Active Control of Vibrations of a Tall Structure Excited by External Forces

Mohsin Jamil[1, 2, 3], S.M.Sharkh[1], M.Nasir Javid[3] and V.V.Nagendra[3]
[1]School of Engineering Sciences, University of Southampton, [2] National University of Science & Technology (NUST) Pakistan, [3]Dalarna University Sweden.
mj2p07@soton.ac.uk

***Abstract*— This paper is concerned with active control of vibrations of tall structures subjected to strong wind or earth quake shocks using an active mass damper (AMD). A linear black box model of the systems is obtained from an experimental scale model of the structure. Two alternative control systems, and associated observers are designed and their performance assessed theoretically and experimentally.**

I. INTRODUCTION

The advent of high strength, light and more flexible construction materials has created a new generation of tall structures such as high-rise buildings, towers and long span bridges. Due to the smaller amount of damping provided by these modern structures, large deflection and acceleration responses result when they are subjected to environmental loads. It has been shown in field studies that tall buildings that are subjected to wind excitation usually oscillate at the fundamental frequency of the building. In some cases this is coupled with torsion motion, when the torsion and lateral natural oscillation frequencies are close. Such motion, in turn, can cause human discomfort or motion sickness in addition to potential damage to the structure's integrity and safety.

Passive, semi active (hybrid), and active vibration control schemes are becoming an integral part of the next generation of tall buildings [1-5]. These schemes can be grouped into three broad categories: (i) base isolation; (ii) passive damping; and (iii) active damping [6]. Of the three, base isolation can now be considered a more mature technology with wider applications compared to the other two [7]. The implementation of passive energy dissipation systems, such as tuned mass dampers (TMDs), to reduce vibrations of civil engineering structures started in the U.S.A. in the 1970s and in Japan in the 1980s. Basically, a TMD consists of a mass attached to a building, such that it oscillates at the same frequency of the structure but with a phase shift. The mass is usually attached to the building via a spring-dashpot system and the energy is dissipated by the dashpot as relative motion develops between the mass and structure [8].

In the mid 1960s, studies on the dynamic characteristics of sloshing liquid eventually initiated the development of a series of natural sloshing liquid dampers [9]. The rotation dampers have some unique advantages such as low cost, easy installation and adjustment of liquid oscillation frequency, and little maintenance, which are unmatched by the traditional TMD system. The rotation dampers work by absorbing and dissipating energy through the sloshing or oscillating mechanisms of liquid inside a container. Two of the major devices developed in this category include the tuned liquid damper (TLD) and the tuned liquid column damper [10].

There are several configurations of active and hybrid damper systems [3]. The active mass damper (AMD) comprises a relatively small mass connected to the main structure through an actuator. The movement of the mass of an AMD is controlled to be out of phase with the building oscillations. Research and development of active control of tall structure progressed greatly during the 80's in both the U.S.A. and Japan [11-12].

This paper discusses the design and performance of two alternative systems for active control of a tall structure using an AMD system. The static and dynamic characteristics of the structure are indentified using system identification tools based on input-output data sets obtained from experiments performed on a scaled-down model of a tall structure.

II. MODEL TALL STRUCTURE

Knowledge of the dynamic characteristics of a system is one of the most important aspects of control system design. An accurate mathematical model of the system is needed to determine whether a controller is likely to work properly or become unstable. But given the complexity and large scale of tall structures, and the stochastic nature of wind and other exciters of structural vibrations, it is often impractical to perform full scale tests. It will be also expensive, and even impossible to develop complex dynamic models of some tall structures whose parameters can have relatively large tolerances. An alternative, which was adopted in this study and reported in an earlier paper by the first author [13], is to conduct tests on

representative scale model of the structure. The scale model is vibrated either with a random excitation or a deterministic one, and the motion of the structure is measured. System identification tools are used to develop a black box model of the system, which adequately represents its essential dynamic characteristics.

For the purpose of this study, which is concerned with assessment of alternative control strategies and system identification techniques, a relatively simple scale laboratory model of a flexible tall building structure was constructed. The scale model comprises two 1 m long, 0.05 m diameter steel rods fixed to a base on the workbench and supporting a platform at the top end as shown in Fig.1. A plate is attached to the middle section of the structure to provide some aerodynamic damping. An accelerometer is placed on top of the model to measure the response of the structure. The active mass damper is mounted on the top platform. It comprises a mass attached at the end of an arm directly coupled to the shaft of a servomotor actuator. Active damping of structural vibrations is active by rotating the mass of the AMD, using the servomotor, to be in the opposite direction to that of the structure's motion.

