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

Groups

Groups	9:30 – 9:48 AM	9:48 – 10:05 AM	10:10 – 10:28 AM	10:28 – 10:45 AM
1-RED	Control Room	Lab Floor	Lab Tour	
2-BLUE	Lab Floor	Control Room	Lab Tour	
3-GREEN	Lab Tour		Control Room	Lab Floor
4-YELLOW	Lab Tour		Lab Floor	Control Room

Back of your name tag has a group label and color

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- RTHS challenges and NHERI Lehigh solutions
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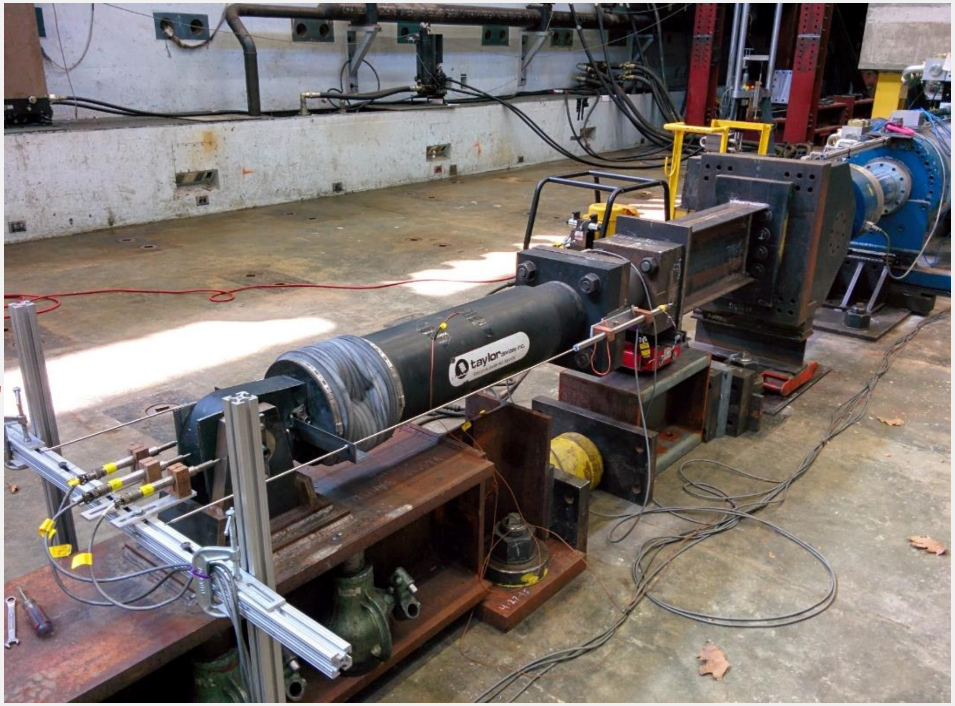
Damper Characterization Test

Nonlinear fluid viscous damper

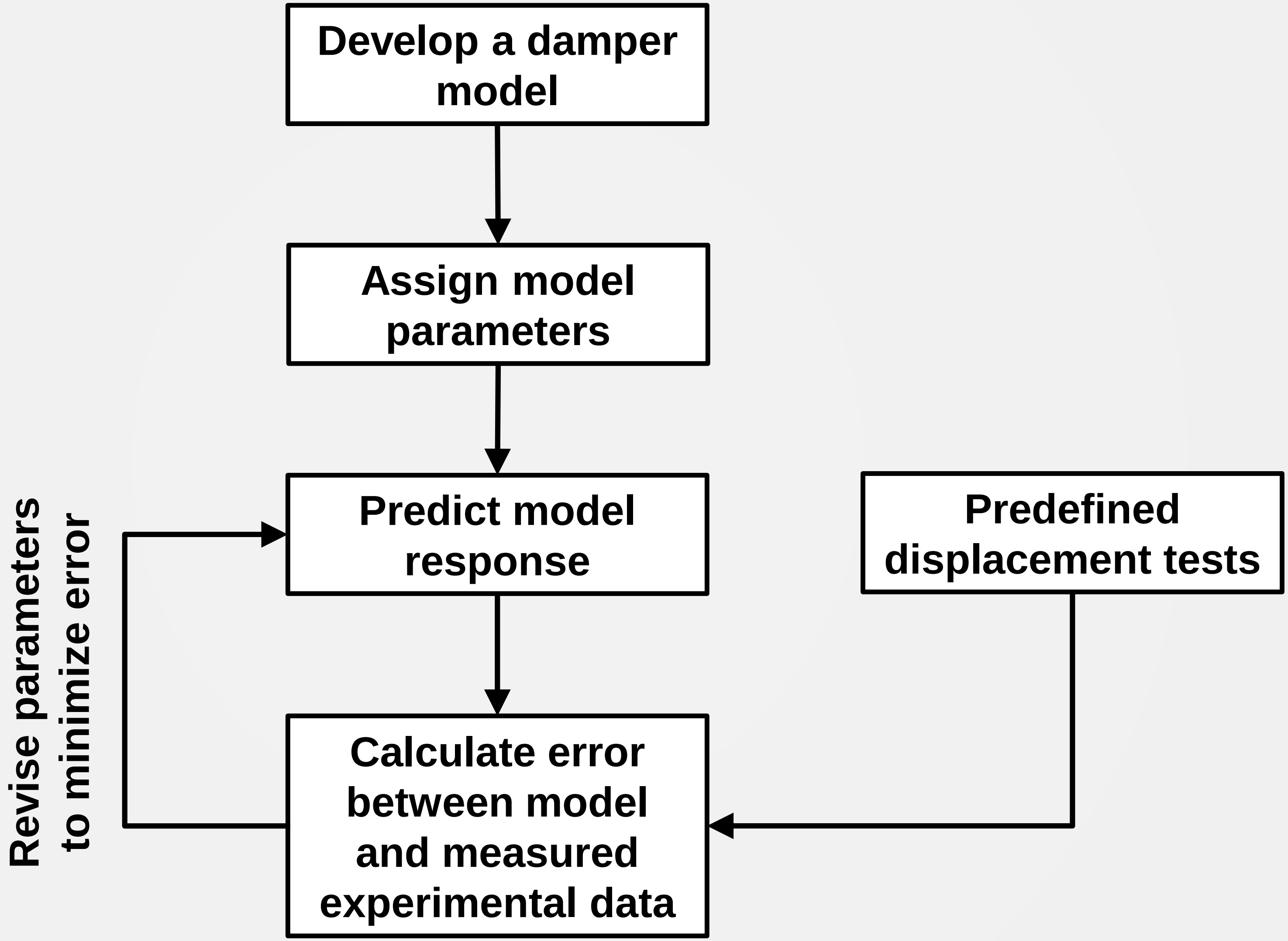
- Make: Taylor Devices Inc.
- Nominal force capacity 600 kN
- Max stroke ± 125 mm
- Theoretical force-velocity:

