Evaluating Parameter Estimation of Stability and Accuracy of Structural Property-Dependent Integration Algorithms

Manuel Ramirez*, Nathan Carlson*, Oskar Granados*, and Madoka Oyama*
Graduate Mentor: Maryam Khan** /Advisor: Cheng Chen, Ph.D.**
*Cañada College 4200 Farm Hill Blvd. Redwood City, CA 94061
**San Francisco State University: Dept. of Engineering 1600 Holloway Ave. San Francisco, CA 94132

Abstract

Real Time Hybrid Simulation (RTHS) is a viable alternative to using shake tables for testing a structure's response to seismic loading. RTHS analyzes both physical and numerical substructures to predict the behavior of the entire structure; it is impossible to know the exact mass, damping, and stiffness of the complete structure. The CR and KR-α Integration algorithms have been widely used to integrate the physical model and analytical model during RTHS. Due to the nature of these algorithms, certain parameters can cause the simulation to be unstable and inaccurate. To effectively use RTHS the structural properties can be estimated. In this research MATLAB and Simulink were used to investigate the structure's response upon seismic loading and explore how varying the parameters affected the stability and accuracy of these integration algorithms. It was found that the error in the mass estimation minimally affected the accuracy and stability of RTHS, while error in the damping and stiffness estimations significantly affected the stability but not the accuracy. Using the results from this research, the effect of parameter estimation on the stability and accuracy of structural property dependent integration algorithms thus providing a guideline for general application of these algorithms in structural testing involving rate-dependent devices.

Background

- With RTHS the structure is modeled by a physical and computational substructure.
- The combination of physical testing and computational modeling, gives a more through examination of the response on civil structures upon seismic loading while reducing the costs and means of an entirely physical structure.
- The physical component consists of a segment of the structure including the servo hydraulic actuators, while the rest of the structure is modeled mathematically through a computational system.
- Explicit integration algorithms, such as the CR-Algorithm and the KR-α are used for solving the dynamic equations of motion. The servo-hydraulic actuator causes a delay that impacts the results which can lead to exponential instability.
- Using the PEERS database, ground motion data of various earthquake histories is processed using MATLAB and Simulink to measure and compare the command and delayed response.
- Different parameters of a system are tested using different ground motions for accuracy.

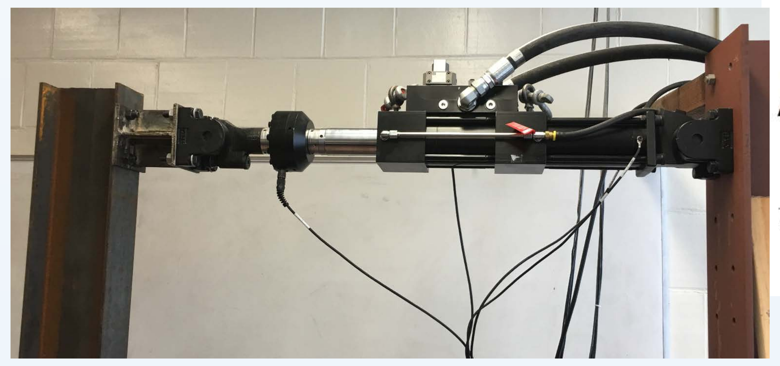


Figure 1. Set up in the Structural and Earthquake Engineering Laboratory at SFSU with servo hydraulic actuator set test performance of B-C moment.

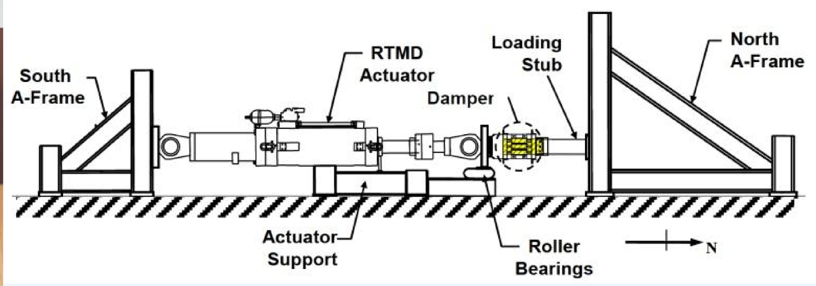


Figure 2. Servo-hydraulic Actuator Components

Objective

- Testing the effectiveness of the system by estimating parameters in RTHS.
- Analyzing RTHS using different ground motion data from previous earthquakes.
- Discovering the impact of using different algorithms.
- Able to predict parameters of RTHS with minimal error %.

