Multiple-Model Seismic Structural Control

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***Abstract*— the aim of this research is to develop an approach for seismic protection of high-risk structures with multiple-model structural control. Structural control provide opportunity to realize measures for reduction of seismic vulnerability of high risk structures, like nuclear power plants, bridges, lifelines, dams, high rise buildings etc. In this paper is proposed an approach for multiple-model for active and semi-active structural control realised with removable cross-braces control systems, where each system corresponds to different actuator or combination of actuators for structural control. After determination of frequencies characteristics, resonances and anti-resonances, is made decision about reconfiguration of the system. The semi-active structural control is realised by engaging a subset of all possible actuators. The choice of the actuator subset, made on the base of frequency response and magnitude characteristics leads to reconfiguration of the structural control system. The active bracing structural control system is realized with acceleration feedback strategies. An algorithm for multiple-model real-time control is proposed. The simulation results for active and semi-active bracing experiments provided with a model of three storey building are shown.**

Keywords*— *Structural Control; Multiple-Model Approach; Simulation and Modeling of Seismic Signals; Strong Motion Seismic Waves; Controllers; Sliding Mode Control.

I. INTRODUCTION

The aim of this research is to develop an approach for seismic protection of high-risk structures with multiple-model structural control. Structural control provide possibility to realize measures for reduction of seismic vulnerability of high risk structures, like nuclear power plants, bridges, lifelines, dams, high rise buildings [5]. Displacements and velocities of the structures during earthquake are not absolute but depend upon inertial reference frame in which they are taken. As it is not always possible to provide structural response measurements during strong motion earthquakes their modelling by computer simulation enable earthquake engineers to compare and study the behaviour of structures during earthquakes, regarding their overall characteristics and potential of structural damages [5]. The structural control theory methods and their applications in state space, allow almost complete elimination of the negative motions in the structure, by employing active or semiactive control [4]. The active control strategies have been developed as one means by which to minimize the effects of seismic loads. The active control systems operate by external energy supplied by actuator to impart forces on the structure. The main drawback of this approach is that in order to achieve this effect it is required to apply control actions with magnitude, similar with the seismic one [7]. This is difficult to accomplish in practice. Actually, full elimination of the seismic effect on the structure is not needed. It is sufficient enough to reduce this effect to a degree to which it can be guaranteed that the structure will not sustain damage or at least will not fail [2]. Due to the possibility of the extreme force of the seismic signal, even this reduction is sometimes difficult to achieve. In order to accomplish this task it is required to take into account specific characteristics of the structure as well as of the seismic signal.

In this paper is proposed an approach for active/semiactive control for structures. It is applicable for both open loop and close loop control systems realizations. Determination of the seismic signals characteristics is from great importance. Due to the fact, that the response spectrum of the seismic signal varies in time it is proposed that it, or its components can be estimated online. The main goal of the control is accomplished, i.e. sufficient reduction of the structures movement, by combine usage of the modelled seismic signals with the structure, controllers and control realization scheme. This is done by minimizing the effect not to the whole seismic signal, but only to the most dangerous components of it – resonance frequencies or close to them.

II. CONTROL SYSTEM

In this paper is proposed an approach for multiple-model active and semi-active structural control realized with active bracing control systems, where each system corresponds to different device or combination of devices for structural control. After determination of frequencies characteristics, resonances and anti-resonances, is made decision about including different subsystems into the overall control system. This leads to reconfiguration of the structural control system – sliding mode control.

