ACTIVE CONTROL OF THE ALONG-WIND AND CROSS-WIND ACCELERATION OF A TALL BUILDING

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INTRODUCTION

In the last few decades, as tall buildings have become taller and slimmer, their susceptibility to wind-induced vibration has increased. In order to meet serviceability criteria many buildings now need some means to reduce excessive vibrations. In the past, predominantly passive means have been employed; however when passive vibration control is insufficient, active control devices, such as the system installed in Landmark Tower in Yokohama [1], must be used.

This paper investigates the active control of along-wind and cross-wind acceleration of a wind loaded 200m tall building with a 32m square section. The first mode of vibration, which has a frequency of 0.18 Hertz and a damping ratio of 0.5% of critical, is controlled by an Active Tuned Mass Damper (ATMD) which decreases the first mode acceleration to the level of the ISO-6897 (1984) criteria, adjusted for a return period of 10 years.

The focus of this paper is on the comparison of two simple control algorithms used to drive the ATMD. One uses first mode acceleration feedback (AF), the other uses first mode velocity feedback (VF). Such a comparison has not before been undertaken for wind loaded structures, and a study of the energy expenditure and ATMD displacement required by each algorithm determines which is the most effective.

ANALYTICAL METHOD

The actively controlled building is symmetric, and is described in one direction by Eq. 1.

$$M\ddot{x} + C\dot{x} + Kx = F_w + U \tag{1}$$

In Eq. 1; M, K, and C are the system mass, stiffness and damping matrices respectively. F_w is the vector of either along-wind or cross-wind forces, U is the control force vector, and x is the vector of displacements relative to the ground. The building is modelled as a 6 degree of freedom (DOF) system, with the ATMD providing a 7th (DOF). Building mass is assumed to be "lumped" at each DOF, and building stiffness is assumed to be provided by massless shear walls. Building damping is calculated by assuming that in modal space the damping of each mode is independent and equal to 0.5% of critical damping for that mode. ATMD mass is set at 0.5% of the total building mass of 48000 tonnes. ATMD damping and stiffness were optimised for each algorithm.

Control Algorithms

Both the AF and VF algorithms calculate a control force u_1, to be applied to the first mode of vibration of the building, using a gain times the appropriate first mode feedback. The equation of motion of the controlled first mode is shown in Eq. 2. The gain is determined by trial and error to reduce the first mode acceleration to the serviceability criteria. The AF and VF algorithms are shown in Eqs. 3 and 4 respectively. In Eqs 2, 3, and 4, m_1, k_1 and c_1 represent first mode mass, stiffness and damping; η represents first mode displacement, and f_{w1} the first mode component of the wind load.

$$m_1 \ddot{\eta} + c_1 \dot{\eta} + k_1 \eta = f_{wl} + u_1 \quad (2)$$

$$u_1 = g_{AF} m_1 \ddot{\eta} \quad (3)$$

$$u_1 = -g_{VF} \dot{\eta} \quad (4)$$

Control and Observation Spillover

The vector U, of the control force in physical space is shown in Eq. 5, and it consists of a force applied to the ATMD and the corresponding reaction force applied to the 6th DOF of the building. The modal control forces, u_i, shown in Eq. 6, are obtained by transforming U into modal space using the modal matrix Φ.

$$U = (0,0,0,0,0,-\alpha,\alpha)^T \quad (5)$$

$$u_i = \alpha . (\phi_{7i} - \phi_{6i}) \quad (6)$$

The value of α in Eq.5 is obtained from Eq.6 with i=1, with u_1 obtained from Eq. 3 or 4. When i is greater than 1 u_i represents control spillover, the unintentional effect of the first mode control force on the higher modes. Observation spillover is the effect of the higher modes on the control force, and it can occur when first mode values are not fully reconstructed from the available measurements. This results in approximations of the first mode feedback, so that u_1, and therefore α and the higher mode control spillover forces, contain some higher mode feedback. Observation spillover and control spillover may lead to a degradation of control effectiveness.

Wind Load

The wind load vector F_w was calculated using a digitised record from wind tunnel tests of a rigid, pressure-tapped model of the building at a 1:200 scale. Pressures acting on the tributary areas of each of the building's six lumped masses were measured using 24 pressure taps per DOF, with 12 taps being equally spaced on 2 opposite faces. The pressures acting on each face were averaged using a 12:1 manifold, and measured with a Honeywell 160PC 1 pressure transducer. Time histories from the pressure transducers were recorded simultaneously and combined to give a time history of the wind forces for each DOF. A mean wind speed corresponding to winds with a 10 year return period at a reference height of 200m for the Sydney region, was used in the force calculation [2].

The testing was carried out in a 1.8m × 2.4m boundary later wind tunnel set up to simulate flow over Terrain Category 2, open country terrain. Transducer output was sampled and low pass filtered at a frequencies corresponding to 2.3 Hertz and 0.92 Hertz respectively in full scale, capturing loading frequencies up to the third mode of the building. Force data was collected in both the along-wind and the cross-wind directions.

RESULTS AND DISCUSSION

Time histories of the building's motion under the influence of each control algorithm, and when no ATMD is present, were obtained by numerical integration of Eq. 1. Table 1 shows the uncontrolled response of the 6th DOF of the building.

