ANALYSIS OF FULL-SCALE TALL BUILDING WIND AND DYNAMIC RESPONSE DATA

Institution of Structural Engineers Research Award:

Executive Summary

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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. Quantifying and identifying trends of modal parameters in a range of different wind conditions can achieve this.

Calculations of the dynamic response of tall buildings use assumptions of the damping, ultimately based on empirical data. Although wind tunnel tests are valuable in assessing the dynamic behaviour of structures, the full-scale damping is still uncertain and some aerodynamic effects may be affected by scaling issues. Therefore, data from measurements of full-scale tall buildings, such as estimates of damping and other modal parameters, are very valuable.

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, covering a wide range of wind conditions. Some preliminary measurements results were presented by Margnelli et al. (2018).

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.

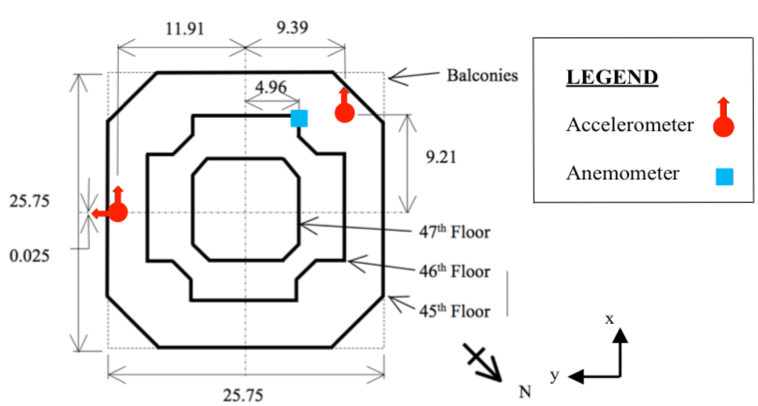

Figure 1. Plan of the top three floors of tower showing locations of instruments and local co-ordinate system (dimensions in m).

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 used is therefore based on the components of the wind velocity in the horizontal plane.

From the three accelerometers on the 45th floor, the *x* and *y* components of the motion were decomposed. The output power spectral density (PSD) of the structural acceleration response was estimated in MATLAB by using the modified Welch's periodogram, in the frequency range 0.1-4.5 Hz. Fitting was performed using the Iterative Windowed Curve-fitting Method (IWCM) developed by Macdonald (2000). This method was developed by Macdonald (2000) for estimating modal parameters from ambient vibration measurements. 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, as expected because of slight differences in the structure in the two directions.

2. WIND CHARACTERISTICS

A histogram of 1hour average wind speeds recorded for the full monitoring period is shown in Figure 2. Results for higher wind speeds are therefore based on relatively few measurements. The total number of 1-hour records is 3587.

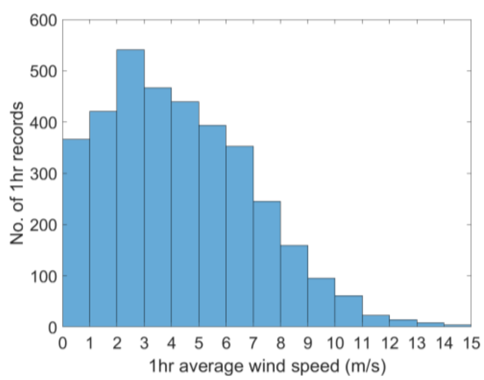

Figure 2. Histogram of 1-hour average wind velocities.

A polar plot of wind velocities measured by the anemometers is shown in Figure 3. All wind directions are expressed as angles clockwise from normal to the building on the north direction. True North coincides with the bottom right-hand side corner of the building in Figure 1, which is 45° with respect to x and y directions. Each cross represents the average wind velocity for a 1-hour record. The location of the building has a considerable effect on the local wind characteristics. The most frequent winds in southern England are typically from the south west direction, with very few winds from the east were experienced at the site. This could be influenced by the location of the anemometer, towards the south west corner of the building, and possibly also by, other tall buildings in London, mainly north east of the building.