The control system consists from two main parts - controller and controlled structure (Fig.1). It is assumed that many actuators a_1, a_2,…,a_n, can be switched on in the

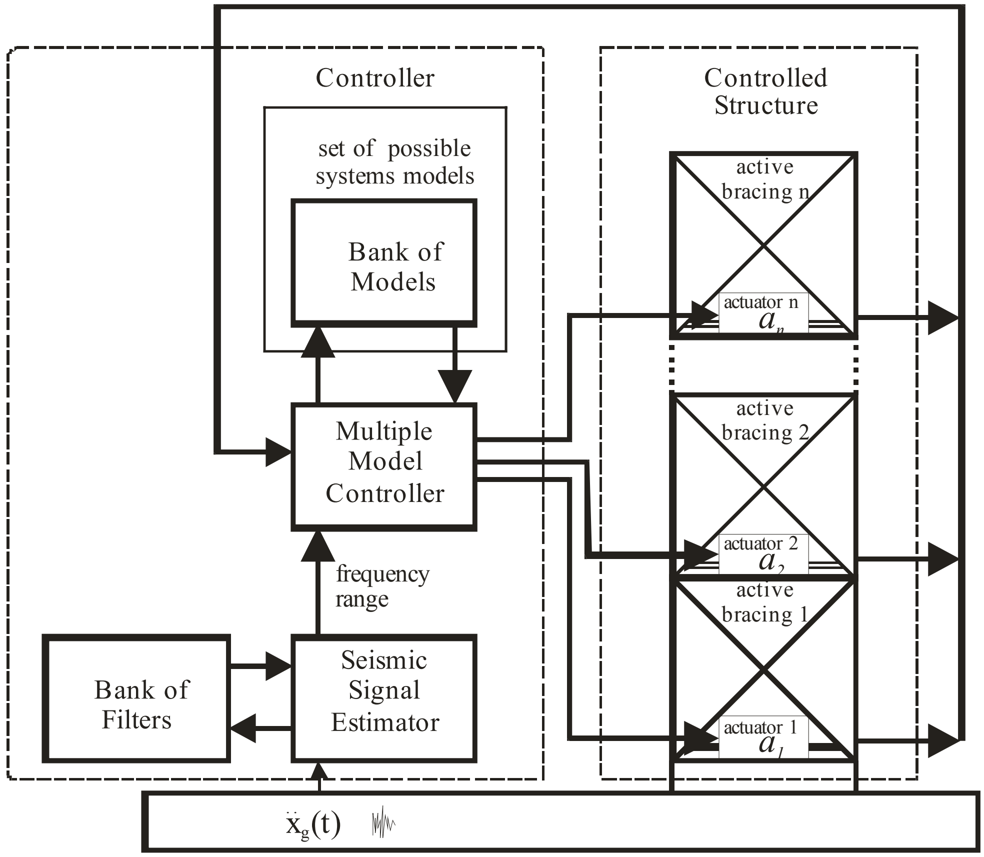

Figure 1 Multiple model seismic structural control system

structure for accomplishment of the control aim. A *set of possible system models* are designed. Each of these models corresponds to a different system's configurations - with one actuator or with different combinations of actuators. Frequency responses, and especially resonance and anti-resonance frequencies and ranges for system models are analyzed.

From the set of all possible models, a subset is selected. This set will be referred as *Bank of Models.* Each model from the model bank corresponds to a particular working regime of the system or to a different system scheme – system in different control configuration. The *Seismic Signal Estimator* determines the seismic resonance range. In order to accomplish this task, a bank of digital filters is set up. This step is performed off-line

During the active faze of the earthquake on-line estimation of the seismic signal resonance is performed. This information is used for *Multiple Model Controller* reconfigurations**.** The reconfiguration task is performed by choosing such control configuration from the model bank that ensures best suppression of the momentary earthquake resonance. In accordance with this selected model, the controller switch on, or switch off the corresponding actuators. By doing so the controller is realizing *sliding mode control* for the system with a variable in time structure. In this way, an adaptation of the control system to the seismic signal is accomplished.

