Real-Time Hybrid Shaking Table Testing: Other Developments & Applications

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Outline

Part I: Analytical Investigation of the Effect of Time Delay on RTHS and Implementation in OpenSees

Part II: TVC Implementation for Improved Control in RTHS Shaking Table Testing

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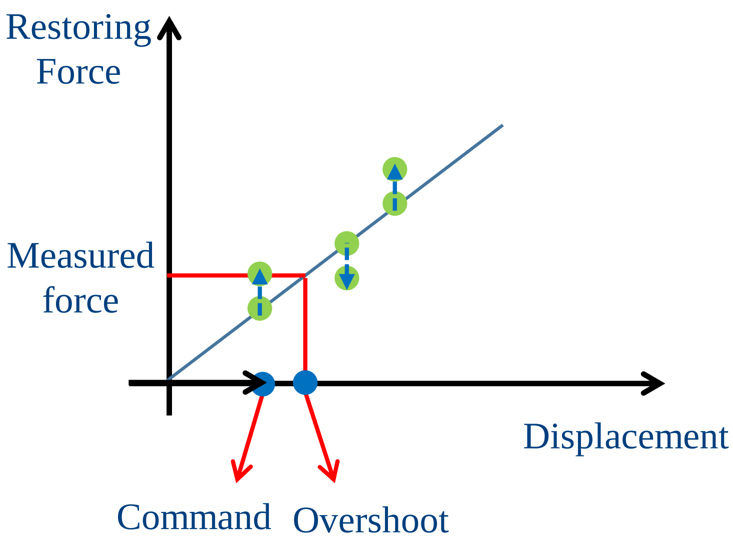
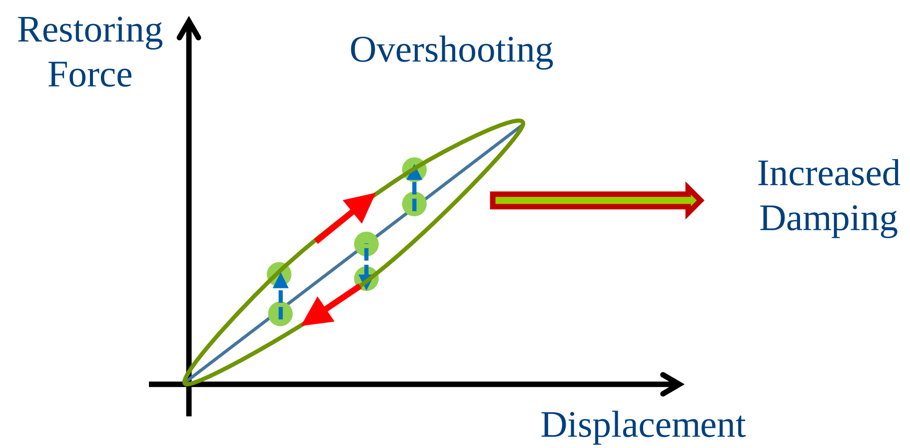
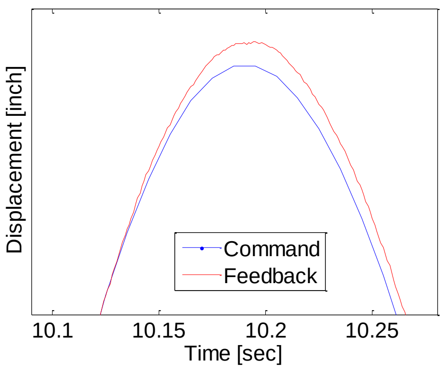
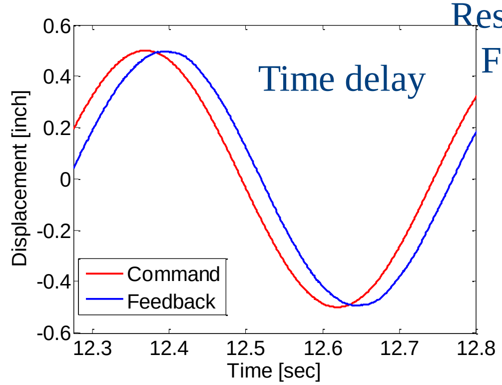
Analytical Investigation of the Effect of Time Delay on RTHS and Implementation in OpenSees

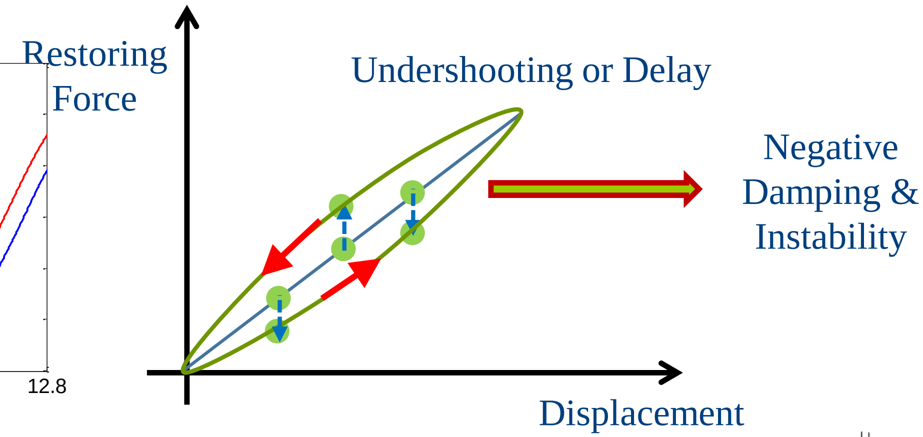
Conceptual Investigation











Simulation Errors Lecture in Yesterday's Morning Session

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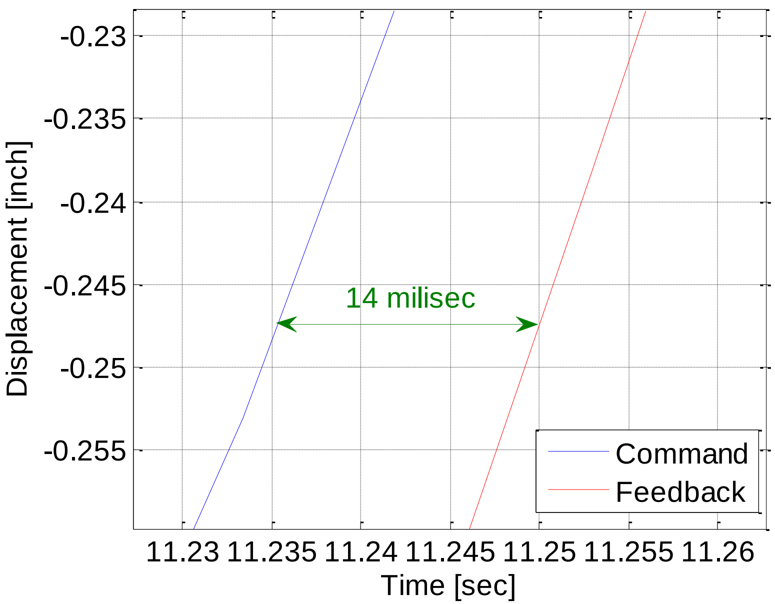
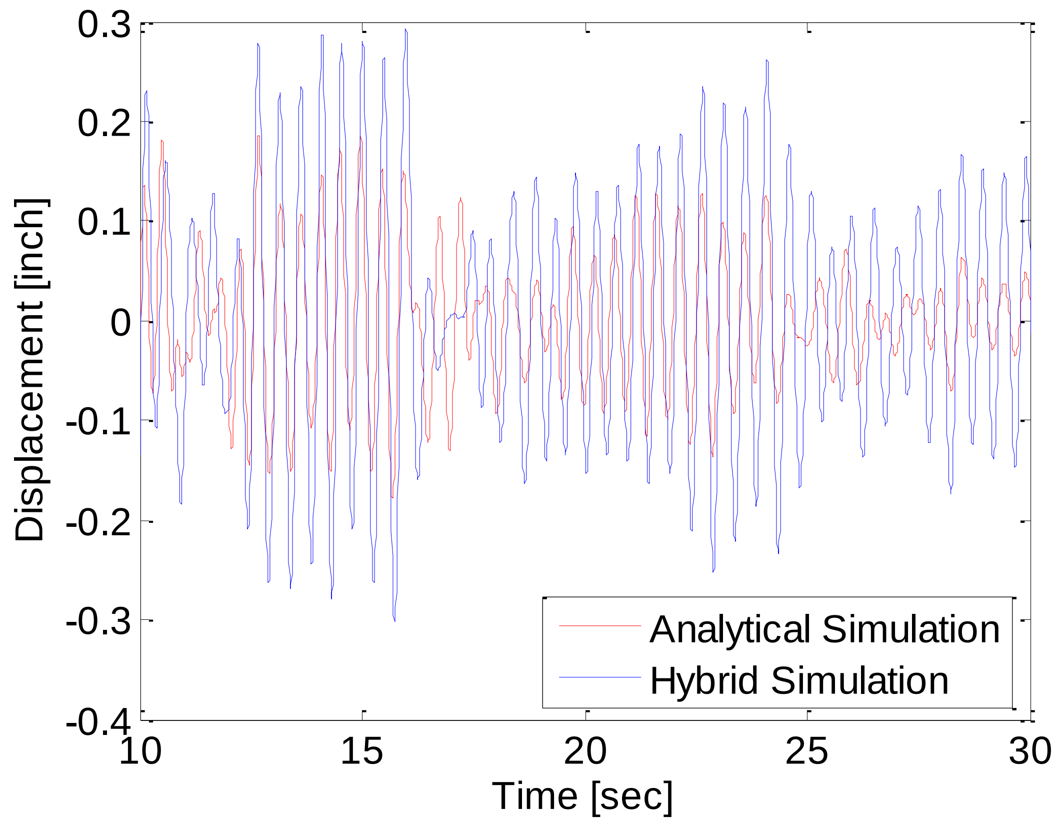
Experimental Investigation





14 millisecond time delay

Application I in Yesterday's Afternoon Session

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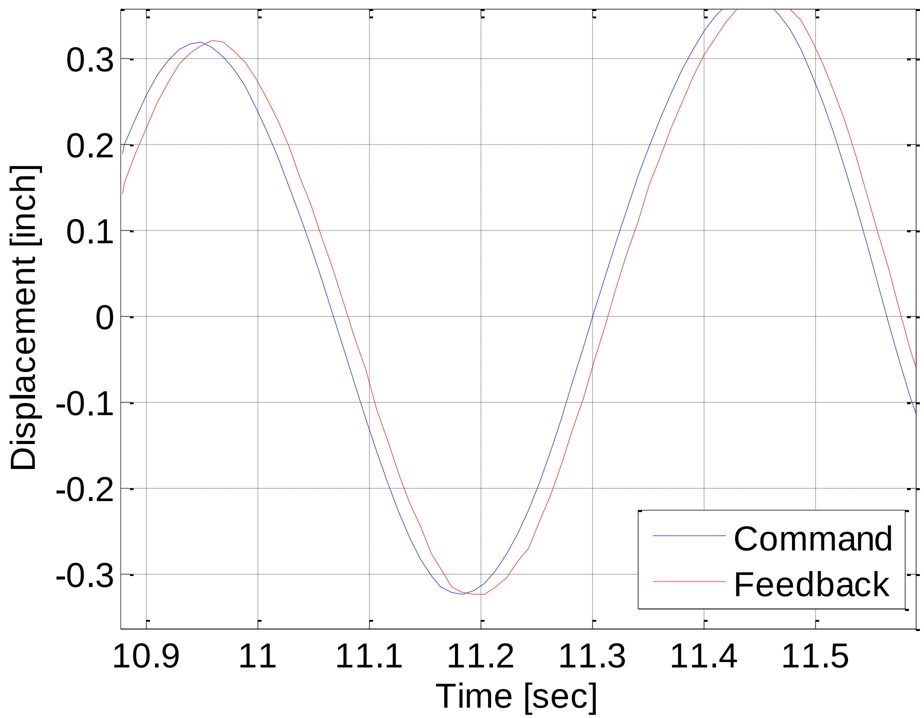
Analytical Investigation

