Journal of Wind Engineering and Industrial Aerodynamics, 41-44 (1992) 1997-2008
Elsevier

TORSION RESPONSE AND VIBRATION SUPPRESSION OF WIND-EXCITED BUILDINGS

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Abstract

A series of wind tunnel model tests and theoretical analyses were conducted to investigate torsion excitation, response and vibration suppression of wind-excited buildings. An aeroelastic model for pure torsion vibration was developed and the aeroelastic test results were compared with those obtained by other wind tunnel test techniques. The comparison and practice indicated that this type of modelling technique can be a convenient and efficient way to explore the mechanisms of torsional excitation and predict the torsional response of tall buildings to wind after considering mode shape correction. It is also shown that tuned mass dampers were effective in suppressing the torsional vibration of the building if the parameters of the tuned mass damper were properly selected.

1. INTRODUCTION

Full-scale building response measurements have shown that wind loads acting on modern tall buildings may cause significant torsional moments and motions. Recent trends towards more complex building shapes and structural systems further accentuate eccentricities between the mass centre, elastic centre and instantaneous point of application of aerodynamic loads. Wind-induced torsional effects on tall buildings are an important consideration in modern building design.

Reinhold [1] first used a direct pressure measurement technique to determine mean and dynamic torsional moments on a rigid square building model. Tallin and Ellingwood [2], Kareem [3], and Islam, Ellingwood and Corotis [4] further utilized pressure measurement results of wind loads to analyse wind induced lateral-torsional motion of tall buildings. On the other hand, Tschanz and Davenport [5] used a base force balance technique to develop a generalised torsional force. Both pressure measurement and force balance techniques disregard aeroelastic effects such as aerodynamic damping. Based on the results of multi-degree-of-freedom (MDOF) aeroelastic model tests, empirical relations for estimating mean, standard deviation and peak base torques in the respective most unfavorable wind directions were presented by Greig [6] and Isyumov [7].

In this paper, an aeroelastic model for pure torsion vibration is described. The model design principle is same as the conventional "stick" aeroelastic model for

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translational vibration. The experimental results, by using this technique, were compared with other wind tunnel test techniques, e.g., direct pressure measurement technique and multi-degree-of-freedom aeroelastic model technique. The comparisons included the mechanism of torsional excitation, torsional response of tall buildings and sensitivity of the torsional response to eccentricity between centres of twist and building geometry. The effectiveness of tuned mass dampers in suppressing the torsional vibration of the building was also demonstrated. A new parametric study method of tuned mass dampers suggested by the authors elsewhere was applied to the present torsional vibration and a mode shape correction factor was presented to adjust the model response results to the prototype results.

2. EXPERIMENTAL ARRANGEMENTS

Wind tunnel tests were performed in the No. 2 Boundary Layer Wind Tunnel at the School of Civil and Mining Engineering, the University of Sydney. The wind tunnel is a 1.5m × 1.2m open jet wind tunnel. A 1:400 scale wind model of natural wind flow over open country terrain was developed by using an augmented growth method which included a set of 4 linearly tapered vorticity generators at the start of the working section and low-pile carpet covering a fetch length of approximately 4.5m. The mean velocity profiles are closely represented by the power-law with an exponent α = 0.15. The turbulence intensity was about 10% at the top of the model and the thickness of the boundary layer was found to be approximately 0.9m at the test section. The integral length scale of turbulence of the measured velocity spectrum was found to be approximately 120m at the top of the building model while that of the Harris-Von Karman spectrum under the same terrain category is 200m, as suggested in Engineering Science Data Unit [8]. The distortion of the scale of turbulence by a factor of 1.7 seems to be acceptable.

The building model was a 9.1 x 18.9 x 48.1 cm tall rectangular prism which has an equivalent full scale height of 192.4 m, width of 75.6 m and depth of 36.4 m according to the wind model scale of 1/400. This model was of a rigid timber construction, but the top cover of the building model was made of transparent plastic and, therefore, the motion of the mass damper could be seen during the testing. For the basic model tests, the elastic centre of the building model was coincident with the mass or geometric centre of the model. However, for the eccentric model tests, both centres did not coincide with each other. The model tuned mass damper consisted of two identical small brass blocks which were fixed at both ends of a very thin steel strip. The centre of the thin steel strip was positioned under the top cover of the building model and was usually kept on the vertical elastic axis of the building model.

