THE SUPPRESSION OF WIND-INDUCED VIBRATIONS IN TALL BUILDINGS BY TUNED MASS DAMPERS - ACTIVE V's PASSIVE

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1. INTRODUCTION

Developments in construction techniques and materials have led to modern tall buildings becoming lighter and more flexible. Occasionally these structures have limited ability to dissipate energy and the structural damping is not high enough to prevent wind-induced motions becoming excessive. In such structures, the motions can be large enough to cause discomfort to occupants, crack partitions and even break glass panels. Many methods that increase the total structural damping have been developed to correct this situation. The most common method of increasing the total structural damping is by the installation of vibration control devices.

One of the most common devices currently in use is the tuned mass damper (TMD). A TMD system is a passive control device and its motions are reactive to the building motion. The manner in which the TMD moves is determined by the parameters it has been set up with. TMDs are usually located near the top floor of the building and are tuned to suppress wind-induced motions in the first fundamental mode. TMDs with a mass of 1% of the total mass of the building are capable of significantly reducing building sways.

The effectiveness of a TMD can be enhanced by the addition of an actuator, which transforms the system to an active tuned mass damper (Chang and Soong 1980). Sensors are usually placed on the structure to measure its dynamic behaviour. The information is then passed on to a computer where a control algorithm determines a control force. The appropriate signal is subsequently transmitted to an actuator which applies the control force and drives the ATMD mass.

ATMDs have the ability to switch between active and passive modes of vibration control. An ATMD is virtually a hybrid control system. The necessity for ATMDs has arisen because of the problems associated with installing either a purely passive or purely active control device in structures such as tall buildings. When a building is excited, it generally experiences one of three phases of wind induced motions. The three phases being small, moderate and extreme motions. When a building experiences small motions it would be quite reasonable to use an optimised TMD, which will transfer vibration motion to heat through absorbers such as dashpots. When the structure enters the moderate range of motion, active vibration control can be used to give a larger magnitude of reduction in vibrations. In the case of active control devices, an actuator is required, which means cost becomes an important factor and it can be prohibitively too costly to install an actuator capable of driving the system in extreme winds. It is therefore more economical to design ATMDs which can be switched to a passive control device in the case of extreme wind conditions or if there is a power failure. For extreme wind conditions, the TMDs are usually sub-optimally tuned or have their damping increased to reduce the displacement of the mass with a subsequent loss of effectiveness.

The key to the effectiveness of both ATMDs and TMDs is the displacement of their mass relative to the top floor displacement of the structure, i.e. the displacement ratio. The larger the ratio the better their performance, which results in larger reductions in building vibrations. Similarly increasing the mass of the systems also increases the performance. For a TMD the displacement ratio is controlled by the tuning of the system. In the case of the ATMD the displacement ratio has a predetermined setting in the control algorithm.

It has already been shown in many investigations (Fujita et al. 1991, Yamazaki et al. 1991, Nishimura et al. 1992) that an ATMD out-performs a TMD when the displacement ratio of the ATMD is very large. This increase in performance is not only due to the larger ratio but also due to the ATMD being driven by a control force, whereas the TMD is reactive to the building motions. By ensuring that both the ATMD and TMD have the same displacement ratio, it is possible to determine how the difference in operating principles between the two systems contribute to the better performance of the ATMD. In the study by Chang and Soong (1980) a numerical comparison was made between a TMD and an ATMD. The ATMD utilised a control force which provided it with a displacement ratio similar to that of the TMD. The ATMD was found to be more effective than the TMD with the same parameters. The experimental investigation in this paper is intended to compare an ATMD with a TMD, both with the same displacement ratio.

This paper compares the performance of an ATMD and a TMD by assessing their effectiveness in suppressing wind-induced building vibrations in a program of wind tunnel model studies. The ATMD developed for this experimental study has already been described in great detail (Facioni et al. 1993 (a) & (b)). The device developed was limited in the displacement ratio with a maximum possible ratio setting of 2.5. Five damper configurations with varying parameters, which gave effectively five distinctively different ATMD devices, were tested. The TMD chosen for the comparison was tuned so the systems would have a displacement ratio of 2.5. The TMD was compared to all the ATMD configurations.

