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Research Article

LQG Control of Along-Wind Response of a Tall Building with an ATMD

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Modern tall buildings use lighter construction materials that have high strength and less stiffness and are more flexible. Although this results in the improvement of structural safety, excessive wind-induced excitations could lead to occupant discomfort. The optimal control law of a linear quadratic Gaussian (LQG) controller with an active tuned mass damper (ATMD) is used for reducing the along-wind response of a tall building. ATMD consists of a second mass with optimum parameters for tuning frequency and damping ratio of the tuned mass damper (TMD), under the stationary random load, was used. A fluctuating along-wind load, acting on a tall building, was treated as a stationary Gaussian white noise and was simulated numerically, in the time domain, using the along-wind load spectra proposed by G. Solari in 1993. Using this simulated wind load, it was possible to calculate the along-wind responses of a tall building (with and without the ATMD), using an LQG controller. Comparing the RMS (root mean square) response revealed that the numerically simulated along-wind responses, without ATMD, are a good approximation to the closed form response, and that the reduced responses with ATMD and LQG controller were estimated by varying the values of control design parameters.

1. Introduction

The majority of today's tall buildings are made from lighter construction materials that are both stronger and more flexible. Although structural safety is greatly improved as a result of using these materials, excessive wind-induced vibration can occur, resulting in occupant discomfort [1]. It is necessary to reduce the wind-induced displacement and acceleration at the top floor level of tall buildings in order to increase occupant comfort and structural safety [2–4]. Although much research has been undertaken to estimate and mitigate the wind-induced structural vibration of tall buildings, the complicated mechanism, interacting with the fluctuating atmospheric flow and building sides, has not been developed successfully [5–7]. The fluctuating along-wind load, which has almost the same property of approaching turbulent flow velocity, could be predicted theoretically, so the along-wind response of a tall building could be estimated by the use of the gust factor method [8, 9]. The across-wind vibration response of a tall building is much more sensitive and larger than that of along-wind response. And the across-wind response is mainly due to the vortex-shedding reattachment and wake flow which occur on the side face of leeward side and cannot be formulated theoretically [6].

Studies on mitigating such an excessive wind-induced vibration have been conducted over several decades [2–4]. In recent years, researchers have utilized the modern optimal control theory and devices to obtain a required control force and reduced vibration response [3, 4, 10, 11]. In 1972, Yao introduced modern control theory into the vibration control of civil engineering structures. Due to the fact that modern tall buildings are subjected to fluctuating wind load, oscillations at the fundamental natural frequency of the building occur. Modern control theory and auxiliary devices have been applied to control wind-induced excitations of tall buildings. One of the common control devices is a tuned mass damper (TMD) system. The concept of TMD and its relation to reducing structural responses comes from Den Hartog [12]. It consists of an auxiliary mass with properly tuned spring and damping devices, which increase damping in the main structure to reduce the response of the main structure. Many studies have been conducted on the behavior and effectiveness of TMD and a number of TMDs have been installed in tall buildings for the control of wind-induced vibration [3, 10]. The Center Point Tower in Sydney is one of the first examples of TMD use in a building. When wind load is modeled as a stationary Gaussian white noise, the TMD parameter for reducing wind-induced excitations in a building could be derived by McNamara [2]. At that time, 400-ton TMD had been installed for the Citicorp Center, a 274 m tall office building in New York. Another TMD has been designed in the John Hancock Tower, Boston. Both of these TMD examples have been installed to reduce wind-induced vibrations [3, 10]. It was accepted as common knowledge that the performance of TMD could be increased by incorporating a feedback controller through the use of an active control force in the design of TMD. This is called an ATMD [3, 11, 13, 14]. An ATMD design for mitigating the wind-induced vibrations endured by tall buildings with an LQR controller that uses a deterministic harmonic wind load was presented by Chang and Soong [10]. Theirs is the first active control study on reducing the wind-induced vibration of tall buildings. Following this, many studies on optimal control algorithms, including LQR, LQG H2, and Hinf, have been developed to obtain the optimal control force for minimizing the wind-induced vibration of a tall building [11, 14–23]. However, it is still believed that ATMD could be superior to TMD in reducing wind-induced vibrations endured by tall buildings [11]. In terms of the modern optimal control theory, fluctuating along-wind load acting on a tall building can be considered a stationary Gaussian white noise process that has a constant power spectral density function. Therefore, a linear control system that has a system noise and measurement noise (a Gaussian white noise) is considered to be a stochastic linear control system. An LQG controller is used to investigate the effectiveness of ATMD in reducing the along-wind response of a tall building [14, 18, 19]. Fluctuating along-wind load, acting on a tall building, was simulated numerically in the time domain using the along-wind load spectra proposed by Solari [24]. The simulation procedure used in this study was taken from Schueller and Shinozuka [26] and Deodatis [25]. Using this simulated fluctuating along-wind load, the estimated along-wind responses of a tall building were undertaken with and without an ATMD, while the LQG controller revealed the effectiveness of the ATMD and the LQG controller in reducing the along-wind response of a tall building.

