Full-scale identification of aeroelastic effects on a tall building

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ABSTRACT: Full-scale measurements have been taken of accelerations of a tall building and the associated wind conditions for a period of over a year. Whereas for long-span bridges aeroelastic effects are important, for buildings they are often neglected. Yet, as buildings become taller they may become increasingly important. This paper aims to quantify the aeroelastic forces from the full-scale measurements in a range of wind conditions. Trends of aerodynamic damping and natural frequency with wind speed have been identified. Vibrations in two orthogonal directions have been considered with the data split into bins corresponding to different relative wind directions. It has been found that the effect of the wind on natural frequency is the strongest for along-wind vibrations, with a reduction of up to 5 \% in natural frequency for a wind speed of 15 m/s (reduced wind speed 2.1). The aerodynamic damping for along-wind vibrations was found to be an order of magnitude greater than estimated by quasi-steady theory.

KEYWORDS: Full-scale measurements, Tall building, Aerodynamic damping, Vibrations, Wind direction.

1 INTRODUCTION

Wind actions are a main concern in the design of tall buildings, but still there exists more uncertainty in these actions and in the resulting dynamic responses than in most other kinds of loads. For this type of structures, occupant comfort is directly related to the wind-induced sway. Since there is a trend in recent years for tall buildings to become more slender, and hence more sensitive to wind-induced vibrations, understanding of these issues is becoming more important.

The dynamic response of tall buildings to wind is defined not only by the external forcing component of the wind, as typically identified from high frequency force balance tests or pressure tap tests in wind tunnels, but also by aeroelastic forces, which may be more uncertain. Whereas aeroelastic effects are very important for long-span bridges, they are often neglected, or at best estimated by simplistic assumptions, for tall buildings. As buildings become taller or more slender, these effects are likely to become more important, hence there is a need to quantify them.

Few papers have presented results of full-scale measurements on tall buildings. Bashor et al. (2005) studied the wind-induced response affecting the occupant comfort of various tall buildings in the City of Chicago. Amplitude-dependence and uncertainty in damping were considered in this paper as well as comparisons to full-scale data to establish agreed criteria defining acceptable motions. It was demonstrated that many of the damping models in the literature are in-
appropriate because of the lack of datasets on tall buildings. A probabilistic framework using Monte-Carlo simulation assessed the reliability of the monitored buildings and found that a typical tall building can have a 30-40% probability of failure in the habitability limit state.

Fu et al. (2012) evaluated the dynamic characteristics and wind effects during a typhoon event on the Guangzhou West Tower (GZWT), which is 432 m high. The random decrement technique was used to find the damping ratio, which exhibited amplitude-dependent behavior. Also, the serviceability performance level was estimated for different return period. Moreover, in order to evaluate the characteristics of the measured wind pressure, the wind-induced pressure at the top of the building surface was investigated. Finally, in order to assess the accuracy of the model test results, the wind-induced acceleration and wind pressure measured for the building were further compared with those obtained from wind tunnel test. However, the damping ratio was not evaluated in terms of the wind speed or wind direction.

Moreover, Huang et al. (2013) tested six aeroelastic models of tall buildings with typical cross sections in wind tunnel. The along- and across-wind aerodynamic damping ratios were identified by using the Random Decrement Technique and the Eigensystem Realization Algorithm method jointly. It was found that, in most cases, the along-wind aerodynamic damping was positive and gradually increased with an increase of reduced velocity. The across-wind aerodynamic damping was positive at low reduced velocity in most cases, but suddenly became negative when reduced velocity was greater than 10.5 for the square cross-section building. For a small corner-chamfered square cross section, the along-wind aerodynamic damping ratio showed some small negative and small absolute values at a low wind speed while for the across-wind aerodynamic damping ratios was always small and positive.

Furthermore, Kim et al. (2018) investigated the aerodynamic damping and aeroelastic instability of a 180° helical supertall building using an aeroelastic model test (rocking vibration model test). Both 180° helical and square models were considered to evaluate the aerodynamic damping ratio using the random decrement technique. It was found that the displacement responses of the 180° helical model in the along- and across-wind direction exhibited better aerodynamic behaviour than those of the square model. While the aerodynamic damping ratios in the along-wind direction of the 180° helical model showed similar trends to those of the square model, the trends in the across-wind direction of the two models were significantly different. In addition, no effect was found for the wind direction on the aerodynamic damping of the 180° helical model.

Finally, detailed analysis of damping of a high-rise building subjected to wind was presented by Gomez & Metrikine (2019). A new method based on an energy flow analysis was developed for damping identification. Damping operators based on the identified energy dissipation were used to compute the modal damping ratios in a model test before they were compared to those identified in full-scale measurements. In order to enable identification of the damping contribution in each part of the structure to the overall damping, the analysis was broken down into two different parts of the building, the superstructure and the soil-foundation system.

