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Exploration of Uni-axial Shaketable Dynamics

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Abstract

Hybrid simulation has enabled engineers to better study dynamic structural behavior, however; the very structural dynamics in which it is based on are site specific. This project aims to substantiate a transfer function model of the shaking table system between valve command and actual system trajectories. Transfer function models of differential pressure, acceleration, and table displacement will take into account the hypothesized influences of hydraulic fluid temperature, viscosity, and servo valve command. These issues regarding the modeling of shaking table systems have been reported and should be explored before further tests are prepared. Once the behavior of the shaketable is modeled, it will facilitate hybrid testing involving the shaketable and a two story scaled-down structure. A well defined model enhances the understanding of the physical portion of the hybrid system. The physical component of the hybrid system can then be programmed to achieve the desired trajectories under sinusoidal excitation using a uni-axial shake table.

1. Introduction

In an effort to explore and model shaketable dynamics for future hybrid testing, the repeatability of frequency response between valve command and table displacement, differential pressure, and acceleration will be investigated. Following the development of a mathematical transfer function model, hybrid testing aims to have a shaking table mimic the motions of the first floor of a two story scaled structure under sinusoidal excitation. A well defined model generated from repeatable results during this project will play an integral role in the control of shaketable trajectory. The input for all frequency response testing is valve command as the servo valve governs table movement. Figure 1 illustrates the tracking process of future hybrid testing. Knowing the response between the input and actual displacement ensures correct tracking of the hybrid system.

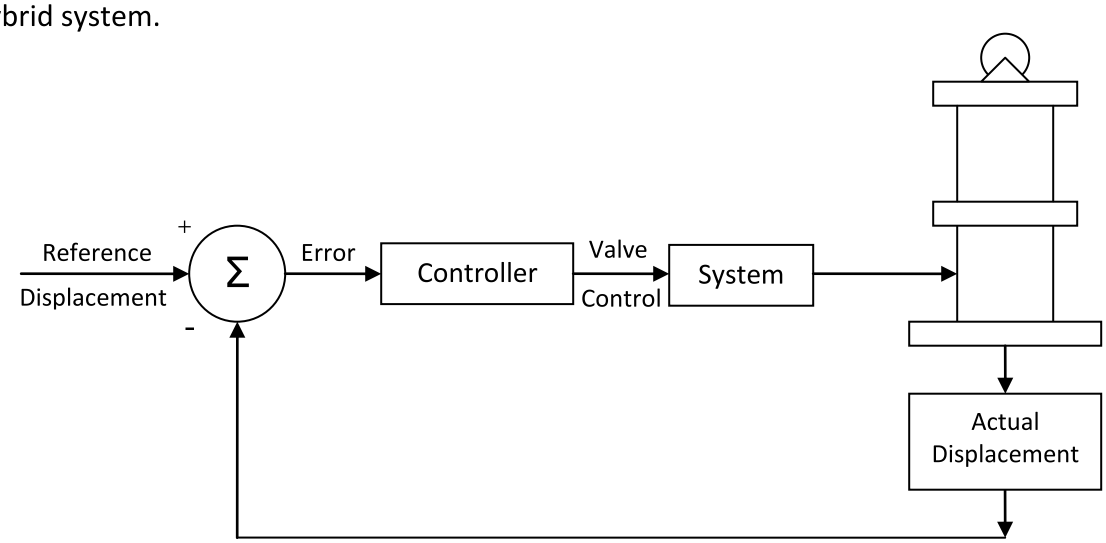

Figure 1: Tracking of Hybrid System

A hybrid system is composed of a physical system that can be tested using various excitation devices and a virtual system that is a component of the total system absent from testing and modeled in real time on a computer. With hybrid simulation being a relatively new subject, much is left to explore. Previous research has mainly focused on simulating noncritical components of structural tests[1]. By replacing the first floor of the structure with a dynamic shaking table, the interactivity of a hybrid simulation will be taken a step further. Instead of replacing physical components with a computer simulation, a computer simulation will run an alternative mechanical component which will respond to sinusoidal excitation analogous to the full system.

With the ability to eliminate an entire floor from the physical testing setup, future hybrid testing will open the door to large scale multistory testing in physically limiting facilities and a deeper understanding of hybrid simulation. Difficulty arises in developing a thorough understanding of the uni-axial shaking table environment. For the shaketable to correctly mimic the trajectories of the first floor, the interaction between the user, controller, and shaketable must be flawless. Since most of the technology involved was not created for this purpose, the setup must first be tested for irregularities. These 'irregularities' in the response of the shaketable to various excitation will be the subject of this preliminary research. When repeatability of frequency response testing is achieved, a brief analysis of the capability of the shaketable transfer function model will follow. A uni-axial shaking table located at the University of Colorado Structures Lab will be the subject of this research.

2. Methodology

2.1 Experimental Setup

Figure 2: Shaking Table

Degrees of Freedom: 1 (Uni-axial)

Weight: 2160 lb

Capacity: 4000 lb

Surface Dimensions: 1.5m x 1.5m

Actuator Capability: 10,000 lb,16 in stroke, 30 gpm servo-valve.

