Hybrid Simulation of Base Isolated Structures (EEI01): 6 Degree of Freedom Model

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OpenFresco

Outline of Presentation

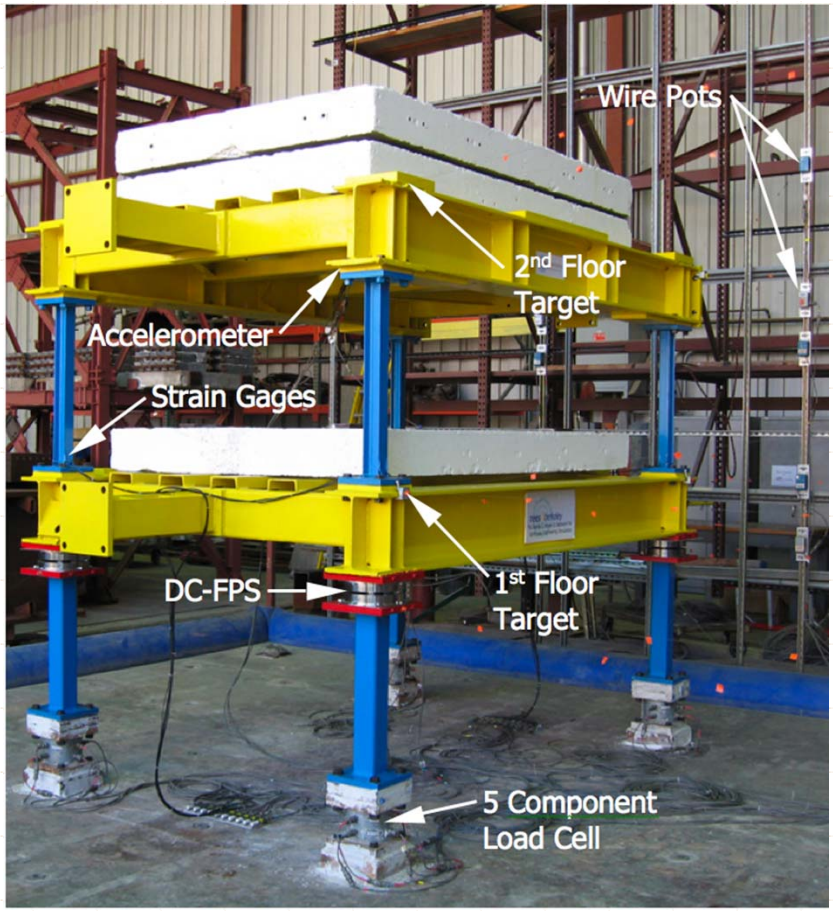
1. Objective of EEI01
2. Isolated Model Structure
3. Hybrid Model and Test Setup
4. Test Procedure
5. Noise Compensation
6. Velocity Dependent Friction
7. Selected Results
8. Conclusions

Objective

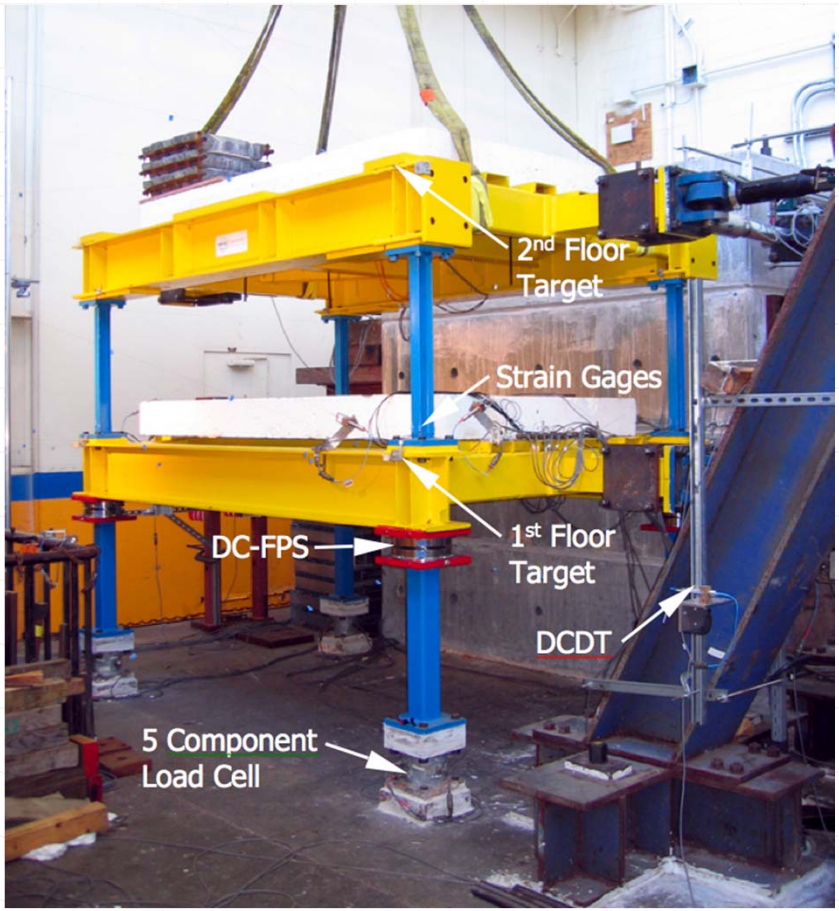
- Verification of Hybrid Simulation against Shake Table testing
- Validation of OpenFresco and OpenSees software developments
- Feasibility study on MDOF, bidirectional Hybrid Simulations
- Comparison of complete vs. partitioned Hybrid Simulations
- Identify relative benefits of Hybrid Simulation and Shake Table testing
- Identify research needs to improve HS
- Not a specific study on seismic isolation