III. STRUCTURE MODELS AND CONTROLLERS

The following matrix differential equation is assumed for a mathematical model of the structure, presented as (1)

$$\mathbf{M}\frac{d^2\mathbf{Y}}{dt^2}+\mathbf{C}\frac{d\mathbf{Y}}{dt}+\mathbf{KY}=\mathbf{FV}+\mathbf{BU}\,. \tag{1}$$

Here **Y** is *n* dimensional vector of the movements in the main points of the structure, **V** is vector representation of the external seismic forces, **U** is *n* dimensional vector of the control signals (it is assumed that control action can be applied to all *n* basic points of the structure), **M**, **C**, **K**, **F** and **B** are matrixes, which represent mass, damping, stiffness, input and control correspondingly.

The feedback principle can be applied for control purpose of this structure. Control vector **U** is computed using information from the vectors of the movements **Y**, velocities dY/dt, accelerations d^2Y/dt^2, as well as combination of these vectors at the structure's basic points. The most general description of the controller can be written in the form (2)

$$\mathbf{U}=-\mathbf{R}_a\frac{d^2\mathbf{Y}}{dt^2}-\mathbf{R}_v\frac{d\mathbf{Y}}{dt}-\mathbf{R}_y\mathbf{Y}. \tag{2}$$

Here $\mathbf{R}_a$ is the feedback matrix in respect to accelerations, $\mathbf{R}_v$ is the feedback matrix in respect to velocities, and $\mathbf{R}_y$ if the feedback matrix in respect to position's movements.

The equation for the closed loop system can be obtained, by substituting the expression (2) into equation (1) as (3)

$$(\mathbf{M}+\mathbf{BR}_a)\frac{d^2\mathbf{Y}}{dt^2}+(\mathbf{C}+\mathbf{BR}_v)\frac{d\mathbf{Y}}{dt}+(\mathbf{K}+\mathbf{BR}_y)\mathbf{Y}=\mathbf{FV}. \quad (3)$$

By comparison between equations (3) and (1), can be observed that components $\mathbf{R}_a$, $\mathbf{R}_v$ and $\mathbf{R}_y$ of the control signal are modifying the plants matrixes **M**, **C** and **K** independently**.** The role of the matrixes **M**, **C** and **K** over the dynamics of the structures is well studied. This makes equation (3) suitable for analysis of the controls signal impact on the systems dynamics (in particular the effect on the discussed below resonance and antiresonance frequencies). This will significantly contribute to the controller design.

From equation (3) it can be analyzed the impact of the controllers matrixes over the properties of the closed loop system: the matrix $\mathbf{R}_v$ of the velocity feedback modifies the damping matrix of the structure **C**. This means that through it, it is possible to be increased the overall damping of the system, i.e. to decrease the resonances. The matrix $\mathbf{R}_y$ of the position feedback modifies the structure's stiffness matrix **K**. This means that with it the resonance frequencies of the system can be changed. Acceleration feedback $\mathbf{R}_a$ has similar impact on the system. It can be stated that the negative acceleration feedback stiffens the system, i.e. it increases its natural frequency. The negative acceleration feedback has the opposite effect – it lowers the plants frequency, i.e. it is equivalent to the increase of the elements of the **M** matrix. The seismic signals are high frequency signals and this will going to produce positive results for the control.

IV. Quality Criteria and Controller Choice

It is convenient to perform system analysis and controller design in accordance to the frequency response approach, due to the clear physical relation between the frequency response and characteristics of the structures movement. Significant danger (during the earthquake) of a structural failure presents coincidence of any natural frequency of the structure with the resonance frequency of the seismic signal. This hazard is increased when the structures has small damping, i.e. with large resonance picks in the magnitude-frequency response.

In this paper is proposed to control the structure's natural frequencies. For controller design purposes it is proposed to be used following quality criteria: *maximum distance between basic natural frequencies of the structure and resonance basic frequencies of the seismic signal*. Of course, in order to apply these criteria, it is essential to have information about the seismic signals. For the spectral composition of the seismic signals or at least his resonance frequencies, some effect can be obtain by the controller if it is tuned in such way that antiresonance of the structure neutralize some of the main resonances of the bedrock.

