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# BASE ISOLATION STUDIES USING REAL-TIME HYBRID SIMULATION AND FIXED BASE BUILDING SHAKE TABLE TESTS

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## *Abstract*

This paper will present a real-time hybrid substructuring (RTHS) shake table test that will allow for innovative tests of a fixed base building model attached to a shake table to explore various configurations of a base-isolated building system. Shake table testing, where the building superstructure is tested on a 1.5m by 1.5m uniaxle shake table while the isolation layer is numerically modeled in MATLAB/Simulink using a dSpace real time controller, can allow for a range of isolation strategies to be examined for a single shake table experiment. A natural extension of this particular test configuration is soil-structure interaction. This RTHS configuration also allows for the challenging responses in the superstructure, such as the response of nonstructural components and high frequency accelerations, to be physically tested while allowing for the flexibility of numerically modeling various aspects of the isolation layer. For this paper a second physical substructure consisting of a passive viscous damper will be tested as it is placed in the isolation layer of the system. As such, this paper will demonstrate the role of a proposed robust stability and performance analysis method for real-time hybrid simulation (RTHS) of an experiment with multiple physical components. The paper will provide a stability and performance analysis to identify the test configurations possible with the given physical experimental setup. The RTHS approach has been previously proposed for base isolated buildings, however, to date it has not been conducted on a base isolated structure isolated at the ground level and where the isolation layer itself is numerically simulated. This configuration provides multiple challenges in the RTHS stability associated with higher physical substructure frequencies and a low numerical to physical mass ratio. The RTHS results demonstrate that this method of testing can capture the dynamic interaction between the various physical and numerical components.

*Keywords: real-time hybrid simulation; base-isolation; robust stability*

## 1. Introduction

Base isolation is one of the most widely used and accepted types of seismic protective systems to reduce structural and nonstructural damage caused by earthquakes. Seismic base isolation reduces the damage by shifting the resonant frequency of the structure below the energy content of the ground motion [1, 2]. This isolation both reduces the inter-story drifts of the superstructure and reduces the floor accelerations throughout the building. Significant research has been conducted on base isolators and high fidelity numerical models are available for base isolator devices. Long period long duration earthquakes can result in large displacements across the isolation layer and result in detrimental pounding effects. One solution is to increase the damping across the isolation layer, however, that reduces the effectiveness of the isolation, and raises concerns of damage to nonstructural components from larger amplitude and higher frequency vibration of the superstructure. This nonstructural damage due to higher frequency modes in the superstructure can be difficult to numerically model and predict. As such, physical testing of the superstructure may be desired to evaluate performance. Further, by numerically modeling the isolation layer it can be easier and less costly to examine a wide range of isolator devices.

Shake table testing, which has been used extensively in earthquake engineering, is an experimental technique to identify the seismic behavior of a structural system [3]. In this testing, the specimens on the shake table are subjected to excitations representative of earthquake ground motion and the results are often considered more representative of the behavior during an actual earthquake. By combining experimental testing and numerical simulation, real-time hybrid simulation (RTHS) testing, also called real-time hybrid substructuring, is an attractive alternative method to the traditional shake table testing. Recent advances in RTHS have been made possible by increased computing power, digital signal processing hardware/software, and hydraulic actuation. RTHS allows a structural dynamic system to be partitioned into physical and numerical substructures. The substructure of interest is physically tested, while the substructure that is better understood is simulated in real-time using analytical or numerical models. In an RTHS test, the numerical and experimental substructures communicate together in real-time by transferring displacement and force signals through a feedback loop using controlled actuation and sensing. The RTHS approach can provide efficient and cost effective methods of considering larger systems than can be tested on the shake table [4]. For example, Ashasi-Sorkhabi et al. [5] conducted a study implementing RHTS with a shake table where a tuned liquid damper (TLD) was physically tested on a shake table and the building structure below the TLD was numerically modeled. Zhang, et al. [6] demonstrated RTHS for a building with a mid-height isolation layer. Early research demonstrated RTHS to be a useful tool in earthquake and structural engineering [7, 10]. RTHS using shake table testing can be used, as demonstrated here, to explore base isolation. This same experimental setup can also be used to explore concepts of soil-structure interaction.

This paper proposes an RTHS test configuration, which has two physical substructure and a numerical substructure. The building superstructure is tested on a 1.5m by 1.5m uniaxle hydraulic shake table located at the University of Connecticut n the Structures Research Laboratory. A viscous damper attached to a 9 kN hydraulic actuator also located in the Structures Research Laboratory at the University of Connecticut is a second physical component, representing a damper located across the isolation layer of the base isolated structure. Lastly, the isolation layer is numerically modeled in MATLAB/Simulink as a 4-degree-of-freedom lumped mass model, using a dSpace real time controller. Fig. 1 shows a block diagram of a closed loop RTHS test for a base isolated structure. At a given time-step, loading, including ground displacement and velocity and the base shear and damper force, is applied to the numerical substructure to determine the numerical displacement, $x_n$, to be imposed on the physical substructures. The numerical displacements are then fed into controllers to identify the command displacements, $x_{a1}$ absolute displacement and $x_{a2}$ relative displacement to send to the hydraulic actuators to insure the displacement imposed upon the physical substructures. The measured base shear, $V_{b,}$, and damper force, $F_d$, is fed back into the numerical substructure, along with the ground displacement and velocity of the next time step, to compute the numerical displacements, marching through time, until the duration of the test is completed.