$$f_D = C_D sgn(\dot{u}_D)|\dot{u}_D|^{\alpha}$$

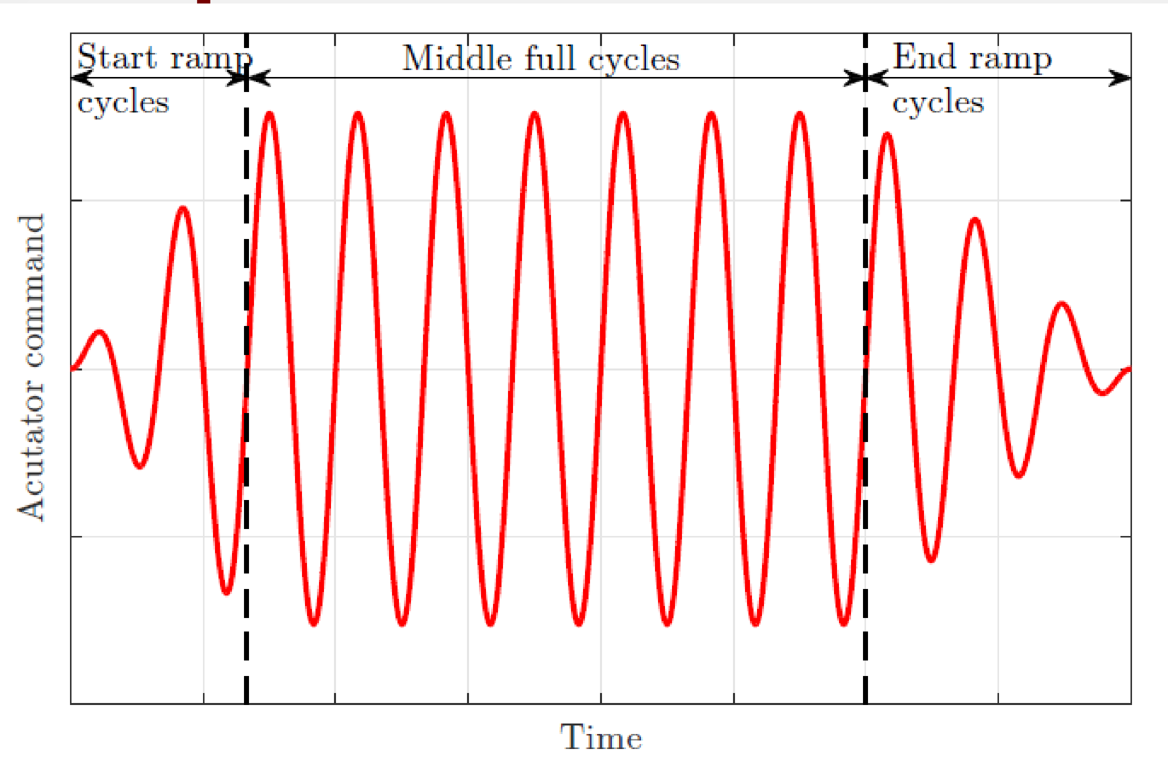
- Manufacturer provided $C_D = 773\, kN.\left(\frac{s}{m}\right)^{\alpha}$ and $\alpha = 0.4$
- Operating temperature: $-6.7°C$ to $+54.4°C$ $(+20°F$ to $+130°F)$



Procedure for Damper Characterization



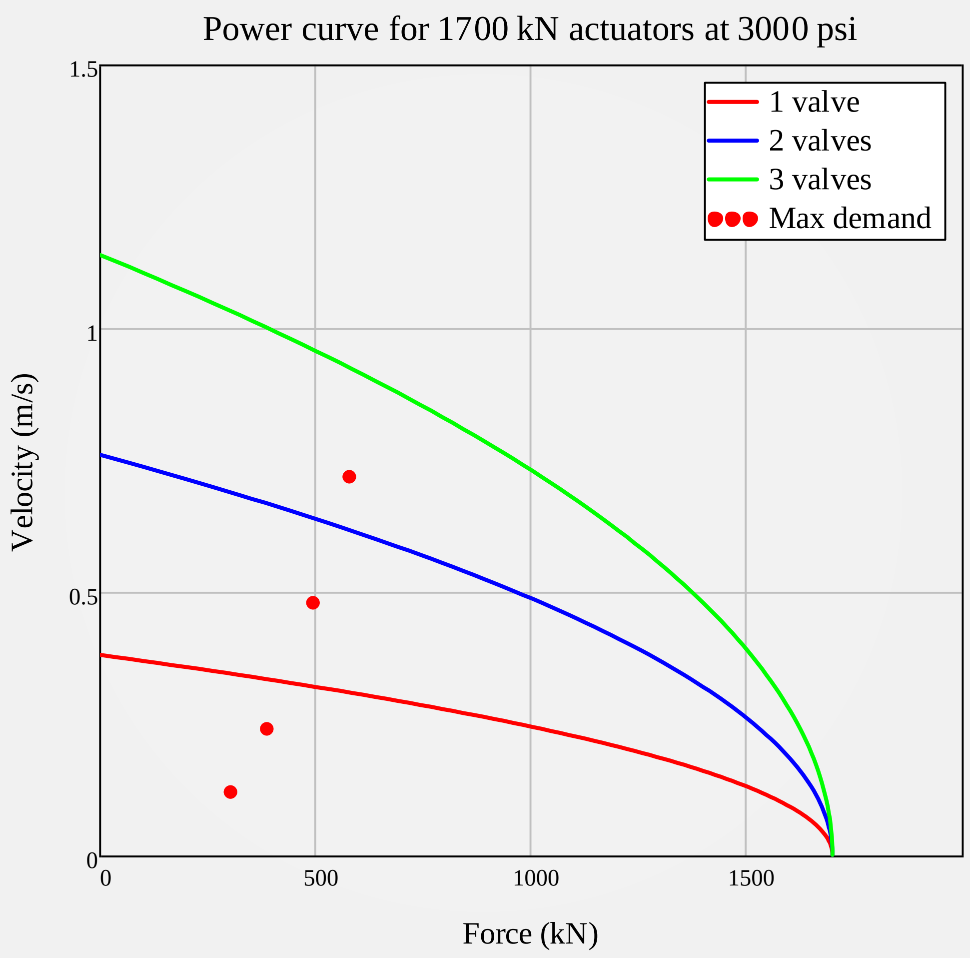
Input Displacement and Test Matrix



Amplitude mm (in.)	Frequency (Hz)			
	0.25	0.50	1.0	1.5
76.2 (3.0)	119.7 (4.7)	239.4 (9.4)	478.8 (18.9)	718.2 (28.3)

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

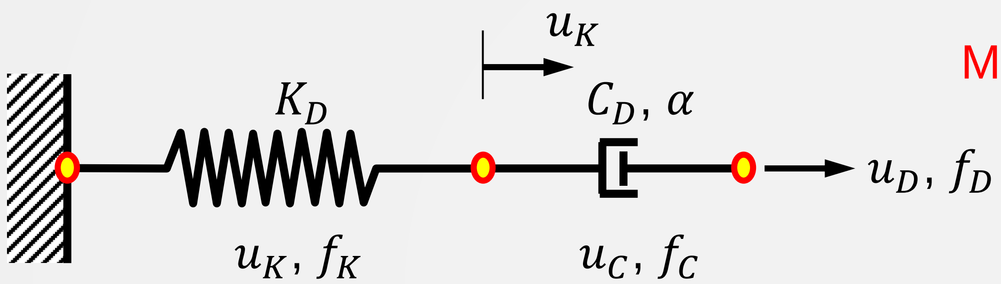
Actuator Power Curve



Damper Characterization Test Data

Nonlinear Maxwell Damper Model

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



Model parameters: K_D, C_D, and α

Total damper deformation: $u_D = u_k + u_c$

Total damper velocity: $\dot{u}_D = \dot{u}_k + \dot{u}_c$

Damper force:

$$f_D = f_K = K_D u_k \Longrightarrow \dot{u}_K = \frac{\dot{f}_D}{K_D}$$

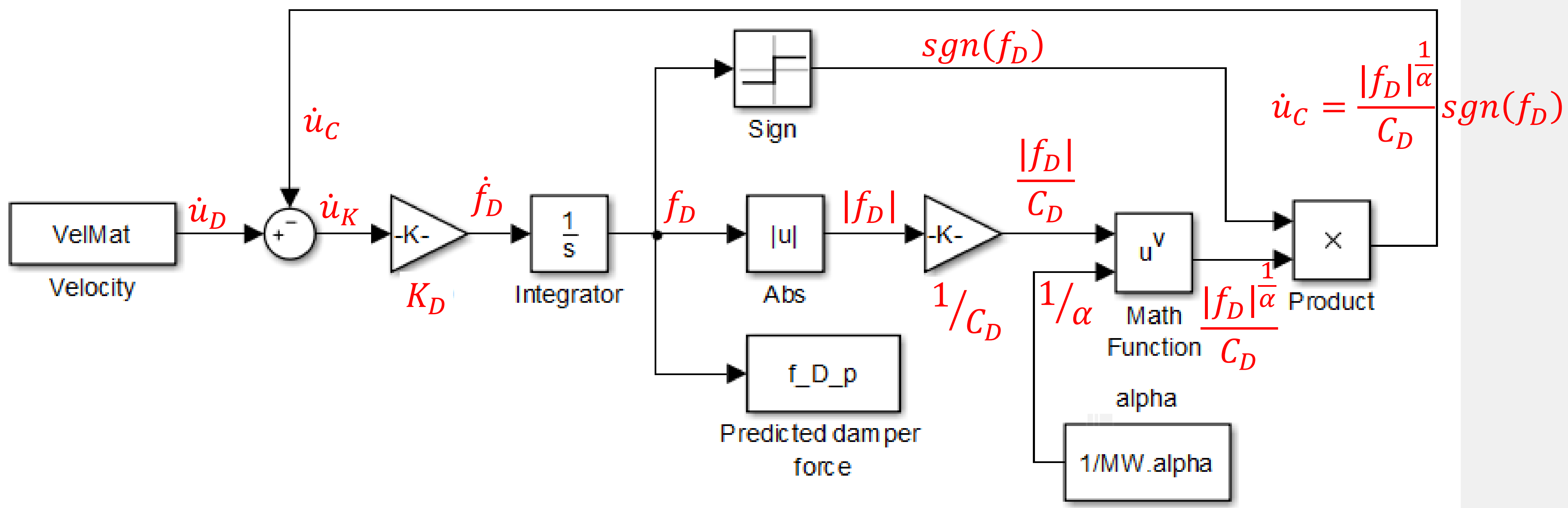
$$f_D = f_C = C_D sgn(\dot{u}_C)|\dot{u}_C|^{\alpha} \Longrightarrow \dot{u}_C = \left|\frac{f_D}{C_D}\right|^{\frac{1}{\alpha}} sgn(f_D)$$

Governing equation (nonlinear ODE)

$$\dot{f}_D + K_D \left|\frac{f_D}{C_D}\right|^{\frac{1}{\alpha}} sgn(f_D) = K_D \dot{u}_D$$

Solution of nonlinear ODE

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



Simulink model for solution of the nonlinear ODE

Solver: variable-step Dormand-Prince solver (ode45) which belongs to 5th order Runga-Kutta familty

Determination of Model Parameters

- Identify K_D, C_D, and α 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

$$F^{obj}(K_D, C_D, \alpha) = \sqrt{\frac{\sum_{n=1}^{N}\left(f_{D_n}^{e} - f_{D_n}^{p}\right)^2}{\sum_{n=1}^{N}\left(f_{D_n}^{e}\right)^2}}$$

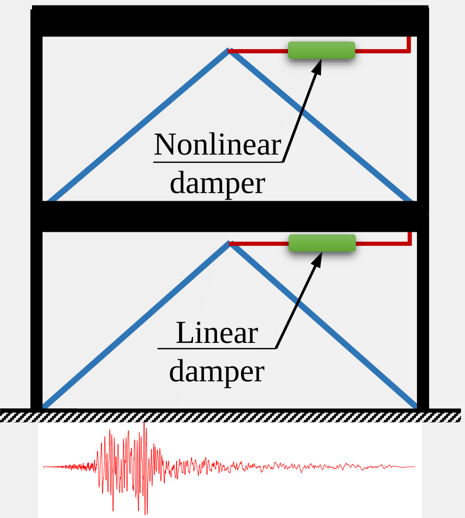
  - f_D^e and f_D^p are experimental and predicted damper forces, respectively
  - N is the total number of samples

