Wind Tunnel Investigation Of Active Vibration Control Of Tall Buildings

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Abstract: *An Active Tuned Mass Damper (ATMD) installed in the top of a rectangular model building was tested in a wind tunnel for its effectiveness in suppressing cross-wind building vibrations. The ATMD was controlled using a sub-optimal control algorithm. Certain parameters critical to the operation of the ATMD were varied to observe how the ATMD's effectiveness would be altered. The ATMD was found to be effective in reducing cross-wind vibrations. The variation in design parameters of the ATMD resulted in different levels of reduction.*

1. INTRODUCTION

There have been numerous investigations, both analytical and experimental, into the area of passive vibration control of tall buildings. Passive vibration control devices such as Tuned Mass Dampers (TMD) have proven to be effective for certain applications but they are limited in the magnitude of motion reduction they can achieve. These limitations have led to the development of active control devices. These devices use a control algorithm which analyses the dynamic structural feedback to create a control force which drives a mass. The theory for active control has been extensively investigated for the past two decades and it has been found to be a superior method of vibration control. Experimental studies have been carried out to support these findings, but most have involved a shaking table to simulate earthquake loadings. To date there has been only one documented wind tunnel investigation (Soong and Skinner (1)) into the effectiveness of an active control system in suppressing wind induced vibrations. The lack of wind tunnel experiments to support the theoretical studies has arisen due to the complexities involved in developing an active control device which can be installed in a model building.

This paper describes the development of a scaled ATMD which is small enough to fit into a 1:100 scale model building without losing any of the integrity associated with active vibration control. The paper also reports on experiments conducted in a wind tunnel on the model building with the ATMD installed. The effect of changing certain parameters is also investigated. The effectiveness of the ATMD in suppressing wind induced vibration is discussed.

2. ACTIVE TUNED MASS DAMPER DEVELOPMENT

The initial intention was to develop an active control device which would be capable of operating in both an active and passive mode. This was required to facilitate a direct comparison between active and passive vibration control. This concept required that the device be designed so that its parameters, such as mass, damping and frequency, could not only be measured but also modified for further research. To keep the design simple the ATMD model is only a one degree of freedom system.

Several attempts were made in developing an ATMD which was suitable for testing. Initially a 1:400 scale model was chosen for testing which proved to be a major problem for several reasons. The modelling requirements for 1:400 scale wind tunnel tests meant that the building chosen had dimensions of 0.45 x 0.115 x 0.075 with a natural frequency of approximately 7Hz and the damper mass could be no more than 10g. The high frequency of vibration and confined space, restricted the selection of possible actuators. It was found that only solenoids could be small in size and still operate at high speeds. High friction between the iron core of the solenoid and the plastic casing resulted in damping values in excess of what could be accepted. The restriction in the mass of the damper meant the iron core had to act as the damper mass itself. The light mass also resulted in a high natural frequency for the device in its passive mode. Attempts at creating a test model at this scale had to be aborted.

The decision was then made to move onto a scale of 1:100 for testing. Using the experience gained from the 1:400 attempts, the model building was designed to have a large working area and a low natural frequency. The larger scale also meant that a larger damper mass could be used. The new scale widened the range of actuators which could be chosen. Servo motors and stepper motors were both considered, but stepper motors were chosen because of their positional accuracy. A problem encountered with the stepper motors was that the torque of the motor dropped off as the speed of the motor increased. This problem was overcome by **selecting the largest motor which could fit in the available space.**

Many devices were developed at the larger scale, but problems were encountered in each attempt. High friction, high natural frequency and an effective driving method all linked to each other in some way. Overcoming one problem created another but eventually all the problems were conquered and a suitable system was developed.

All design criteria of the initial concept were satisfied in the final design which is illustrated in Fig.1. This was achieved by having an adjustable mass, with four roller bearings to guide the direction, suspended by four chains. Springs were attached to the ends of the mass via hooks and a paddle extending from the base of the mass to an oil container provided the damping. A shaft, with pivots at both ends, connecting one end of the mass to a lever arm on the stepper motor, was used to provide the drive force.