Expression of the displacement with time delay:

$$u_{real} = u_{comp} - vel \times delay$$



Analytical Investigation: MATLAB

Simple code in Matlab for numerical integration of a linear SDOF system with Explicit Newmark integration

```
for i=1:L-1
    uD(i+1) = uD(i) + dtint * vD(i) + dtint^2 * aD(i)/2;
    udelD(i+1) = uD(i+1) - vD(i) * delayt;                  %displacement with delay
    fD(i+1) = k * udelD(i+1);
    peffD(i+1) = -m*Gmaccr(i+1) - fD(i+1) - c*(vD(i) + dtint * (1-gama) * aD(i));
    aD(i+1) = peffD(i+1)/meff;
    vD(i+1) = vD(i)+dtint * ((1-gama) * aD(i)+  gama * aD(i+1));
    atD(i+1) = aD(i+1) + Gmaccr(i+1);
end
```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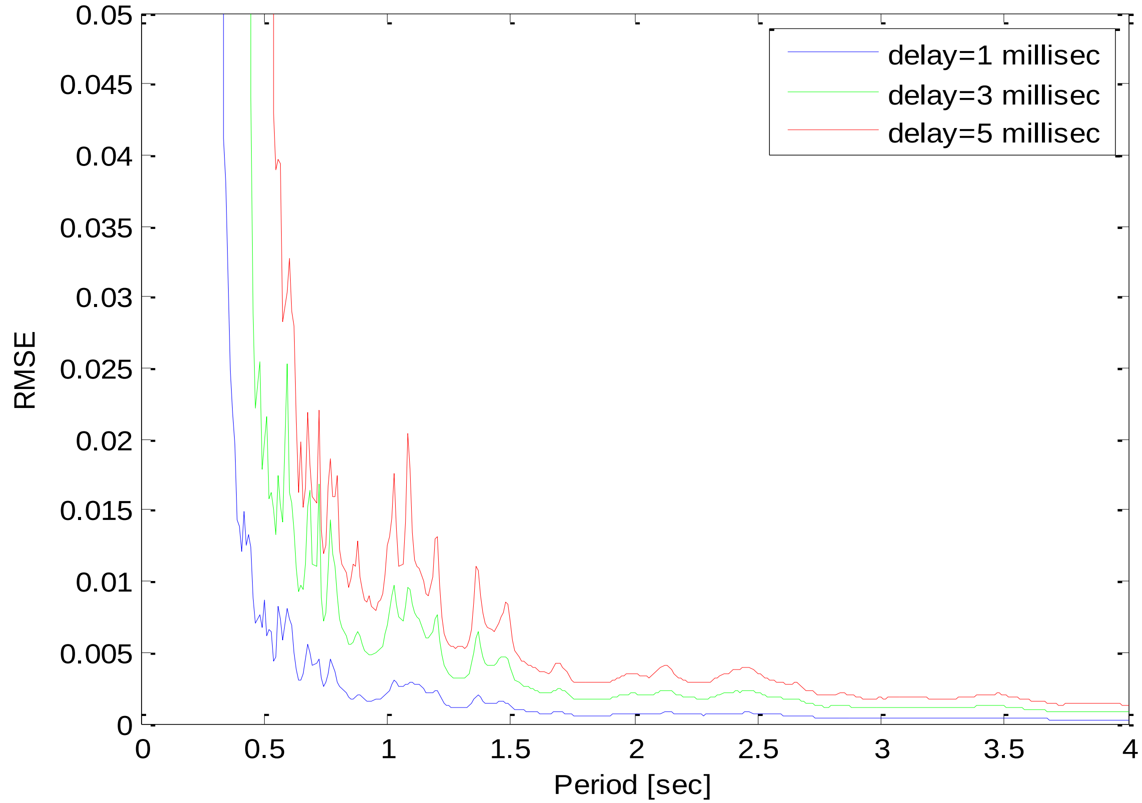
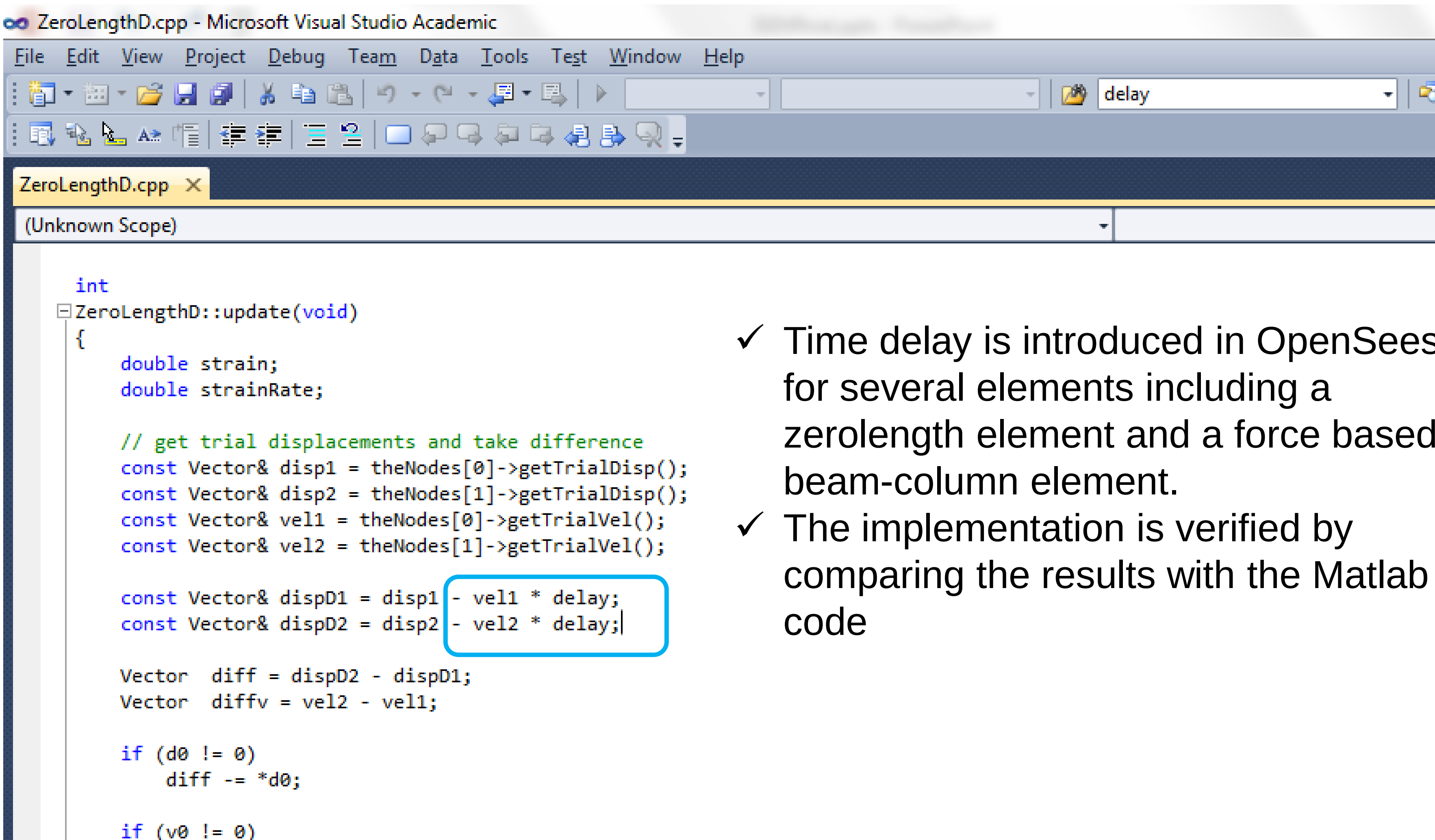
Analytical Investigation: MATLAB



$$RMSE = \frac{\sqrt{\sum_i \left(abs\left(u_{app,i} - u_{ref,i}\right)\right)^2} \Big/ N}{median\left(abs\left(u_{ref}\right)\right)}$$

app: Approximate (with delay)
ref: Reference (without delay)

Analytical Investigation: OpenSees



- ✓ Time delay is introduced in OpenSees for several elements including a zerolength element and a force based beam-column element.
- ✓ The implementation is verified by comparing the results with the Matlab code

TVC Implementation for Improved Control in RTHS Shaking Table Testing

Background

HS category	Accuracy Required for	How to Reduce Control Errors
Slow	Displacement	• Tuning • Reduction of loading rate • Explicit checking of command and feedback
RTHS in actuator configuration	Displacement, Velocity	• Tuning • Error compensation methods
RTHS in shaking table configuration	Displacement, Velocity, Acceleration	Three Variable Control

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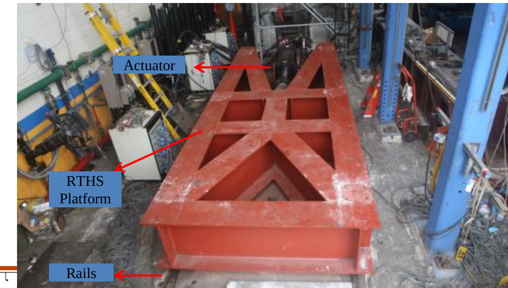
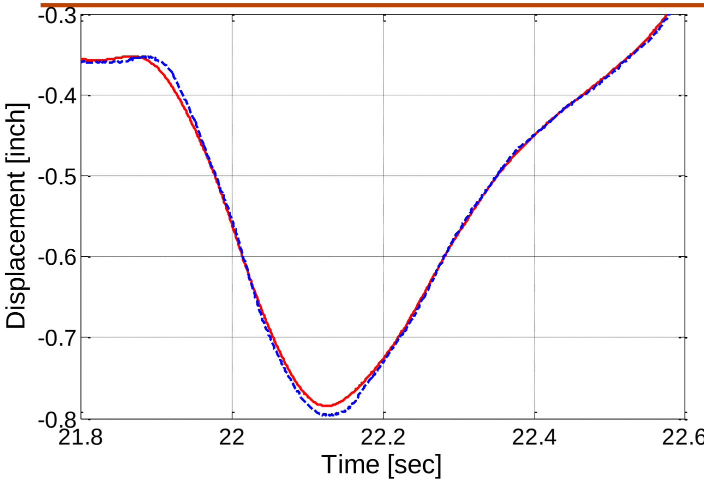
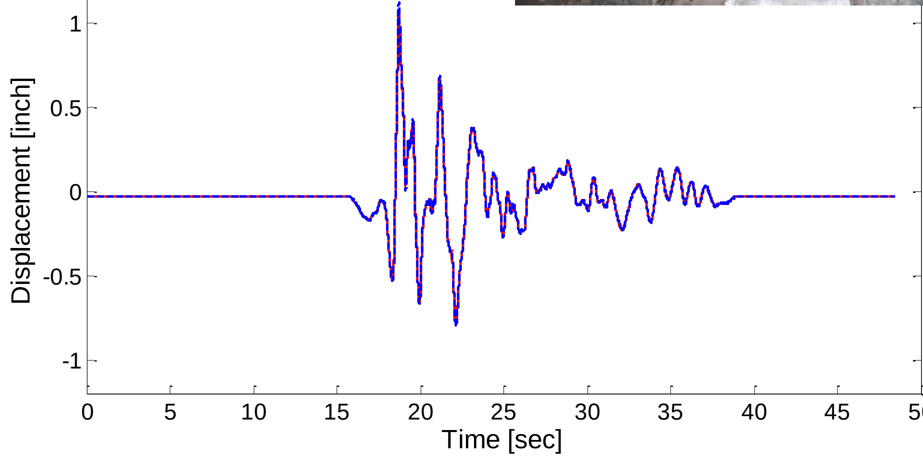
Background



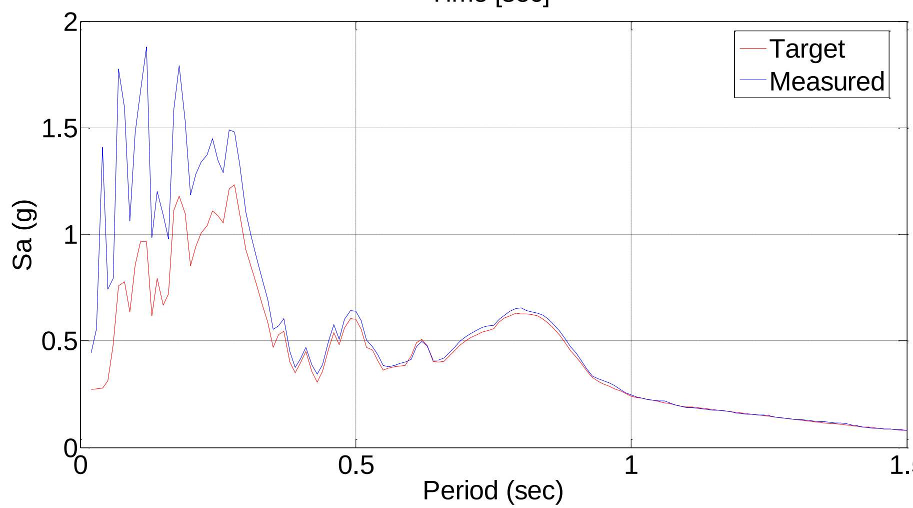




Acceleration mismatch at low periods (high frequencies)

$Sa = \omega^2 Sd$

Requirement for acceleration and velocity control



Three Variable Control (TVC), developed by MTS, is a well established displacement-velocity-acceleration control method

TVC Implementation

Existing Controller:

- **MTS-493 real-time digital controller, operating at 1024 Hz and accompanying STS software**
- **Closed loop proportional-integral-derivative (PID), feed-forward, and differential pressure (Delta-P) control capabilities**
- **<u>Does not offer any additional shaking table control features</u>**

- ❑ Passes the control to an external source
- ❑ Servo-valve can be commanded from an external source such as a simulink model

- ❑ Other useful features of STS are still active
  - Interlocks
  - 3-stage valve drivers
  - AC/DC Conditioners
  - Emergency shutdown button
  - Data Recorder
  - Digital Readouts

