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Evaluation of HFBB Analysis under the Effects of Surrounding Buildings

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Abstract

As an alternative to the more conventional application of general mode shape correction factors in the high frequency base balance (HFBB) analysis, a methodology referred to as the linear-mode-shape (LMS) method has been recently developed to allow better estimates of the generalized forces by establishing a new set of centres at which the translational mode shapes are linear. The LMS method was applied to a tall building project in Hong Kong in the current study, which is located in a heavily developed business district and surrounded by tall buildings and mixed terrain. The HFBB results validated the versatility of the LMS method for the structural design of an actual tall building subjected to the varied wind characteristics caused by the surroundings. In comparison, the application of mode shape correction factors in the HFBB analysis did not directly take into account the influence of the site specific characteristics on the actual wind loads, hence their estimates of the building responses have a higher variability.

Introduction

The high-frequency base balance (HFBB) technique has become one of the most common wind tunnel testing techniques for predicting wind-induced forces for tall building design since it was developed in the early 1980s (Davenport and Tschanz, 1981; Tschanz and Davenport, 1983). Recent trends towards irregular building shapes and increased building heights have resulted in buildings having significantly nonlinear and/or three-dimensional (3D) mode shapes that have typically been treated through the application of mode shape correction factors (e.g. Boggs and Peterka, 1989; Chen and Kareem, 2004; Holmes, 1987; Holmes et al., 2003; Lam and Li, 2009; Xu and Kwok, 1993). However, the correction factors inherently introduce other uncertainties and the effects of surroundings on the accuracy of the generalised wind force predictions have not been investigated in detail in the literature. An alternative analysis methodology, referred to as the linear-mode-shape (LMS) method, has been recently developed to minimise the potential uncertainties in the estimation of generalised wind forces by "linearizing" the sway components of the 3D mode shapes without the need to assume or surmise the likely form of the wind load distributions.

The LMS method has been evaluated and compared with the methods using mode shape correction factors for a rectangular building, which was wind tunnel tested in isolation in an open terrain (Tse et al., 2009). The results demonstrated that the LMS method has the potential to provide more accurate predictions of the wind-induced loads and responses for buildings with translational-torsional coupled mode shapes. For the current study, a real tall building and its surroundings, which included tall buildings and mixed terrain, were modelled to examine the effects of the surroundings on the accuracy, versatility and reliability of the LMS method as well as the application of mode shape correction factors. The details of the wind tunnel tests, results and performance of the methods under different wind loading environments due to the surroundings are outlined and discussed in this paper.

Details of the Subject Building and its Surroundings

The subject building considered in this paper is a 36-storey residential tower on top of a 4-level commercial podium. The tower structure consists of load bearing walls and a simple beam and slab construction. Lateral wind loads acting on the tower are resisted by the core walls and load bearing walls of the tower. The tower structure is supported on a transfer beam sitting on the columns and walls of the podium. A typical floor plan, showing the reference axes, and an elevation of the building are presented in Figure 1. The studied building has a height of approximately 151 m above ground level over a small site coverage area of approximately 25 m by 13 m, resulting in an aspect ratio (H:W:D) of 12:6:1.

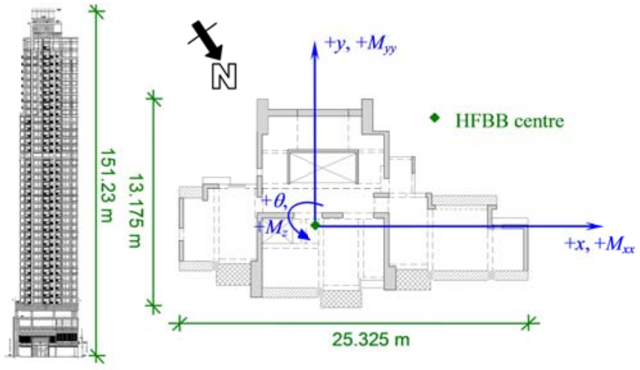

Figure 1. Elevation and typical plan of the subject building.