3. CONTROL THEORY

The building model with the ATMD installed is a two degree of freedom system as shown in Fig.2 and the equations of motion for the system are;

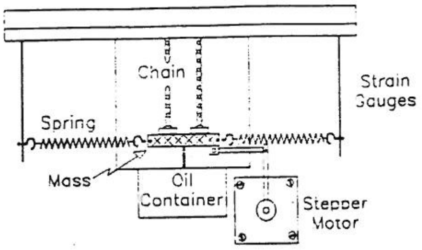

Fig.1. EXPERIMENTAL ATMD

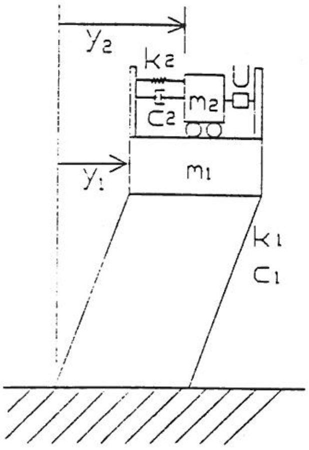

Fig.2. ANALYTICAL MODEL

PASSIVE MODE :

$$m_1\ddot{y}_1+c_1\dot{y}_1+k_1y_1-(\dot{y}_2-\dot{y}_1)\,c_2-(y_2-y_1)\,k_2=0 \qquad (1)$$

$$m_2\ddot{y}_2+(\dot{y}_2-\dot{y}_1)\,c_2+(y_2-y_1)\,k_2=0 \qquad (2)$$

ACTIVE MODE:

$$m_1\ddot{y}_1+c_1\dot{y}_1+k_1y_1-(\dot{y}_2-\dot{y}_1)\,c_2-(y_2-y_1)\,k_2+U=0 \qquad (3)$$

$$m_2\ddot{y}_2+(\dot{y}_2-\dot{y}_1)\,c_2+(y_2-y_1)\,k_2-U=0 \qquad (4)$$

where y_1, m_1, c_1 and k_1 are the top floor displacement, first mode generalised mass, damping constant and stiffness of the building model, respectively; y_2, m_2, c_2 and k_2 are the displacement, mass, damping and stiffness of the ATMD. U is the control force used when the ATMD is in active mode. A sub-optimal control algorithm which uses displacement feedback and drives the ATMD proportionally to the top floor displacement of the building is used to generate the control forces required to drive the mass. An equation to express the principle is;

$$U=y_1k_2R_F+\dot{y}_1c_2R_F \qquad (5)$$

where R_F is the ratio of the mass displacement to the building displacement, and is set at 2.5 for the experiments described in this paper.

4. EXPERIMENTAL PROGRAM

4.1 Experimental Set-up

The ATMD was installed in the 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 AS1170.2-1989 (2) was generated by a combination of spires and roughness blocks. The model building used in the experimental program was a 1:100 scaled model 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 vibrate only in one translational mode with a constant mode shape. Fig.3 shows the experimental set-up.

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

TABLE1. PROPERTIES OF MODEL BUILDING

4.2 Control System

Fig.4 is a schematic diagram of the control system used for the experiments. Strain gauges mounted at the base of the building have been 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 sends a signal to the stepper motor. A sampling rate of 300Hz was used for all experiments.