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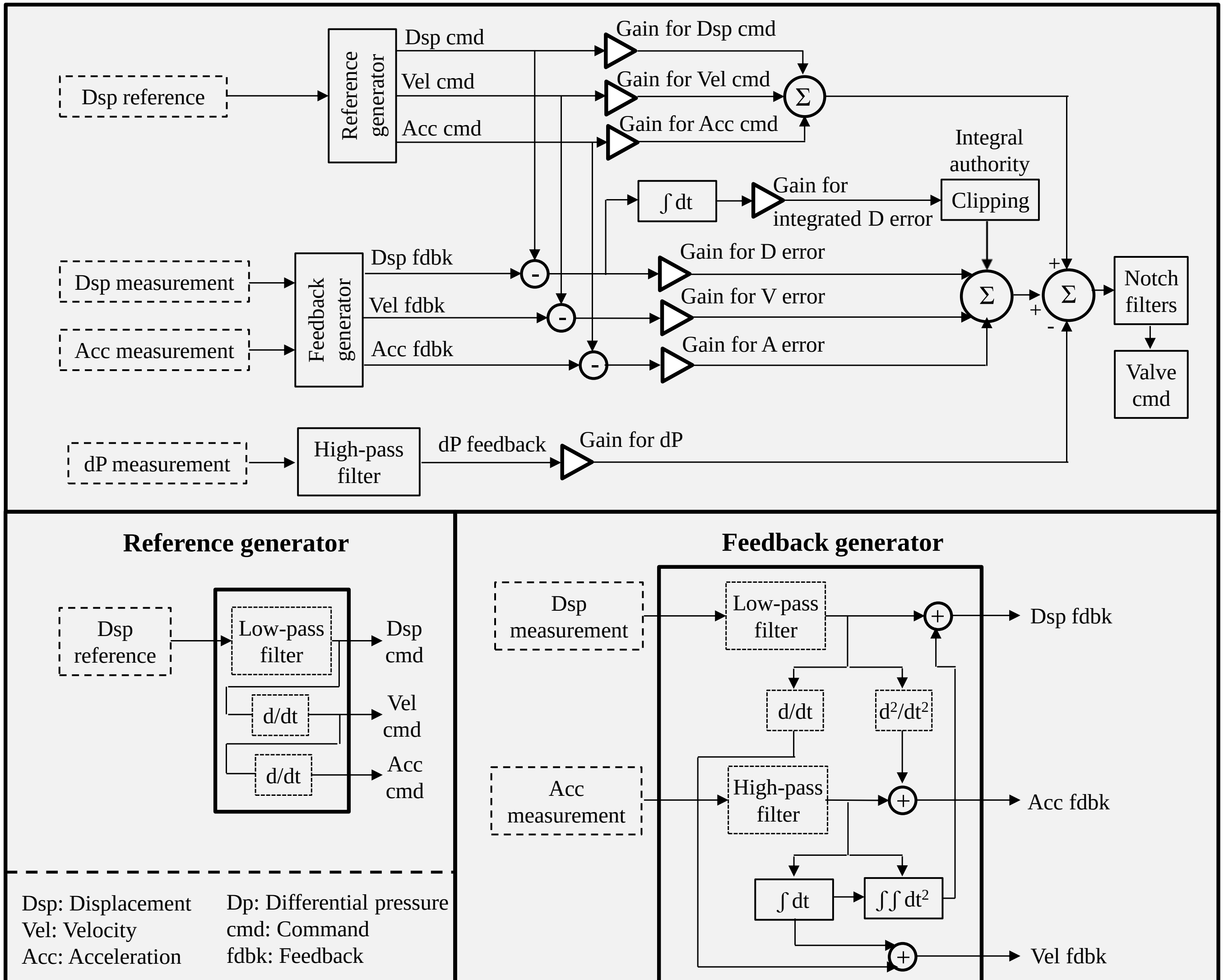
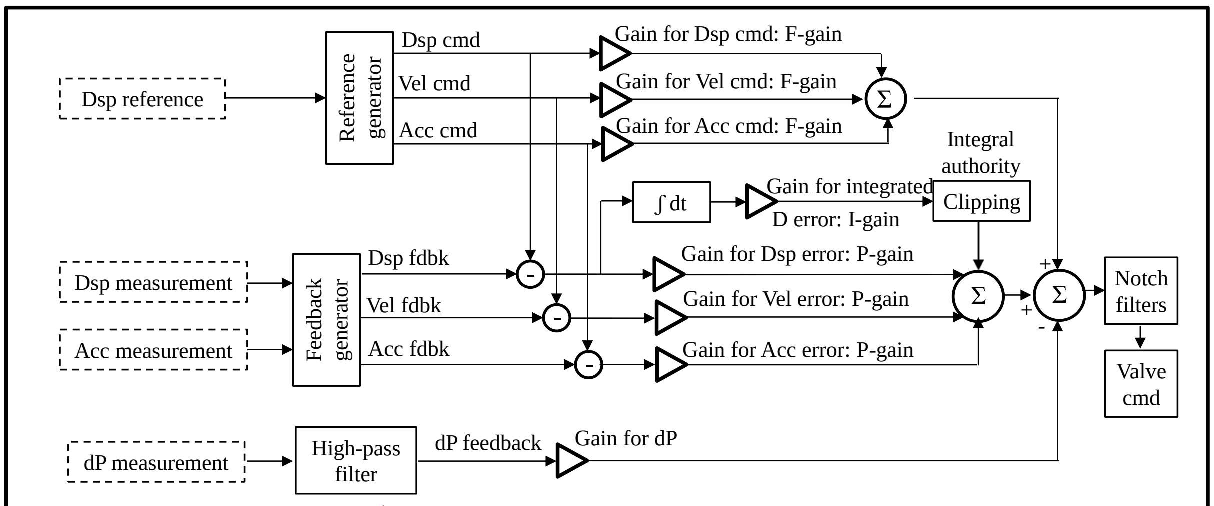
TVC Implementation

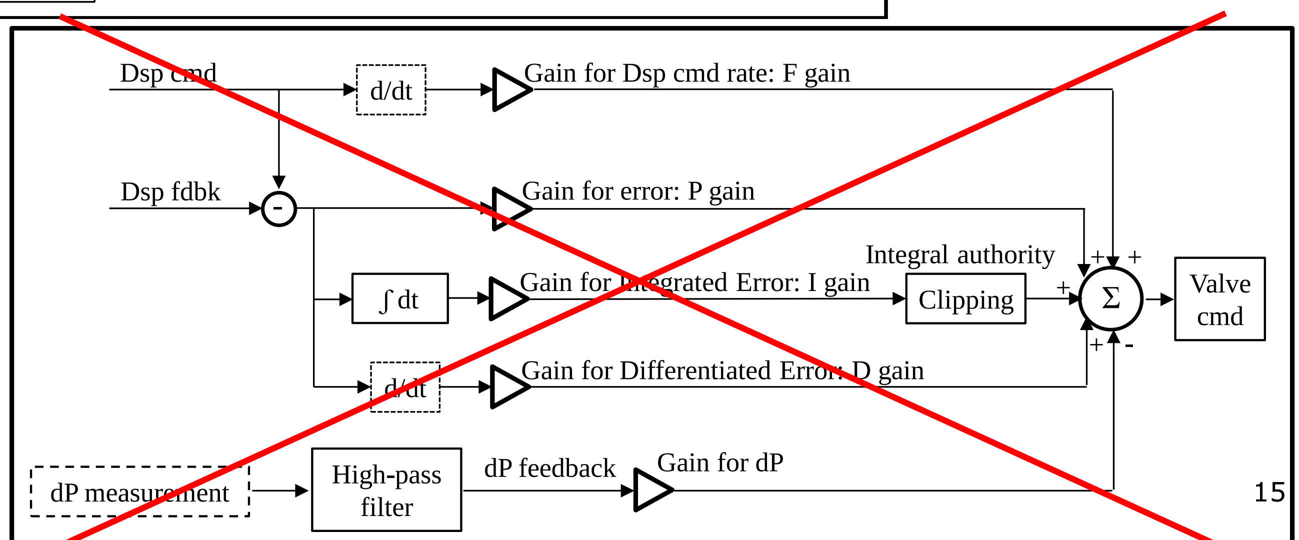


TVC block diagram as implemented in a Simulink model

TVC Implementatio



TVC



STS: Existing Controller

TVC Implementation

Three Variable Control (TVC) Implementation Phases: Consideration of Safety and Prevention of Unexpected Equipment Damage

1. Construct the simulink model to hold a single standalone actuator on the lab floor (not connected to a specimen)

```
feedbackave ← 0
for n = 1:ntest
  If n < nlimit
    command ← feedback
    feedbackave ← feedbackave + feedback/nlimit
  else
    command ← feedbackave
  endif
end
```

nlimit=1~10 msec

TVC Implementation

Three Variable Control (TVC) Implementation Phases: : Consideration of Safety and Prevention of Unexpected Equipment Damage

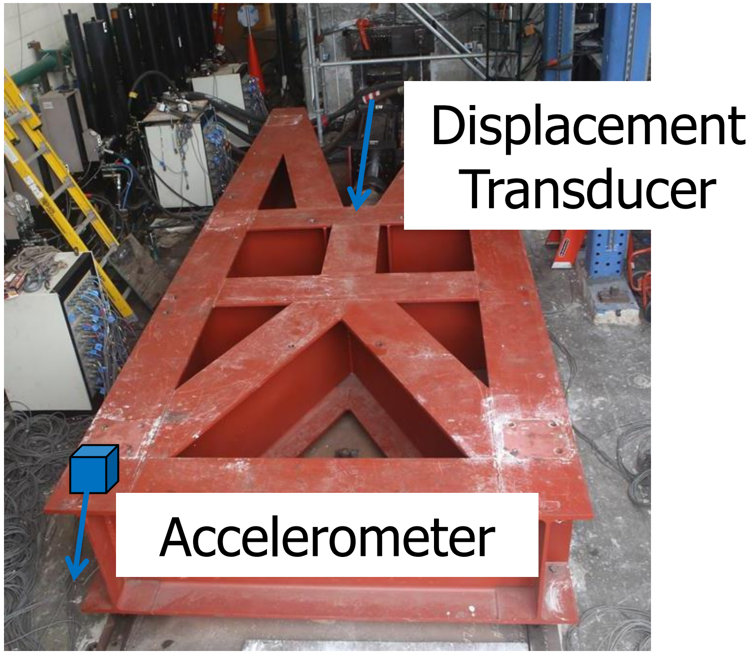
2. Improve the model to move the same actuator with a harmonic signal

```
feedbackave ← 0
for n = 1:ntest
  If n < nlimit
    command ← feedback
    feedbackave ← feedbackave + feedback / nlimit
  elseif nlimit ≤ n < nlimit2
    command ← feedbackave
 else
    command ← feedbackave + harmonic signal
 endif
end
```

TVC Implementation

Three Variable Control (TVC) Implementation Phases: Consideration of Safety and Prevention of Unexpected Equipment Damage

3. Improve the model to move the shaking table with a harmonic signal

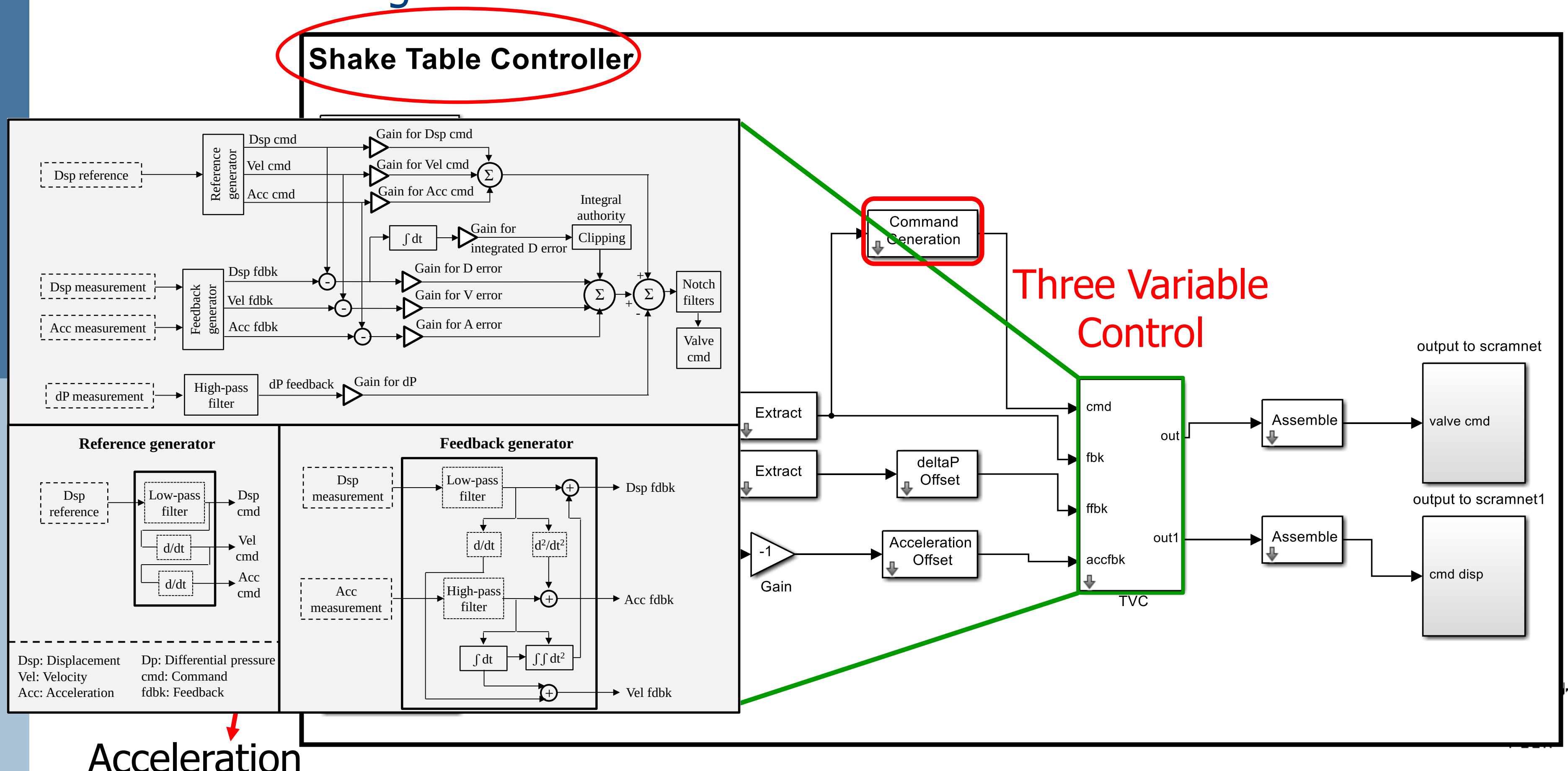


Important: Positive/negative directions of the accelerometer and displacement transducers need to be consistent for the TVC to function properly, otherwise the servo-valve commands due to the acceleration and displacement incorrectly cancel each other.

