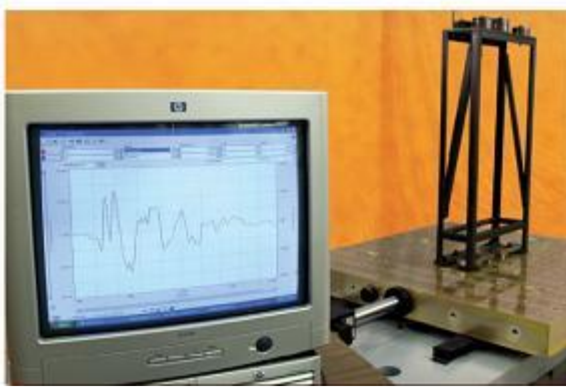
be certain.

Structural Testing System Modeling and Control Techniques

X. Shawn Gao, PhD PE



Outline

- Why System Modeling?
- Dynamical System Modeling Approaches
  - Simulink Modeling
  - ADAMS MBD Modeling
  - Robust Modeling
- Control/Compensation Techniques
  - Adaptive Feedforward Compensation (AFC)
  - Robust H-infinity Loop Shaping Optimal Control
  - Specimen Dynamic Compensation (SDC)
- Summary

Why are Models Necessary?

- Advanced Testing Requires Multidisciplinary Knowledges
  - Structural Engineering
  - Computational Mechanics
  - Control Theory
  - Physics or phenomenological modeling
  - Real-time Computing
  - Embedded System
  - Sensors and Actuators
  - System Modeling

Why are Models Necessary?

- Structural testing systems are dynamically complex :
  - Actuator servovalves have significant nonlinearities
  - Test specimens are often very heavy and underdamped, interacting greatly with actuator mechanical response
  - Hydraulic flow demand is high, causing pressure drops that affect actuator response
  - Significant modal cross-coupling exists between multiple actuators through specimen with its own dynamics
  - Real-time hybrid system imposes stringent criterion on high precision motion control, which requires system models
  - No iterative control is allowed
- Models can help answer two questions:
  - Capacity - can the test be performed at all?
  - Fidelity - how well can the test be performed?

What Effects can be Modeled?

Servovalve Dynamics

- Bandwidth limitations
- Spool overlap and underlap
- Flow gain variation due to
  - Flow saturation
  - Supply/return pressure variations
  - Pressure switching

Hydraulic System Dynamics

- Pump flow limits
- Pressure losses
  - Pump droop
  - Piping resistive losses
- Line accumulators
- Blowdown accumulators

Specimen Dynamics

- Rigid mass
- One modal mass
- One 6 DOF static force to ground
- One 6 DOF spring to ground
- One 6 DOF linear/nonlinear damper to ground

Actuator Dynamics

- Unequal area effects
- Variable volume effects with piston stroke
- Volumetric and compressibility flows
- Cross-piston leakage flow
- Parasitic damping
- Additional trapped oil volume
- End cushion profiling
- Seal friction
- Static support

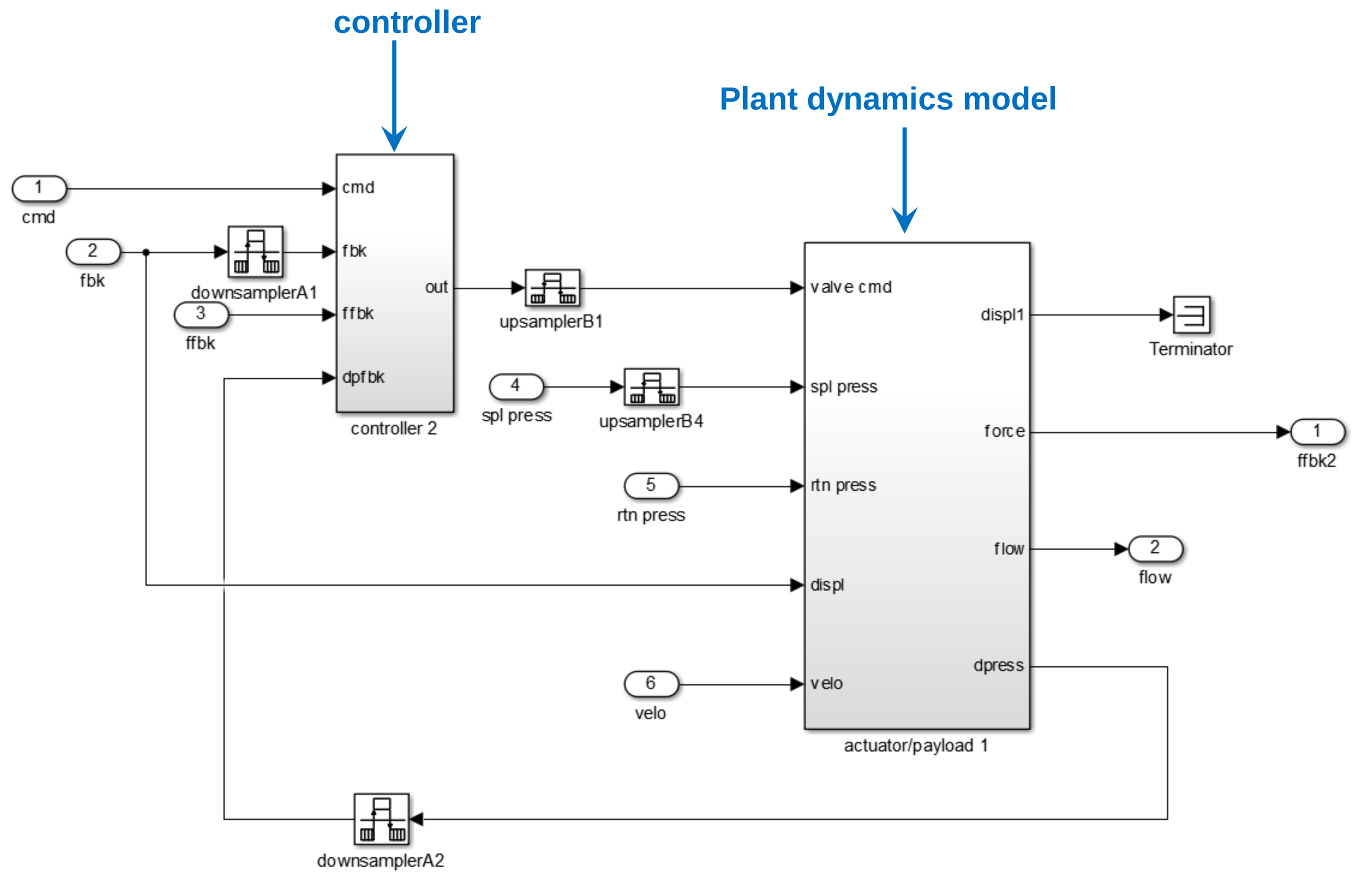
Table Dynamics

- Rigid body in 6 DOFs
- Actuator bowstring resonance

Scalability

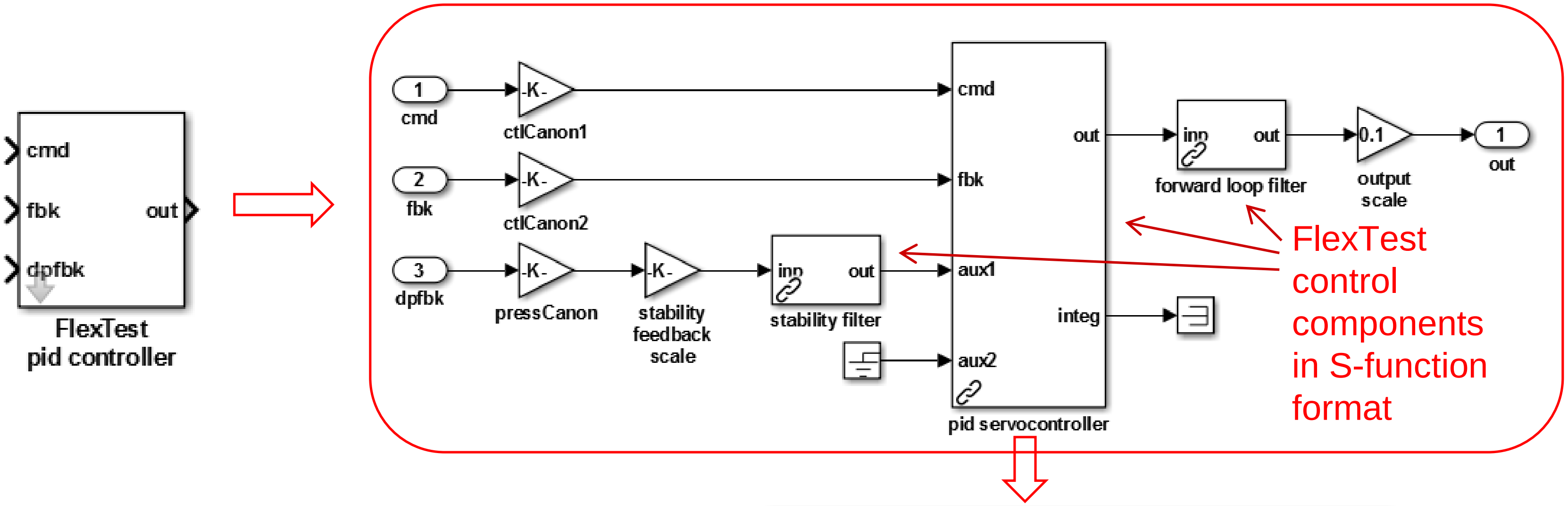
- Any number of DOFs (including just one)
- Any number of actuators (incl. just one)
- Any number of accelerometers (incl. none)
- Actuators can be any of five types
  in any combination