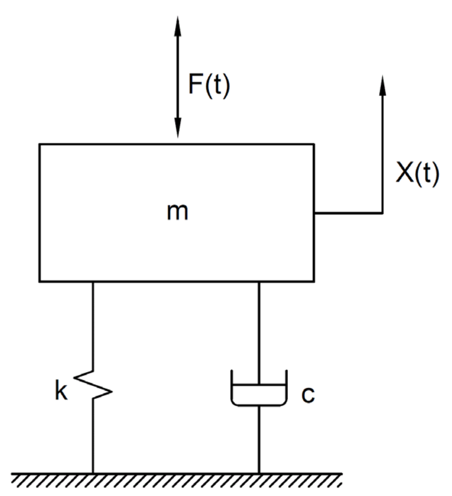


Figure 3: Model of SDOF structure upon Excitation, F(t) with Dampening and Stiffening elements

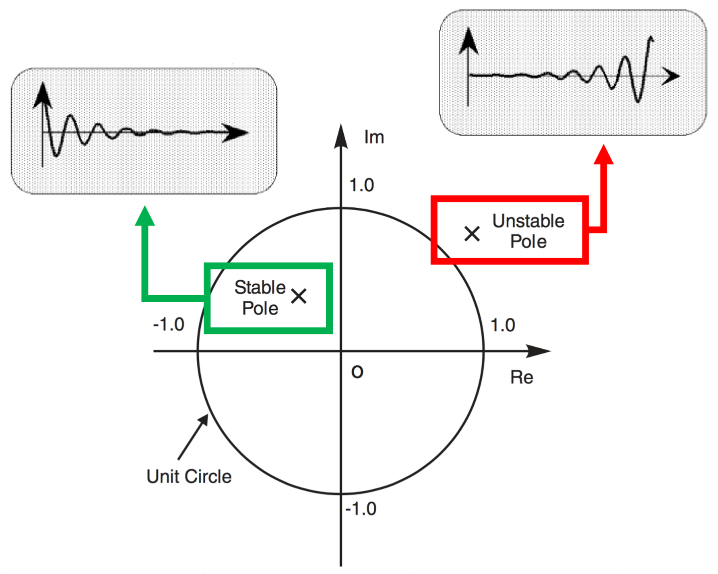
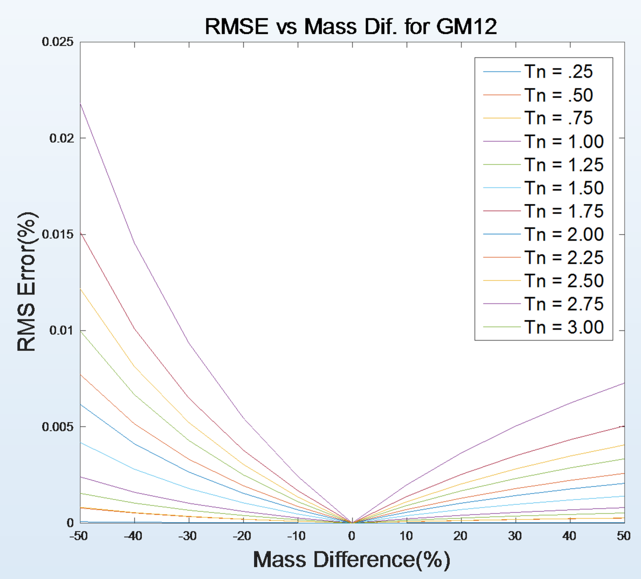
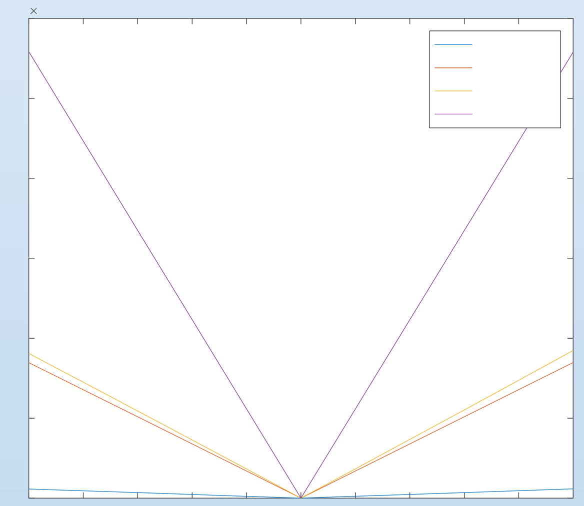


