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Active mass damper system using time delay control algorithm for building structure with unknown dynamics

Dong-Doo Jang[1], Hyung-Jo Jung[*1] and Yeong-Jong Moon[2]

[1]*Department of Civil and Environmental Engineering, KAIST, Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea*
[2]*Construction Technology Center, Samsung C&T Corporation, Seocho 2-dong, Seocho-gu, Seoul, 137-857, Korea*

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Abstract. This paper numerically investigates the feasibility of an active mass damper (AMD) system using the time delay control (TDC) algorithm, which is one of the robust and adaptive control algorithms, for effectively suppressing the excessive vibration of a building structure under wind loading. Because of its several attractive features such as the simplicity and the excellent robustness to unknown system dynamics and disturbance, the TDC algorithm has the potential to be an effective control system for mitigating the vibration of civil engineering structures such as buildings and bridges. However, it has not been used for structural response reduction yet. In this study, therefore, the active control method combining an AMD system with the TDC algorithm is first proposed in order to reduce the wind-induced vibration of a building structure and its effectiveness is numerically examined. To this end, its stability analysis is first performed; and then, a series of numerical simulations are conducted. It is demonstrated that the proposed active structural control system can effectively reduce the acceleration response of the building structure.

Keywords: structural control; adaptive control; time delay control; unknown dynamics; vibration mitigation

1. Introduction

The reduction of excessive responses of a structure caused by various dynamic loads such as earthquakes and strong winds has been a main issue for many years in the field of structural engineering. It becomes more important since many super high-rise buildings are being constructed and planned over the world recently. High-rise buildings are susceptible to strong winds because of their dynamic characteristics such as inherent low damping ratios and low natural frequencies.

It is common and effective that inertial control-type dampers (e.g., tuned mass damper, active mass damper, hybrid mass damper, etc.) are applied to mitigate the undesirable vibration by increasing effective damping ratio of the building. Among them, an active mass damper (AMD) has a high control efficiency, good adaptability and relative insensitivity to site conditions, thus

*Corresponding author, Professor, E-mail: hjung@kaist.ac.kr

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more than 40 buildings have implemented those since Kyobashi Seiwa building in Japan was equipped with AMD firstly in the world in 1989 (Kobori *et al*. 1991a, b).

A lot of control algorithms for an AMD system have been studied (Datta 2001). The most popular control algorithm is based on linear optimal control theory which has a closed-loop system such as LQG and H_2 (Yang 1975, Chang and Soong 1980, Burl 1999). In these algorithms, the control input is to be chosen in such a way that predefined appropriate criteria is minimized. These algorithms need an exact mathematical model of the structure, which leads severe robust problem. Robust control methods such as H_∞ and μ-synthesis can solve that problem by inserting the uncertainties into the algorithm; however, an approximate structure model is required for the better performance and also a complex design procedure should be taken (Burl 1999, Spencer *et al*. 1994, Zhou and Doyle 1998). The pole assignment technique is an approach to choose the gain matrix in such a way that the eigenvalues of the modified matrix take a set of values prescribed by a designer. In the independent modal space control method, a control system is designed similarly to classical linear optimal control methods; however, the design process takes place in the modal space.

The above mentioned control algorithms generally deal with well-known linear time-invariant systems. However, it is obvious that the system parameters are poorly known, time varying or nonlinear in practical applications. For civil engineering structures, especially, the modeling error due to the limited degrees of freedom, nonlinear excursions or time dependent degradation could result in the significant loss of the control effectiveness. Several control methodologies have been developed for resolve those problems. The sliding mode control (SMC) algorithm which can deal with nonlinear systems is one of them. In the SMC algorithm, a sliding surface is generated consisting of a linear combination of state variables and controllers are designed such that they drive the response trajectory on to the sliding surface based on the Lyapunov stability criterion (Yang *et al*. 1994). Intelligent control algorithms such as neural network or fuzzy logic are another powerful strategy (Chen *et al*. 1995, Teng *et al*. 2000). They do not provide strictly optimal control, but are better in terms of practical applications, more versatile and flexible compared to the classical control theories. Adaptive control is an approach that modifies control law used by a controller (Mareels and Poldman 1996, Ioannou and Sun 1996). In the adaptive control algorithm, uncertain plant and controller parameters are estimated recursively with measured information, and then the control input is computed so that the plant output closely follows the desired response.

