Reliability Assessment Analysis for Real Time Hybrid Simulation with Fluid Viscous Dampers

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Abstract

By combining physical testing of experimental substructures and numerical modeling of substructures, real-time hybrid simulation technique enables large- or full-scale structural performance under earthquakes to be replicated in size limited laboratories. Due to servo-hydraulic dynamics, desired response might not be able to be accurately applied on to the experimental substructures and the resulting unsynchronized restoring force could further lead to inaccurate structural responses in experimental results. Reliability assessment of real time hybrid simulation results therefore is critical to appropriately interpret the structure performance under investigation. Viscous damping devices have been recognized to provide great energy dissipation for seismic hazard mitigation of civil engineering structures. Real-time hybrid simulation provides an effective and efficient technique to experimentally evaluate recent development in design methodology of structures with viscous damping devices. In this study the effect of actuator dynamics on real-time hybrid simulation of structures with nonlinear viscous dampers are analyzed. The resulting error is evaluated through comparison with actual response. A recently proposed approach for reliability assessment is further assessed using the computational results. The collaboration between SFSU and Cañada College provides an effective way to involve engineering students into advanced earthquake engineering research.

Introduction

Due to the active faults all over the world, earthquakes pose significant dangers to human societies which can lead to disasters unless effective engineering countermeasures are taken into account. This natural disaster can lead to an overwhelming structural damages and loss of human lives do to the sudden release of energy form within the earth. Earthquakes urgently demand more research for more reliable and sustainable civil engineering infrastructures. Real-time hybrid simulation seamlessly integrates physical testing with numerical simulation, thus providing a cost-effective technique to evaluate seismic performance of large or full-scale structures in limited size laboratories[1]. Figure 1 presents the schematic concept for real-time hybrid simulation. The structure is divided into experimental substructures and analytical substructures, where the experimental substructures are tested in laboratories and the analytical substructures are numerically modeled by computer program.

Actuator delay presents great challenge for real time hybrid simulation. Various procedures have been developed to compensate for these delays to improve the accuracy of simulation results. Past research projects, such as the work from the professors of engineering in San Francisco State published in 2012 which develop a probabilistic approach for reliability assessment of real-time hybrid simulation results[2] especially when the true structural response is not available. A linear elastic single-degree-of-freedom structure is used to determine the statistical distribution of actuator delay values corresponding to certain accuracy[3]. Nonlinear structural behavior is considered through the Bouc-Wen model[4]. The Bouc-Wen model is used in modeling the hysteresis phenomenon in the dynamically excited nonlinear structures it is used to help further obtain and modify the statistical distribution to account for structural nonlinearity[4]. The proposed probabilistic approach enables meaningful reliability assessment of real-time hybrid simulation results. To further increase the capabilities of the past research and the use of the statistical approach, fluid viscous dampers are incorporated in a similar simulation. The statistical approach is used to help analyze the data acquired and the reliability of the test.

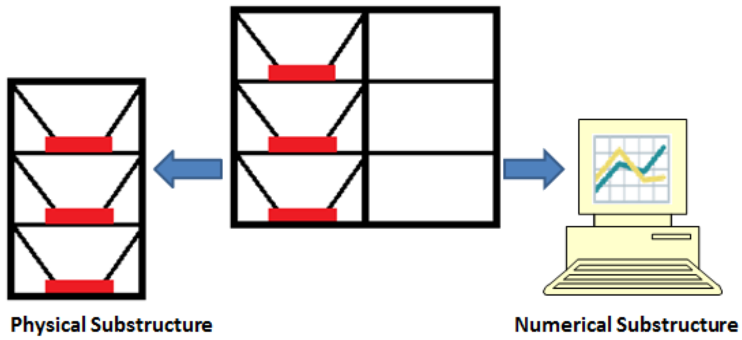

Figure 1. Schematic of real-time hybrid simulation.