 

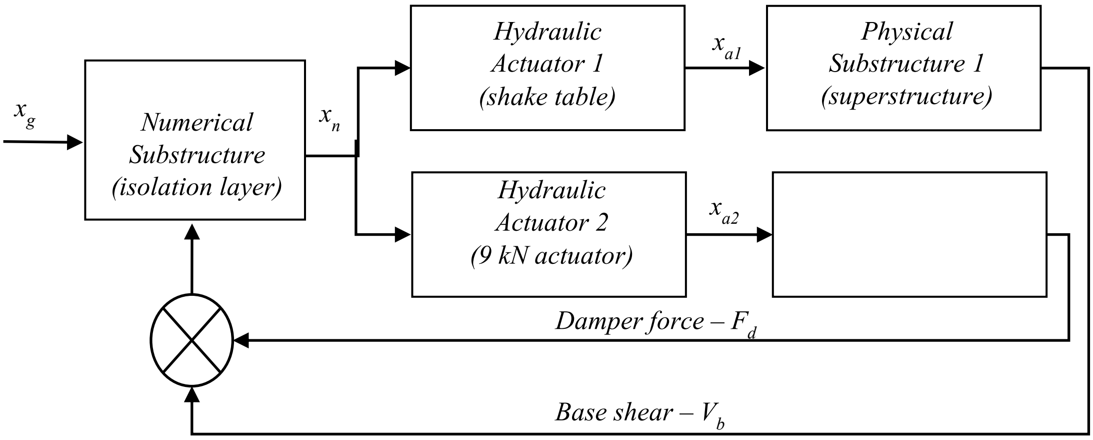


Fig.1 - Feedback Loop Block Diagram for RTHS

Since RTHS involves a feedback loop, the inherent time delay of the actuator transfer system can lead to inaccuracy in the actuator tracking and potential instability during closed-loop testing. Horiuchi et al. [10] initially considered the effect of time delay on RTHS testing. To improve the closed-loop stability and performance of RTHS, researchers have developed a variety of techniques for compensating the time delay or more generally the frequency dependent dynamics of the actuator transfer system. The techniques range from polynomial extrapolation in Horiuchi et al. [10] and inverse compensation in [11] to reduce the actuator delay as well as adaptive techniques in [12-13]. Carrion and Spencer [14] used a controls approach to develop model-based feedforward-feedback control to compensate the frequency-dependent magnitude and phase of the actuator dynamics. Phillips and Spencer [15] extended this approach with a more accurate feedforward inverse of the actuator dynamics and added linear-quadratic Gaussian (LQG) feedback control. Christenson and Lin [16] employed virtual coupling to balance closed-loop stability and performance in RTHS testing of large-scale MR dampers. Gao et al. [17] developed an H-infinity robust loop-shaping controller to compensate the actuator dynamics for RTHS testing of lightly damped steel frame structures. Nakata and Stehman [18] introduced a model-based actuator delay compensation and a force correction technique to achieve desired interface acceleration tracking. Shi et al. [19] introduced a Kalman filter to cancel the noises in the measured actuator displacement for enhanced performance. Lin et al. [20] illustrate the use of the predictive indicators for an RTHS, and effectiveness and accuracy of the approach examined. Further, Ou et al. [21] describe a new actuator control algorithm for achieving design flexibility, robustness, while Maghareh et al. [22] introduced a rate-transitioning and compensation technique that enables implementation of multi-rate RTHS. The ultimate goal of these compensation techniques is to provide effective displacement tracking of the actuator transfer system over the desired frequency range of the RTHS test, called the control band. This prior research to improve the dynamics of the actuator transfer system has been largely successful in this regard. A standard model-based feedforward control is implemented here.

With extensive effort to improve actuator tracking, stability and performance must still be quantified. Many stability analysis techniques provide insight into the stability behavior of RTHS, however, they assume pure time delay for the actuator dynamics and are limited to lumped parameter descriptions of the numerical and physical substructures. The robust stability and performance analysis method considered here involves casting the actuator dynamics of the RTHS feedback loop as a multiplicative uncertainty and then applying the small gain theorem to derive sufficient conditions for robust stability and performance for RTHS. This paper demonstrates robust stability and performance for multi-actuator RTHS. The method uses the measured frequency response functions of the actuator dynamics as well as measured frequency response functions of the physical substructure to provide a more direct measure of stability and performance and to allow for modifications of the numerical substructure to achieve desired levels of performance.