The mode shapes corresponding to the first three modes of vibration, associated with the storey mass centres over the building height, are displayed in Figure 2. It should be noted that the torsional components were multiplied by the overall radius of gyration (i.e. ~8.3 m) of the building to maintain dimensional consistency among the three (x, y, z) components for the sake of presentation. The first mode of vibration has a dominant translational component along the x axis and a significant torsional component. The second mode is basically a translational mode of vibration (i.e. having a negligible torsional component) with a dominant component along the y axis. The third mode is a predominantly torsional mode of vibration with modest translational components. The natural frequencies of the first three modes were 0.238 Hz, 0.258 Hz and 0.429 Hz respectively.

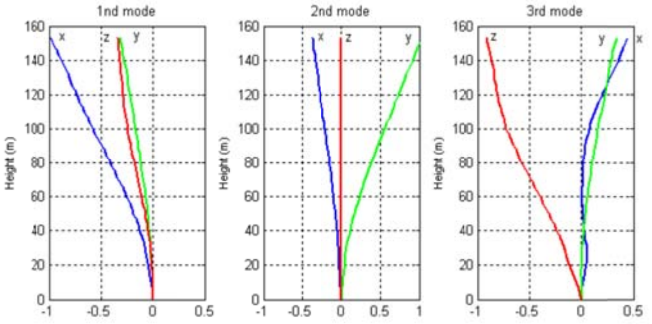

Figure 2. Mode shapes of the subject building.

The building site is close to the harbourfront in Hong Kong and surrounded by topography comprising mixtures of open water, urban and built-up terrain on both sides of the harbour, and mountainous areas on Hong Kong Island to the south and in the New Territories to the north. A 1:2000 scale topographical study was undertaken to quantify the effects of local topography on mean and gust wind speeds approaching the site of the subject building. Results of the topographical study showed that the building has relatively open exposures towards the northeast and northwest directions, whereas it is sheltered from southerly winds by nearby mountains with peaks in excess of 400 m – 500 m. For the majority of wind directions, wind conditions approaching the building site were similar to wind flow over a large city centre and were designated as condition A. For the remaining wind directions tested, wind conditions were similar to wind flow over urban terrain and designated as condition B. Mean wind speed and turbulence intensity profiles for the two approach conditions are presented in Figure 3 along with power law functions that provided the best overall fit to the measured data.

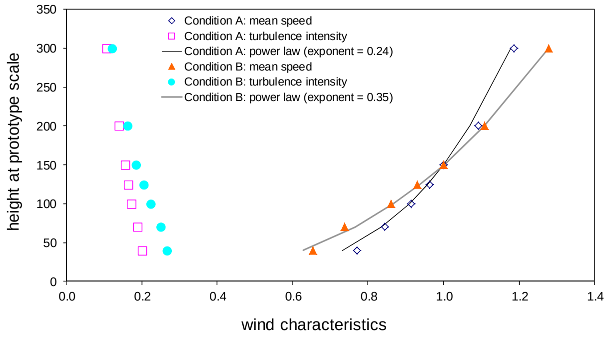

Figure 3. 1:400 scale wind characteristics: approaching wind conditions A and B.

Wind Tunnel HFBB Test Setup

A lightweight, 1:400 scale model of the subject building was mounted on a rigid base balance such that the overall mass and stiffness of the entire system produced sway and torsional natural frequencies that were well above the range of interest for the HFBB tests. The force balance was calibrated by applying a range of known static loads to the model prior to the wind tunnel testing to provide direct measurements of the wind loads. Measurements were taken for 36 wind directions at 10° intervals, for the full 360° azimuth, where a wind direction of 0° or 360° corresponds to an incident wind approaching directly from the north, and winds from 30° are approximately perpendicular to the wide face of the subject building.

All known existing and planned surrounding buildings and topographical features within a radius of 500 m were modelled to the same linear scale and were included in the HFBB tests to simulate their effects on wind flows around the site and subject building. A map showing the coverage of the surrounding buildings is presented in Figure 4, in which the buildings having heights significantly taller than the subject building are hatched. The remaining areas are mainly slopes, open spaces and structures with heights less than 100 m. For ease of reference, the distribution of approaching wind conditions is also illustrated in Figure 4.

