한국전산구조공학회
1999년도 가을학술발표회 논문집

H_2제어 기법을 적용한 3층 건물의 능동제어 실험

Experimental Study on the Active Control of a Three-story Building using H_2 method

주 석 준*	민 경 원**	이 성 경***	김 성 춘****	홍 성 목*****
Joo, Soek-Jun	Min, Kyung-Won	Lee, Sung-Kyung	Kim, Sung-Choon	Hong, Sung-Mok

ABSTRACT

For the study of the seismic-response control, it is necessary to use an experimental system with an earthquake simulator and control devices employing a hydraulic actuator system. However, such system is too expensive to prepare at the university laboratory. In this research, an economical experimental system is developed which has a small-sized earthquake simulator and an AMD using AC servo motors. An accurate mathematical model of the three-degree-of-freedom test structure with an AMD is developed from the measurement of the input/output relationships of the structure. This paper demonstrates experimentally the efficacy of the frequency domain optimal control algorithm H_2 in reducing the response of seismically excited building to verify the performance of the experimental system.

1. INTRODUCTION

In the area of control of civil structures, it is well-recognized that experimental verification of control strategies is necessary to focus research efforts in the most promising directions. However, civil structures are too big and massive to perform the experiment for structural control in a real scale. Consequently, the majority of control studies to date have been analytical in nature, a substantial number of which have employed models that lacked important features of the physical problems such as system identification, actuator and sensor dynamics, control-structure interaction, actuator

---

* 서울대학교 건축학과, 박사수료
** 인천대학교 건축공학과, 교수
*** 인천대학교 건축공학과, 연구원
**** 인천대학교 건축공학과, 석사과정
***** 서울대학교 건축학과, 교수

saturation effects, output feedback design, limited availability of sensors, digital control implementations, *etc.* This paper focuses the development and verification of economical small-scale experimental system to allow for study of above-mentioned intrinsic features, which include test structure for system identification, an earthquake simulator, and an active mass driver (AMD). The test structure is a model of a flexible building with 3 floors and the earthquake simulator and the AMD are driven by AC servo motors. Of many intrinsic features for structural control, this paper studies mainly system identification and its verification and output feedback design with H_2 control algorithm[1], [2], [3].

2. EXPERIMENTAL SYSTEM

Figs. 1 and 2 show the building model with AMD on the earthquake simulator. The motion of small-size earthquake simulator is controlled by an AC servo motor and the AMD, whose mass is installed on the ball screw, is driven by an AC servo motor and exerts the inertia control force on the building model. The motion performance of the earthquake simulator and AMD is verified and discussed in Min, *et al.* [2].

The motion of the building model under the earthquake load is measured by the accelerometers attached at each floor and converted into digital signals by A/D board. The acceleration signals are used to estimate the building's relative displacements and velocities by Kalman filter and these state variables are based on the derivation of the optimal feedback signal into the controller of the AC servo motor of AMD by employing H_2 algorithm.