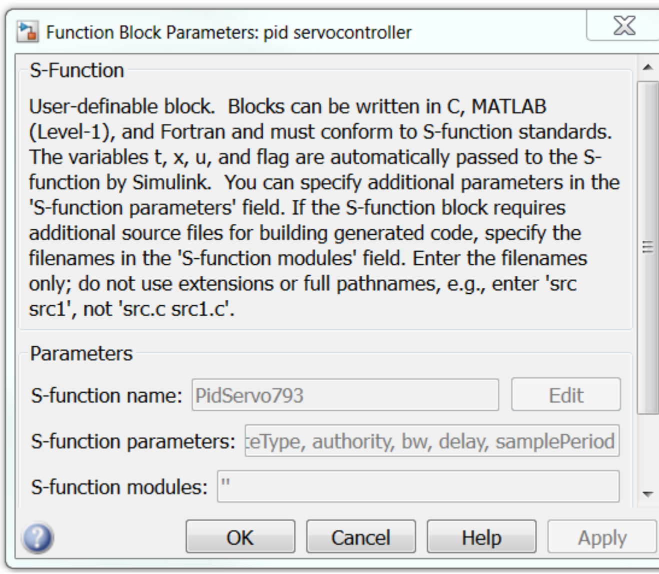
Dynamical System Modeling with Simulink



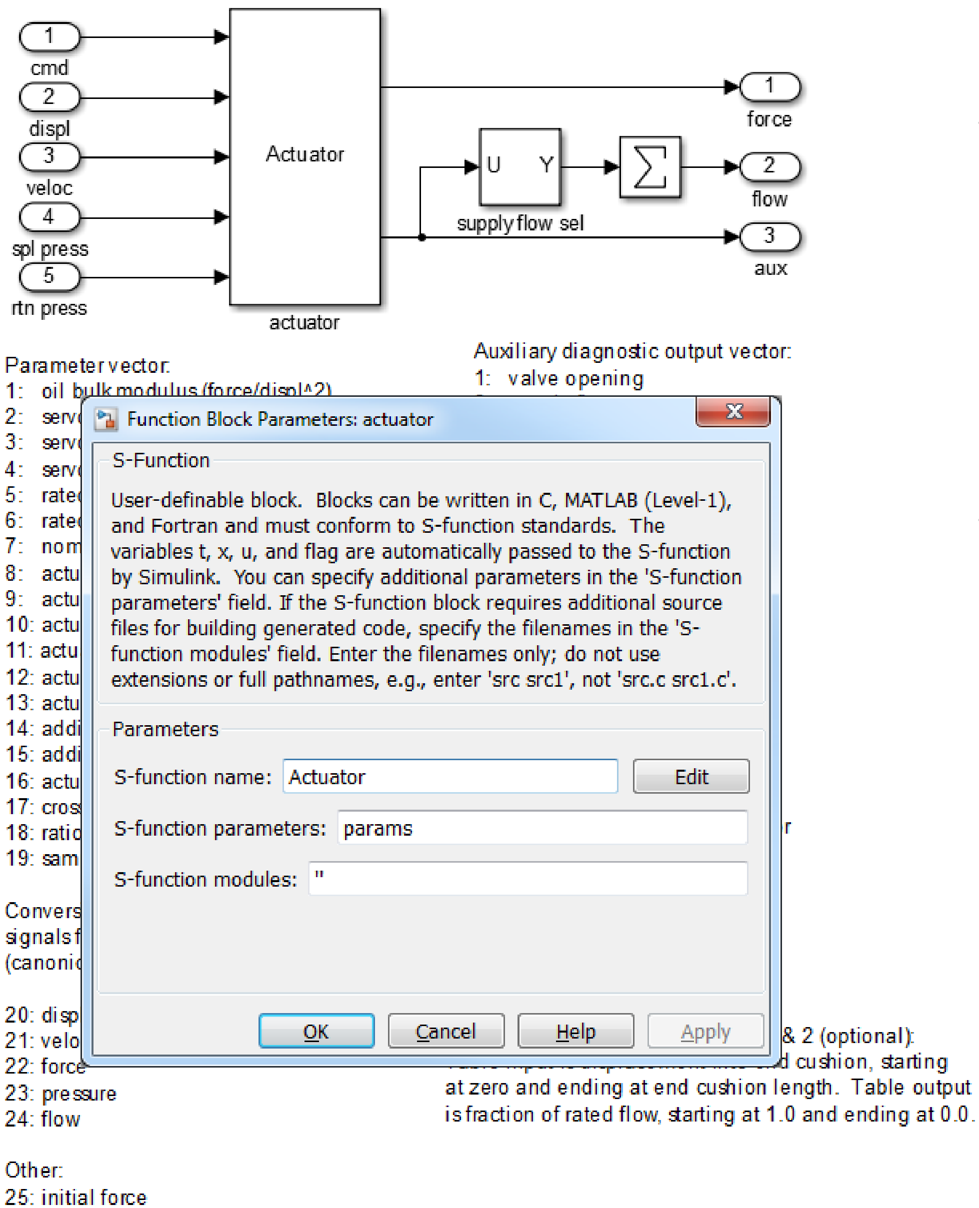
Models are implemented in the Simulink™ modeling environment

FlexTest Controller Simulink Model





Actuator Plant Dynamic Model



<u>Servovalve Dynamics</u>

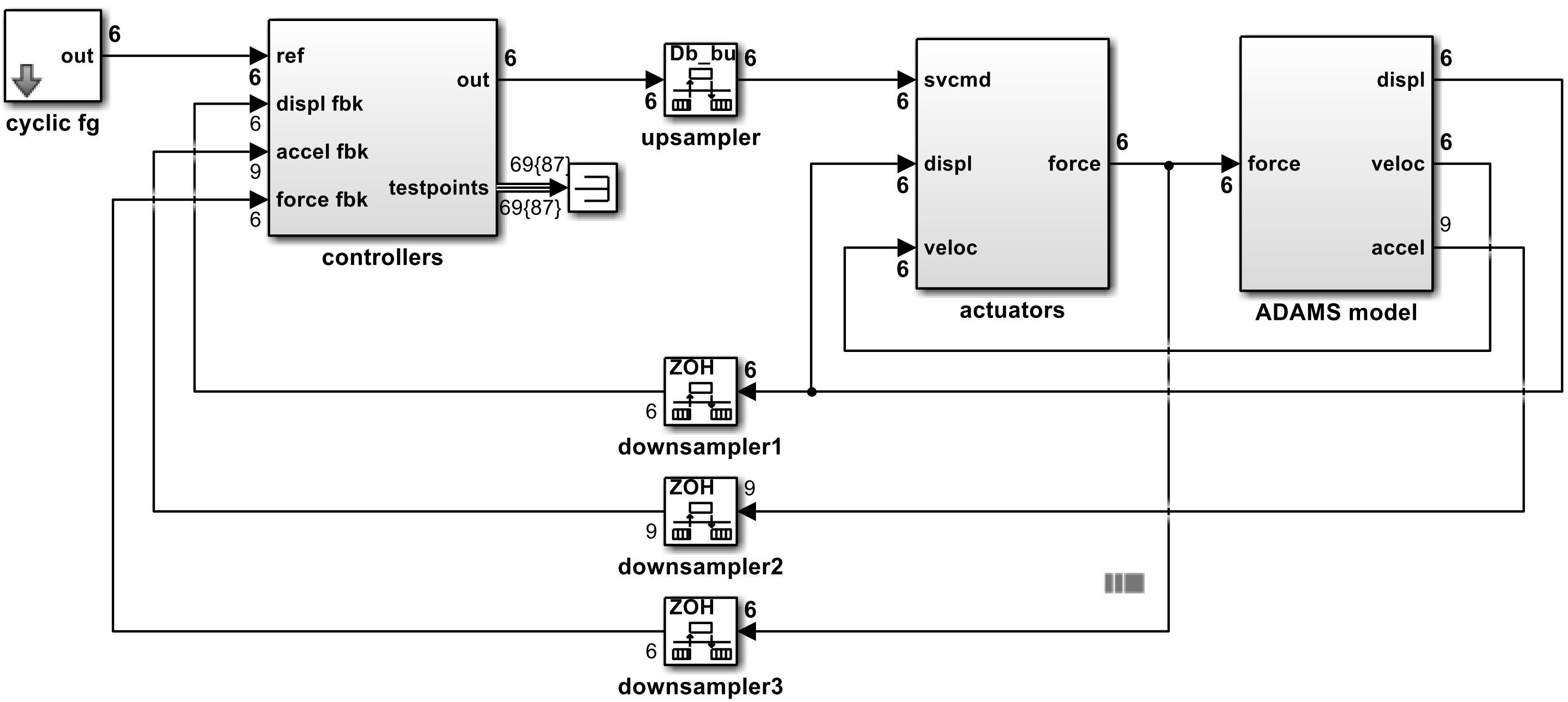
- Bandwidth limitations
- Spool overlap and underlap
- Flow gain variation due to:
  - Flow saturation
  - Supply/return pressure variations
  - Pressure switching

<u>Actuator Dynamics</u>

- Unequal area effects (incl. single-area)
- Variable volume effects with piston stroke
- Volumetric and compressibility flows
- Cross-piston leakage flow
- Parasitic damping
- Additional trapped oil volume
- End cushion profiling
- Seal friction

Specimen Modeling with ADAMS

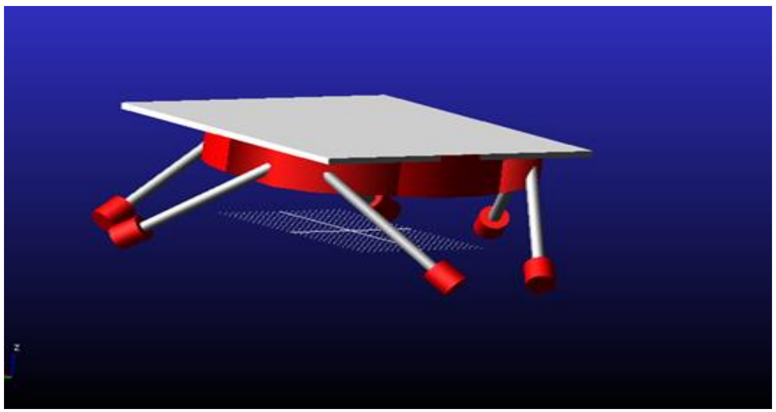
Characterize the dynamic interactions between loading system and testing specimen, which has its own dynamics

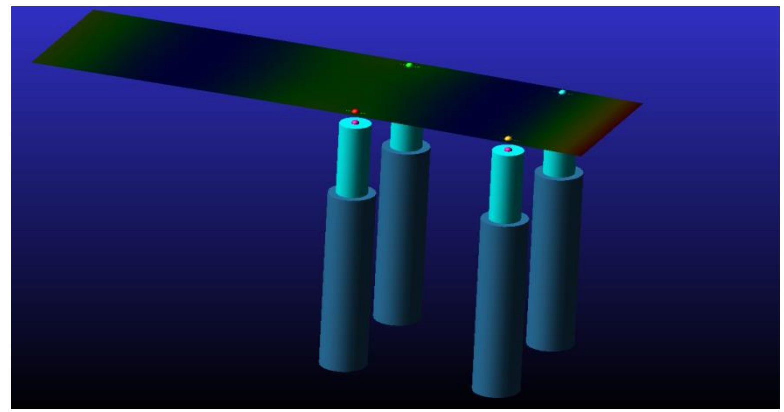


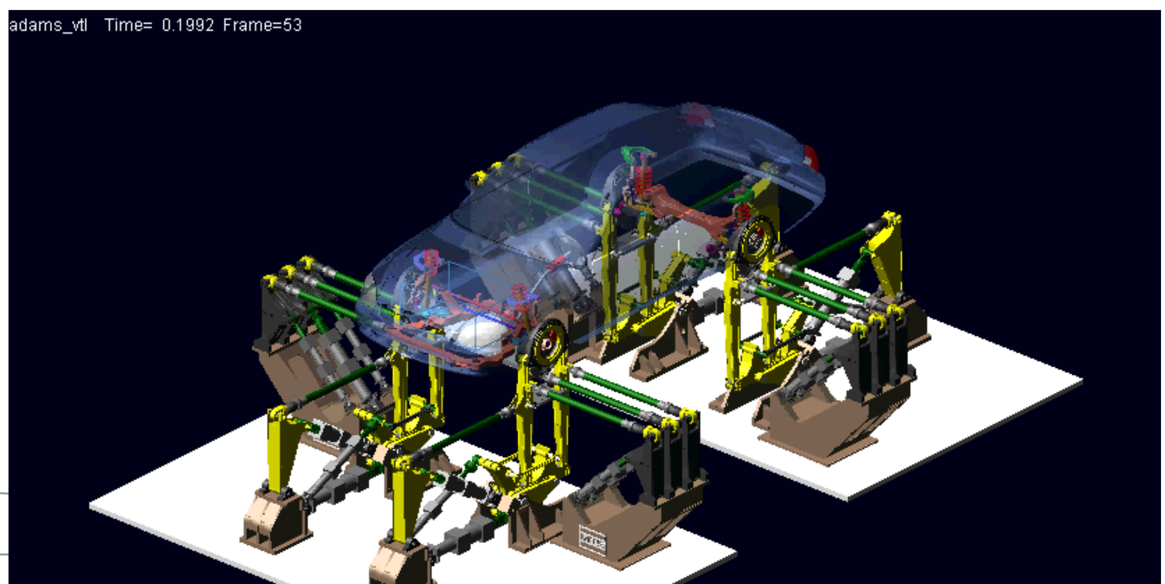
ADAMS - Multibody Dynamics (MBD) Software

MTS®

- Model moving parts, motions, forces, and joints of a test system and specimen
- Model flexible parts through Modal Neutral File from FEA model