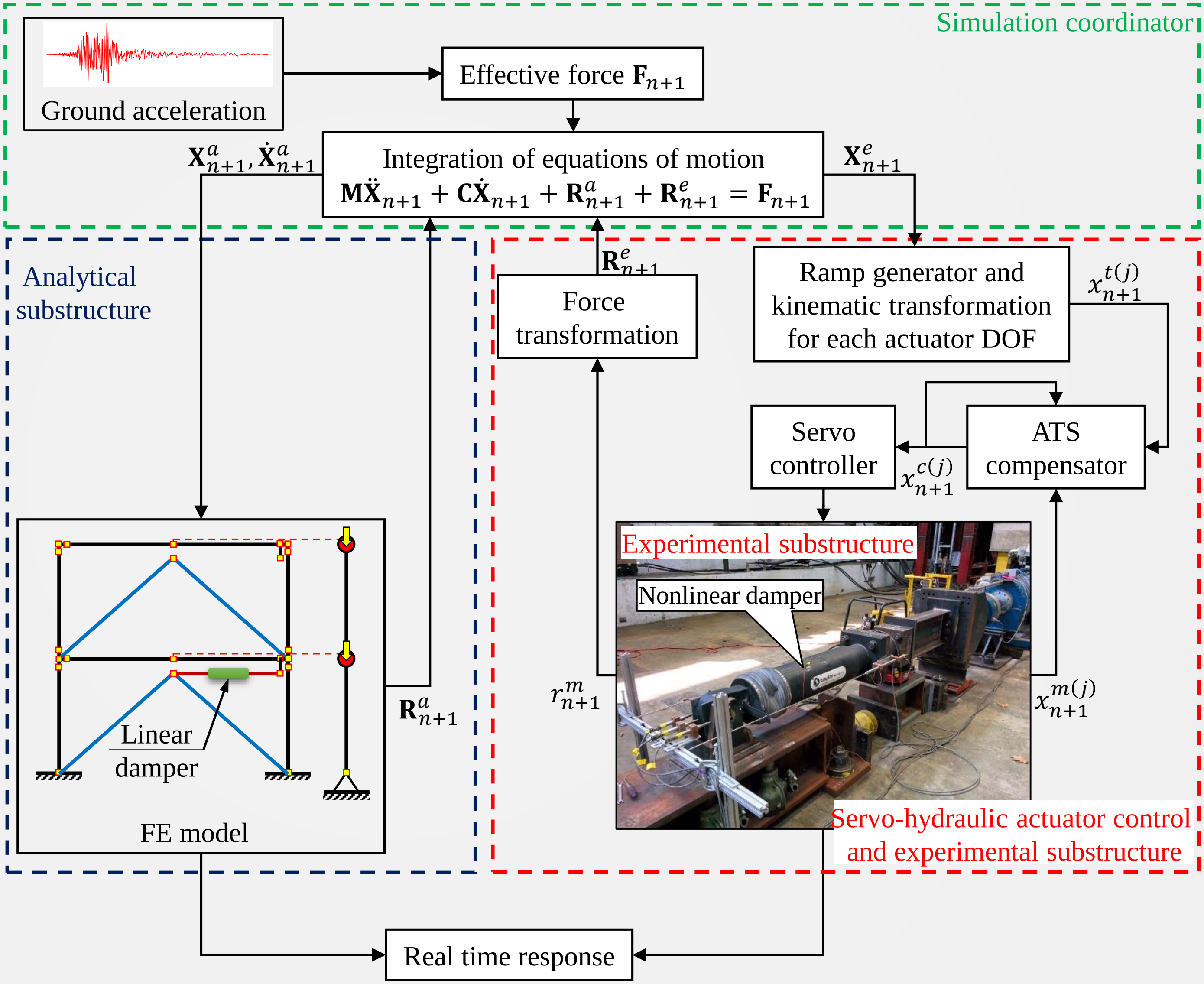
Measured vs Model Prediction

Outline

- Large-scale nonlinear viscous damper characterization test
- RTHS implementation challenges and NHERI Lehigh solutions
- RTHS of a RC building with nonlinear viscous damper

Introduction: RTHS





Kolay, C. “Parametrically Dissipative Explicit Direct Integration Algorithms for Computational and Experimental Structural Dynamics”. Ph.D. Dissertation. Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, USA, 2016

RTHS: Implementation issues and challenges

Simulation coordinator

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

Preferred

- ❑ Fast communication

Analytical substructure

- ❑ Fast and accurate state determination procedure for complex structures

Experimental substructure

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

LEHIGH UNIVERSITY. ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE NSF DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY

RTHS: Implementation issues and challenges

Simulation coordinator

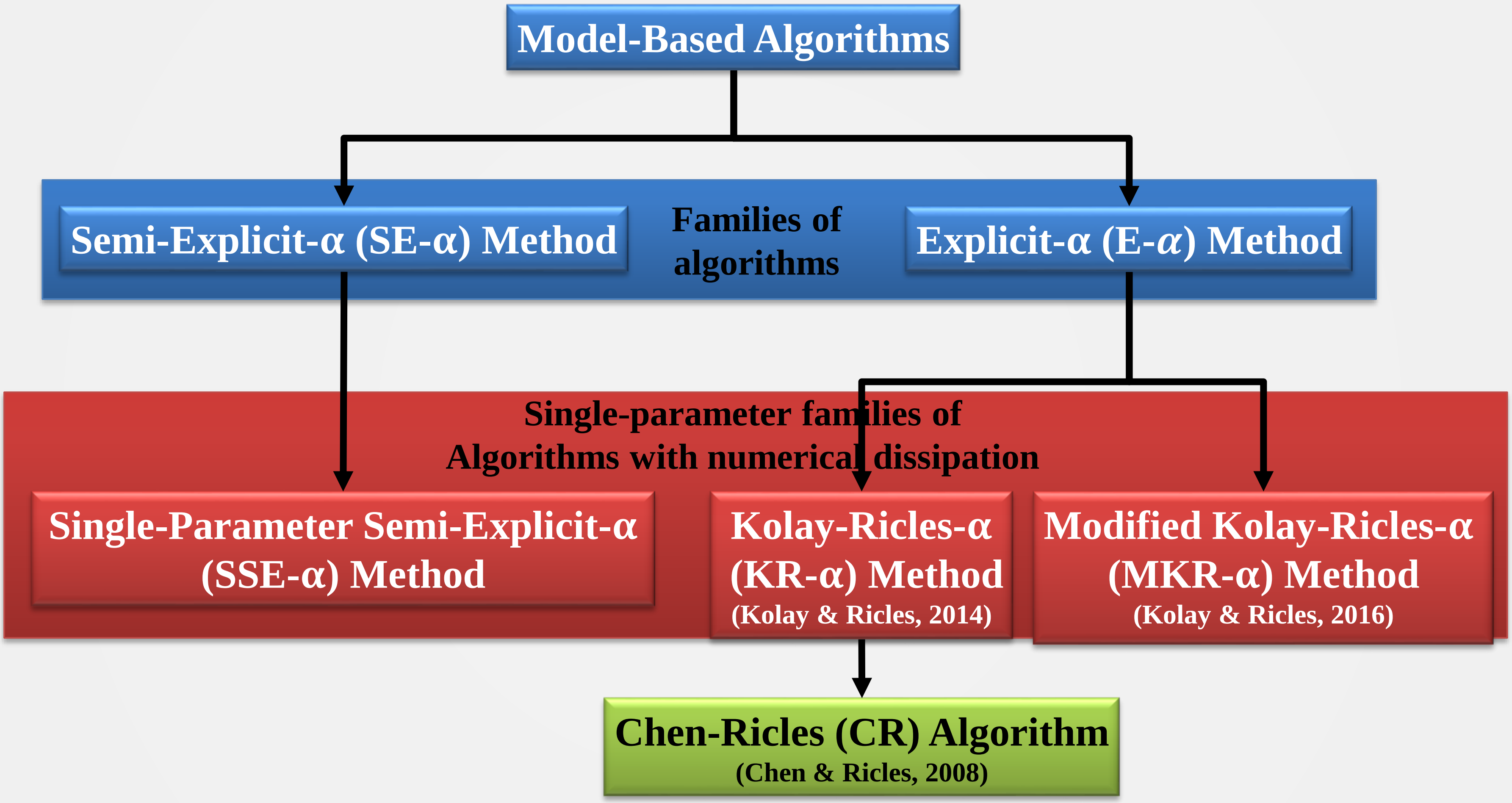
- ❑ Numerical integration algorithm
  - Accurate
  - Explicit
  - Unconditionally stable
  - Dissipative
- ❑ Fast communication

NHERI Lehigh Solutions

- Various explicit model-based algorithms
- RTMD real-time integrated control architecture