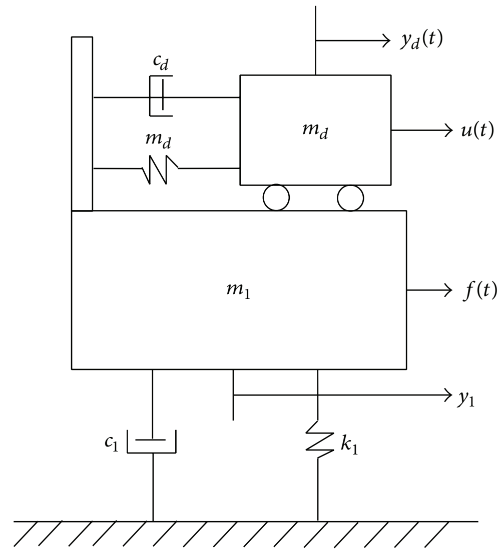

Figure 1: Building-ATMD system.

2. Equations of Motion

A tall building, which has ATMD installed at the top floor level with an active control force (such as an actuator), is shown in Figure 1. The building is modeled as an equivalent single degree of freedom system with a generalized mass m_1, damping c_1, and stiffness k_1, which corresponds to the first mode modal mass, damping, and stiffness of the building. m_d, c_d, and k_d are the corresponding quantities of mass, damping, and stiffness constant of TMD, while $f(t)$ represents the along-wind force. $u(t)$ is the active control force of the LQG controller. The linear dynamic equations of the motion of the system can be written as [10, 27, 28]

$$\begin{aligned} m_1 \ddot{y}_1(t) + c_1 \dot{y}_1(t) + k_1 y_1(t) &= c_d \dot{r}(t) + k_d r(t) + f(t) - u(t), \\ m_d \ddot{r}(t) + c_d \dot{r}(t) + k_d r(t) &= u(t) - m_d \ddot{y}_1(t). \end{aligned} \quad (1)$$

Here, $r(t) = y_d(t) - y_1(t)$ is the displacement of m_d relative to that of m_1.

This equation can be written in terms of the state-space formulation, where

$$\dot{X}(t) = AX(t) + Bu(t) + Hf(t), \quad (2)$$

$X(t) = [y_1 \;\; r \;\; \dot{y}_1 \;\; \dot{r}]^T$ denotes the state vector of the system,

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\dfrac{k_1}{m_1} & \dfrac{k_d}{m_1} & -\dfrac{c_1}{m_1} & \dfrac{c_d}{m_1} \\ \dfrac{k_1}{m_1} & -\left(\dfrac{k_d}{m_d} + \dfrac{k_d}{m_1}\right) & \dfrac{c_1}{m_1} & -\left(\dfrac{c_d}{m_d} + \dfrac{c_d}{m_1}\right) \end{bmatrix} \quad (3)$$

is a system dynamic matrix,

$$B = \left[0 \;\; 0 \;\; -\frac{1}{m_1} \;\; \frac{1}{m_1} + \frac{1}{m_d}\right]^T \quad (4)$$

is a location vector of $u(t)$, and

$$H = \begin{bmatrix} 0 & 0 & \frac{1}{m_1} & -\frac{1}{m_1} \end{bmatrix}^T \quad (5)$$

is a location vector of $f(t)$ [29].