Model Structure

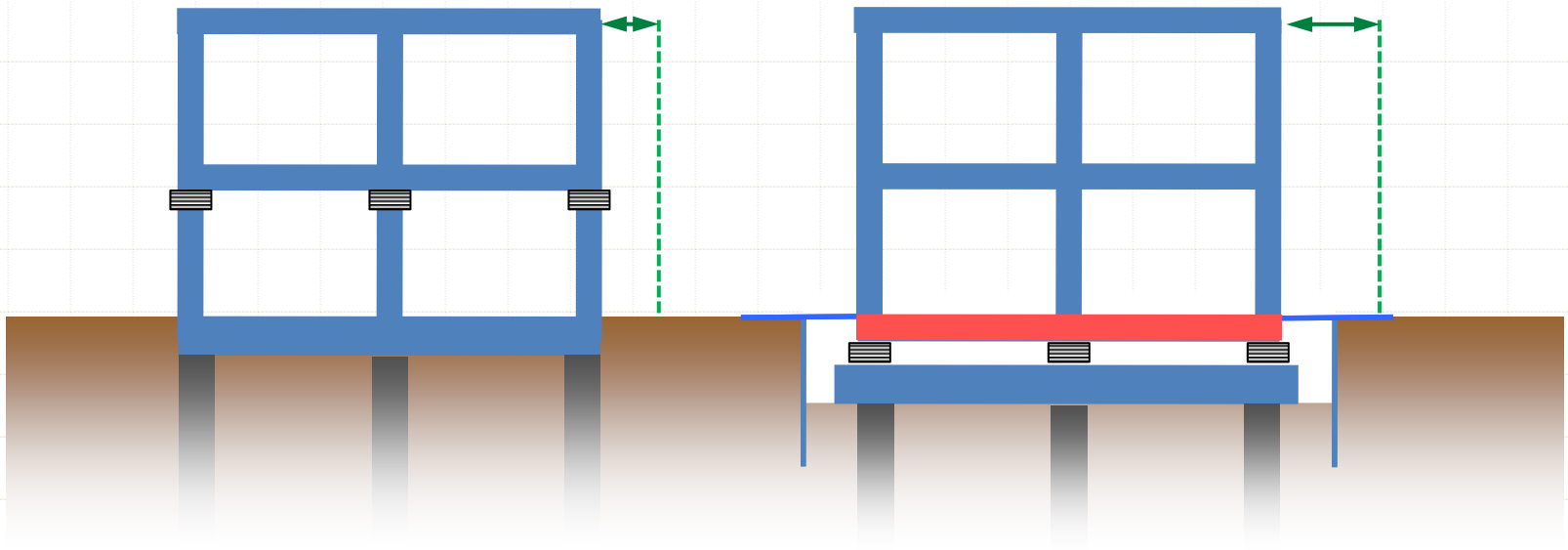
Shake Table Tests



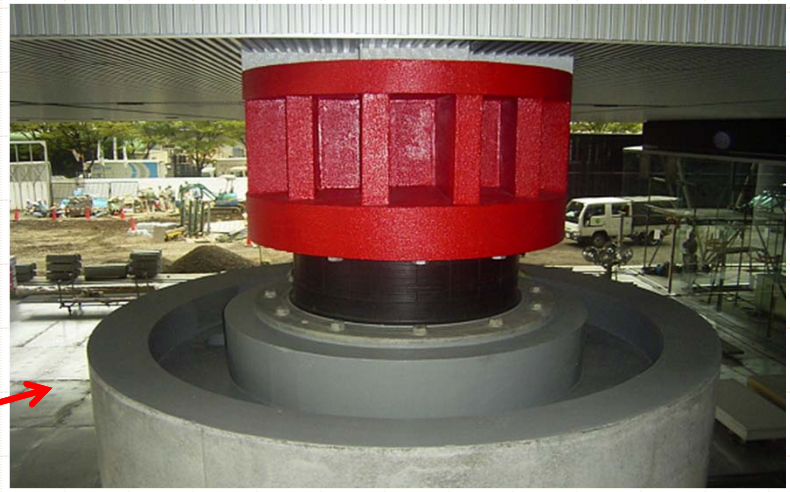
Hybrid Simulation Tests



Base vs. Midlevel Isolation

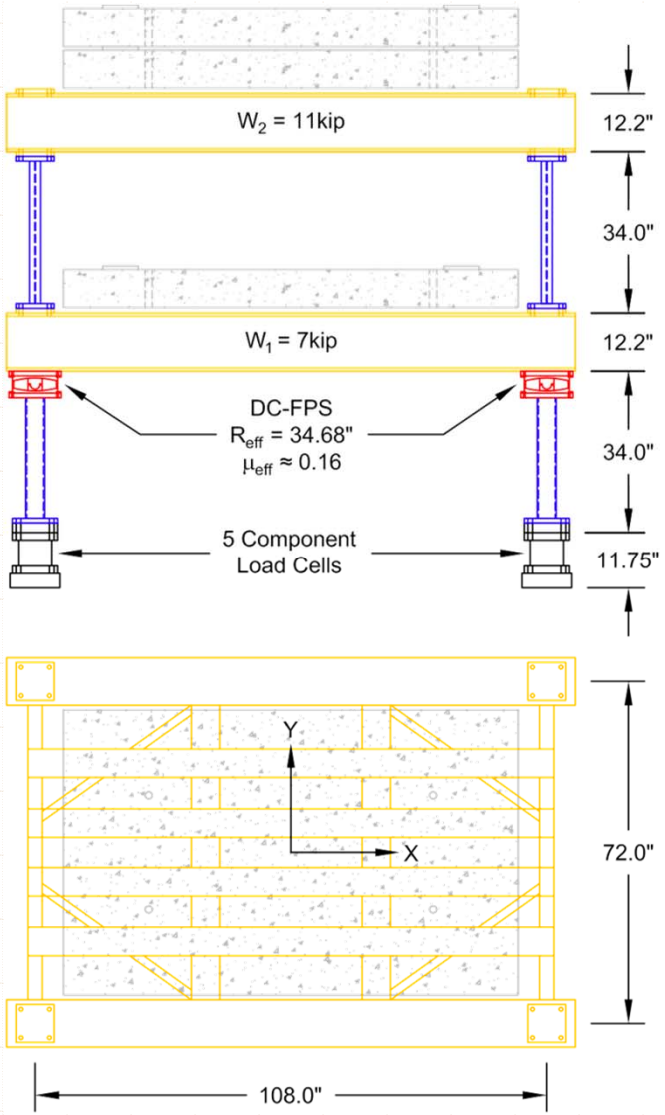


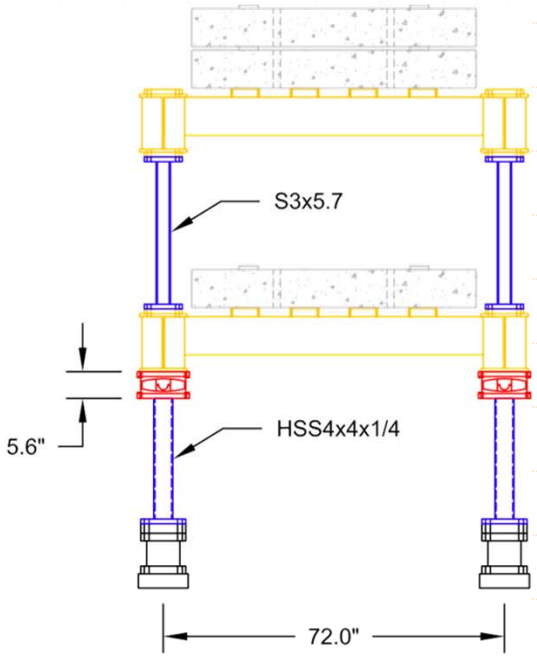
Isolators at top of first story columns



Shimizu Research Center, Tokyo, Japan

Plan and Elevation Views

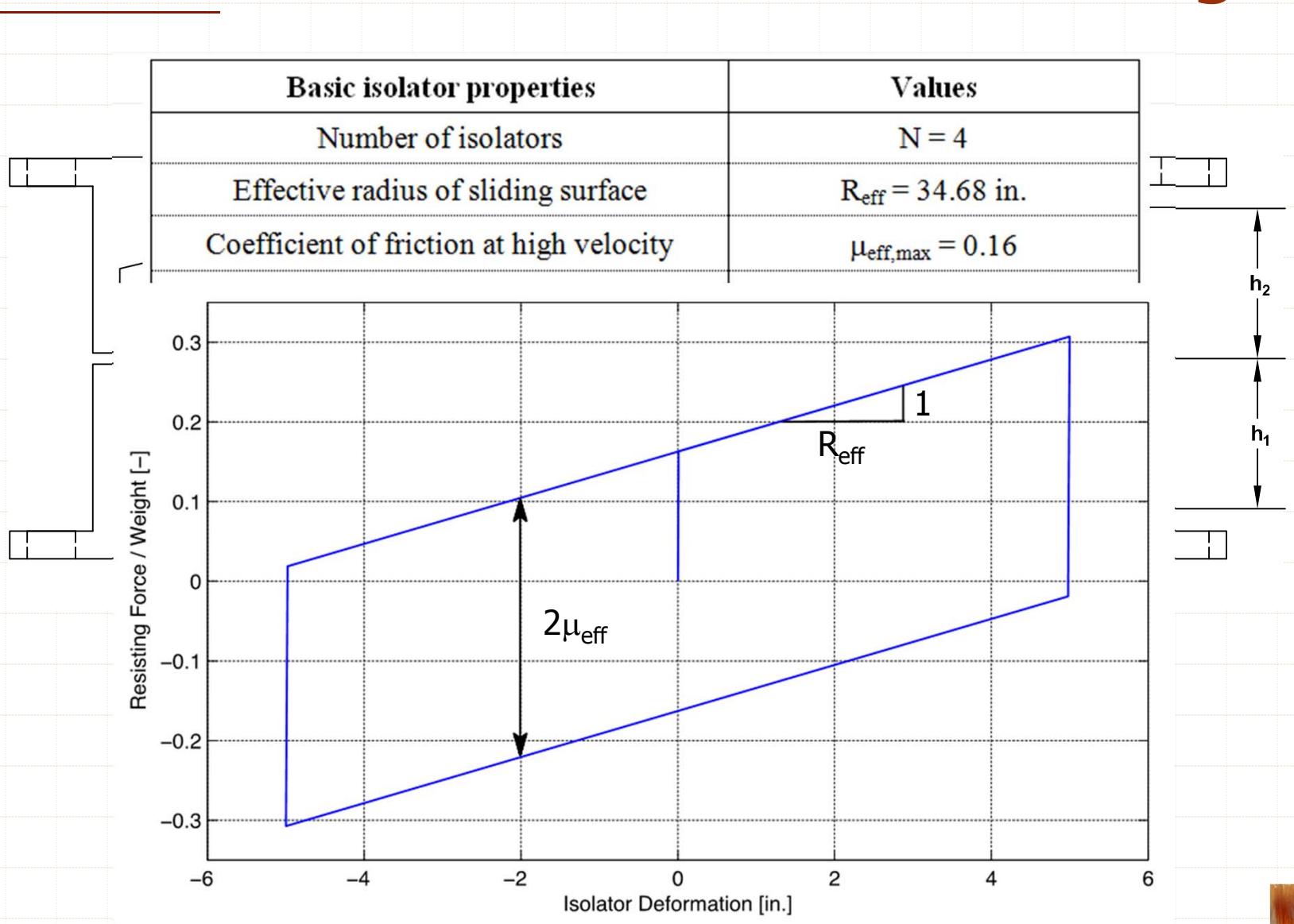




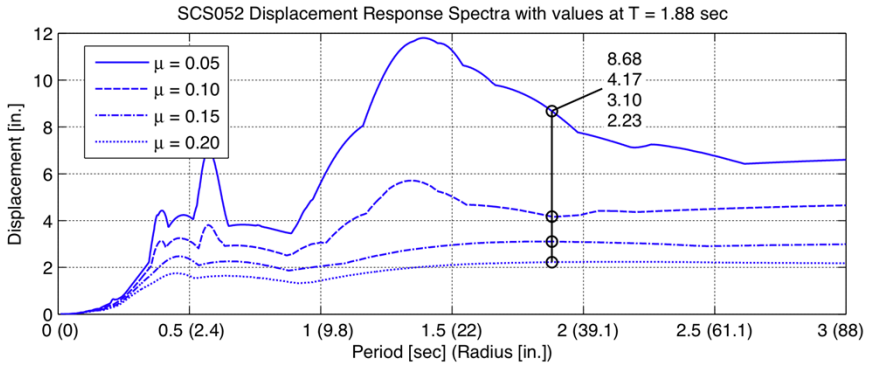
¼ scale of full-size prototype building

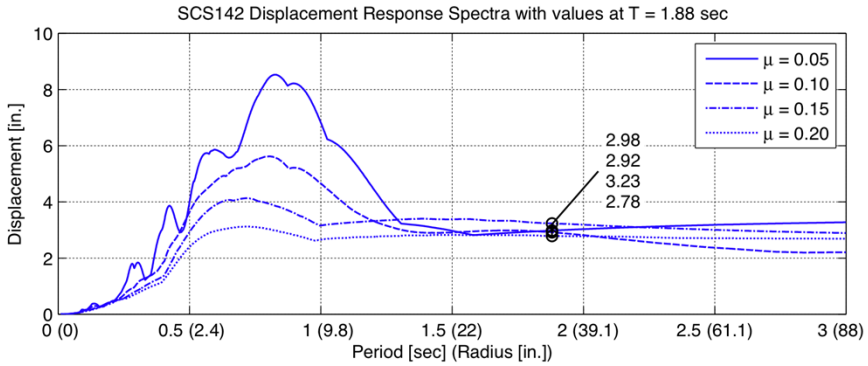
Double Friction Pendulum Bearings

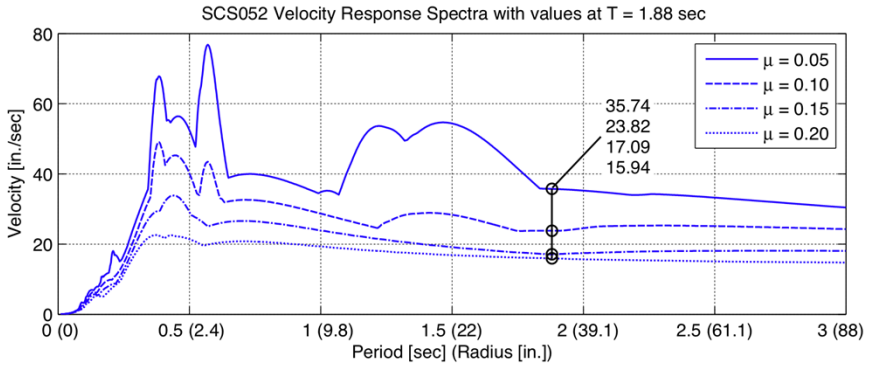
Basic isolator properties	Values
Number of isolators	N = 4
Effective radius of sliding surface	R_{eff} = 34.68 in.
Coefficient of friction at high velocity	$\mu_{eff,max}$ = 0.16

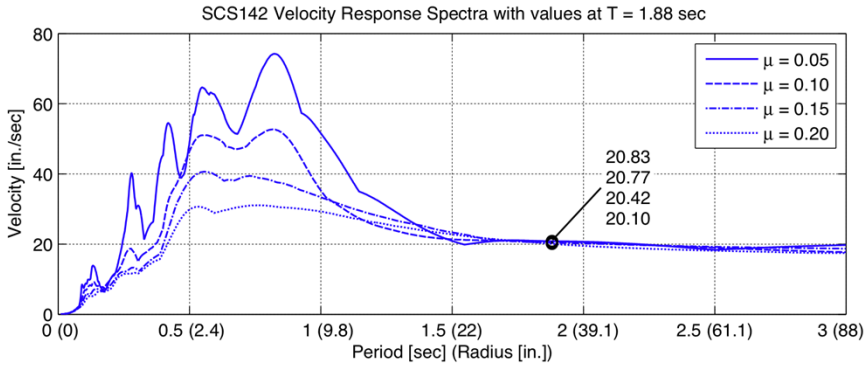


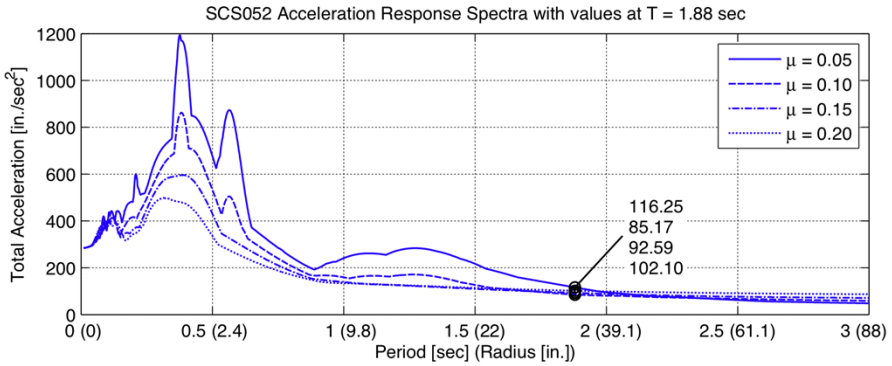
Nonlinear FPS Response Spectra

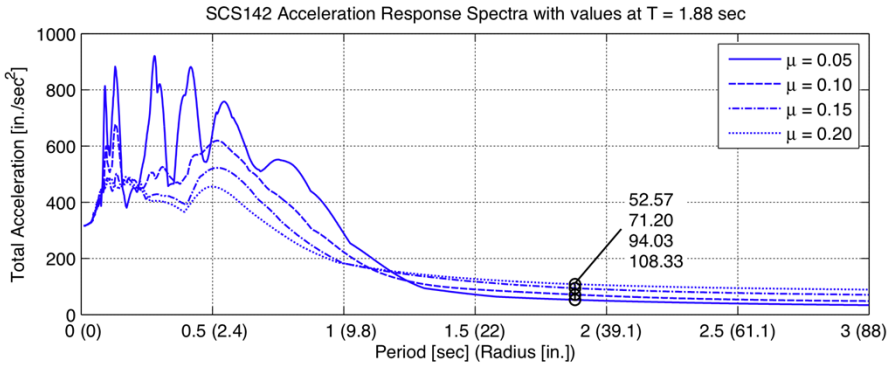




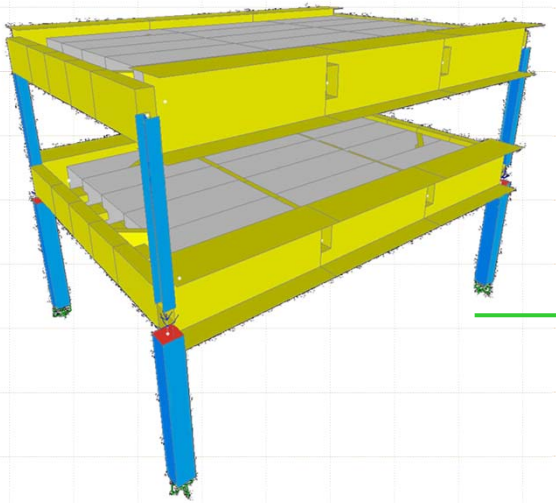