A schematic representation of the aeroelastic torsion testing rig is shown in Fig.1. The building model was fixed on an aluminium bar which was mounted on two precision bearings or flexural pivots, thus maintaining a constant magnitude mode shape. The model was further restrained by a flexible steel strip and four helical springs, which provided the required torsional stiffness. A strain gauge bridge attached to the flexible steel strip was used to provide an indication of wind induced twist angle and base torque. Two oil baths were designed to simulate viscous structural damping of torsional motion, while two ballast weights could be adjusted to achieve correct inertial scaling.

The mean (static) and standard deviation (dynamic) twisting angle responses $\bar{\theta}$ and σ_θ as well as the base torque responses $\bar{T}$ and σ_T were measured at reduced wind velocities U_r (= $\bar{u}/n_0b$) ranging from 1 to 4.5 (wide face) and 2 to 10

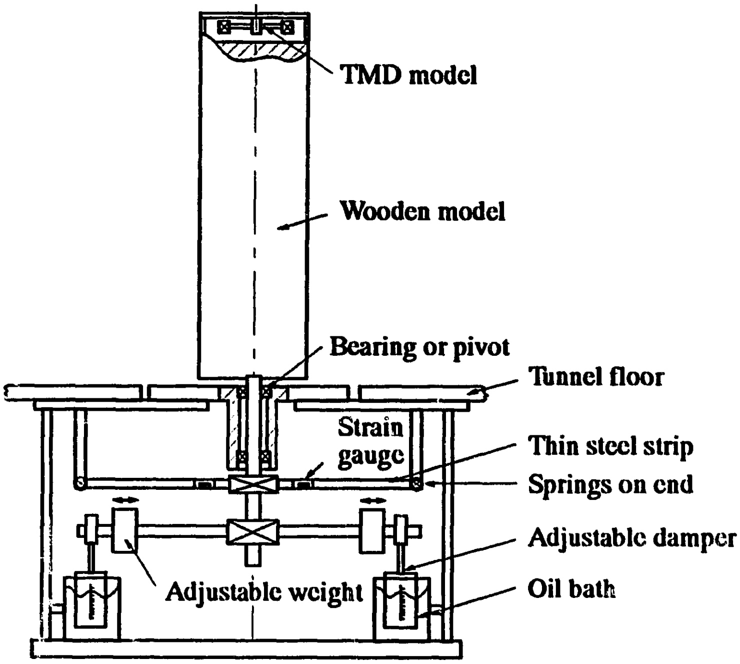

FIG.1 SCHEMATIC REPRESENTATION OF AEROELASTIC TORSION MODEL

(narrow face), and at a structural damping value of 1.2% of critical damping. The reduced velocities were based on the width of the building, b, normal to the wind. In some cases which will be particularly pointed out, the reduced velocity was based on the length parameter L $(=\int |r| ds/A^{\frac{1}{2}})$ as suggested by Greig [6] and defined as V_r $(= \bar{u}/n_0 L)$. $\bar{u}$ is the mean wind velocity at the top of the building; n_0 is the natural frequency of the torsional vibration of the building without any dampers; ds is the elemental length of the building perimeter; $|r|$ is the torque arm of the element ds and A is the cross-sectional area of the building. The torsional response signals were processed in real-time by a micro-computer and the data were transferred and analysed further to obtain response spectra, excitation spectra, probability distributions of the responses and other statistical quantities. The test program consisted of basic model tests and eccentric model tests with and without the tuned mass damper.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Basic model tests

3.1.1 Torsional response

The experimental results showed that the instantaneous unbalanced fluctuating wind force caused fluctuating responses on a symmetrical building and increased the fluctuating responses of the building with increasing reduced wind velocities, whether the incident wind was normal to the wide face or narrow face of the model. The trends of torsional responses with wind direction were consistent with those obtained by Isyumov and Poole [9], using the direct pressure measurement technique, on a rigid model of nearly the same proportions. It was confirmed that, for the rectangular symmetric building studied, the most unfavorable wind direction for the mean base torque was about 10°. Fig.2 shows that the mean torques in this orientation were proportional to V_r^2 and in good agreement with the predicted values obtained by the empirical formulae presented by Isyumov in the ASCE State-of-the-Art Report [10] based on MDOF aeroelastic model tests. However, Fig.3 shows that the standard deviation torques at the most unfavorable wind direction, i.e., $\alpha = 0°$, were not uniformly proportional to $V_r^{2.68}$ and were 2 times the results on average as suggested in [10]. This was attributed mainly to the difference in mode shape of the present "stick" aeroelastic rig and partly to the simplicity of the empirical formulation.