 

## 2. RTHS test Configuration

This paper examines the top floor acceleration response of a 4-story base isolated building with linear rubber bearing and a supplemental viscous damper. The scaled building model and passive Taylor damper are physically tested in the Structures Research Laboratory at the University of Connecticut. Fig. 2 illustrates the substructuring employed for the RTHS test where the 4-story physical building is mounted on uniaxial shake table, the passive damper is attached to a hydraulic actuator, and the isolation layer is a numerical model implemented in a dSpace real-time controller. All three components interact in real-time to conduct the RTHS test.

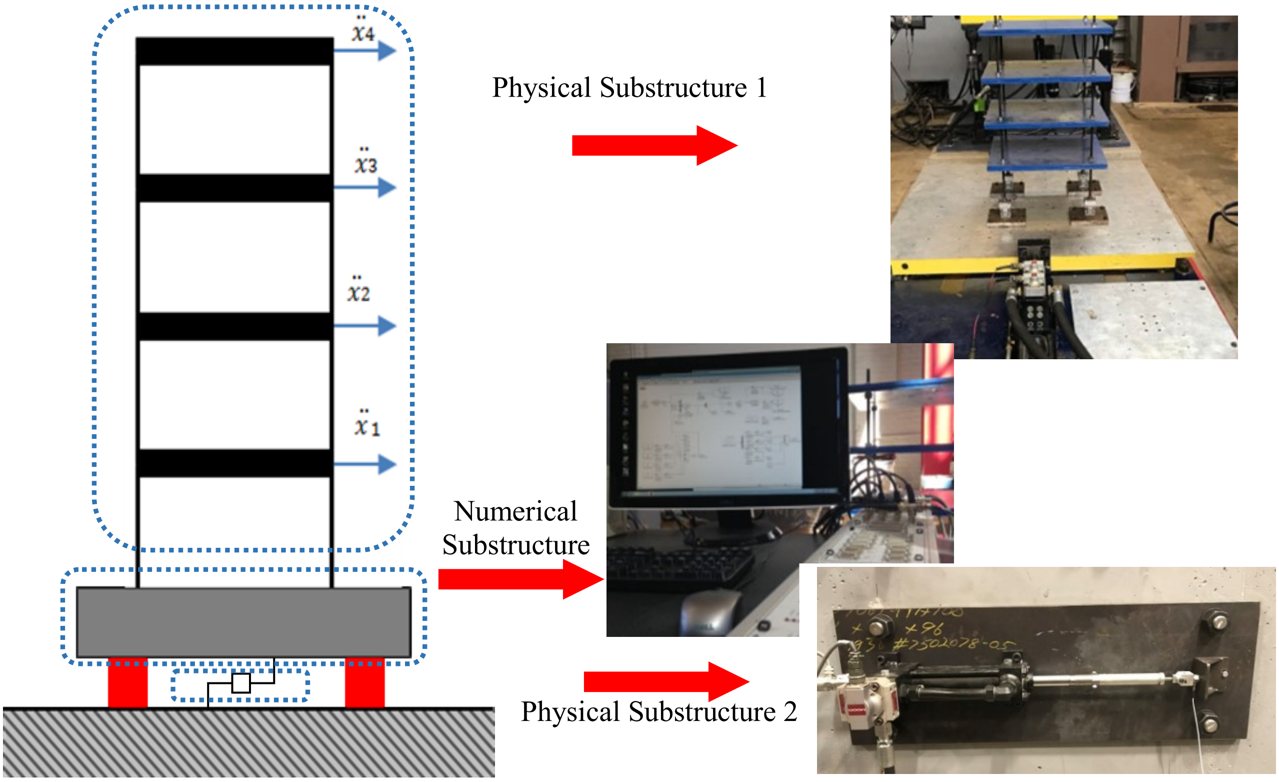


Fig.2 RTHS test configuration of a base isolated four story building structure

A SDOF model, which consist of base mass, a base mass, $m_b$, isolator stiffness, $k_b$, and isolator damping, $c_b$, is used as a numerical model of the base isolation layer. This model can be extended to provide more complex and nonlinear realizations. The mass of the isolation layer is characterized by the mass ratio, defined as $\mu = {m_b}/{\sum_{i=1}^{4} m_i}$, and is set to mass ratios of $\mu$=1, $\mu$ =2 and $\mu$ =15 in this paper. The natural frequency of the base isolated structure, defined as $\omega_b = \sqrt{{k_b}/{\left(m_b + \sum_{i=1}^{4} m_i\right)}}$, is 0.33 $Hz$, such that the stiffness of the base isolation layer is calculated as $k_b = \omega_b{}^2\left(m_b + \sum_{i=1}^{4} m_i\right)$. The damping ratio of the isolation layer is 5%, $\zeta$ = 0.05 and the damping coefficient of the isolation layer is calculated as $c_b = 2\zeta\left(m_b + \sum_{i=1}^{4} m_i\right)\omega_b$.