3. Optimum Parameters of ATMD

While the basic concept of TMD on reducing the main body of structural response has been well established, the optimal parameters of TMD could be different for different structures and external loading conditions [30]. Warburton investigated the effectiveness of TMD on reducing the random responses of the main structure under a random load, which has Gaussian white noise spectra of constant value. Warburton derived the optimum parameters for the tuning frequency (f_{opt}) and the damping ratio (ξ_{opt}) of the passive TMD, under stationary random excitations, which have white noise spectra. The optimum TMD parameters of tuning frequency and damping ratio were determined for a mass ratio μ [30] as

$$f_{\text{opt}} = \frac{\sqrt{1 + (1/2)\mu}}{1 + \mu}, \quad (6)$$

$$\xi_{\text{opt}} = \sqrt{\frac{\mu\left(1 + (3/4)\mu\right)}{4\left(1 + \mu\right)\left(1 + (1/2)\mu\right)}}. \quad (7)$$

Here, μ = mass ratio of m_d/m_1.

The optimal tuning frequency ratio is greater for random excitation than for harmonic excitation [31]. However, the optimal damping ratio is smaller for random excitation than for harmonic excitation. The optimum parameters of ATMD, meanwhile, are the same as those of passive TMD.

4. Numerical Simulation of Fluctuating Along-Wind Load

Fluctuating along-wind load (treated as a random process of stationary Gaussian white noise) can be simulated numerically in the time domain using along-wind load power spectral density data. This is particularly useful for some response estimations, which are more or less narrow banded random processes, such as the along-wind response of a tall building. The numerical simulation procedure presented in this work is taken from Scheuller and Shinozuka [26] and Deodatis [25] as

$$f(t) = \sum_{k=1}^{N} 2\sqrt{S_F(f_1)\,\Delta\omega}\cos\left(\omega_k t + \phi_t\right). \quad (8)$$

Here, $S_F(f_1)$ = the value of the spectral density of the along-wind load, corresponding to the first modal resonant frequency.

$\Delta\omega = (\omega_u - \omega_l)/N$,

$\omega_k = \omega_l + (k - (1/2)/N)$,

ω_u = upper frequency of $S(\omega)$,

ω_l = lower frequency of $S(\omega)$,

ϕ_t = uniformly distributed random numbers in 0–2π,

N = number of random numbers.

The along-wind load power spectral density, used in (6), is by Solari [24]. It is as follows:

$$S_F(n) = \left[\rho BHC_D\overline{V}(h)\,\sigma_v(h)\,K_b\right]^2 S^*_{\text{veq}}(n), \quad (9)$$

where

$$S^*_{\text{veq}}(n) = \frac{S_v(h;n)}{\sigma_v^2(h)} L\left[0.4\frac{nC_xB}{\overline{V}(h)}\right]$$
$$\frac{1}{C_D^2}\left[C_w^2 + 2C_wC_\ell L\left[\frac{nC_yD}{\overline{V}(h)}\right] + C_\ell^2\right] L\left[0.4\frac{nC_zH}{\overline{V}(h)}\right], \quad (10)$$

where

$$L(\eta) = \frac{1}{\eta} - \frac{1}{2\eta^2}\left(1 - e^{-2\eta}\right),$$

$$K_b = \frac{1}{H\overline{V}(h)\,\sigma_v(h)}\int_0^H \overline{V}(z)\,\sigma_v(z)\,\psi_1(z)\,dz, \quad (11)$$

$$\frac{nS_v(z;n)}{\sigma_v^2(z)} = \frac{6.868\left(fL_v/z\right)}{\left(1 + 10.302\left(fL_v/z\right)\right)^{5/3}},$$

where $f = nz/\overline{V}(z)$, C_x, C_z = lateral and vertical exponential decay coefficients, C_y = cross-correlation coefficient of pressure acting on the windward and leeward face, $L_v(h)$ = integral length scale of turbulence at height h, ρ = air density, B = width of building, H = height of building, h = reference height of building, C_D = drag coefficient, C_m, C_e = absolute values of mean pressure coefficients on windward and leeward face, $\overline{V}$ = mean wind velocity, σ_v = standard deviation of longitudinal turbulence, n = frequency, and $S_F(n)$ = power spectrum of first fluctuating modal force.