Viscous Fluid Dampers

Viscous fluid dampers are able to help buildings survive an earthquake by providing a large reduction in stress and deflection by dissipating energy from the structure.[5] Figure 2 shows the typical structure of a viscous fluid damper. This device works like the shocks in a car, to dissipate the forces as the car passes over a bump. This analogy is how the fluid viscous damper is able to help a bridge or a building when an earthquake hits it. Fluid viscous dampers are able to reduce stress and deflection in a structure because the force from the damping is completely out of period with the stresses due to the bending of the column.[5] These fluid viscous dampers are not only for earthquake forces but they can also help dissipate wind forces on tall structures like skyscrapers. Using this component is an effective and inexpensive way to acquire a reliable component for earthquake resistant structures.

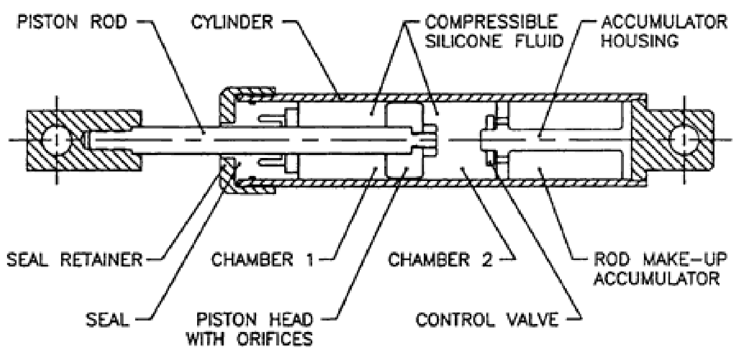

Figure 2. Fluid viscous damper[2]

Fluid viscous dampers have the ability to reduce or prevent a system from oscillating. Being able to mathematically model the device helps further understand the effects of the component in the system. Equations that need to be considered when dealing with dampers are shown below, equation 1 is the equation of motion were m represents the mass of the structure, k is the spring constant and c is the damping coefficient while F represents the external excitation of the structure. The force of the damper is calculated by equation 2, where c is the damping coefficient, v is the velocity, and α is the velocity component. The Damping ratio is another equation that needs to be dealt with when dealing with these viscous components, although it is a dimensionless unit it is able to describe how oscillations in the system decay.

$$m\ddot{x} + c\dot{x} + kx + c_d \times |v|^{\alpha} = F(t) \qquad (1)$$

$$F_{damper} = c * v^{\alpha} \qquad (2)$$

$$\zeta = \frac{c}{2\sqrt{mk}} \qquad (3)$$

Methodology

To analyze and design this research project the fundamentals of vibrations have to be taken into consideration. A single-degree-of-freedom (SDOM) is a basic form to visualize and calculate oscillating system which can imitate more complex structures. This vibratory system is defined by a solitary mass attached to a spring and dashpot, allowing the mass to travel in one direction. Figure 3 demonstrates a mass spring damper system which is use to establish a general idea in mechanics of vibrations class and the idea of SDOM.[3]

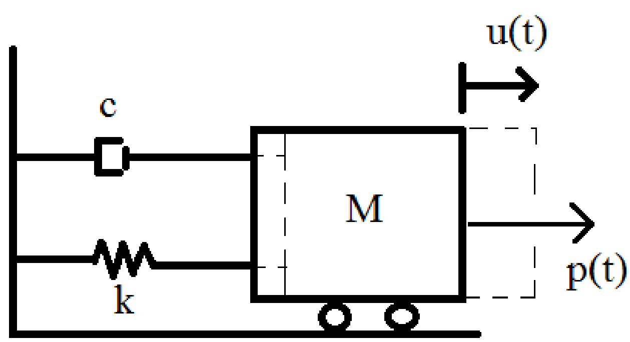

Figure 3. Mass-spring damper system.

