TORSIONAL RESPONSE AND VIBRATION SUPPRESSION OF WIND-EXCITED TALL BUILDINGS

By

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1. INTRODUCTION

Full-scale building response measurements have shown that wind loads acting on modern tall buildings may cause significant torsional moments and motions. At least two major buildings which have suffered permanent structural damage as a result of wind action (Mayer-Kaiser, Miami; Great Plains Life, Lubbock, Texas) exhibited marked permanent deformations in torsion. However, very little is known about the mechanism of torsional excitation and suppression of torsional vibration and, furthermore, it has not been uncommon to omit the torsional mode from the more simple aeroelastic models.

Reinhold (1977) first used a direct pressure measurement technique to determine mean and dynamic torsional moments on a rigid square building model, while Tschanz and Davenport (1983) used a base force balance technique to develop a generalised torsional force. Both techniques disregard aeroelastic effects such as aerodynamic damping. Based on the results of multi-degree-of-freedom aeroelastic model tests, empirical relations for estimating mean, standard deviation and peak base torques in the respective most unfavorable wind direction were presented by Greig (1980) and Isyumov (1982).

Recently, a "stick" aeroelastic model for pure torsion vibration has been developed at the Fluids Laboratory of the University of Sydney. A series of wind tunnel model tests were carried out to investigate the mechanism of torsional excitation, torsional response of tall buildings, sensitivity of the torsional response to eccentricity between centres of twist and building geometry, as well as the effect of tuned mass dampers on the torsional response of tall buildings. The following is a brief description of some of the experimental techniques and results.

2. EXPERIMENTAL TECHNIQUES

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 an open circuit wind tunnel with a working section of 1.5m × 1.2m and is approximately 4.5m long. A 1:400 scale wind model of natural wind flow over open country terrain was developed over the fetch of the working section using an augmented growth method which included a set of four 1.2m high spires at the windward edge and low-pile carpet. The mean wind speed profile and the longitudinal turbulence intensity profile, as well as integral scale of turbulence, were found to be consistent with those suggested by the Australian Wind Loading Code, AS 1170.2-1989.

The building model was a 9.1 × 18.9 × 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. This model was of a rigid wooden construction and was fixed on an aluminium bar which was mounted on two bearings as shown in Fig.1, 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. Two oil baths were used to simulate viscous structural damping of torsional motion. The mass distribution was assumed to be uniform and was adjusted to give a structural density of 200kg/m^3. Strain gauge bridges attached to the flexible steel strip were used to measure the twist deflection angle and base torsional moment of the model.

The model tuned mass damper consisted of two small brass blocks which were fixed at both ends of a very thin steel strip. The centre of the thin steel strip was positioned at the top cover of the building model. The damping of the model tuned mass damper was provided by covering the steel strip with plastic tape.

The mean (static) and standard deviation (dynamic) twisting angles and base torsional moments were measured at reduced wind velocities U_r ($= \overline{u}/n_0 b$ or $\overline{u}/n_0 \iota$) ranging from 1 to 4.5 (wide face) and 2 to 10 (narrow face) as well as at a structural damping value of 1% of critical damping. The reduced velocities were based on the width of the building, b, normal to the wind and, in some cases, based on the length parameter ι ($= \int |r| ds / A^{\frac{1}{2}}$). $\overline{u}$ 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, probalility distributions of the responses and other statistical quantities.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Basic model tests: The experimental results showed that instantaneous unbalanced fluctuating wind forces caused fluctuating torques on a symmetrical building and increased the fluctuating torques of the building with increasing reduced wind velocites, whether the incident wind was normal to the wide face or narrow face of the model. At the same time, the base mean torques were seen to be relatively small for the two orientations within the whole studied range of reduced velocities. As the angle of wind incidence was changed from 0° to 90°, the dynamic torque decreased from a maximum at around 0° to a minimum at around 45° and then increased for higher values of angle. However, the two peak values of the mean torque occurred at 15° and 60° (in the opposite direction), where the wind directions were not aligned with the axes of the model symmetry. These trends of torsional responses with wind direction were consistent with those obtained by Isyumov and Poole (1983) on a rigid model of nearly the same scale. Furthermore, it was found that the mean torques at the most unfavorable wind direction were proportional to U_r^2 and in good agreement with the predicted values obtained by the empirical formulae suggested by Isyumov (1982). The standard deviation torques at the most unfavorable wind direction were approximately proportional to $U_r^{2.68}$, but were higher than the results obtained using the empirical formulae.

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 the reduced wind velocity of 8, two peaks could be readily identified at the reduced frequencies of about 0.04 and 0.15. From the viewpoint of energy distribution, both spectral shapes look similar to the corresponding cross-wind force spectral shapes and therefore the mechanisms of torsional excitation of the tall buildings might be closely related to those of cross-wind excitation. With the accumulation of generalised torsional excitation spectra of buildings with different shapes and sizes, a design procedure similar to cross-wind resopnse prediction (Kwok, 1982) can be developed. In addition, the upcrossing probability analysis of the building torsional response showed that dynamic torque responses were essentially normally distributed.

By analysing the decay curve of the torsional response autocorrelation function, torsional aerodynamic damping was evaluated. It was found that, with the incident wind normal to the narrow face of the building, aerodynamic damping increased with increasing reduced wind velocity. However, with the incident wind normal to the wide face of the building, the aerodynamic damping at the reduced velocity of 8 was smaller than that at the reduced velocity of 4.