5. Linear Quadratic Gaussian Controller

A tall building that is subjected to a fluctuating along-wind load and has a stationary white noise spectrum can be considered as the linear dynamic system, which has a system and measurement noise. If the system and measurement noises are zero-mean Gaussian white noise that has a constant covariance intensity, they are stationary white noise spectra matrices. If the external random load (a fluctuating along-wind load, for instance) acting on a tall building is considered a system noise that has a constant power spectral density of Gaussian white noise, we can formulate a plant model dynamic with an LQG controller in modern optimal control theory. This is as follows [27]:

$$\dot{X}(t) = AX(t) + Bu(t) + \omega(t), \quad (12)$$

$$Y(t) = CX(t) + Du(t) + v(t). \quad (13)$$

Here, we let $D = 0$ for simplicity. $X(t)$ and $Y(t)$ are the state and output vectors, while $\omega(t)$ and $v(t)$ are the system and measurement noises, respectively. These are assumed to be uncorrelated zero-mean Gaussian white noises that have covariance intensity matrices of W and V, respectively. That is,

$$\begin{aligned} E\left[\omega(t)\,\omega(t+\tau)^T\right] &= W\delta(\tau), \\ E\left[\nu(t)\,\nu(t+\tau)^T\right] &= V\delta(\tau), \\ E\left[\omega(t)\,\nu(t+\tau)^T\right] &= 0, \\ E\left[\nu(t)\,\omega(t+\tau)^T\right] &= 0, \end{aligned} \quad (14)$$

where E means the expectation operator and is a $\delta(t-\tau)$delta function.

It is known that the optimal controller $u(t)$ in (12) is obtained when all states $X(t)$ of the system and the output $Y(t)$ are a combination of all states. However, in practice, all states $X(t)$ are not available and system and output measurements are driven by stochastic disturbance (called noises), which have a constant power spectral density of Gaussian white noise. In these situations, we need a state estimator or observer to estimate all states of the system. The design of the state observer could then be performed using a Kalman filter, an optimal state observer for a stochastic dynamic system [27].

If we take $X(t)$ to be the state estimate and $Xe(t) = X(t) - \widehat{X}(t)$ to denote the estimation error, then the state can be estimated using a Kalman filter. This is described as

$$\dot{\widehat{X}}(t) = A\widehat{X}(t) + Bu(t) + L\left(Y(t) - C\widehat{X}(t)\right), \quad (15)$$

where the observer gain matrix (L) is given by

$$L = \Gamma C^T V^{-1}, \quad (16)$$

where

$$\Gamma = E\left[Xe(t)\,Xe(t+\tau)\right] \quad (17)$$

and where Γ satisfies the filter algebraic Riccati equation (FARE)

$$A\Gamma + \Gamma A^T + W - \Gamma C V^{-1} C \Gamma = 0. \quad (18)$$

In the LQG controller problem, the optimal controller $u(t)$ in (12), which minimizes the cost functional J of (19), is subjected to constrained (15). This is determined, separately, as the deterministic LQR controller problem.

As with the deterministic LQR problem, the optimal control law that minimizes the same quadratic cost functional has a tradeoff between the state cost and control cost [28]. However, as with a stochastic dynamic system, such as an optimal control problem of wind-induced vibration of a tall building, the cost functional for the deterministic LQR problem cannot be employed due to the stochastic nature of the state space formulation of the stochastic differential equation, as shown in (12). That is, the ensemble average over all possible realizations of the excitation is considered, so the cost functional J is given by

$$J = E\left\{\lim_{T\to\infty}\frac{1}{T}\int_0^T \left[X(t)^T Q x(t) + u(t)^T R u(t)\right] dt\right\}. \quad (19)$$

Here, Q and R are positive semidefinite and positive definite weighting matrices. The term $X(t)^T Q x(t)$, in (19), is a measure of control accuracy and the term $u(t)^T R u(t)$ is a measure of control effort. Minimizing J, while keeping the system response and the control effort close to zero, requires an appropriate choice of the weighting matrices Q and R [15, 27]. If it is desirable that the system response be small, then large values for the elements of Q should be chosen. The selected matrix should be diagonal and the diagonal element should have a large value for any respective state variable to be small [15]. If the control energy is required to be small, then large values of the elements of R should be chosen. The unique state-feedback optimal controller $u(t)$, which minimizes the cost functional J of (19), is determined as follows:

$$u(t) = -K\widehat{X}(t). \quad (20)$$

Here, $K = RBP$, where P is the unique symmetric, positive semidefinite solution to the algebraic Riccati equation (ARE), given by

$$AP + PA^T - PBR^{-1}B^T P + Q = 0. \quad (21)$$

It is noted that we can determine the LQR controller feedback gain matrix K and the observer gain Kalman filter matrix L, independently. This is the so-called separation principle. In the LQR control problem, the optimal controller is revealed by tuning some weighting matrix Q and R. If the value of Q is relatively large compared to R, the state vector $X(t)$ is small, relative to the control $u(t)$ [28]. That is, more control force is applied to the main structure. This means that larger values of Q result in the poles of the closed-loop system matrix $(A - B * K)$ far left in the s-plane, so the state decays faster to zero state [28].

