主動控制於南京電視傳訊高塔之抗風減振應用研究

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中文摘要

為落實國內結構主動控制技術於高塔結構的抗風減震應用，中美學者在中國南京電視傳訊高塔上裝設主動質量驅動裝置，做為測試主動控制應用的研究之用。本研究以 *LQG* 控制理論設計出加速度迴饋方式，以減低觀測塔台的振動，增加人員的舒適性。南京塔的受風行為包含水平與扭轉向的偶合效應，以交頻譜分別模擬順向風及橫向風的擾動。數值模擬包括時域與隨機分析，結果顯示:（1）*LQG* 控制之減振效果卓越；（2）*LQG* 控制對風攻角之不確定性具控制強健性。本研究成果可視為高塔結構應用主動控制的可行性分析，對於爾後國內落實高層建築抗風的主動控制技術應用有相當參考價值。

關鍵詞：結構主動控制、主動質量驅動裝置、*LQG* 控制、水平與扭轉向偶合效應、風攻角

Abstract

The 310 m Nanjing TV transmission tower in China will be installed with an active mass driver in order to reduce the acceleration responses under strong wind gusts. This paper presents the Linear Quadratic Gaussian (*LQG*) control strategy using acceleration feedback to reduce the tower responses under coupled lateral-torsional motion. The along-wind and across-wind components of the wind velocity are defined by the cross-power spectra. In the simulation analysis, both deterministic and stochastic approaches have been used. Simulation results demonstrate that (i) the performance of the active mass driver using the *LQG* control strategy is remarkable in reducing coupled lateral-torsional motions of the tower, and (ii) the *LQG* strategy is robust with respect to uncertainties in the angle of attack of wind loads. The *LQG* strategy is suitable for the full-scale implementation of active mass driver on Nanjing Tower.

Keywords: structural active control, active mass driver, Linear Quadratic Gaussian (*LQG*) control, coupled lateral-torsional motion, angle of attack.

INTROUCTION

The newly constructed 310-meter Nanjing Tower in China consists of three prestressed concrete legs with hollow rectangular sections, as shown in Fig. 1(a) and (b). Preliminary investigations indicate that the acceleration response of the upper observation deck is too high and that a passive mass damper is not capable of reducing the acceleration response to an acceptable level [Cao et al (1998)]. Consequently, an active mass driver system, in the form of a ring mass driven by three actuators was designed [Cao et al (1998)] to be installed on the upper observation deck to reduce the acceleration response. Active control of wind-excited tall buildings has been investigated in the literature, including the applications of advanced control theories, such as H_2 control [e.g., Suhardjo et al (1992)], *LQR* and H_∞ static output feedback control [e.g., Wu et al (1998)], sliding mode control [e.g., Yang et al (1997)], etc. Today, full-scale active tuned mass dampers have been installed on many high-rise buildings in Japan [e. g., Kobori et al (1998), etc.].

The structural properties of Nanjing

Tower in the along-wind direction, as modeled by a discrete 16-degree-of-freedom system shown in Fig. 1(c), have been described in Cao et al (1998). Previous investigations [Wu et al (1997a,b, 1998b), Cao et al (1998)] assumed that the tower is completely symmetric and the axes of mass centers, elastic centers, and aerodynamic centers coincide with each other. In reality, the elastic center and mass center may not coincide, for instance, the mass centers of the observation decks may not locate at the elastic center of the cross-section due to the arrangement of indoor furnitures and equipments. As such, coupled lateral-torsional motion is introduced when the tower is subject to wind gusts. Since the tower is not symmetric in one of the principal axes, the aerodynamic center may be different from the elastic center and mass center. Hence, the wind forces acting on the aerodynamic center will introduce an eccentricity, resulting in an external torque to the tower [Wu & Yang (1998c)].

In this paper, we present the Linear Quadratic Gaussian (*LQG*) control strategy for the acceleration reduction of the tower equipped with an active mass driver, taking into account the coupled lateral-torsional motion. The performance of the *LQG* controller is measured by the acceleration reduction criterion. In reality, since the tower may be subject to wind velocity from different angles of attack, the robustness of the performance and stability of the controller in this regard has been investigated based on numerical simulations. It is demonstrated that the *LQG* controller is quite suitable for practical implementations and the performance of the active mass driver using the *LQG* strategy is remarkable.

SIMULATION RESULTS

The control performance of the *LQG* controller in reducing the coupled lateral-torsional response of the Nanjing tower will be demonstrated through numerical simulations. The mass centers of the tower are different from the elastic centers only for both observation decks, i.e., x_{c10} = 2 m, y_{c10} = 2 m, x_{c12} = 1 m, and y_{c12} = 1 m, see Fig.1(c). A 60 metric tons active mass driver (mass ratio of 0.194%) will be installed on the upper observation deck (12-th node). For numerical simulation, we modify the active mass driver system into an active tuned mass damper in computing the x_{17}, y_{17}, θ_{17} and required control forces u_1, u_2 and u_3, respectively, in x, y and θ directions. A tuned mass damper with a damping ratio of 7% in each direction (x, y and θ) and the frequency tuned to the first mode in each direction will be used in the simulation.