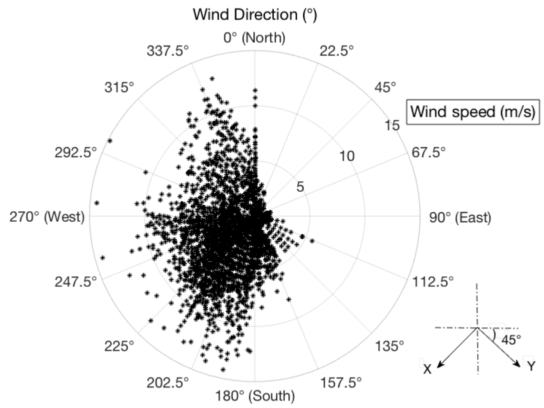

Figure 3. Polar plots of 1-hour average wind velocities.

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, for each one-hour period. Then, it has been compared against the corresponding 1-hour mean wind speed as it is shown in Figure 4 for the first mode in the *x* and *y* directions. The regression curves of the amplitude responses are defined by:

$$\sigma = a\,U^{b}$$

Where σ is the modal RMS acceleration amplitude in the relevant mode, U is the mean wind speed and the equation corresponds to a straight line on a log-log plot, as shown in Figure 4, 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 5 m/s have been used for the fitting. It can be noticed in Figure 4 that the amplitude responses tend to increase monotonically directly proportional in logarithmic scale to the mean wind speed approximately at a cubic power rate approximately.

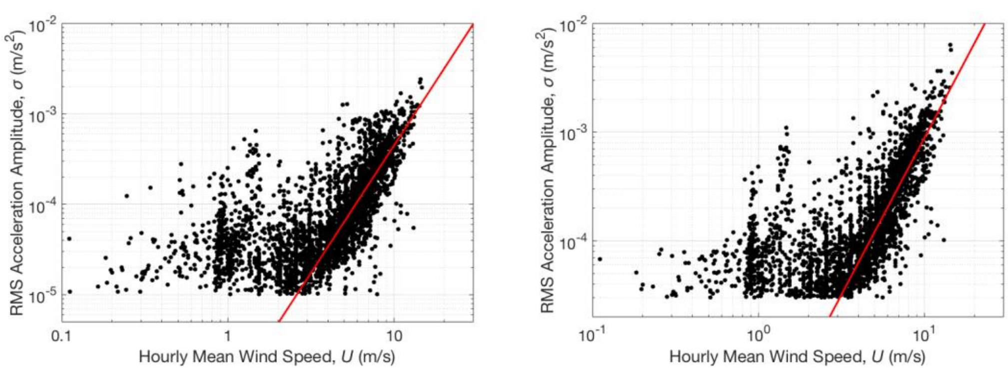

Figure 4. Relationship between modal RMS acceleration amplitude and the corresponding 1-hour mean wind speed in the *x* (left hand-side plot) and *y* directions (right hand-side plot).

4. ESTIMATED MODAL PARAMETERS

Trends of aerodynamic damping and natural frequency with wind speed have been identified. 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 more consistently 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. However, in this case, it has been found a large variation in natural frequencies with time due to the long monitoring period considered. The coefficient of variation between different damping ratios were up to 144%, although using the large number of records available, underlying trends could be found.

4.1 Damping Ratio

Although there is much scatter of the individual estimates, an underlying trend of increasing damping ratio is apparent with increasing wind speed for motion in the two different directions considered, *x* and *y*. The relationship between the variables can be observed in Figure 5.