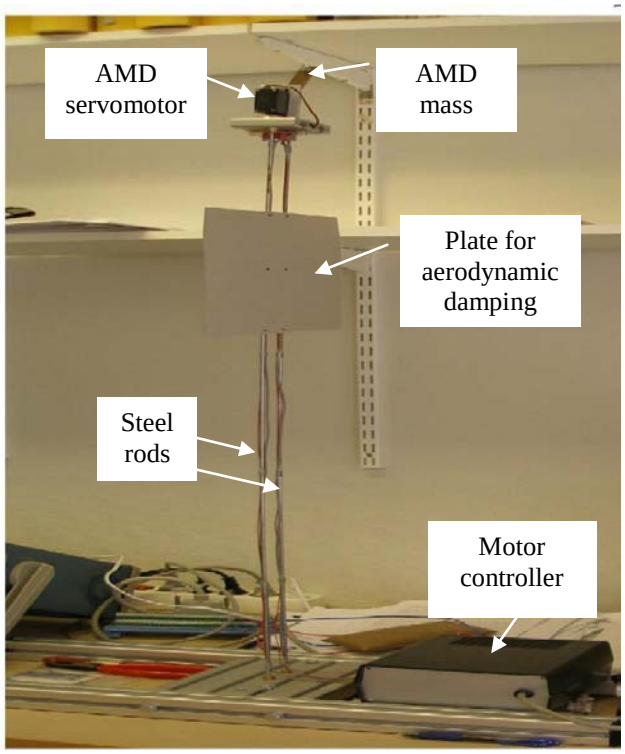

Figure. 1: Experimental Setup

In a typical system identification experiment, a pseudorandom binary signal (PRBS) is applied to the actuator's input resulting in pseudorandom motion of the mass of the AMD. The ensuing vibrations measured by the accelerometer are recorded by the computer. The data was subsequently analysed using the Matlab System Identification Toolbox as discussed in [13].

III. System Identification

Detailed comparison of alternative models ARX, ARMAX, output error and system identification techniques were published previously in [13]. The ARX model was found to provide the best fit.

The discrete identified mathematical model can be represented as follow:

$$\begin{bmatrix} x_1(k+1) \\ x_2(k+1) \\ x_3(k+1) \\ x_4(k+1) \end{bmatrix} = \underbrace{\begin{bmatrix} 3.111 & 1 & 0 & 0 \\ -4.176 & 0 & 1 & 0 \\ 2.882 & 0 & 0 & 1 \\ -0.8708 & 0 & 0 & 0 \end{bmatrix}}_{F} \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \\ x_4(k) \end{bmatrix} + \underbrace{\begin{bmatrix} 0.031 \\ 0 \\ 0 \\ 0 \end{bmatrix}}_{G} u(k) \tag{1}$$

$$y(k) = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}}_{C} \begin{bmatrix} x_1(k) \\ x_2(k) \\ x_3(k) \\ x_4(k) \end{bmatrix} \tag{2}$$

The input $u(k)$ is the actuator demanded relative angular position and the out $y(k)$ is the measured acceleration.

IV. Controller Design

Different types of controller could be used for this application including Fuzzy and LQG (Linear Quadratic Gaussian) controller [14], among others.

Two alternative controllers were investigated:
--Pole placement controller (Polynomial Approach)
--State-space pole placement controller
To estimate unknown states an observer has been also designed. The controllers and observers were designed using the MATLAB software.

A. *Controller 1: Pole Placement Controller*

This controller design method is based on an algebraic solution of the characteristic equation for specified locations of the desired poles of the control system. The solution obtained using a linear recursive algorithm. The pole placement design is based on a model of the process, where the model is formulated as a discrete transfer function $H(z)$ derived from (1) and (2),

$$H(z) = \frac{B(z)}{A(z)} \tag{3}$$

It is assumed that the process is observable and controllable, which means that the system has no common poles or zeros. Specific disturbance models are not used. However, the design method can handle

deterministic disturbances such as load disturbances. From Fig. 2 the transfer function of the control system can be formulated as:

$$\frac{Y(z)}{R(z)} = k_r \frac{B(z)}{A(z)C(z) + B(z)D(z)} \tag{4}$$

where k_r is the steady state static gain. From (4) we can write the characteristic equation as follow:

$$P(z) \equiv A(z)C(z) + B(z)D(z) \tag{5}$$

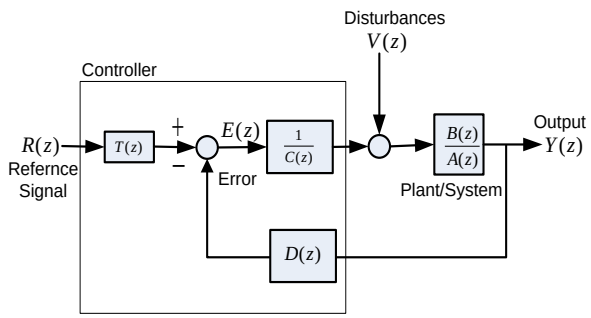

Figure 2: General Pole Placement Design

The unknown polynomials $C(z)$ and $D(z)$ can be calculated using Diophatnus equation. This can be found by defining the orders of the polynomials as:

$$\begin{cases} nc = nb - 1 \\ nd = na - 1 \\ np = na = nb - 1 \end{cases} \tag{6}$$

where *na*, *nb*, *nc* and *nd* represent the order of polynomials A, B, C and D, respectively.

The $C(z)$ and $D(z)$ polynomials are as follows,

$$C(z) = 1 + c_1 z^{-1} + \ldots\ldots\ldots\ldots\ldots\ldots c_{nc} z^{-nc} \tag{7}$$

$$D(z) = d_o + d_1 z^{-1} + \ldots\ldots\ldots\ldots\ldots\ldots d_{nd} z^{-nd} \tag{8}$$

$$p(z) = (1 - q_1 z^{-1})(1 - q_2 z^{-2})\ldots\ldots\ldots(1 - q_n z^{-n}) \tag{9}$$

In the above equations q_1, q_2, q_n represent the closed poles of system. We have some ideas about where the poles should be located. It is obvious that the poles must be located within the unit circle; otherwise the system will be unstable.

The effect of the location of the closed loop poles was investigated experimentally. It was observed that when the poles we located at $z > 0.8$ the system became unstable. This early instability is thought to be due to the unmodelled dynamics and transport time lags in the control system.

The fastest response is achieved when the poles are located at the origin, which gives a dead-beat response. But when we move the poles towards the origin the control effort (actuator input signal) is increased.

As a compromise, the poles were located at z = 0.75, which gives a satisfactory response. The following are the values of the controller parameter that result in the closed loop poles to be at z = 0.75:

Kr=0.1302

C= [1; 0; 0; 0]

D= [3.3333; -26.8333; 40.0833; -18.4531]

B. *Controller 2: State-Space Controller*

A linear state-space model is the basis when the controller is formulated.

$$\begin{cases} x(k+1) = Fx(k) + Gu(k) \\ y(k) = Cx(k) \end{cases} \tag{10}$$

where *F*, *G* and *C* are defined in (1) and (2)

Suppose that all states can be either measured using transducers or estimated using an observer, the control signal is formed by the feedback structure shown in Fig. 3, where $r(k)$ is reference, K_r is constant gain factor and weight factor *L* is a row vector of *n* elements.

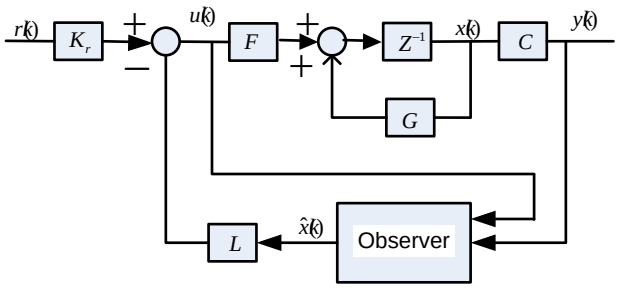

Figure 3: Block Diagram of State- Space Controller

--Observer Design:

Based on the linear discrete model, the observer is formulated as follows:

$$\underbrace{\hat{x}(k+1)}_{\text{Estimated States}} = \underbrace{F\hat{x}(k) + Gu(k)}_{\text{Predictive States}} + \underbrace{K\left\{y(k) - C\hat{x}(k)\right\}}_{\text{Correction Term}} \tag{11}$$

Let M_o be the Observability matrix *and* $P_o(F)$ *is* a function of the model matrix *F* and desired observer poles. Using the Ackermann's formula we obtain,

$$K = P_o(F) M_o^{-1} \begin{bmatrix} 0 & . & . & . & 1 \end{bmatrix}^T \tag{12}$$

$$P_0(F) = (F - q_1 I)\ldots\ldots\ldots\ldots(F - q_n I) \tag{13}$$

$$M_o = \begin{bmatrix} C & CF & . & . & CF^{n-1} \end{bmatrix}^T \tag{14}$$

After testing for observability, the observer gains were calculated to be:

$$K = \begin{bmatrix} 0.9113 \\ -2.3609 \\ 2.2168 \\ -0.7793 \end{bmatrix} \tag{15}$$