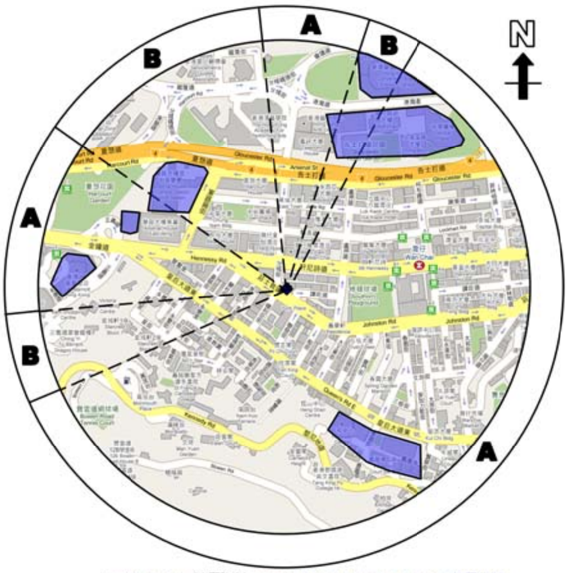

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Figure 4. Coverage of the 1:400 scale model.

It is evident that the subject building was exposed to a wide range of wind loading environments, resulting from the combinations of the two different approaching wind conditions and the effects of the nearby surrounding buildings. For example, at a wind direction of 20°, the subject building is located downstream of a tall building complex; at a wind direction of 100°, the upper levels of the subject building were exposed to the approaching wind whereas the up-stream buildings provided significant shielding to the lower levels; at wind directions of 140° – 150°, the subject building was again situated downstream of a tall building complex and it was subjected to the less turbulent wind condition A. It was evident that the wind loads experienced by the subject building were considerably altered by the varied surroundings and unlikely to follow the approaching wind profiles.

Comparison of HFBB Analysis Methods

Mode Shape Correction Factors

For each of the 36 wind directions tested, the measured wind loads were combined with the dynamic properties of the subject building to evaluate analytically the dynamic loads and building responses corresponding to a return period of 50 years (Building Department, HKSAR 2004). Structural damping ratios for the subject building were assumed to be 1.5% of critical damping for modes 1 and 2 and 2% of critical damping for mode 3.

In the conventional HFBB analysis, the generalised wind forces were computed using three different sets of mode shape correction factors, as listed in Table 1, which are intrinsically related to the power law exponents of the building's mode shapes and the mean wind speed profile for the corresponding approach condition. The mode shape power law exponents were obtained by performing a least-squares fit to the mode shape values. Similarly, the power law exponents of the mean wind speed profiles were found to be 0.24 and 0.35 for wind conditions A and B, respectively. It worth noting that the measured mean wind speed profiles and the building's mode shapes, in particular the torsional component of mode 1 and the x-translational component of mode 3, were not satisfactorily fitted with a power law function. Hence uncertainties were inherently introduced in the calculations of mode shape correction factors and the subsequent generalised wind force predictions.

	Low Correlation (Xu & Kwok, 1993)	High Correlation (Boggs, 1989)	Simplified (Holmes, 1987)
Translation (X_{jx}, X_{jy})	$\sqrt{\frac{3+2\alpha}{1+2\alpha+2\beta}}$	$\frac{2+\alpha}{1+\alpha+\beta}$	$\sqrt{\frac{4}{1+3\beta}}$
Twist ($X_{j\theta}$)	$\sqrt{\frac{1+2\alpha}{1+2\alpha+2\beta}}$	$\frac{1+\alpha}{1+\alpha+\beta}$	$\sqrt{\frac{1}{1+2\beta}}$

α is the power law exponent of the mean wind speed profile; and
β is the mode shape power law exponent

Table 1. Correction factors for the estimation of generalised wind forces.

The three sets of mode shape correction factors, corresponding to low and high correlations of wind load and the simplified form, were subsequently computed. The low and high correlation mode shape correction factors had the largest and smallest values respectively, whilst the simplified factors were essentially between the two limits. Comparing the two approach wind conditions, the simplified mode shape correction factors are the same for both wind conditions since the calculations were independent of the power law exponent of the mean wind velocity profile. For the low and high correlation factors, the mode shape correction factors for wind condition A were always smaller than those for wind condition B because of the smaller power law exponent of the mean wind velocity profile for wind condition A.

