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

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Outline

<u>Part I</u>: 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



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



Conceptual Investigation



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Simulation Errors Lecture in Yesterday's Morning Session

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



Analytical Investigation: MATLAB



Analytical Investigation: OpenSees

😎 ZeroLengthD.cpp - Mi	rosoft Visual Studio Academic	
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```
int
```

```
ZeroLengthD::update(void)
 {
     double strain;
     double strainRate;
     // get trial displacements and take difference
     const Vector& disp1 = theNodes[0]->getTrialDisp();
     const Vector& disp2 = theNodes[1]->getTrialDisp();
     const Vector& vel1 = theNodes[0]->getTrialVel();
     const Vector& vel2 = theNodes[1]->getTrialVel();
     const Vector& dispD1 = disp1 - vel1 * delay;
     const Vector& dispD2 = disp2 - vel2 * delay;
     Vector diff = dispD2 - dispD1;
     Vector diffy = vel2 - vel1:
     if (d0 != 0)
         diff -= *d0:
     if (v0 != 0)
```

- ✓ Time delay is introduced in OpenSees for several elements including a zerolength element and a force based beam-column element.
- \checkmark 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	TuningError compensation methods
RTHS in shaking table configuration	Displacement, Velocity, Acceleration	Three Variable Control





Background



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



Existing Controller:

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

Structural Test S	ystem: Set_mtsNEES13RTHS_2012_simulinkco	ntroller.set
File Calibratio	n Configuration Operation View Service	
HPS On (2) HSM 1 2 3 4 5 6 7 8 9 HSM Lo (2) HSM Hi (2)	Interlocks Enabled Reset Image: Constrained Program Scrammet Image: Constrained Image: Co	Master gain 100 % Image: Stop Run Pause Abort

- 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 ¹³
- Digital Readouts





TVC block diagram as implemented in a Simulink model





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



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

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.

Three Variable Control (TVC) Implementation Phases:

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





Three Variable Control (TVC) Mo4. Improve the model to move motion signal



Function Block Parameters: Big table TVC	
Proportional-Integral-Derivative (PID) Controller (mask)	
(with auxiliary stabilization input)	
Parameters	
Proportional gain	
10	
Integral gain	
0.1	ES.
Max authority (percent)	
5	with a ground
Derivative gain	
0	
Feedforward gain	
0.0	
Dynamic force gain	
-0.4	
Dynamic force frequency (Hz)	
11	
Bandwidth (Hz)	
1024	E
Max units	
24	
Max force units	
5000	
Acc. Proportional gain	output to scramnet
0.2	
Acc. Feedforward gain	
1.6	Assemble valve cmd
Vel. Proportional gain	
0.0	
Vel. Feedforward gain	output to scramnet
0.396	Assemble
Jerk Feedforward gain	
0.000026	
Number of samples to start motion: nOffset2	
60000	
Sample period (sec)	
0.0009765625	
	<u>y</u>



PEER HS System



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

Parai	neter	Shaking Table	RTHS
	P-gain	10	10
	I-gain	0.1	0.1
Displacement	Integral authority	5	5
	F-gain	0	0
	Full range	24	24
	P-gain	0.1	0.04
Acceleration	F-gain	0.36	0.33
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	P-gain	0	0
Velocity	F-gain	0.5	0.5
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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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Crossover filter	Damping ratio	0.03	0.03

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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Acceleration Feedback



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Acceleration Feedback



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Acceleration Feedback



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Displacement Tracking



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
- $\mathbf{u}_{i+1} = \mathbf{p}_{eff} \# \text{ of operations to solve the linear system of equations } \alpha \text{ nb}^2 \qquad \text{``system UmfPack;}$
- ✓ An efficient linear sytem solver: "algorithm Linear –factorOnce;" Factorization of the coefficient matrix only once at the beginning of the simulation



RTHS-TVC Validation Application: Other Features

Reduction of computation duration due to the efficient linear system solver



RTHS-TVC Validation Application

Displacement and Acceleration Tracking with TVC



RTHS of Interconnected Equipment





RTHS of Interconnected Equipment: Multiple Shaking Tables

RTHS with two tables using TVC





Small shaking table



RTHS Platform (Big shaking table)



I Function Block Parameters: Big table TVC Proportional-Integral-Derivative (PID) Controller (mask) (with auxiliary stabilization input) Parameters Proportional gain 10 10 Integral gain 0.1 Max authority (percent) 5 Derivative gain 0 Feedforward gain 0.0 Dynamic force gain -0.4 Dynamic force frequency (Hz) 11 Bandwidth (Hz) 1024 Max nits 24 Max force units 5000 Acc. Feedforward gain 0.2 Acc. Feedforward gain 0.396 Derk Feedforward gain 0.000026 Number of samples to start motion: nOffset2 60000 Sample period (sec) 0.0009765625			
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Function Block Parameters: Small table TVC	×	n
Proportional-Integral-Derivative (PID) Controller (mask)		1
(with auxiliary stabilization input)		
Parameters		
Proportional gain		
1.75	- 11	
Integral gain		
0.1	- 11	
Max authority (nercent)		
5		
Derivative gain		
	- 11	
Eedforward gain		
	- 11	put to MTS (STS)
Dynamic force gain		
	- 11	ster span
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Acc. Proportional gain	- 11	in the PC
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0.030	- 11	
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Number or samples to start motion: nOffset2		rce
Sample period (sec)	_	ne
0.0009703023	-	
OK Cancel Help	Apply	RT ActualTest

RTHS of Interconnected Equipment: RTHS Setup



RTHS of Interconnected Equipment: Test Matrix



RTHS of Interconnected Equipment: Results



For flexible support structures, $f_1 < 6 \text{ Hz} \rightarrow \text{Testing w/o cable underestimates}$ the response.

Thank You