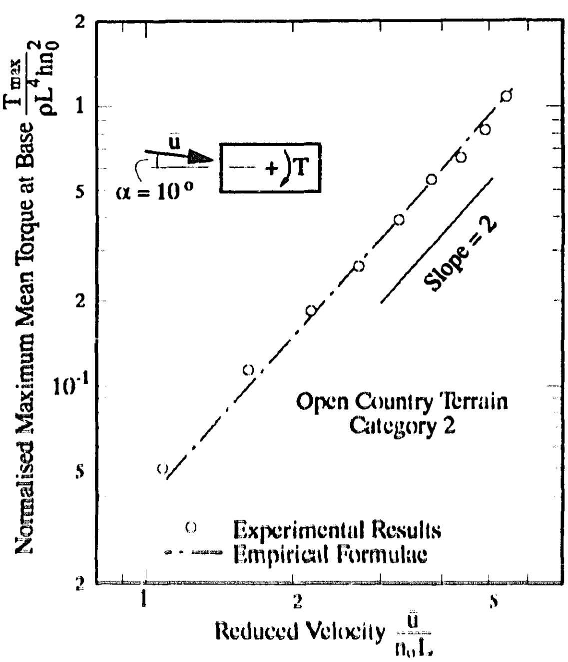

FIG.2 COMPARISON OF MAXIMUM MEAN TORQUE

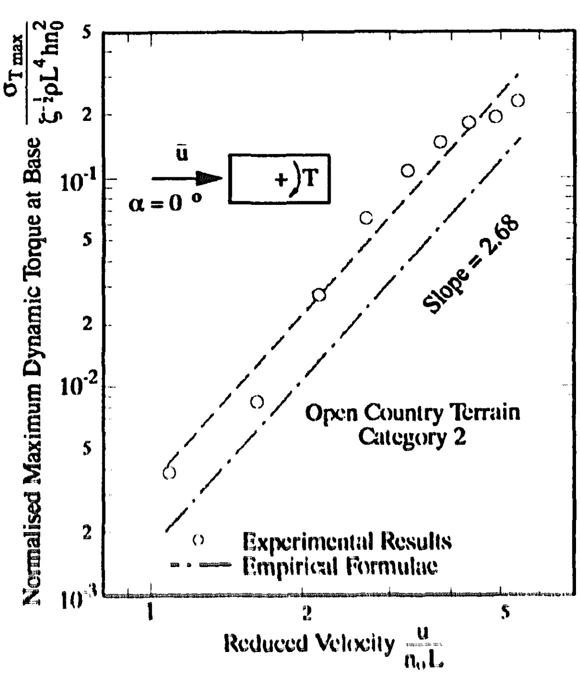

FIG.3 COMPARISON OF MAXIMUM DYNAMIC TORQUE

3.1.2 Torsional response and excitation spectra

The twist angle response spectra of the building model were obtained by Fast Fourier Transformation of the recorded response signals. Normalised response spectra, corresponding to the wide and narrow faces of the building model, are presented in Fig.4. The shapes of these spectra were different but the largest peaks were both located at the natural frequency of the building model.

The difference between the response spectra was attributed to different torsion excitation mechanisms, which can be identified by analysing generalised torsional excitation spectra. The procedure to obtain the generalised torsional spectra was similar to that suggested by Saunders and Melbourne [11] for crosswind force spectra. As shown in Fig.5, with the incident wind normal to the wide face of the building, the generalised torsional excitation spectrum has a dominant peak at a reduced frequency of about 0.1 at which there is concentrated excitation energy associated with the vortex shedding process. With the incident wind normal to the narrow face of the building, the peak in the torsional excitation spectrum was relatively broad and, at a reduced wind velocity of 8, two peaks could be readily identified at reduced frequencies of about 0.04 and 0.15. The mechanisms of the two peaks will be discussed later, combined with the results of the eccentric model tests. The experimental results of the basic model tests also showed that different wind directions caused different generalised torsional excitation of the rectangular building. A detailed description has been reported by the authors [12].