A scaled and idealized 4-story superstructure building is considered in this study as the physical substructure, as shown in Fig. 2. The building is 81.28 cm (32 in) tall and 61 cm (24 in) by 61 cm in plan. Four 1.27 cm (0.5 in) diameter steel threaded rods are used as columns, with the length of each fixed-fixed column between the stories set to 6 in. The effective diameter of the threaded rods is 0.95 cm (0.375 in) after taking into account the threads role in the moment of inertia. Further, the presence of the force transducers at the base of the structure added an effective length to the columns at the base, such that the first story columns are assumed have a length of 20.32 cm (8 in). The floors consist of 2 stacked 86.36 cm (24 in) square 2.54 cm (1 in) thick steel plates held in place with nuts and washers on the column threaded rods.

The 4-story building is mounted on medium-scale uniaxial seismic simulator with a 152 by 152 cm slip table with a ±15 cm available stroke. A linear-variable-differential-transformer (LVDT) is used to measure shake table displacement. The base shear of the physical superstructure, $V_b$, can be determined directly by using the sum of the $x$-axis measurements of four PCB (model: 261A02) three component ICP triaxle force transducers attached at the base of each column of the building. For larger test specimens, this approach may not be feasible. As such, the base shear can be *calculated* by summing the product of the calculated mass and measured acceleration at each of the four stories of the building. A Shore Western digital controller is used to command the-hydraulic actuator to enforce the displacements from the numerical model. The second physical substructure is viscous damper from Taylor Devices, Inc. The damper is actuated with a servo-hydraulic actuator comprised of a Quincy Ortman Cylinder with MOOG servo-valve. The hydraulic actuator has a ±19 cm stroke. The hydraulic actuator is controlled with a Parker Hannifin Corporation analog controller, employing displacement feedback with internal displacements provided by Micropulse linear position transducer. A PCB force sensor (Model 208C04) is used to measure the damper force. A Data Physics SignalCalc Mobilyzer dynamic signal analyzer is used to acquire the physical displacement and force for system evaluation.

## 3. Robust Stability and Performance Analysis for Multi-Actuator

A more detailed feedback loop for the multi-actuator RTHS is illustrated in **Error! Reference source not found.**. 3. The transfer function $N_1$ relates input numerical displacement ($x_g$) to output displacement responses ($x_n$) where $s$ is the Laplace variable. For the numerical substructure, the transfer functions $N_{21}$ and $N_{22}$ relate the input restoring force ($V_b$) and damper force ($F_d$) to output displacement, respectively. The transfer function $P_{21}$ relates input actuator displacement ($a_1$) to a measured base shear ($V_b$) at the same time the transfer function $P_{22}$ relates input actuator displacement ($a_2$) to a measured damper force ($F_d$).

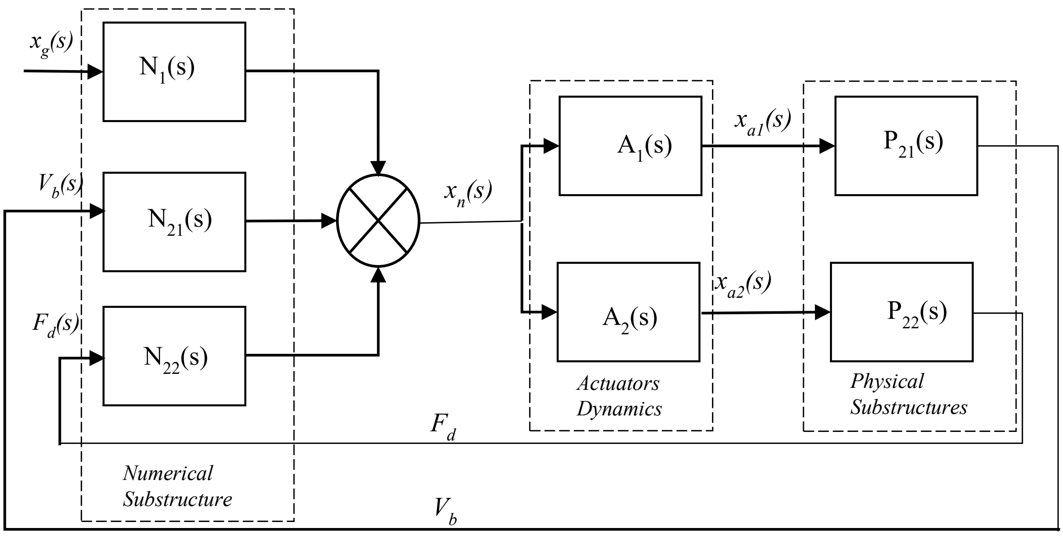


Fig.3 - The RTHS Feedback Loop for a Seismically Excited Base Isolated Building

The base shear and damper force can be defined as follow;

$$\begin{bmatrix} V_b \\ F_d \end{bmatrix} = \begin{bmatrix} P_{21} & 0 \\ 0 & P_{22} \end{bmatrix} \begin{bmatrix} x_{a1} \\ x_{a2} \end{bmatrix} \tag{1}$$