6. Numerical Example

This numerical example is from "Numerical Examples" in Solari [24]. The tall building's height $H = 180$ m, width $B = 60$ m, depth $D = 30$ m, first modal natural frequency $n1 = 0.27$ Hz, critical damping ratio = 0.015, and so forth. $h = 120$ m, $V(h) = 40.96$ m/s, $\sigma_v(h) = 5.39$ m/s, $L_v(h) = 582.48$ m, $C_x = 16$, $C_z = 10$, $C_w = 0.8$, $C_\ell = 0.5$, $K_b = 0.5$, and so forth. Additional data for the along-wind load and properties of the building were seen in [24]. The optimum parameters of ATMD are considered to be of the same value as the passive TMD. The optimum parameters of TMD have a mass ratio of $\mu = 0.01$, a tuning frequency of $f_{\text{opt}} = 1.0$, and damping ratio of $\xi_{\text{opt}} = 0.05$. The numerically simulated along-wind load, along with response without ATMD, is shown in Figures 2 and 3. RMS displacement response, without ATMD, is shown in Figure 3 and is 0.021, a good approximation to that of Solari's closed form response of 0.027 m. It was known that the relative displacement response of ATMD to that of the main structure was five to ten times larger than that of the main structure, demonstrating that

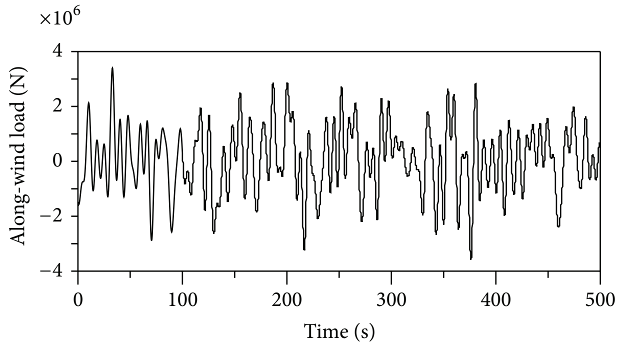

Figure 2: Time series of simulated along-wind load (RMS = $1.2361*10^6$ m).

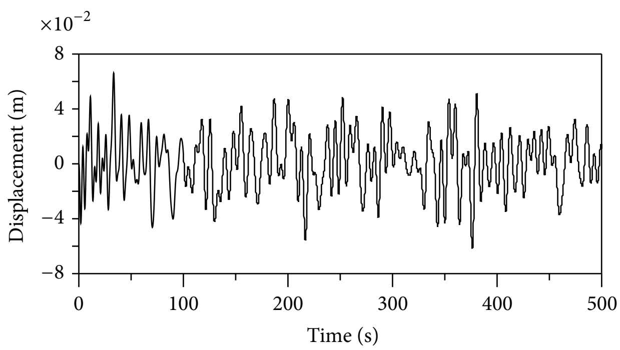

Figure 3: Time series of along-wind response without ATMD (RMS = 0.021 m).

ATMD works well. Therefore, the values for the diagonal elements of weighting matrix Q and R are selected as

$$Q = 1.0 \times 10^8 \times \begin{bmatrix} 100 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 100 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$R = 1.0 \times 10^{-12}. \tag{22}$$

Using those values of Q and R and an assumed value of $V = 1.0e-008$, the estimated reduced response with ATMD, using LQG controller, is shown in Figure 4. The RMS value of the estimated reduced response is 0.0190 m, which shows around a 10% reduction of the response without ATMD. The estimated relative displacement response of ATMD to that of the main structure is shown in Figure 5, with RMS value of 0.2217 m. This is roughly 12 times larger than that of the main structure. The active control force of the LQG controller is shown in Figure 6. If the value of $V = 1.0e-004$ is used as an increased measurement noise, then the estimated reduced response with ATMD, using the LQG controller, is shown in Figure 7. The RMS value of the estimated reduced response is 0.0072 m, which is about a 65% reduction of the response without ATMD. The estimated relative displacement response of ATMD to that of the main structure is shown in Figure 8, with an RMS value of 0.0815 m that is roughly 11 times larger than that of the main structure.