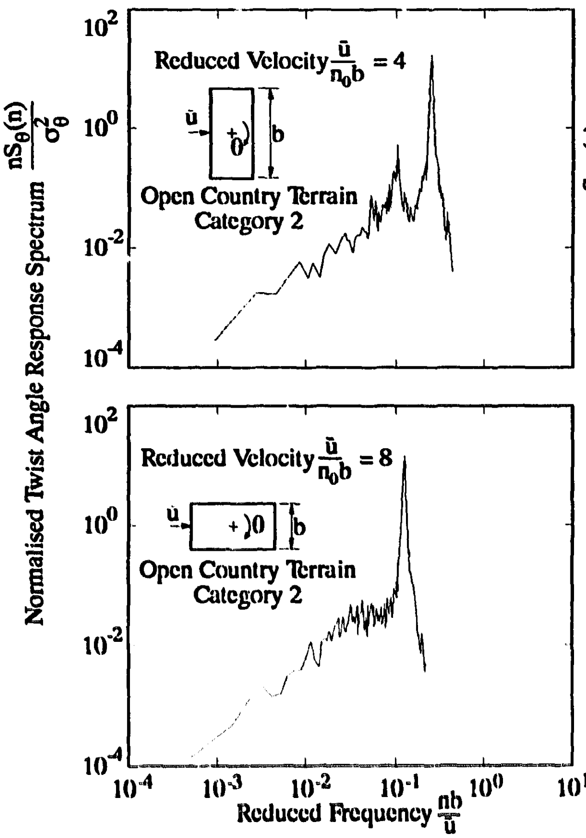

FIG.4 TWIST ANGLE RESPONSE SPECTRA

(Basic Model)

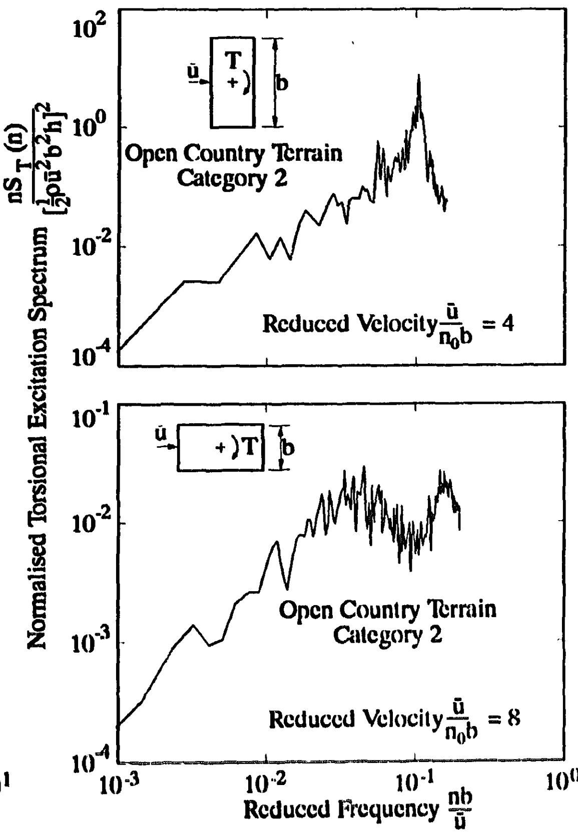

FIG.5 TORSIONAL EXCITATION SPECTRA

(Basic Model)

3.1.3 Upcrossing probability distribution

As discussed by Melbourne [13], it is often more convenient to express the probability distribution of the response of a tall building in terms of upcrossing, i.e., the rate of exceeding a given response amplitude, rather than on a time basis. The upcrossing probability analysis can be performed by digital analysis, and the results can be used to determine the variations from that of a normally distributed process. It was found that in the reduced wind velocity range studied, the torsional responses were essentially normally distributed as shown in Fig.6, whether the incident wind was normal to the wide face or narrow face of the model.