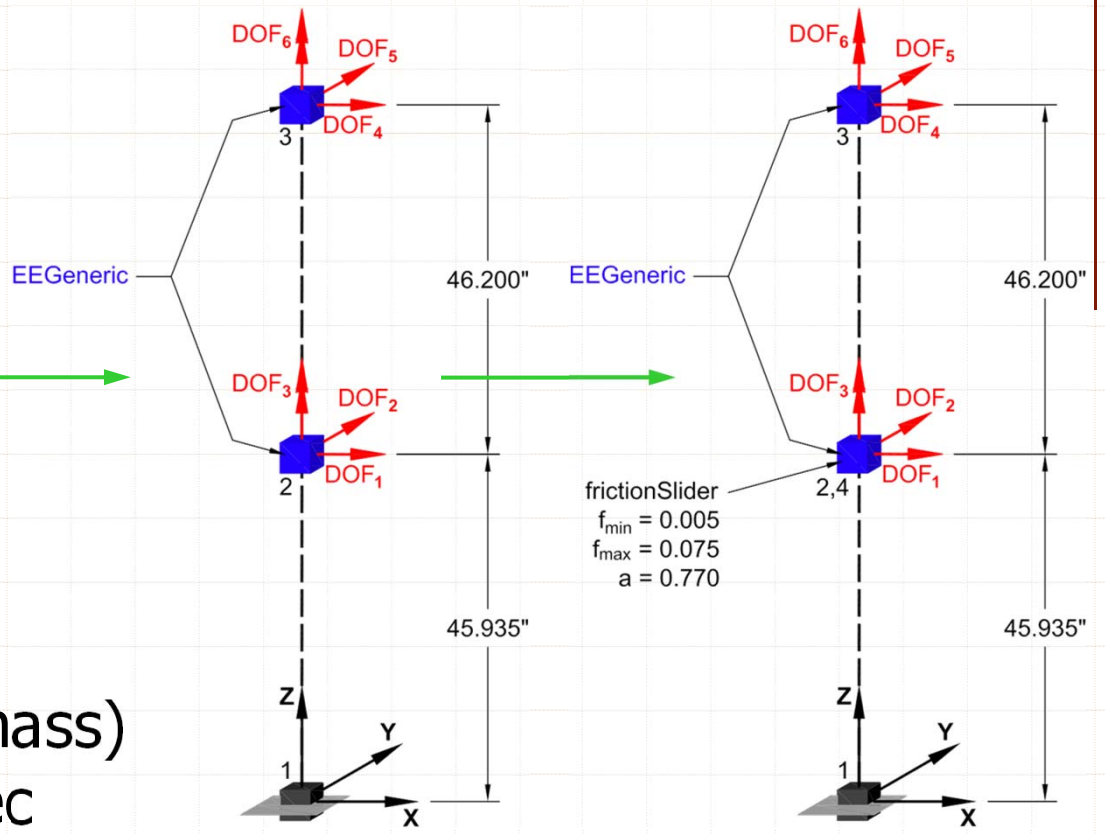






Hybrid Model





Properties of Model:

- NDOF = 6 (6 with mass)
- Period: T_1 = 1.88 sec
- R_{FPS} = 36 in, μ_{FPS} = 16%
- Gravity Load: P = 18 kips

- ExpElement: EEGeneric
- ExpSetups: ESThreeActuators
- ExpControl: ECxPCtarget

Determine Model Properties

- Estimate weight of floor diaphragms

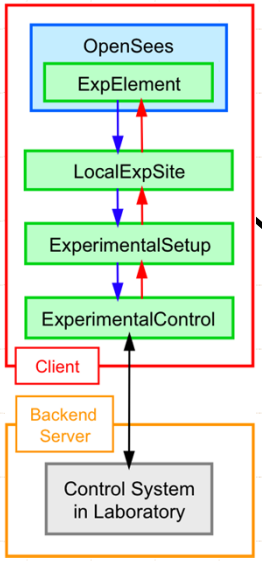
$$\mathbf{M} = \begin{bmatrix} 0.0181 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.0181 & 0 & 0 & 0 & 0 \\ 0 & 0 & 25.4545 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0285 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.0285 & 0 \\ 0 & 0 & 0 & 0 & 0 & 40.0000 \end{bmatrix}$$

- Perform pull-back and hybrid pushover tests

$$\mathbf{K}_i = \begin{bmatrix} 79.5 & 0 & 0 & -19.5 & 0 & 0 \\ 0 & 121.0 & 0 & 0 & -61.0 & 0 \\ 0 & 0 & 455868.0 & 0 & 0 & -203148.0 \\ -19.5 & 0 & 0 & 19.5 & 0 & 0 \\ 0 & -61.0 & 0 & 0 & 61.0 & 0 \\ 0 & 0 & -203148.0 & 0 & 0 & 203148.0 \end{bmatrix}$$

[kip, in.]