Figure 3: Control Setup

Controls: The table can be controlled through an ***MTS 458 analog controller*** working harmoniously with a real time application on the user's host computer. **A National *Instruments PXI controller hub*** which converts the MTS 458 controller's analog signal to a digital one allows this harmonious linkage between the host application, the analog controller, and the shaketable.

2.2 Recording Frequency Response Data

Before the program may be used, one must first verify the host machine is connected to the Real Time (RT) Target. This can be done by turning off the RT controller hub and turning it back on. Connection will be established when the message "Shaketable Application Started" appears. Upon loading the Shake Table GUI, 4 windows will open: The real time networking device, data recorder, oscilloscope, and a function generator (pictured on following page).

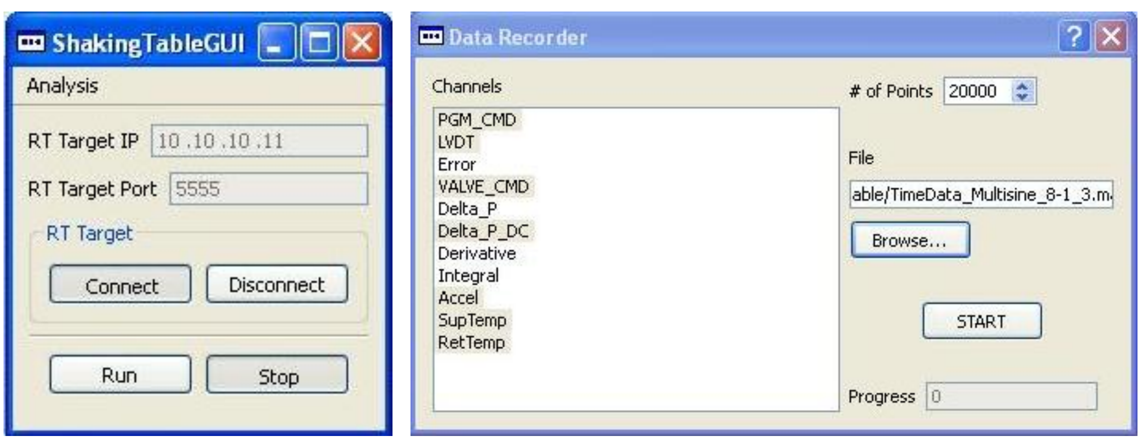

Figure 4: Shaking Table User Interface

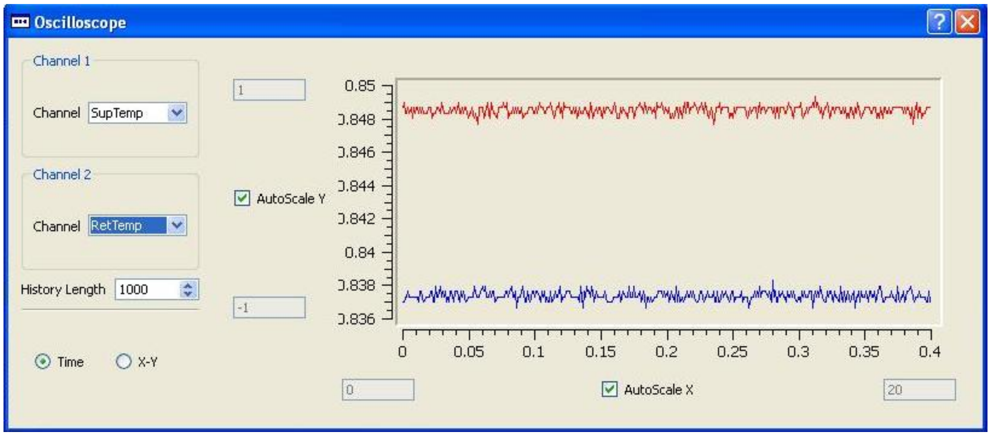

Figure 5: Oscilloscope

Frequency response data was acquired using three methods. A single sine transfer function analyzer allows the user to record three output channels simultaneously per input and plots the response for a single frequency. To record frequency response using this method, the user must connect to the RT target and select ‘run’ on the GUI. Then, the analysis toolbar is brought up and ‘Single Sine’ selected. The analysis data block size, governed by equation 1, is dependent on the number of cycles the user wishes to analyze.

$$\frac{\#CyclesDesired \cdot SamplingFrequency}{MeasuredFrequency} \qquad (1)$$

Since the sampling frequency is fixed at 1000 Hz, if the user wanted to analyze 5 cycles at a frequency of 10 Hz, the desired analysis data block size would be 500. In the case of this experiment, a frequency range of 0-128 Hz was used and the input channel was fixed to valve command. Output channels of interest in this research were valve displacement, differential pressure, and acceleration.

