for Damper Characterization

1. Develop a damper model
2. Assign model parameters
3. Predict model response
4. Calculate error between model and measured experimental data
5. Revise parameters to minimize error
6. Predefined displacement tests
## Input Displacement and Test Matrix

<table>
<thead>
<tr>
<th>Amplitude (mm (in.))</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>76.2 (3.0)</td>
<td>119.7 (4.7)</td>
</tr>
</tbody>
</table>

Numbers in the cells are max velocities in mm/s (in/s)
Actuator Power Curve

Power curve for 1700 kN actuators at 3000 psi

- 1 valve
- 2 valves
- 3 valves
- Max demand

<table>
<thead>
<tr>
<th>Force (kN)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>500</td>
<td>1.0</td>
</tr>
<tr>
<td>1000</td>
<td>0.5</td>
</tr>
<tr>
<td>1500</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Force (kN) vs. Velocity (m/s) graph showing different valve configurations.
Damper Characterization Test Data
Nonlinear Maxwell Damper Model

- Damper shows strong frequency dependent behavior
- Usually modeled using a nonlinear Maxwell model

Total damper deformation: \( u_D = u_k + u_c \)
Total damper velocity: \( \dot{u}_D = \dot{u}_k + \dot{u}_c \)
Damper force:
\[
 f_D = f_K = K_D u_k \implies \dot{u}_K = \frac{\dot{f}_D}{K_D}
\]
\[
 f_D = f_C = C_D \text{sgn}(\dot{u}_C)|\dot{u}_C|^\alpha \implies \dot{u}_C = \left| \frac{f_D}{C_D} \right|^\frac{1}{\alpha} \text{sgn}(f_D)
\]

Model parameters: \( K_D, C_D, \text{and } \alpha \)

Governing equation (nonlinear ODE)
\[
 \dot{f}_D + K_D \left| \frac{f_D}{C_D} \right|^\frac{1}{\alpha} \text{sgn}(f_D) = K_D \dot{u}_D
\]
Solution of nonlinear ODE

Governing equation (nonlinear ODE): \[ \dot{f}_D + K_D \left| \frac{f_D}{C_D} \right|^{\frac{1}{\alpha}} \text{sgn}(f_D) = K_D \dot{u}_D \]

Simulink model for solution of the nonlinear ODE

Solver: variable-step Dormand-Prince solver (ode45) which belongs to 5\textsuperscript{th} order Runga-Kutta family
Determination of Model Parameters

- Identify $K_D$, $C_D$, and $\alpha$ so that the error between the model prediction and experimental data are minimized.

- We use particle swarm optimization (PSO) algorithm (Kennedy and Eberhart, 1995; Ye and Wang, 2007; Chae, 2011).
  - The algorithm in Matlab script is available for users.

- Objective function: Normalized root mean square error

$$F^{obj}(K_D, C_D, \alpha) = \sqrt{\frac{\sum_{n=1}^{N} (f^e_D - f^p_D)^2}{\sum_{n=1}^{N} (f^e_D)^2}}$$

- $f^e_D$ and $f^p_D$ are experimental and predicted damper forces, respectively.

- $N$ is the total number of samples.
Measured vs Model Prediction
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**Introduction: RTHS**

Ground acceleration

Integration of equations of motion

\[ M\dddot{x}_{n+1} + C\dot{x}_{n+1} + R^n_{n+1} + R^e_{n+1} = F_{n+1} \]

Ramp generator and kinematic transformation for each actuator DOF

Servo controller

ATS compensator

Experimental substructure

Nonlinear damper

Linear damper

FE model

Real time response

Simulation coordinator

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
Simulink Block Diagram for E-\(\alpha\) Method

Block 1 & 5 runs at \(\delta t = \frac{1}{1024}\) sec

Others run at \(\Delta t = n\delta t = \frac{4}{1024}\) sec (say)
RTHS: Implementation issues and challenges

Analytical substructure

- Fast and accurate state determination procedure

NHERI Lehigh Solutions

- HybridFEM
- Multi-grid real-time hybrid simulation
Lehigh HybridFEM

NHERI Lehigh Solutions to RTHS Challenges

- MATLAB and SIMULINK based computational modeling and simulation coordinator software

- 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

Lehigh HybridFEM

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
  • Displacement-based NL beam-column fiber element
  • Force-based beam NL 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)
Servo Hydraulic Actuator Control

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

It is important to compensate

- Variable amplitude error and time delay in measured specimen displacement

- Inaccurate structural response
- Delayed restoring force adds energy into the system (negative damping)
- Can cause instability
Servo Hydraulic Actuator Control

- Actuator delay compensation
  - Inverse compensation (Chen 2007)
  - Adaptive inverse compensation (AIC, Chen and Ricles 2010)
  - Adaptive time series (ATS) compensator (Chae et al. 2013)

Adaptive Time Series (ATS) Compensator

2nd order ATS compensator

\[ u^c_k = a_{0k} x^t_k + a_{jk} \dot{x}^t_k + a_{2k} \ddot{x}^t_k \]

- \( u^c_k \): compensated input displacement into actuator
- \( x^t_k \): 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.