OpenSees/OpenFresco Details



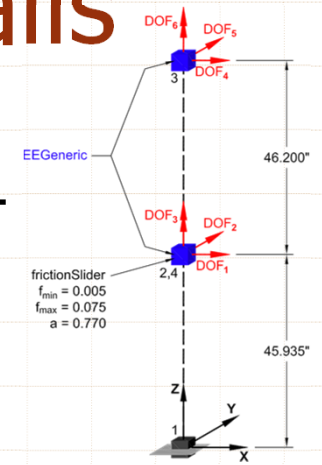
OpenSees Finite Element Model

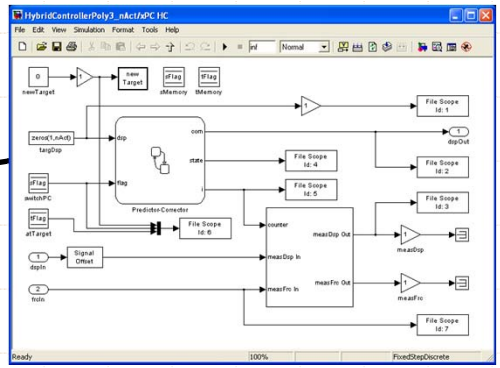
OpenFresco Middleware

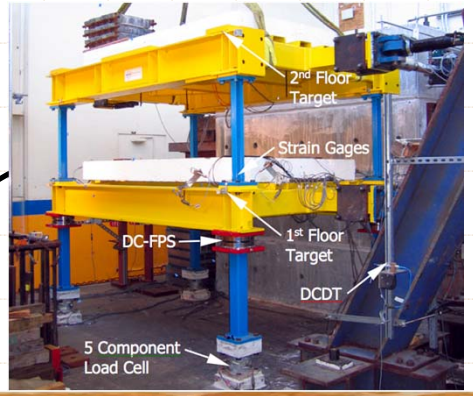
xPC-Target real-time Predictor-Corrector

