

## Active Base Isolation of Building Structures in Two Dimensions

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### ABSTRACT

In seismic design, base isolation is a useful mechanism for improving the structural response to dynamic excitation such as an earthquake. Previous research has demonstrated the viability of this method, which has led to its implementation in many real world applications. Historically, base isolation research has focused on passive isolation; to date, active base isolation has been given only a cursory investigation. This paper will build on the foundation of research performed by Mullenix, et al. and investigate the effectiveness of an active control strategy coupled with base isolation in two dimensions. The governing control law will be based on a frequency-domain based system identification and developed using the LQG algorithm. An uncontrolled case will serve as the base line to measure the effectiveness of the active control strategy. The results of this research will be experimentally verified by shake table testing of a scaled two-story, two-bay, steel frame structure in subsequent studies.

### INTRODUCTION

The idea of base isolation was originally conceived over one hundred years ago; however until recently, it has not been put into wide-spread practice. Within the last thirty years, research into base isolation has matured and led to its adoption in full scale buildings. Consequentially, most research has focused on passive isolation instead of active or hybrid isolation, which is the basis for this research.

Buckle and Mayes, while investigating the history of base isolation, developed a set of criteria to define base isolation for civil infrastructure. First, the system must employ a flexible mounting so that the natural period of the total system is lengthened. Second, a damper or energy dissipator is used to keep relative deflections between the structure and the ground within reasonable levels. Finally, a base isolation system must provide rigidity to the system under service loads such as wind or small earthquakes (1990). These criteria give a footing to compare the different base isolation concepts.

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Passive isolation has been the focus of most research and as a result has become a mature technology with many deployments into full-scale buildings. Passive isolation schemes rely on either hysteretic or friction energy dissipation. Hysteretic energy dissipation is usually implemented by metallic yielding either from mild steel or lead. The isolator is made by laminating alternating layers of steel plates and hardened rubber to achieve vertical stiffness while holes are drilled to accommodate the yielding material. Friction energy dissipation is used in sliding isolation systems which dissipate energy due to the work done by friction. Frequently, friction does not offer adequate protection against excessive relative displacements so a restoring force is used. This restoring force can either be a spring or else the sliding surface may be slightly curved to allow gravity to settle the structure (Chopra, 1991). Thus, passive isolation is characterized by its choice of dampening method.

Active base isolation is defined by using a hydraulic actuator to provide the dampening to the base isolation system. Mullenix, et al. (2006) has shown that coupling a passive isolation system with an active control strategy can reduce base shear. However, these results were found by only investigating one dimensional excitation and planer motion of the structure. This paper will expand on that body of research by discussing the system identification process for the full three-dimensional structural system, as well as future plans for control design and experimental verification.

## EXPERIMENTAL SETUP

To experimentally evaluate the performance of the active control strategy, a model building was constructed at the Smart Structures Laboratory at the University of Illinois at Urbana-Champaign. This structure has an isolation layer and is outfitted with three hydraulic actuators to provide active control. Feedback measurement are provided by accelerometers placed at each floor level and the LVDTs that are co-linear with the actuators.

In this current phase of research, a two-story building was considered. The test structure is a two bay steel frame building with floors consisting of 45" x 28" x 1" steel plates weighing 360 lbs. each. Each story is supported by six columns made of 100 ksi steel. At a later stage of research, the full six story structure will be tested. This model building was designed to be dynamically similar to an existing building for which an isolation system was considered to address seismic deficiencies.

The isolation layer used was provided by WorkSafe Technologies, consisting of six ISO-Base units which employ two conical load plates around a 1" ball bearing. This product is used to protect data servers and other valuable equipment from seismic ground motions. This setup provides for low-friction isolation that is appropriate for scale-model testing and allows for a meaningful tests of the active control strategy.

Three hydraulic actuators are used to provide active control to the structural system. Each actuator has a stroke of  $\pm 4.38$ " and a force capacity of 750 lbs. at 3000 psi. The

actuators are tuned with a simple proportional gain controller to provide consistent response in the frequency range of 0-50 Hz. The actuators were excited with a 50 Hz band limited white noise input signal to provide a response in the frequency range of interest. The transfer functions from the input control signal to the output LVDT measurements over a 50 Hz bandwidth are shown in Figure 1.