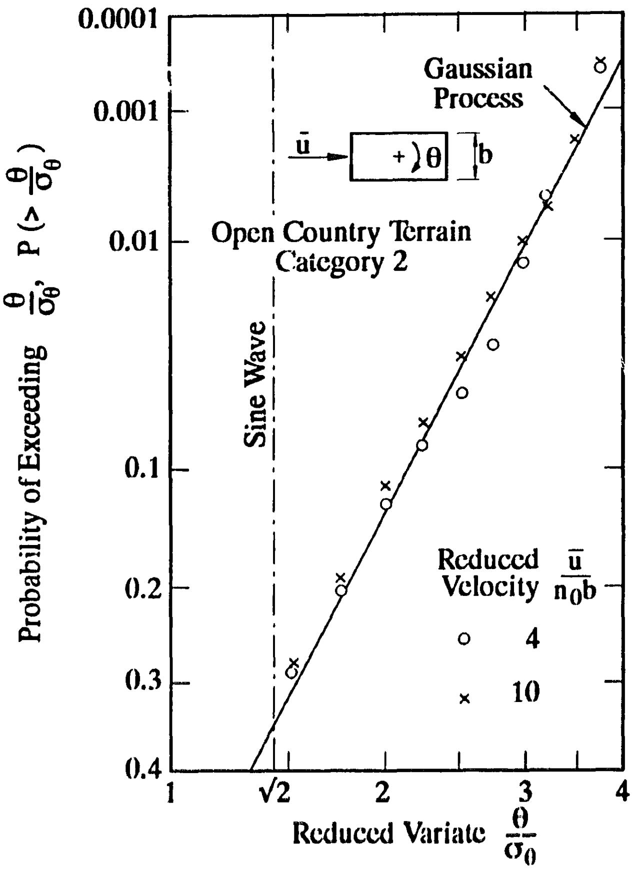

FIG.6 UPCROSSING PROBABILITY DISTRIBUTIONS OF TORSIONAL RESPONSE (Narrow Face)

3.1.4 Aerodynamic damping

As a building moves through the fluid in response to the wind loading, an aeroelastic force which depends on the building motion may be generated. This force is usually referred to as the aerodynamic damping force which can be estimated by the aerodynamic damping. Aerodynamic dampings of prismatic bodies in the drag and lift directions have been discussed by Davenport [14], although the relevant data are still not plentiful. However, very little information on torsional aerodynamic damping of a prism is available. By analysing the decay curve of the torsional response autocorrelation function, the torsional aerodynamic damping was evaluated approximately. Fig.7 shows log plots only of the autocorrelation envelopes of the torsional responses with the wind incidence normal to the narrow face of the building. The total damping of the building, ζ_t, is the sum of the structural damping ζ_s and the aerodynamic damping ζ_a. It was found that the torsional aerodynamic damping was small for both wind directions and for all studied reduced wind velocities. The maximum positive aerodynamic damping ratio was less than 0.4 %, and there was a negative aerodynamic damping ratio of approximately −0.2 % at a reduced velocity of 8 and with the wind incidence normal to the narrow face of the building. However, larger negative aerodynamic damping may occur at reduced wind velocities above the studied range.

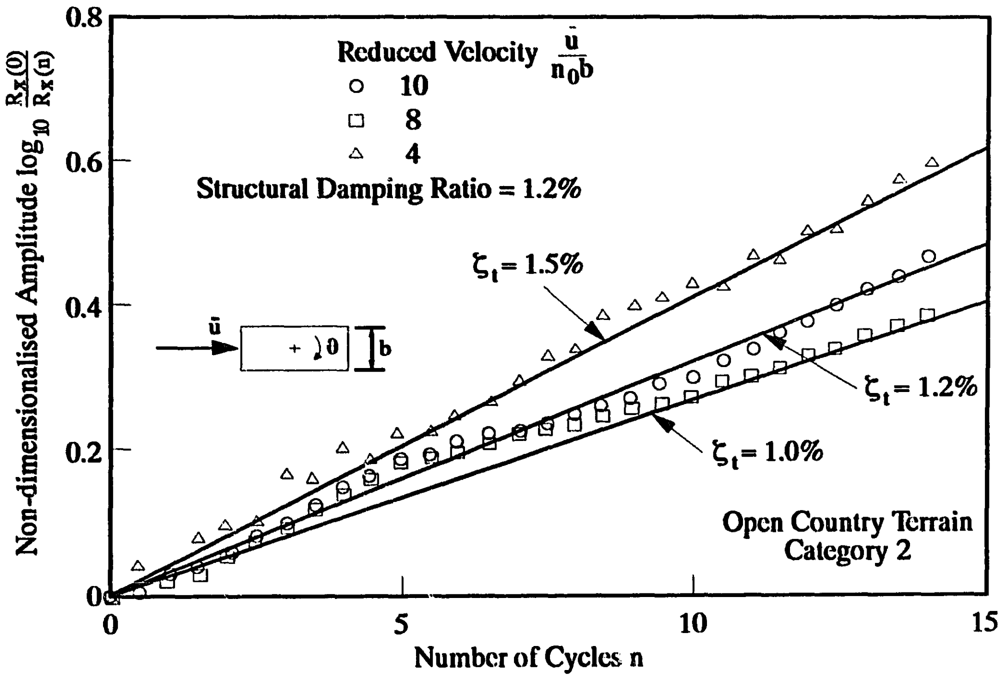

FIG.7 AUTOCORRELATION ENVELOPE OF TORSIONAL RESPONSE
(Narrow Face)

3.2 Eccentric model tests

The torsional responses of tall buildings can be amplified by asymmetrical wind pressure loading about the elastic axis, or inertial loading resulting from non-coincidence of the centre of mass with the elastic axis. In order to estimate this influence and further investigate the torsional excitation mechanism, the elastic centre of the basic model was shifted away from the mass (geometry) centre of the basic model by about 10% of the width of the model, in the longer axis of the model section. As a result, the building model generalised mass moment of inertia increased by 9.8% and the corresponding natural frequency decreased by 4.6%. None of the other parameters changed.