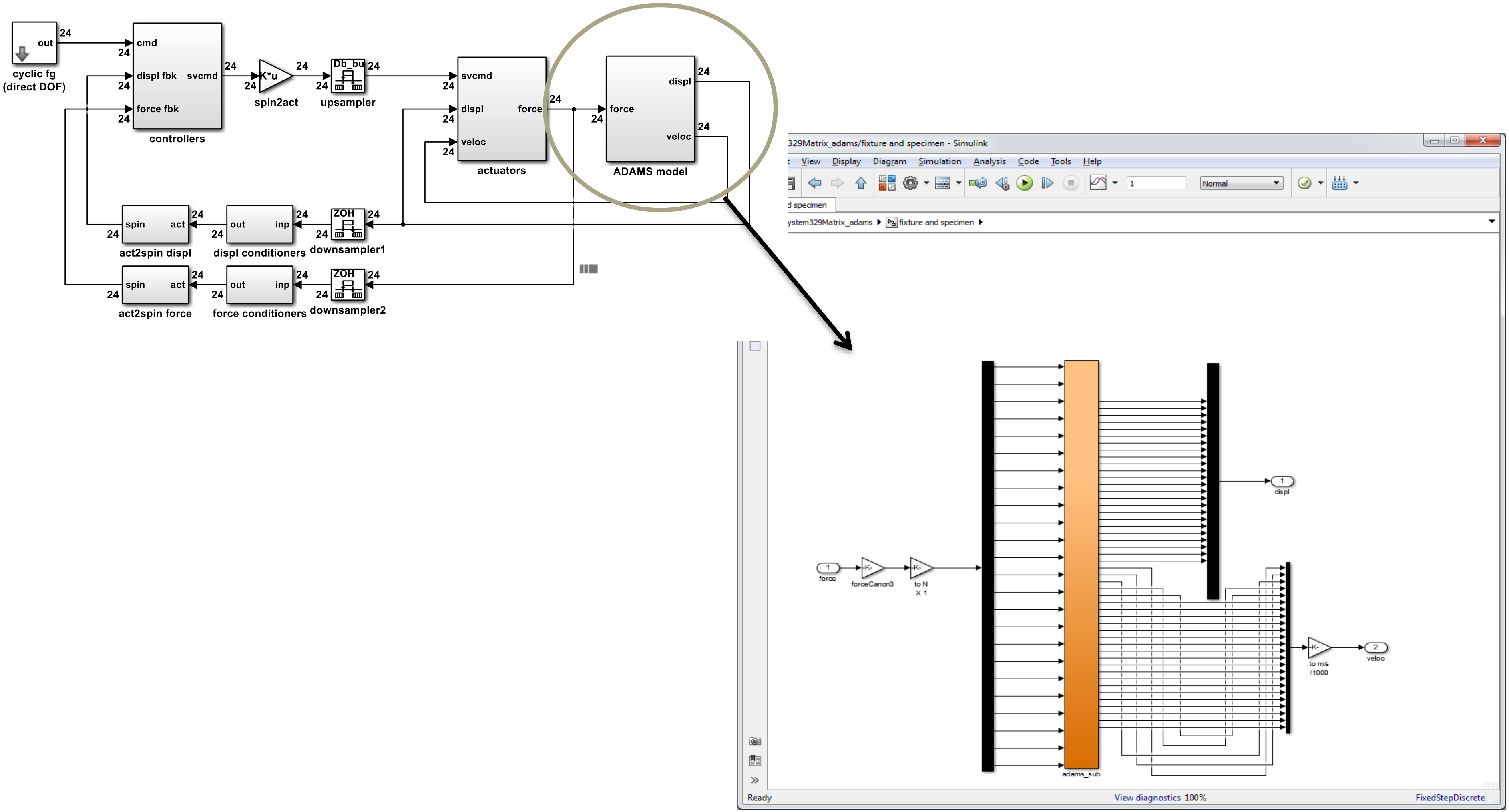




ADAMS and Simulink Co-Simulation

- ADAMS models mechanical parts, joints, bushings, dampers.
- Simulink models hydraulic elements and controller.
- ADAMS export the plant model to be integrated into Simulink model.
- Simulink model provides actuator forces to ADAMS model.
- ADAMS model provides actuator displacement and velocity based upon the actuator forces provided by the Simulink model.

Integration in Simulink Model

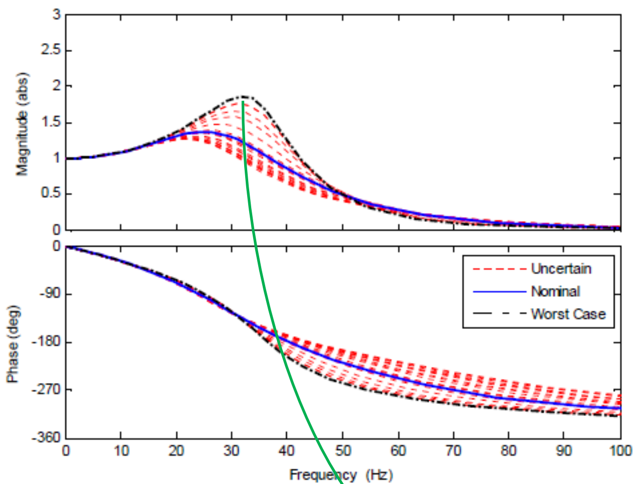


ADAMS Model

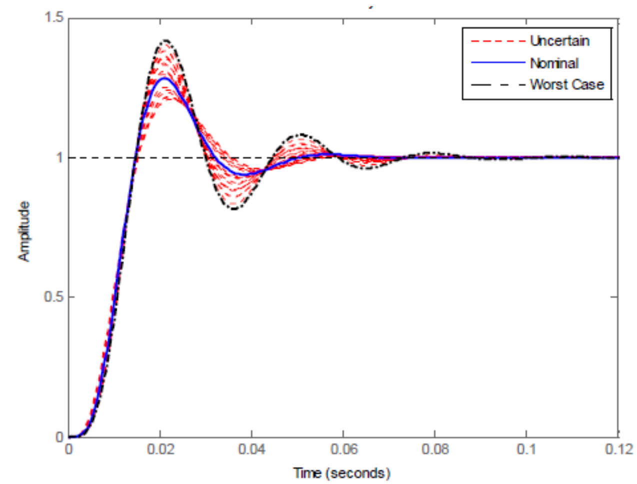
Robust Modeling

MTS®

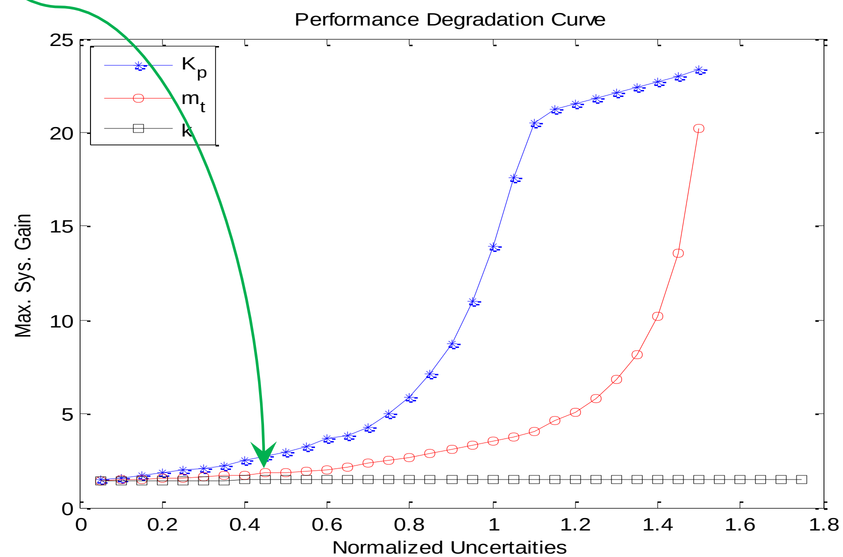
Modeling with parametric and non-parametric uncertainties



Frequency Response Function (FRF)



Step Response



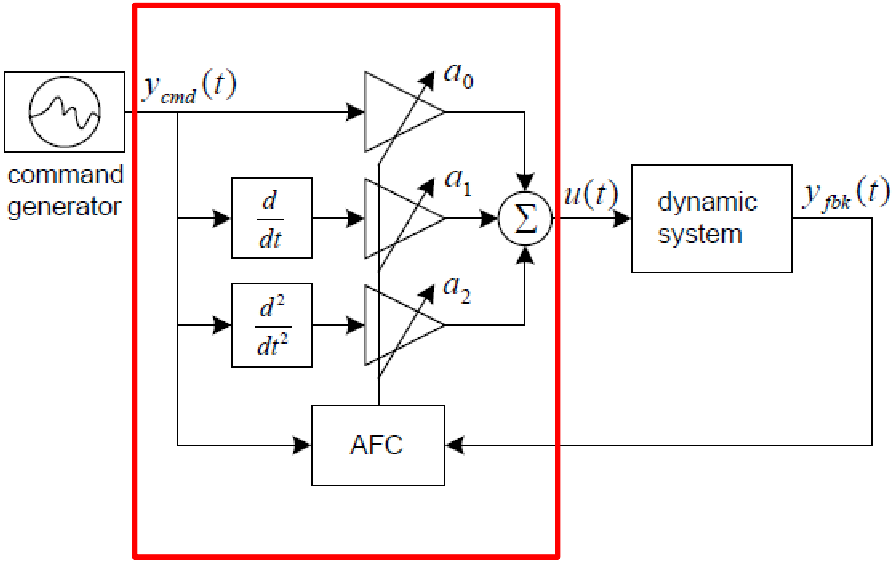
Performance Degradation Curve

be certain.

Actuator Motion Control/Compensation Techniques

Adaptive Feedforward Compensation (AFC)

Basic idea is an inverse compensation scheme, i.e. one that derives a compensator from the inverse dynamics of the system to be controlled.



Assume the dynamic system can be described as

$$\frac{Y(s)}{U(s)} = \frac{K\omega_0^2}{s^2 + 2\varsigma\omega_0 s + \omega_0^2}$$

The inverse transfer function (non-proper system)

$$\frac{U(s)}{Y(s)} = \frac{s^2 + 2\varsigma\omega_0 s + \omega_0^2}{K\omega_0^2}$$

In the time domain the compensator is

$$u(t) = a_0 y(t) + a_1 \dot{y}(t) + a_2 \ddot{y}(t)$$

Batched Least Square Optimization

MTS®

The coefficients are not known and are not constant, so they will be determined through an online adaptive optimization process.

$$\begin{bmatrix} u_{k-1} \\ u_{k-2} \\ \cdots \\ u_{k-q} \end{bmatrix} = \begin{bmatrix} y_{k-1} & \dot{y}_{k-1} & \ddot{y}_{k-1} \\ y_{k-2} & \dot{y}_{k-2} & \ddot{y}_{k-2} \\ \cdots & \cdots & \cdots \\ y_{k-q} & \dot{y}_{k-q} & \ddot{y}_{k-q} \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} \longrightarrow \underline{\hat{u}} = \underline{\underline{Y}}\,\underline{a}$$