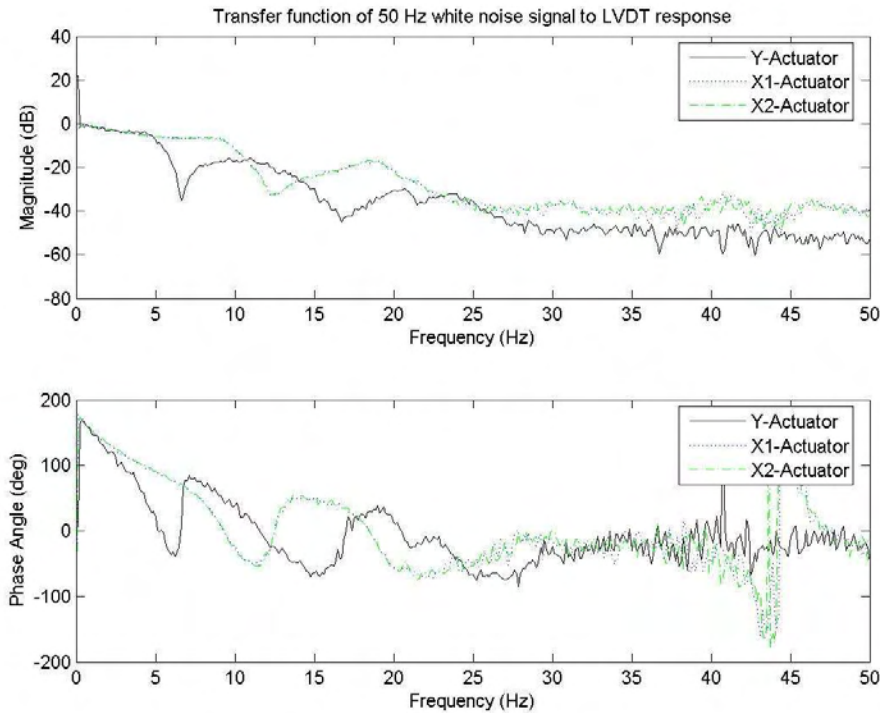


Figure 1: Transfer function from input command to LVDT responses.

Figure 1 Shows that the two X actuators have a nearly identical transfer function which indicates that the structure is symmetric and that the actuators are well-tuned which should make rotational control easier.

Feedback measurements are provided by accelerometers and LVDTs. Accelerometers are placed at each story and co-linear with each actuator. Using this arrangement, each story's acceleration is determined in the X and Y direction as well as determining the angular acceleration of the structure corresponding the torsion degree of freedom. LVDTs are attached to the actuators, not only providing closed-loop feedback control for the actuators themselves, but also the ground floor displacement in the X and Y directions and the ground floor rotation corresponding to torsion.

A picture of the experimental structure is shown below in Figure 2.



Figure 2: Picture of test structure during system identification stage

## SYSTEM IDENTIFICATION AND VALIDATION

To develop a well-defined control law, an accurate system identification needs to be completed. There are two major ways to identify a system, either analytically or experimentally. An analytical model requires detailed knowledge of the structural parameters of the system and is not practical with full scale structures. Therefore, experimental system identification is used, where the system is modeled as linear and time-invariant. Multi-input multi-output (MIMO) model is thus obtained. This procedure has been experimentally validated by previous tests (Dyke, et al, 1995; Dyke, et al, 1996).

System identification was done using a 50 Hz band limited white noise exciting the structure in the X, Y, and  $\theta$  directions. This was accomplished by developing a transformation model that took an input signal of X and Y displacements and Z rotation and transformed the signal into actuator commands. This arrangement isolated certain structural modes when the system was excited along a specific axis.

Transfer functions were calculated from the respective input excitation to the output LVDT and acceleration measurements. The plots of these transfer functions are shown in Figures 3-10.