Linear-Mode-Shape (LMS) Method

As an alternative to the conventional application of mode shape correction factors, Tse et al. (2009) developed an analysis methodology, referred to as the linear-mode-shape (LMS) method, to minimise the potential uncertainties in the estimation of generalised wind forces by "linearizing" the sway components of the 3D mode shapes without the need to assume or surmise the likely form of the wind load distributions.

The LMS method allows the exact computation of the sway components of the generalised wind force to be determined by establishing a new set of centres, referred to as the LMS centres, at which the translational mode shapes are "linearized" by axis transformations. The torsional component of the generalised wind force is still reliant on an appropriate selection of a torsional mode shape correction factor, as the twist mode shapes are independent of the axis transformation. It should be pointed out that the LMS method is based on the linearization of the translational mode shapes via axis transformation, which relies entirely on the existence of the twist component of the mode shape to alter the shape of the sway components. Hence the LMS method is applicable to buildings with translational-torsional coupled mode shapes. Detailed derivations and explanations of the LMS method were presented in Tse et al. (2009).

Base Overturning Moment Responses

The peak base overturning moment response coefficients about the x-axis, C_{Mx}, were determined for each set of applied mode shape correction factors and the LMS method, as presented in Figure 5. The largest wind-induced base moment response coefficients were measured for a wind direction of 310°, i.e. for wind approaching the site approximately from the northwest. The measured results for 310° exhibited enhanced turbulent energy, probably due to the presence of the upstream structures northwest of the subject building. The maximum and minimum peak overturning moment response coefficients for this wind direction are 1.38 and 1.11, obtained from the application of low and high correlation mode shape correction factors.

In terms of the accuracy of the different methods considered in this study, the results presented in Figure 5 demonstrated a similar trend to the results of the benchmark building tested in isolation (Tse et al., 2009). Comparable results were found for the simplified correction factor and the LMS method, providing values in between the upper and lower limits obtained from the application of low and high correlation mode shape correction factors, respectively. Furthermore, the results of the high correlation mode shape correction factors may underestimate the base moment responses for some wind directions.

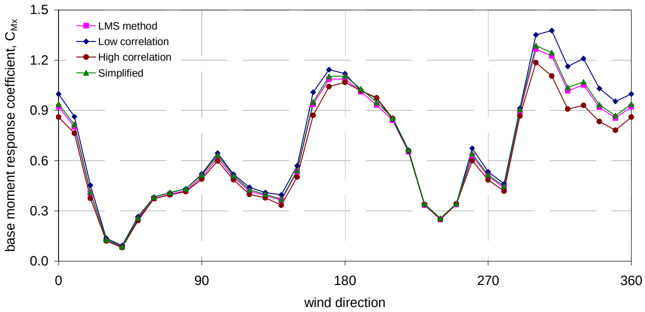

Figure 5. Maximum base overturning moment response about x-axis.

It can also be seen from Figure 5 that the variations of base moment response coefficients obtained using the different methods were higher at some directions, such as for 300° – 360°. In order to more comprehensively investigate the performance of the various analyses under different wind conditions due to the surroundings, the "coefficient of variation" of the base overturning moment coefficients, defined as the standard deviation normalised by the mean value (i.e. $\sigma_M / \overline{M}$) and expressed as a percentage, are presented in Figure 6. The distribution of wind conditions and the locations of tall building complexes are also included in Figure 6 for better illustration. It is evident that the applicability and suitability of mode shape correction factors in the HFBB analysis were significantly influenced by the wind conditions and the characteristics of the surrounding terrain. For the wind directions of 50° – 130° and 180° – 260°, the subject building was relatively exposed as the surrounding buildings were shorter and the coefficients of variation were relatively small, with values as low as 1% or less. However, the coefficients of variation were considerably higher when the subject building was located downstream of a tall building complex, e.g. 20° – 40°, 140° – 160°, 270°, and 310° – 350°, and particularly under the influence of the higher turbulent wind condition B.