V. Frequency Response, Resonance and Antiresonance

The paper considers acceleration feedforward and feedback strategies for reduction of structural response during seismic activity with active bracing structural control. Used methods for experimental determination of frequency response function break down into two fundamental types: swept-sine and the broadband approaches using fast Fourier transforms. Both methods can produce accurate frequency response functions estimates.

The swept-sine approach is rather time-consuming, because it analyzes the system one frequency at a time. The broadband approach estimates the frequency response function simultaneously over a band of frequencies. The first step is to independently excite each of the system's inputs over the frequency range of interest.

Exciting the system at frequencies outside this range is typically counter productive; thus the excitation should be bound limited (e.g., pseudo-random). Assuming the two continuous signals (input $u(t)$ and output $y(t)$) are stationary, the frequency response function is determined by dividing the cross spectral density of the two signals S_{uy} by the auto-spectral density of the of the input signal S_{uu}.

More precise investigation of the control effect, natural frequencies and antiresonance as well as controller design can be performed by system's transfer function. By applying the Laplas transform to the equation (3) was received (4)

$$[(\mathbf{M}+\mathbf{BR}_a)s^2+(\mathbf{C}+\mathbf{BR}_v)s+(\mathbf{K}+\mathbf{BR}_y)]\mathbf{Y}(s)=\mathbf{FV}(s). \quad (4)$$

The transfer function can be obtained as (5).

$$\begin{aligned} W(s) &= \frac{\mathbf{Y}(s)}{\mathbf{V}(s)} = \\ &= [(\mathbf{M}+\mathbf{BR}_a)s^2+(\mathbf{C}+\mathbf{BR}_v)s+(\mathbf{K}+\mathbf{BR}_y)]^{-1}=\mathbf{F}, \end{aligned} \quad (5)$$

from which it is easy to compute the resonance frequencies – roots of the polynomial in the denominator and antiresonance frequencies – roots of the polynomial (polynomials) in the nominator. From the transfer function the frequency response of the system can be easily obtained as well.

In cases of high order models of the system, some concerns, regarding the inverse of the polynomial matrix in (5), may rise. In such case a state space model of the closed loop system can be obtained and applied for control purposes. Using the following notations:

$$\mathbf{M}_a=\mathbf{M}+\mathbf{BR}_a,\ \mathbf{C}_v=\mathbf{C}+\mathbf{BR}_v,\ \mathbf{K}_y=\mathbf{K}+\mathbf{BR}_y,$$

equation (3) is transformed to(6).

$$\frac{d^2\mathbf{Y}}{dt^2}+\mathbf{M}_a^{-1}\mathbf{C}_v\frac{d\mathbf{Y}}{dt}+\mathbf{M}_a^{-1}\mathbf{K}_y\mathbf{Y}=\mathbf{M}_a^{-1}\mathbf{FV}. \quad (6)$$

Then, by introduction of the *2n* dimensional state vector $\mathbf{X}^T = [\mathbf{Y}^T (d\mathbf{Y}^T / dt)]$, the model of the closed loop system in state space becomes (7).

$$\dot{\mathbf{X}} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}_a^{-1}\mathbf{K}_y & -\mathbf{M}_a^{-1}\mathbf{C}_v \end{bmatrix} \mathbf{X} + \begin{bmatrix} \mathbf{0} \\ \mathbf{M}_a^{-1}\mathbf{F} \end{bmatrix} \mathbf{V} \tag{7}$$

The resonance and antiresonance frequencies can be obtained from it as well (for example with Matlab® 6.5).

VI. Semi-Active Structural Control

The feedback from the control structure to the controller (Fig.1) creates a possibility for application of active control strategy. This kind of control allows almost complete elimination of the structures movements. However in order to achieve such control, large control action is required.