 

$$\begin{bmatrix} x_{a1} \\ x_{a2} \end{bmatrix} = \begin{bmatrix} \hat{A}_1 & 0 \\ 0 & \hat{A}_2 \end{bmatrix} \begin{bmatrix} x_n \\ x_n \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} x_n \\ x_n \end{bmatrix} = \begin{bmatrix} N_{21} & N_{22} \\ N_{21} & N_{22} \end{bmatrix} \begin{bmatrix} V_b \\ F_d \end{bmatrix} \quad (3)$$

where $P_2$ is the matrix of $P_{21}$ and $P_{22}$ in Eq. (1), $A$ is the matrix of $A_1$ and $A_2$ in Eq. (2), and $N_2$ is the matrix of $N_{21}$ and $N_{22}$ in Eq. (3). Applying robust stability theory for feedback control [24], the compensated actuator dynamics is cast as a multiplicative uncertainty, the complimentary sensitivity matrix [23], is defined as

$$[T(s)] = [I + T_0(s)\Delta(s)]^{-1}[T_0(s)][\Delta(s) + I] \quad (4)$$

where the uncertainty matrix can be found from the actuator matrix from $\left[\hat{A}(s)\right] = [\Delta(s)] + [I]$, and the nominal complimentary sensitivity matrix for the feedback loop above can be written as follow:

$$[T_0(s)] = [I + N_2(s)P_2]^{-1}[N_2(s)][P_2(s)] \quad (5)$$

Presence of actuator dynamics introduces $[T_0(s)\Delta(s)]$ in the denominator, when this term approaches -1 system will go unstable. The sufficient condition for MIMO robust stability is

$$\|[T_0(s)\Delta(s)]\|_\infty < 1 \quad (6)$$

and the sufficient condition for MIMO robust performance is

$$\|[T_0(s)\Delta(s)]\|_\infty \ll 1 \quad (7)$$

In the above expressions, $\| \|_\infty$, denotes the maximum singular value over the control band. $[T_o(s)]$ is the nominal complimentary sensitivity matrix and $[\Delta(s)]$ is the uncertainty matrix.

## 4. Results

Robust stability and performance analysis can provide important information about the stability of the test prior to closing the loop on any RTHS test. An unstable test can damage the actuator, shake table or specimen. Prior to conducting an RTHS test, the robust stability and performance margins can be determined using the experimentally measured frequency response functions of the physical superstructure, $P_{21}(\omega)$ and $P_{21}(\omega)$.and compensated damper actuator, and shake table, $A_1(\omega)$ and $A_2(\omega)$, and the numerically calculated frequency response function of the numerical isolation layer $N_2(\omega)$. Fig. 4 shows transfer function for the viscous damper and 4-story structure. These transfer function were measured in the laboratory and used in the stability and performance analysis.

Fig. 5 illustrates compensated and uncompensated transfer function for the actuators. Model-based feedforward inverse compensation methods are used to improve the actuator frequency response functions for both actuators to get the magnitude close to 0 dB and the phase to 0 degrees over the frequency bandwidth of interest. Note that the red compensated curves in Fig. 4 are the $A_1(\omega)$ and $A_2(\omega)$ used in the robust stability and performance analysis.