Time delay control (TDC) belongs to robust and adaptive control algorithms. It was first proposed in the field of mechanical engineering for motion control (Youcef-Toumi and Ito 1987a, 1988). The control input for the TDC algorithm consists of two parts of canceling the uncertainties and adding the desired trajectory and the reference model dynamics. In the first part, the direct estimation of a function representing the uncertain system dynamics and disturbances, which is achieved using values of control inputs, state variables and their derivatives at the previous time step (i.e., time-delayed values), is used to eliminate the unknown system dynamics and disturbances simultaneously. And then, through the second part, the desired dynamics are achieved. It is especially useful for systems with slow dynamics such as civil engineering structures such as buildings and bridges, because it calculates the control input by estimating approximately unknowns simply from the information just in a few previous time steps. The TDC algorithm does not require a complex procedure for identifying exact system dynamics or complex calculation; thus, it is very simple and has excellent robustness properties to unknown dynamics and disturbances. It can be also used for the nonlinear system (Youcef-Toumi and Ito 1987b). Several studies for application of the TDC algorithm such as control of robot manipulator, electrohydraulic servo system, and DC servo motor system were carried out (Hsia and Gao 1990, Chang *et al*. 1995, Chin *et al*. 1994, Chang and Lee 1994). Only a few researchers adopted the TDC algorithm for the vibration isolation table (Shin and Kim 2009, Sun and Kim 2012). However, the researches for vibration mitigation of large-scale structures such as buildings, bridges and towers using the TDC algorithm have not been done yet in the field of civil engineering.

This paper proposes an active mass damper (AMD) system employing the time delay control (TDC) algorithm, which is one of the robust and adaptive control algorithms, for effectively reducing the wind-induced vibration of a building structure and its feasibility is numerically investigated. The structural control problem is defined and the TDC algorithm for structural control is introduced. And then, a simple stability analysis is performed. The effectiveness of the control system using the TDC algorithm is investigated through a series of numerical simulations.

2. Structural control system using TDC algorithm

2.1 Analytical model of building and active mass damper system

An *n*-degree-of-freedom (*n*-DOF) building structure is considered in this study. It is assumed that only one active control system is implemented at the top floor and the responses of the structure can be measured only at the top floor in view of practical situation.

The equation of motion for the *n*-DOF building structure with the active mass damper system at the top floor is described by the following equation

$$\mathrm{M}\ddot{\mathbf{x}}(t) + \mathrm{C}\dot{\mathbf{x}}(t) + \mathrm{K}\mathbf{x}(t) = \mathrm{E_c}\,\mathrm{f_c}(t) + \mathrm{F_e}(t) \tag{1}$$

where M, C and K are the mass, damping and stiffness matrices of the structure, respectively; $\mathrm{f_c}(1\times1)$ and $\mathrm{F_e}(n\times1)$ are the control force and the external force vector such as the wind force, respectively; $\mathbf{x}=[x_1\ \ x_2\ \ \cdots\ \ x_n]^T$ is the displacement vector of the structure; $\mathrm{E_c}=[0\ \ 0\ \ \cdots\ \ 0\ \ 1]^T$ is a constant matrix defining the location of the control force. Let $\varphi_j(n\times1)$ be the *j*-th mode shape vector, which is normalized as $\varphi_j(n)=1$. Then, applying the modal transformation

$$\begin{aligned}\mathbf{x}(t) &= \Phi\mathbf{q}(t)\\ \Phi &= [\varphi_1, \varphi_2, \cdots, \varphi_n], \qquad \varphi_j(n)=1\\ \mathbf{q}(t) &= [q_1(t), q_2(t), \cdots, q_n(t)]^T\end{aligned} \tag{2}$$

and substituting it into Eq. (1), it is transformed into the following modal equation

$$\overline{\mathrm{M}}\ddot{\mathbf{q}}(t) + \overline{\mathrm{C}}\dot{\mathbf{q}}(t) + \overline{\mathrm{K}}\mathbf{q}(t) = \mathbf{1}\mathrm{f_c}(t) + \Phi^T\mathrm{F_e}(t) \tag{3}$$

where $\overline{\mathrm{M}}=\Phi^T\mathrm{M}\Phi$, $\overline{\mathrm{C}}=\Phi^T\mathrm{C}\Phi$ and $\overline{\mathrm{K}}=\Phi^T\mathrm{K}\Phi$ are the modal mass, damping and stiffness matrices, respectively; $\mathbf{1}(n\times1)$ is a vector whose elements are all unity. Eq. (3) can be converted into the state-space form as follows

$$\dot{\mathbf{z}}(t) = A\,\mathbf{z}(t) + B f_c(t) + H(t) \tag{4}$$

where $\mathbf{z}(t) = [\mathbf{q}(t) \quad \dot{\mathbf{q}}(t)]^T$ is the state vector and

$$A = \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ -\mathrm{diag}(\omega_j^2) & -\mathrm{diag}(2\xi_j\omega_j) \end{bmatrix},\quad B = \begin{bmatrix} 0_{n\times 1} \\ \overline{M}^{-1}\,\mathbf{1} \end{bmatrix},$$

$$H(t) = \begin{bmatrix} 0_{n\times 1} \\ h(t) \end{bmatrix},\quad h(t) = \overline{M}^{-1}\,\Phi^T F_e(t) \tag{5}$$

in which ω_j and ξ_j $(j = 1\sim n)$ are the *j*-th natural frequency and the corresponding damping ratio, respectively. Since Eq. (4) is decoupled, it can be separated as follows

$$\dot{\mathbf{z}}_j(t) = A_j\,\mathbf{z}_j(t) + B_j f_c(t) + H_j(t)\,, \qquad j = 1\sim n \tag{6}$$