TVC Implementation

Three Variable Control (TVC) Implementation Phases:

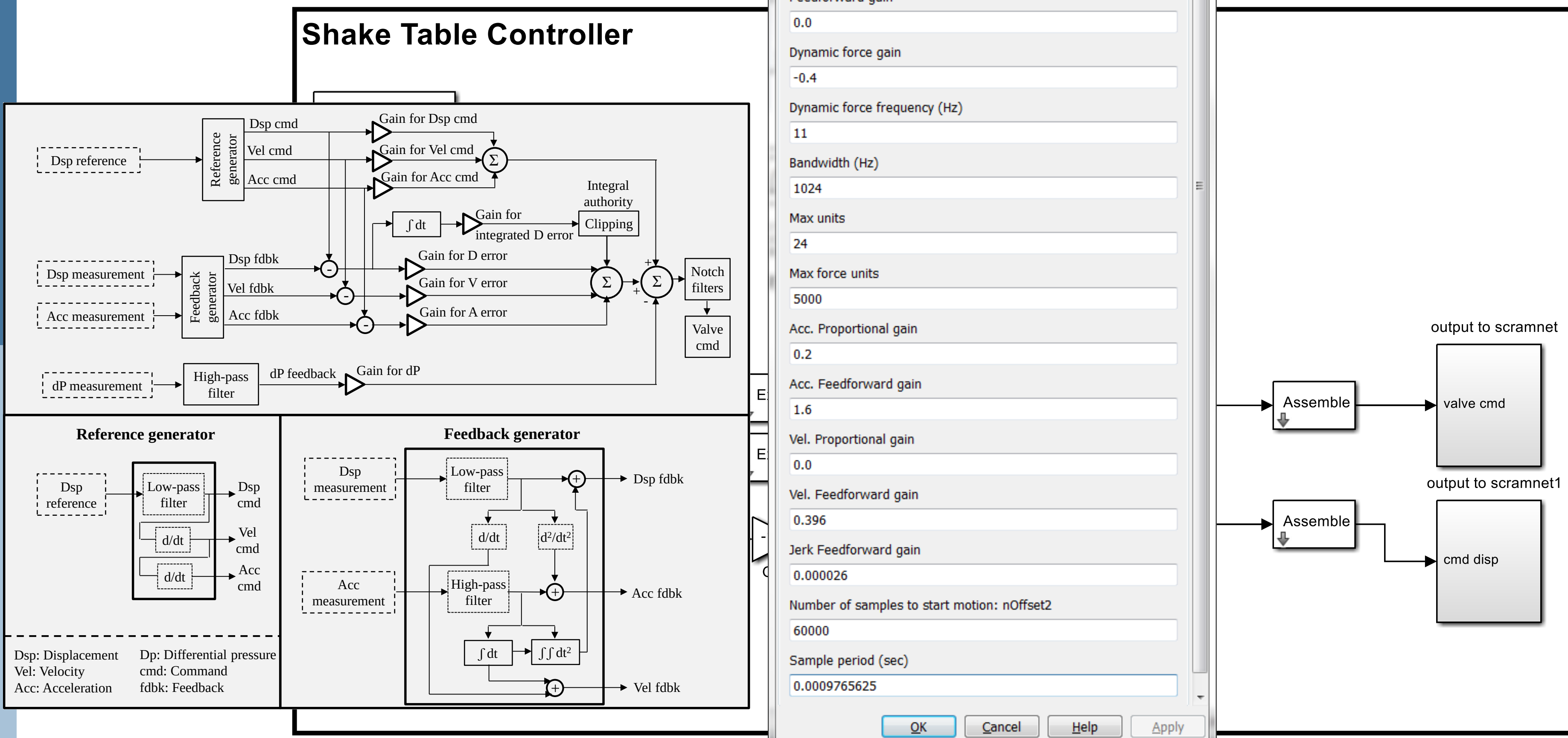
4. Improve the model to move the shaking table with a ground motion signal



TVC Implementat

Three Variable Control (TVC) Mo es:

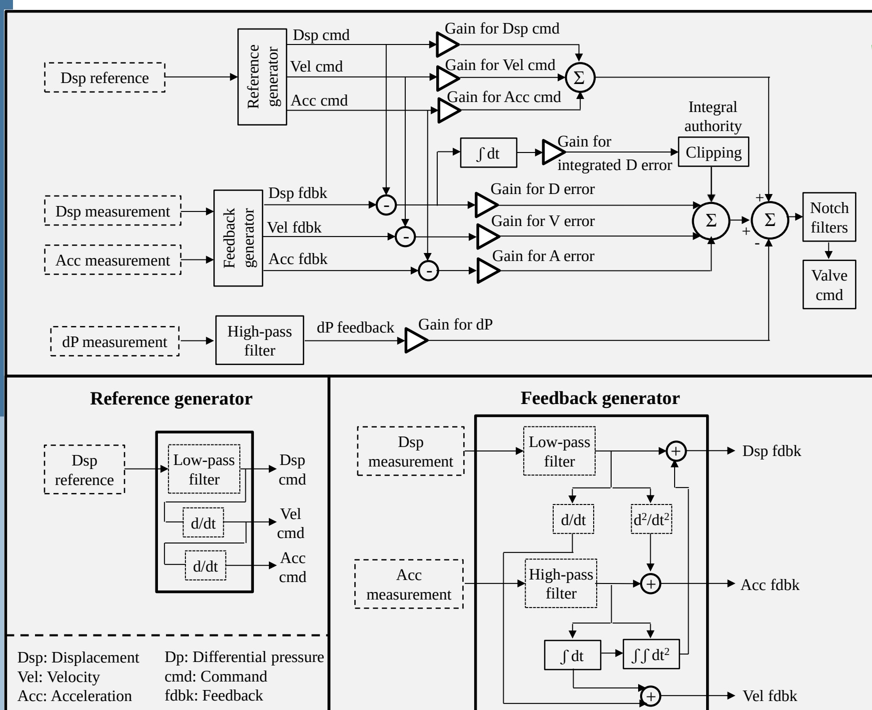
4. Improve the model to mo with a ground motion signal