2. EXPERIMENTAL SET-UP

2.1 Wind Tunnel

The ATMD was installed in a rectangular model building and tested in the No.1 Boundary Layer Wind Tunnel at the School of Civil and Mining Engineering, the University of Sydney. The wind tunnel used is of the open circuit type with a 2.4m x 1.8m working section. A Terrain Category 3 wind profile in accordance with the Australian Wind Load Code (AS1170.2-1989) was generated by a combination of spires and roughness blocks over a 12m fetch length of working section. The model building used in the experimental program was a 1:100 scaled aeroelastic model of rigid construction with physical properties as listed in Table 1. The model was mounted on a single degree of freedom translational aeroelastic testing rig with strain gauges mounted to monitor the models dynamic behaviour. The system was designed so that the model would only vibrate in one translational mode with a linear mode shape.

2.2 Model ATMD And TMD

The active control device chosen for the experiments in this paper was an Active Tuned Mass damper. The ATMD design is illustrated in Figure 1. The ATMD model accurately simulated the full scale features required of an ATMD. The ATMD was designed so that parameters could be modified. The ATMD model tested was set-up for five cases of varying parameters giving in effect five different ATMDs. The parameters varied were mass, damping and stiffness. The values used for each parameter were generalised mass ratio of 1.59% or 2.59%, damping of 6% or 18% of critical damping and stiffness ratio of 0.02 or 0.03. Table 2 lists the physical properties of the ATMD for each case tested.

The ATMD was designed to operate as a Tuned Mass Damper when the drive shaft was disconnected. The disconnection of the drive shaft allows the mass to swing freely in a pendulum motion. The model TMD used in the comparison was ATMD3 with the drive shaft disconnected (referred to as TMD3 from hereon). The properties of TMD3 are listed in Table 3. TMD3 was chosen for the comparison because its tuning allowed the damper mass to have a displacement ratio, relative to the top floor of the building model, of 2.5.

2.3 Control System

Strain gauges mounted at the base of the building were calibrated to monitor the top floor displacement of the model. The displacement signal was then amplified and filtered. The signal was then passed through an analogue to digital (A/D) converter, and relayed to a 486 personal computer, where the control algorithm was executed. The control signal was subsequently transmitted via a digital to analogue (D/A) converter to the stepper motor controller, which in turn sent a signal to the stepper motor. A sampling rate of 300Hz was used for all experiments.

3. EXPERIMENTAL PROGRAM

A direct comparison was made between the effectiveness of an ATMD and a TMD in suppressing wind-induced building vibrations. The comparison was conducted in the serviceability wind range within which wake excitation is believed to be the dominant excitation mechanism. Three distinctly different comparisons were investigated during which the building properties and wind conditions were maintained constant for each comparison. A summary of the fundamental properties of each comparison are listed in Table 4.

In the first comparison, the performance of TMD3 was compared to the performances of ATMD3 and ATMD4. In this particular comparison the ATMDs and TMD all had the same mass and displacement ratio. In the second caparison, The performance of TMD3 was compared to that of ATMD1, ATMD2 and ATMD5. Each of the ATMDs has the same displacement ratio as the TMD, however, the mass at the ATMDs was only 1.59% of the building first mode generalised mass. In the third comparison, the performance of TMD3 was again compared to the performances of ATMD3 and ATMD4. However, in this comparison the displacement ratio of the ATMDs was set at 1.5.

For all the comparisons, the normalised standard deviation cross-wind top floor displacement responses of the building model were measured at reduced velocities ranging from 4 to 8 for the three cases of no control, control with the ATMD installed and finally control with the TMD installed. The response signals were also recorded for autocorrelation analysis and spectral analysis. The total structural damping of the model building was determined for each of the cases investigated by means of free vibration decays.