Table 1: Uncontrolled Along-Wind and Cross-Wind DOF 6 Response

Load Type	Mode 1 Acc, milli-g Std. Dev .	Total Acc, milli-g Std. Dev.	Total Disp, mm Std. Dev.
Cross-Wind	13.4	13.8	114
Along-Wind	7.5	7.85	62

Controlled results are presented for each algorithm where the first mode feedback is calculated using one of two methods. In Case 1 measurements from all DOF, and the modal transformation $\eta = \Phi^{-1}x$, were used to completely reconstruct the first mode feedback and so no observation spillover was present. In Case 2 measurements from the 6th DOF only were used, resulting in observation spillover from all the other modes. Table 2 shows the controlled cross-wind response and Table 3 the controlled along-wind response. As the cross-wind direction is the more critical one; the ATMD frequency, f_{rATMD} which is expressed as a ratio of the first mode frequency, and ζ_{ATMD}, the ATMD damping expressed as a percentage of critical and the control gains used fior the cross-wind case are also used in the along-wind direction. To illustrate the level of control provided Fig. 1 shows the spectral density of the 6th DOF cross-wind acceleration for Case 1, note that both algorithms produced an identical spectra as they were adjusted to provide the same level of control.

Table 2: Controlled Cross-Wind DOF 6 and ATMD Response

Algorithm	f_{rATMD}	ζ_{ATMD}	Mode 1 Acc Std Dev, m-g	Total Disp Std Dev, mm	ATMD Disp Std Dev, mm	ATMD Force Std Dev, kN
AF Case 1	0.99	5.33	5.6	62.2	388	2.71
AF Case 2	0.99	5.33	5.6	62.0	391	2.69
VF Case 1	0.94	2.72	5.6	62.6	470	12.1
VF Case 2	0.94	4.70	5.6	62.6	468	12.2

Table 3: Controlled Along-Wind DOF 6 and ATMD Response

Algorithm	f_{rATMD}	ζ_{ATMD}	Mode 1 Acc Std Dev, m-g	Total Disp Std Dev, mm	ATMD Disp Std Dev, mm	ATMD Force Std Dev, kN
AF Case 1	0.99	5.33	2.4	26.6	164	1.22
AF Case 2	0.99	5.33	2.4	26.6	165	1.39
VF Case 1	0.94	2.72	2.5	27.0	203	4.99
VF Case 2	0.94	4.70	2.5	27.0	204	5.15

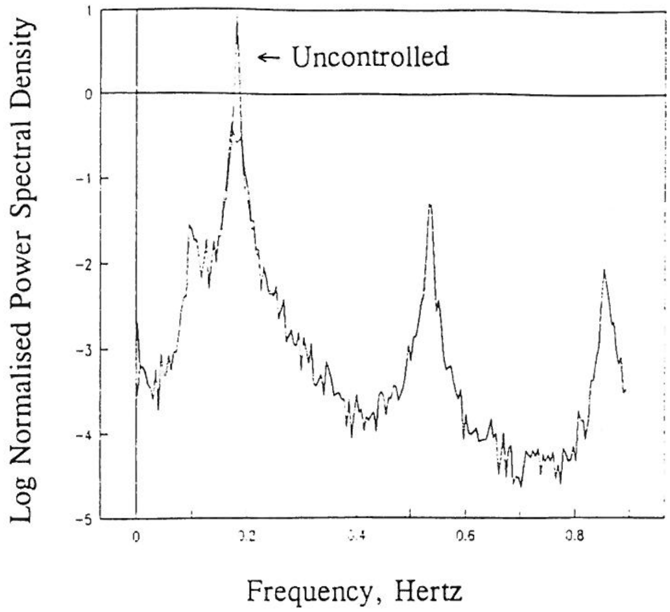

Figure 1: Cross-Wind Acceleration Spectrum, Case 1 Control

Both algorithms successfully control the building's first mode, reducing the first mode acceleration to acceptable levels, using a damper mass only half that used in conventional passive devices. The AF algorithm markedly outperforms the VF algorithm in both wind directions, with and without observation spillover present, requiring markedly less force and ATMD displacement to achieve the control. While the AF algorithm is not significantly affected by observation spillover, the VF algorithm requires more ATMD damping in the presence of observation spillover in order to elicit the same performance as when no spillover is present. This is because some of the control spillover force being applied to the ATMD mode contains ATMD mode feedback when observation spillover is present. For the VF algorithm this has the potentially destabilising effect of effectively taking damping away from the ATMD mode, so a higher initial value of ATMD damping is needed to prevent this.

CONCLUSION

While both algorithms provided adequate control to the first mode of the building, the AF algorithm was shown to out-perform the VF algorithm significantly. This result shows that the choice of software used to drive an active control system is vitally important to the effecient working of that system.

REFERENCES

[1] Yamazaki, S., Nagata, N., and Abiru, H. (1992), "Tuned Active Damper Installed in the Minato Mirai (MM) 21 Landmark Tower in Yokohama", Journal of Wind Engineering and Industrial Aerodynamics, Vol 41-44, pp 1937-1948.

[2] SAA Loading Code Part 2: Wind Loads, (1989), Standard Australia, pp78.