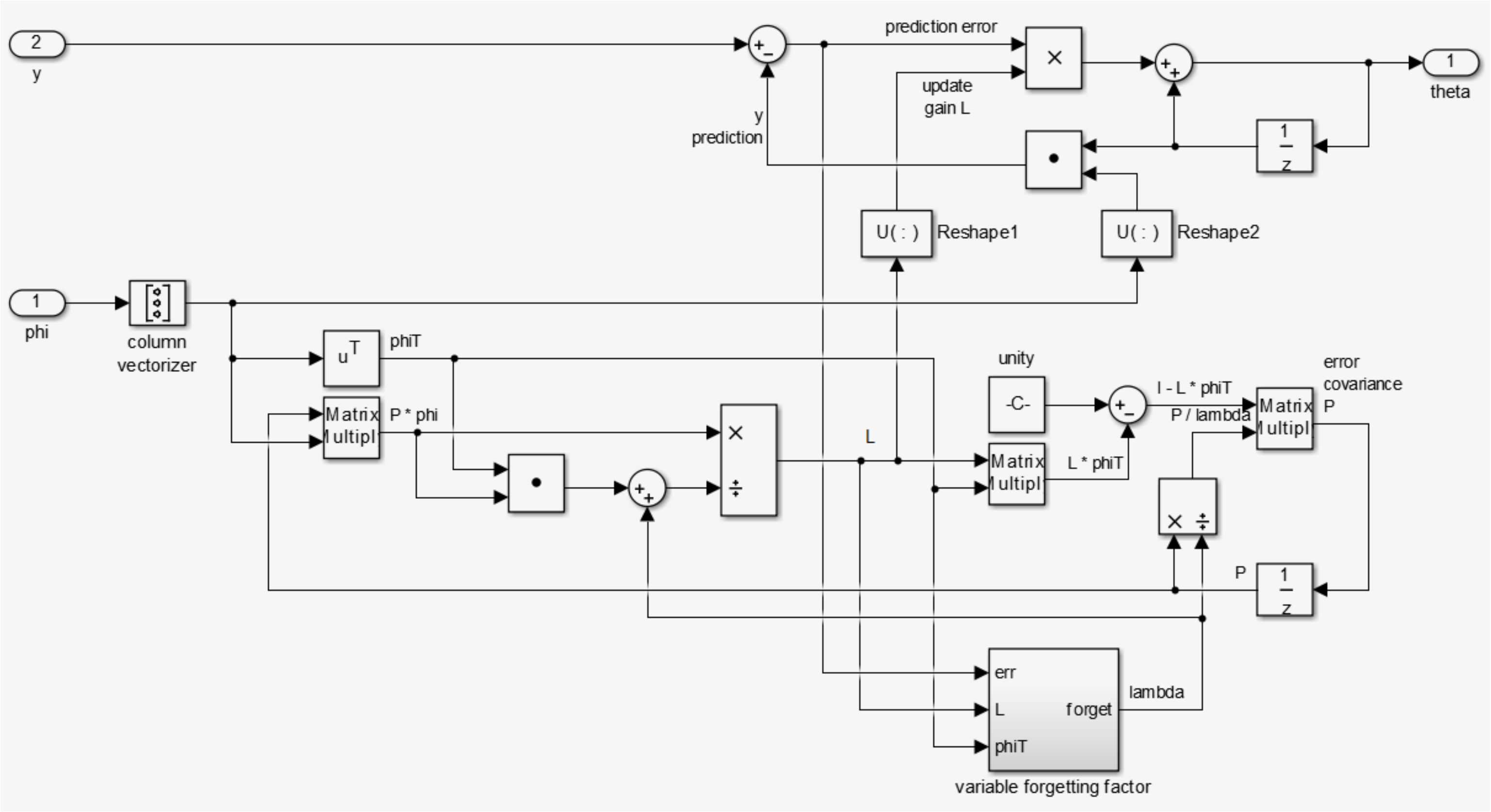
The cost function $f(a) = \sum_i (u_i - \hat{u}_i)^2 = \sum_i \left(u_i - \underline{y}_i^T \underline{a}\right)^2 = \left(\underline{u} - \underline{\underline{Y}}\,\underline{a}\right)^T \cdot \left(\underline{u} - \underline{\underline{Y}}\,\underline{a}\right)$

The optimal least square solution that minimize the cost function

$$\underline{a} = \left(\underline{\underline{Y}}^T \underline{\underline{Y}}\right)^{-1} \underline{\underline{Y}}^T \underline{u}$$

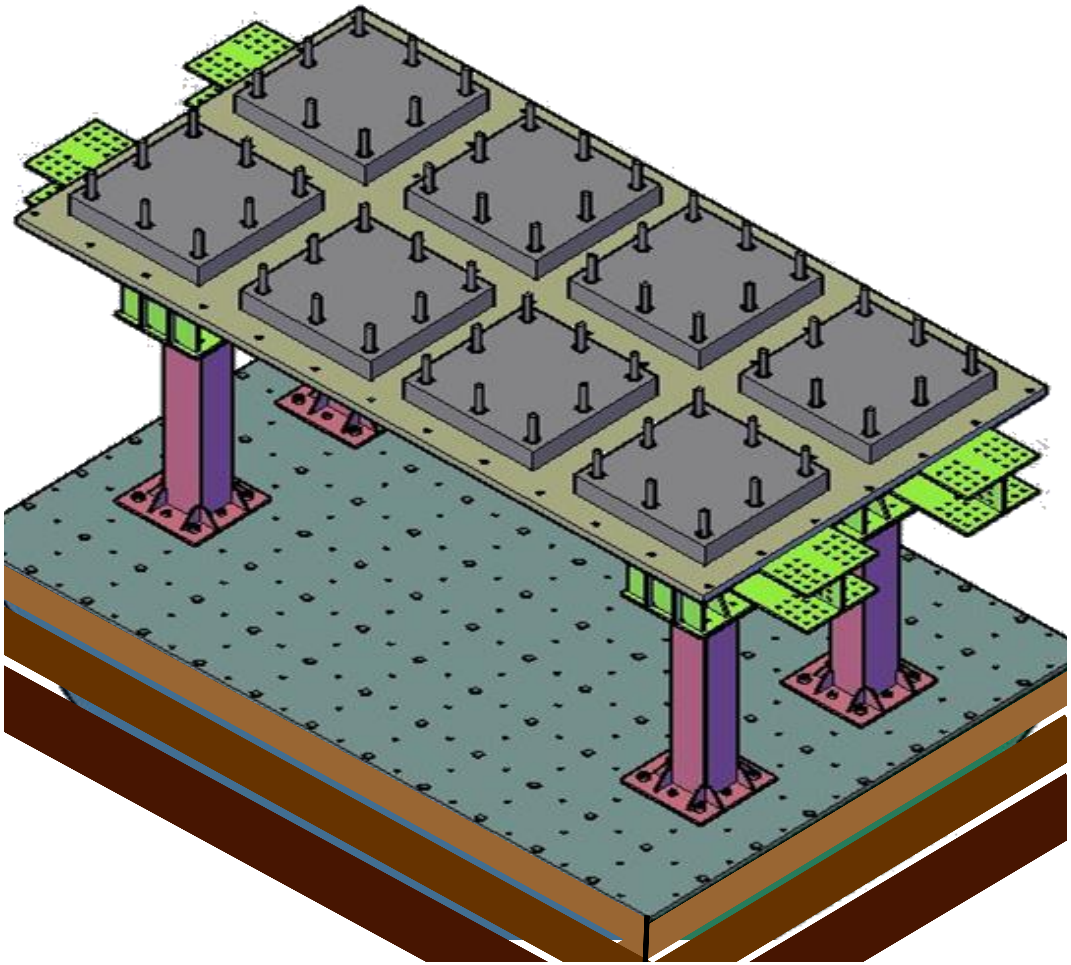
Chae, Y., Kazemibidokhti, K., and Ricles, J.M., Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation, Earthquake Engineering and Structural Dynamics, 42(11), 1697-1715, 22 April 2013.

Recursive Least Square Optimization

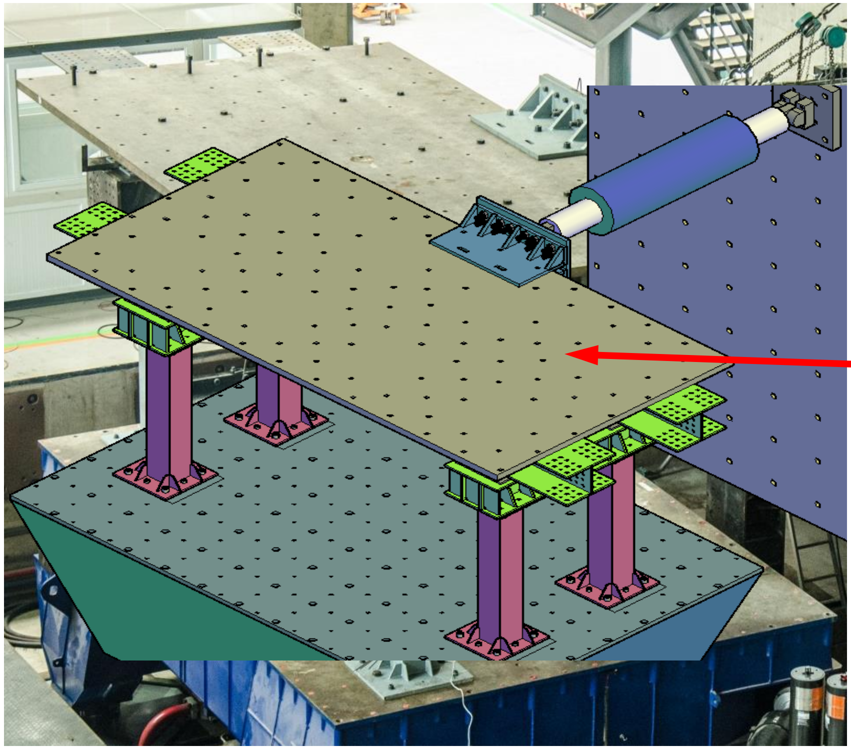


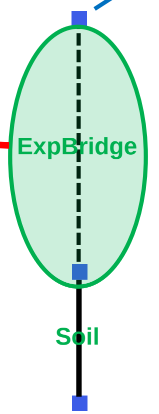
MTS improved the technique to use Recursive Least Square optimization, which requires much less computational resources for large window size.

Hybrid test performed by MTS, UC Berkeley, and Tongji



Actual Bridge Configuration (with foundation + soil)

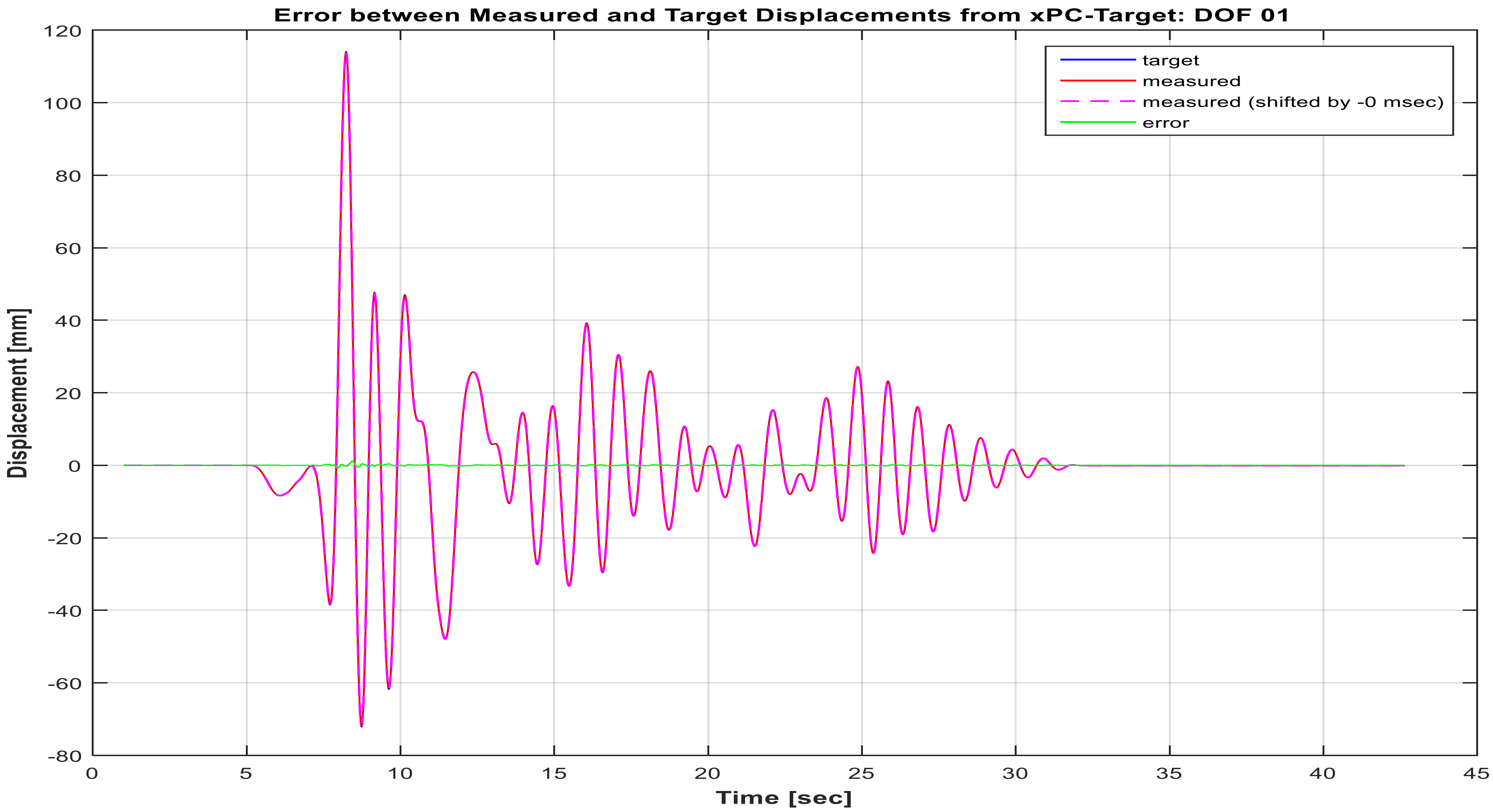




Physical Test Specimen (columns + isolators + partial-weight bridge deck)