Figure 4: Plotting poles and zeros of and z-domain.

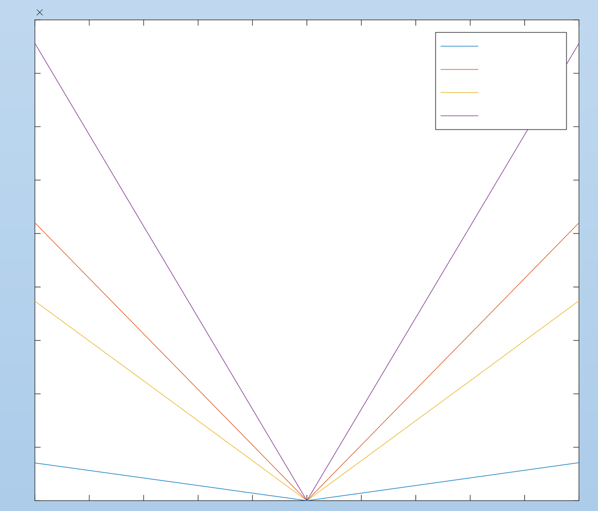
Accuracy



(a)



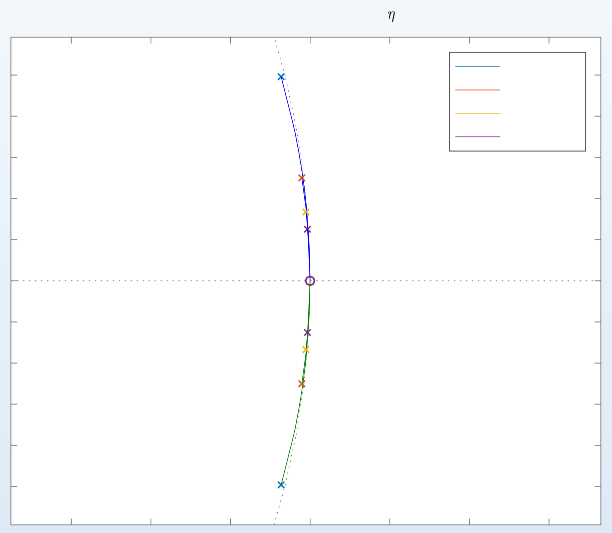
(b)



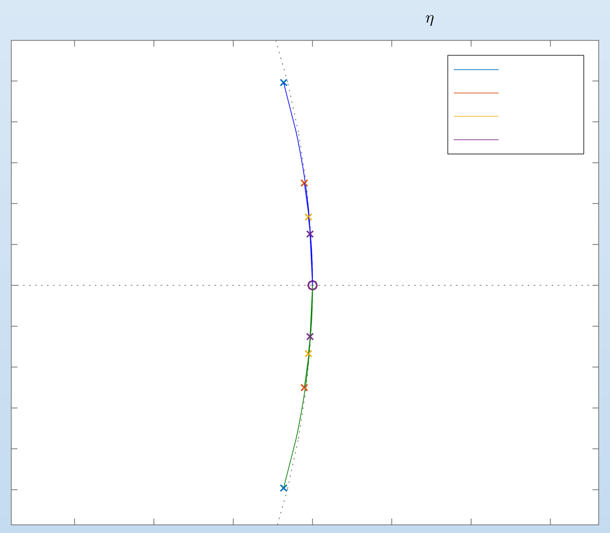
(c)