where $\mathbf{z}_j(t) = [q_j(t) \quad \dot{q}_j(t)]^T$ and

$$A_j = \begin{bmatrix} 0 & 1 \\ -\omega_j^2 & -2\xi_j\omega_j \end{bmatrix},\quad B_j = \begin{bmatrix} 0 \\ 1/\overline{m}_j \end{bmatrix},\quad H_j(t) = \begin{bmatrix} 0 \\ h_j(t) \end{bmatrix},\quad h_j(t) = \frac{1}{\overline{m}_j}\varphi_j^T\,F_e(t) \tag{7}$$

where $\overline{m}_j = \varphi_j^T M \varphi_j$ is the *j*-th modal mass. Summation *n* equations of Eq. (6) throughout and substituting Eq. (8) into it, we obtain Eq. (9).

$$x_n(t) = [\varphi_1(n), \varphi_2(n), \cdots, \varphi_n(n)]^T\,\mathbf{q}(t) = \sum_j q_j(t) \tag{8}$$

$$\dot{\mathbf{x}}_n(t) = f(\mathbf{q}(t), \dot{\mathbf{q}}(t)) + B_n f_c(t) + D_n(t) \tag{9}$$

where

$$\mathbf{x}_n(t) = [x_n(t) \;\; \dot{x}_n(t)]^T,\quad f(\mathbf{q}(t), \dot{\mathbf{q}}(t)) = \begin{bmatrix} \dot{x}_n(t) \\ f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) \end{bmatrix},$$

$$B_n = \begin{bmatrix} 0 \\ b_r \end{bmatrix},\quad b_r = \sum_j 1/\overline{m}_j\,,\quad D_n(t) = \begin{bmatrix} 0 \\ d_r(t) \end{bmatrix},\quad d_r(t) = \sum_j H_j(t) = \sum_j \frac{1}{\overline{m}_j}\varphi_j^T\,F_e(t) \tag{10}$$

and $f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t))$ is the function of modal responses, x_n is the top floor displacement of the building. In Eq. (9) $f(\mathbf{q}(t), \dot{\mathbf{q}}(t))$ can be regarded as the unknown system dynamics.

2.2 TDC algorithm

In this study, the TDC algorithm is used to cancel the undesired system dynamics $f(\mathbf{q}(t), \dot{\mathbf{q}}(t))$ and disturbances $D_n(t)$ in Eq. (9), and generate the desired dynamics of the reference model. Let us define the reference model that generates the desired trajectory as a linear time-invariant system as described below

$$\dot{\mathbf{x}}_{\mathbf{m}}(t) = A_m \mathbf{x}_{\mathbf{m}}(t) + B_m r(t) \tag{11}$$

where $\mathbf{x}_{\mathbf{m}}(2\times1)$ denotes the state vector of the reference model, $r(1\times1)$ is the command input, set here to zero, and

$$A_m = \begin{bmatrix} 0 & 1 \\ \multicolumn{2}{c}{A_{mr}} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_m^2 & -2\xi_m\omega_m \end{bmatrix},\quad B_m = \begin{bmatrix} 0 \\ b_{mr} \end{bmatrix} \tag{12}$$

where ω_m and ξ_m are the natural frequency and damping ratio of the reference model, respectively.

The control objective is to force the error which difference between the actual trajectory in Eq. (9) and the desired one in Eq. (11) to vanish with the following error dynamics equations:

$$\dot{\mathbf{e}}(t) = \dot{\mathbf{x}}_{\mathbf{m}}(t) - \dot{\mathbf{x}}_{\mathbf{n}}(t) = A_m \mathbf{e}(t) \tag{13}$$

By substituting Eqs. (9) and (11) into Eq. (13), the following equation can be obtained as

$$\dot{\mathbf{e}}(t) = A_m \mathbf{e}(t) + \left[-f(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - B_n f_c(t) - D(t) + A_m \mathbf{x}_n(t)\right] \tag{14}$$

By letting the latter term in Eq. (14) be **0**, the control input $f_c(t)$ is given by

$$f_c(t) = \frac{1}{b_r}\left[-f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - d_r(t) + A_{mr}\mathbf{x}_n(t)\right] \tag{15}$$