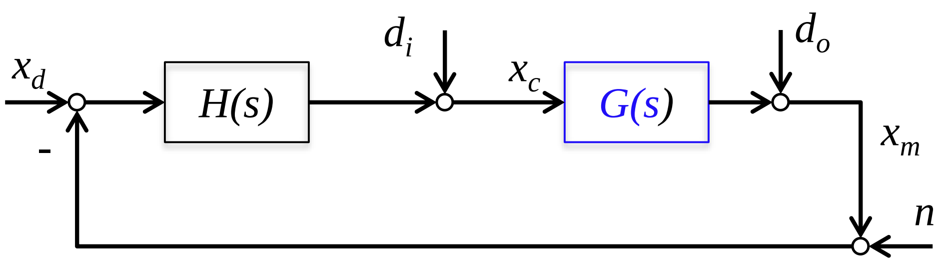
Simplified Hybrid OpenSees Model of Bridge (Stage 2)

Shaker Table Displacement Tracking

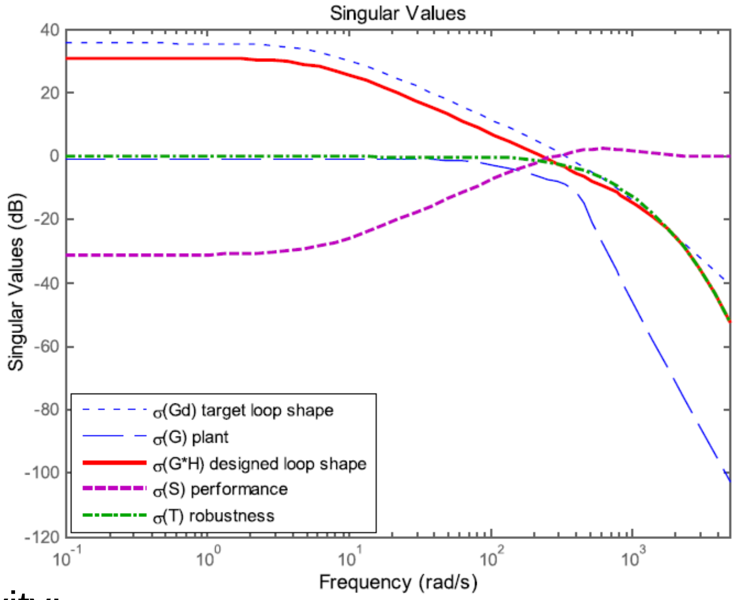


Robust H-infinity Loop Shaping Optimal Control

Robust H-infinity Loop Shaping Optimal Control



$$x_m = T_0(x_d - n) + S_0 G d_i + S_0 d_o$$



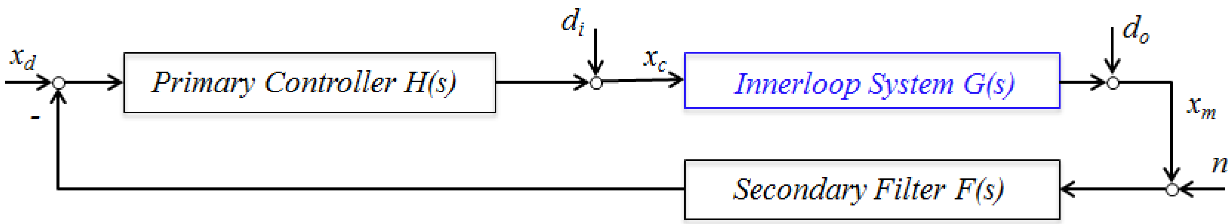
System output sensitivity and complementary sensitivity:

$$S_o = (I + GH)^{-1} \qquad T_o = I - S_o = GH(I + GH)^{-1}$$

Control design goal: $T_0 \Longrightarrow I$, $S_0 \Longrightarrow 0$

Transform closed-loop tracking design specification into open-loop gain shaping problem. Shape the open-loop system gain (*GH*). High loop gain means better performance, but with a tradeoff of reduced robustness.

H-infinity Controller Design Steps



Step 1: Design the open-loop system $G_d(s)$ that specifies the target openloop gain

$$G_d(s) = G(s)W(s) \equiv \begin{bmatrix} A & B \\ C & D \end{bmatrix}$$

Step 2: Solve a H∞ optimization problem to synthesize a controller K(s)

$$\left\| \begin{bmatrix} K \\ I \end{bmatrix} (I - G_d K)^{-1} \tilde{M}^{-1} \right\|_\infty \le \gamma$$

$$K = \begin{bmatrix} A^c + \gamma^2 W_1^{*-1} Z C^* (C + DF) & \gamma^2 W_1^{*-1} Z C^* \\ B^* X & -D^* \end{bmatrix}$$

Step 3: Primary controller combines K(s) with the pre-compensator W(s)

$$H(s) = W(s)K(s)$$

Step 4: Secondary low-pass filter F(s) in the feedback path

$$\frac{X_m(s)}{X_d(s)} = \frac{G(s)H(s)}{I + F(s)G(s)H(s)}$$

Dynamically Coupled MIMO System

For SISO System:

Loop Shaping of FRF Magnitude

For MIMO System:

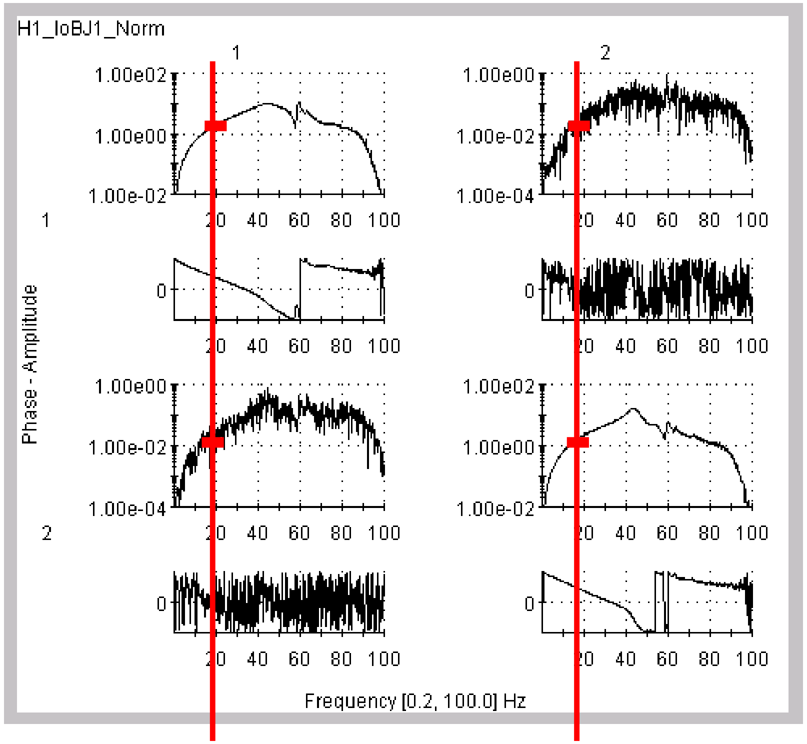
$$Y(s) = G(s)U(s)$$

I/O Euclidean Norm

$$\|u\| = \sqrt{|u_1|^2 + |u_2|^2 + \ldots + |u_n|^2} = \sqrt{u^* u}$$

Loop Shaping of Maximum Singular Value

$$\|G\|_\infty = \sup_{\|u\|\neq 0} \frac{\|Y\|}{\|U\|} = \sup_{\|u\|\neq 0} \frac{\|GU\|}{\|U\|} = \sup_{\|u\|\neq 0} \frac{\sqrt{U^* G^* G U}}{\sqrt{U^* U}} = \sqrt{\lambda_{\max}\{G^* G\}}$$



One frequency - 4 amplitude values

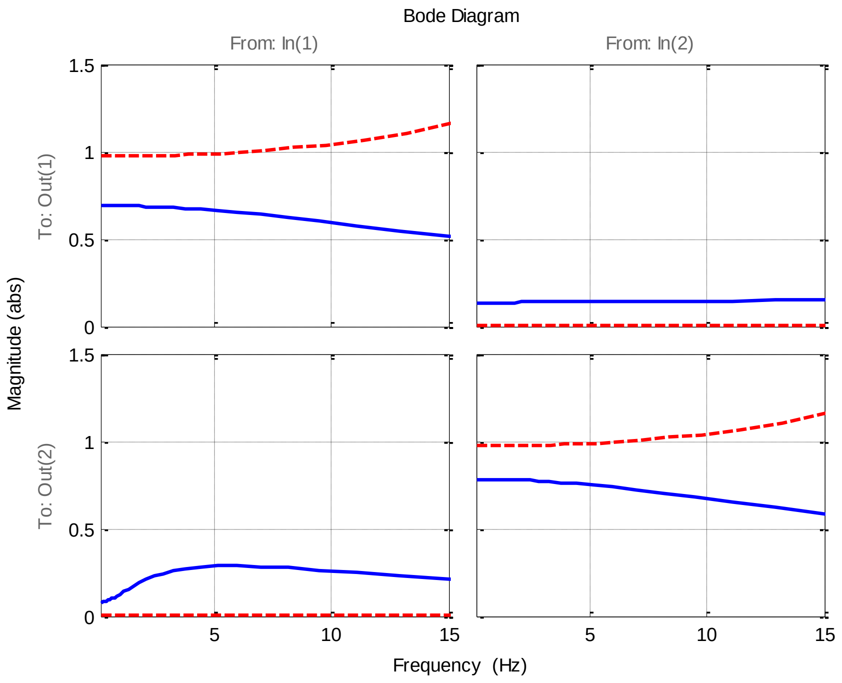
[Y] = [G][U]

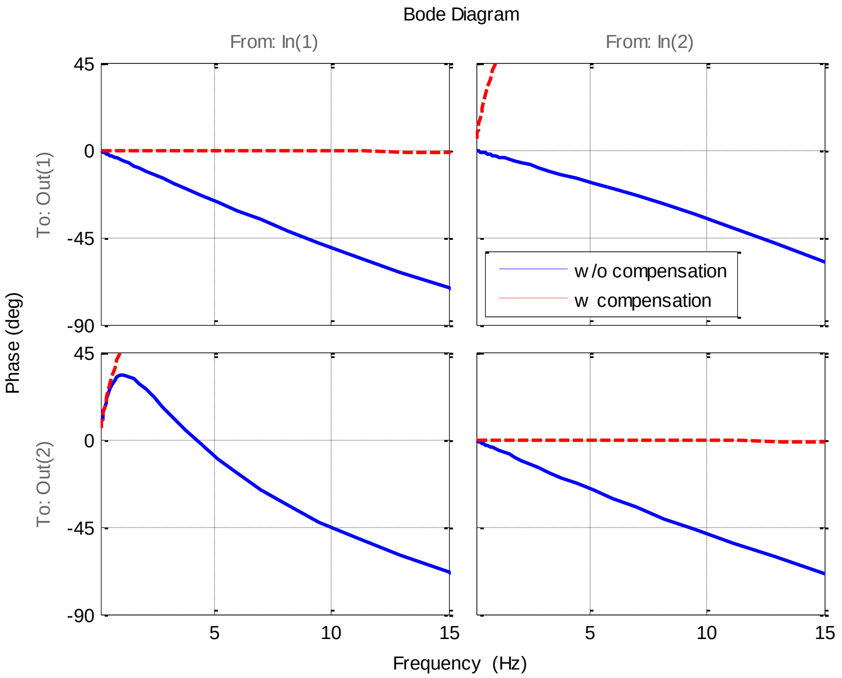
[G] = [M][S][N]’