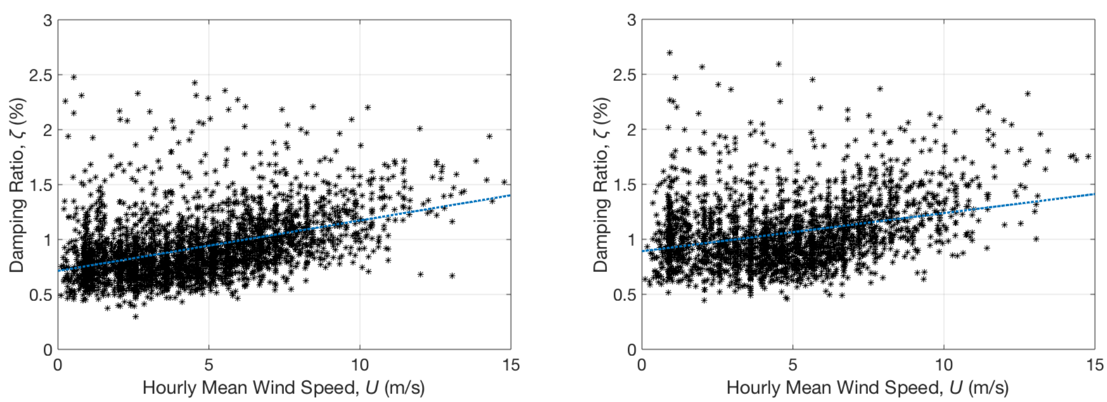

Figure 5. Relationship between damping ratio of the first mode and the corresponding 1-hour mean wind speed in the *x* (left hand-side plot) and *y* directions (right hand-side plot).

From results presented in Figure 6, it has been found a trend of increasing damping ratio with increasing acceleration amplitude. Actually, there is still an open discussion on the amplitude-dependent behaviour of damping at higher amplitudes. The coefficient of determination for damping ratio with respect to acceleration amplitude is higher than it is for wind speed. It can be stated that the obtained results indicate the amplitude-dependency of the damping, as it has been observed in some previous studies of full-scale measurements in tall buildings.

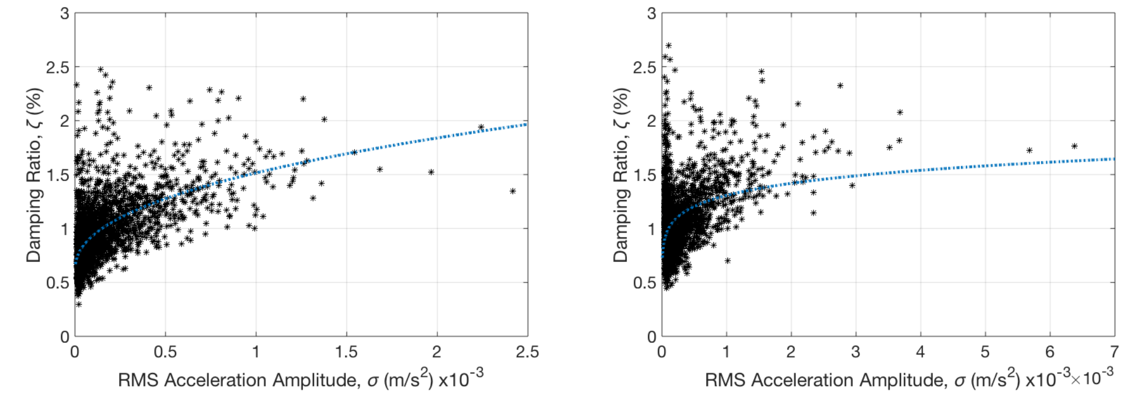

Figure 6. Relationship between damping ratio of the first mode and the corresponding RMS acceleration amplitude in the *x* (left hand-side plot) and *y* directions (right hand-side plot).

For tall buildings between 100 and 200 metres-high, damping ratio values assumed in design vary between 1 and 2% for serviceability and ultimate wind design respectively. These values can be considered conservative or unconservative depending the level of amplitude. Given peak damping ratio occur at high amplitude, this practice may be justified, despite the fact that there is a lower number of damping ratio measurements for high amplitude responses.

4.1 Natural Frequency

The same analysis previously presented for damping ratio has been also made for the estimated natural frequencies for motion in the two different directions considered, *x* and *y*. In contrast with the damping ratios, the natural frequency estimates decrease with increasing wind speed.