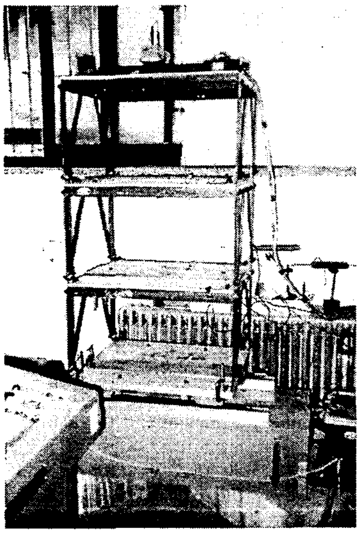


Fig. 1 Experimental Model

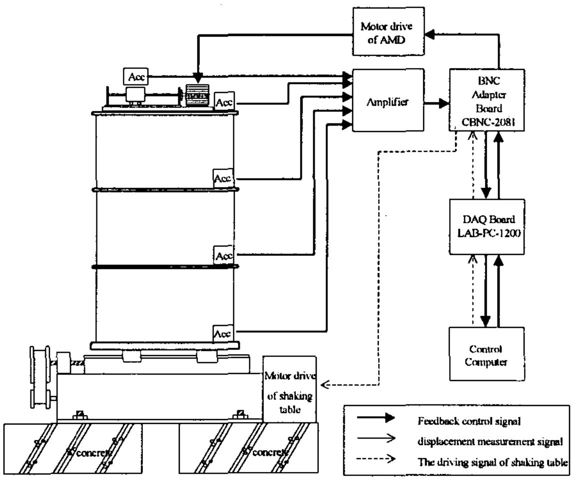


Fig. 2 Experimental Set-up

3. SYSTEM MODEL AND IDENTIFICATION

The input/output relationships of the three-degree-of-freedom test structure with an AMD are measured to develop an accurate mathematical model of the structure. A block diagram of the structural system to be identified is shown in Fig. 3. The two inputs are the ground excitation $\ddot{\mathbf{x}}_g$ and the acceleration of the AMD $\ddot{\mathbf{x}}_m$ relative to the absolute acceleration of the third story. The four measured output vector y include the absolute accelerations of the three floors of the structure and the AMD.

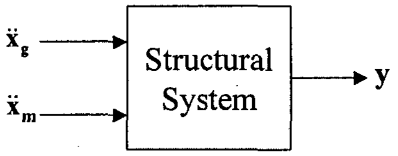


Fig. 3 Block diagram of input/output relationships

The system under consideration is a multi-input/multi-output system (MIMO), two inputs and four outputs system. Thus, a 4×2 transfer function matrix must be identified to describe the characteristics of the system. Because a construction of MIMO system is not straightforward, two separate systems are considered, each with a single input corresponding to one of the two inputs to the system[3].

First, the state equation modeling the input/output relationship between the $\ddot{\mathbf{x}}_g$ and the measured outputs can be realized as

$$\begin{aligned} \mathbf{x}_1 &= \mathbf{A}_1\mathbf{x}_1 + \mathbf{B}_1\ddot{\mathbf{x}}_g \\ \mathbf{y} &= \mathbf{C}_1\mathbf{x}_1 + \mathbf{D}_1\ddot{\mathbf{x}}_g \end{aligned} \tag{1}$$

The second state equation modeling the input/output relationship between the relative acceleration of the AMD to the third floor acceleration and the measured responses are given by

$$\begin{aligned} \dot{\mathbf{x}}_2 &= \mathbf{A}_2\mathbf{x}_2 + \mathbf{B}_2\mathbf{u}_r \\ \mathbf{y} &= \mathbf{C}_2\mathbf{x}_2 + \mathbf{D}_2\mathbf{u}_r \end{aligned} \tag{2}$$

where $\mathbf{u}_r$ is the control force of AMD, which is directly related to $\ddot{\mathbf{x}}_m$.

Because the transfer function characteristics from the inputs to the building response are dominated by the dynamics of the three-degree-of-freedom building, the system requires only six states, corresponding to the three modes of the building. The dynamics of the building are redundantly represented in the above two state equations. The model reduction is performed to represent the state space corresponding to the building dynamics given by

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}_1\ddot{\mathbf{x}}_g + \mathbf{B}_2\mathbf{u}_r \\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{D}_1\ddot{\mathbf{x}}_g + \mathbf{D}_2\mathbf{u}_r + v \end{aligned} \tag{3}$$

where v represents the measurement noise and A, B_1, B_2, C, D_1, D_2 are the state space matrices.

To verify the mathematical model obtained experimentally from the system identification, the simulated and experimental transfer functions are compared. Figs. 4 and 5 show that the simulated transfer functions matched the measured transfer functions well.