4. EXPERIMENTAL RESULTS

The results of free vibration decays and autocorrelation analysis at a reduced velocity of 8 are listed in Table 5. It is obvious that the installation of any of the vibration control devices investigated increases the total structural damping which corresponds to an increase in the ability of the building to dissipate energy and results in a corresponding reduction in the wind-induced response. Generally, the TMD was observed to have a lower total structural damping than any of the ATMD configurations investigated. Thus, it is expected that the ATMD would be more effective in reducing wind-induced building vibrations.

4.1 Comparison 1

The cross-wind response results for the model building with no control, with active vibration control using ATMD3 and ATMD4 with a R_F setting of 2.5, and finally with passive control using TMD3 are presented in Figure 2. The figure presents the normalised standard deviation top floor cross-wind displacement response σ_y/b versus reduced velocity. σ_y represents the standard deviation cross-wind top floor displacement response of the building and b is the width of the building normal to the wind.

In this particular comparison the two ATMDs and the TMD had the same mass and displacement ratio. The ATMD devices were superior to the TMD in suppressing wind-induced building vibrations. At a reduced velocity of 8, the installation of the TMD was observed to reduce the standard deviation displacement response by 31%, whereas ATMD3 and ATMD4 reduced the standard deviation building displacements by 45% and 41%, respectively. It was obvious that the ATMDs, which had the same damper mass and displacement ratio as the TMD, were able to further reduced the top floor building displacement response of the building with their active control capacity. For a reduced velocity of 4, all the control devices whether active or passive were at par.

4.2 Comparison 2

The cross-wind response results for the model building with no control, with active vibration control using ATMD1, ATMD2 and ATMD5 all with a R_F setting of 2.5, and finally with passive control using TMD3 are presented in Figure 3. In this comparison, the ATMDs and the TMD had the same displacement ratio, however, the ATMDs had a mass which was only 0.6 of the TMD mass. In spite of this, the ATMD devices were still slightly more effective than the TMD in suppressing the wind-induced building vibrations. This suggests that an ATMD with a significantly lower damper mass but the same displacement ratio as a TMD can achieve the same degree of response reduction as a TMD.

4.3 Comparison 3

The cross-wind response results for the model building with no control, with active vibration control using ATMD3 and ATMD4 with a R_F setting of 1.5, and finally with passive control using TMD3 are presented in Figure 4. In this comparison the ATMDs and the TMD had the same mass, however, the ATMDs had a smaller displacement ratio which was only 0.6 of the TMD. The ATMD devices were again found to be just as effective as the TMD in suppressing wind induced building vibrations. This suggests that an ATMD with the same damper mass as a TMD can reduce the building displacement response of the structure by the same amount as the TMD, but with a smaller damper mass movement.

5. CONCLUSIONS

The wind tunnel experiments conducted in this paper have shown that both ATMD and TMD systems are effective in suppressing wind-induced vibrations. The ATMD was superior to the TMD in controlling building vibrations. The following general conclusions can be made.

1. An ATMD with same mass and displacement ratios as a TMD achieves a better reduction in wind-induced building vibrations, especially in the larger reduced velocity range.

2. An ATMD can reduce the cross-wind response of the building by the same amount as a TMD but with only 60% of the TMD mass.

3. An ATMD can also reduce the cross-wind response of the building by the same amount as a TMD but with only 60% of the displacement ratio. This implies that the same response reduction can be achieve by the ATMD but in a much more restricted space.