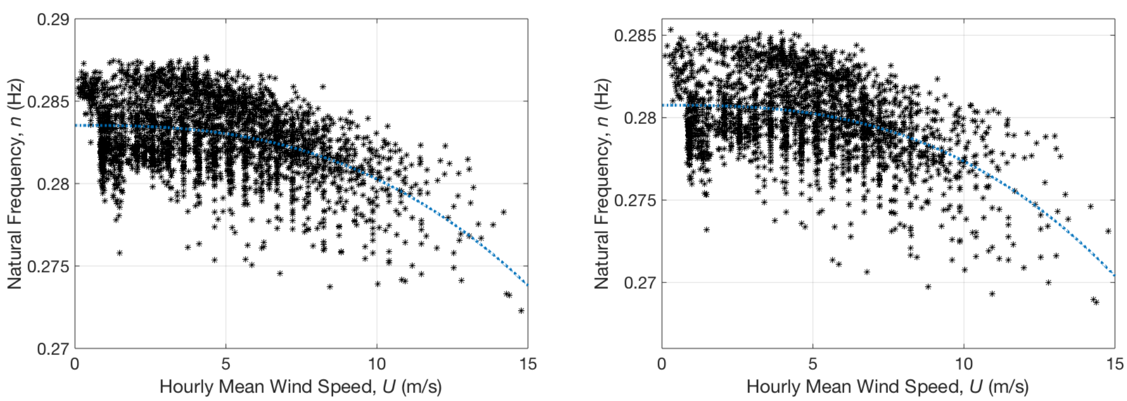

Figure 7. Relationship between first natural frequency and the corresponding 1-hour mean wind speed in the *x* (left hand-side plot) and *y* directions (right hand-side plot).

The relationship between natural frequency and the corresponding RMS acceleration amplitude is presented in Figure 8. As well as for wind speed, the natural frequencies also decrease with increasing amplitude. Coefficient of determination for natural frequency with respect to acceleration amplitude is also higher than it is for wind speed, which indicates modal parameters estimated for this building are more dependent on the acceleration amplitude than they are on wind speed.

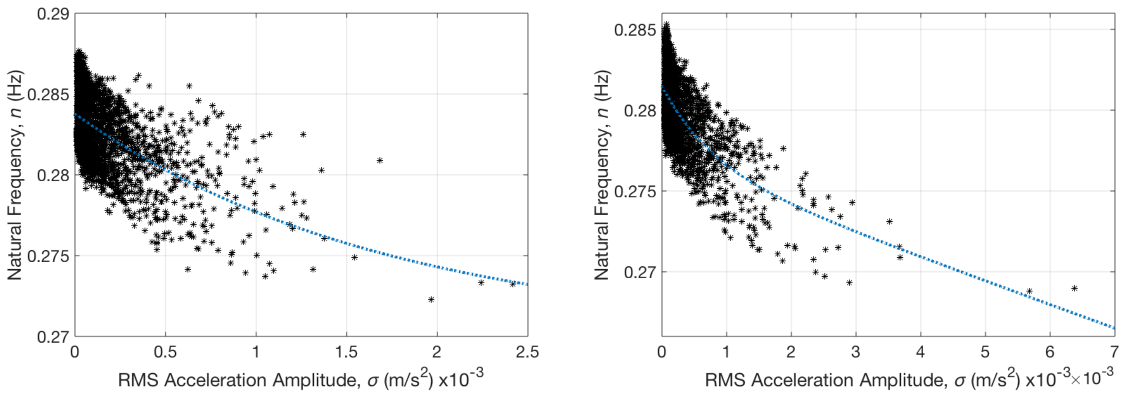

Figure 8. Relationship between first natural frequency and the corresponding RMS acceleration amplitude in the *x* (left hand-side plot) and *y* directions (right hand-side plot).

Natural frequencies obtained by BMT wind tunnel test reports for the first mode was found to be 0.22 Hz. This value is 26% lower than the estimated natural frequencies at zero wind speed and amplitude conditions.

5. KEY CONCLUISONS

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 trends of modal parameters from accelerations in two orthogonal directions and the effect of wind velocity and the orientation of the motion on the aerodynamic damping have been investigated. The acceleration amplitude responses tend to increase monotonically directly proportional in logarithmic scale to the mean wind speed approximately at a cubic power rate approximately.

Although there is scatter between the individual estimates, damping has been found to be positive and gradually increases with an increase in wind velocity and amplitude for vibration in the first mode in two orthogonal planes. In addition, significant decreases in the estimated natural frequencies of the structure were found with increasing wind speed and amplitude responses.

Damping ratio estimates from full-scale measurements in this building match relatively well with design values from codes and standards. Wind tunnel testing has underestimated the value of the natural frequencies compared to the results obtained from full-scale measurements.

6. ACKNOLWDEGEMENTS

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