Multiple model control can be realized without feedback. In this case the controller is working in open loop. The controller determines the control action only on the base on the information for the seismic signal, obtained from the seismic signal estimator. The control is very similar to the gain scheduling. Of course, in such case the control will not be effective as in the closed loop scheme (with the feedback), but still it can be archived significant reduction in the structures movement. The main advantage of the semi-active control is that the control strategy requires significantly less energy for control purposes. Such control can be achieved for example by switching on and off by an actuator (actuators) additional structural elements – removable cross-braces.

On Fig.2 is shown an experimental setup of a model of three degrees of freedom structure with only one actuator. By switching on and off the removable cross-braces the stiffness of the structure is altered. On Fig.3 are presented magnitude characteristics of the structure in nominal regime (without switching the removable cross-braces), as well as in other regime – in which all removable cross-braces are switched on. It can be observed that only these two models are sufficient for damping the seismic signal in the important frequency range. This means that for each frequency at least one of the two characteristic is with negative values. The shown values are expectable the whole range, which guaranties sufficient damping of the seismic signal. This proves that only these two systems models (with switched off and all removable cross-braces switched on) are sufficient to form the model set (Fig.1). Each of the model is preferred than the other one in two frequency ranges. This means that four filters are required for frequency range separation. They form the filter bank of the Seismic Signal Estimator. In that way the crucial frequency range (the range around the resonance frequency of the seismic signal) can be estimated for each time instant. The proposed digital filters are eight orders Butterworth filters. The chosen characteristics of the filters are presented in Fig. 4. During the earthquake the Seismic Signal Estimator detects the presence of the strong signal and estimates his main frequency range. Depending on the predominant magnitude of the corresponding filter the model is chosen. The removable cross-braces system is

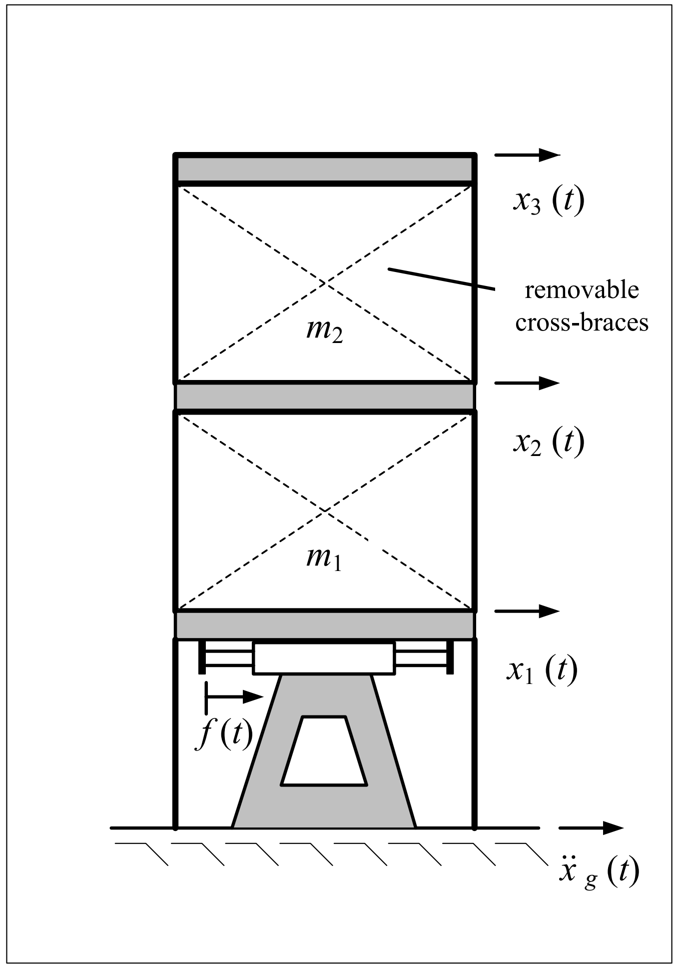

Figure 2 Experimental setup of active bracing control system

switched on and off according to the chosen model, thus the sliding mode control is realized.