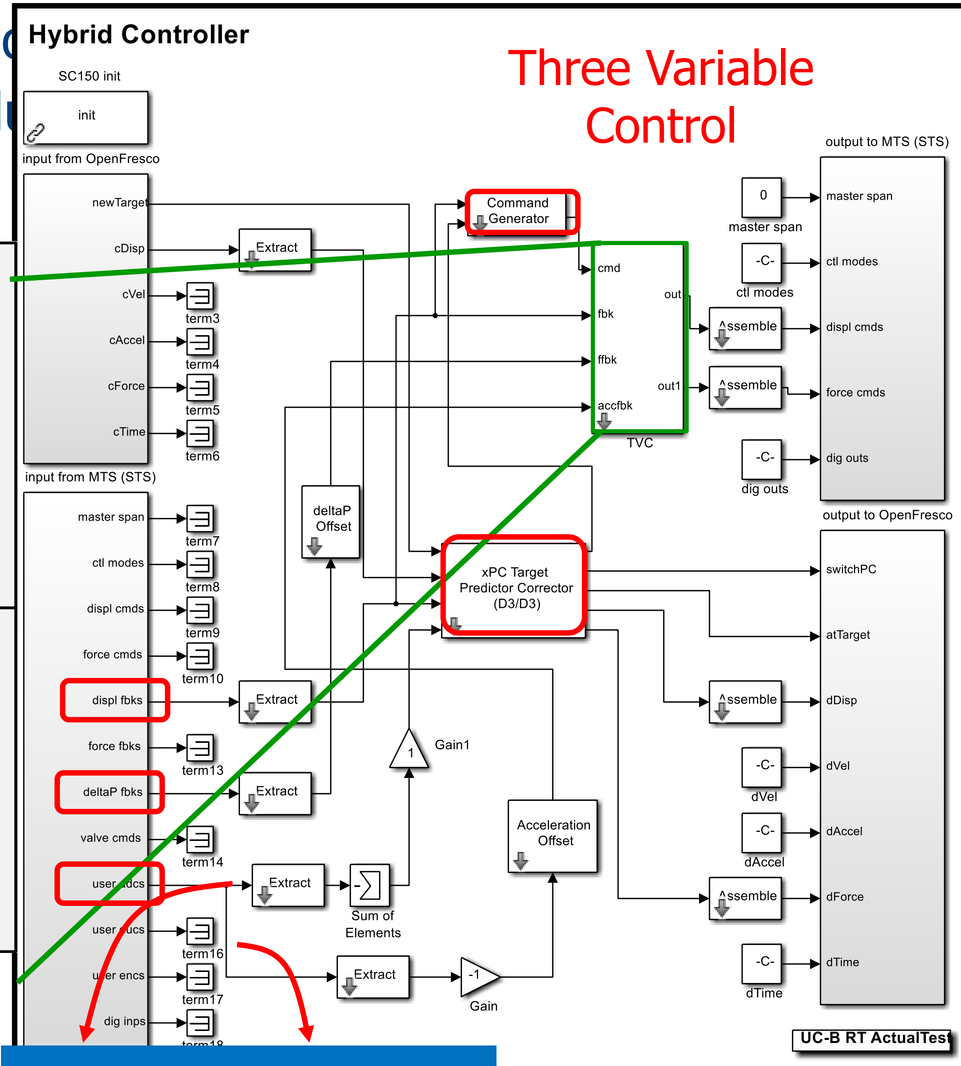


TVC Implementation

Three Variable Control (TVC) Mo

5. Improve the model to condu

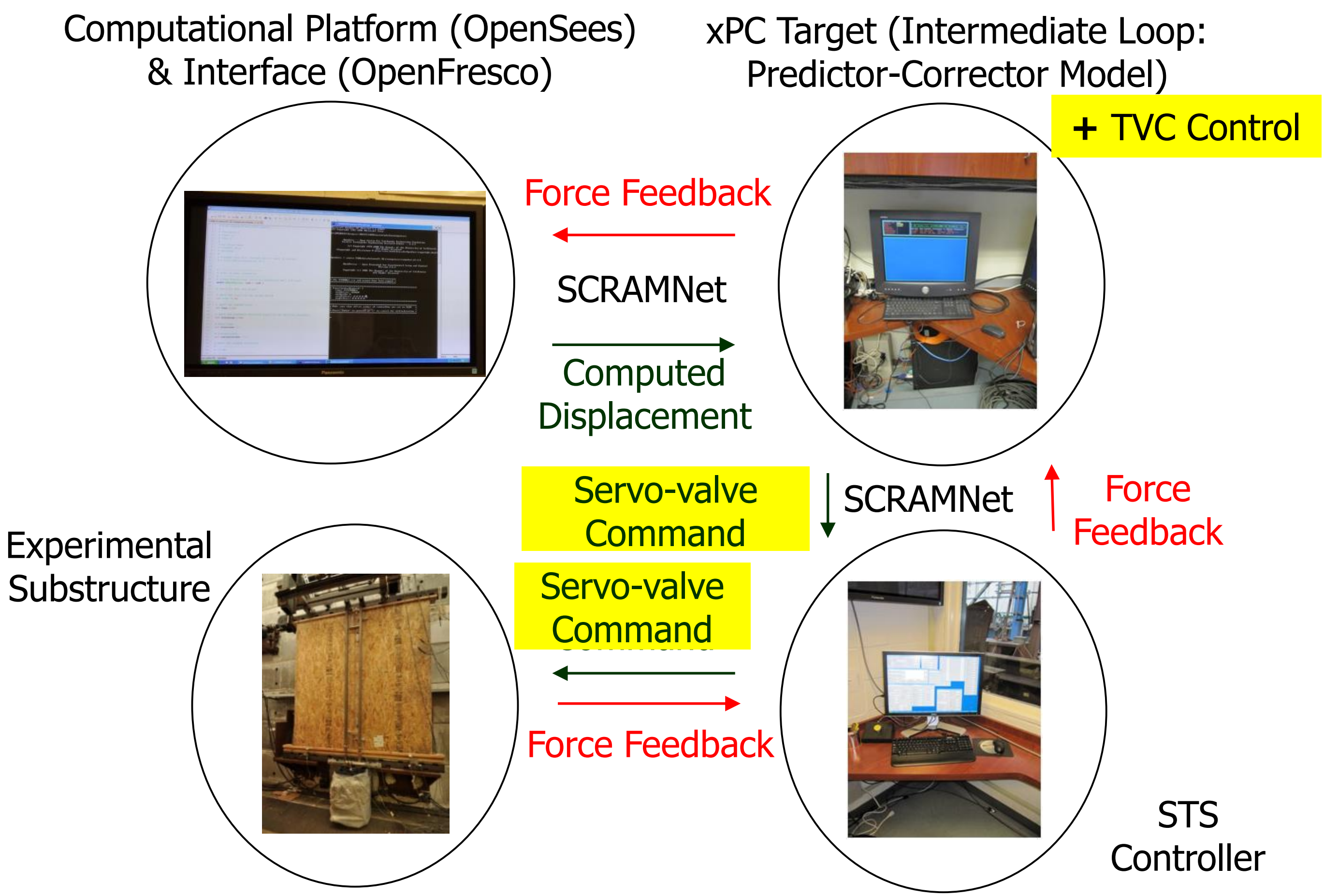




Force   Acceleration

TVC Implementation

PEER HS System



TVC Implementation

Parameter		Shaking Table	RTHS
Displacement	P-gain	10	10
	I-gain	0.1	0.1
	Integral authority	5	5
	F-gain	0	0
	Full range	24	24
Acceleration	P-gain	0.1	0.04
	F-gain	0.36	0.33
	Full range	5	5
Velocity	P-gain	0	0
	F-gain	0.5	0.5
	Full range	30	30
Jerk	F-gain	0.0022	0.0022
	Full range	2000	2000
Differential pressure	Gain for dP	0.4	0.4
	Dynamic Force Frequency	11	11
Crossover filter	Crossover frequency	1.4	1.4
	Damping ratio	0.03	0.03

- Tuning for RTHS is different than conventional shaking table tuning
- Tuning with a random function generator may not be sufficient as it is required to eliminate the time delay
- F-gains on acceleration and velocity was particularly useful to eliminate the time delay

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TVC Implementation

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- Overshooting caused by F-gain was reduced with the acceleration P-gain and the jerk F-gain

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TVC Implementation

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- dP was particularly useful to eliminate the artificial forces generated by the oil column frequency that can make RTHS go unstable

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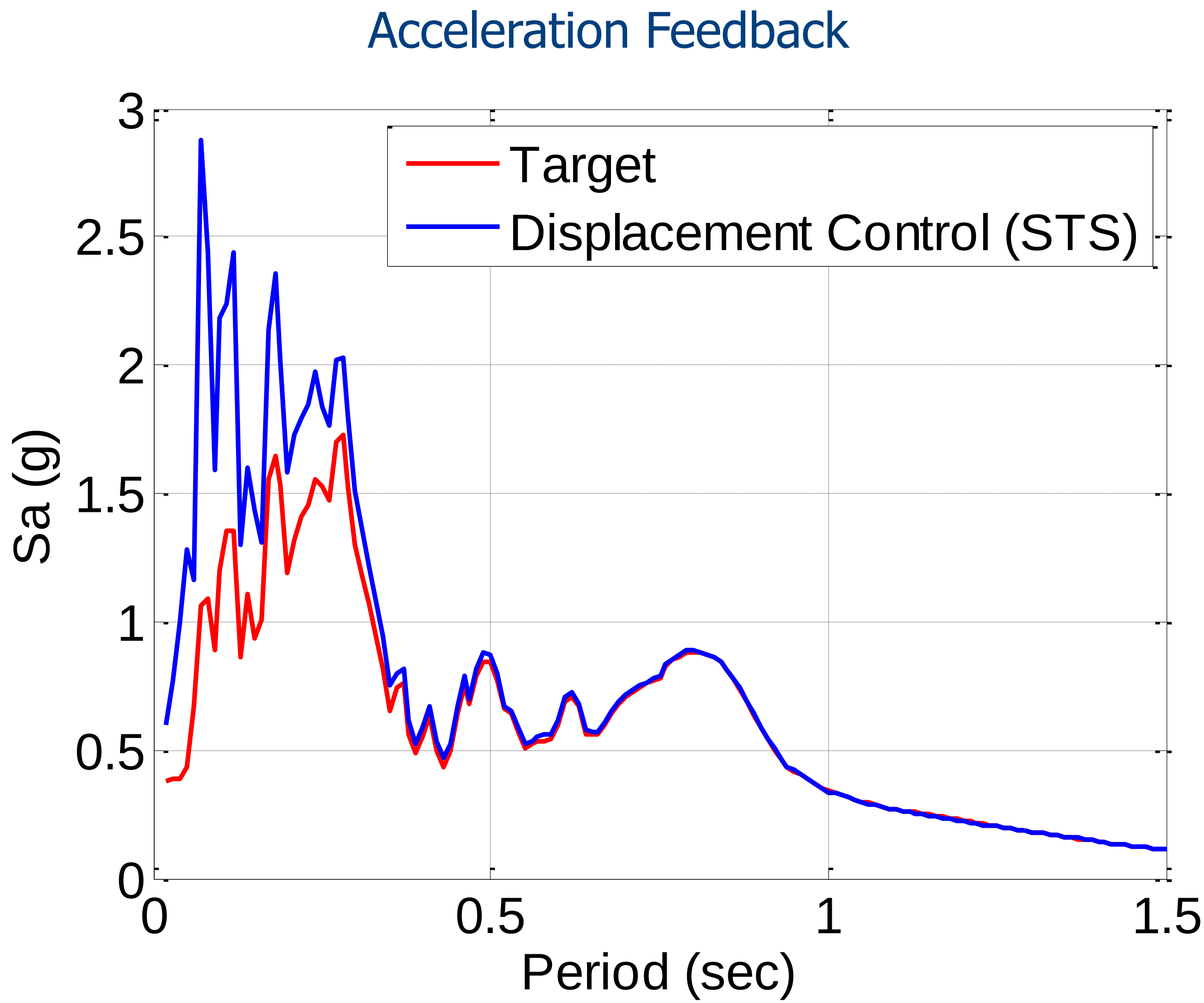
Response Enhancement



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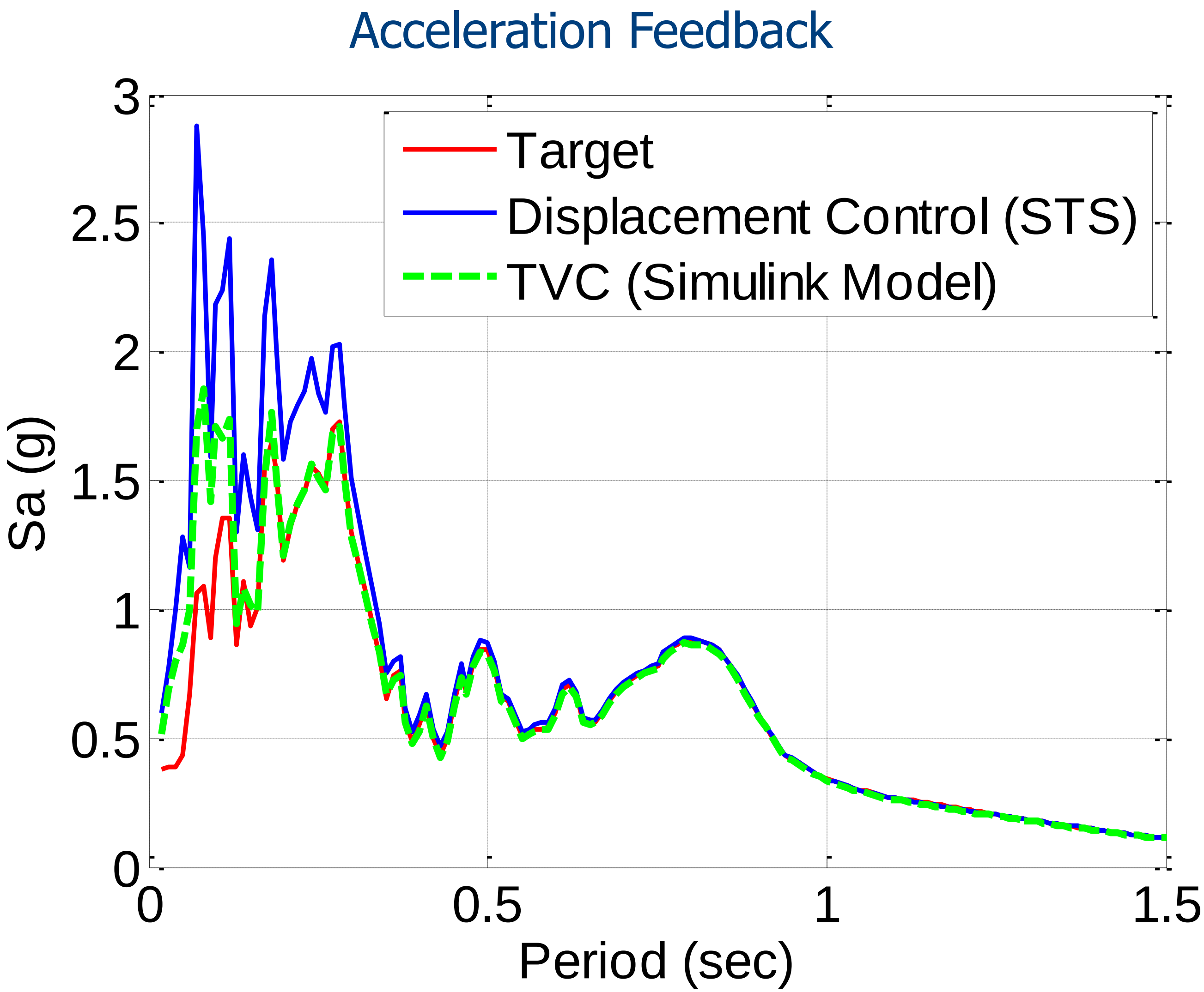
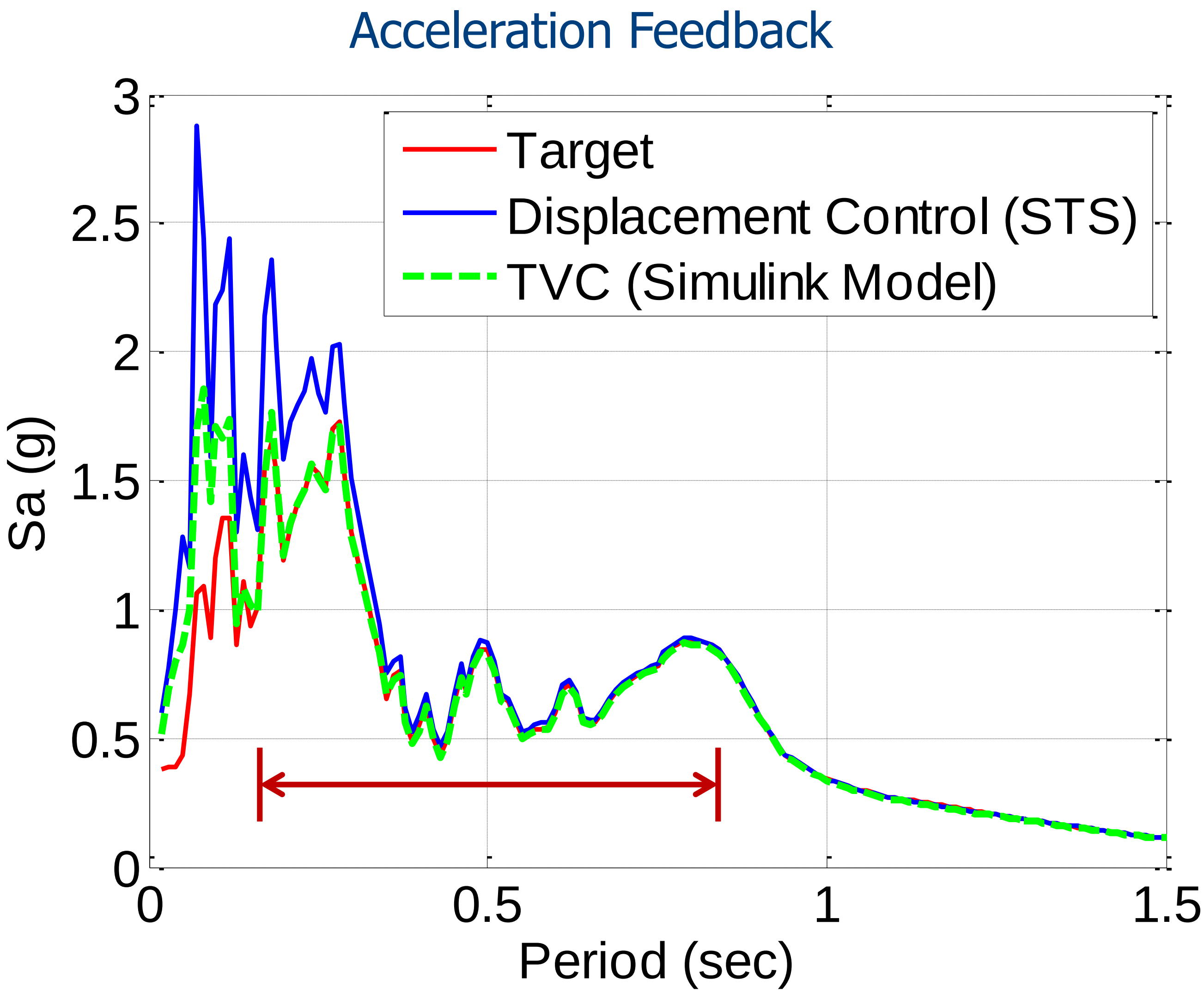
Response Enhancement