The fluctuating wind velocities in the along-wind and across-wind directions are uncorrelated random processes with zero mean, and their cross-power spectra are considered to be identical in the simulation for simplicity. Since the applied torsional moment is also induced by the off-set between elastic centers and aerodynamic centers, a set of aerodynamic centers is assumed in the simulation to investigate the structural response and the performance of active control as follows: x_{Ai} (i = 1, 2, ..., 16) are all zero and y_{Ai} (i = 1, 2, ..., 16) are 15/4, 12/4, 10/4, 9/4, 8/4, 7/4, 6/4, 5/4, 4/4, 0, 0, 0, 0, 0, 0 and 0 m, respectively.

Both the stochastic and deterministic analyses were used to compute the response quantities of the tower. In reality, the direction of along-wind velocity cannot be predicted precisely. To investigate the effect of different wind directions on structural responses, simulations were conducted by varying the angle of attack (β) of along-wind velocity from $-90°$ to $90°$ with $15°$ of resolution. The robustness of *LQG* controller due to such an uncertainty will be also examined. Based on the stochastic analysis, the *rms* accelerations of the upper observation deck in x, y and θ directions with β varying from $-90°$ to $90°$ are plotted in Figs. 2-4. These figures are presented in the form of chart diagrams. On the left plane, the radial length represents the *rms* acceleration in cm/s^2 for a corresponding angle of attack, whereas on the right plane, the radial length represents the reduction percentage with respect to the 'No Control' case. The reduction percentages for acceleration *rms* of the upper observation deck in x, y and torsional directions for all range of β are only about 18%, 20% and 5%. In particular, the effectiveness of passive damper in reducing torsional acceleration is almost trivial.

LQG Controller : The main objective of control is to reduce the accelerations $\ddot{x}_{12}$, $\ddot{y}_{12}$ and $\ddot{\theta}_{12}$ of the upper observation deck. Likewise, the actuator constraints, including the peak stroke of 75 cm and the peak force of 150 kN should not be exceeded. Although other measurements can be made, we only install three acceleration sensors to measure the accelerations at the upper observation decks, i. e., $\ddot{x}_{12}$, $\ddot{y}_{12}$, and $\ddot{\theta}_{12}$. The control parameters used for the *LQG* controller are as follows : the controlled output $\mathbf{z}_r = [\ \ddot{x}_{10},\ \ddot{x}_{12},\ \ddot{x}_{17a},\ \ddot{y}_{10},\ \ddot{y}_{12},\ \ddot{y}_{17a},\ \ddot{\theta}_{10},\ \ddot{\theta}_{12},\ \ddot{\theta}_{17a}\ ]'$, $\mathbf{Q} = \text{diag}\ [\ 10^5, 10^5, 0, 10^5, 10^5, 0, 10^2, 10^2, 0]$, $\mathbf{R} = \text{diag}\ [\ 7\text{x}10^{-3}, 7\text{x}10^{-3}, 10^{-10}\ ]$, $\bar{\mathbf{S}}_{vv} = \text{diag}\ [7.7\text{x}10^{-13}, 2.1\text{x}10^{-13}, 1.0\text{x}10^{-9}]$. The parameter $\bar{\mathbf{S}}_{WW}$ are designed based on $\beta=0°$, that is, $\bar{\mathbf{S}}_{WW} = 10^{-2} \cdot \mathbf{S}_{WW}(\omega)$ at $\omega = 1.6$ rad/sec, where $\mathbf{S}_{WW}(\omega)$ is the cross-power spectral density of the wind load. It is important to emphasize that in designing the observer, although the wind loads are assumed to be Gaussian white noise processes, their spatial correlations should be taken into account.

For the stochastic analysis, the acceleration *rms* of the upper observation deck in three directions by varying the angle of attack are plotted in Figs. 2-4. As observed from Figs. 2-4, the percentages of acceleration reductions for the peak and *rms* responses of the upper observation deck are remarkable. In particular, a 55% reduction for the *rms* values of torsional acceleration of the upper deck has been achieved. Moreover, although the control parameter $\bar{\mathbf{S}}_{WW}$ are chosen based on $\beta=0°$ in the controller design, the robustness of performance using such a controller is demonstrated in Figs. 2-4 in which the percentages of reduction are almost the same as β varies.

CONCLUSIONS

The *LQG* control strategy using dynamic output feedback controller has been applied to the 310 meters Nanjing TV transmission tower equipped with an active mass driver. The coupled lateral-torsional motion due to noncoincidence of the mass center, elastic center and aerodynamic center has been considered. The along-wind and across-wind velocities are both modeled as random processes defined by cross-power spectra. The main objective of active control considered herein is to reduce the acceleration response of two observation decks under the design wind gusts. Extensive numerical simulations, including a variation of the angle of attack from 0 to 90 degrees, have been conducted to investigate the robustness of the

LQG controller. Based on the stochastic and deterministic analyses, simulation results demonstrate that (i) the performance of passive mass damper is not satisfactory, (ii) the performance of the active mass driver using *LQG* control strategy is remarkable in reducing the coupled lateral-torsional motion of the tower, and (iii) the *LQG* controller is robust with respect to the angle of attack of wind direction. Therefore, the *LQG* controller is suitable for full-scale implementations of the active mass driver system on Nanjing tower.