The same ideology can be used to represent a one story structure being subjected to an external force shown in figure 4. The massless columns are able to move laterally but can't move vertically making them rigid in the vertical direction. If the roof is displaced a certain distance (u) and then released the building will oscillate and this oscillation will continue forever with an amplitude of the displacement (u). To make this a more effective and probable cause is having decreasing amplitude as time progresses until the structure comes back to rest at its original position. The fluid viscous damper is integrated as the absorbing element of energy to make the structures decrease in amplitude over time.

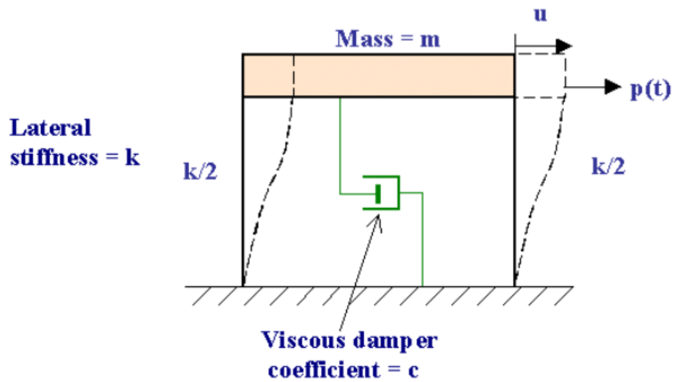

Figure 4. One story structure with damper[6]

The model incorporated in the simulation is taken from a previous work a professor of civil engineering at University of California at Berkeley[7]. A one story frame with a lumped weight of w=100kips , natural vibration period Tn= 1sec, damping ratio ζ=5% and non-linear fluid viscous damper with α=.5 and Cα=3kips/(in/sec)$^{.05}$ [7]. Furthermore 44 ground motions where taken from The Pacific Earthquake Engineering Research Center PEER Ground Motion Database. Within each ground motion three aspects were incorporated scale factors, delay, and eta. Scale factors were introduced ranging from .25 to 3 with even increments of .25 making a total of 12 scale factors. The delay ranged from 0 to .05 with evenly spaced increments of .0025 making 21 different delays. Four eta values were introduced the values were .25, .50, .75, and 1 these represent the strength factor. After gathering multiple data points for each ground motion further analysis was done to find a probable trend that will be able used.

Computational Results

Real-time hybrid simulation greatly affects its application as an efficient and economical technique to evaluate seismic performance of structures under earthquakes. This study presents the reliability assessment of real-time hybrid simulation results by accounting for nonlinear behavior[5]. A delay differential equation is analyzed for real-time hybrid simulations with actuator delay. It is found that the effect of nonlinear structural behavior can be accounted for in the reliability assessment by incorporating the ductility demand during the simulation into the probabilistic time delay model. The reliability of the real-time hybrid simulation results can be evaluated by comparing the time history of tracking indicator from experiments with those using selected value from the probabilistic distribution. The proposed approach is successfully applied to real-time hybrid simulation results of a single story with a fluid viscous damper.

Matlab Simulink model was created to represent the fluid viscous damper in a SDOM structure. It had to be taken in consideration the linear and non-linearity of the fluid viscous damper. Linear fluid viscous dampers are used because they are modeled by a linear dashpot. Although it may be simplified, the component is able to reduce seismic loads on the building. A drawback on linear fluid viscous dampers is that they may develop excessive damper forces were strong velocities occur.[7] On the other hand non-linear fluid viscous dampers are able to manage this velocity and force relationship and have the capability to limit the highest damper force of structural velocities while still providing sufficient damping[7,8]. To acquire an accurate model for the non-linearity the Bouc-Wen model was used to account for this do to the versatile and mathematical tractability it has. Mathworks develop a graphical programming language tool for modeling, simulating and analyzing multidomain dynamic systems called Simulink. Simulink is a block diagram system which provides the user with graphical editor and customizable block libraries. Simulink is combined with MatLab which helps the user integrate algorithms into models as well as transfer simulation results to MatLab for further investigation. In the Simulink model of the viscous damper a displacement is passed through a transport delay. This transport delay is then derived to gather a velocity. The velocity acquired from the derivation is processed through math functions to obtain a restoring force. The restoring force of the damper is then broken down with the restoring force of the building. The combination of these two forces is analyzed further.