S – Diagonal Scaling Matrix

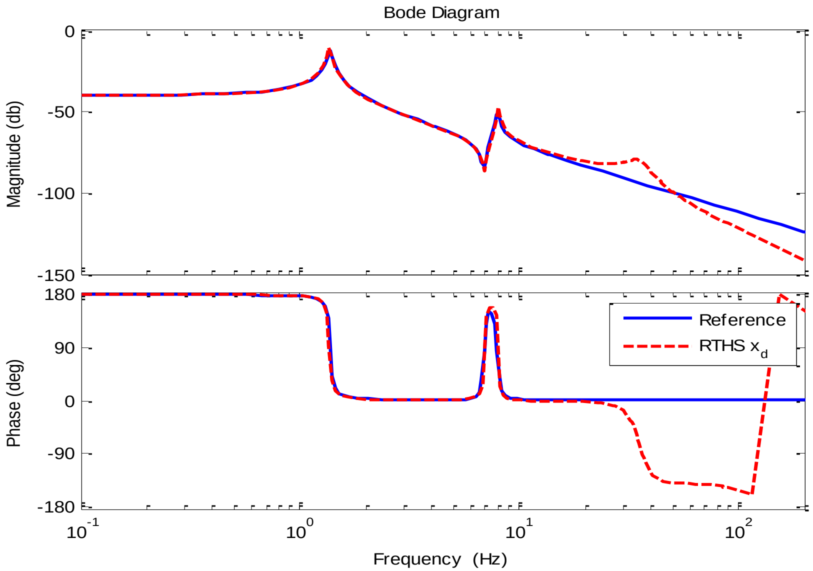
M and N – Rotation Matrices

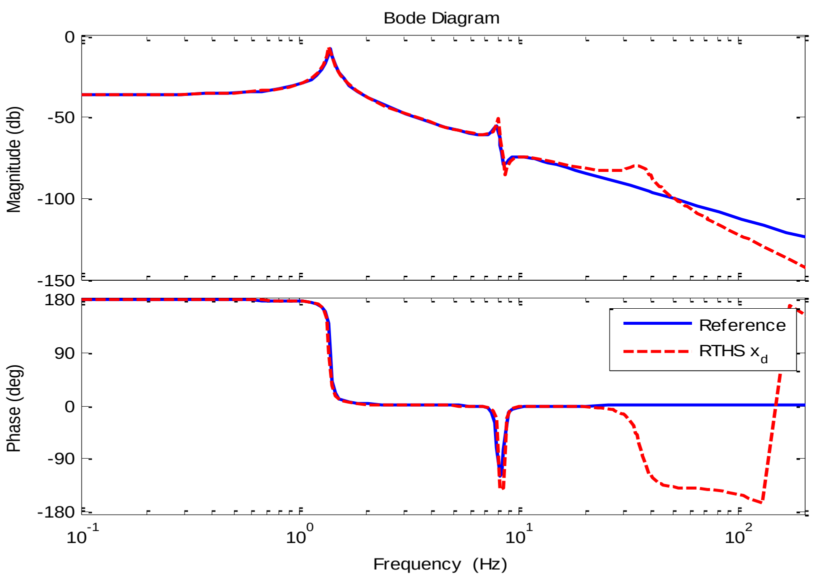
H-infinity Control Performance

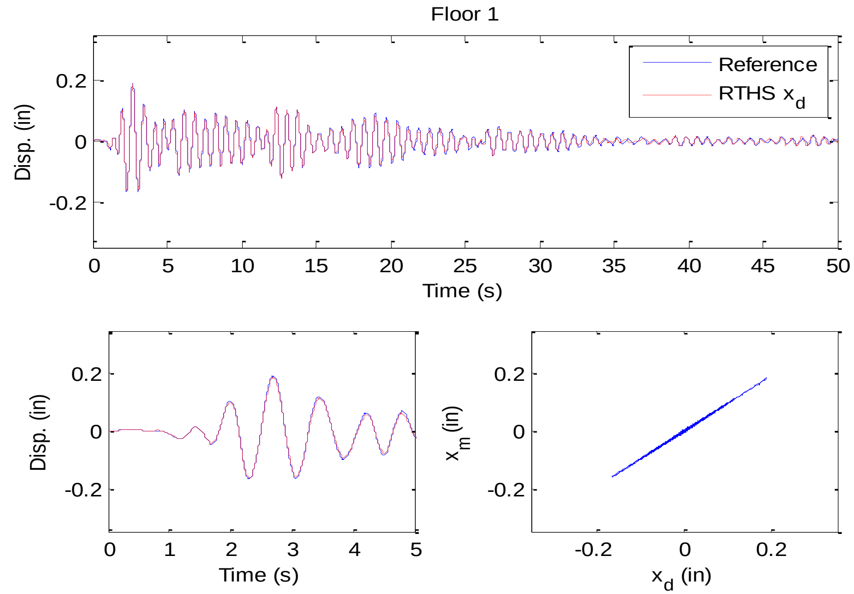


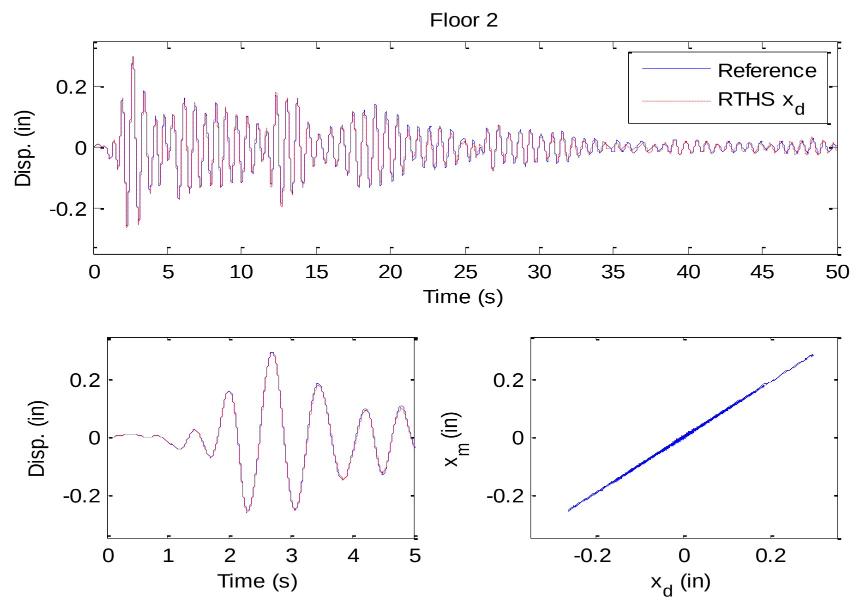


Real-time Hybrid Simulation Validation



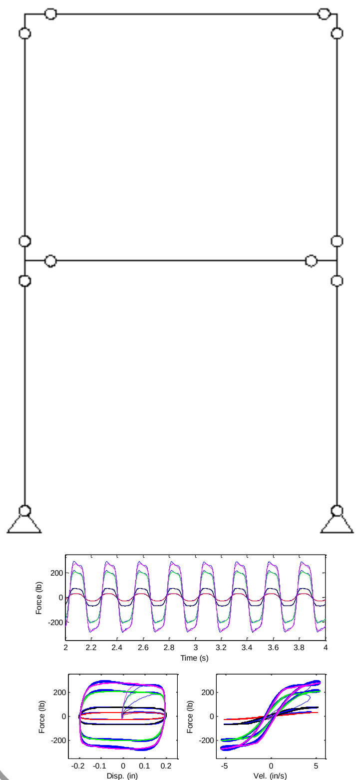




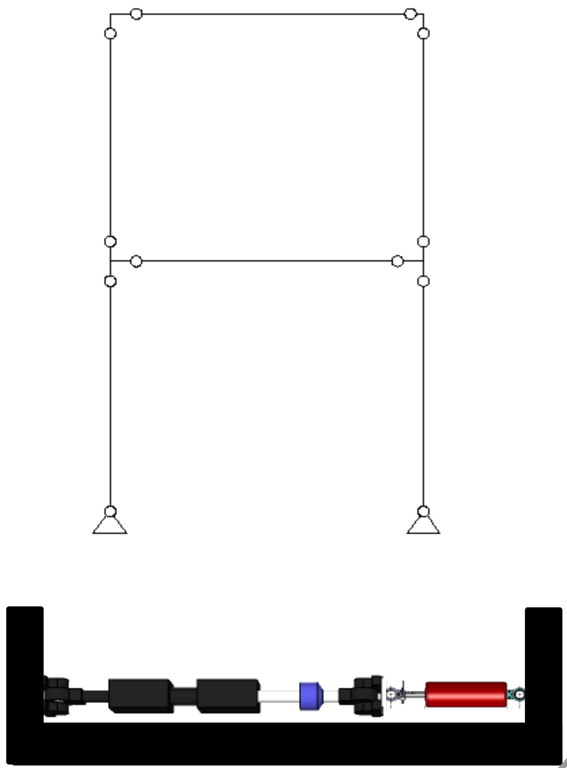


Real-time Hybrid Simulation with Damper Device

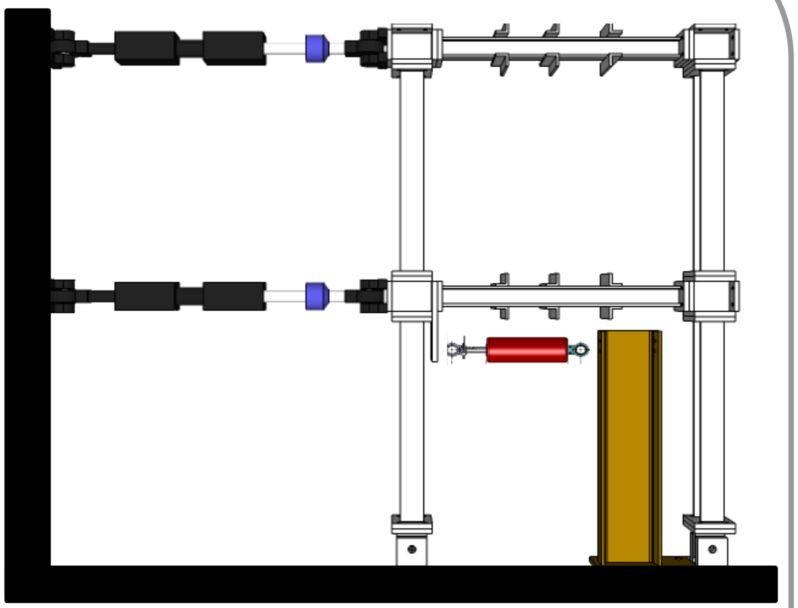
Phase I