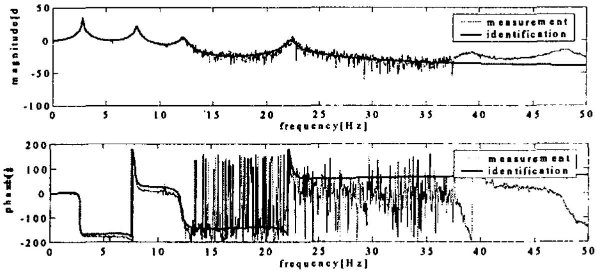


Fig.4 Comparison of Mathematical Model and Experimental Transfer Function from the Ground Acceleration to the Third Floor Acceleration

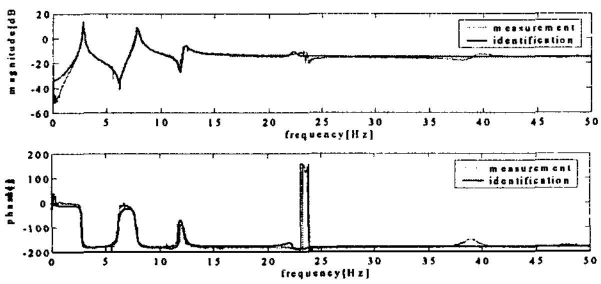


Fig.5 Comparison of Mathematical Model and Experimental Transfer Function from the AMD Acceleration to the Third Floor Acceleration

Furthermore, Figs. 6 and 7 show the comparison of experimental and simulated accelerations under base acceleration and AMD loading in the time domain. In both cases, the experimental and analytical responses matched well, indication that the simulation model is quite accurate.

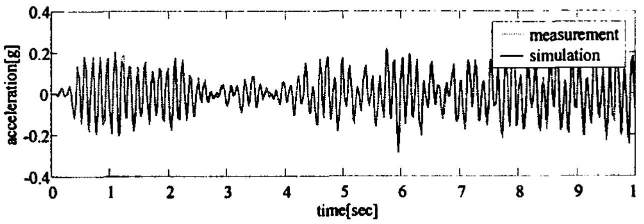


Fig.6 Comparison of Mathematical Model and Experimental Acceleration of the Third Floor from the Ground acceleration

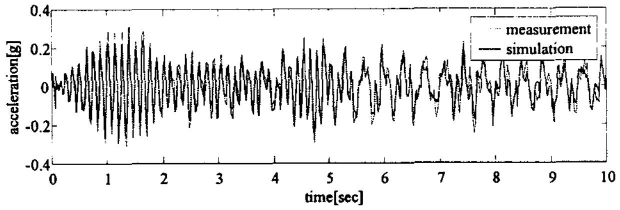


Fig.7 Comparison of Mathematical Model and Experimental Acceleration of the Third Floor from the AMD Acceleration

4. H_2 CONTROL DESIGN

Of many control strategies, linear quadratic control is widely used as it is easy to implement and analyze [4]. However, the strategy has the limitation that it needs the real-time measurements of all state variables (*i.e.*, building's displacements and velocities), which are difficult to achieve for the building structures under earthquakes. Also, the design of controller with the strategy is performed in the time domain. While this study has yielded promising results, choosing meaningful weighting matrices in the performance function of linear quadratic regulator has posed a major difficulty for control designers. Optimal control design methods which are carried out in the frequency domain have recently been presented in the control literature and offer attractive features. Two frequency domain methods for control design are H_2 and H_∞ controls. In this paper H_2 control strategy is used for the control of the building model with an AMD[3]. The H_2 control design searches for a stabilizing controller which minimizes H_2 norm of a transfer function matrix of the system.

Consider a structural control problem in Fig. 8. The structural system ***P*** is excited by disturbance **d** and has two outputs, the measured output y and the regulated output z. The measured output is the result of sensor measurements and is fedback through the controller ***K*** to produce the control force u.