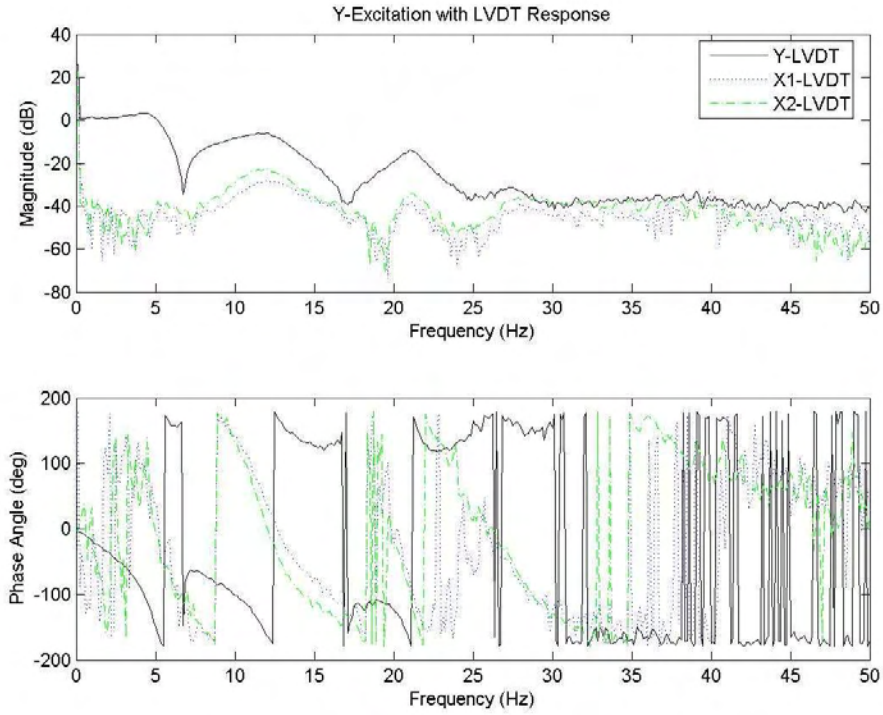


Figure 3: Y Excitation with LVDT Response

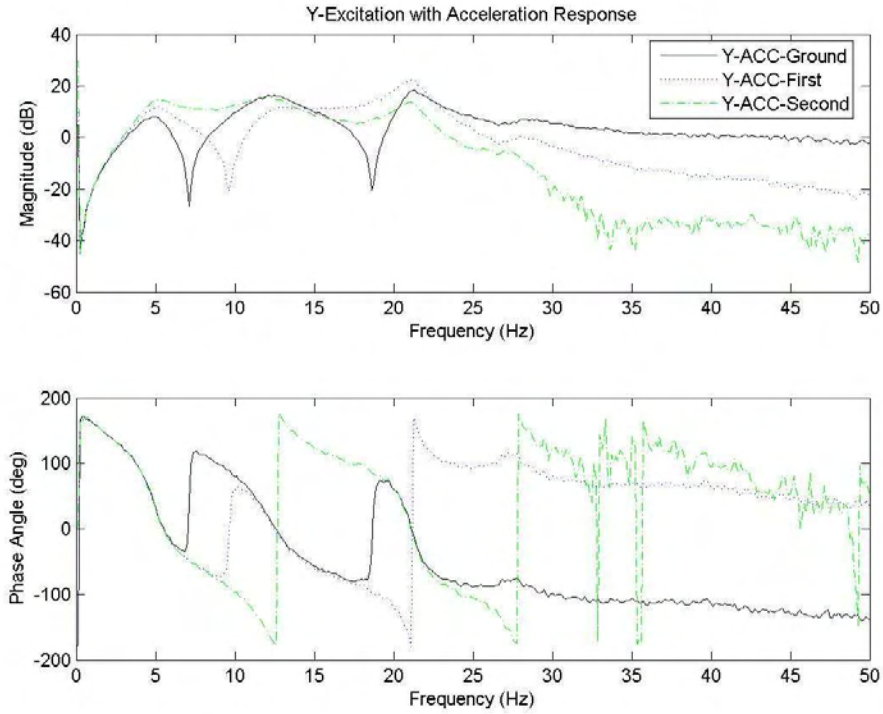


Figure 4: Y Excitation with Acceleration Response

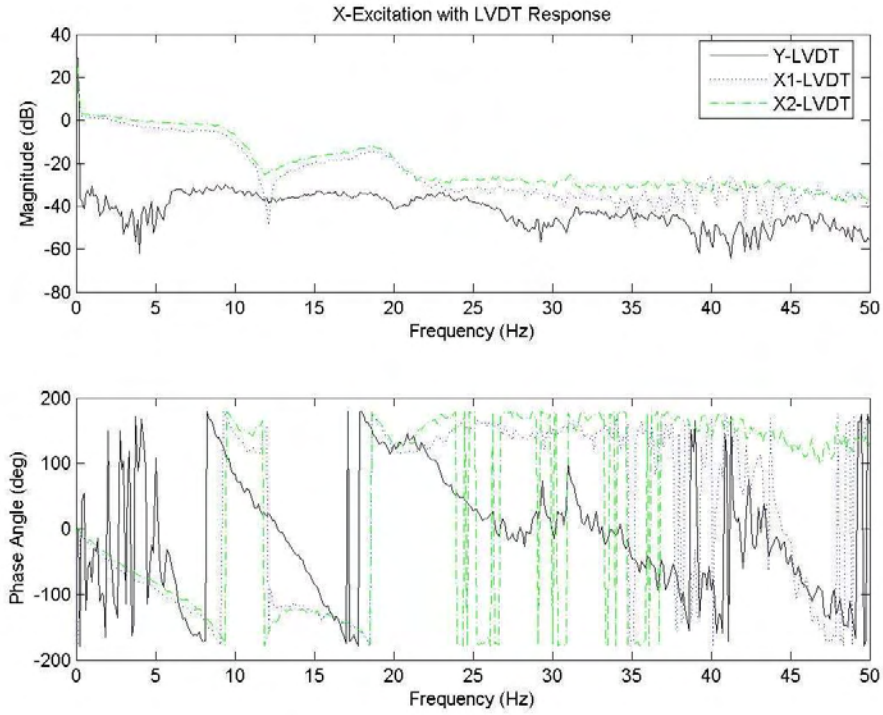