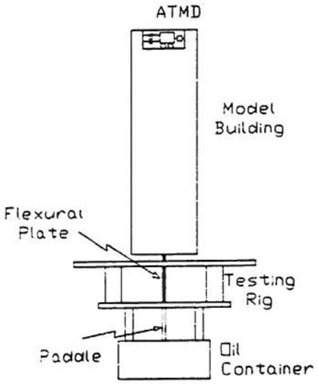

Fig.3. EXPERIMENTAL SET-UP

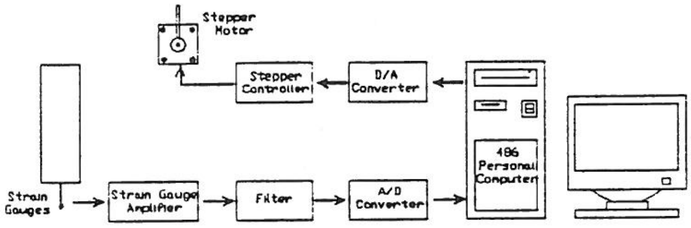

Fig. 4. CONTROL SYSTEM

4.3 Experimental Investigation

The normalised standard deviation cross-wind displacement at the top of the building model with and without the ATMD installed was measured at different reduced wind velocities. The ATMD was tested for five cases of varying parameters. **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 and stiffness ratio of 0.02 or 0.03. Table 2 lists the physical properties of the ATMD for each case tested. Table 3 lists the parameter changes pertinent to different ATMD's. A comprehensive parametric investigation will be carried out in future studies.

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
Frequency (f_2)	3.8 Hz	2.98 Hz	3.3 Hz	2.65 Hz	2.9 Hz
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
Mass Ratio (m_2/M)	0.53%	0.53%	0.86%	0.86%	0.53%
Generalised Mass Ratio (m_2/m_1)	1.59%	1.59%	2.59%	2.59%	1.59%
Stiffness Ratio (k_2/k_1)	0.03	0.02	0.03	0.02	0.02

TABLE2. PROPERTIES OF ATMD'S

ATMD'S	PARAMETER CHANGE
ATMD1-ATMD2	Decrease Stiffness Ratio 0.03 to 0.02.
ATMD1-ATMD3	Increase Generalised Mass 1.59% to 2.59%.
ATMD2-ATMD5	Increase Damping 6.8% to 18%.
ATMD2-ATMD4	Increase Generalised Mass 1.59% to 2.59%.
ATMD3-ATMD4	Decrease Stiffness Ratio 0.03 to 0.02.

TABLE3. ATMD COMPARISON

5. EXPERIMENTAL RESULTS

The normalised standard deviation cross-wind responses σ_y/b and σ_{ya*}/σ_y are presented in Table 4 for the ATMD's in their active mode. Figure 5 is a plot of the normalised standard deviation cross-wind responses σ_y/b and σ_{ya3}/b verses reduced velocity. σ_y represents the standard deviation cross-wind top floor displacement response of the structure, σ_{ya*} represents the standard deviation cross-wind top floor displacement response of the structure with ATMD* installed in it's active mode. The * subscript represents the ATMD case number and b is the width of the structure normal to the wind.

Device Installed	Response	Reduced Velocity 4	Reduced Velocity 6	Reducea Velocity 8
None	σ_y/b	0.00150	0.00472	0.01395
ATMD1	σ_{ya1}/b	0.00123	0.00334	0.00922
	σ_{ya1}/σ_y	0.82	0.71	0.66
ATMD2	σ_{ya2}/b	0.00125	0.00342	0.00962
	σ_{ya2}/σ_y	0.83	0.72	0.69
ATMD3	σ_{ya3}/b	0.00115	0.00307	0.00763
	σ_{ya3}/σ_y	0.77	0.65	0.55
ATMD4	σ_{ya4}/b	0.00117	0.00318	0.00828
	σ_{ya4}/σ_y	0.78	0.67	0.59
ATMD5	σ_{ya5}/b	0.00122	0.00329	0.00875
	σ_{ya5}/σ_y	0.81	0.70	0.63