Figure 5: RMSE
(a) Mass
(b) Damping
(c) Stiffness

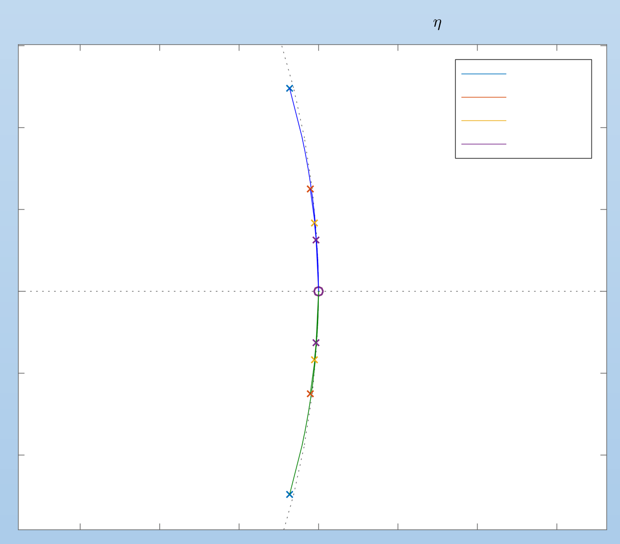
Stability



(a)



(b)



(c)

Figure 6: Root Locus
(a) Mass
(b) Damping
(c) Stiffness

Methodology

Using the equation of motion for a SDOF system (figure 1), the transfer function for the integration algorithm can be derived.

$$F(t) = m\ddot{X}(t) + c\dot{X}(t) + kX(t) \qquad \text{Eqn. 1}$$

Estimated parameters for the CR algorithm

Numerator		Denominator	
n_2	0	d_2	$k_{est}\Delta t^2 + 2c_{est}\Delta t + 4m_{est}$
n_1	$4\Delta t^2$	d_1	$-8m_{est} + 2k_{est}\Delta t^2$
n_0	0	d_0	$k_{est}\Delta t^2 - 2c_{est}\Delta t + 4m_{est}$

$$\alpha_1 = \alpha_2 = \frac{4m_{est}}{k_{est}\Delta t^2 + 2c_{est}\Delta t + 4m_{est}}$$

Equation for the CR Algorithm, with estimated parameters, is as follows:

$$G(z) = \frac{X(z)}{F(z)} = \frac{n_2 z^2 + n_1 z + n_0}{d_2 z^2 + d_1 z + d_0} \qquad \text{Eqn. 2}$$

RMSE:
Using root-mean-square-error (RMSE) is the best way to show larger differences (taking into account the outliers) than other methods by measuring the quality and predictability of the models.

Root Locus: A graphical analysis that shows the trajectory of poles, with divergence of stable and unstable poles. (Figure 4).

Results

- The accuracy is not significantly affected by low measures of natural periods while estimating mass, damping and stiffness. However, based on Figures 5 (a), (b) and (c) significant higher errors are expected for higher periods as the damping estimation increases.
- The system is stable as shown in Figure 6 (a), (b), (c) for small estimation limits starting on 1kg of mass, 0.68 Ns/m and 295.84 N/m for damping and stiffness respectively. Nonetheless, it is necessary the further investigation to determine an exact boundary for estimations on stiffness and damping, in order to remain between the stable region.

Conclusion and Future Study

Using our research, engineers know that when conducting RTHS, estimating structural properties does not have to be incredibly precise to get accurate results. RTHS is very useful when retrofitting buildings with dampers by testing substructures when predicting a structure's response to seismic loading.

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