For incident wind normal to the narrow face of the eccentric model, two wind directions, i.e., 0° and 180°, were considered. Compared with the basic model excitation spectrum, the generalised torsional excitation spectra for these two orientations at the reduced velocity of 8 also have two obvious peaks, but the two peak values were different for different eccentricity levels, as shown in Fig.8. With the forward shift of the elastic centre of the building model, the magnitude of the first peak decreased, but the second peak values increased. The situation was reversed for the backward shift of the elastic centre. Compared with the experimental results obtained by Isyumov and Poole [9], it is thought that the first peak is related to crosswind excitation due to incident turbulence, which is mainly distributed on the windward halves of the two side faces of the building. The second peak is thought to be caused by flow re-attachment intermittencies on the leeward halves of the two side faces of the building. Note that the frequency corresponding to the second peak was relatively close to the natural frequency of the building model and, therefore, this excitation mechanism is dominant in the present study.

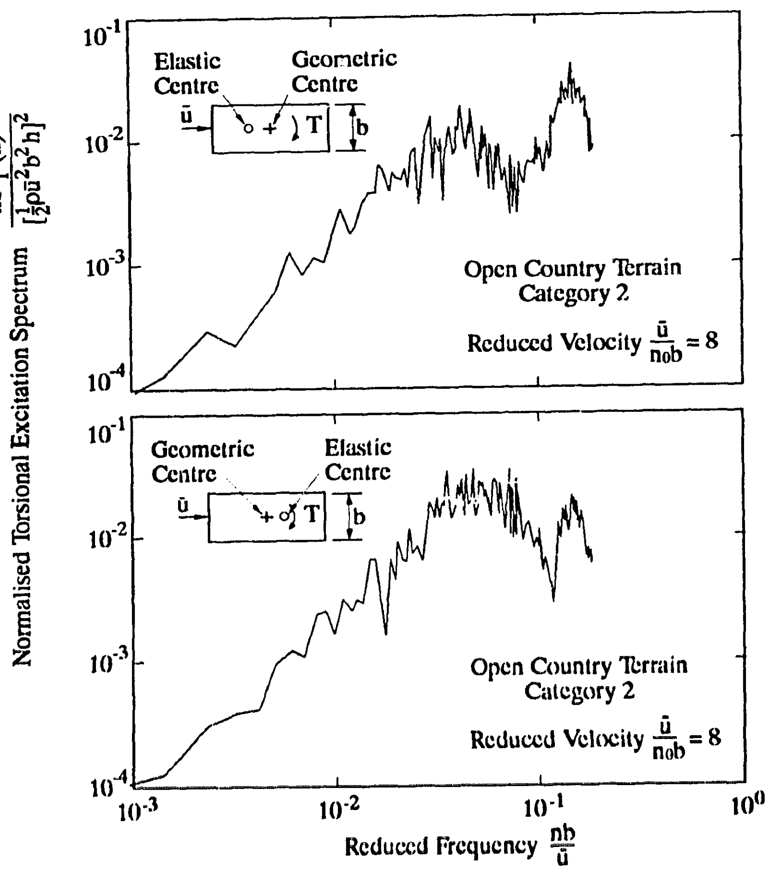

FIG.8 TORSIONAL EXCITATION SPECTRA (Eccentric Model)

Compared with the test results of the basic model with the wind incidence normal to the wide face of the model, the dynamic twist angle response increased by up to 40% and a significant mean twist angle response, which was still proportional to V_r^2, occurred. The effect of angle of wind incidence on the torsional response of the eccentric model was also investigated. The maximum dynamic torque still occurred at around 0° or 180° while the maximum mean torque was located at 120°. At the reduced wind velocity of 8, the maximum dynamic torque of the eccentric model increased by 30% and the maximum mean torque increased by a factor of 2 or more, compared with the values of the basic model.