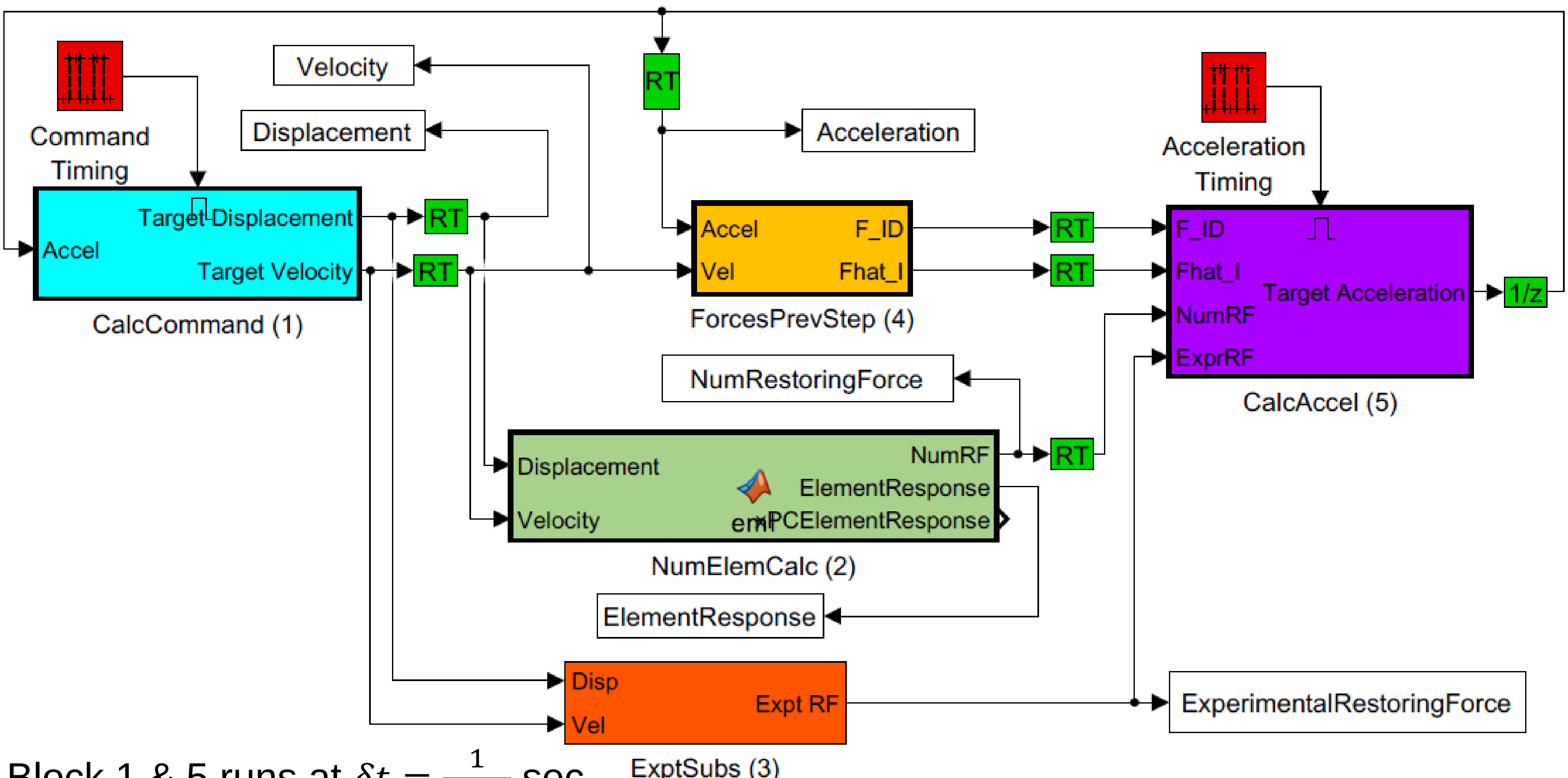
Model-based explicit algorithms for RTHS

NHERI Lehigh Solutions to RTHS Challenges



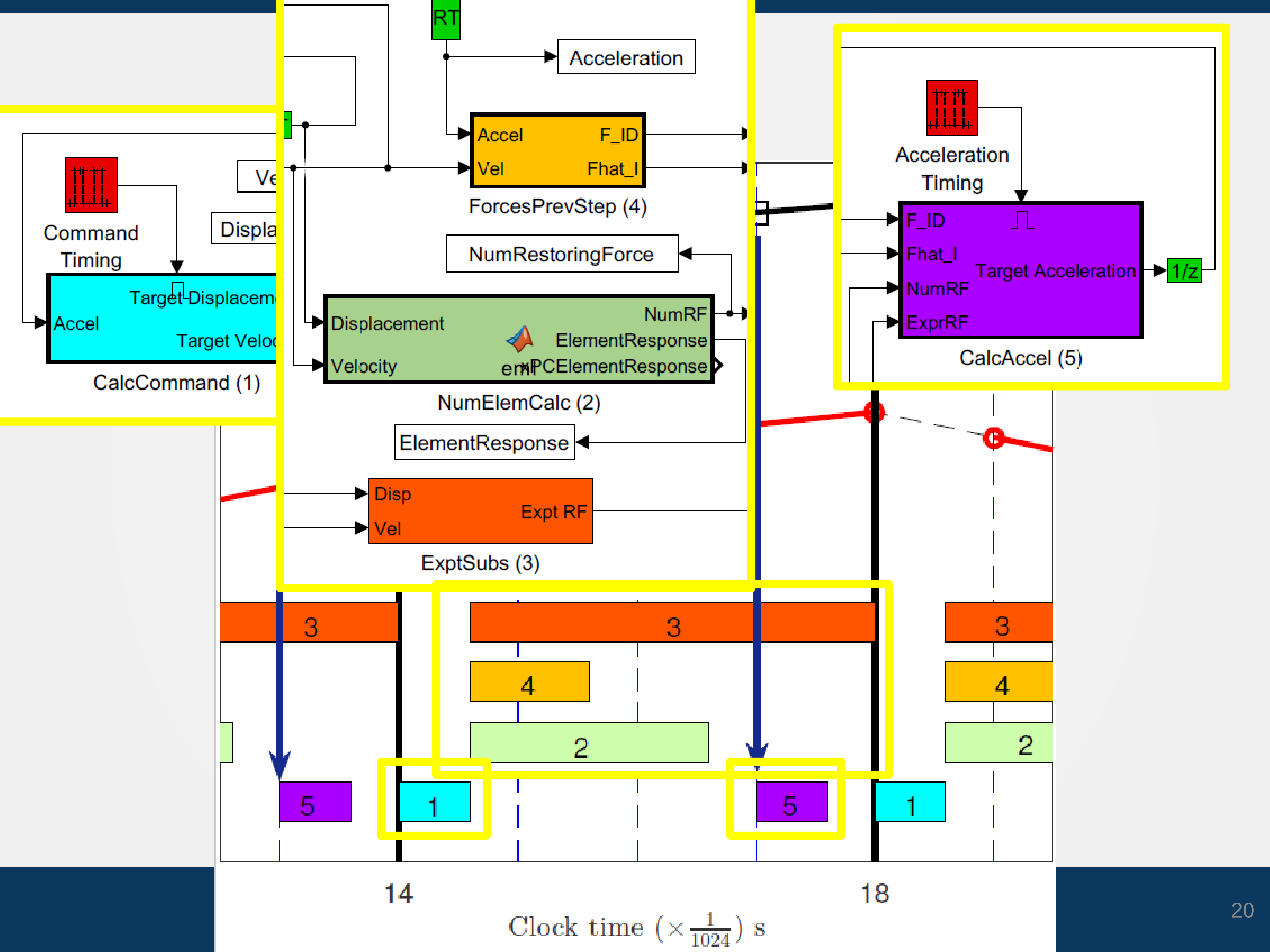
Kolay, C., & Ricles, J. M. (2015). Assessment of explicit and semi-explicit classes of model-based algorithms for direct integration in structural dynamics. *International Journal for Numerical Methods in Engineering*. doi:10.1002/nme.5153

Simulink Block Diagram for E-α 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)


RT
Acceleration
Accel
F_ID
Vel
Fhat_I
ForcesPrevStep (4)
NumRestoringForce
Displacement
NumRF
ElementResponse
Velocity
PCElementResponse
NumElemCalc (2)
ElementResponse
Disp
Expt RF
Vel
ExptSubs (3)
Command
Timing
Accel
CalcCommand (1)
Acceleration
Timing
F_ID
Fhat_I
NumRF
ExprRF
Target Acceleration
1/z
CalcAccel (5)
3
3
3
4
4
2
2
5
1
5
1
14
18
Clock time $(\times \frac{1}{1024})$ s

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

Karavasilis, T. L., Seo, C.-Y., & Ricles, J. M. (2012). *HybridFEM: A program for dynamic time history analysis and real-time hybrid simulation* (ATLSS Report). *ATLSS Report* (Vol. 08–09). Bethlehem, PA.