Figure 5: X Excitation with LVDT Response

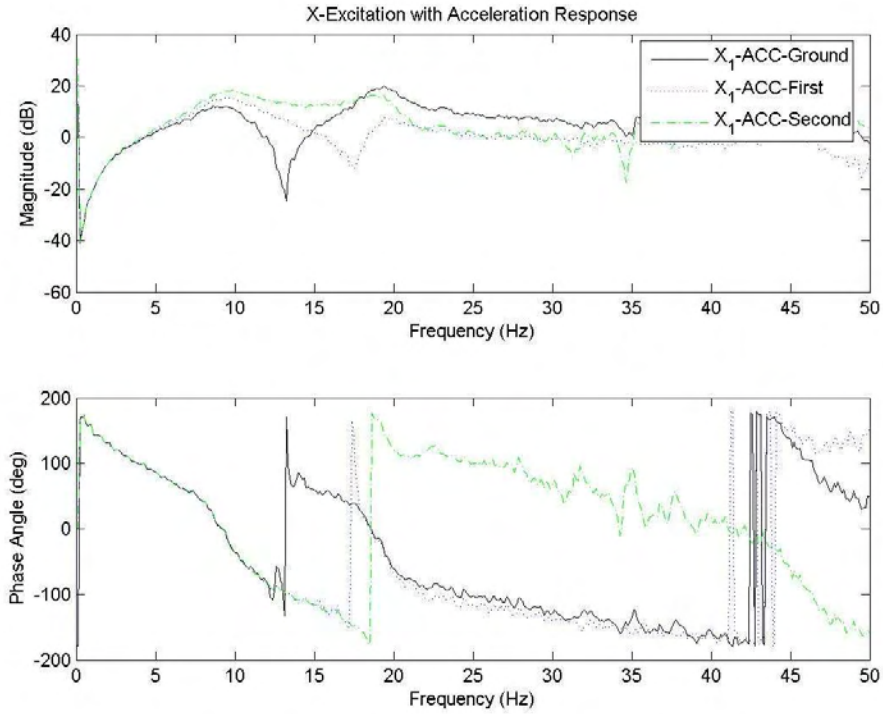


Figure 6: X Excitation with Acceleration Response

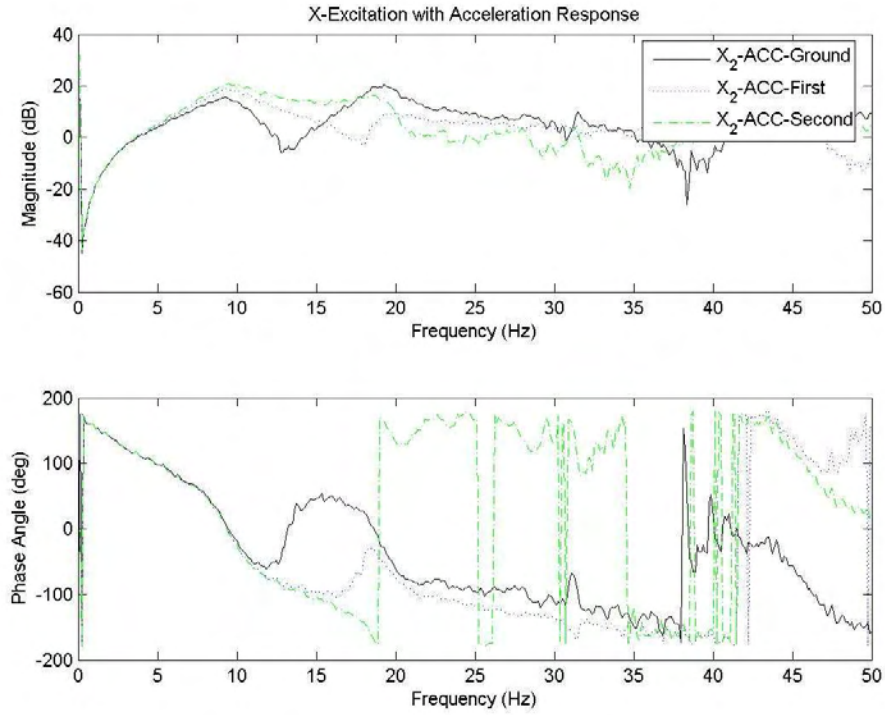


Figure 7: X Excitation with Acceleration Response, cont.