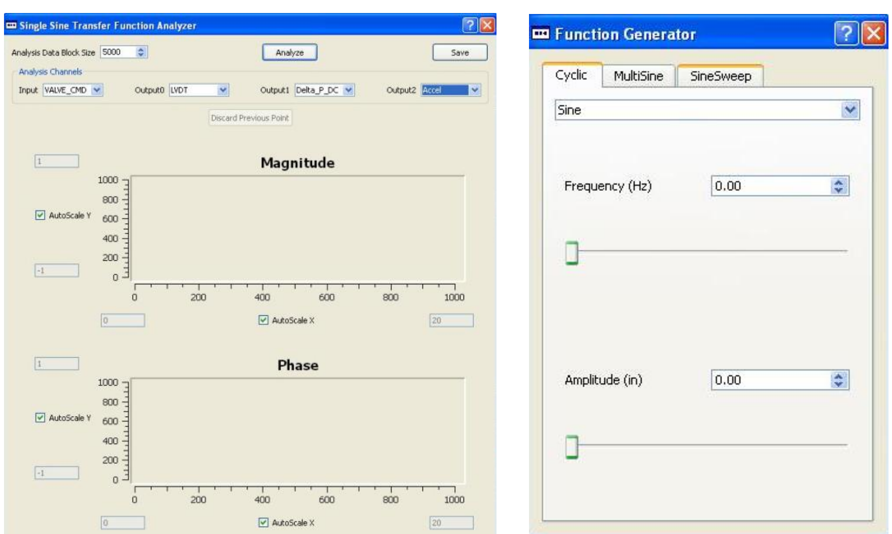

Figure 6: Single sine Transfer Function Analyzer and Function Generator

Single-sine data was recorded in intervals of ½ Hz from 0-32 Hz for preliminary testing. When analyzing the shaketable model, varying intervals from 0-128 Hz were recorded to satisfy graphical requirements. For each frequency, seven channels of time data were recorded: program command, valve displacement, valve command, differential pressure, acceleration, and actuator fluid supply and return temperature. This data allowed offline creation of frequency response plots, which are believed to be more definitive than real time analysis.

Using the program's Multisine Transfer Function Analyzer, the desired range of frequencies is sequentially analyzed for a single input and output. For this experiment, 4096 Fast Fourier Transforms (FFT) was a constant throughout testing. The number of multisine frequencies was altered depending on the desired range of frequency excitation. Equation 2 defines the range of excitation:

$$\frac{(SamplingFrequency)}{(\#\,FFTpts)}\cdot(\#MSFrequencies) \qquad (2)$$

For example, inserting 512 multisine frequencies into the equation, $\frac{(1000Hz)}{(4096FFTpts)}\cdot(512)=125$, provides the user with excitation from 0-125 Hz.

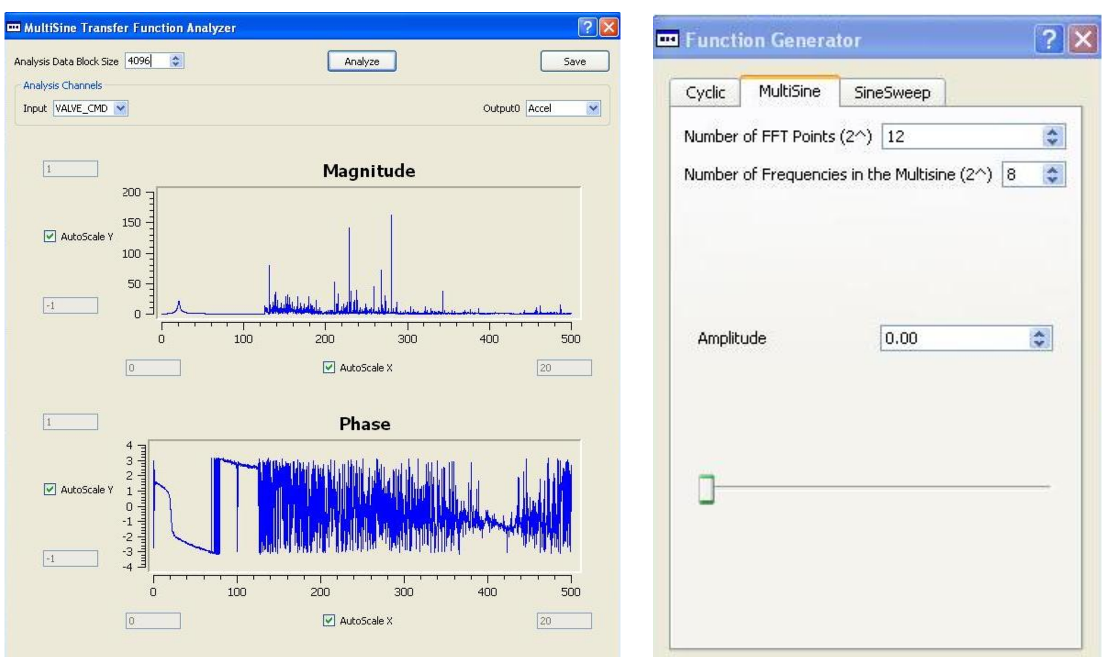

Figure 7: Multisine Transfer Function Analyzer and Function Generator

2.3 Verifying the Repeatability of Testing

Verifying the response of the table to various input frequencies reinforces the crucial repeatability factor of the experiment. If the response of the table differs from the programmed input, there will be no legitimate basis for comparison to strengthen the shaketable model. Small differences in damping ratios between singlesine and multisine tests were hypothesized to be temperature dependent. To test this hypothesis, 8 multisine tests were run at different temperatures holding all other inputs constant. All 8 frequency response tests between valve command and LVDT (Linear Variable Differential Transformer) were plotted on the same graph. Since amplitude directly relates to the damping ratio, peak amplitude was plotted against supply temperature to determine if a relationship exists. Assuming the increase in temperature between supply and return values was vastly due to friction; peak amplitude was also plotted against the difference between supply and return temperature. Frequency response at resonance was also plotted against valve command for 1 singlesine and 3 multisine tests to investigate a plausible relationship. It is also relevant to note that program command data stored in 'time data' files was analyzed prior to each test to verify the periodic nature of the sinusoidal input.