On the base on the above discussion an algorithm for control is proposed. It consists from two parts. The first one is design of banks of filters and controllers. The next step is performed in real-time and it is on the base of the obtained from the previous step system.

A. System design

1. Design of a set from possible models for the closed loop system. Each of the models consist of the controlled structure and a controller (or a combination of controllers), which can perform the control tasks without exceeding predefined boundaries of the necessary additional energy for control purposes.
2. Determination of (for each of the closed loop system models) the frequencies response, resonance and antiresonance ranges.
3. Selection of model's bank from a multiple model set. The selection is made in such a way that the antiresonance frequency range overlaps whole possible frequency ranges of the seismic signal.

4. Design of bank from digitals filters. Each of the filters corresponds to the important frequency range of the seismic signal. For the particular model it can be more than one filter.

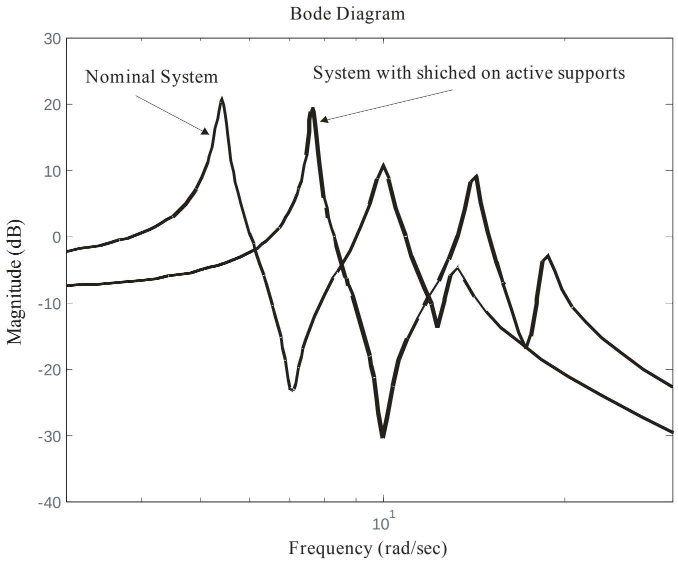

Figure 3 Frequency - magnitude characteristics of the nominal system with removable cross braces.

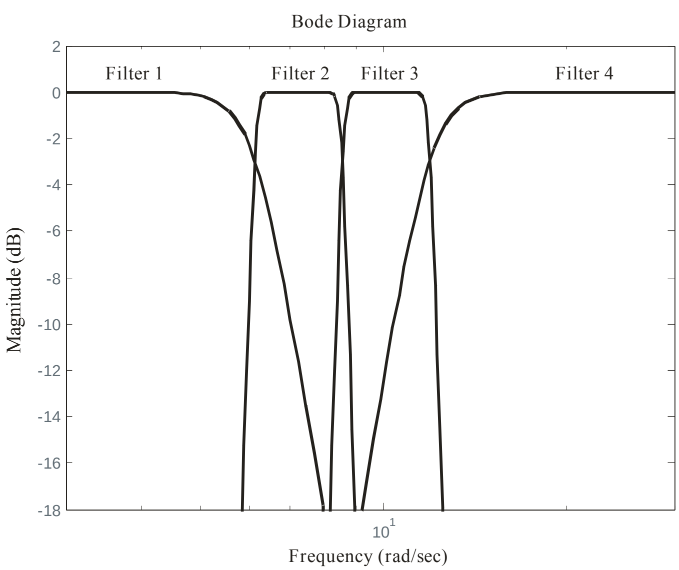

Figure 4 Frequency - magnitude characteristics of the proposed Butterworth filters.

B. *Real-time control*

1. Probability analysis for the arrival moment of the destructive phase of the seismic signal, based on the initial phase of the earthquake (P wave).
2. Estimation of the current resonance frequency of the seismic signal.
3. Model selection from the multiple models set. This is done is such a way that the antiresonance frequencies of the chosen model have the best overlap of the resonance range of the seismic signal.
4. Switch on the chosen controller.