Response Enhancement



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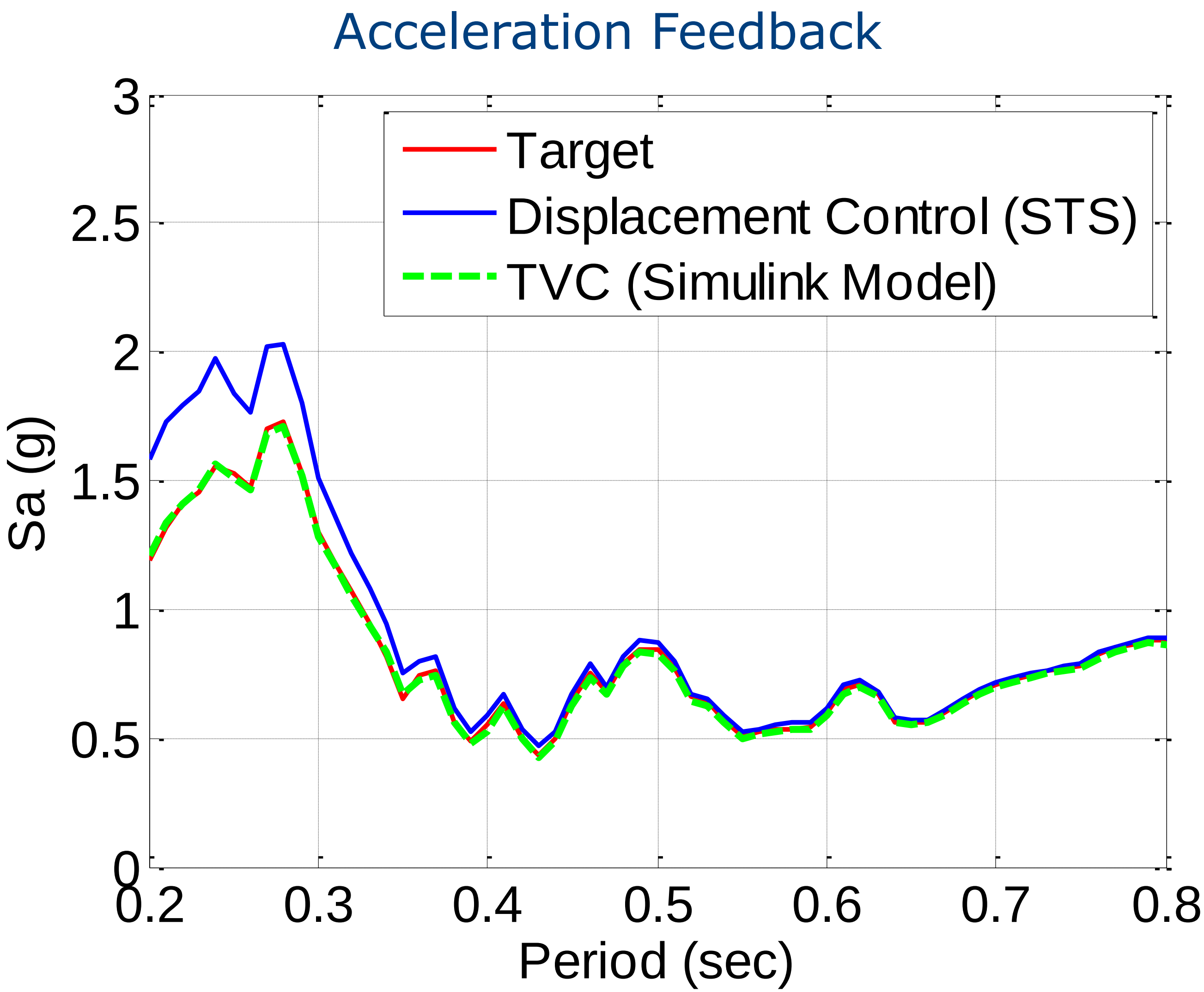
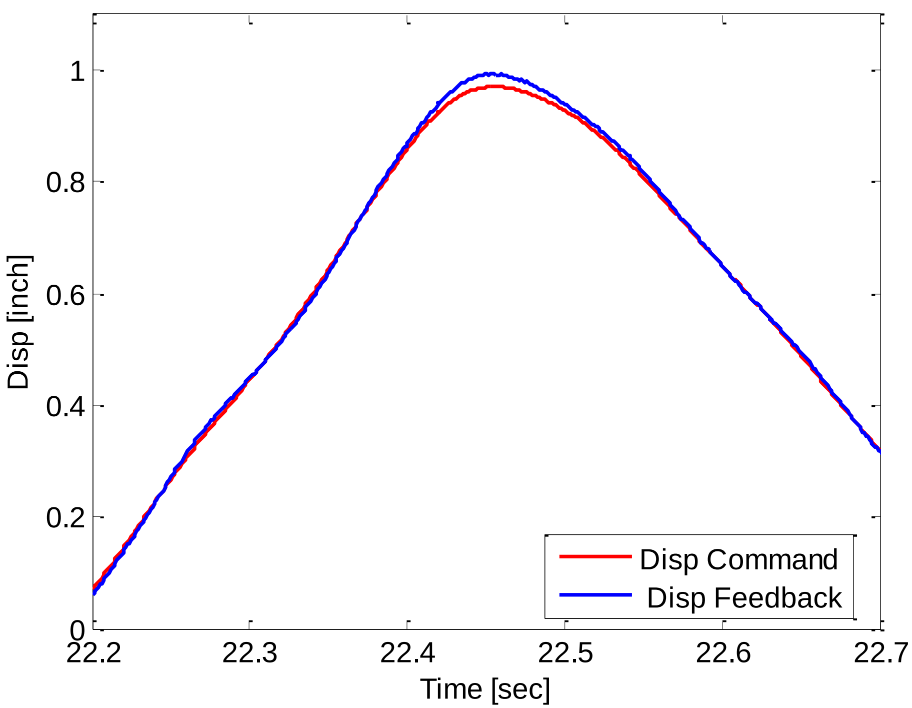
Response Enhancement

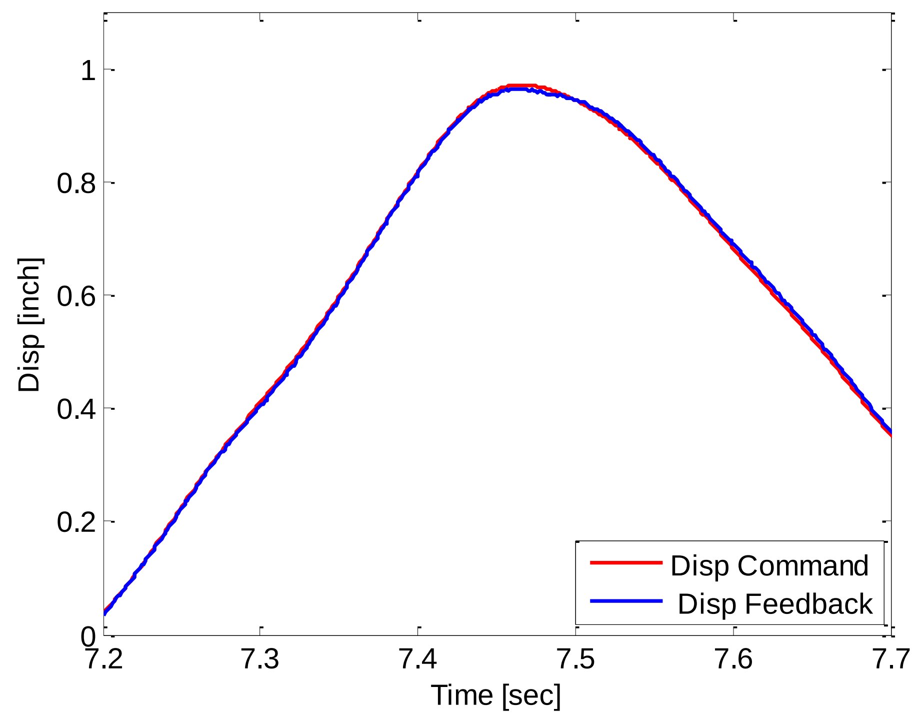


Response Enhancement

Displacement Tracking

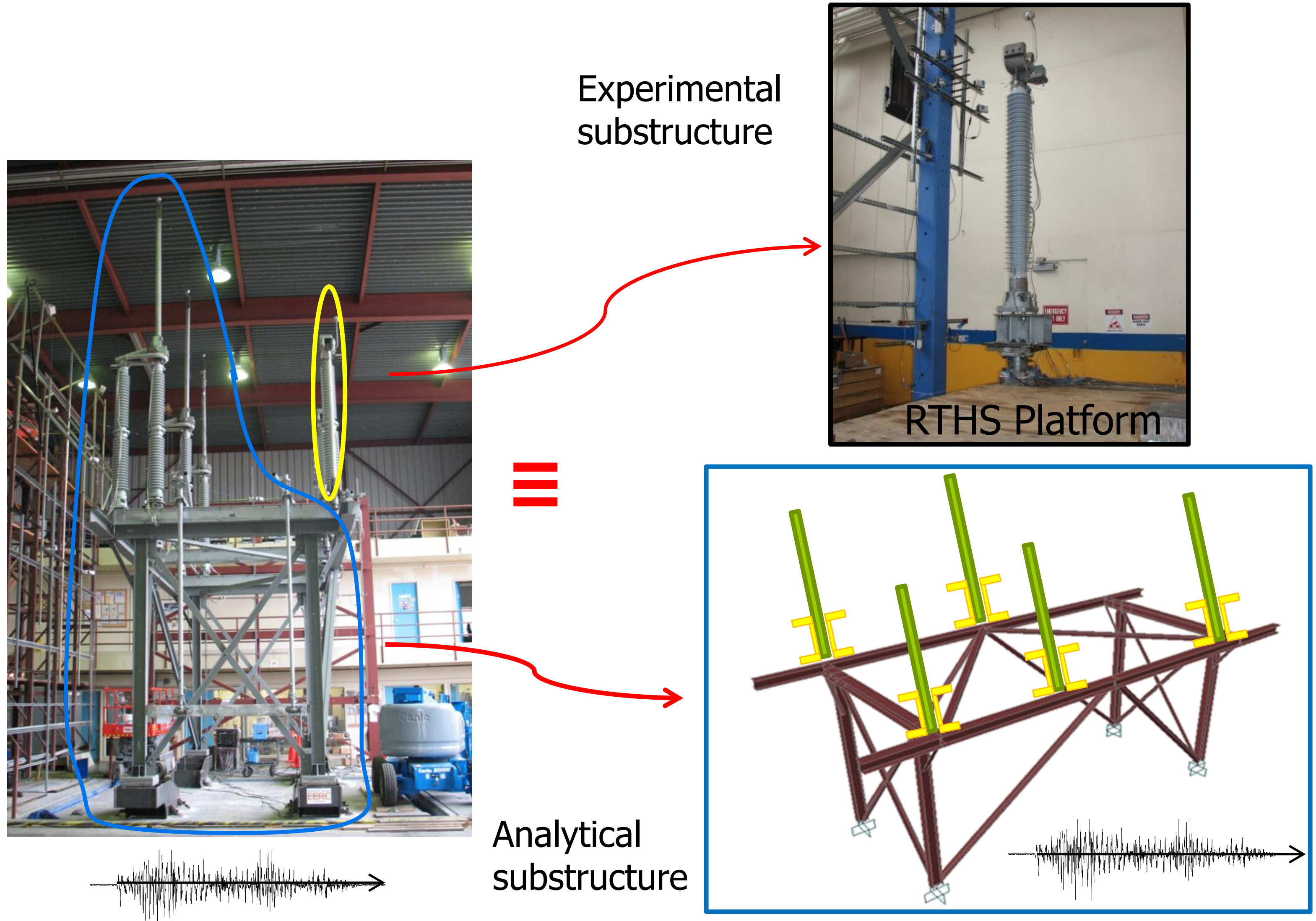


STS



TVC

RTHS-TVC Validation Application



RTHS-TVC Validation Application: Other Features

- ✓ RTHS compatible integrator: Alpha-OS
- ✓ Analysis Type in OpenSees: Multi-support ground motion

  Required in order to apply total displacements to the table
- ✓ Three dimensional analytical substructure
- ❑ # of DOF (n): 223, stiffness matrix bandwidth (b): 143
- ❑ b for a 2D system with similar n: 53
- ❑ $\boxed{\mathbf{k}_{\text{eff}}}\Delta\mathbf{u}_{i+1} = \mathbf{p}_{\text{eff}}$ # of operations to solve the linear system of equations α nb^2 "system UmfPack;
- ✓ An efficient linear sytem solver: "algorithm Linear –factorOnce;"