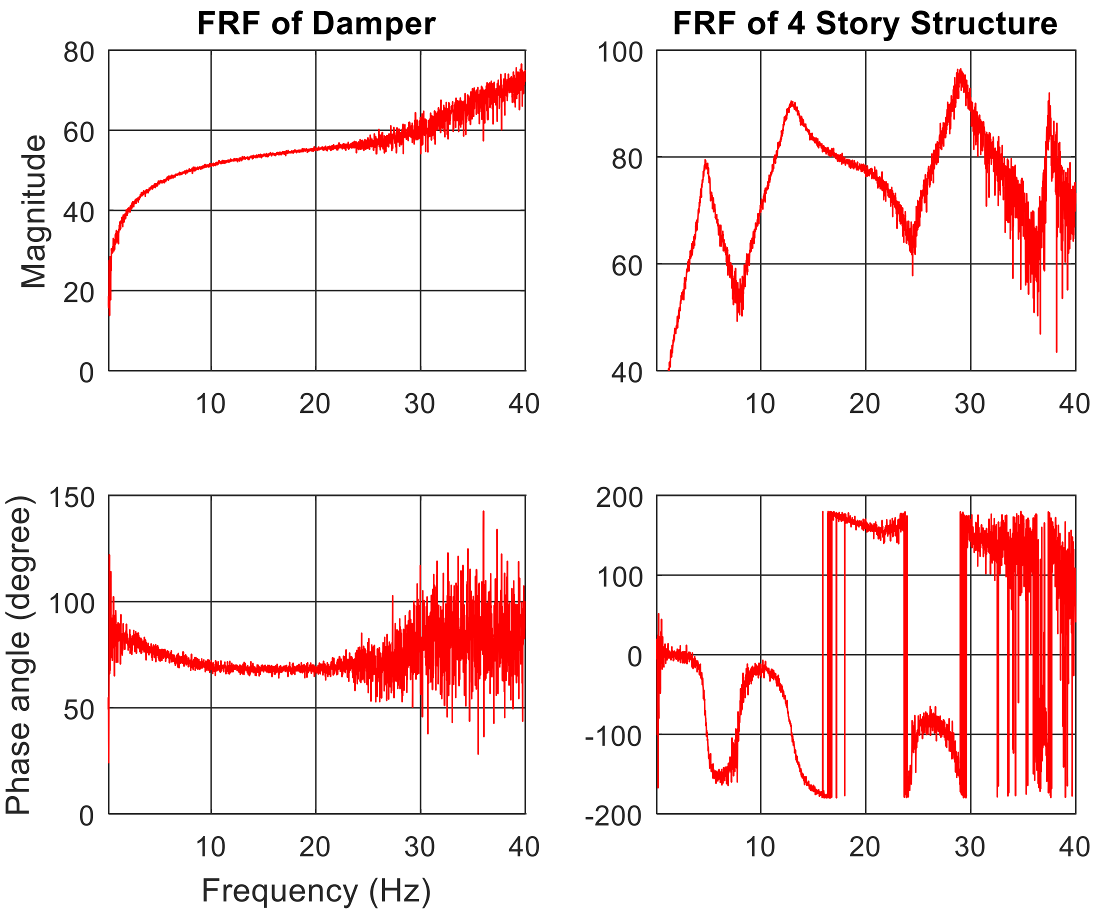


Fig.4 Transfer function of the viscous damper (left) and 4-story structure (right)

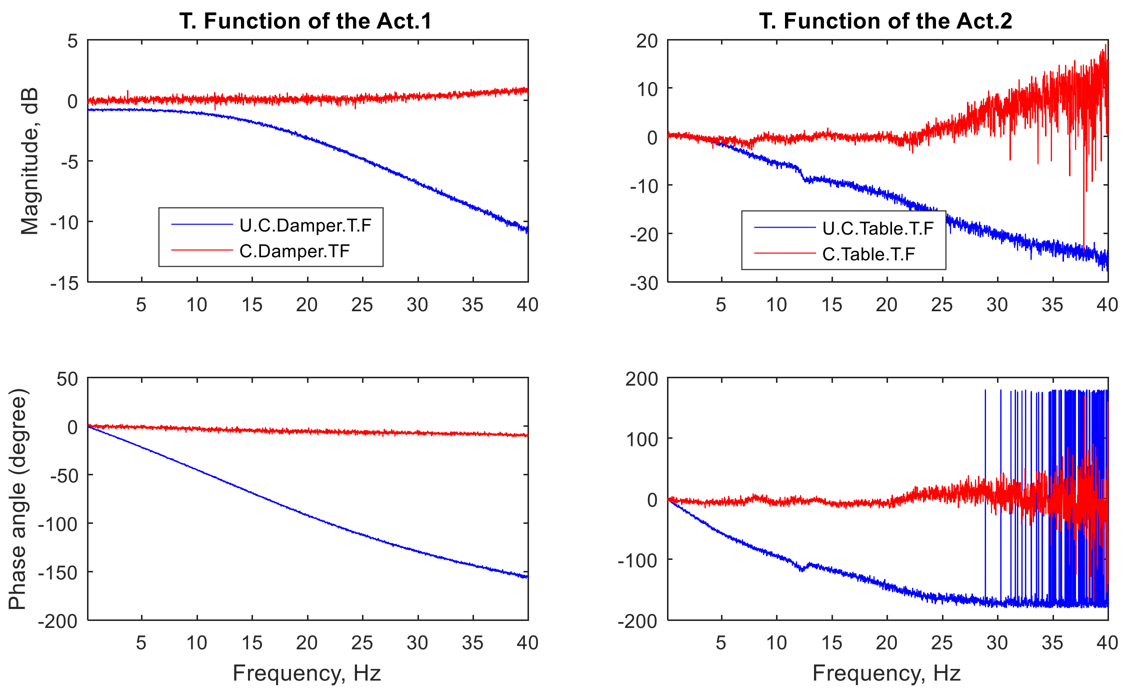


Fig. 5 Compensated and uncompensated Frequency response function of the actuators



 

Fig. 6 shows the performance margins for three different mass ratios (μ=1, μ=2, and μ=15). It can be seen from the figure if mass ratio of one (μ=1) is used, system will go unstable because the stability margin goes above 0 dB threshold around 3 Hz. By using mas ratio of 2 (μ=2), the RHTS test become stable but for robust performance it is also not sufficient. For robust performance mass ratio of 15 (μ=15) is necessary to keep the performance margin below -20dB over the bandwidth of interest (0-40 Hz).