3.3 Eccentric model with tuned mass damper (TMD)

Tuned mass dampers as an energy dissipation device can be used to increase the overall effective damping of the main structure and accordingly to reduce wind-induced building vibration. Full-scale tuned mass dampers have been designed and fitted to some wind sensitive structures and tall buildings such as the Sydney Tower, Sydney; the CN Tower, Toronto; the John Hancock Tower, Boston; the Citicorp Center, New York City and others. Aeroelastic tests of structure and tall building models with tuned mass dampers have also been conducted in boundary layer wind tunnels [15-18]. All these studies have indicated the effectiveness of TMD systems in reducing the alongwind and crosswind vibrations of tall buildings and structures. However, very little information on suppression of torsional vibration of tall buildings is available, although the TMD on the John Hancock Tower was designed mainly to suppress the torsional vibration of the tower.

As a preliminary study, a symmetric tuned mass damper, with about 1.2% of the building model generalised mass moment of inertia, was positioned under the top cover of the building model. The damper damping was 4.8% of critical and the total system then had 2.9% of critical damping. The damper frequency was tuned to the frequency of the building model. The experimental results showed that a TMD can effectively suppress wind-induced torsional vibration within the studied range of wind reduced velocities and angles of wind incidence. There is up to a 30% reduction in response corresponding to the wide face of the model and a 45% reduction corresponding to the narrow face of the model, even though the parameters of the tuned mass damper tested were not the optimum. The variation of normalised dynamic torques with angle of wind incidence and the effectiveness of the tuned mass damper are shown in Fig.9.

The twist angle response spectra of the building model with and without the damper were compared for the incident wind normal to the wide and narrow faces of the building model. It was found that the reduction in energy amplitudes around the natural frequency of the building was quite significant [12].

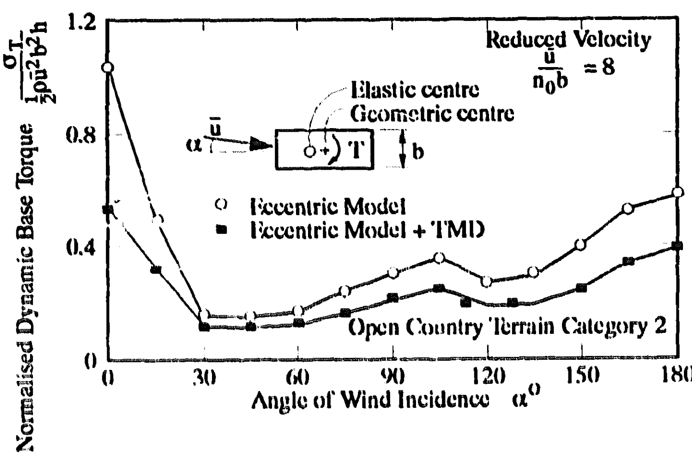

FIG.9 EFFECT OF ANGLE OF WIND INCIDENCE AND TMD

4. PARAMETRIC STUDIES OF TMD

Most parametric studies of a TMD in suppressing wind-induced building motion are conducted through theoretical analyses. A tall building with a TMD is usually modelled as a two-degree-of-freedom system and wind excitation is simplified to white noise excitation or band-limited white noise excitation [16]. The theoretical results of TMD parametric studies, without considering actual wind excitation mechanisms and effects of building size, shape and surroundings on the wind loads, can be unreliable and inconsistent with experimental results obtained from aeroelastic model tests or prototype measurements. Hence the reliability of large scale tuned mass dampers is affected by the shortcomings in existing design procedures.

Recently, the authors proposed a predictable and economical method for parametric studies of TMD, which combines experimental and analytical techniques [18]. This technique is based on modal analysis, random vibration theory, and direct measurement in the wind tunnel of wind excitation or response spectra of the plain building without the damper. The effects of wind intensity, surrounding environment, building size, shape, mass, stiffness, and natural damping on the responses of the building can readily be investigated. The comparison between the experimental and the semi-analytical results was found to be satisfactory.