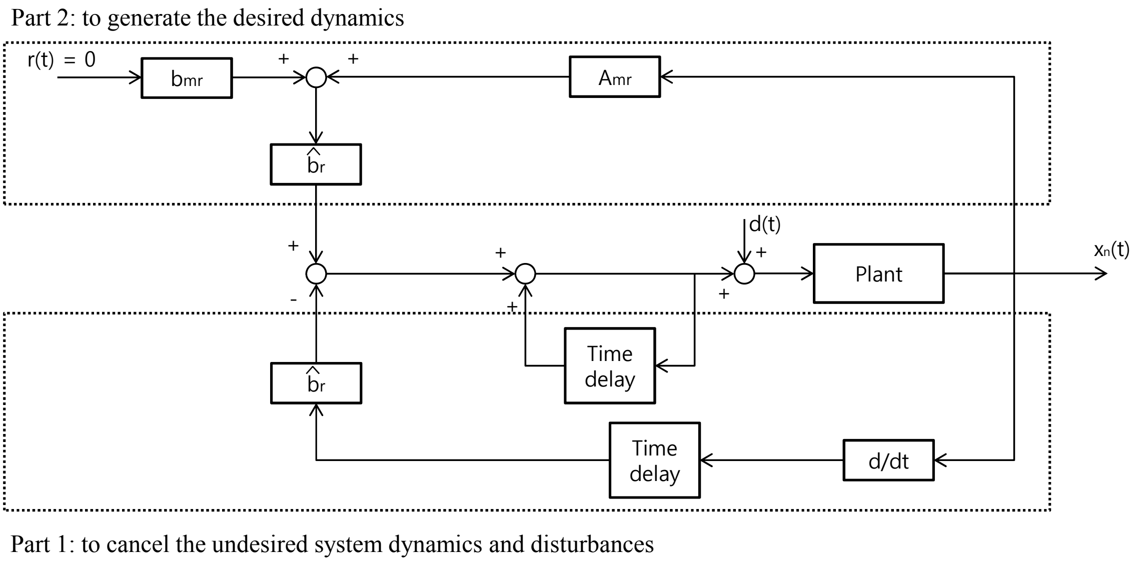


Fig. 1 Block diagram of the TDC algorithm

In this equation, $f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t))$, $d_r(t)$ and b_r are unknown. Let $\hat{b}_r$ be the estimate of b_r, and assume $f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t))$ and $d_r(t)$ are continuous and have slow dynamic characteristics.
Then, $f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) + d_r(t)$ in Eq. (15) can be replaced approximately with $f_r(\mathbf{q}(t-\Delta t), \dot{\mathbf{q}}(t-\Delta t)) + d_r(t-\Delta t)$, where Δt is a time delay very small relative to the time characteristics of the system, and it is determined from Eq. (9) as follows

$$\begin{aligned} f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) + d_r(t) &\cong f_r(\mathbf{q}(t-\Delta t), \dot{\mathbf{q}}(t-\Delta t)) + d_r(t-\Delta t) \\ &\approx \ddot{x}_n(t-\Delta t) - \hat{b}_r f_c(t-\Delta t) \end{aligned} \tag{16}$$

Substituting Eq. (16) and $\hat{b}_r$ into Eq. (15), we get

$$f_c(t) = f_c(t-\Delta t) + \frac{1}{\hat{b}_r}\left[-\ddot{x}_n(t-\Delta t) + A_{mr}\,\mathbf{x}_n(t)\right] \tag{17}$$

Thus, the control input can be obtained with the states and their derivatives which are measured directly or estimated via integration or observer system. Fig. 1 presents the block diagram of the TDC algorithm.

2.3 Stability analysis

Stability is one of the most important performance qualities of a control system and means the ability of a system to approach one of its equilibrium points once displaced from it (Tewari 2002). At this section, the stability of the proposed control system is discussed in detail.
Substituting Eq. (17) into Eq. (9), we get

$$\begin{aligned} \dot{\mathbf{x}}_n(t) &= \begin{bmatrix} \dot{x}_n(t) \\ f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) \end{bmatrix} + \begin{bmatrix} 0 \\ b_r f_c(t) \end{bmatrix} + \begin{bmatrix} 0 \\ d_r(t) \end{bmatrix} + \left\{ \begin{bmatrix} 0 \\ \hat{b}_r f_c(t) \end{bmatrix} - \begin{bmatrix} 0 \\ \hat{b}_r f_c(t) \end{bmatrix} \right\} \\ &= \begin{bmatrix} \dot{x}_n(t) \\ f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) + (b_r - \hat{b}_r) f_c(t) + d_r(t) + \hat{b}_r f_c(t-\Delta t) - \ddot{x}_n(t-\Delta t) + A_{mr}\,\mathbf{x}_n(t) \end{bmatrix} \\ &= \begin{bmatrix} \dot{x}_n(t) \\ f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - f_r(\mathbf{q}(t-\Delta t), \dot{\mathbf{q}}(t-\Delta t)) + (b_r - \hat{b}_r)\{f_c(t) - f_c(t-\Delta t)\} \\ + A_{mr}\,\mathbf{x}_n(t) + d_r(t) - d_r(t-\Delta t) \end{bmatrix} \end{aligned} \tag{18}$$

In the above equation, $f_c(t) - f_c(t-\Delta t)$ can be obtained from Eq. (17); thus, we obtain

$$\dot{\mathbf{x}}_n(t) = \begin{bmatrix} \dot{x}_n(t) \\ f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - f_r(\mathbf{q}(t-\Delta t), \dot{\mathbf{q}}(t-\Delta t)) + (1 - b_r/\hat{b}_r)\ddot{x}_n(t-\Delta t) \\ + b_r/\hat{b}_r\, A_{mr}\,\mathbf{x}_n(t) + d_r - d_r(t-\Delta t) \end{bmatrix} \tag{19}$$