2.4 Analyzing Shaketable Model

The final step in the analysis of the uni-axial shaketable dynamics is the testing of its model. It was decided that time data captured while simultaneously analyzing single sine frequency response from 0-128 Hz was the best form of graphical analysis. When analyzing the shaketable model, data was recorded in intervals of ½ Hz from 0-32 Hz , 1 Hz from 33-60 Hz, and 4 Hz from 60-128 Hz. Intervals were chosen to best illustrate systematic changes in the Bode plots which mostly occur between 0-32 Hz. An existing mathematical transfer function can predict frequency response by substituting the complex number iω for s:

$$H(s) = \frac{b_0 + b_1(s) + b_2(s^2)..+b_m(s)^m}{(s)^l\left(a_0 + a_1(s)...+a_{n-1}(s^{n-1}) + s^n\right)} \qquad (3)$$

Thus the predicted response for frequency ω would be given as:

$$H(iw) = \frac{b_0 + b_1(iw_k)..+b_m(iw_k)^m}{(iw_k)^l\left(a_0 + a_1(iw_k)^n\right)} \qquad (4)$$

Knowing the accompanying measured value from the singlesine testing, $H_{meas}(iw_k)^n$, one implement the linear least squares approach in MATLAB to find $b_0 \ldots b_m$ and $a_0 \ldots a_{n-1}$ so that $H_{meas}(i\omega_k) \approx H(i\omega_k)$.

2.5 LabVIEW Architecture

Real time data acquisition was captured using LabVIEW developed software created by M.V. Sivaselvan (PhD). All data flows through four queues simultaneously where it is sorted and directed accordingly.