MTS 493 real-time Controller

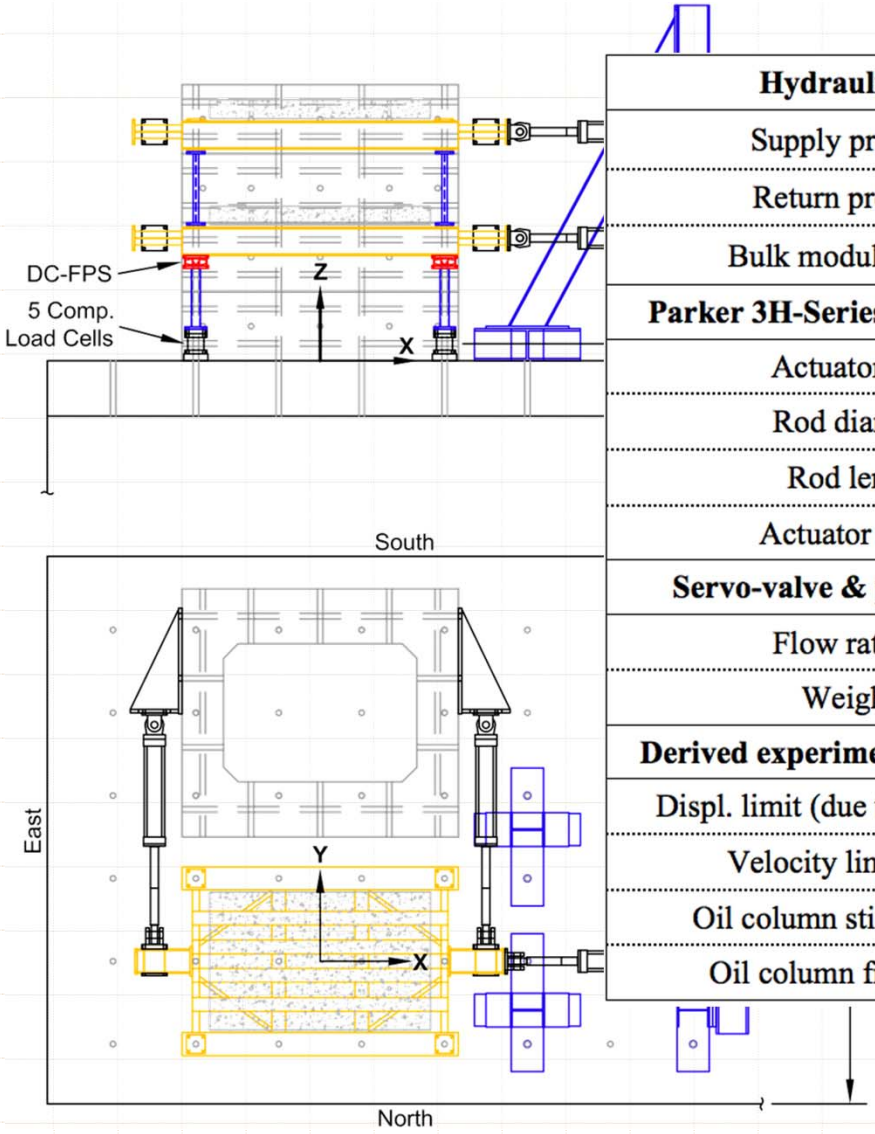
Physical Specimen in NEES Lab





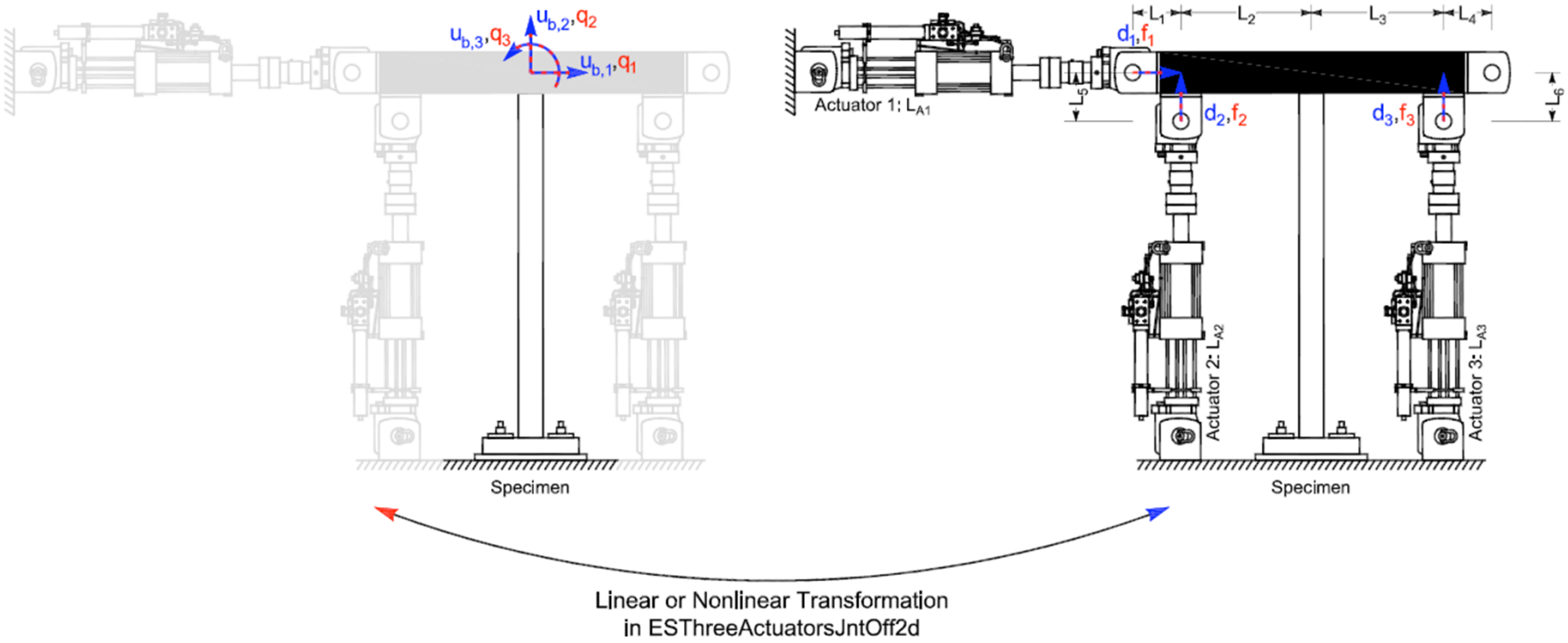


Hybrid Test Setup



Hydraulic properties	X1	X2	Y1	Y2
Supply pressure p_s [ksi]	3	3	3	3
Return pressure p_r [ksi]	0.05	0.05	0.05	0.05
Bulk modulus of oil β [ksi]	100	100	100	100
Parker 3H-Series actuator properties	**X1**	**X2**	**Y1**	**Y2**
Actuator bore b [in.]	8	8	8	8
Rod diameter d [in.]	3.5	3.5	3.5	3.5
Rod length L [in.]	52	52	52	52
Actuator stroke S [in.]	+29/-7	+29/-7	±18	±18
Servo-valve & payload properties	**X1**	**X2**	**Y1**	**Y2**
Flow rate q [in^3/sec]	231.0	231.0	38.5	38.5
Weight W [kip]	7.3	8.8	3.8	4.6
Derived experimental setup properties	**X1**	**X2**	**Y1**	**Y2**
Displ. limit (due to isolators) d_{max} [in.]	±5.0	±5.0	±5.0	±5.0
Velocity limit v_{max} [in./sec]	4.60	4.60	0.77	0.77
Oil column stiffness K_{oc} [kip/in.]	469.1	469.1	499.4	499.4
Oil column frequency f_{oc} [Hz]	25.0	22.8	35.7	32.7

OpenFresco Experimental Setup

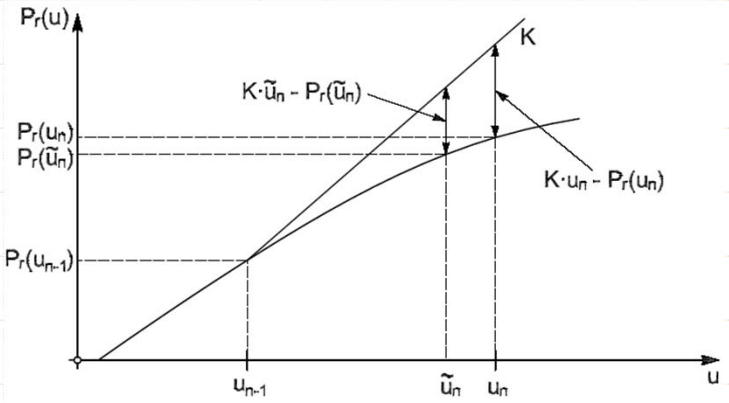


Direct Integration Methods for HS

- Explicit Integrators
  - explicit Newmark Method
  - explicit Alpha Method
  - explicit Generalized-Alpha Method

Direct Integration Methods for HS

- Implicit Integrators with sub-stepping (constant number)
  - Newmark HS FixedNumIter Method
  - Generalized-Alpha HS FixedNumIter Method
- Predictor-Corrector Integrators
  - Alpha-OS Method
  - Generalized-Alpha-OS Method



Warm-up Procedure

- Warm-up oil, servo-valves and actuators
- Improved tracking performance
- For this system actuators were not disconnected

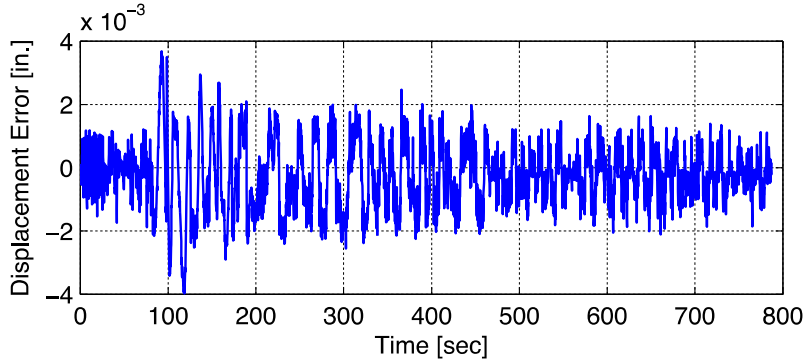
Procedure:

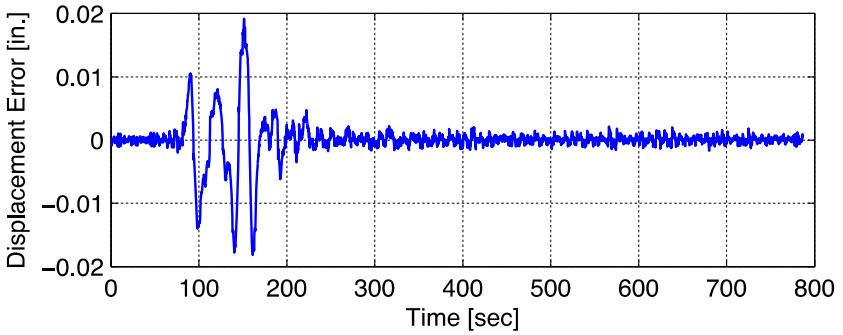
- Manually center and make superstructure force-free
- Run figure-8 motions at various amplitudes and frequencies
- Run random noise signal to vibrate isolators back into force-free equilibrium position

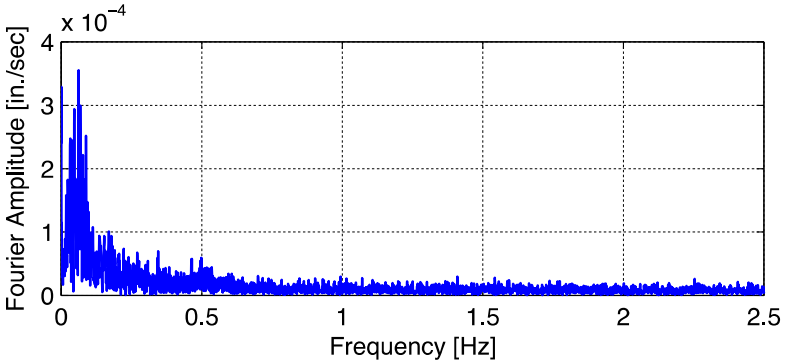
Quasi Static Tests

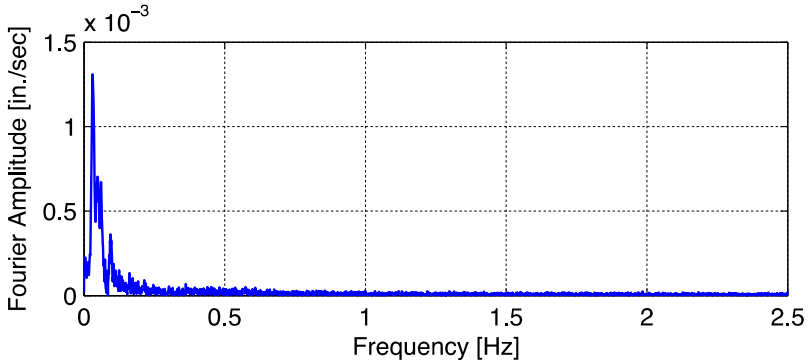
- Check correctness of of the model and analysis parameters in OpenSees and OpenFresco and the calibration factors and polarities in the control and data acquisition systems
- Estimate average delay between the command and measured actuator displacements
- Compensate for average 0.0664-sec (= 27% of Δt_{sim}) time delay by polynomial extrapolation
- Verify non-linear large-displacement geometric transformations in OpenFresco