To investigate the stability, the external force, $d_r(t)$, is set to zero, then the above equation can be rewritten as follows

$$\dot{\mathbf{x}}_n(t) = C\mathbf{x}_n(t) + \begin{bmatrix} 0 \\ f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - f_r(\mathbf{q}(t-\Delta t), \dot{\mathbf{q}}(t-\Delta t)) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 1 - b_r/\hat{b}_r \end{bmatrix} \dot{\mathbf{x}}_n(t-\Delta t) \tag{20}$$

where $C = \begin{bmatrix} 0 & 1 \\ b_r/\hat{b}_r A_{mr} \end{bmatrix}$

For small Δt, $f_r(\mathbf{q}(t), \dot{\mathbf{q}}(t)) - f_r(\mathbf{q}(t-\Delta t), \dot{\mathbf{q}}(t-\Delta t)) \approx \dot{f}_r(\mathbf{q}(t), \dot{\mathbf{q}}(t))\Delta t$, and if Δt is chosen small enough such that $\dot{f}_r(\mathbf{q}(t), \dot{\mathbf{q}}(t))\Delta t \approx 0$, then the second term in the right hand side of Eq. (20) can be ignored in comparison to the other terms. Thus, Eq. (20) can be simplified to

$$\dot{\mathbf{x}}_n(t) = C\mathbf{x}_n(t) + \begin{bmatrix} 0 & 0 \\ 0 & 1 - b_r/\hat{b}_r \end{bmatrix} \dot{\mathbf{x}}_n(t-\Delta t) \tag{21}$$

Rewriting Eq. (21) with t replaced by $t-\Delta t$, and subtracting it from Eq. (21), the following equation is obtained

$$\dot{\mathbf{x}}_n(t) - \dot{\mathbf{x}}_n(t-\Delta t) = C\{\mathbf{x}_n(t) - \mathbf{x}_n(t-\Delta t)\} + \begin{bmatrix} 0 & 0 \\ 0 & 1 - b_r/\hat{b}_r \end{bmatrix} \{\dot{\mathbf{x}}_n(t-\Delta t) - \dot{\mathbf{x}}_n(t-2\Delta t)\} \tag{22}$$

Once again, $\mathbf{x}_n(t) - \mathbf{x}_n(t-\Delta t) \approx \dot{\mathbf{x}}_n(t)\Delta t$ for small Δt, and if Δt is chosen small enough such that $\|C\|\Delta t << 1$, then the second term in the right hand side of Eq. (20), $C\dot{\mathbf{x}}_n(t)\Delta t$ can be ignored in comparison to $\dot{\mathbf{x}}_n(t)$.

$$\dot{\mathbf{x}}_n(t) - \dot{\mathbf{x}}_n(t-\Delta t) = \begin{bmatrix} 0 & 0 \\ 0 & 1 - b_r/\hat{b}_r \end{bmatrix} \{\dot{\mathbf{x}}_n(t-\Delta t) - \dot{\mathbf{x}}_n(t-2\Delta t)\} \tag{23}$$

It can be seen that Eq. (23) is the discrete state-space equation by letting $\mathbf{y}(t) = \dot{\mathbf{x}}_n(t) - \dot{\mathbf{x}}_n(t-\Delta t)$.

$$\mathbf{y}(t) = \begin{bmatrix} 0 & 0 \\ 0 & 1 - b_r/\hat{b}_r \end{bmatrix} \mathbf{y}(t-\Delta t) \tag{24}$$

The characteristic equation can be derived as follows

$$\det\left[zI - \begin{bmatrix} 0 & 0 \\ 0 & 1 - b_r/\hat{b}_r \end{bmatrix} \right] = \det\begin{bmatrix} z & 0 \\ 0 & z - 1 + b_r/\hat{b}_r \end{bmatrix} = z\,(z - 1 + b_r/\hat{b}_r) = 0 \tag{25}$$

The system is stable if all roots of Eq. (25) are inside of the unit circle according to the stability analysis of a discrete system; thus, the range of possible $\hat{b}_r$ is

$$\hat{b}_r > \frac{1}{2} b_r \tag{26}$$

In other words, if a designer selects $\hat{b}_r$ as larger than $\frac{1}{2} b_r$, then the system is stable.

In order to apply the TDC algorithm, therefore, $\hat{b}_r$ should be determined first by considering the inequality condition of Eq. (26) for guaranteeing the stability of a control system. As presented in Eq. (10), $b_r = \sum_j^n 1/\overline{m}_j$, where $\overline{m}_j = \varphi_j^T M \varphi_j$ is the *j*-th modal mass. Because mode shapes are normalized such that $\varphi_j(n)=1$, the first modal mass, $\overline{m}_1$, is the smallest. Therefore, the following inequality can be derived