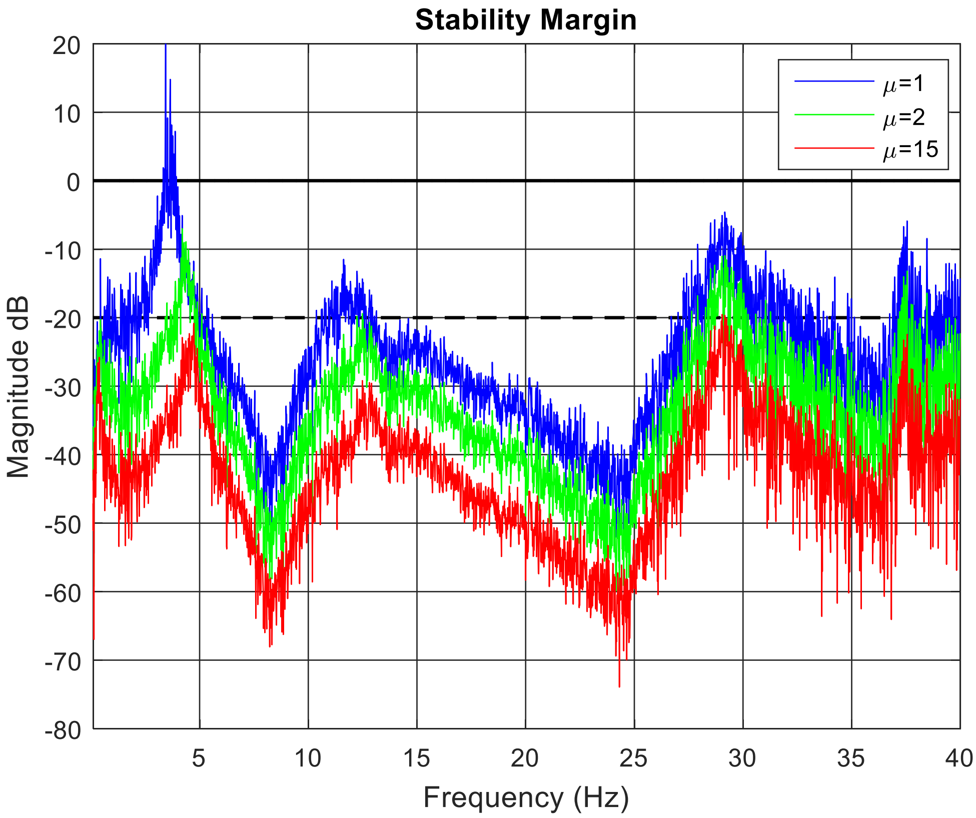


Fig. 6 Robust stability and performance margins of base isolated structure with a supplemental damper

The building structure is excited by a band limited white noise ground displacement with a root mean square (RMS) of 0.32 cm and a bandwidth of 0-40 Hz. The relative displacement between the isolation layer and first floor sent to the damper and measured damper force feedback to the numerical structure as well as the base shear. The frequency response functions of the superstructure absolute accelerations to input ground acceleration are measured during the RTHS test. Fig. 7 illustrates the magnitude of the measured frequency response functions for the four stories of the superstructure with the mass ratio of 15. This result indicate the prediction of the robust stability analysis that the RTHS with μ=15 are stable. Further, Fig. 8 shows time histories of a successfully completed RTHS test with a mass ratio of 15 used. It can be seen that there is no sign of instability on the time histories, which are verifying the prediction robust stability and performance analysis.



 