Figure 5 show the simulated response of a 6.9 magnitude earthquake (recording stating Nishi-Akashi) in Kobe Japan. The figure shows the exact response compared to the response when a delay is entered into the model. With a delay of 10 msec. incorporated between the command and measured, the delay produced a max error of 9.54% difference between the two. The percentage error increased as the delay increased. By having a small increment in the delay it greatly affects the simulation, this time parameter has to be acknowledged when using real-time hybrid simulation do to the effect it has to the data. Figure 6a displays all linear data for all 44 ground motions with a strength factor of 0.25. The graph shows as delay values increase the error increases. In Figure 6b the difference between the linear and nonlinear data are compared for the same earthquake. The red (nonlinear) and blue (linear) demonstrate the behavior at a scale factor of .25 which appear identical and no visible difference is seen. By taking the same ground motion and increasing the scale factor to 2.50 it is then visible that the nonlinear (magenta) data of the same ground motion has a higher max error throughout the graph compared to the linear, this trend is seen in all earthquakes and all 12 scale factors.

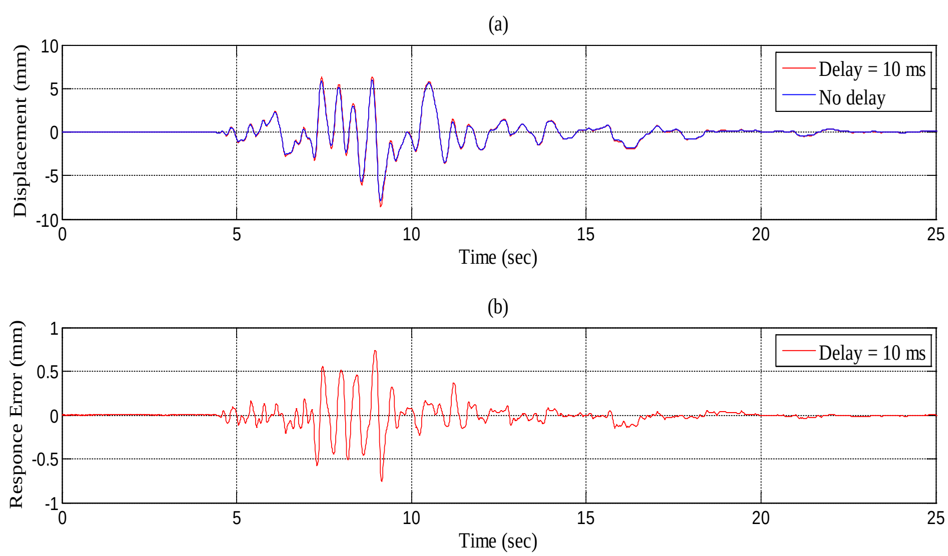

Figure 5. Measured Response vs Exact Response.