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
  - $\boxed{\text{Force-based beam NL column fiber element}}$
  - 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

- 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

It is important to compensate

Servo Hydraulic Actuator Control

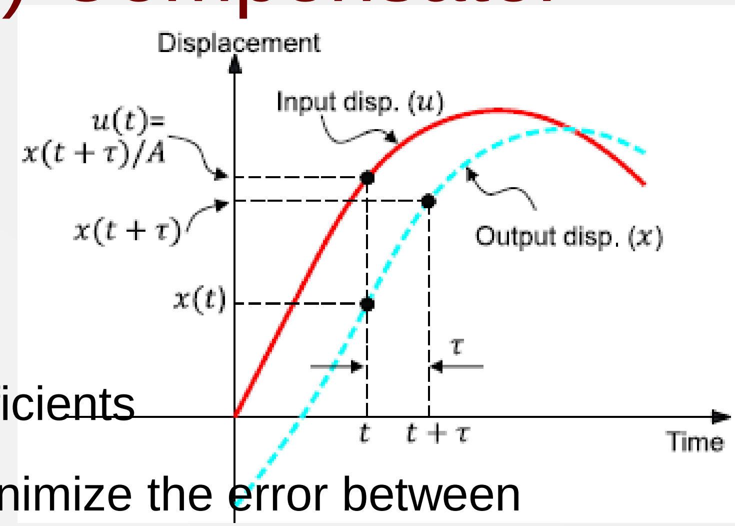
- Actuator delay compensation
  - Inverse compensation (Chen 2007)
  - Adaptive inverse compensation (AIC, Chen and Ricles 2010)
  - Adaptive time series (ATS) compensator (Chae et al. 2013)

- Chae, Y., Kazemibidokhti, K., and Ricles, J.M. (2013). “Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation”, Earthquake Engineering and Structural Dynamics, DOI: 10.1002/ eqe.2294..
- Chen C. Development and numerical simulation of hybrid effective force testing method. *Ph.D. Dissertation, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA* 2007.
- Chen, C. and Ricles, J.M. Tracking error-based servohydraulic actuator adaptive compensation for real-time hybrid simulation. *ASCE Journal of Structural Engineering*, 2010; **136**(4):432-440.

Adaptive Time Series (ATS) Compensator

2nd order ATS compensator

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



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

$$\mathbf{A} = \left(\mathbf{X}_m^T \mathbf{X}_m\right)^{-1} \mathbf{X}_m^T \mathbf{U}_c$$

$$\mathbf{A} = \left[a_{0k}\ a_{1k} \cdots a_{nk}\right]^T \qquad \mathbf{X}_m = \left[\mathbf{x}^m\ \dot{\mathbf{x}}^m \cdots \frac{d^n}{dt^n}\left(\mathbf{x}^m\right)\right]^T$$

$$\mathbf{x}^m = \left[x_{k-1}^m\ x_{k-2}^m \cdots x_{k-q}^m\right]^T$$ (Output (measured) specimen displacement history)

$$\mathbf{U}_c = \left[u_{k-1}^c\ u_{k-2}^c \cdots u_{k-q}^m\right]^T$$ (Input actuator displacement history)

Chae, Y., Kazemibidokhti, K., and Ricles, J.M. (2013). "Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation", *Earthquake Engineering and Structural Dynamics,* DOI: 10.1002/ eqe.2294.

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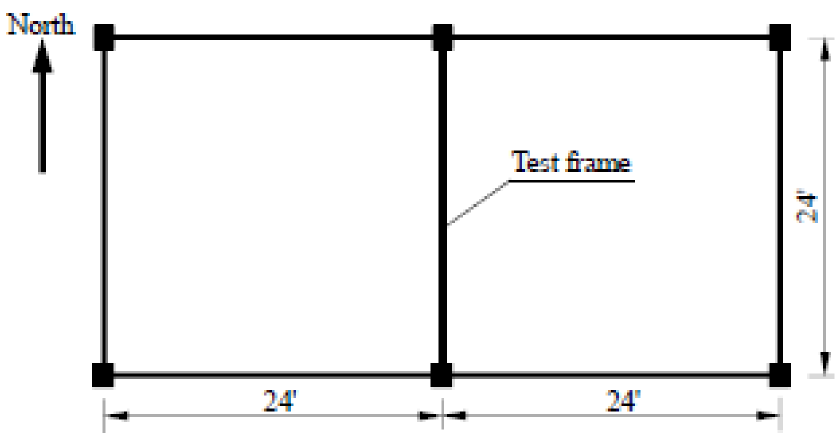
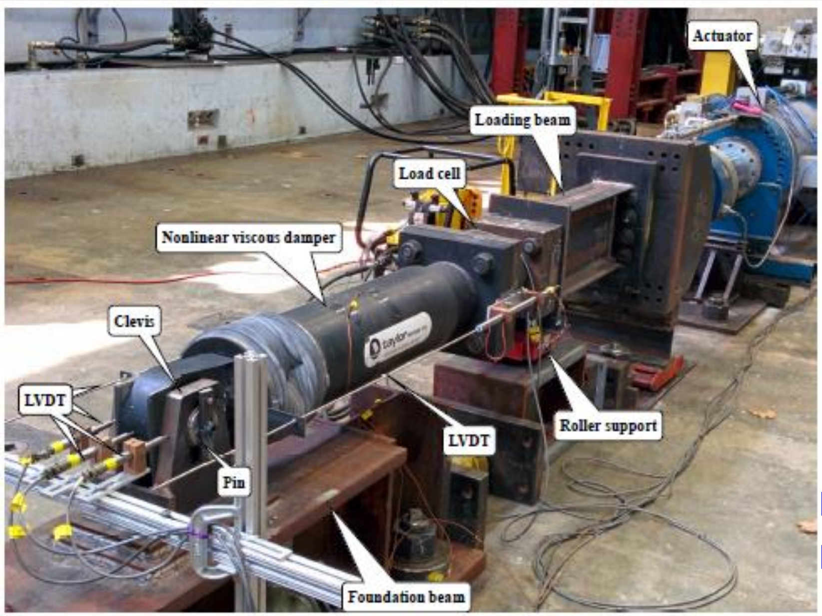
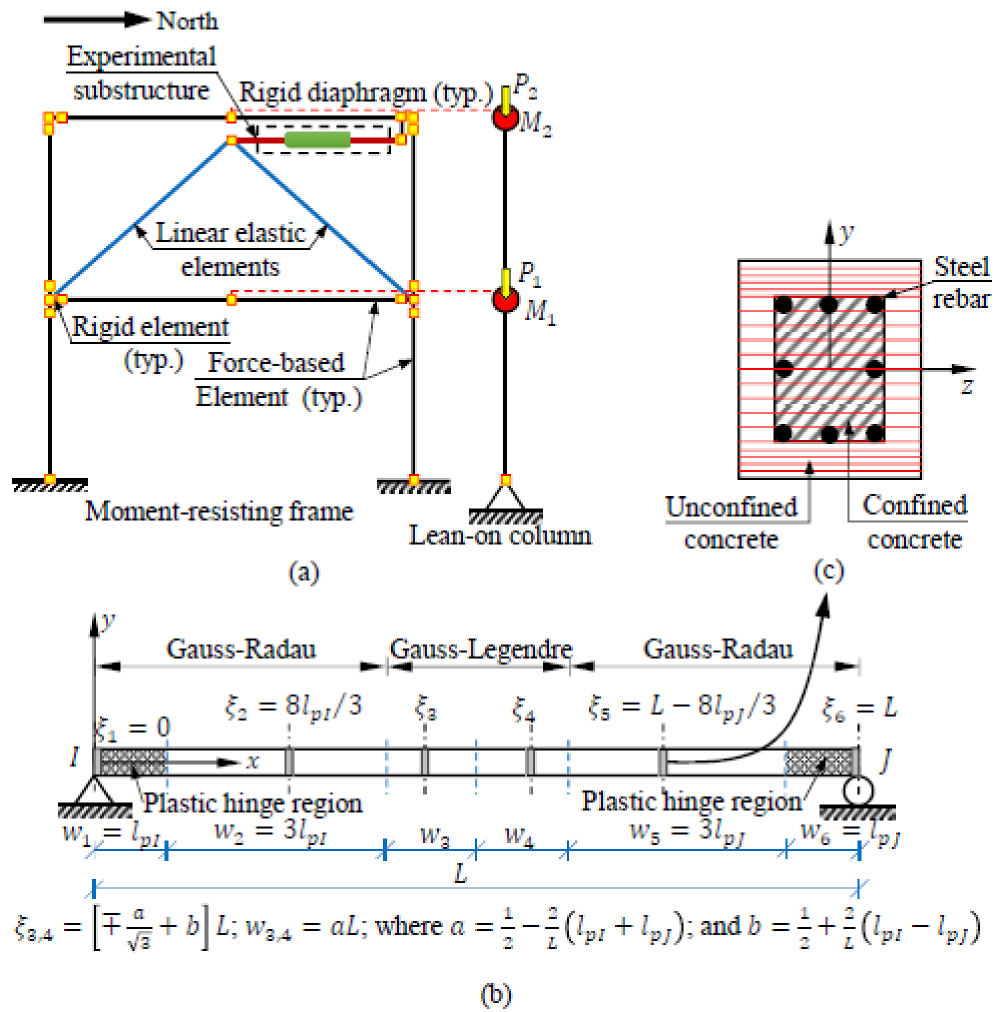
RTHS configuration