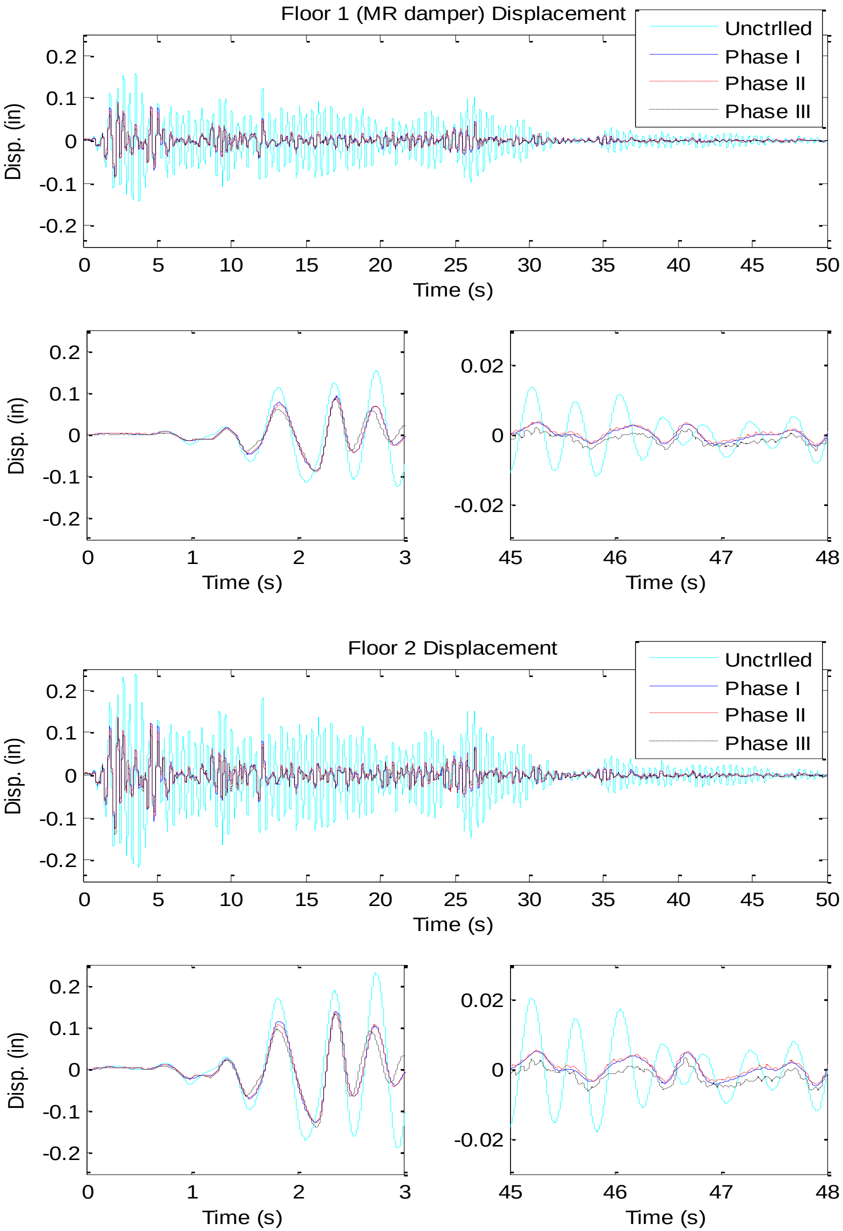


Phase II

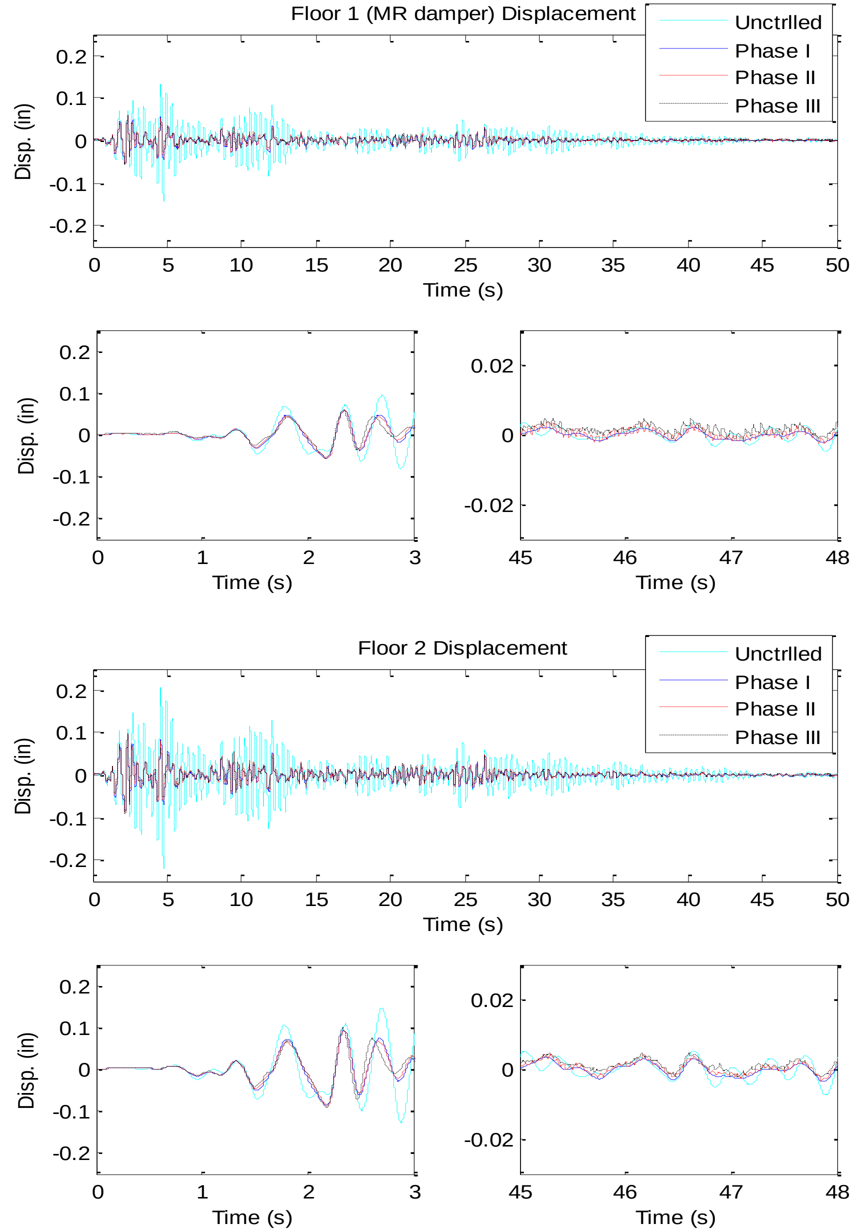


Phase III





ω_1=1.95Hz, ω_2=11.21Hz



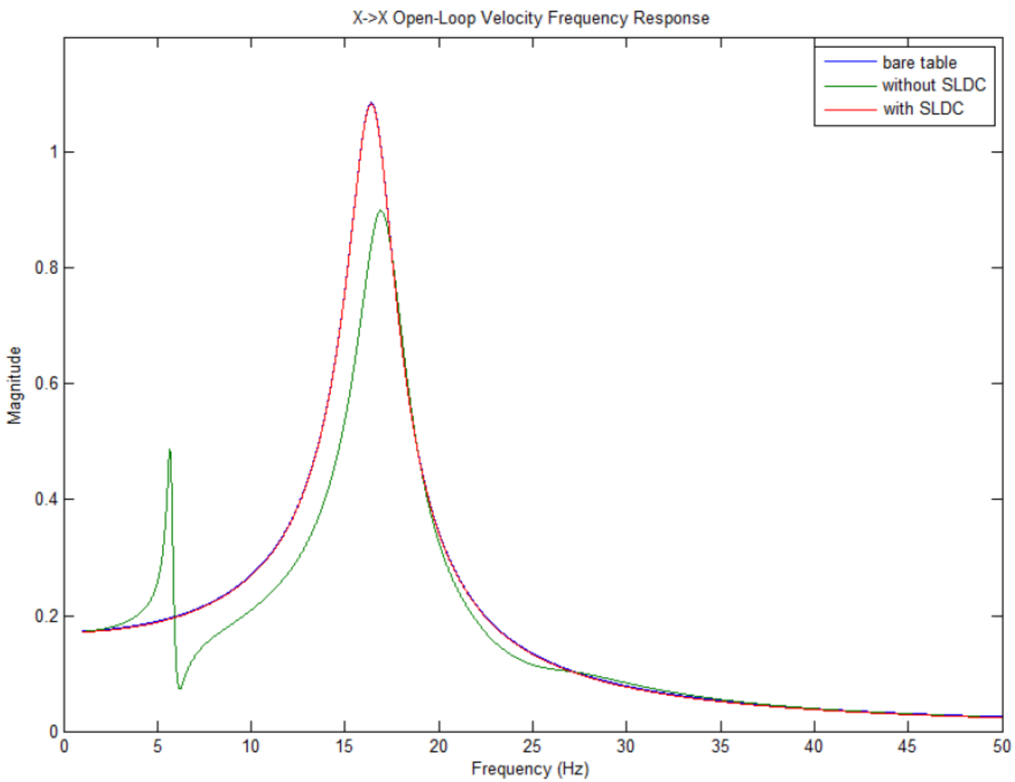
ω_1=2.75Hz, ω_2=15.85Hz

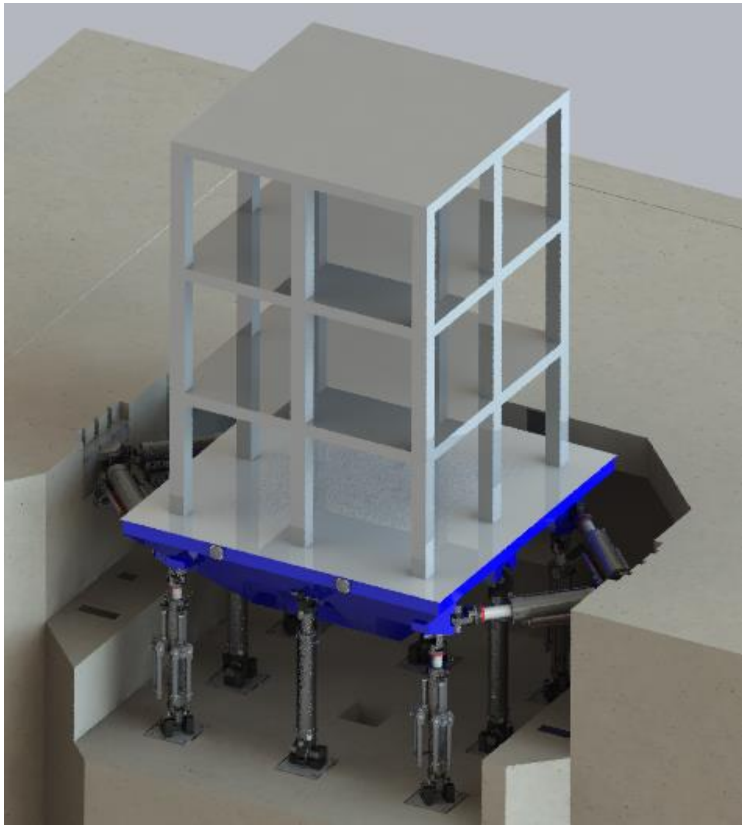
SPECIMEN DYNAMIC COMPENSATION (SDC)

Originator: Brad Thoen

SDC is a feedback compensator

- Removes the effect of a resonant specimen from the motion dynamics of a shake table – including over-turning moment.
- Restores the motion response to that of the bare table.