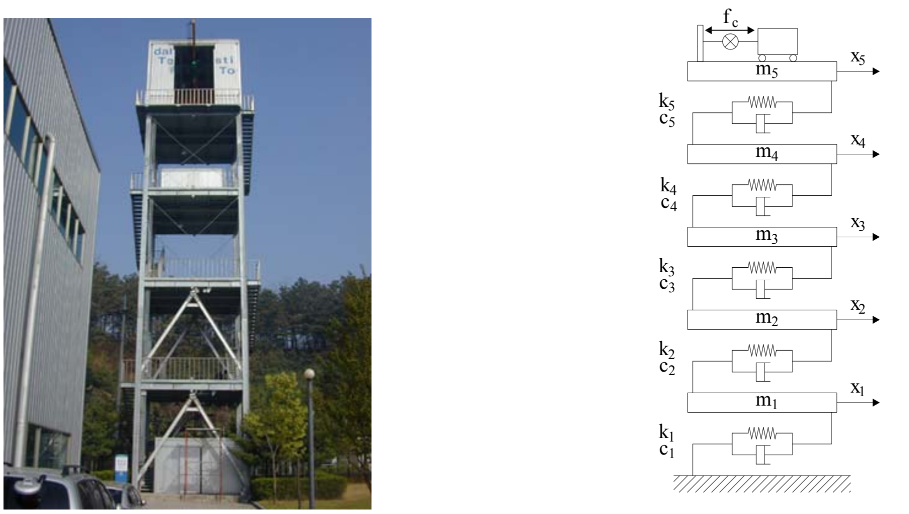
$$b_r = \sum_j^n \frac{1}{\overline{m}_j} < \frac{n}{\overline{m}_1} < \frac{n}{m_n} \tag{27}$$

where m_n denotes the mass of the *n*-th floor. Thus, if we choose $\hat{b}_r$ as $\frac{n}{m_n}$, then the stability condition of Eq. (26) is satisfied obviously. The mass of the *n*-th floor, m_n, can be assumed easily, and it does not need to be exact.

3. Numerical simulations

3.1 Structure model

Fig. 2(a) presents the full-scale five-story steel frame building structure considered in the simulation. The structure is simplified as a 5DOF structure model and an AMD is installed at the top floor as shown in Fig. 2(b) based on the dynamic characteristics of the structure (i.e., the lowest five natural frequencies and the corresponding damping ratios) are presented in Table 1. These dynamic properties were obtained through the system identification using experimental data.



(a) Building structure (b) 5DOF structure model

Fig. 2 Five-story steel frame building structure

Table 1 Dynamic properties of the structure

Mode no.	Natural frequency (Hz)	Damping ratio (%)
1	0.52	1.98
2	1.73	2.01
3	2.95	1.98
4	3.68	1.93
5	5.38	1.98

3.2 Dynamic load

In the simulation, an artificially generated time history of wind load was used as an external force. The wind load can be expressed as (Dyrbye and Hansen 1996)

$$F(t) = \frac{1}{2}\rho C A\bar{V}^2 + \rho C A\bar{V} v'(t) + \frac{1}{2}\rho C A v'(t)^2 \tag{28}$$

where $\rho, C, A, \bar{V}$ and v' are an air density, wind force coefficient, area, mean and fluctuation wind velocity, respectively. The first term of right hand side in Eq. (28) means the static wind load and the other terms denote the wind load fluctuation, and the static wind load is neglected in this study.

A wind velocity fluctuation is defined as the sum of three vectors of along-, cross-wind and vertical directions in general, only along-wind direction component is considered in this simulation though. The power spectral density of the along-wind velocity fluctuation can be written as follows (Kaimal *et al*. 1972)

$$S_v(\omega) = \frac{1}{2}\frac{1}{2\pi} 200\, U_*^2 \frac{z}{\bar{V}(z)} \frac{1}{\left(1 + 50\dfrac{|\omega| z}{2\pi\bar{V}(z)}\right)^{5/3}} \tag{29}$$

where ω is the angular frequency, z is the height, $\bar{V}(z)$ is the mean wind velocity at the height of z, and U_* is the shear velocity. Then, the time history of a wind velocity fluctuation, $v'(t)$, can be obtained using spectral representation method, which is referred to Shinozuka-Deodatis method as follows (Shinozuka and Deodatis 1991, Deodatis 1996)

$$v'(t) = \sqrt{2\Delta\omega} \sum_{i}^{N} \sqrt{S(\omega_i)} \cos(\omega_i t + \phi_i) \tag{30}$$

where $\Delta\omega$ is frequency step, N is the number of frequency points, and ϕ is phase angle randomly defined at the range of 0 ~ 2π. The time history and power spectrum of the generated wind load where $\Delta\omega$ and N are set to 0.0767 and 8192 respectively, are presented in Figs. 3 and 4, respectively.