Prototype floor plan





- ❑ 1999 Chi-Chi EQ record scaled to MCE hazard level
- ❑ Time step: $\Delta t = \frac{3}{1024}$ 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-α method (parameter ρ_∞^*)
  - Model-based integration parameters ($\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$, $\boldsymbol{\alpha}_3$) determined from characterization test data
- ATS Compensator for adaptive time delay and amplitude compensation

Explicit Modified KR-α (MKR-α) Method

$\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$, and $\boldsymbol{\alpha}_3$: model-based integration parameters

Velocity update: $\dot{\mathbf{X}}_{n+1} = \dot{\mathbf{X}}_n + \Delta t \boldsymbol{\alpha}_1 \ddot{\mathbf{X}}_n$

Displacement update: $\mathbf{X}_{n+1} = \mathbf{X}_n + \Delta t \dot{\mathbf{X}}_n + \Delta t^2 \boldsymbol{\alpha}_2 \ddot{\mathbf{X}}_n$

Weighted equations of motion: $\mathbf{M}\hat{\ddot{\mathbf{X}}}_{n+1} + \mathbf{C}\dot{\mathbf{X}}_{n+1-\alpha_f} + \mathbf{K}\mathbf{X}_{n+1-\alpha_f} = \mathbf{F}_{n+1-\alpha_f}$

where,

$$\hat{\ddot{\mathbf{X}}}_{n+1} = (\mathbf{I} - \boldsymbol{\alpha}_3)\ddot{\mathbf{X}}_{n+1} + \boldsymbol{\alpha}_3 \ddot{\mathbf{X}}_n$$

$$\dot{\mathbf{X}}_{n+1-\alpha_f} = (1-\alpha_f)\dot{\mathbf{X}}_{n+1} + \alpha_f \dot{\mathbf{X}}_n$$

$$\mathbf{X}_{n+1-\alpha_f} = (1-\alpha_f)\mathbf{X}_{n+1} + \alpha_f \mathbf{X}_n$$

$$\mathbf{F}_{n+1-\alpha_f} = (1-\alpha_f)\mathbf{F}_{n+1} + \alpha_f \mathbf{F}_n$$

Initial acceleration: $\mathbf{M}\ddot{\mathbf{X}}_0 = [\mathbf{F}_0 - \mathbf{C}\dot{\mathbf{X}}_0 - \mathbf{K}\mathbf{X}_0]$

Kolay, C., & Ricles, J. M. (2014). Development of a family of unconditionally stable explicit direct integration algorithms with controllable numerical energy dissipation. *Earthquake Engineering and Structural Dynamics*, *43*(9), 1361–1380. http://doi.org/10.1002/eqe.2401

Integration Parameters

- Parameter controlling numerical energy dissipation
  - ρ_∞ = spectral radius when $\Omega = \omega \Delta t \to \infty$
    - varies in the range $0 \le \rho_\infty \le 1$
  - ρ_∞ = 1: No numerical energy dissipation
  - ρ_∞ = 0: Asymptotic annihilation
- Scalar integration parameters:
  - $\alpha_m = \frac{2\rho_\infty^3 + \rho_\infty^2 - 1}{\rho_\infty^3 + \rho_\infty^2 + \rho_\infty + 1}$; $\alpha_f = \frac{\rho_\infty}{\rho_\infty + 1}$; $\gamma = \frac{1}{2} - \alpha_m + \alpha_f$; $\beta = \frac{1}{2}\left(\frac{1}{2} + \gamma\right)$
- Model-based integration parameter matrices:
  - $\boldsymbol{\alpha}_1 = [\mathbf{M}_{IP} + \gamma \Delta t \mathbf{C}_{IP} + \beta \Delta t^2 \mathbf{K}_{IP}]^{-1} \mathbf{M}_{IP}$; $\boldsymbol{\alpha}_2 = \left(\frac{1}{2} + \gamma\right) \boldsymbol{\alpha}_1$
  - $\boldsymbol{\alpha}_3 = [\mathbf{M}_{IP} + \gamma \Delta t \mathbf{C}_{IP} + \beta \Delta t^2 \mathbf{K}_{IP}]^{-1} \left[\alpha_m \mathbf{M}_{IP} + \alpha_f \gamma \Delta t \mathbf{C}_{IP} + \alpha_f \beta \Delta \mathrm{t}^2 \mathbf{K}_{IP}\right]$
  - IP stands for integration parameters
  - $\mathbf{M}_{IP}$, $\mathbf{C}_{IP}$, and $\mathbf{K}_{IP}$ need to be formed based on the hybrid system