  Factorization of the coefficient matrix only once at the beginning of the simulation

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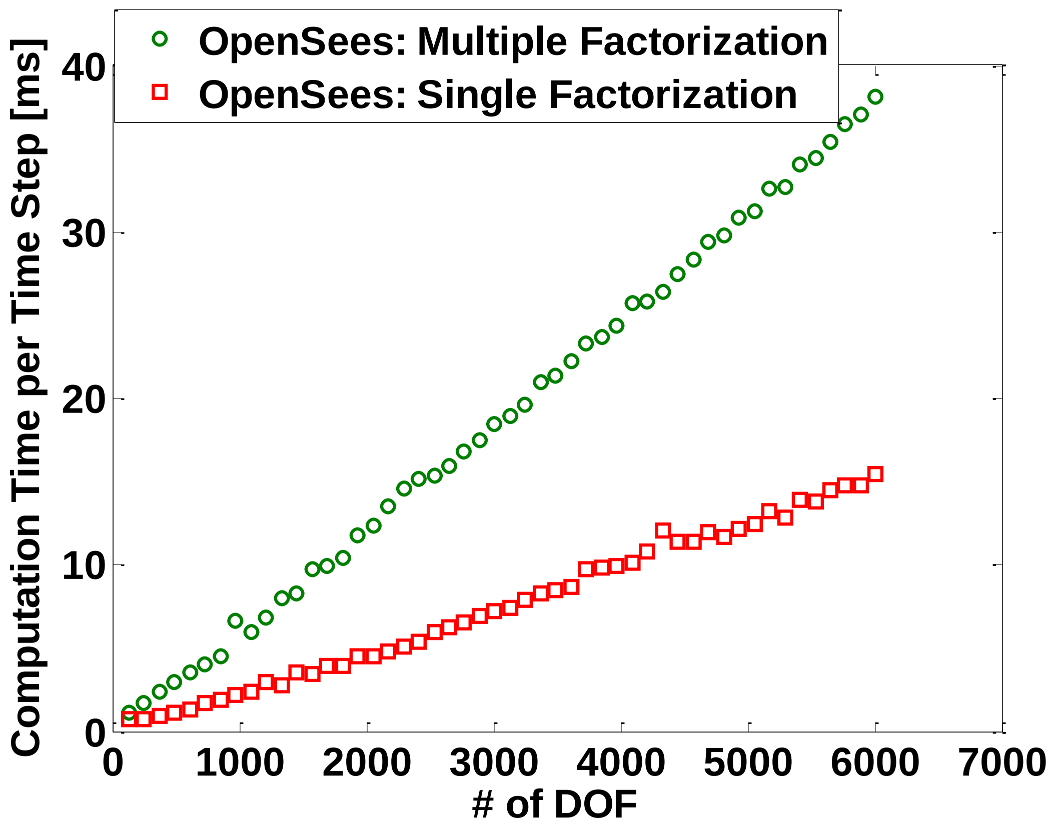
RTHS-TVC Validation Application: Other Features

Reduction of computation duration due to the efficient linear system solver



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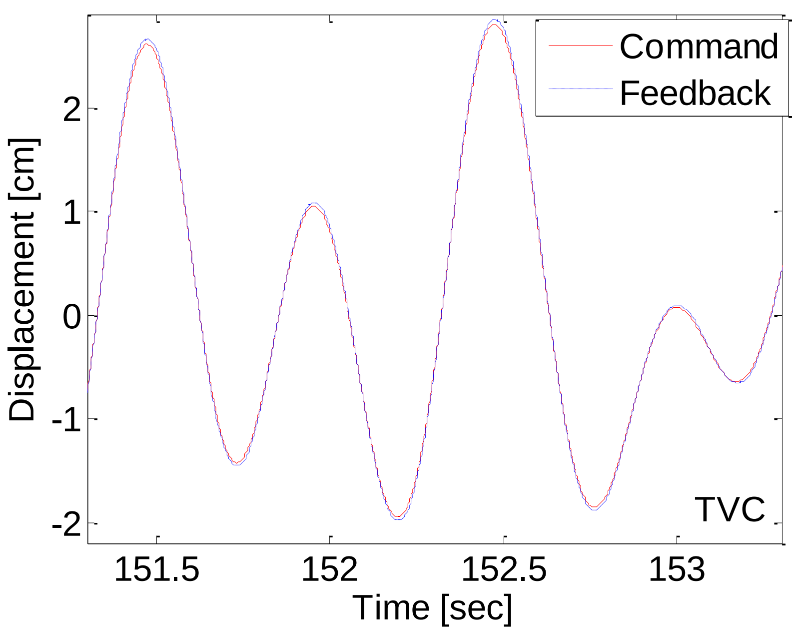
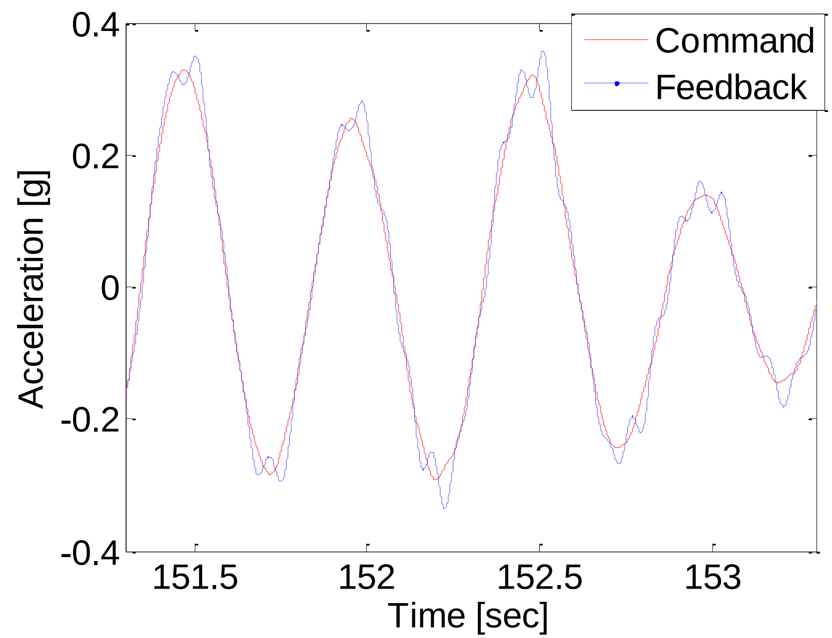
RTHS-TVC Validation Application

Displacement and Acceleration Tracking with TVC





Displacement

Acceleration

RTHS of Interconnected Equipment

Connected equipment in an electrical substation with conductor cables

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RTHS of Interconnected Equipment: Multiple Shaking Tables

RTHS with two tables using TVC

RTHS Platform
(Big shaking table)

Small shaking table

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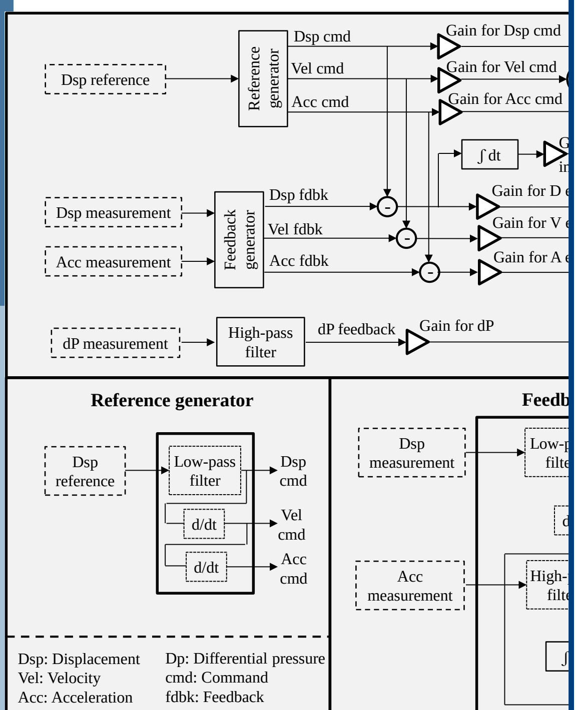
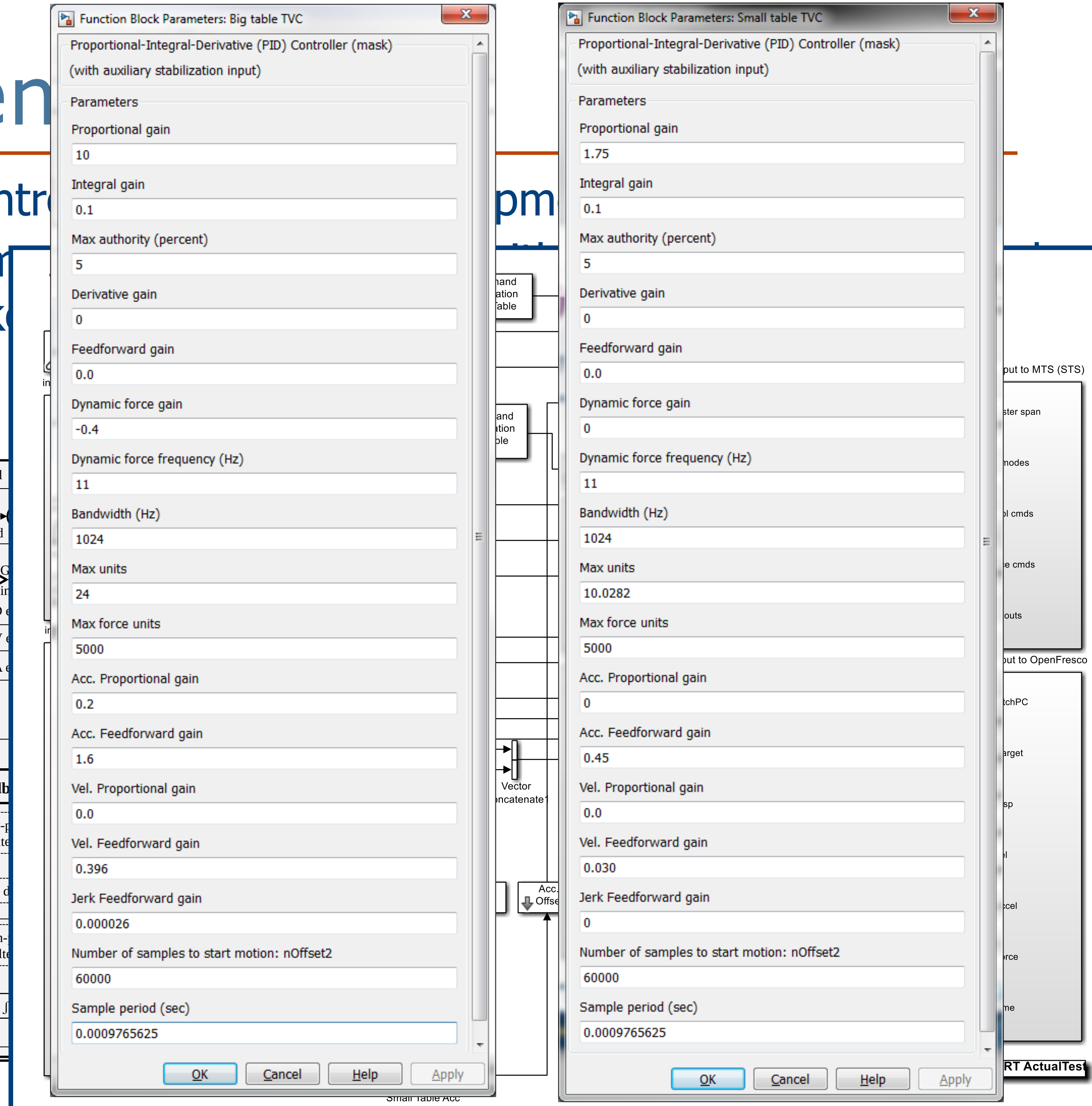
TVC Implen

Three Variable Contr ... pm

6. Improve the m ...
the small shak ...





Function Block Parameters: Big table TVC / Function Block Parameters: Small table TVC