The same technique was applied to the present eccentric torsion model. Two twist angle response spectra of the plain building model were selected as input spectra to conduct optimum parametric studies of the TMD: one for incident wind normal to the wide face of the model and at a reduced wind velocity of 4; another for incident wind normal to the narrow face, at a reduced velocity of 8, and with the forward shift of the elastic centre of the model. The shapes of both input spectra were quite different as mentioned before. It was found that, for different torsional excitation spectra, the tuned mass damper has a different effectiveness. With the wind incidence normal to the narrow face of the model, the TMD system was more effective, and the effectiveness of the TMD system approached the results obtained by using simple white noise excitation. However, at the reduced velocity of 4 and with the wind incidence normal to the wide face of the model, the TMD system was less efficient for the measured torsional excitation than for white noise excitation. The results of an optimum parametric study indicated that, for a mass moment ratio of 4%, the maximum torsional response reductions are 38% and 57% for wind normal to the wide and narrow faces of the building respectively.

5. ESTIMATE OF MODE SHAPE CORRECTION

The present aeroelastic building model is maintained at a constant magnitude mode shape and there is a mismatch between the model and prototype torsional mode shapes. As a result, significant corrections are invariably needed to adjust the torsional responses. The same problem exists in the force balance technique and the conventional "stick" aeroelastic model for 2 fundamental sway modes if the prototype mode shapes of translational vibration depart significantly from a straight line mode shape. Based on a reasonable assumption of the co-spectra of wind excitations and actual generalised mass or mass moment of inertia, expressions for translational and torsional mode shape corrections were recently suggested by the authors to adjust the experimental response results to the prototype results [19]. The derived expressions are more general than results currently available in the literature and the corresponding curves are in agreement with the experimental results.

For torsional responses, the practical mode shape correction factor η_t should conservatively be taken as follows:

$$\eta_t = \left[\frac{4\gamma + 1}{4\gamma + 2\beta + 1}\right]^{\frac{1}{2}} \qquad (1)$$

where γ is the power law exponent of the mean wind velocity profile; β is the exponent in the mode shape function expressed in power law format.

Referring to the comparison between the experimental data and empirical values of the dynamic base torque, which are shown in Fig.3, the error can now be partly explained. For a terrain category 2 and $\gamma = 0.15$, η_t ranges from 0.72 (β =0.5) to 0.46 (β = 1.5). The corresponding values in Fig.3 would be 0.5 on average. Therefore, the error shown in Fig.3 can be adjusted by an appropriate factor to some extent, but the dynamic responses remained not uniformly proportional to $V_r^{2.68}$ as suggested in [10]. Further comparison of the present aeroelastic model with the MDOF aeroelastic model should be based on several different building models because the mode shape parameter β and the mass moment distribution of the building are not directly reflected in the empirical formulae.

6. CONCLUSIONS

1. Aeroelastic modelling technique for pure torsion vibration can be a convenient and efficient way to explore the mechanism of torsional excitation and predict the torsional response of tall buildings to wind. Some aeroelastic effects can be investigated and the effectiveness of active and passive systems to control dynamic motion of buildings can also be demonstrated.

2. From the basic model tests, it was shown that the experimental results of the maximum mean torque were in good agreement with the empirical values suggested by Greig and Isyumov [10]. However, there was some difference in the maximum dynamic torque, even after mode shape corrections were considered. With the wind incidence normal to the wide face of the building, vortex shedding is believed to be the dominant mechanism of torsional excitation. With the wind incidence normal to the narrow face, it is thought that incident turbulence and flow re-attachment intermittencies on the two side faces of the building might be the main excitation mechanisms. Experimental results also showed that the torsional responses were essentially normally distributed and the torsional aerodynamic damping was small in the reduced wind velocity range studied.

3. For the model with a 10% geometric eccentric ratio, the maximum dynamic torque occurred at around 0° or 180° similar to the basic model tests, while the maximum mean torque was located at 120°. At a reduced wind velocity of 8, the maximum dynamic torque of the eccentric model increased by 30% and the maximum mean torque increased by a factor of 2 or more, compared with the values of the basic model.

4. The aeroelastic tests of the eccentric model with a TMD demonstrated that a TMD can effectively suppress wind-induced torsional vibration. There is up to a 30% reduction in response with wind incidence normal to the wide face of the building and a 45% reduction with wind incidence normal to the narrow face of the building, even though the parameters of the TMD tested were not the optimum. The parametric studies of TMDs, based on the proposed semi-analytical method, showed that the TMD system was usually less effective for the measured torsional excitation than for white noise excitation.

7. ACKNOWLEDGEMENTS

The pure torsional dynamic rig was built at the Fluids Laboratory of the University of Sydney. The efforts of Mr. David Cockram are acknowledged with thanks. The contribution of Dr. L. Apperley for his valuable suggestions and data acquisition system, and the assistance of Mr. R. Brew and Miss K.L. Pham in tracing graphs, are also acknowledged.

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