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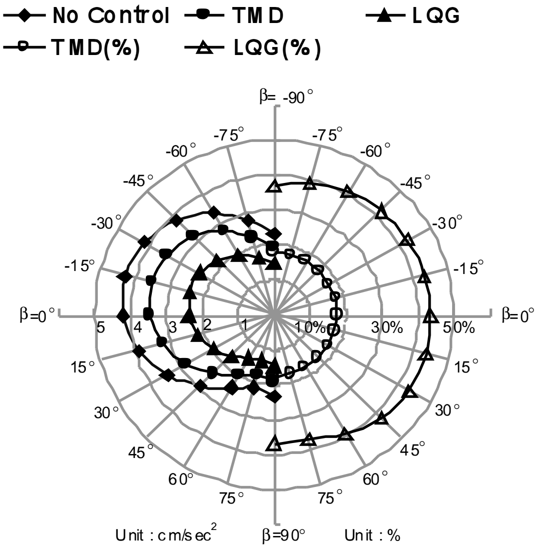

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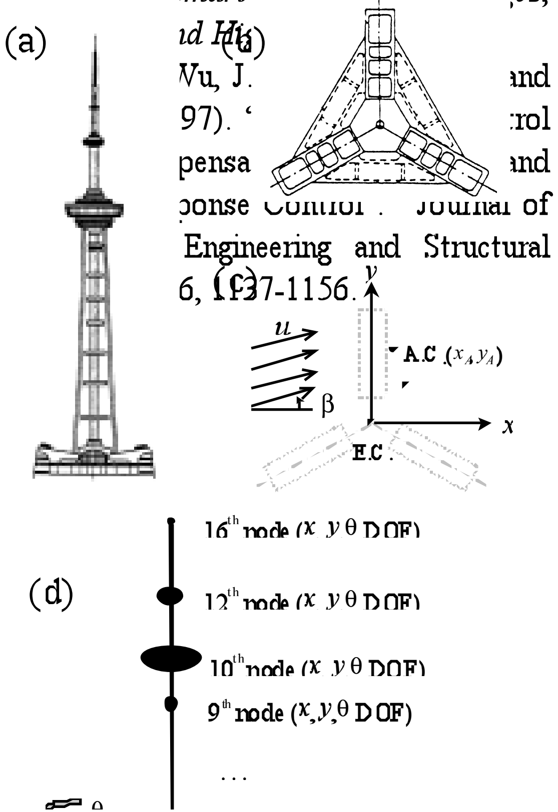

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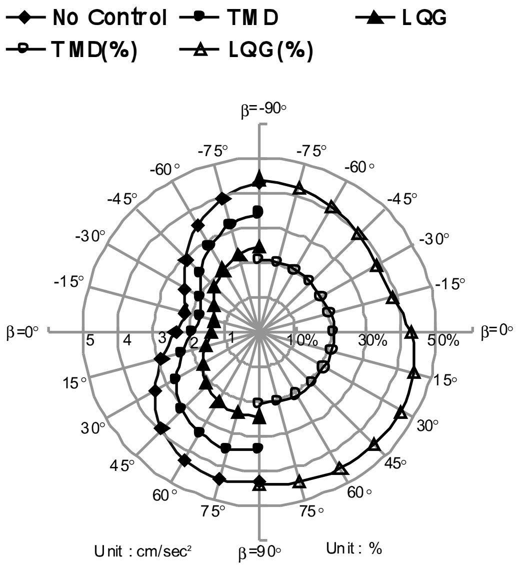

Fig. 3 : RMS Acceleration Responses of the Upper Observation Deck in *y* Direction Due to Wind Velocities from Different Angles of Attack.

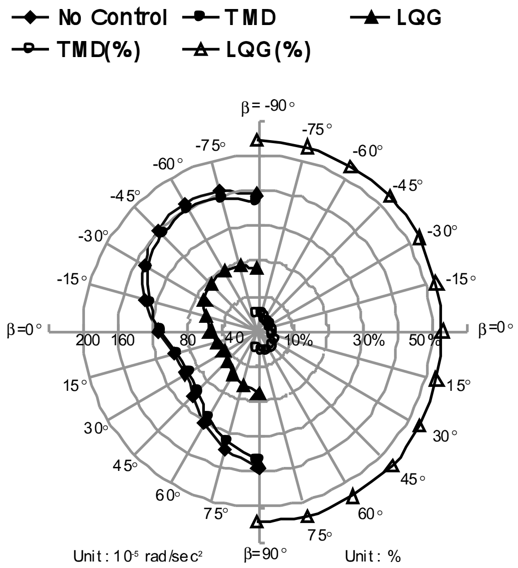

Fig. 4 : RMS Acceleration Responses of the Upper Observation Deck in θ Direction Due to Wind Velocities from Different Angles of Attack.