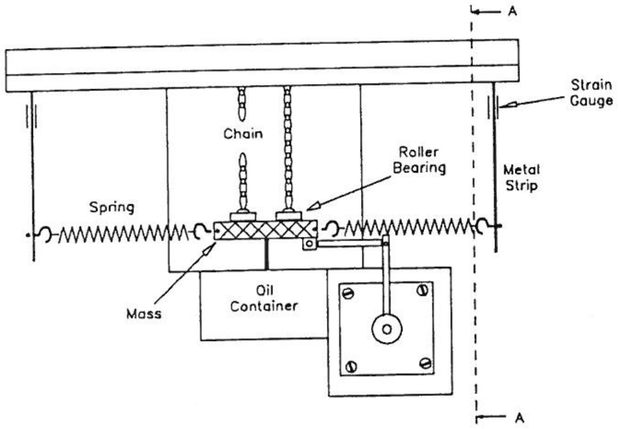
4. It is believed that the ATMD can outperform the TMD even further if the ATMD adopts a larger displacement ratio. An optimised TMD can have a maximum displacement ratio of around 4.5, whereas an ATMD can have it set as high as 15 or more, depending on the capability of the actuator and the building space available for the travel of the mass. This principle will be investigated in subsequent papers.

Dimensions	0.2 x 0.3 x 1.1 (m)
Density (ρ_1)	228 (kg/m^3)
Mass (M)	15.05 (kg)
Generalised Mass (m_1)	5.02 (kg)
Natural Frequency (f_1)	2.9 (Hz)
Structural Damping (ζ_1)	1.05% of critical
Generalised Stiffness (k_1)	1.67 KN/m

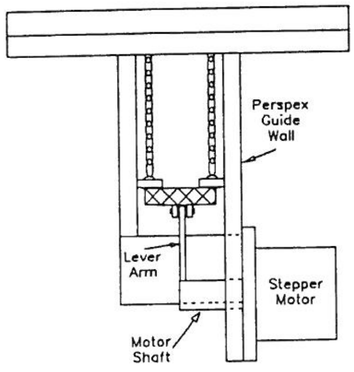
TABLE 1. PHYSICAL PROPERTIES OF MODEL BUILDING

Mass (m_2)	0.13kg
Damping (ζ_2)	5.9% of critical
Stiffness (k_2)	50N/m
Frequency	3.3Hz
Frequency Tuning Ratio	1.14
Generalised Mass Ratio (m_2/m_1)	2.59%

TABLE 3. PROPERTIES OF TMD3



Front View



A–A Section

FIGURE 1 MODEL ATMD

ATMD Type	ATMD 1	ATMD 2	ATMD 3	ATMD 4	ATMD 5
Mass (m_2)	0.08 kg	0.08 kg	0.13 kg	0.13 kg	0.08 kg
Damping (ζ_2)	6%	6.8%	5.9%	6%	18%
Stiffness (k_2)	55.6 N/m	34.5 N/m	50.0 N/m	31.3 N/m	34.5 N/m
Generalised Mass Ratio (m_2/m_1)	1.59%	1.59%	2.59%	2.59%	1.59%

TABLE 2. PROPERTIES OF ACTIVE TUNED MASS DAMPERS

INVESTIGATION	DEVICE TYPE	MASS {% of first mode vibration}	DISPLACEMENT RATIO
Comparison 1	TMD3	2.59%	2.5
	ATMD3	2.59%	2.5
	ATMD4	2.59%	2.5
Comparison 2	TMD3	2.59%	2.5
	ATMD1	1.59%	2.5
	ATMD2	1.59%	2.5
	ATMD5	1.59%	2.5
Comparison 3	TMD3	2.59%	2.5
	ATMD3	2.59%	1.5
	ATMD4	2.59%	1.5

TABLE 4. FUNDAMENTAL PROPERTIES OF COMPARISON

Device Installed	Free Vibration Decay	Autocorrelation {Reduced Velocity 8}
None	1.05%	1.06%
TMD3	2.20%	2.38%
ATMD1 - R_F=2.5	2.40%	2.64%
ATMD2 - R_F=2.5	2.59%	2.40%
ATMD3 - R_F=2.5	3.45%	3.34%
ATMD4 - R_F=2.5	3.40%	3.30%
ATMD5 - R_F=2.5	2.60%	2.78%
ATMD3 - R_F=1.5	2.43%	2.38%
ATMD4 - R_F=1.5	2.50%	2.47%