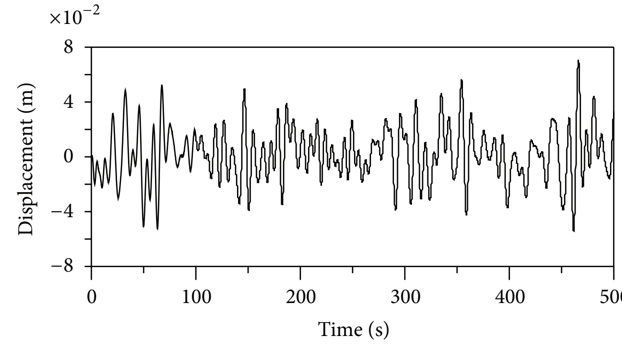

Figure 4: Estimated reduced response with ATMD ($V = 1.0e-008$, RMS = 0.0190 m).

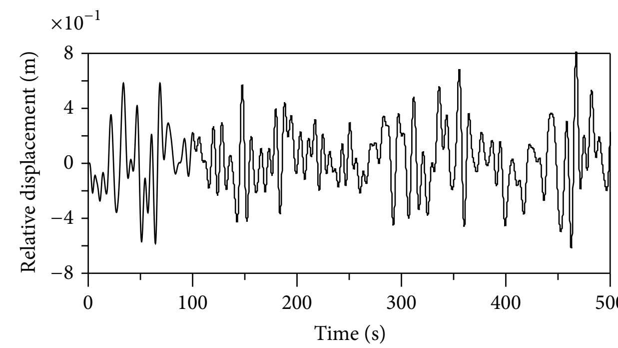

Figure 5: Estimated relative displacement of ATMD to that of the main building ($V = 1.0e-008$, RMS = 0.2217 m).

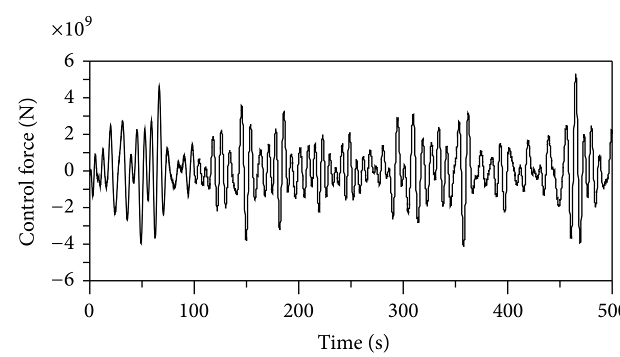

Figure 6: LQG control force ($V = 1.0e-008$, RMS = $1.4371*10^9$ N).

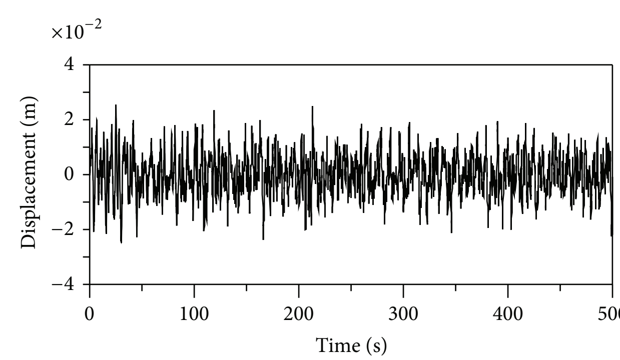

Figure 7: Estimated reduced response ($V = 1.0e-004$, RMS = 0.0075 m).

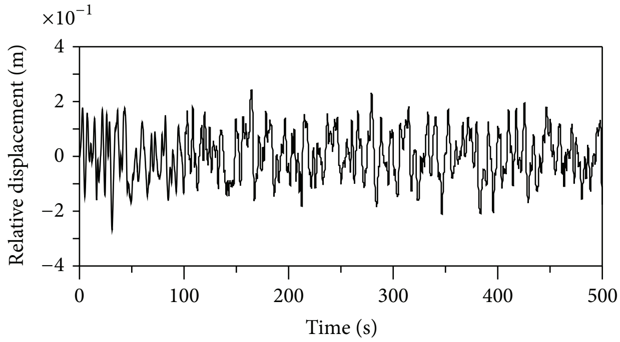

Figure 8: Estimated relative displacement of ATMD to that of the main building ($V = 1.0e - 004$, RMS = 0.0815 m).