The step 2 of the algorithm is evaluated for each time instant and in case of significant change of the seismic signal resonance frequency the new model selection (steps 3) is selected and new controller configuration is engaged (Step 4).

VII. Experimental Results

In this chapter are presented experimental results for the closed loop system. The simulator used for this investigation consists of a hydraulic actuator servo/valve assembly that drives a 122cm × 122 cm aluminium slip table mounted on high-precision, low-friction linear bearings. The capabilities of simulator are: maximum displacement ±5 cm, maximum velocity ±90 cm/sec, and maximum acceleration ±4 g/s with a 450 kg test load. The operational frequency range of the simulator is nominally 0-50 *Hz*. The test structure, shown on Fig.5, was a model of a three-storey single-bay scale model building. The building frame was constructed on steel with a height of 160 cm. the floor masses of the model weighted a total of 230 kg, distributed evenly between the three floors. The time scale factor was 0,2 making the natural frequencies of the model approximately five times those of the prototype.

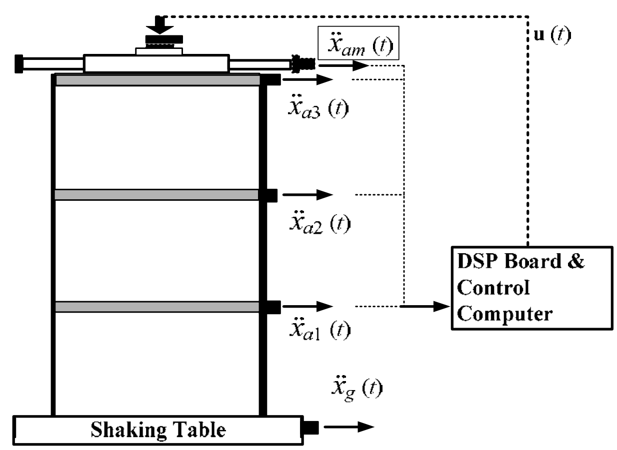

Figure 5. Experimental setup of a three degree of freedom model

As shown in Fig. 5 accelerometers positioned on the each floor of the structure measured the absolute accelerations of the model, and an accelerometer located on the base measured the ground excitation.

To develop a high quality, control-oriented model, an eight channel data acquisition system consisted of eight Syminex XFM82 3 decade programmable anti-aliasing filters were employed. The data acquisition system consists as well of an Analogical CTRTM-05 counter-timer board and the Snap-Master software package. The XFM82 offer programmable pre-filter gains to amplify the signal into the filter, programmable post-filter gains to adjust the signal so that it falls in the correct range for the A/D converter, and analog anti-aliasing filters which are programmable up to 25 *kHz*.

Implementation of the digital controller was performed using the Spectrum Signal Processing Real-Time Signal Processor (DSP) System. The on-board A/D system has two channels with 16 bit precision and a maximum sampling rate of 200 *kHz*. The two D/A channels, also with 16 bit precision, allow for even greater output rates so as not to be limiting.

Typically, times the closed-loop system bandwidth, as was the case in this experiment, the discrete equivalent system will adequately represent the behaviour of the emulated continuous-time system over the frequency range of interest.

Two series of experimental tests were provided to evaluate the performance of the controllers that were designed. First a broadband signal (0-50 *Hz*) was used to excite the structure and root mean square responses were calculated. In the second series of the tests an earthquake-type excitation was applied to the structure and peak responses were determined.