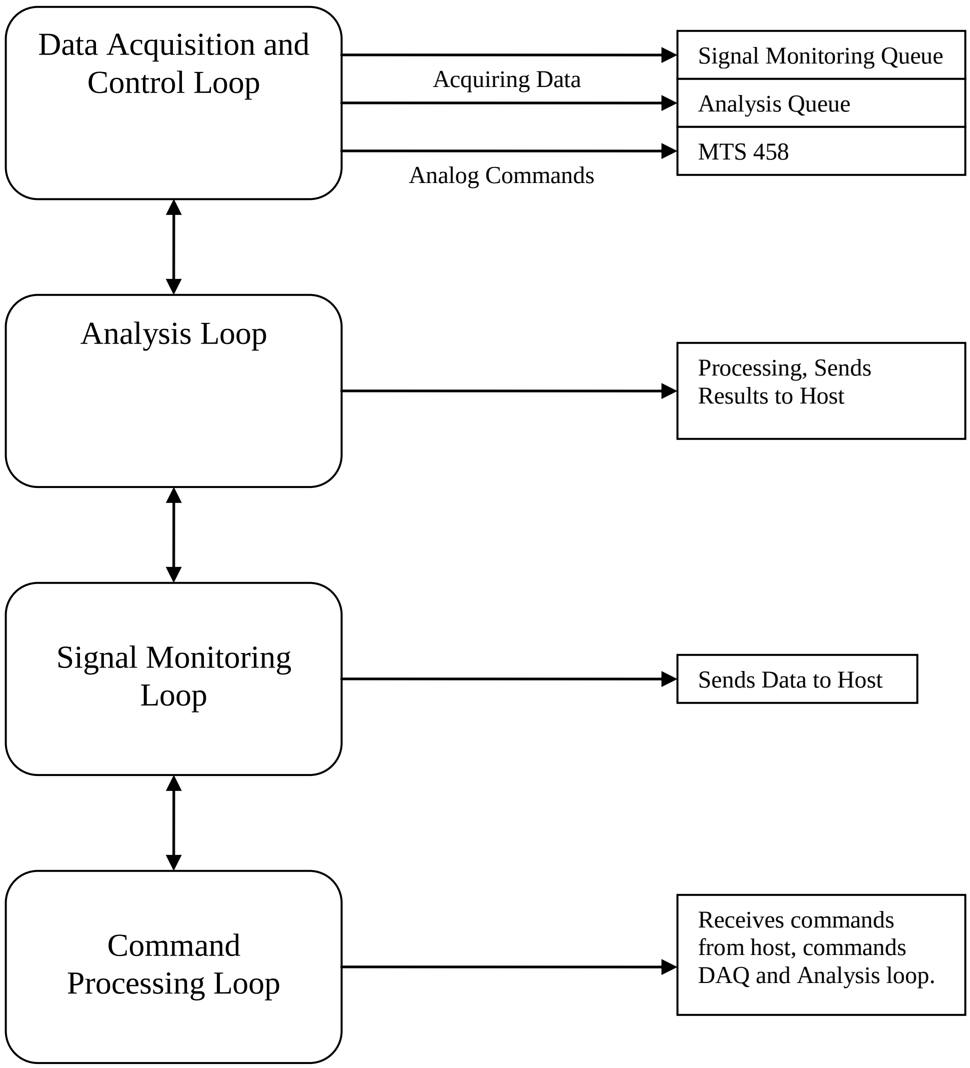

Figure 8: Labview Architecture

2.6 Collaboration

Portions of recorded and processed data were uploaded onto a Media Wiki[4] created and hosted by M.V. Sivaselvan (PhD). (http://shakthi.colorado.edu/mediawiki/index.php/Main_Page) (Restricted access)

3. Results

3.1 Hydraulic Fluid Analysis

When comparing frequency response data from singlesine and multisine tests, magnitude plots displayed a disparity between the damping ratios of each test. Specifically, multisine frequency response illustrated lower damping at most frequencies compared to singlesine tests. Multisine tests were done prior to singlesine measurement, thus the hydraulic fluid was at a cooler temperature. It was hypothesized that the cooler fluid temperatures produced a more viscous fluid that resonated more intensely than warmer, less viscous fluid. For this hypothesis to be true, multisine tests ran at different temperatures would clearly indicate an indirect relationship between amplitude and hydraulic fluid temperature and thus a direct relationship between damping and temperature.

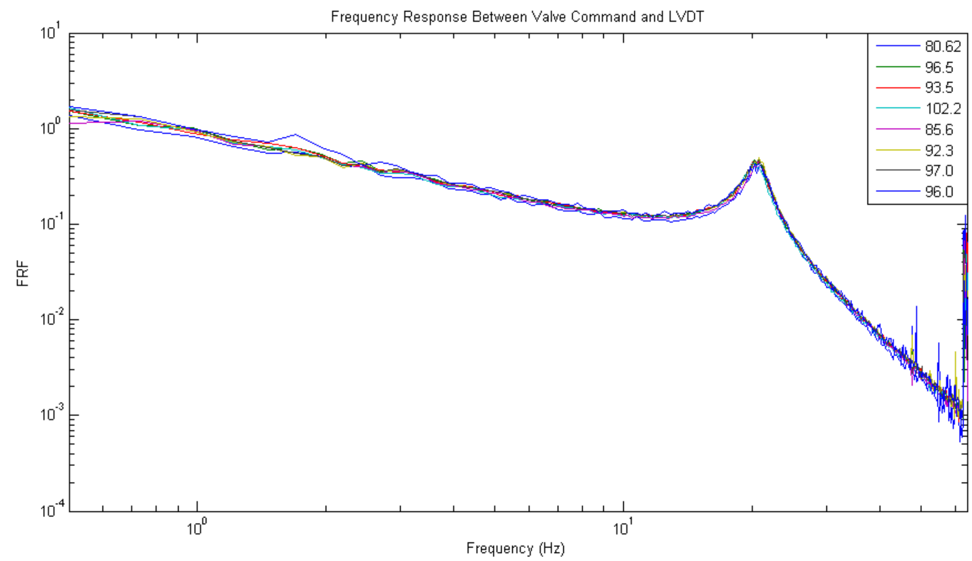

Figure 9: 8 FRF magnitude plots between valve command and LVDT

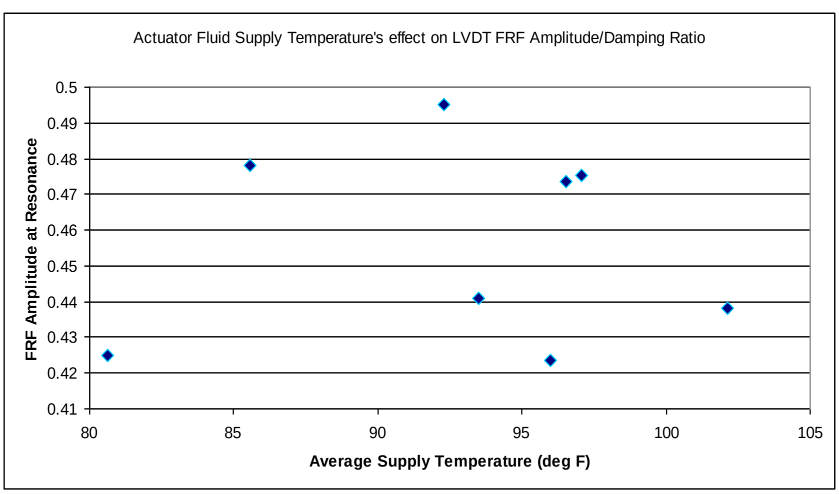

Figure 10: Hydraulic fluid supply temperature has little effect on system damping at resonance

Looking at the frequency response between valve command and LVDT in Figure 9, there does not appear to be any significant relationship between temperature and damping. Figure 10 confirms this finding with a closer look at the supply temperature's lack of an effect on resonance amplitude.