The most suitable way to evaluate predictions of the performance of full-scale tall buildings involves identification methods from in-situ measurements. Since there is no theoretical method to estimate the structural damping and aerodynamic effects may be affected by scaling issues in wind tunnels, reliable measures of the damping can only be obtained from full-scale measurements. This paper uses full-scale measurements made in October and November 2017 and January 2018 on a 150m-high building in London to estimate the aeroelastic forces. Some preliminary relationship between the measurements were presented by Margnelli et al. (2018). This paper goes into more detail and considers additional effects. In the first instance, wind-induced response analysis was performed by using the Root Mean Square (RMS) acceleration amplitude. Next, the Power Spectral Densities (PSDs) of the accelerations have been estimated in order to identify the vibration modes of the building, and subsequently, the natural frequency and damp-
ing ratio of each mode after curve-fitting was applied. Then, the correlation between the aerodynamic damping ratio and mean wind velocity has been used to study the effect of wind direction on the vibrations in the two orthogonal directions. The along-wind aerodynamic damping results from full-scale measurements were compared to theoretical predictions based on quasi-steady theory. Finally, the natural frequencies and mean wind velocity relationship is presented.

2 DESCRIPTION OF TOWER AND MONITORING SYSTEM

This project is based on a test case of a 47-floor and 150m-high tower in London. A set of accelerometers and an ultrasonic anemometer were installed on the tower to monitor the effects of the wind on the structure from October 2017 for a continuous period of about a year, giving a wide range of wind conditions. Three representative sets of data corresponding to measurements made in October and November 2017 and January 2018 have been used in this paper. The remaining datasets will be further evaluated. Pressure sensors were also deployed at certain points around the perimeter of the building for a short period.

The two top floors of the building are set back from the main façade, so the accelerometers were installed on the highest full concrete slab level, in the external area on the 45th floor. Three accelerometers were installed on this floor in two horizontal directions normal to each other. Two sensors monitored motion in the tower’s local x direction, offset from each other to measure translational and rotational motion, and one sensor monitored motion in the local y direction. Figure 1 shows the plan of the 45th to 47th floors with the locations of the instruments and the local co-ordinate system. The accelerations were acquired continuously at a sampling frequency of 61 Hz. The structure is octagonal on plan with triangular balconies on the four corners of the building.

Figure 1. Plan of the top three floors of tower showing locations of instruments and local co-ordinate system (dimensions in mm).

The wind velocity was measured at a sampling frequency of 1 Hz using an ultrasonic anemometer (Figure 1) installed at the highest accessible point, on the edge of the building on the 46th floor. The measured wind velocity exhibited a large vertical angle of attack (mean 30°), presumably due to the proximity of the anemometer to the building itself. The mean wind speed and turbulence intensity used are therefore based on the components of the wind velocity in the horizontal plane.
3 WIND-INDUCED RESPONSE ANALYSIS

The Root Mean Square (RMS) acceleration amplitude has been used to characterize the wind-induced response of the building in key vibration modes. It has been obtained from the integral of the PSD over the frequency range of the relevant resonant peak, as detailed by Bendat & Piersol (2010) for each one-hour period. Then, it has been compared against the corresponding 1-hour mean wind speed as it is shown in Figure 2 for the first mode in the $x$ direction (Mode X1). The regression curves of the amplitude responses for each direction are defined by:

$$\dot{y}_{\text{RMS}} = a \ U^b$$ (1)

Where $\dot{y}_{\text{RMS}}$ is the RMS acceleration amplitude in the relevant mode, $U$ is the mean wind speed and Equation 1 corresponds to a straight line on a log-log plot, as shown in Figure 2, $a$ and $b$ are the estimated curve-fitting parameters. Considering the large scatter of results for low wind speeds, presumably due to dynamic excitation mechanisms other than the wind, only data points for wind speeds above 6 m/s have been used for the fitting, giving 729 one-hour records from the data sets used. The exponent $b$, from the gradient at the log-log plot, was found to be 3.09 for Mode X1.

It can be noticed in Figure 2 that the amplitude responses tend to increase monotonically directly proportional in logarithmic scale to the mean wind speed at a cubic power rate approximately. The difference between along or across wind effects on the wind-induced response of the building has not been taken into account for the analysis.