The results include responses for the relative displacement of the actuators, the absolute accelerations of the three floors, $\ddot{x}_{a_1}, \ddot{x}_{a_2}, \ddot{x}_{a_3}$, and the applied control force *f*. The *zeroed-control* case corresponds to the case in which the actuator is attached, but the command signal is set equal to zero (i.e., u=0). From the response of the zeroed configuration it is shown that the “stiffness” of the actuator has a significant effect on the displacement (97,4%) and a moderate effect on the accelerations. Notice that with control, the absolute accelerations of the three floors are reduced by 37,8%, 56,4% and 61,0%, respectively, over the uncontrolled responses, and the first floor displacement is reduced by 95,6%. The controlled responses are achieved by using less force than the zeroed-control case.

Comparison of the uncontrolled, zeroed and controlled transfer functions for the ground acceleration to the first floor absolute acceleration is shown on Fig. 6. Notice that the peaks of the controlled transfer functions from the ground acceleration to the structural responses are significantly smaller those of the zeroed transfer functions. Only the controlled transfer function from the ground acceleration to the actuator displacement is larger in magnitude than the zeroed response, because in the zeroed configuration the actuator attempts to remain in the locked position.

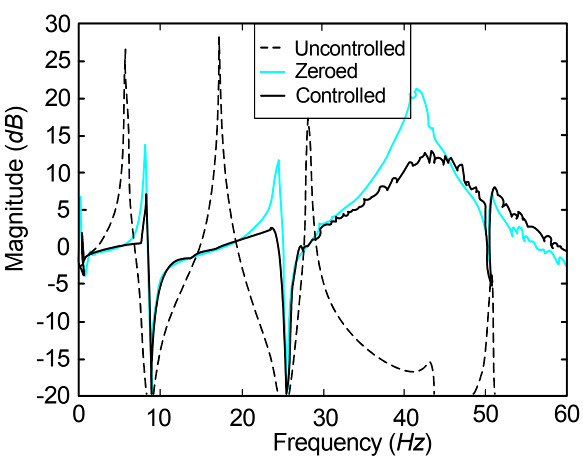

Figure 6. Comparison of uncontrolled zeroed and controlled transfer functions: ground acceleration to the first floor absolute acceleration.

Comparison of the uncontrolled, zeroed and controlled transfer functions for the ground acceleration to the second floor absolute acceleration is shown on Fig. 7.

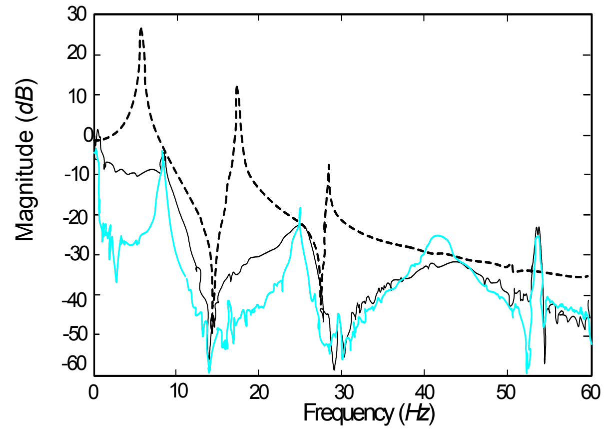

Figure 7. Comparison of uncontrolled zeroed and controlled transfer functions: ground acceleration to the second floor absolute acceleration.

VIII. Conclusions

An approach for seismic protection of high-risk structures with multiple-model structural control has been proposed and evaluated. The effects on actuator dynamics and control structure interaction were incorporated into the system identification procedure, where each control system corresponds to different device or combination of devices for structural control. After determination of the frequencies characteristics, resonances and anti-resonances, a decision about including or not some parts of the system into the total control system is made. This leads to reconfiguration of the structural control system.

Under the broadband excitation on the experimental setup was achieved in total approximately 78% reduction of acceleration responses and a significant response reduction were achieved in different modes of the system. When excited by an earthquake disturbance, the peak response reduction of the top floor acceleration was 68%. The received results show that proposed approach should be regarded as viable and effective for mitigation of structural response due to seismic excitations.

Acknowledgment

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