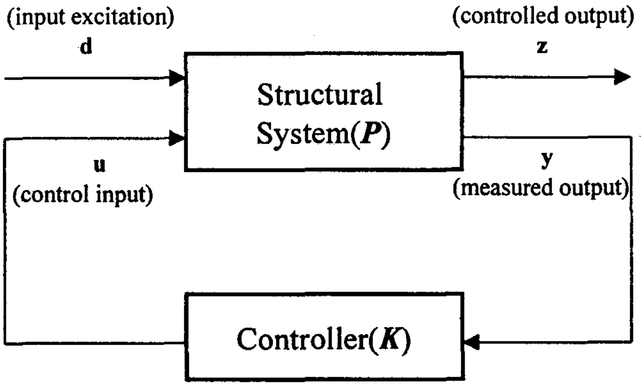


Fig. 8 Basic Structural Control System

To illustrate this approach, consider the problem of controlling a three story building under earthquake excitation. One possible block diagram set up for ***P*** is depicted in Fig. 9.

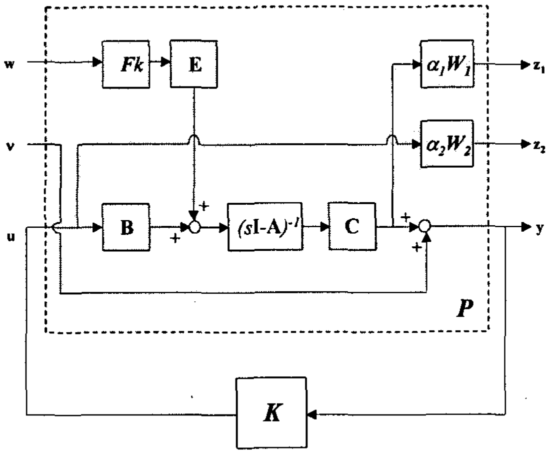


Fig. 9 Control Problem for Structure under Earthquake Excitation

In Fig. 9, **A**, **B**, **E**, **C** are the matrices which are obtained from the previous system identification and form the state-space representation of the experimental model. The input excitation vector **d** consists of a white noise excitation vector **w** and a measurement noise vector **v**. The filter *F* shapes the spectral content of the disturbance modeling the earthquake excitation with El centro earthquake. The scalar parameter *k* is used to express a preference in minimizing the norm of the transfer function form **w** to **z** versus minimizing the norm of the transfer function from **v** to **z**. The matrix weighting functions $\alpha_1 W_1$ and $\alpha_2 W_2$ are frequency dependent, with $\alpha_1 W_1$ weighting the components of regulated response and $\alpha_2 W_2$ weighting the control force vector **u**. The task here is to design a stabilizing controller so that the norm of the transfer function from the disturbance **d** to the regulated output **z** is minimized.

5. EXPERIMENTAL VERIFICATION

In this section, the control performance of an AMD system is verified with the experimental and analytical study on the three-story building model using the H_2 control in reducing the response of seismically excited building. The accelerometer sensors located on the each floor measure the absolute accelerations, which are fed back to estimate the state variables by Kalman filter. Earthquake loadings are generated by using the El centro earthquake. Earthquake loading is transformed to the command signal to drive the earthquake simulator. The earthquake loading is used as an process noise and accelerometer noises of each floor as sensor noises to design the Kalman filter. Fig. 10 shows the comparison of the estimated acceleration and the measured acceleration of the third floor.

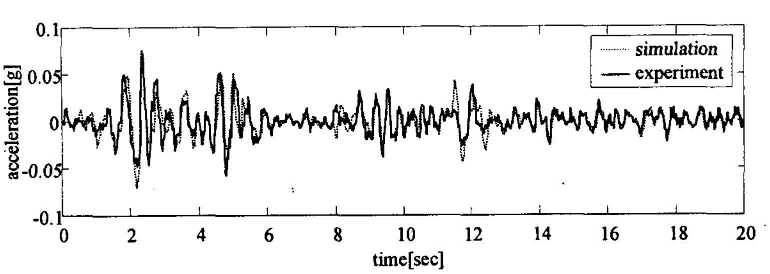
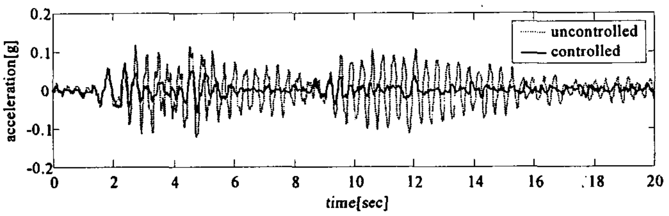