![Figure 2. Relationship between RMS acceleration amplitude in Mode X1 and the corresponding 1-hour mean wind speed.](image)

4 SYSTEM IDENTIFICATION

From the three accelerometers on the 45th floor, the $x$, $y$ and torsional components of the motion were decomposed. From the Power Spectral Densities (PSDs) of the accelerations, four clear modes in each of the sway directions and five torsional modes were identified below 5 Hz. The output PSD of the structural acceleration response was estimated in MATLAB by using the modified Welch’s periodogram as it was detailed by Marple (1987), in the frequency range 0.1-4.5 Hz. Fitting was performed using the Iterative Windowed Curve-fitting method (IWCM). This
method was developed for estimating modal parameters from ambient vibration measurements by Macdonald (2002), and it has been successfully applied to other structures previously by Macdonald & Daniell (2005) and Macdonald (2008).

From the curve-fitting of the PSDs for the acceleration responses, the natural frequency and damping ratio of each mode were identified. It was found that the structural natural frequencies in the $x$ direction were slightly higher than those of the corresponding modes in the $y$ direction. The differences in natural frequencies ranged from 0.96% for the first mode pair to 2.47% for the fourth mode pair. These slight differences were expected since, although the tower is close to rotationally symmetric, there are slight differences in the structure in the orthogonal directions. The natural frequencies of the five torsional modes below 5Hz were relatively well spaced from those of the sway modes.

An example of the measured and fitted PSDs for the acceleration responses in the $x$ direction is shown in Figure 3. PSDs for the other components of motion have been fitted similarly. In Figure 3, two PSD curves corresponding to acceleration responses measured at different wind velocities have been included. There is consistency between the frequencies of the peaks for the two curves, but the magnitudes of the PSDs for the acceleration responses are clearly different. It is also notable that the peaks are relatively broader for the higher wind speed, implying higher total damping.

![Figure 3. Typical measured and fitted PSDs of acceleration in the x direction.](image)

5 ESTIMATED MODAL PARAMETERS AND AEROELASTIC EFFECTS

The effect of wind direction on the behaviour and vibrations in the two orthogonal directions has been evaluated in this section. In order to quantify the aeroelastic effects, the data were split into a series of 1-hour records. For each record the mean wind velocity was found and the modal parameters were estimated from the curve-fitting. As is usual from full-scale ambient vibration data, the natural frequencies were identified consistent between different records, with coefficients of variation of 0.2% or lower, for comparable wind conditions, but the damping ratios were much more variable due to the fundamental difficulty in estimating them accurately from individual records. The coefficient of variation between different damping ratios were up to 144%. However, using the large number of records available, underlying trends could be found.
5.1 Modal damping estimation

The modal damping estimates and the linear correlation between damping ratio and mean wind velocity are presented in Figure 4 for the dataset measured between October 2017 and January 2018 (black dots).

Figure 4. Damping ratio estimates for Modes X1 and Y1, versus hourly mean wind velocity for different equivalent wind directions. Individual (dashed) and constrained (solid) fitted trendlines are also shown. The inset diagrams in the top right corner of each sub-plot indicate the motion (blue arrow) and wind (red arrow) directions.
The effect of wind direction on the wind-induced vibrations and the aerodynamic damping has been evaluated in three different equivalent wind directions, considering the symmetry of the building, for accelerations responses recorded in both $x$ (Mode X1) and $y$ (Mode Y1) directions. Wind range directions were split into eight 45° bins in order to identify different aeroelastic behaviour. Two bins correspond to wind in the $x$ direction that is perpendicular to northeast and southwest facades (Wind X), another two bins coincide with wind in the $y$ direction that is perpendicular to southeast and northwest facades (Wind Y), and the remaining four bins correspond to wind directed towards the corners of the building (Wind 45°). Since the building (Figure 1) has two orthogonal planes of symmetry, the aerodynamic damping induced by wind coming from two different parallel facades should be equivalent. Although there is much scatter of the individual estimates, an underlying trend of positive aerodynamic damping is apparent with increasing wind speed for all the different directions considered.

In modal analysis from ambient vibration data, damping ratios are difficult to estimate accurately, as opposed to natural frequencies, which are relatively easy to identify. Two important parameters to be considered when evaluating the damping ratio are the structural damping ratio, which is defined as the damping ratio for no-wind conditions (i.e. the ordinate axis intercept of the trendline), and the aerodynamic damping gradient, defined as the gradient of the damping ratio trendline. These two variables are clearly illustrated by the trendlines of the six sub-plots in Figure 4. The dashed lines represent the individually fitted trendlines for each plot, while the continuous lines result from combined fitting, in which it has been considered that the structural damping ratio should be equal for all the plots where the motion was measured in the same direction. The values of the structural damping ratio equivalent, and aerodynamic damping gradient for each mode and wind direction are displayed in Table 1, where only the combined fitted values are shown.