Friction generated by moving hydraulic fluid was also hypothesized to affect how the table responds to various frequencies of motion. Specifically, additional friction would impede the system and less damping would be necessary. Assuming the increase in temperature between supply and return temperatures was mostly due to friction, it was plotted against FRF amplitude at resonance in Figure 11 to see if damping was affected.

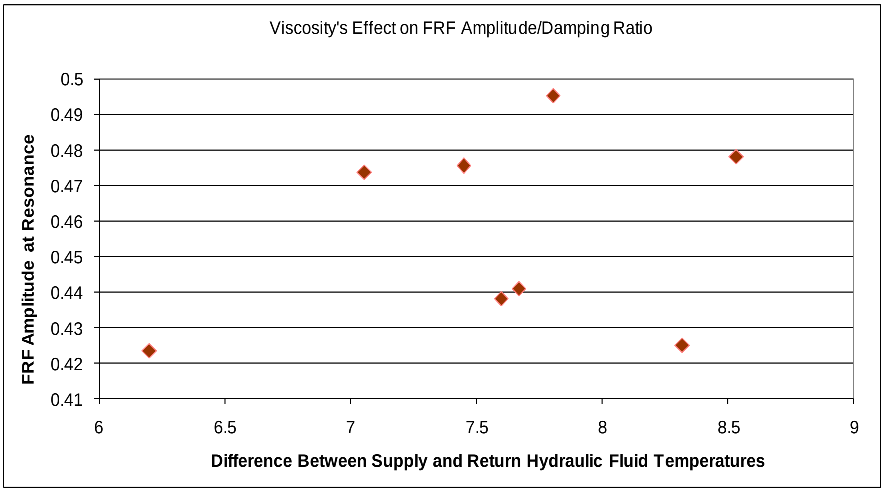

Figure 11: Hydraulic fluid viscosity also shows little effect on system damping

Though a direct relationship is plausible, the correlation was too low to believe friction significantly affected table frequency response.

3.2 Valve Command Analysis

With the hypothesis that a significant temperature or friction dependence may exist proven to be void, the two testing methods were investigated to verify the equality of their input. After further analyzing the time data, valve command illustrated a difference in response magnitude between multisine and singlesine tests. This was surprising as amplitudes were held constant during initial singlesine and multisine testing using the analog controller. It is believed that multisine testing's increased demand on the valve lessened its impact on system damping. Valve commands and LVDT frequency response amplitudes, both at resonance, were plotted for three multisine tests and a singlesine test indicated by the cyan oval. Beyond showing an acceptable trend, the data holds true to system dynamics. The largest amplitude at resonance is a good

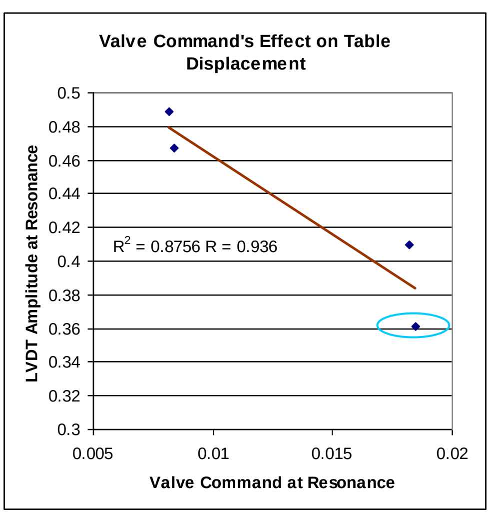

Figure 12: Variable valve command has a significant effect on damping.

indicator of the test with the least damping. For the case of low damping, the valve would operate at a proportionally low opening to maintain the desired motion. Thus the higher damping seen near resonance in singlesine tests can be explained by larger valve commands.

3.3 Hydraulic Shaking Table Model

The mathematical model held up well for frequency response between valve command and LVDT, especially for frequencies between 16.5 and 78 Hz.