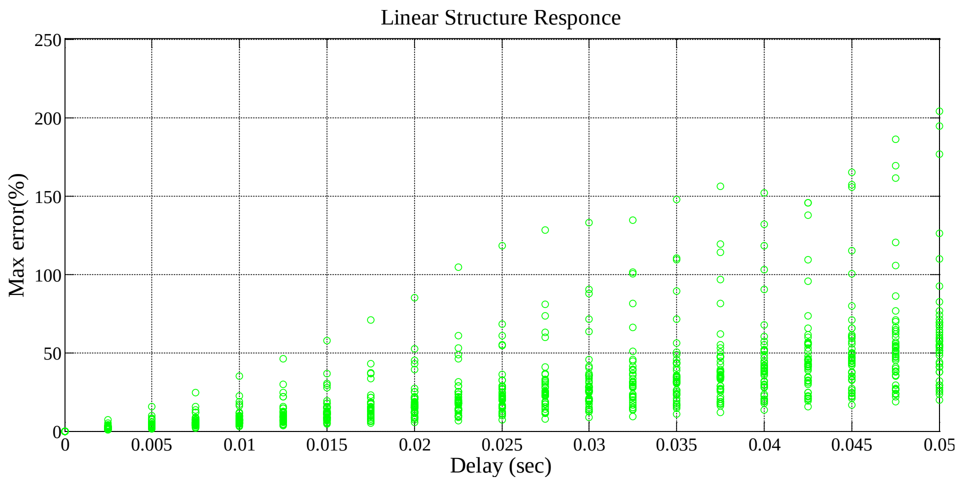

Figure 6a. Delay vs max error.

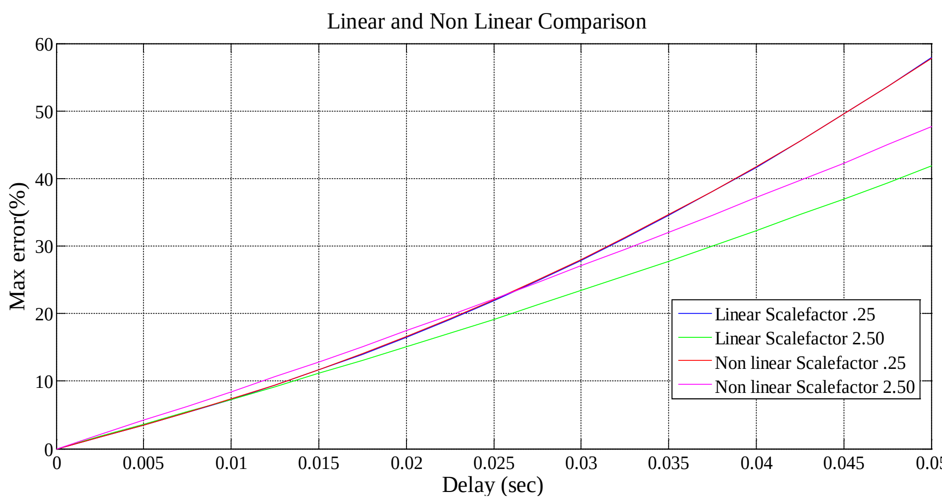

Figure 6b. Linear vs Non Linear.

Integration with NASA CIPAIR Internship Program

Cañada College and San Francisco State University made joint efforts to install an internship in order to intensify the minority interest in the STEM fields. Thus came about COMETS, Creating Opportunities for Minorities in Engineering, Technology, and Science. This internship is sponsored by the National Aeronautics and Space Administration's, NASA, Curriculum Improvement Partnership Award for the Integration of Research into the Undergraduate Curriculum (CIPAIR). From the COMETS collaboration stemmed the Capstone Design Project, which provided the opportunity to participate in a year-long senior design project at San Francisco State University to four current community college students.

The civil engineering student Abbyanna Davis was selected to help on this research through this internship the student was able to work with simulations and allowed her to put the knowledge she has acquired through her academic pursuits to test, as well as acquire new knowledge such as the use of MatLab Simulink in order to simulate the fluid viscous dampers and the ability to give her an experience of upper division course work and research. Three main tasks include inputting the data, running simulations and analyzing the data acquired from simulation. By having meetings every two weeks and contact through email the teamwork between the two students researchers helped make the internship much more efficient. NASA CIPAIR COMETS internship made it possible for Community College student to gain experience in the field on earthquake engineering.

Summary and Conclusion

Real-time hybrid simulation is an efficient system to incorporate in limited size laboratories. Incorporating this simulation is able to expand the research possibilities for researches in earthquake engineering. The implementation of the viscous fluid damper in the simulation and the use of the model are able to help further comprehend the effects of this component on earthquake resistant structures without increasing major cost for the institution. The COMETS program has been successful in engaging minorities in community college in research opportunities and further interest in math and science major. The integration between the NSF BRIGE project and the NASA CiPair project provides an effective way to engage community college students into advanced earthquake engineering research.

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