| Table 1. Structural damping ratio and aerodynamic damping gradient values. |
|-----------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| Mode            | Structural Damping Ratio ($\%$) | Wind X Aerodynamic Damping Gradient ($\%$/$\text{m}$) | Wind Y Aerodynamic Damping Gradient ($\%$/$\text{m}$) | Wind 45° Aerodynamic Damping Gradient ($\%$/$\text{m}$) |
| Mode X1         | 0.80             | 0.039           | 0.035           | 0.041           |
| Mode Y1         | 0.91             | 0.038           | 0.019           | 0.040           |

There is good agreement between the trendlines fitted individually and combined between the individual plots implying that the combined results give a good fit to the data. While both lines are almost identical for the Wind 45° direction, which has the most data points, there is a slightly more discrepancy in the Wind Y direction, assumed to be due to the fact that there is a smaller number of data points. The structural damping ratios in vibration modes X1 and Y1 are close to each other. Similar aerodynamic damping gradient have been found in all cases except for wind and motion both in the $y$ direction, though there were fewer records for this direction so the result is less reliable than for other wind directions. There is good consistency of the aerodynamic damping gradient for the two modes for Wind 45°, and also for the two cross-wind cases (Mode X1 with Y wind and Mode X1 with X wind). There is less effect of the wind direction than may have been expected but further analysis of more data records will explore this issue further.

Aeroelastic forces that occur when a structure vibrates in the presence of wind are approximately proportional to the velocity of the structure. Total viscous damping of a structure consists of the structural damping and the aeroelastic forces that are equivalent to additional damping termed ‘aerodynamic damping’.
Davenport (1962) showed that, based on quasi-steady theory, for along-wind vibrations of a uniform structure in uniform wind, the aerodynamic damping gradient is given by:

\[
\frac{\xi_{\text{aero}}}{U} = \frac{\rho B C_D}{4\pi f_n m}
\]  

(2)

where: \(\rho\) is the air density (1.25 kg/m\(^3\)), \(B\) is the width of the structure, \(C_D\) the drag coefficient, \(f_n\) the natural frequency of the mode of vibration and \(m\) the mass per unit height of the building.

Based on the building mass per unit height of 215000 kg/m and a drag coefficient of 0.6 obtained from wind tunnel tests, the along-wind aerodynamic damping gradient estimated from this formula for the current structure is 0.002 %s/m. However, this theoretical value is considerably smaller than the values displayed in Table 1, which is believed to be because the reduced velocity for the full-scale measurements is so low (maximum of 2.1), so quasi-steady theory is not applicable.

### 5.2 Estimated Natural Frequencies

The estimated natural frequencies responses of the building from the measurements in Mode X1, over each one-hour period, are compared against the corresponding 1-hour mean wind speed in Figure 5. There is a marked decrease in natural frequency as the wind velocity increases giving up to 5 % drop for a mean wind speed of 15 m/s. It is assumed that the changes are due to aeroelasticity rather than amplitude-dependency of the vibrations.

![Figure 5. Relationship between natural frequency and the corresponding 1-hour mean wind speed for Mode X1.](image)

The effect of wind direction on the estimated natural frequencies is illustrated in Figure 5 by the three different quadratic trend curves, which correspond to the three wind directions considered. Natural frequency estimates obtained from records for the Wind Y direction (normal to the motion) are clearly higher than the values in the Wind X (along the direction of motion) and Wind 45° directions, which decrease more rapidly with increasing wind speed. The estimated natural frequency for no-wind conditions is 0.286 Hz for this vibration mode. Similar behaviour has been found for Mode Y1.
6. CONCLUSIONS

Measurements of wind-induced vibrations and associated wind conditions have been measured on a 150 m tall building over a period of over a year. The results have identified aerodynamic damping and the effect of wind direction and the orientation of the motion on the aerodynamic damping have been investigated. Although there is scatter between the individual estimates, the aerodynamic damping has been found to be positive and gradually increases with an increase in wind velocity. Similar results of the structural damping and the aerodynamic damping gradient have been found for vibration in the first mode in two orthogonal planes. The along-wind aerodynamic damping from the full-scale measurements was an order of magnitude larger than the theoretical value from quasi-steady theory, which is expected to provide a good estimation only when the reduced velocity is somewhat larger than in this case. From the data analysed to date there is little evidence of the effect of wind direction on the aerodynamic damping. In addition, significant decreases in the estimated natural frequencies of the structure were found with increasing wind speed due to aeroelastic effects for every wind direction, with some evidence of dependency on the direction. Ongoing work aims to investigate these issues in more detail using data from the full monitoring period and considering finer ranges of wind directions.

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