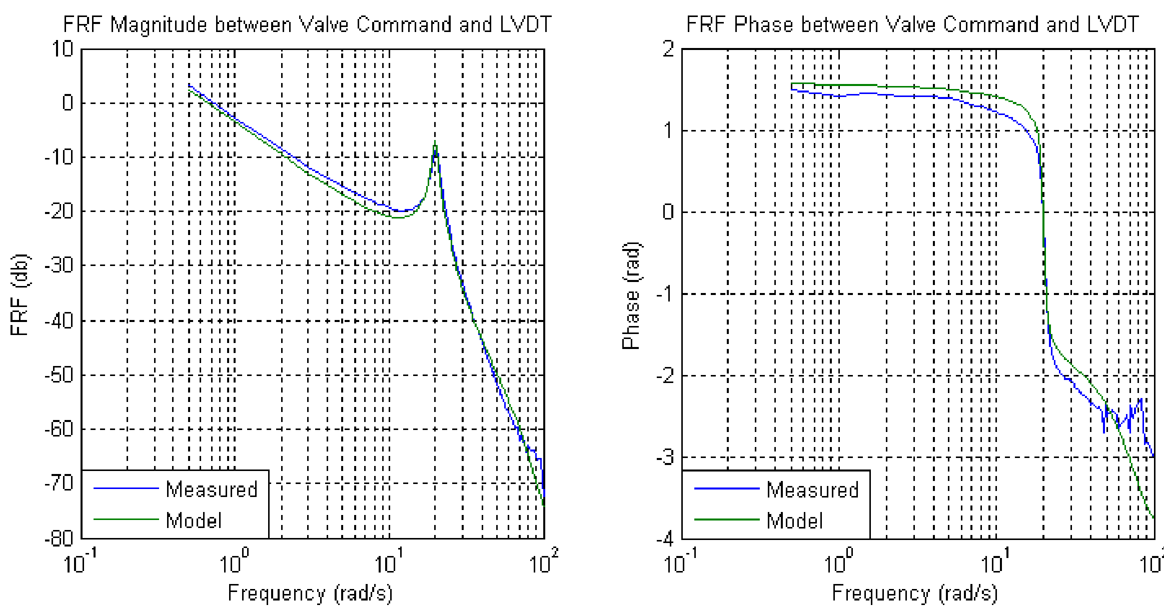

Figure 13: Model illustrates acceptable fidelity. (0-80 Hz +/- 2 db)

The model approximated frequency response to the most accurate degree between valve command and acceleration. Values were nearly identical for frequencies ranging from 5 to 76 Hz. A noticeable divergence between the measured and modeled response is present between 76 and 100 Hz; however, frequencies will not approach these values during hybrid testing.

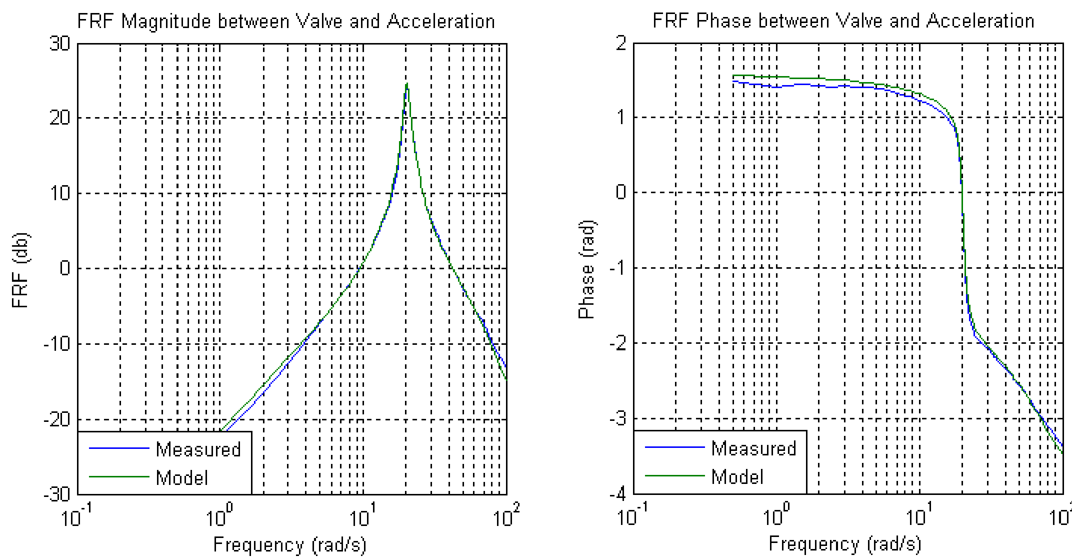

Figure 14: Model shows high fidelity. (0 Hz – 80 Hz +/- 1 db)

In the case of frequency response between valve command and differential pressure, the mathematical model could not follow the measured response to a satisfactory degree.