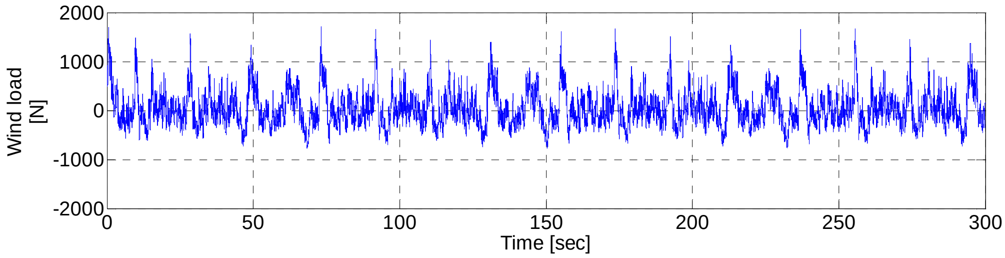


Fig. 3 Time history of the generated wind load

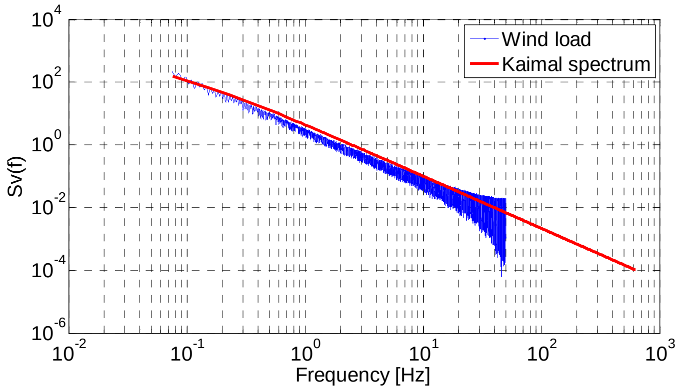
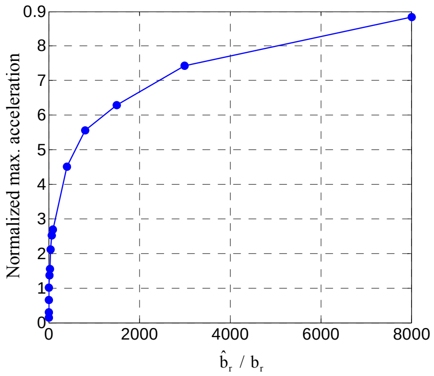


Fig. 4 Power spectrum of the generated wind load

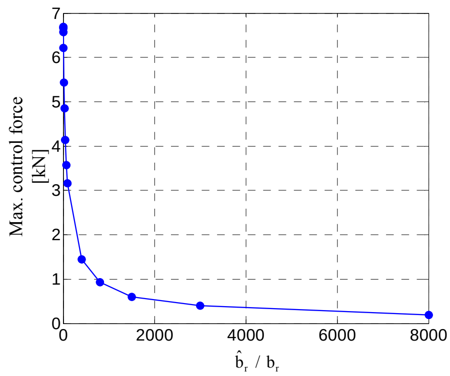
3.3 Simulation results

In order to verify the effectiveness of the proposed control system, a series of numerical simulation are carried out. The reference model (i.e., A_m in Eq. (12)), which generates the desired trajectory, should be designed carefully. In this simulation, the natural frequency and the damping ratio of the reference model were chosen as 0.1 Hz and the critical (i.e., $\xi_m = 1$), respectively, by considering the first natural frequency of the structure (i.e., 0.52 Hz). The time delay, Δt, was set as the sampling time (i.e., 0.001 s). It is assumed that each story of the building structure is subjected to the same wind load shown in Fig. 3.

It is well known that there is a trade-off between control effectiveness (response reduction) and economy (control force requirements) (Soong 1990). That is, a control system usually requires the larger control force in order to reduce the response more effectively. On the other hand, if economy is more important, its control effectiveness will deteriorate due to the smaller control force. Fig. 5, in which (a) top floor's maximum acceleration normalized with respected to the uncontrolled case and (b) maximum control force, clearly shows this trade-off condition of the proposed control system. As seen from the figures, the normalized maximum acceleration at the top floor increases as the ratio $\hat{b}_r / b_r$ increases from 0.51 to 8000, whereas the required maximum control force decreases as the ratio increases.