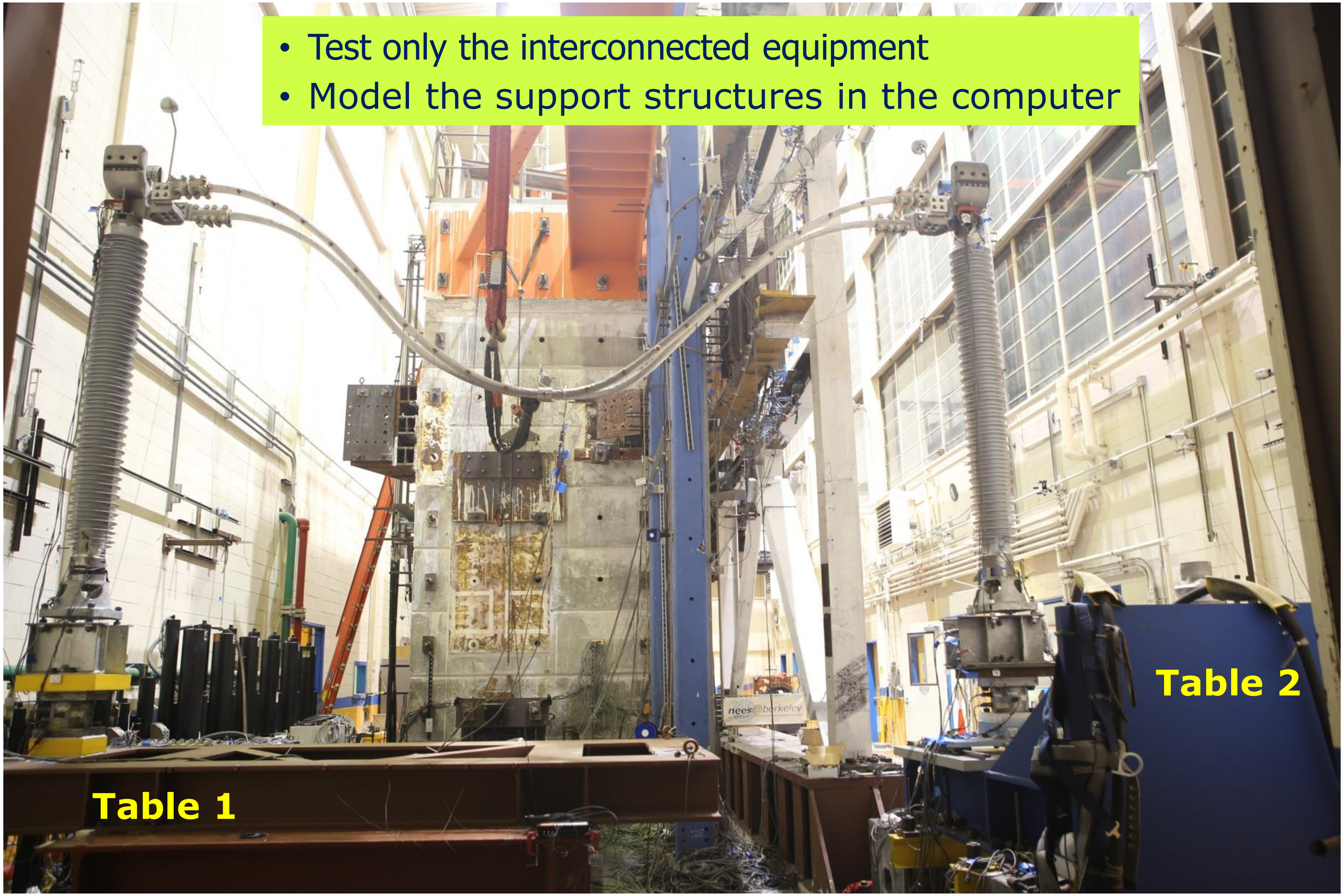
Proportional-Integral-Derivative (PID) Controller (mask)
(with auxiliary stabilization input)

Parameters

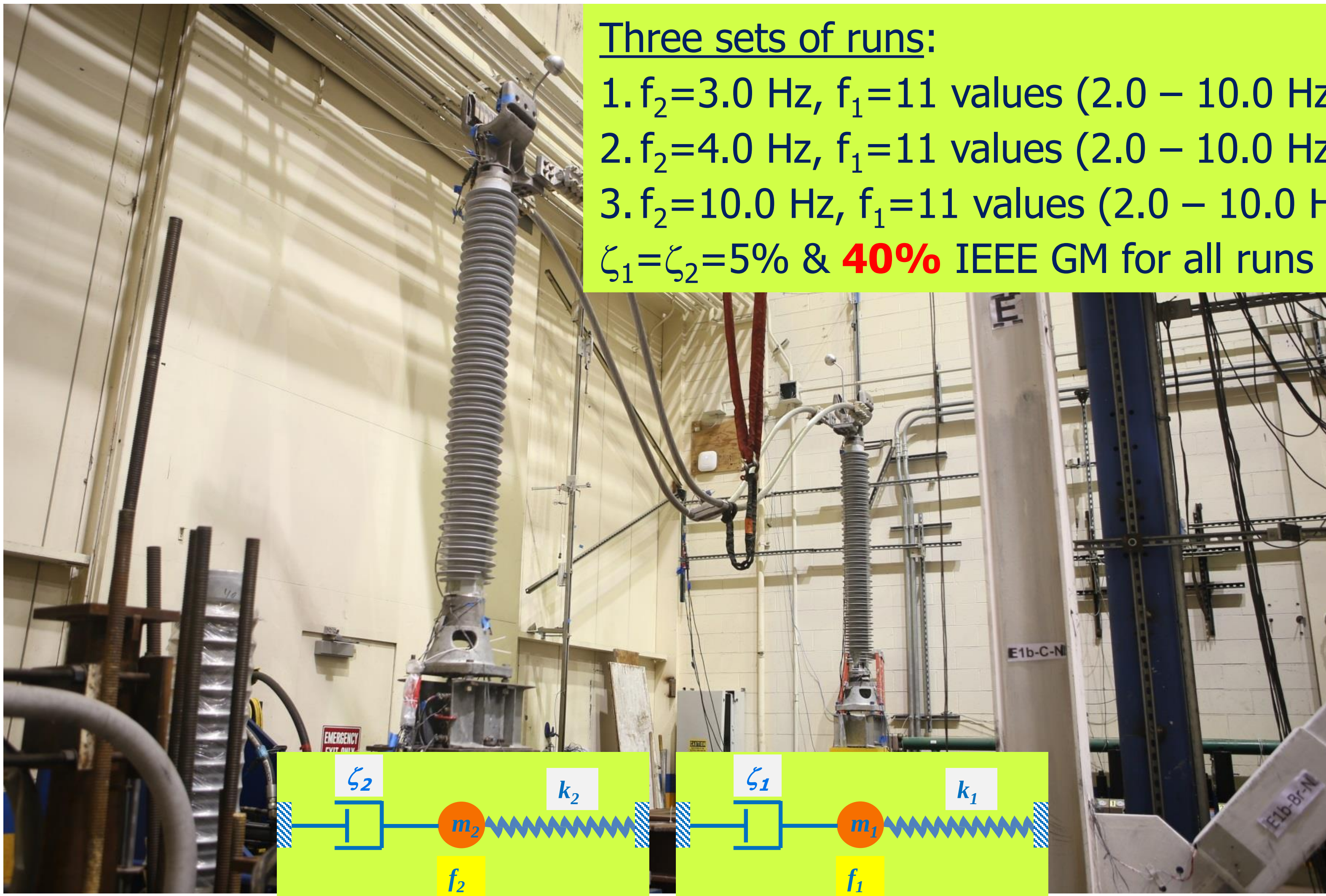
Parameter	Big table TVC	Small table TVC
Proportional gain	10	1.75
Integral gain	0.1	0.1
Max authority (percent)	5	5
Derivative gain	0	0
Feedforward gain	0.0	0.0
Dynamic force gain	-0.4	0
Dynamic force frequency (Hz)	11	11
Bandwidth (Hz)	1024	1024
Max units	24	10.0282
Max force units	5000	5000
Acc. Proportional gain	0.2	0
Acc. Feedforward gain	1.6	0.45
Vel. Proportional gain	0.0	0.0
Vel. Feedforward gain	0.396	0.030
Jerk Feedforward gain	0.000026	0
Number of samples to start motion: nOffset2	60000	60000
Sample period (sec)	0.0009765625	0.0009765625

OK Cancel Help Apply

RTHS of Interconnected Equipment: RTHS Setup



RTHS of Interconnected Equipment: Test Matrix



<u>Three sets of runs</u>:

1. f_2=3.0 Hz, f_1=11 values (2.0 – 10.0 Hz)
2. f_2=4.0 Hz, f_1=11 values (2.0 – 10.0 Hz)
3. f_2=10.0 Hz, f_1=11 values (2.0 – 10.0 Hz)

$\zeta_1=\zeta_2$=5% & **40%** IEEE GM for all runs

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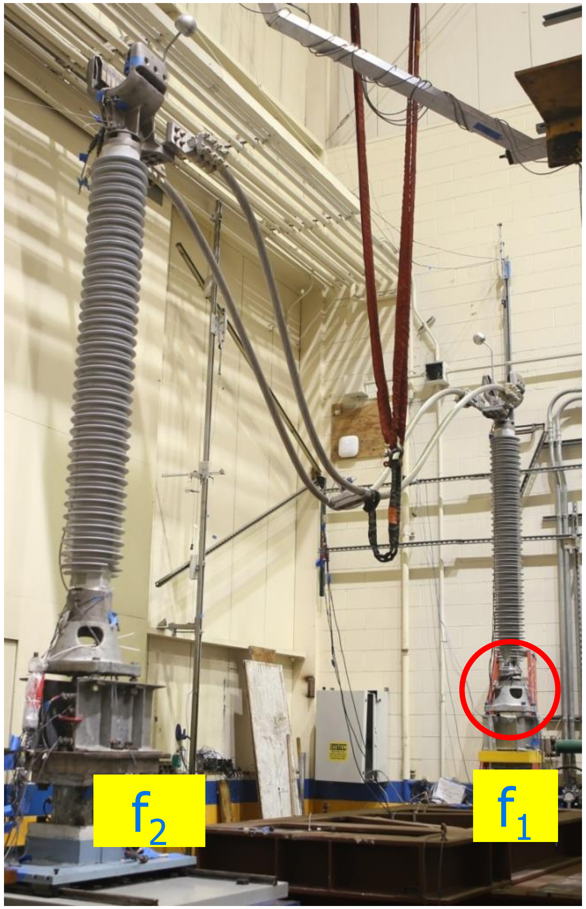
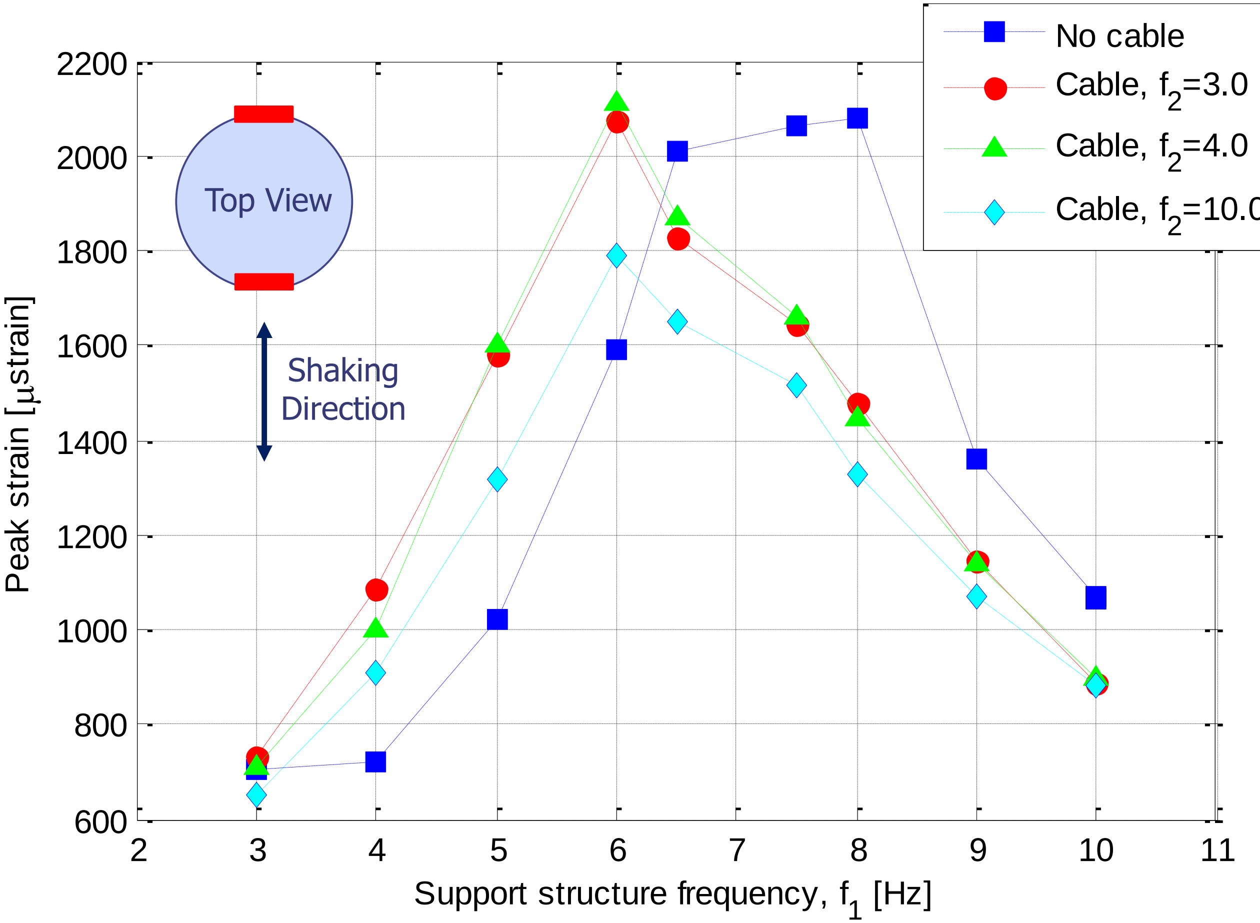
RTHS of Interconnected Equipment: Results





For flexible support structures, f_1<6 Hz → Testing w/o cable **underestimates** the response.

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Thank You

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