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

\[
A = [a_{0k} \ a_{1k} \ldots a_{nk}]^T
\]

\[
X_m = [x^m \ \dot{x}^m \ldots \frac{d^n}{dt^n}(x^m)]^T
\]

\[
x^m = [x^m_1 \ x^m_2 \ldots x^m_q]^T
\]

(Output (measured) specimen displacement history)

\[
U_c = [u^c_1 \ u^c_2 \ldots u^c_q]^T
\]

(Input actuator displacement history)

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RTHS configuration

- 1999 Chi-Chi EQ record scaled to MCE hazard level
- Time step: $\Delta t = \frac{3}{1024} \text{ s}$
RTHS configuration

- Analytical substructure modeled using force-based elements with fixed number of iterations and linear elastic elements
- Mass, tangent, and initial stiffness proportional inherent damping
- Time step: $\Delta t = \frac{3}{1024}$ s
- MKR-$\alpha$ method (parameter $\rho^*$)
  - Model-based integration parameters ($\alpha_1$, $\alpha_2$, $\alpha_3$) determined from characterization test data
- ATS Compensator for adaptive time delay and amplitude compensation
Explicit Modified KR-\(\alpha\) (MKR-\(\alpha\)) Method

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:
\[
M \dddot{X}_{n+1} + C \dot{X}_{n+1 - \alpha_f} + K X_{n+1 - \alpha_f} = F_{n+1 - \alpha_f}
\]

where,
\[
\dddot{X}_{n+1} = (I - \alpha_3) \dddot{X}_{n+1} + \alpha_3 \dddot{X}_n
\]
\[
\dot{X}_{n+1 - \alpha_f} = (1 - \alpha_f) \dot{X}_{n+1} + \alpha_f \dot{X}_n
\]
\[
X_{n+1 - \alpha_f} = (1 - \alpha_f) X_{n+1} + \alpha_f X_n
\]
\[
F_{n+1 - \alpha_f} = (1 - \alpha_f) F_{n+1} + \alpha_f F_n
\]

Initial acceleration:
\[
M \dddot{X}_0 = [F_0 - C \dot{X}_0 - K X_0]
\]

Integration Parameters

- **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

- **Scalar integration parameters:**
  - \( \alpha_m = \frac{2\rho_\infty^3 + \rho_\infty^2 - 1}{\rho_\infty^3 + \rho_\infty^2 + \rho_\infty + 1}; \quad \alpha_f = \frac{\rho_\infty}{\rho_\infty + 1}; \quad \gamma = \frac{1}{2} - \alpha_m + \alpha_f; \quad \beta = \frac{1}{2} \left( \frac{1}{2} + \gamma \right) \)

- **Model-based integration parameter matrices:**
  - \( \alpha_1 = \left[ M_{IP} + \gamma \Delta t C_{IP} + \beta \Delta t^2 K_{IP} \right]^{-1} M_{IP}; \quad \alpha_2 = \left( \frac{1}{2} + \gamma \right) \alpha_1 \)
  - \( \alpha_3 = \left[ M_{IP} + \gamma \Delta t C_{IP} + \beta \Delta t^2 K_{IP} \right]^{-1} \left[ \alpha_m M_{IP} + \alpha_f \gamma \Delta t C_{IP} + \alpha_f \beta \Delta t^2 K_{IP} \right] \)
  - \( M_{IP}, C_{IP}, \) and \( K_{IP} \) need to be formed based on the hybrid system

RTHS: Model-Based Integration Parameters

- Model-based integration parameters ($\alpha_1$, $\alpha_2$, and $\alpha_3$) require $M_{IP}$, $C_{IP}$, and $K_{IP}$

- For the present study
  - $M_{IP} = M =$ analytically modeled mass matrix
    - Experimental substructure mass is small
  - $C_{IP} = (a_0 M + a_1 K^a_l) + C_{eq}$
    - $K^a_l =$ initial stiffness matrix of analytical substructure
    - $C_{eq} =$ equivalent damping matrix of experimental substructure
    - $a_0$ and $a_1$ are Rayleigh damping coefficients
  - $K_{IP} = K^a_l + K_{eq}^e$
    - $K_{eq}^e =$ equivalent stiffness matrix of experimental substructure

- How can we determine $C_{eq}^e$ and $K_{eq}^e$?
Model-based integration parameters

Linearization of nonlinear Maxwell model at a small velocity (0.5 in/s) and determination of frequency dependent equivalent Kelvin-Voigt model parameters

What is the value of $\tilde{\omega}$?
# RTHS Test Matrix

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$maxIter$</th>
<th>$\tilde{\omega}$</th>
<th>$\rho_\infty^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0.75</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>$\frac{\omega_1}{2}$</td>
<td>0.75</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>$\omega_1$</td>
<td>0</td>
</tr>
</tbody>
</table>
RTHS Test Data
References


Thank you