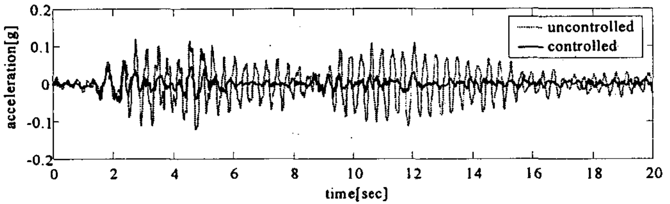
Fig. 10 Comparison of the Third Floor Accelerations from the Experiment and Kalman Filter

The control input **u** for the system is the scalar force generated by the AMD. The regulated output consists of the weighted acceleration of the top floor of the building and the control force, *i.e.*, $\mathbf{z}_1=\alpha_1 W_1 \ddot{\mathbf{x}}_3$ and $\mathbf{z}_2=\mathbf{u}$, where $\ddot{\mathbf{x}}_3$ is the acceleration of the third floor. The frequency dependent weighting function rolls-off at high frequencies to minimize high frequency control effort that can be deleterious to system performance. The weighting function is chosen to roll-off at higher frequency than the first three dominant modes of the building.

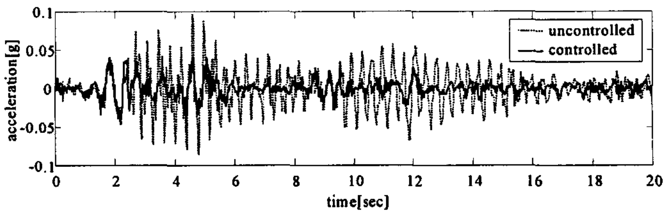
Experimentally measured responses using the H_2 control are compared with the uncontrolled responses and the responses with full-state feedback (*i.e.*, displacement and velocity measurements of the structure) in Fig. 11. It shows that the performance of H_2 controller is verified.



(a) 3rd floor acceleration



(b) 2nd floor acceleration



(c) 1st floor acceleration

Fig. 11 Comparison of Uncontrolled and Controlled (Full-State Feedback and Output Feedback) Accelerations

6. CONCLUSIONS

This paper focuses the development and verification of economical small-scale experimental system including test structures, an earthquake simulator, and an AMD to allow for study of system identification and its verification and output feedback design with H_2 controller. The test structure is a model of a flexible building with three floors. The earthquake simulator and the AMD are driven by AC servo motors. These experimental systems are economical to prepare at the university laboratory. An accurate mathematical model of the three-degree-of-freedom test structure with the AMD is developed from the measurement of the input/output relationships of the structure. This paper demonstrates experimentally the application of the frequency domain optimal control strategy H_2 in reducing the response of seismically excited building to verify the performance of the experimental system.

ACKNOWLEDGEMENT

This research was performed for the natural Hazards Prevention Research Project, one of the Critical Technology-21 Programs, funded by the Ministry of Science and Technology of Korea and Unison Industrial Co., Seoul, Korea.

REFERENCES

[1] M. Battani, G. Yang and B.F. Spencer, Jr., 1998, "Bench-Scale Experiment for Structural Control", Technical Report CMS 95-00301 and CMS 95-28083

[2] K.W. Min and S.K. Lee, 1999, "Experimental System Design and Verification for Seismic- Response Control Using an Active Mass Damper", EASEC-7, in press

[3] B.F. Spencer, Jr., J. Suhardjo and M.K. Sain, 1994, "Frequency Domain Optimal Control for Asesmic Protection Protection", J. Engrg. Mech., ASCE, Vol, No. 1, pp. 135-159

[4] B.D.O. Anderson and J.B. Moore, 1989, "*Optimal Control : linear quadratic methods*", Prentice-Hall International, Inc., pp.1~6