Conclusions

HFBB test results for a real tall building project in Hong Kong were analysed by using mode shape correction factors and the LMS method to examine the reliability, versatility and accuracy of the two methods under varied wind loading environments. The results demonstrated that the accuracy and reliability of HFBB analysis methods depend significantly on the terrain characteristics of the nearby surroundings. When the subject building was relatively exposed to the approaching wind, consistent results among various methods were obtained. However, high coefficients of variation were found among the application of low and high correlation mode shape correction factors for the wind directions at which the tested building was downstream of a tall building complex, especially under highly turbulent winds. This is because the application of mode shape correction factors in the HFBB analysis did not directly take into account the influence of the site specific characteristics on the actual wind loads. Therefore, mode shape correction factors should be applied with caution in HFBB analyses when tall building complexes exist in the surrounding proximity. In comparison, the LMS method, which does not require knowledge of the wind load distributions, provided more reliable predictions and hence demonstrated its adaptability in typical tall building environments where wind loading conditions are significantly influenced by the surroundings.

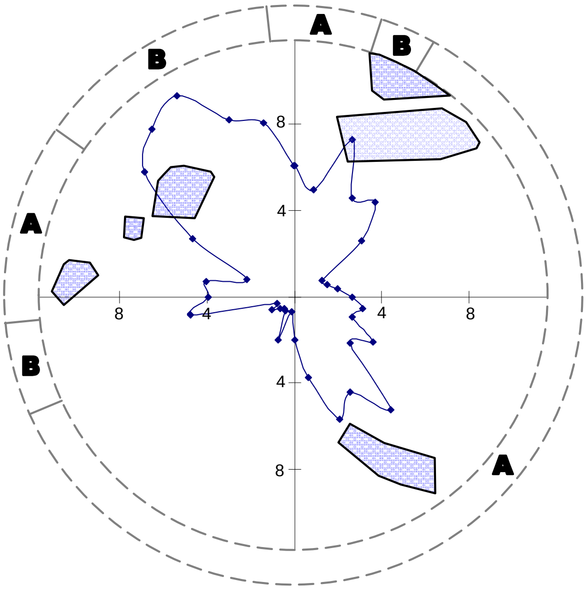

Figure 6. Coefficients of variation (%) for M_x over the different HFBB analysis methods.

Acknowledgments

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References

Boggs, D.W. and Peterka, J.A. (1989) Aerodynamic model tests of tall buildings, Journal of Engineering Mechanics, ASCE, 115(3):618-635

Buildings Department (HKSAR), Code of Practice on Wind Effects in Hong Kong, 2004

Chen, X. and Kareem, A. (2004) Equivalent static wind loads on buildings: new model, Journal of Structural Engi-neering, ASCE, 130(10):1425-1435

Davenport, A.G. and Tschanz, T. (1981) The response of tall buildings to wind, Proc. 4th U.S. Nat. Conf. of Wind Engineering, July 27-29, Seattle, Washington, U.S.A

Holmes, J.D. (1987) Mode shape correction factors for dynamic response to wind, Engineering Structures, 9:210-212

Holmes, J.D., Rofail, A. and Aurelius, L. (2003) High frequency base balance methodologies for tall buildings with torsional and coupled resonant modes, Proc. 11th International Conf. on Wind Engineering, June 1-5, Lubbock, Texas, U.S.A

Lam, K.M. and Li, A. (2009) Mode shape correction factors for wind-induced dynamic responses of tall buildings using time-domain computation and wind tunnel tests, J. Sound and Vibration, 322:740-755

Tschanz, T. and Davenport, A.G. (1983) The base balance technique for the determination of dynamic wind loads, Journal of Wind Engineering and Industrial Aerodynamics, 13:429-439

Tse, K.T., Hitchcock, P.A. and Kwok, K.C.S. (2009) Mode Shape Linearization for HFBB Analysis of Wind-Excited Complex Tall Buildings, Engineering Structures, 31:675-685

Xu, Y.L. and Kwok, K.C.S. (1993) Mode shape corrections for wind tunnel tests of tall buildings, Engineering Structures, 15:387-392