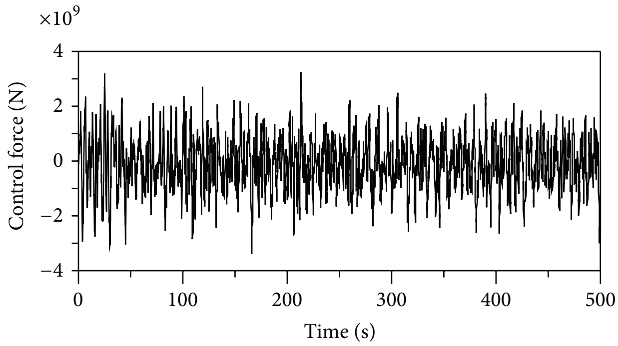

Figure 9: LQG control force ($V = 1.0e - 004$, RMS = $9.1268 * 10^8$ N).

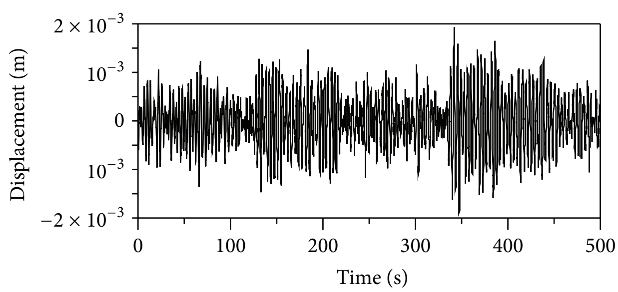

Figure 10: Estimated reduced response ($V = 1.0$, RMS = 0.00055026 m).

The active control force of the LQG controller is shown in Figure 9. If a value of $V = 1.0$ is used, the estimated reduced response of ATMD, using the LQG controller, is shown in Figure 10. The RMS value of the estimated reduced response is 0.00055026 m, which shows around a 97% reduction of the response without ATMD. The estimated relative response of ATMD to that of the main structure is shown in Figure 11, where the RMS value is 0.0041 m. This is around 7 times greater than that of the main structure. The active control force of the LQG controller is shown in Figure 12. As shown in the above results, the reduced along-wind responses of a tall building with ATMD using LQG controller are obtained as LQG control design parameters are varied. Therefore, LQG control for reducing along-wind response of a tall building with ATMD is effective for reducing wind-induced vibrations endured by tall buildings.

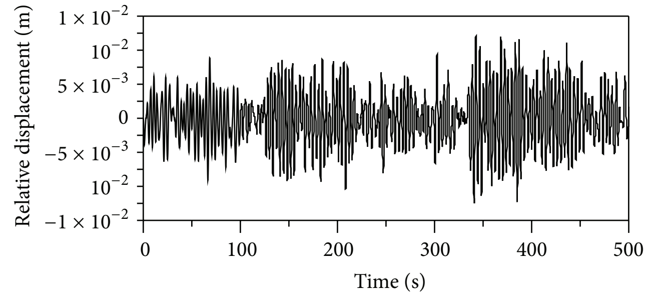

Figure 11: Estimated relative displacement of ATMD to that of the main building ($V = 1.0$, RMS = 0.0041 m).

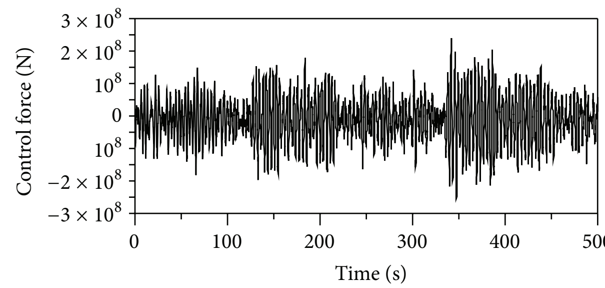

Figure 12: LQG control force ($V = 1.0$, RMS = $7.134 * 10^7$ N).

7. Conclusions

The optimal control technique of LQG for obtaining the reduced along-wind responses of a tall building with ATMD has been investigated. The fluctuating along-wind load, acting on a tall building, was simulated numerically and using this simulated along-wind load, we calculated the along-wind responses of a tall building without ATMD and with ATMD, using the LQG controller. The estimated along-wind response without ATMD is good when considered to the closed form response. The reduced across-wind responses, controlled with ATMD using the LQG controller, were estimated as varying the LQG control design parameters. Therefore, ATMD system using LQG controller is effective and useful for the design of mitigating wind-induced vibrations endured by tall buildings.

Conflict of Interests

The authors declare no conflict of interests regarding the publication of this paper.

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