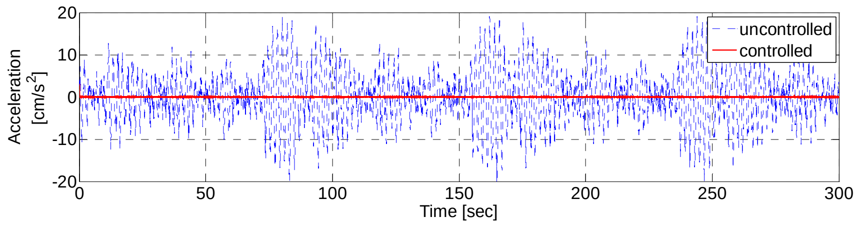


(a) Normalized maximum acceleration

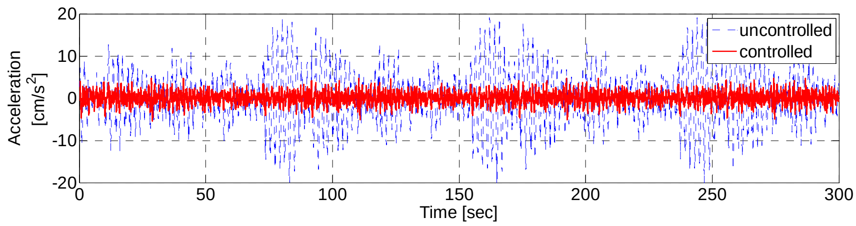


(b) maximum control force

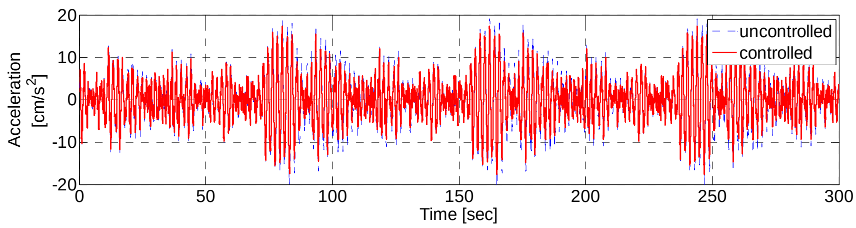
Fig. 5 Normalized maximum acceleration and control force versus $\hat{b}_r / b_r$



(a) $\hat{b}_r / b_r = 1$



(b) $\hat{b}_r / b_r = 100$

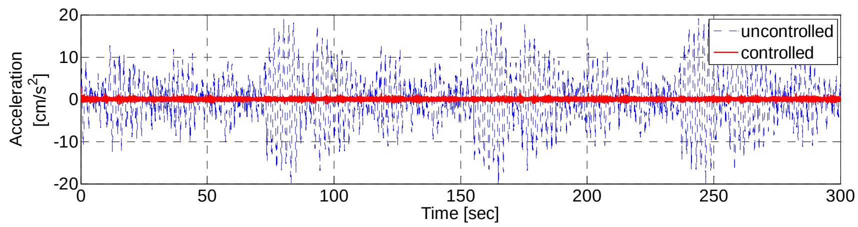


(c) $\hat{b}_r / b_r = 8000$

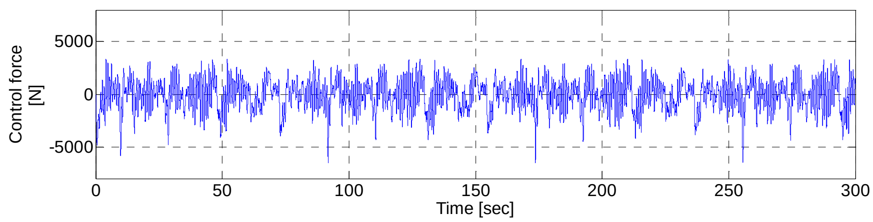
Fig. 6 Acceleration responses at the top floor with different values of $\hat{b}_r / b_r$

Fig. 6 shows time histories of the acceleration at the top floor in three different values of $\hat{b}_r / b_r$ (i.e., 1, 100, and 8000). If a small value of the ratio is chosen as shown in Fig. 6(a), the acceleration response can be almost completely mitigated; on the other hand, much larger control force is needed (see Fig. 5(b)). When the ratio is very large as shown in Fig. 6(c), the control performance is very poor, because the control input value is very small (see Fig. 5(b)). Thus, a designer should carefully trade off the control performance against the capacity of control system.

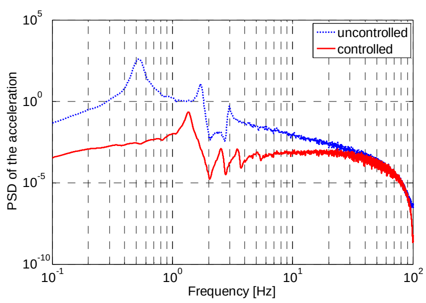
For example, let us assume that the mass of the 5th floor (i.e., m_n) is 20,000 kg. Then, $\hat{b}_r = \dfrac{5}{20{,}000} = 0.00025 \approx 5\, b_r$, which satisfy the stability condition (i.e., Eq. (26)). A numerical simulation was carried out with the calculated value. Fig. 7 represents (a) the acceleration response at the top floor, (b) the corresponding control force, and (c) PSD of the acceleration at the top floor, respectively. As seen from the figures, the maximum response is almost completely mitigated with the reasonable magnitude of the control force. Therefore, it is verified that the proposed control system is quite effective in reducing the unwanted wind-induced vibration of a building structure.



(a) Acceleration at the top floor



(b) Control force



(c) PSD of the acceleration at the top floor

Fig. 7 Numerical simulation results in the case of $\hat{b}_r / b_r = 5$

4. Conclusions

In this paper, an AMD system employing the TDC algorithm is proposed in order to effectively mitigate the excessive vibration of a building structure under wind loading and its effectiveness is numerically examined. To this end, the stability analysis of the proposed control system is first performed. And then, a series of numerical simulations are conducted with a 5DOF structure model and an artificially generated wind loading. It is demonstrated from the numerical simulations that the proposed active structural control system could effectively suppress the acceleration response of the building structure.

In order to more clearly validate the applicability of the AMD system with the TDC algorithm for structural control, additional studies related to several practical issues such as the time delay (Δt) and allowable control gain range should be conducted because they may affect the control performance as well as the stability of the control system. In addition, the experimental validation of the proposed control system should be performed.

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