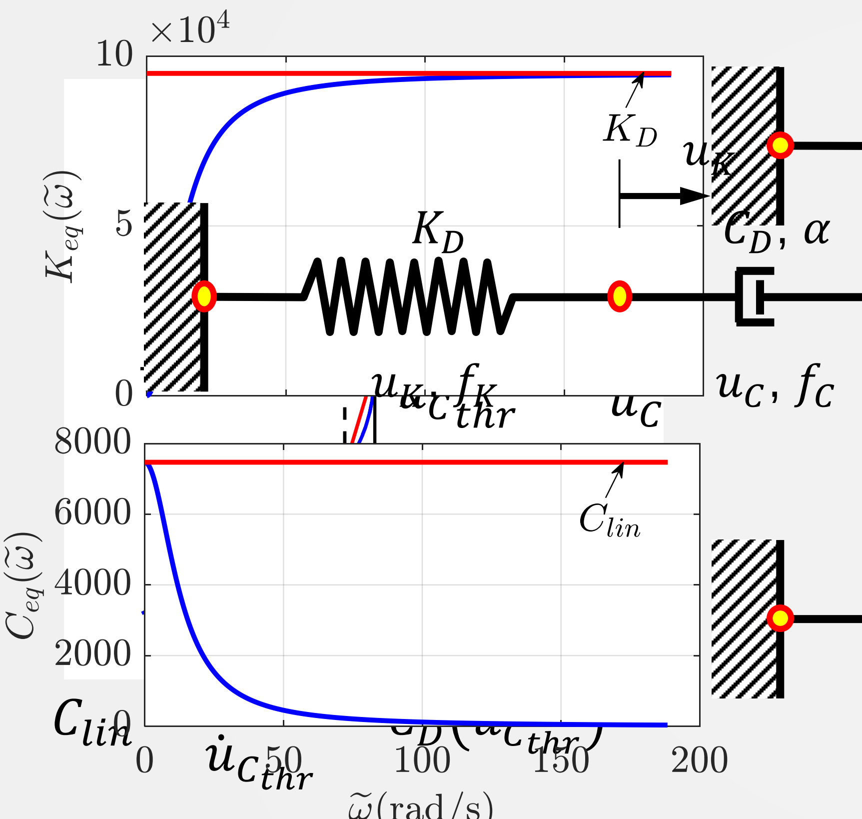
Kolay, C., & Ricles, J. M. (2016). Improved explicit integration algorithms for structural dynamic analysis with unconditional stability and numerical dissipation. Submitted to *Journal of Earthquake Engineering*.

RTHS: Model-Based Integration Parameters

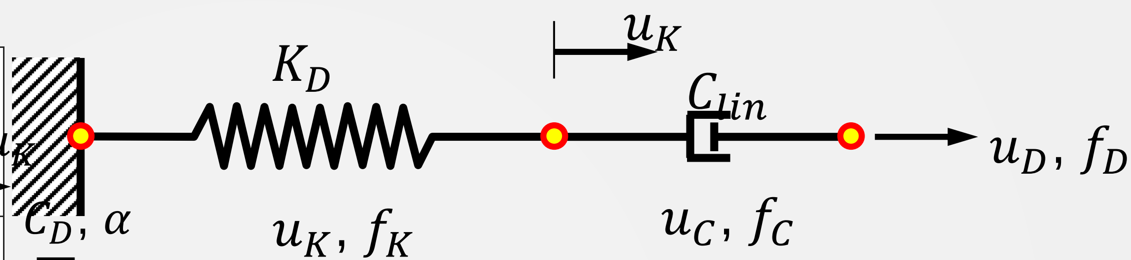
- Model-based integration parameters ($\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$, and $\boldsymbol{\alpha}_3$) require $\mathbf{M}_{IP}$, $\mathbf{C}_{IP}$, and $\mathbf{K}_{IP}$
- For the present study
  - $\mathbf{M}_{IP} = \mathbf{M}$ =analytically modeled mass matrix
    - Experimental substructure mass is small
  - $\mathbf{C}_{IP} = (a_0\mathbf{M} + a_1\mathbf{K}_I^a) + \mathbf{C}_{eq}^e$
    - $\mathbf{K}_I^a$ = initial stiffness matrix of analytical substructure
    - $\mathbf{C}_{eq}^a$ =equivalent damping matrix of experimental substructure
    - a_0 and a_1 are Rayleigh damping coefficients
  - $\mathbf{K}_{IP} = \mathbf{K}_I^a + \mathbf{K}_{eq}^e$
    - $\mathbf{K}_{eq}^e$ =equivalent stiffness matrix of experimental substructure
- How can we determine $\mathbf{C}_{eq}^e$ and $\mathbf{K}_{eq}^e$?

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

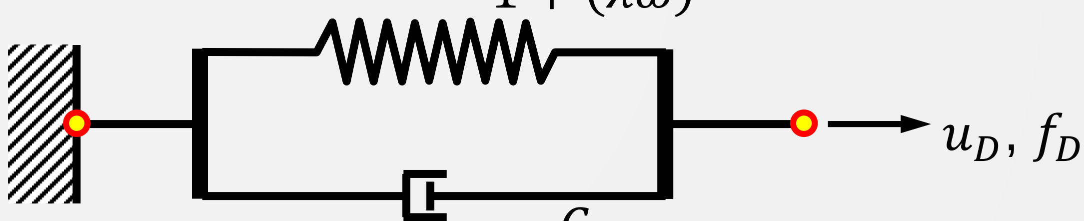


Linearization



Linearized Maxwell model

$$K_{eq}(\widetilde{\omega}) = \frac{K_D(\lambda\widetilde{\omega})^2}{1+(\lambda\widetilde{\omega})^2}$$



$$C_{eq}(\widetilde{\omega}) = \frac{C_{lin}}{1+(\lambda\widetilde{\omega})^2}$$

Equivalent Kelvin-Voigt model

- ❑ What is the value of $\widetilde{\omega}$?

RTHS Test Matrix

Test No.	$maxIter$	$\tilde{\omega}$	ρ_∞^*
1	1	0	0.75
2	2	0	0.75
3	2	$\frac{\omega_1}{2}$	0.75
4	2	ω_1	0

RTHS Test Data

References

- Chae, Y. (2011). “Seismic Hazard Mitigation of Building Structures Using Magneto-Rheological Dampers.” Ph.D. dissertation, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA.
- Chae, Y., Kazemibidokhti, K., & Ricles, J. M. (2013). Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation. *Earthquake Engineering & Structural Dynamics*, *42*(11), 1697–1715. doi:10.1002/eqe
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- Kolay, C., & Ricles, J. M. (2014). Development of a family of unconditionally stable explicit direct integration algorithms with controllable numerical energy dissipation. *Earthquake Engineering and Structural Dynamics*, *43*(9), 1361–1380. http://doi.org/10.1002/eqe.2401
- Kolay, C., & Ricles, J. M. (2016). Force-based frame element implementation for real-time hybrid simulation using explicit direct integration algorithms. Submitted to *Journal of Structural Engineering*.
- Kolay, C., & Ricles, J. M. (2016). Improved explicit integration algorithms for structural dynamic analysis with unconditional stability and numerical dissipation. Submitted to *Journal of Earthquake Engineering*.
- Kolay, C., Ricles, J. M., Marullo, T. M., Mahvashmohammadi, A., & Sause, R. (2015). Implementation and application of the unconditionally stable explicit parametrically dissipative KR-α method for real-time hybrid simulation. *Earthquake Engineering & Structural Dynamics*, *44*(5), 735–755. http://doi.org/10.1002/eqe.2484
- Ye, M. and Wang, X. (2007). “Parameter estimation of the Bouc-Wen hysteresis model using particle swarm optimization.” Smart Materials and Structures, 16(6), 2341–2349.

Thank you