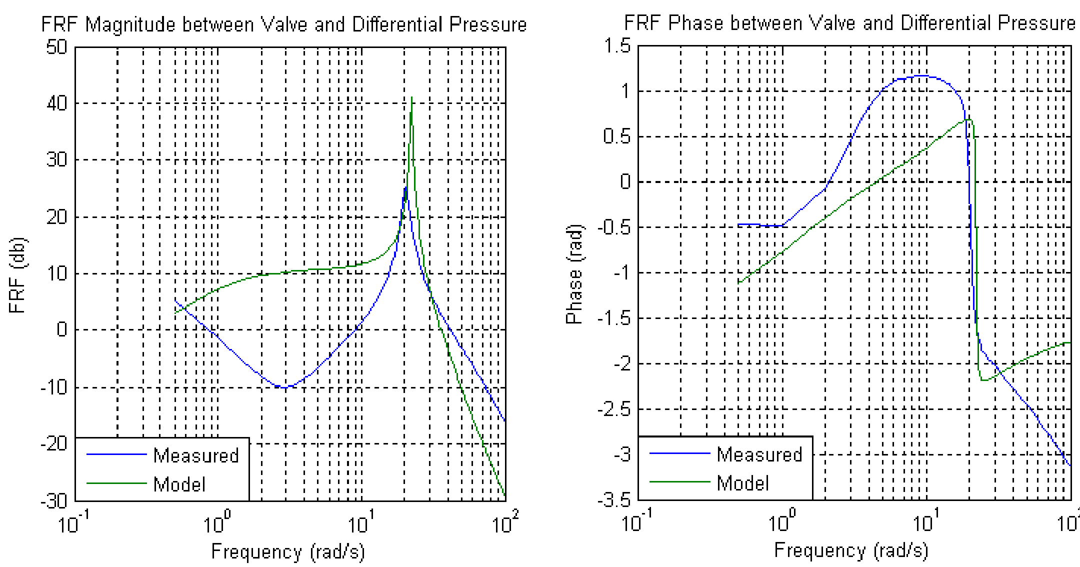

Figure 15: Model fails to correlate with measured data

4. Conclusion

Preliminary analysis indicated frequency response during singlesine testing to be more damped than when using the multisine method. This inconsistency negatively affected the repeatability of future experiments. Further testing proved initial hypotheses that the inconsistency of fluid temperature and viscosity were the cause of such discrepancies to be void. After analyzing all differences recorded in the time data, the valve commands of the two testing methods were surprisingly different in magnitude. Though this does not affect the integrity of each testing method on its own, future singlesine testing that needed to be compared directly with multisine tests was altered by this finding. Valve command data recorded when doing multisine testing was plotted and reference for singlesine testing. While recording singlesine data, the oscilloscope provided in the software displayed current valve command data. Amplitudes were adjusted to remain as close as possible to multisine valve commands throughout future testing.

The existing transfer function model performed well in predicting frequency response between valve command and LVDT. The correlation was even stronger between valve command and acceleration. The model was unable, however, to fit a curve that correlated to an acceptable degree with the measured frequency response between valve command and differential pressure. The current hypothesis is that nonlinearities due to oil column viscosity invalidates the use of the linear least squares approach to determining model coefficients. This is subject to future investigation.

5. Future Work

In addition to researching why the frequency response involving differential pressure seems subject to nonlinearities while LVDT and acceleration are not, additional testing late in the research process produced new curiosities. The current model is built around the assumption that the average position, or set point, of the table is centered at the zero position. Measurements of frequency response at varying set points indicated a trend that was contrary to intuition. It was expected that the resonance frequency would shift with the altering of the oil column distribution. It was also assumed that there would be symmetry about the zero position of the piston. While the negative set points illustrated a consistent shift, the shift of resonance frequencies for the positive center positions decreased the further from the zero position. Non-symmetry in regard to the construction of the shaketable hydraulics is hypothesized to create this effect.

Hybrid testing will follow the satisfactory completion of the shaketable model. The model will serve to facilitate control of the servo valve; the device managing shaketable motion.

6. Related Work

Conte 2007 and Trombetti (2007) [2]

Modeling of shaking table systems is a well documented science that has aided in addressing the imperfections of reproducing dynamic signals. Analytical modeling has proven that linear approximations of transfer functions governing the hydraulic components of shaketables are quite acceptable for small amplitude excitations [Conte 2007 and Trombetti 2007]. These approximations have facilitated the creation of servovalve-actuator, servo-hydraulic, and shaking table transfer functions. Conte and Trombetti have documented how servovalve-actuator transfer functions must compensate for issues such as the flow of fluid leaking through actuator seals and the compressibility of oil in the pressure chamber. Between the servovalve and hydraulic system, an electrical component that compensates for any error that may result between desired and actual displacement built into the feedback system. Shaking table transfer functions have also taken into account the flexibility of the reaction mass. Table sensitivity studies compiling interactions with system parameters have also aided in maintaining accuracy in future experiments. Servovalve time delay was found to significantly alter the amplitude and phase of shaking table transfer functions in experiments carried out by Conte and Trombetti. Though there was no observed trend, it should be experimentally measurable to determine if it is a factor.

Twitchell and Symans (2003) [4]

It is also relevant to note that actuator fluid compressibility does not significantly affect the tracking performance of the simulation if frequencies of motion are near or below typical earthquake values of 10 Hz. (Natural Frequency of Oil Column approximately 34Hz) [Twitchell and Symans 2003].

Christenson, Lin, Emmons, and Bass (2008) [1]

Hybrid Simulation has evolved from a deep knowledge of structural and test systems modeling and has enabled researchers to test critical system components and represent the remainder in a complex computer simulation. Recently, Hybrid Simulation was implemented in the performance testing of Magneto-rheological (MR) damping systems. Testing involved three large scale MR Fluid dampers as the physical component with the simulated component being a three-story structure subject to ground motion [Christenson, Lin, Emmons, Bass, 2008]. Using the University of Colorado at Boulder's Fast Hybrid Testing Facility (FHT), one of three NEES (Network for Earthquake Engineering Simulation) facilities with FHT capabilities, it was determined that MR fluid dampers do in fact allow a structure to yield under intense dynamic loading. Perhaps just as important, it was verified that virtual coupling both increased stability while maintaining performance. The effect of virtual coupling between physical and numerical components was observed by researchers in the open loop transfer function. Here, terms representing virtual stiffness and damping were able to be altered to deliver the appropriate balance of performance and stability for the real-time hybrid testing needs. This research also noted that in addition to MTS technology that can minimize time delay, a graphical approach involving a Nyquist plot on a Bode plot can be utilized if the technology is not available.

Acknowledgements:

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MTS Systems

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