FFTs of displacement errors





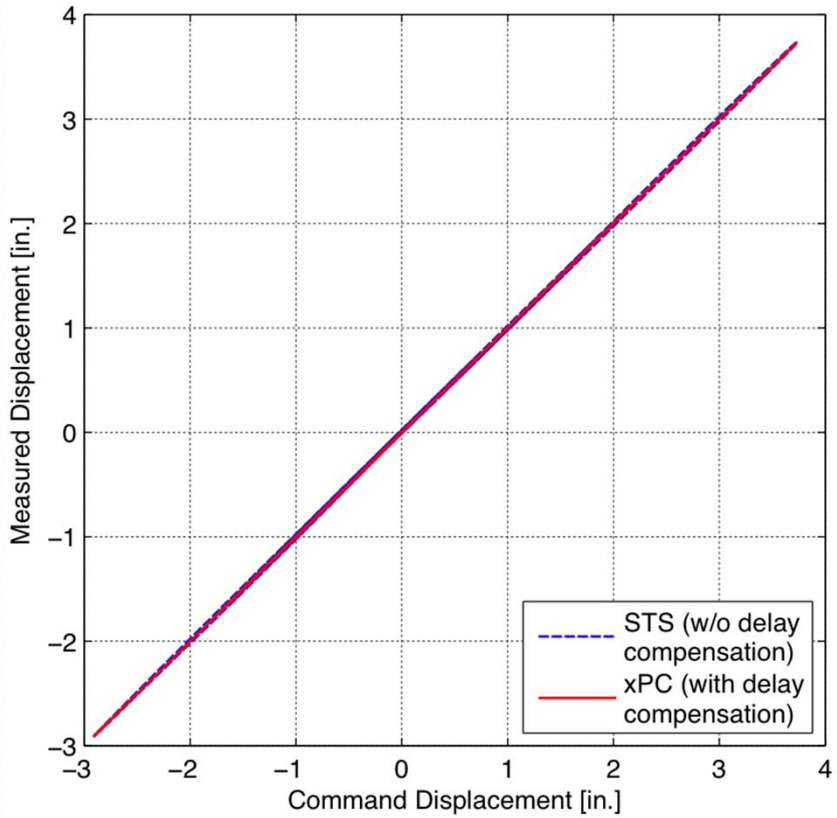




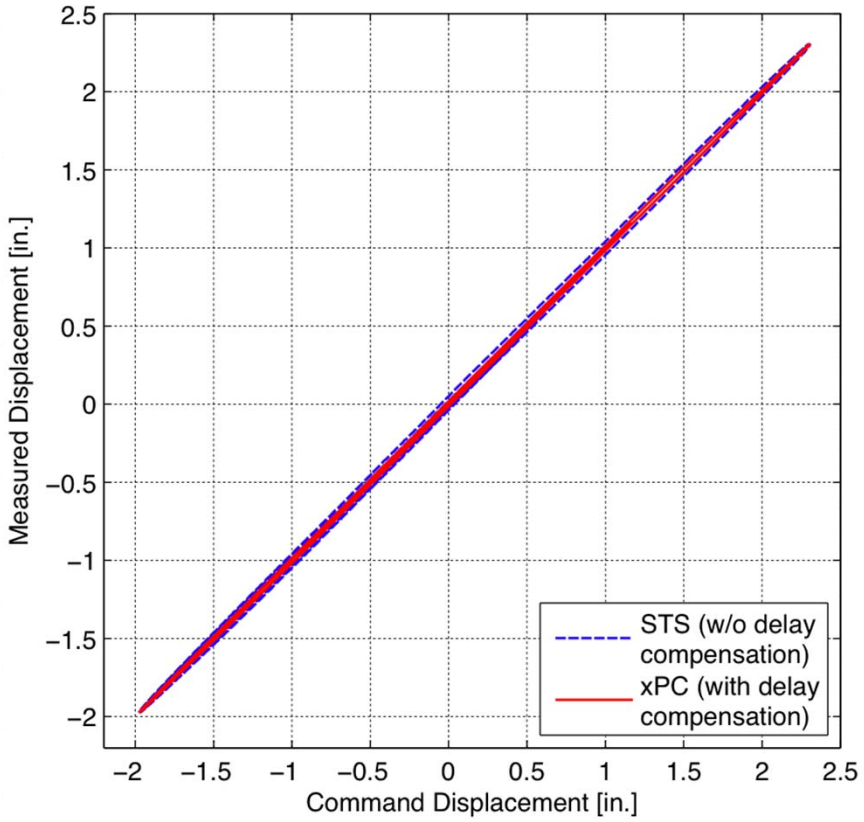
The only frequencies that were picked up in the Fourier amplitude spectra were the frequencies of the structural response in the two directions (0.062 Hz in the global X-direction and 0.031 Hz in the global Y-direction)

Synchronization Subspace Plots

Actuators Global-X

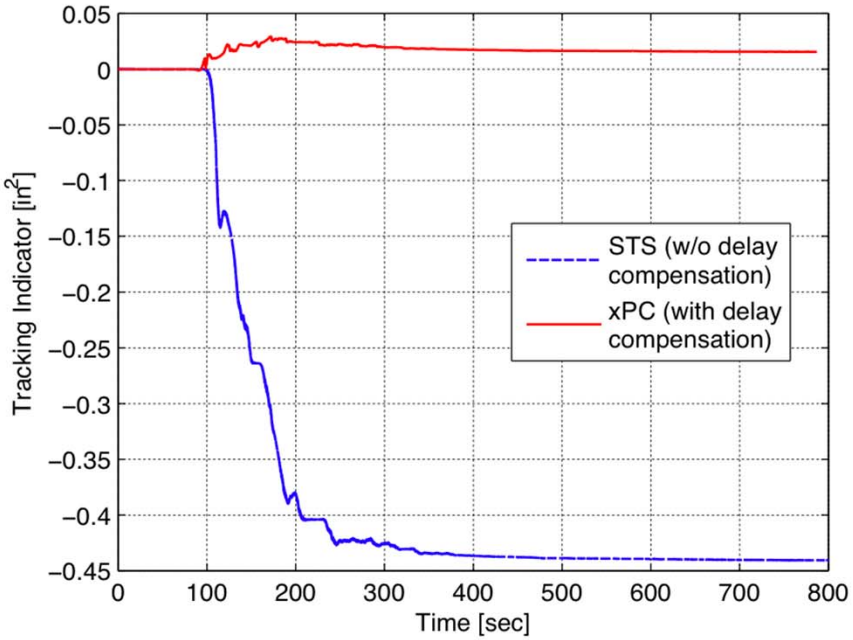


Actuators Global-Y

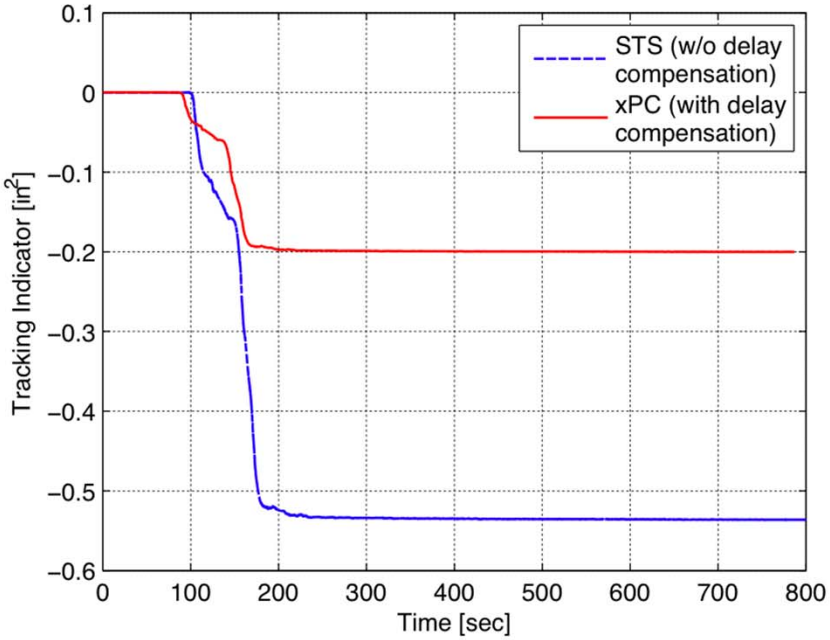


Tracking Performance

Actuators Global-X



Actuators Global-Y

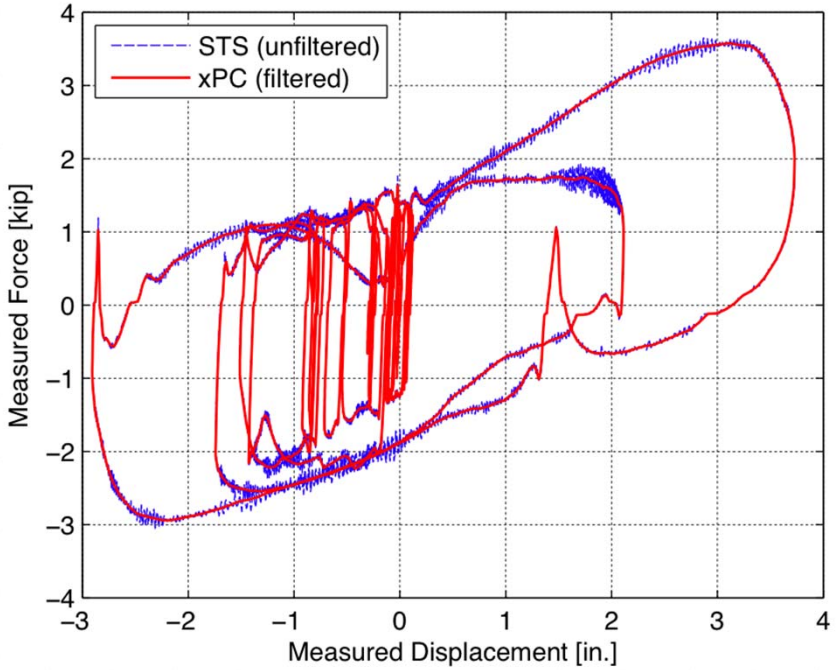


Noise in Force Feedback

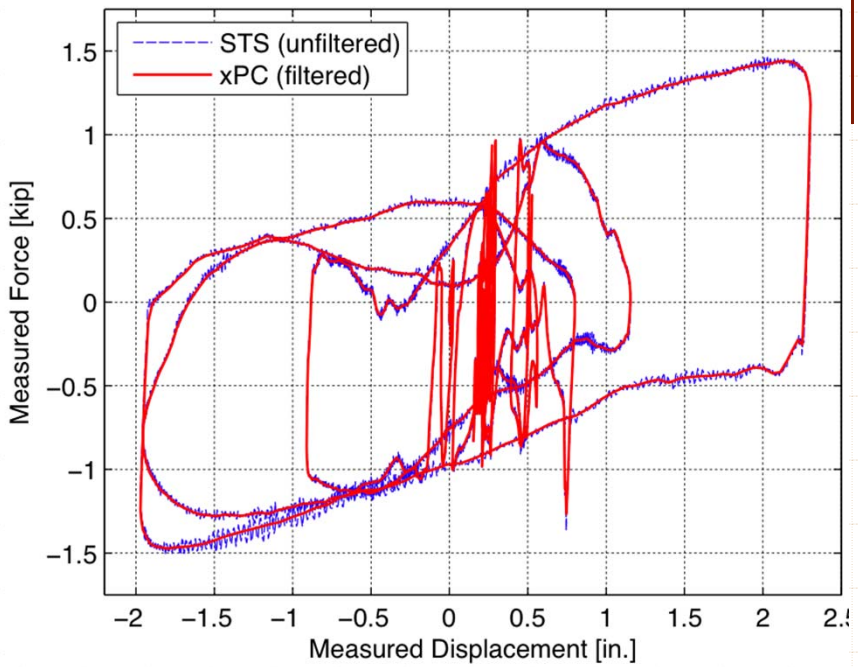
- Noise in force measurements feeds back into the numerical analysis and ultimately affects the quality of the test results
- Force fluctuations related to the inertia effects of the large masses and the six actuators fighting each other
- Implement moving average filter which is optimal for reducing random noise (100 sampling points)
- This creates additional 0.0488-sec time delay that needs to be compensated for
- Total time delay corresponds to 61% of Δt_{sim}

Noise in Force Feedback cont.