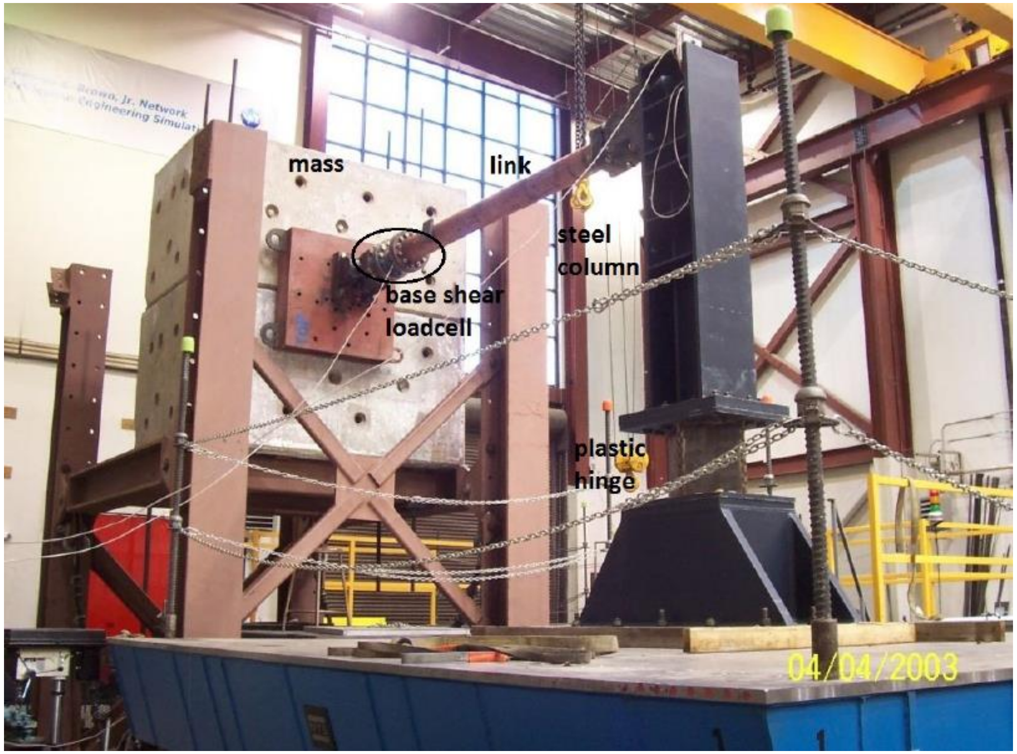


How SDC Works?

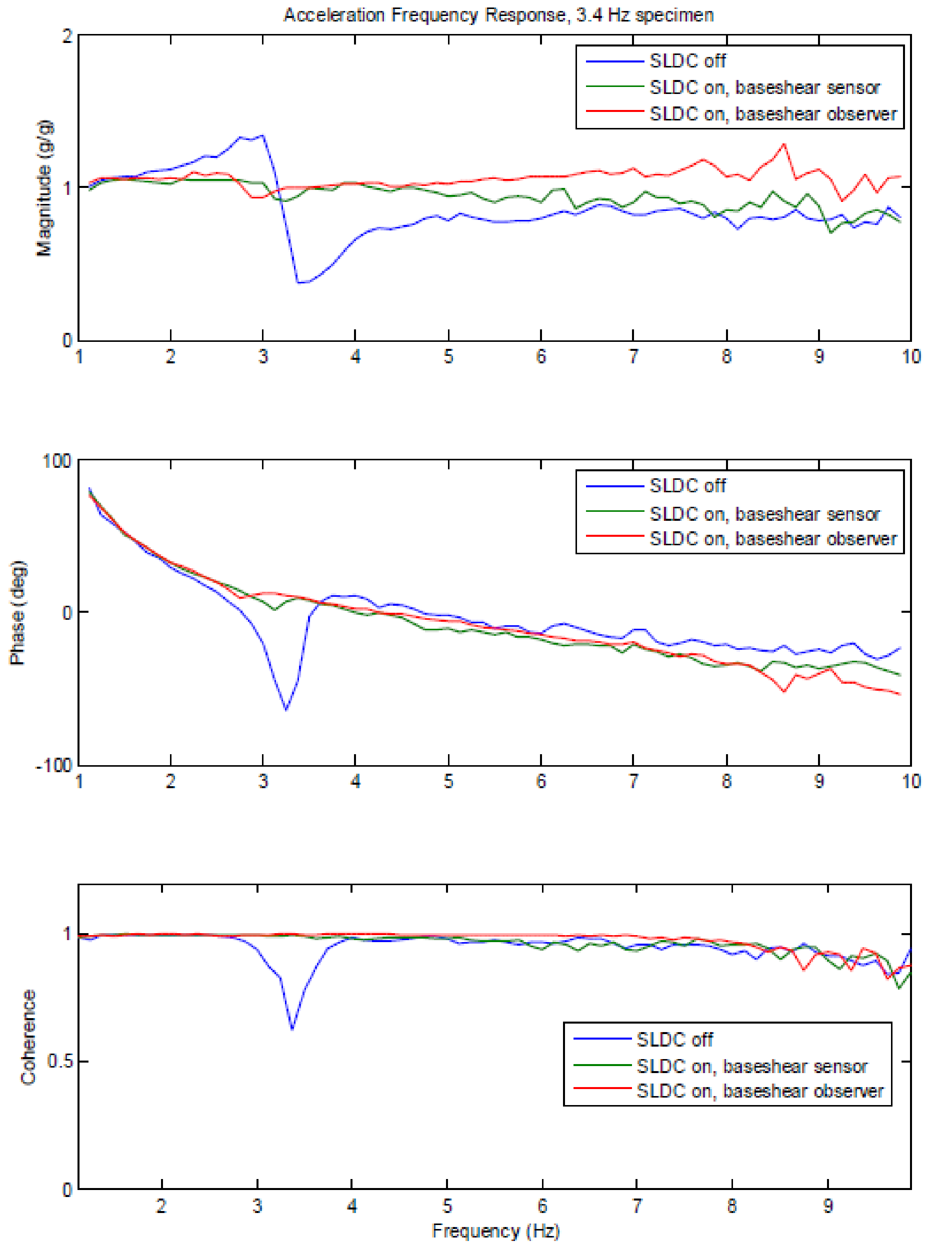
- Specimen reaction force as the feedback signal
- SDC augment actuator force by an amount equivalent to the specimen reaction force
- The table driving force is the correct amount to move the empty table
- Specimen reaction force can be obtained either
  - From a load cell between specimen and table
  - Or estimated through an observer using existing acceleration sensors

Field Test – Uniaxial Test

- Test Rig at the University of Nevada-Reno
- 30 ton mass is linked to test specimen using dynamic rated ball-joint swivels
- Provides a rigid low friction connection with no additional vibration
- Cantilevered steel column with “plastic deformation hinge” used to connect the specimen and table



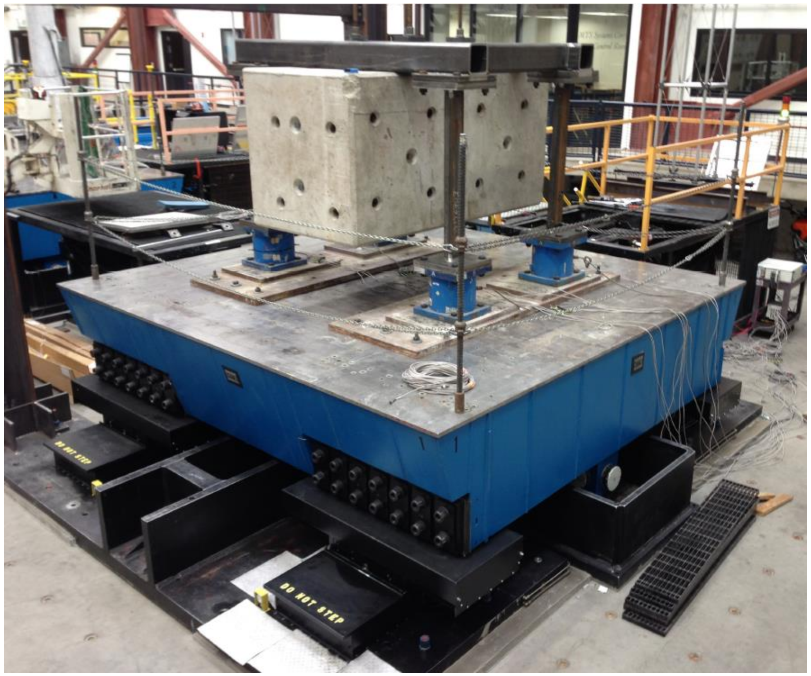
Column F_n: 4 Hz; Damping: ~1%



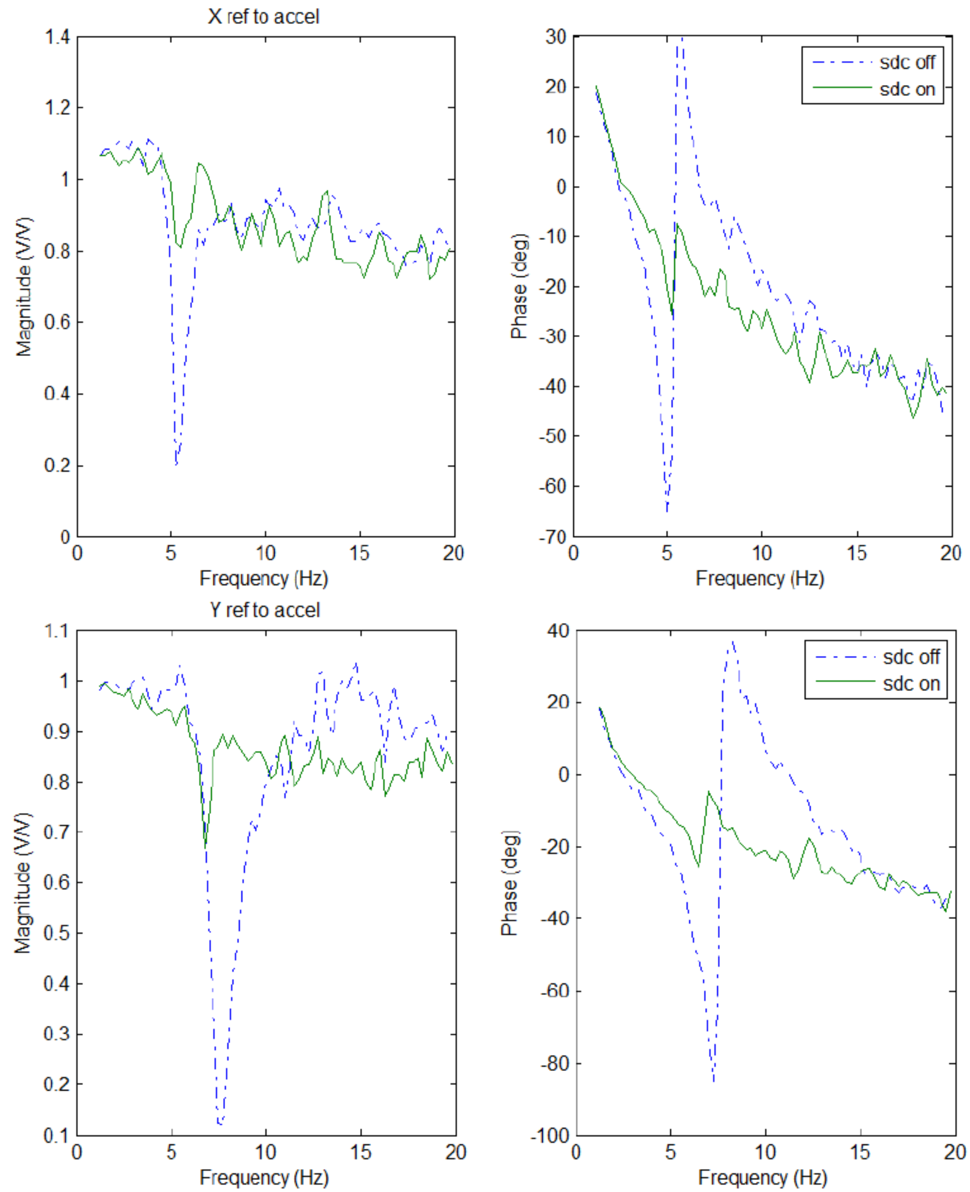
Notes:

- »"baseshear" is structural engineers word for "reaction force"
- »"baseshear sensor" (green): direct reaction force measurement
- »"baseshear observer" (red): reaction force estimated from table accels and delta-P sensors

Field Test – Biaxial Test



Specimen F_n and Damping
X Axis: 5.51 Hz, 0.99%
Y Axis: 7.63 Hz, 1.39%



Summary

- System modeling is important for dynamic testing. Gain system level understanding of testing stability limit and performance accuracy.
  - Simulink – Control System Dynamics
  - MBD – Mechanical System Dynamics
  - FEA – Flexible Body Dynamics
- Advanced motion control strategies are enablers of complicated dynamic testing.
  - Adaptive Feedforward Compensation (AFC)
  - Robust H-infinity Loop Shaping Optimal Control
  - Specimen Dynamic Compensation (SDC)