3.2 Eccentric model tests: The elastic centre of the basic model was then shifted away from the mass 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 mass moment of inertia increased by 9.8% and the corresponding natural frequency decreased by 4.6%. None of the other parameters was changed. For incident wind normal to the narrow face of the eccentric model, two wind directions, i.e. 0^0 and 180^0, were considered. It was found that there was a significant difference in mean torque and a relatively small difference in dynamic torque because of the different eccentricity directions. Generalised torsional excitation spectra for the two orientations and at the reduced velocity of 8 also have two obvious peaks and the peak values were different for different eccentricity levels. Combined with the experimental results obtained by Isyumov and Poole (1983), the first peak is considered to be the variation of the lift force and its location resulting from fluctuations in the approaching flow. The second peak is related to flow re-attachment intermittencies on the back sharp edges of the two side faces.

Compared with the testing results of the basic model and with the wind incidence normal to the wide face of the model, the mean torque showed a marked increase and the dynamic torque increased by up to 40%. The maximum dynamic torque still occurred at around 0^0 or 180^0 while the maximum mean torque was located at 15^0 or 120^0.

3.3 Eccentric model with Tuned Mass Damper (TMD): A symmetric tuned mass damper, with about 1.2% of the building model mass moment of inertia, was positioned at the top cover of the building model. The total system then has 2.75% of critical damping. 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 50% reduction corresponding to the narrow face of the model. The variation of normalised dynamic torques with angle of wind incidence and the effectiveness of the TMD are shown in Fig.2, in which σ_t is the standard deviation of the building base torque; ρ and h are respectively the air density and the building height.

Based on the measured torsional excitation or response spectra, an optimisation parametric study was also conducted by numerical calculation to determine the torsional TMD tuning and damping required to produce the smallest building torsional dynamic response for each of a number of mass ratios.

Last but not least is torsional mode-shape correction. Two mode shape correction factors suggested by Boggs and Peterka (1989) for the force balance method were inverted and applied to the present "stick" aeroelastic model.

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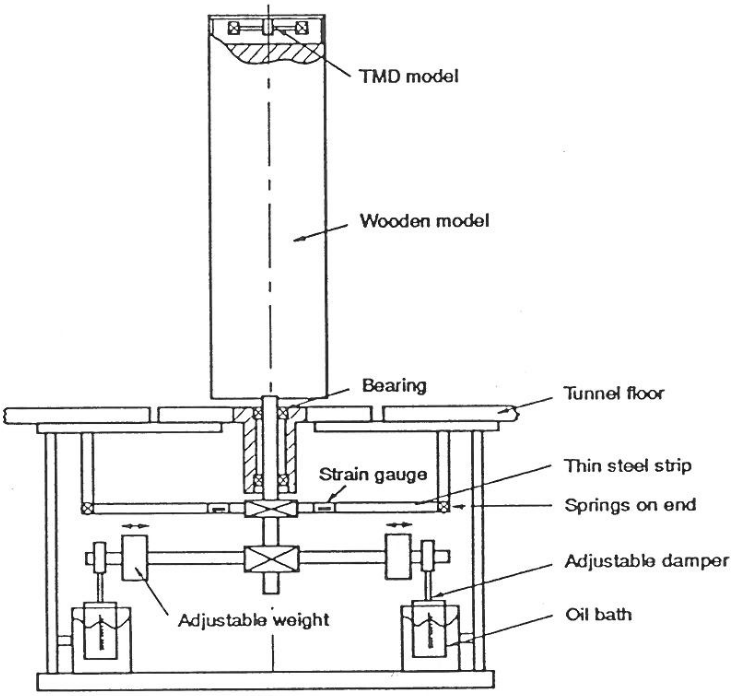

FIG.1 SCHEMATIC REPRESENTATION OF AEROELASTIC TORSION MODEL

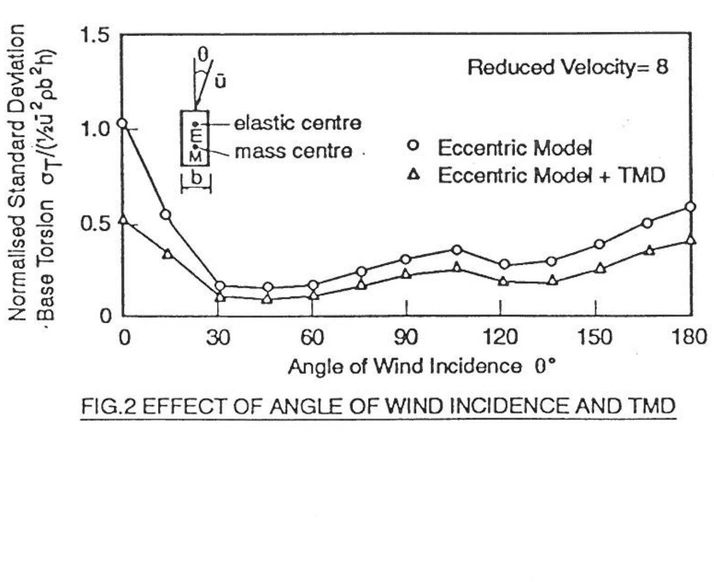

FIG.2 EFFECT OF ANGLE OF WIND INCIDENCE AND TMD