Global-X Direction



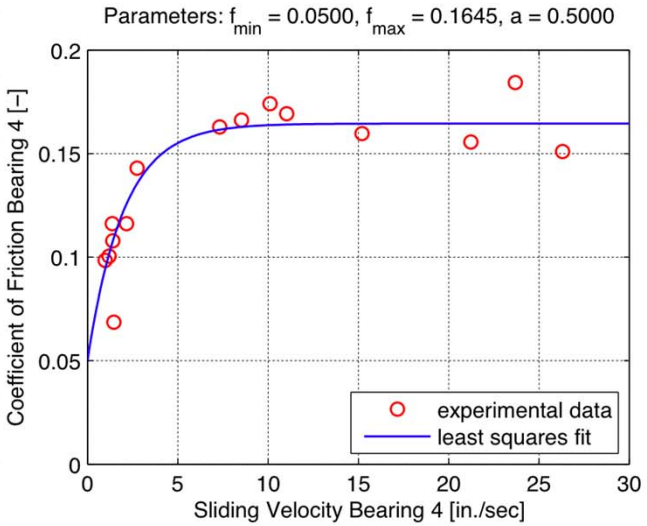
Global-Y Direction

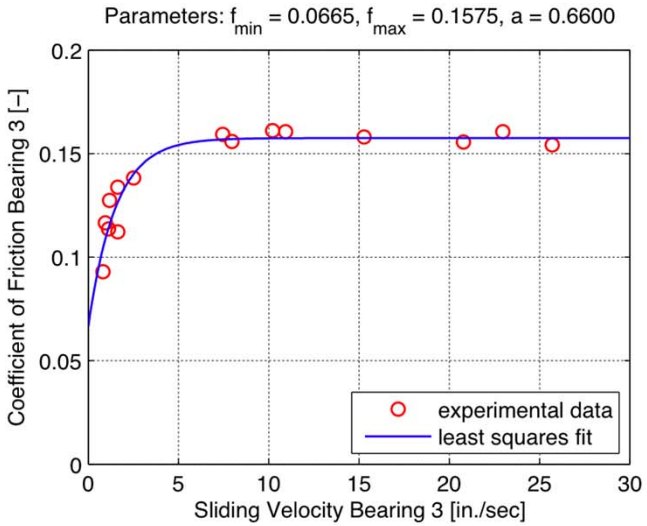


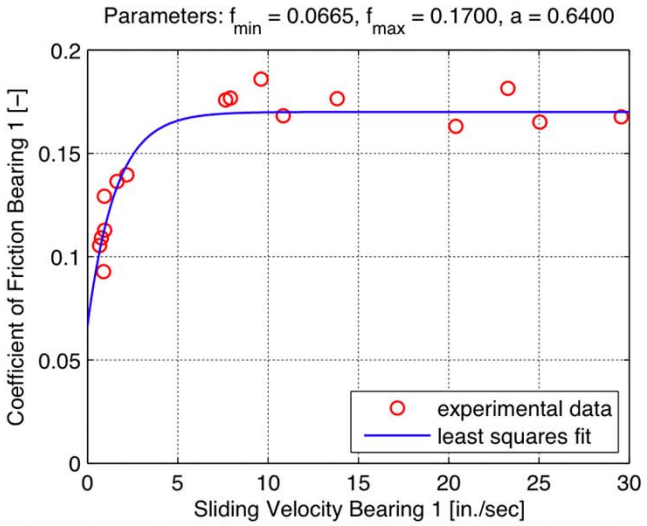
Compensation for Velocity Dependence

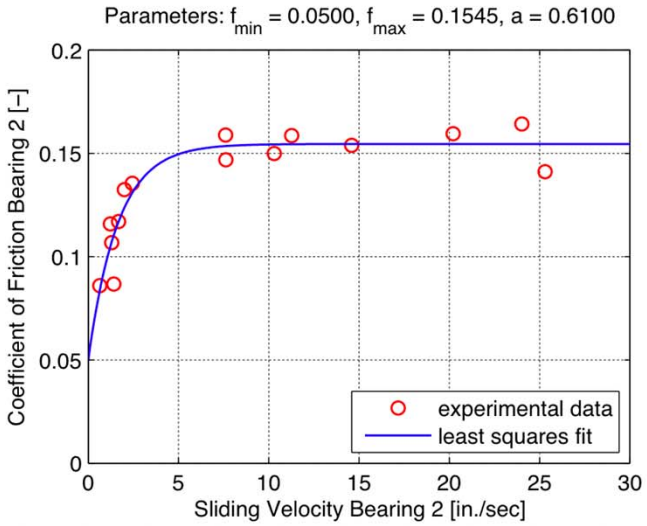
- Coefficients of friction of the PTFE to stainless steel interfaces are velocity dependent due to the low contact pressures in the bearings
- Hybrid simulations were performed at a rate 37.5-times slower than real-time, which yielded much lower coefficients of friction than the ones observed during the shaking table tests
- An analytical, velocity dependent friction element (flatSliderBearing) was implemented in OpenSees and then added to the hybrid model to compensate for the velocity dependence of the physical isolation system