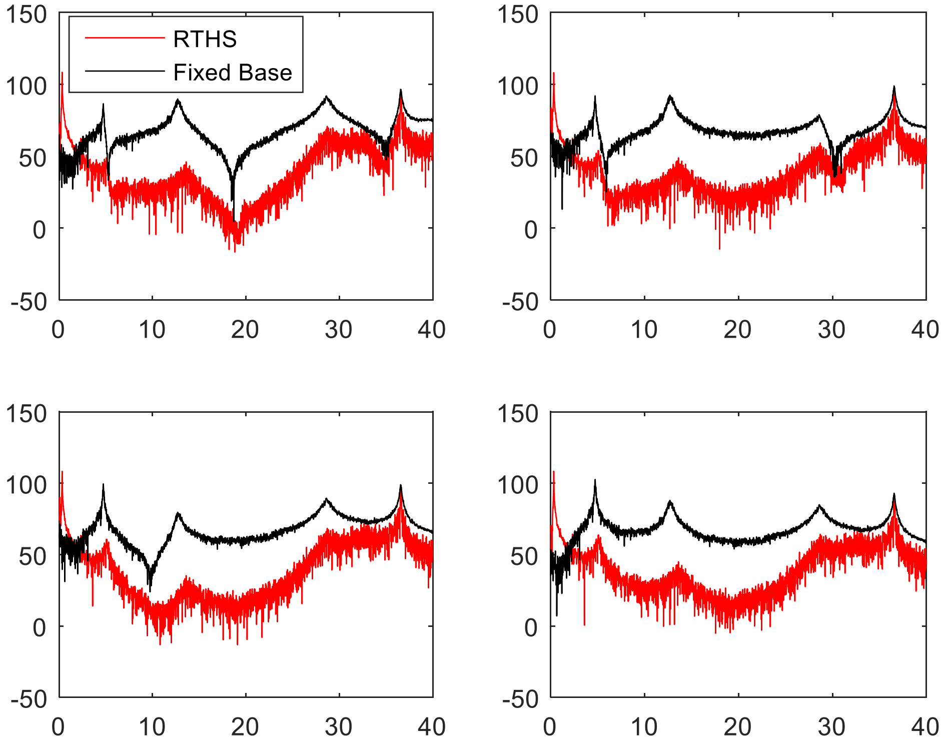


Fig. 7 Experimentally Determined Transfer Functions of Absolute Story Acceleration to Ground Acceleration for Fixed-Base(black) and Base Isolated (red) 4-Story Buildings.

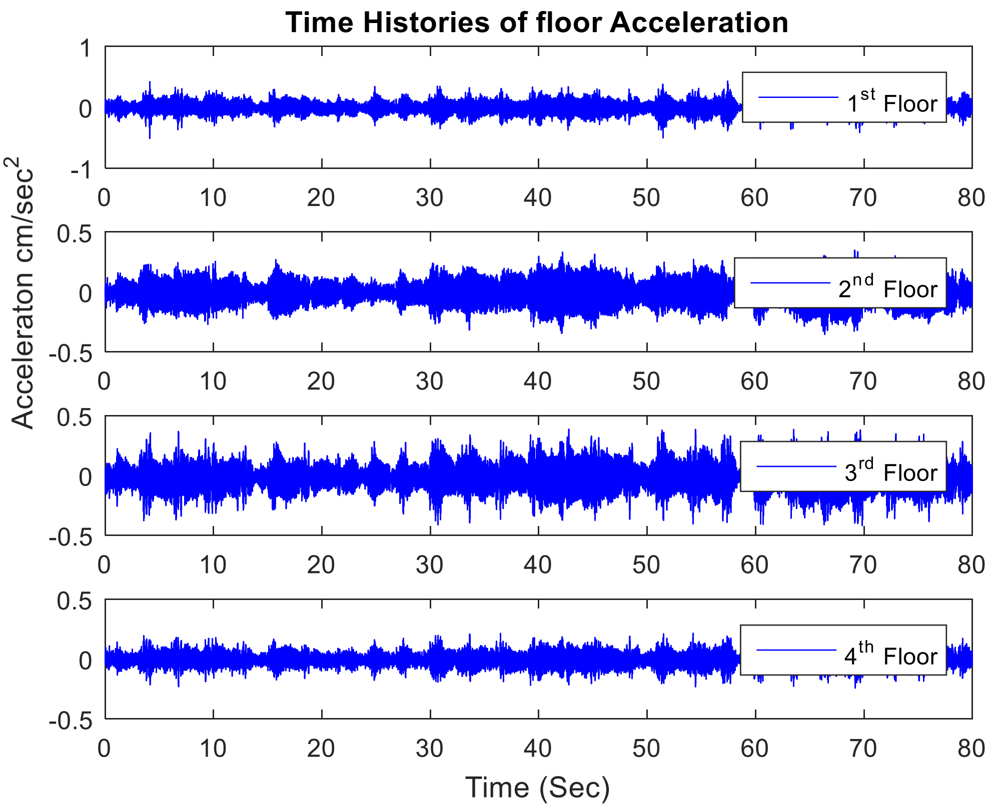


Fig. 8 Time Histories of Floor Acceleration on Base Isolated Superstructure.



 

## 5.Conclusion

It this paper the role of a proposed robust stability and performance analysis method for real-time hybrid simulation (RTHS) of an experiment with multiple physical components is examined. The experiment considered is a seismically excited base isolated building with a supplemental viscous damper located at the isolation layer. This paper presents a description and implementation of the proposed robust stability and performance analysis and insight into the decisions made in substructuring the system. The robust stability method is developed, casting the actuator dynamics as a multiplicative uncertainty and applying the small gain theorem to derive the sufficient conditions for robust stability and performance. Previous stability analysis techniques suppose pure time delay for the actuator dynamic, however this method accommodates linearized modeled or measured frequency response functions for both the physical substructures and actuator dynamics, which make makes it an attractive method. The proposed robust stability and performance analysis method is verified to predict stable results that provide marginal and good experimental results, as observed in the measured frequency response functions. Result tells that Robust stability and performance analysis method is a useful tool for decision making process as well post-test diagnostic period.

## 6. Acknowledgments

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