--Controller Design:

From Fig. 3 we can write:

$$u(k) = K_r r(k) - Lx(k) \tag{16}$$

After testing controllability, the weight factor L can be found using Ackermann's formula [15]:

$$L = \begin{bmatrix} 0 ..... & 0 & 1 \end{bmatrix} M_c^{-1} P(F) \tag{17}$$

Where M_c be the controllability matrix and $P(F)$ is a function of the model matrix F and the desired poles (q_1 .. q_n),

$$P(F) = (F - q_1 I) ..... (F - q_n I) \tag{18}$$

$$M_c = \begin{bmatrix} G & FG & ..... & F^{n-1}G \end{bmatrix} \tag{19}$$

After suitable selection of poles location at z= 0.75 we get value of L and K_r as below:

$$\begin{cases} \text{L} = [3.6005 \quad 20.6017 \quad 23.7902 \quad 9.7116] \\ \text{Kr} = 0.126 \end{cases} \tag{20}$$

V. EXPERIMENTAL RESULTS

Fig. 4 shows the impulse response of the system without the controller. It typically takes 100 seconds for the system vibrations to die out.

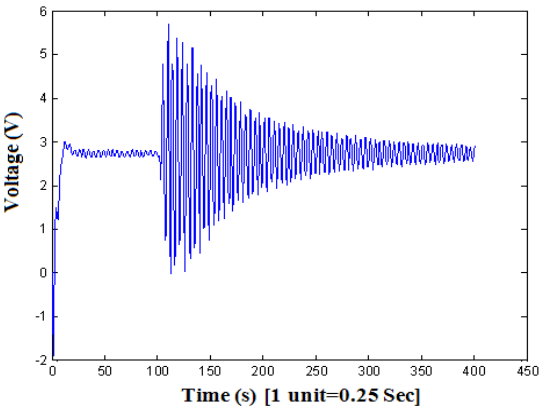

Figure 4: Impulse response without feedback control

Figures 5 and 6 show the impulse response of the system when Controller 1 is used. The vibrations die out more quickly, within 12.5 seconds or so. But the system continues to chatter and the controller does not seem to be effective at damping the self vibrations of the structure.

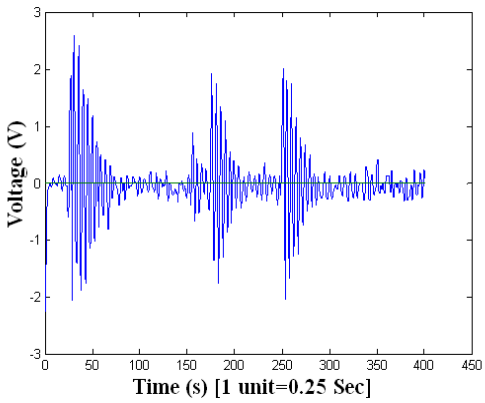

Figure 5: Closed loop multiple impulse responses using controller 1

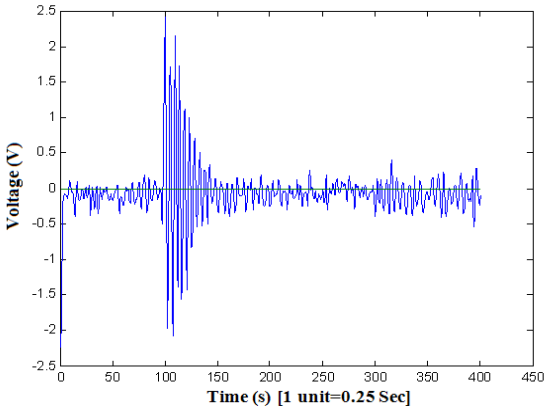

Figure 6: Closed loop single impulse response using controller 1

Figures 7 and 8 show the closed loop impulse response of the system when Controller 2 is used. Again the vibrations are damped very quickly. Additionally, the controller is also capable of almost eliminating the structure's self vibrations.