TABLE4. RMS CROSS-WIND RESPONSE ACTIVE MODE

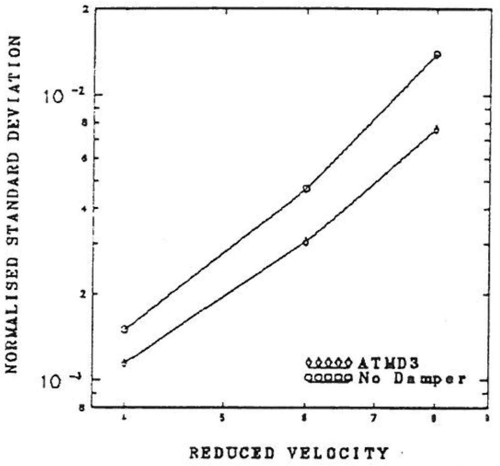

FIG.5. RMS RESPONSE

It can be seen from the results in Table 4 that the 1:100 scale active control device developed for wind tunnel testing is effective in reducing building vibrations. The control performance of the system is seen to be good for all the configurations tested. The performance is seen to improve with increasing reduced velocity, which **is clearly seen in Fig.5. This is due to the fact that at low reduced velocities the building model vibrates with a broad range of frequencies, whereas at reduced** velocity 8 the vibration tends to be around the natural frequency of the building. The nature of the ATMD developed is such that it operates more effectively when it is being driven in a regular manner, such as a sine wave, than a more random type vibration. A random vibration requires quicker operations from the stepper motor which are beyond the motors capabilities.

Looking at each reduced velocity individually, all the ATMD's can be seen to have reduction performance within a narrow range. This is due to the R_F ratio being set at 2.5, ensuring each ATMD case had a mass/building displacement ratio close to 2.5 as shown in Table5. σ_{ma} is the standard deviation mass displacement for the ATMD. Any difference in reduction performance was a direct result of the parameter configuration.

Device ATMD*	Active Mode σ_{ma}/σ_{ya*}
ATMD1	2.45
ATMD2	2.52
ATMD3	2.38
ATMD4	2.57
ATMD5	2.48

TABLE5. MASS/BUILDING DISPLACEMENT RATIO

Looking at each ATMD independently and comparing it's active control performance, it can be seen how different parameters affect the system. The parameters chosen for ATMD1 show a maximum active vibration control reduction of 34% for reduced velocity 8. For other velocities the system is still seen to be effective.

ATMD2 has the same parameters as ATMD1 except the stiffness has been lowered. The control performance of the system reduces the vibrational response of the building by 31% at reduced velocity 8. This is slightly lower than the reduction experienced for ATMD1. This trend is seen for all the reduced velocities tested. The effect of lowering the stiffness of the ATMD is a loss in its active vibration control performance.

The parameters of ATMD3 are the same as those for ATMD1 except the mass has been increased. With an increase in mass a noticeable increase in the control performance of the system was observed for all reduced velocities investigated. At reduced velocity 8 a reduction of 45% is achieved with active vibration control.

ATMD4 has the same parameters as ATMD2 and ATMD3 except for higher mass and lower stiffness, respectively. Comparing this system with ATMD3 which has higher stiffness, a loss of effectiveness is observed because of lowering the stiffness. Comparing this system with ATMD2, the increase in mass results in a more effective system. Both of these observations, support the previous findings.

ATMD5 is the same as ATMD2 but with an increased damping. The control performance of the system is a 37% reduction in vibrations at reduced velocity 8. The higher damping is seen to increase the active control performance for all the velocities tested.

It must be emphasised that for all ATMD's a better response reduction could be **achieved if a larger R_F value is used. The performance of the control system can be further enhanced by adopting an optimal control algorithm rather than the sub-optimal** one used here for these experiments. This will be investigated in further research.

7.CONCLUSION

An ATMD has been developed and successfully tested in a wind tunnel with significant reductions in building vibrations. The main conclusions from this investigation are:

1. Active vibration control can effectively be tested at a small scale in a wind tunnel while still maintaining its integrity.
2. Wind tunnel investigations offer a quick and much needed method of confirming the results of the theoretical studies conducted.
3. For an ATMD the active vibration control performance of the system can be seen to improve by simply modifying some parameters. Increasing parameters such as stiffness, mass and damping, increase the vibration control performance.

References:

1. Soong, T.T and Skinner, G.T (1981). Experimental study of active structural control, *J. Eng. Mech., ASCE,* Vol. 107, No. EM6, Dec., pp.1057-1068.
2. AS1170.2 - 1989, Wind Loads. Standards Association of Australia.