TABLE 5. TOTAL STRUCTURAL DAMPING

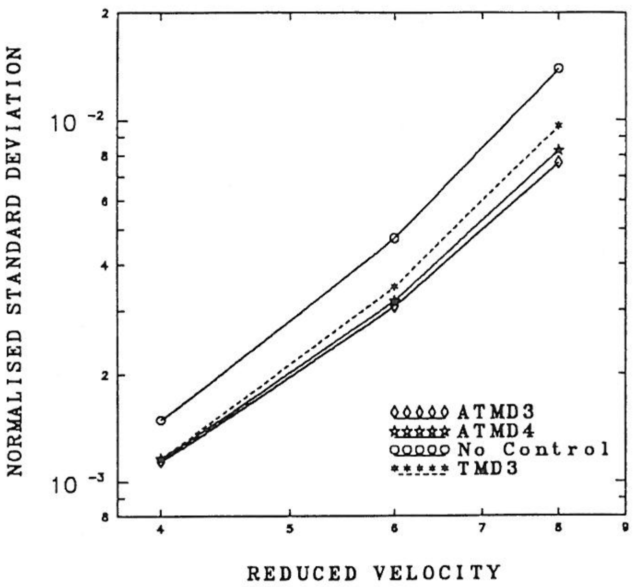


Figure 2 Standard Deviation Cross-Wind Response

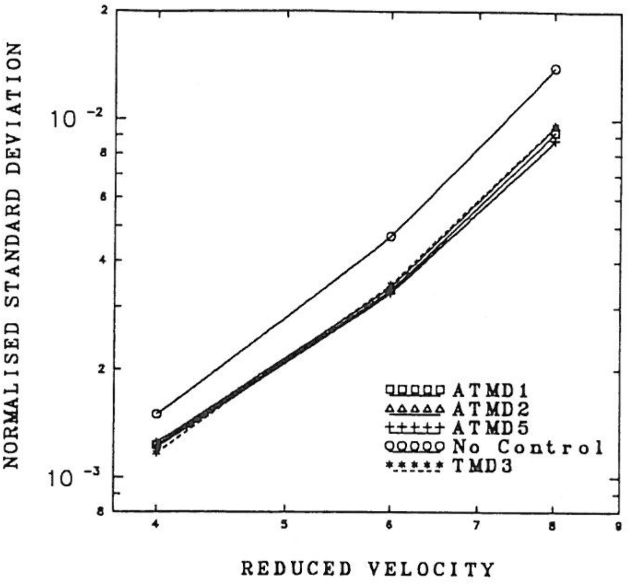


Figure 3 Standard Deviation Cross-Wind Response

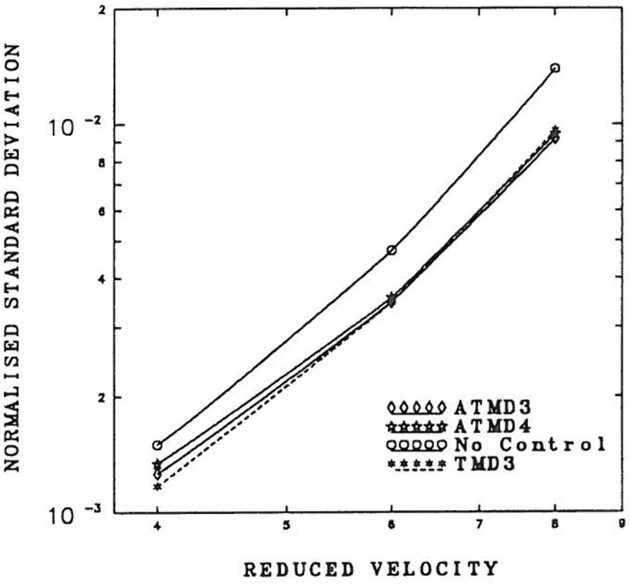


Figure 4 Standard Deviation Cross-Wind Response

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