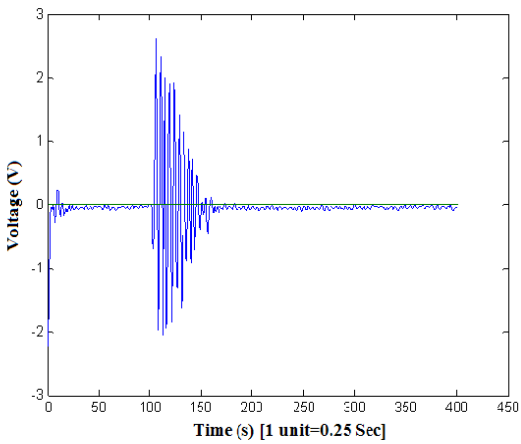

Figure 7: Closed loop single impulse response using controller 2

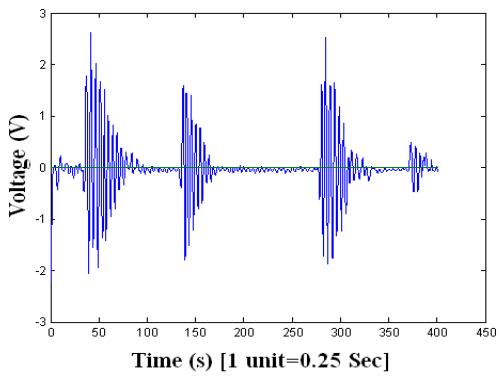

Figure 8: Closed loop single impulse response using controller 2

VI. CONCLUSIONS

The state-space controller appears to be more effective at damping self vibrations of the structure. Both controllers are capable of effective damping of forced vibrations.

ACKNOWLEDGMENT

We would like to thank Bjorn Sohlberg, professor of Dalarna University Sweden for his help and guidance during the project and entire master studies.

REFERENCES

[1] K. SETO, "Large Scale Structures and Their Vibration Problems," vol. 1, No.2 Special Trends of Motion & Vibration Control, pp. pp105-119, 2007.

[2] F. Ricciardelli, A. Occhiuzzi, and P. Clemente, "Semi-active Tuned Mass Damper control strategy for wind-excited structures," Journal of Wind Engineering and Industrial Aerodynamics, vol. 88, pp. 57-74, 2000.

[3] B. F. Spencer, Jr. and M. K. Sain, "Controlling buildings: a new frontier in feedback," *Control Systems Magazine, IEEE,* vol. 17, pp. 19-35, 1997.

[4] K. C. S. Kwok and B. Samali, "Performance of tuned mass dampers under wind loads," Engineering Structures, vol. 17, pp. 655-667, 1995.

[5] M. Gu and F. Peng, "An experimental study of active control of wind-induced vibration of super-tall buildings," Journal of Wind Engineering and Industrial Aerodynamics, vol. 90, pp. 1919-1931, 2002.

[6] Y.Fujino, T.T.Soong, and B. F. S. Jr., "Structural Control: Basic Concepts and Applications," in Proceedings of the 1996 ASCE Structures Congress,, Chicago, Illinois, April 15-181996.

[7] A.Martelli, "International Seventh Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures", Assisi, October 2001.

[8] R.J Faciani, K.C.S.Kwok, and B.Samali, "Wind tunnel investigation of active vibration control of tall buildings," Journal of Wind Engineering and Industrial Aerodynamics vol. 54-55, pp. pp 397-412, 1995

[9] V. J. Modi and S. R. Munshi, "An Efficient Liquid Sloshing Damper For Vibration Control," Journal of Fluids and Structures, vol. 12, pp. 1055-1071, 1998.

[10] James T. P. Yao, "Concept of Structural Control," Journal of the Structural Division, vol. Vol. 98, pp. pp. 1567-1574 July 1972.

[11] A Mazen Wahbeh, John P Caffrey, and S. F. Masri., "A Vision-based approach for the direct measurement of displacements in vibrating systems," Institue of Physics Publishing on Smart Materials & Structures, vol. 12, 2003.

[12] Motoichi Takahashi, Takuji Kobori, Tadashi Nasu, Naoki Niwa, and N. Kurata., "Active Response control of buildings for large earthquakes seismic response control system with variable structural characteristics" Journal on Smart Material Structures, vol. 7, pp. pp.522-529, 1998.

[13] Mohsin Jamil et al."Modelling & Identification for Active Control of Tall Structure Excited By External Forces", Proceeding of 13th IEEE/IFAC Conference on Methods & Models In Automation & Robotics(MMAR 2007) Poland.,pp.1203-1208,August 27-30,2007.

[14] Wu Jong-Cheng and P. Bo-Chen., "Wind tunnel verification of actively controlled high-rise building in along-wind motion," Journal of Wind Engineering and Industrial Aerodynamics, vol. 90, pp. 1933-1950, 2002.

[15] N. S. Nise, Control System Engineering, 4th ed.: John Willy and Sons, 2004.