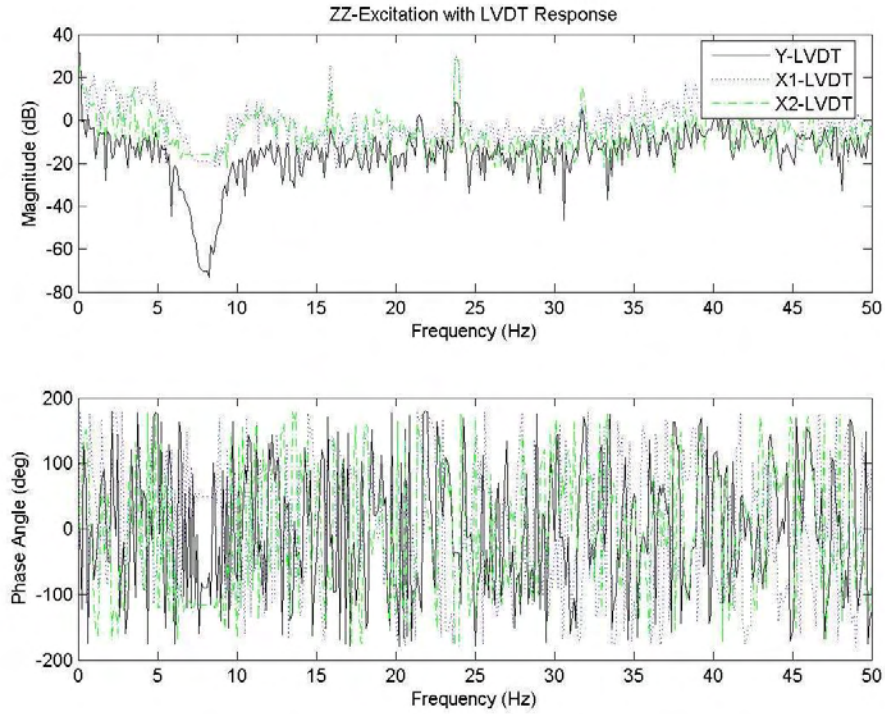


Figure 8: ZZ Excitation with LVDT Response

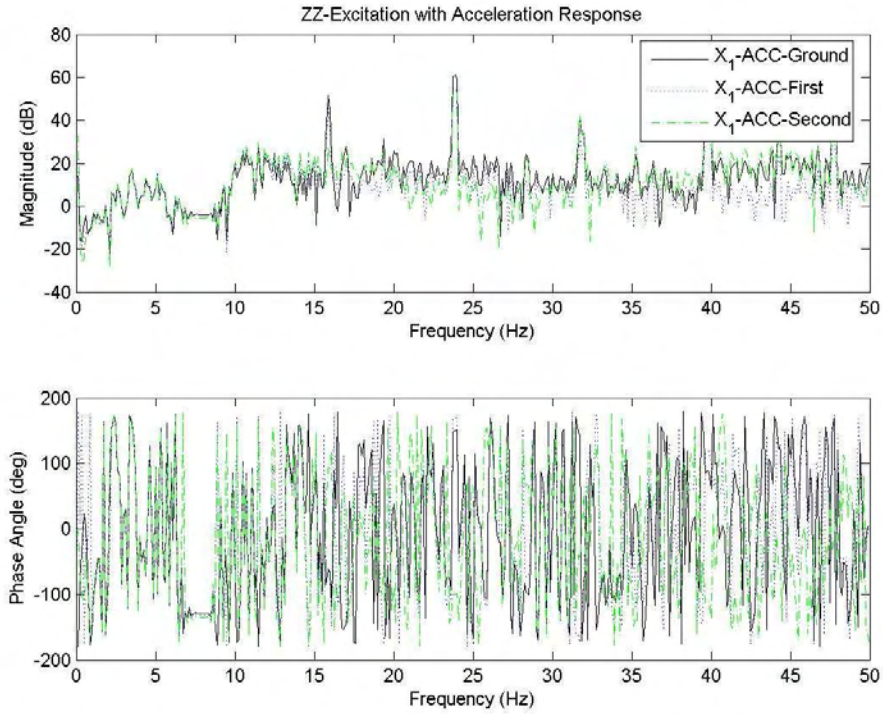


Figure 9: ZZ Excitation with Acceleration Response

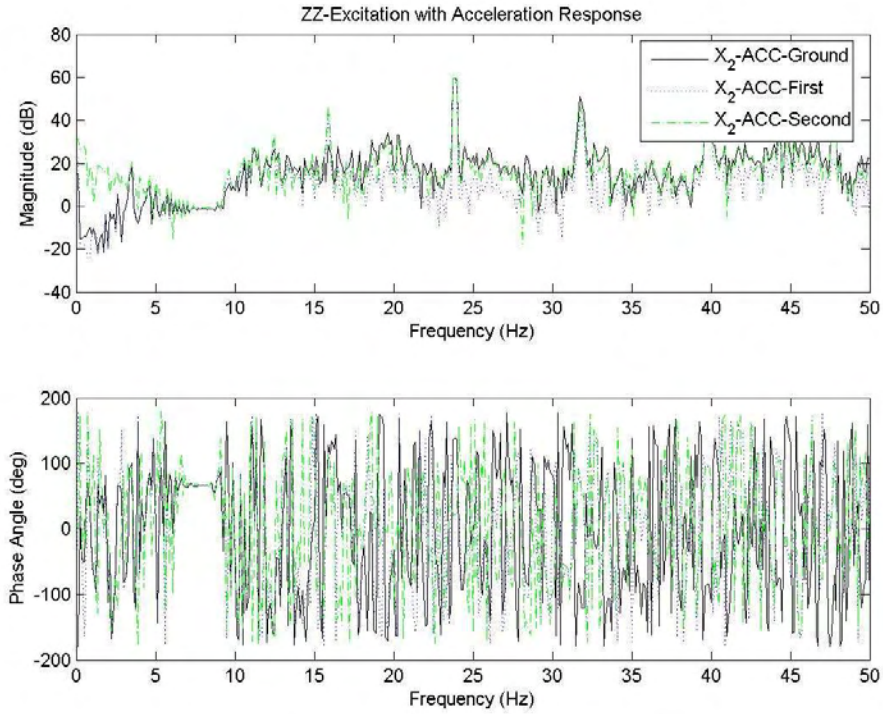


Figure 10: ZZ Excitation with Acceleration Response, cont.

The excitations for X and Y had a root mean square amplitude of 0.2 in. and the resulting transfer functions met expectations. Using data from Mullenix, et al. (2006), the Y excitation transfer functions were compared and found to be nearly identical.

However, the Z rotation excitation transfer functions (Figures 8-10) do not clearly show the relevant poles corresponding to the torsion modes of the structure. There are two reasons why the data is deficient. First, the amplitude of the excitation was 0.18 degrees which may or may not be a large enough magnitude to excite the structure. Second, the torsion modes may be in a higher frequency range than was collected and a detailed numerical analysis would be useful to determine if this contributed to the problem. Therefore, more experimentation is necessary to identify the structure for torsion modes.

To build an analytic model of the structure, the transfer function data was curve-fit using MFDID. MFDID is a three stage frequency domain identification program which utilizes the linear least-squares algorithm and then refines this estimate with Steglitz-McBride method and the Levenber-Marquardt method (Kim, et al., 2005). This model will be used for control design in later stages of research.

## CONCLUSIONS AND FUTURE WORK

System identification of the structure proved effective for X and Y translation excitation. The resulting transfer function data will enable a control law to govern the structure in two dimensions; however, it will be unable to realize rotational control due to the incomplete data from the Z excitations.

In the future, the process outlined in this paper will be extended to develop a control law to govern the horizontal degrees of freedom. The effectiveness of this control law will be experimentally tested by subjecting the structure to historical ground motions and monitoring the structural response.

Also, more work is necessary to identify the structural system when it is subjected to Z rotations. This will enable the controller to compensate for the torsion modes of the structure.

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