Velocity Dependence of μ





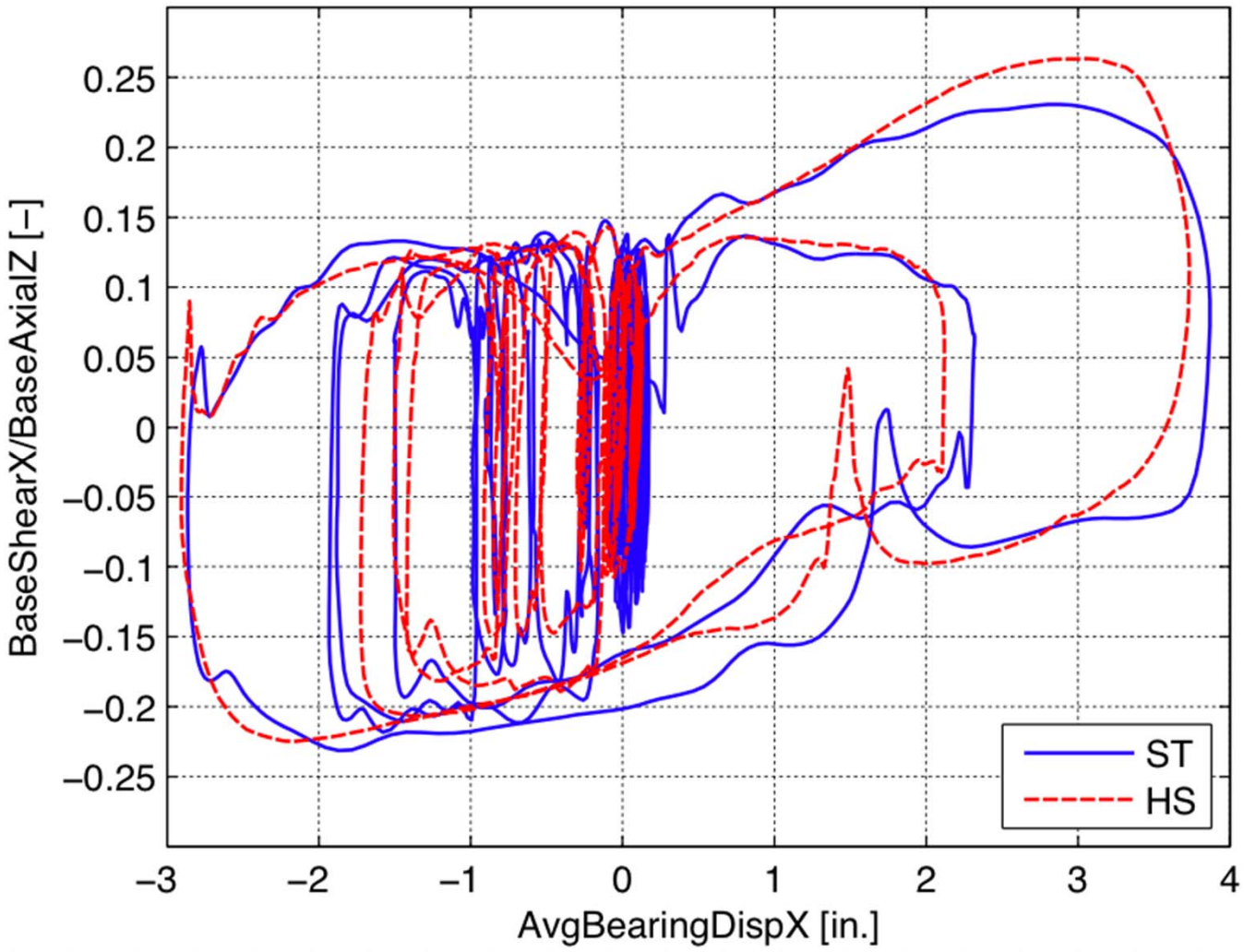




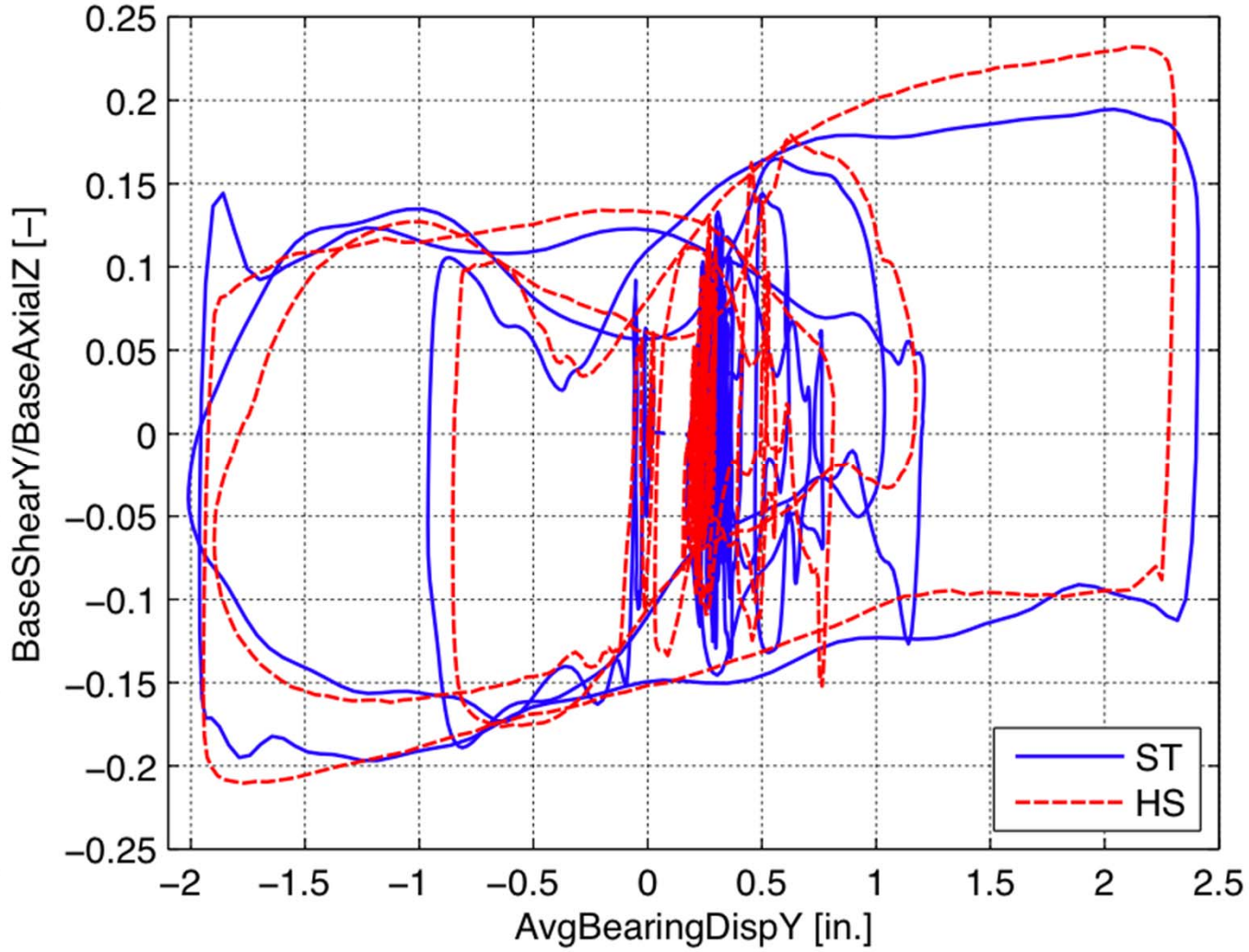
Shake Table Test

Hybrid Simulation Test

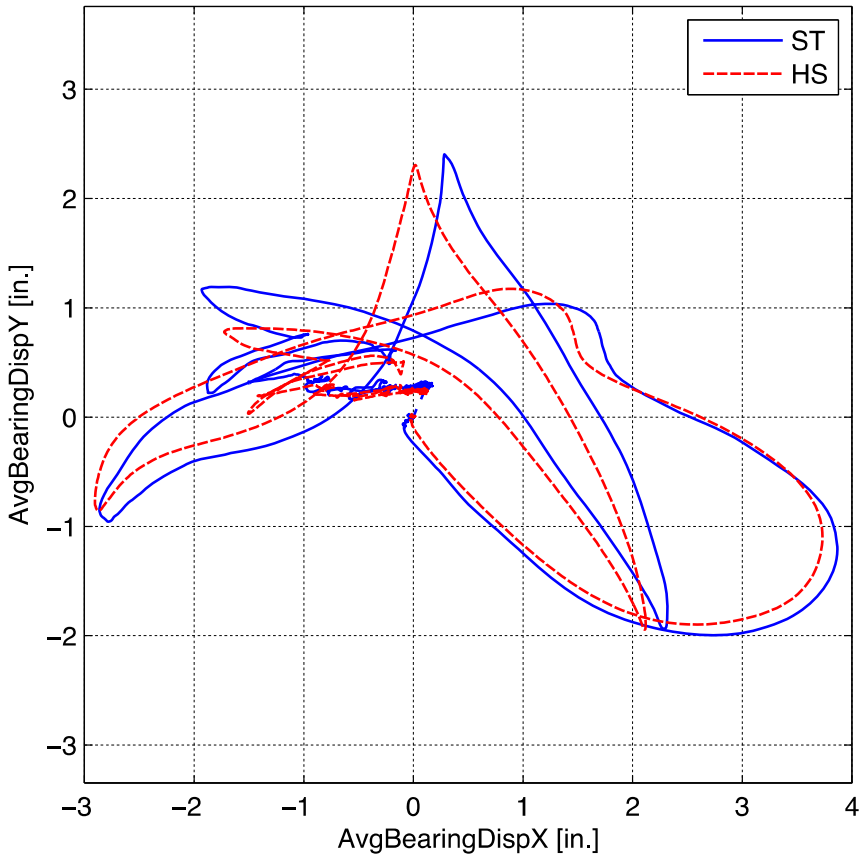
Response Comparison Global-X

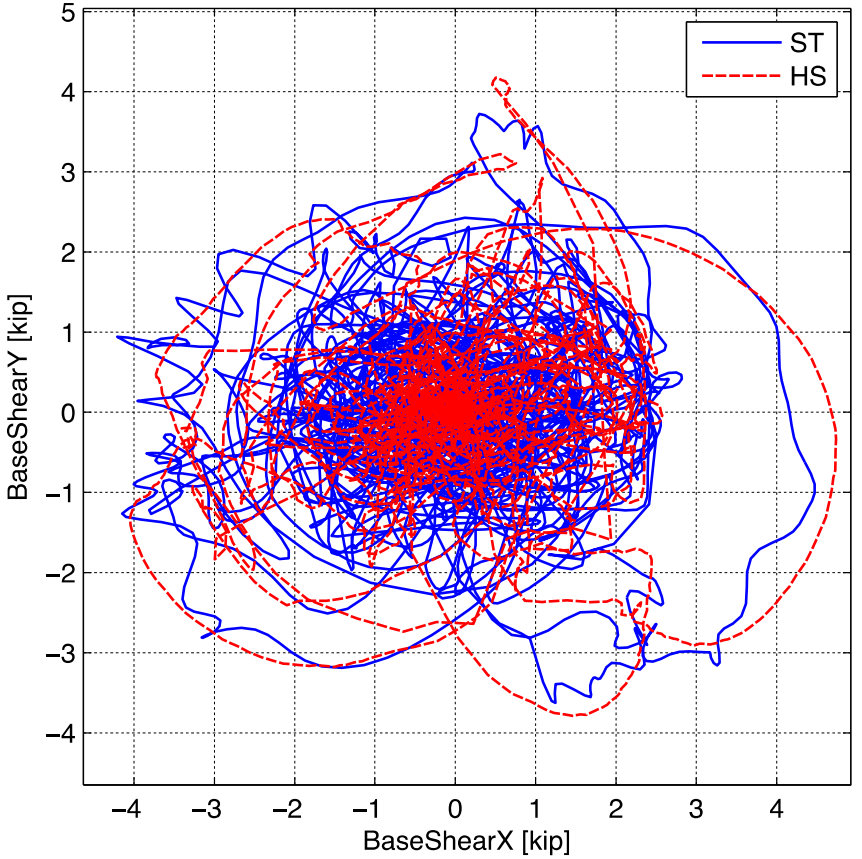


Response Comparison Global-Y



Response Comparison





Conclusions

- OpenFresco, the environment-independent software framework for hybrid simulation provided an excellent platform for performing MDOF, bi-directional tests
- Several testing and error compensation procedures for conducting complex hybrid simulations have successfully been implemented and validated.

Conclusions

- The overall response of the isolated test structure, especially in terms of isolator displacements, compared well between shake table tests and hybrid simulations
- However, the hybrid simulations missed some of the high frequency inertia force effects that were observed in the shake table tests
- Faster, more accurate and more uniform control is necessary for future hybrid simulations of MDOF systems

Questions?
Thank you!

http://openfresco.berkeley.edu/

The development of OpenFresco has been sponsored in parts by the National Science Foundation through grants from the NEES Consortium, Inc.