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Acceleration Response of a Medium-Height Building to Wind-Gust Excitation

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ABSTRACT: This paper presents results and analysis of observed wind induced acceleration response of an office building of intermediate height, in an urban location. Natural frequencies and damping ratios of the structure were identified. The study included records taken at times of low ambient temperature and the data indicates a relationship between the localized wind velocity above the building and the ambient temperature. The analysis revealed relationship of the vibration amplitude to wind velocity and direction, and to the estimated values of damping and natural frequency. These relationships are presented and discussed.

KEYWORDS: Buildings, full-scale measurements, thermal effects, wind induced acceleration, system identification, damping.

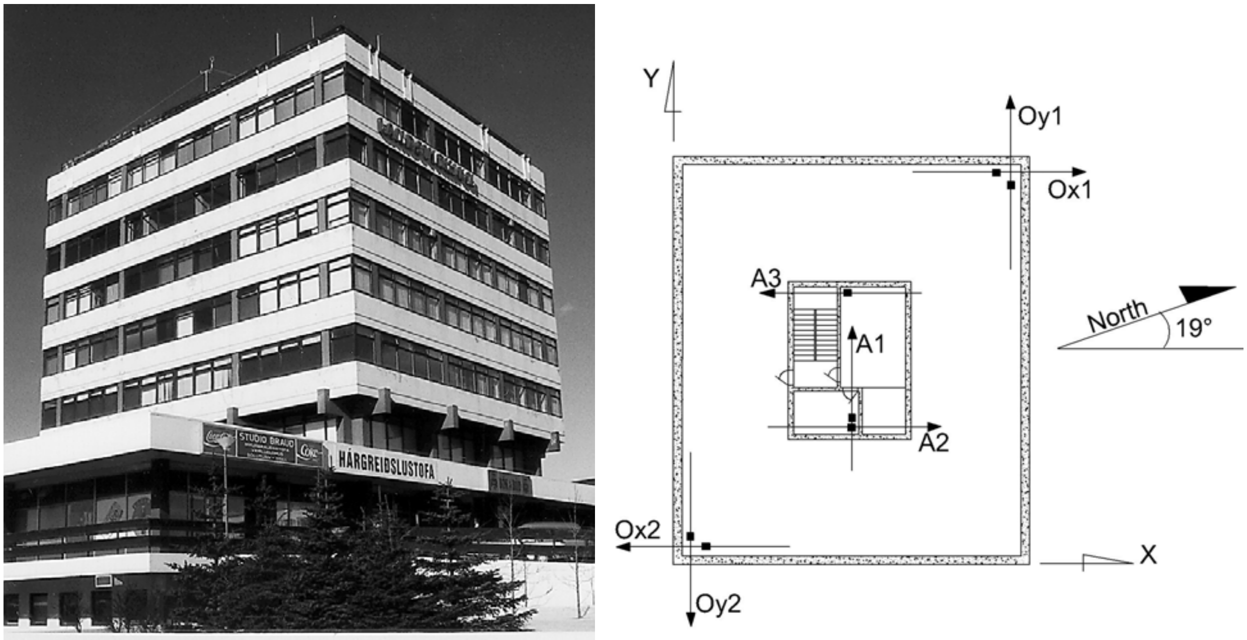
1 INTRODUCTION

This study is focused on wind induced acceleration response of an office building of intermediate height measured at full-scale, with companion wind-tunnel data. The building is in an urban location, with buildings of comparable size, although lower, at a relatively open spacing. The building is a six-story tower (cube) approximately 19 × 22 m in area and 22 m high, built upon a two-story shopping centre, making in total eight stories with a height of 30 m. The structural system of the tower consists of a central shear-core, frames on the outer sides and reinforced concrete floors, poured in situ. Some results from full-scale measurements in the building have been reported previously [9,10]. Although the building cannot be considered as a particularly wind sensitive structure according to traditional criteria, wind induced vibrations are easily perceived on the upper floors during moderately strong windstorms.

2 EXPERIMENTAL SET-UP

The investigation utilises several data sets, obtained at different occasions, using slightly different instrumentation. However, the bulk of the data was obtained in 1997, during a period of three months when horizontal acceleration at one level in the building was under constant observation. Three uni-axial accelerometers were positioned at roof level in the utility room on the top floor of the building shear core (see Fig. 1). Reference wind velocity and micro-meteorological data was recorded in a mast above the roof as well as at a meteorological site about 700 m west of the building. Each record is sampled at 30 Hz over 12 minute intervals.

During earlier recordings of several single storm events, uni-axial accelerometers were located in opposite corners of the building on the seventh floor (Fig. 1) i.e., one story below roof level.



a) b)

Figure 1. a) The building, b) A plan view of the tower and its shear core. The location and directionality of accelerometers in the 1997 experiment is given by A1, A2 and A3. The location and directionality of accelerometers during earlier experiments are given by Ox1, Oy1, Ox2 and Oy2. The coordination system is defined by X and Y.

3 THE ACCELERATION DATA

During the 1997 experiment the accelerometers were located in a rather noisy environment, close by ventilation and elevator equipment. The noise phenomena were mapped by systematic analysis of the data [10]. The main sources of noise along with the associated response and excitation frequencies were identified, something that was not possible through earlier data [9], as those measurements were single event recordings, but not a part of continuous monitoring.

Based on earlier experiments and FE-modelling, the first two natural frequencies of the building were known to be just above 2 Hz and the third just below 3 Hz. Higher modes are not excited by the wind to the degree of being identifiable in the data.

A multi-band-pass filter was applied to remove the environmental noise from the raw acceleration data. A zero-phase forward and reverse digital filtering was used, applying a sharp FIR filter. The result has zero phase distortion and care was taken to minimize start-up and ending transients by matching initial conditions. Figure 2, shows an example of multi-band-pass filtered time series containing two separate frequency bands of 1.9 Hz to 2.3 Hz and 2.7 Hz to 3.0 Hz. The signal pictured is a narrow band process, marked by bursts of high acceleration of 5 to 10 s duration. This intermittency in the signal corresponds well to the motion perceived by the first author in the building during a storm in February 1991.

The acceleration data was generally found stationary within a 5% level of significance. However, it was found that the acceleration time series generally do not meet the normality criteria. The reason lies in the kurtosis value, which is a measure of how outlier-prone a distribution is. The acceleration series have a varied kurtosis that can lie on either side of 3, the kurtosis value for a normal distribution. Generally the kurtosis values are above 3, often around 4, which is in agreement with findings in [6].

Since the building is fixed at its base, a zero-mean process is assumed. The peak values can be related to the standard deviation for a zero mean process by defining a peak factor g_a as the mean peak-to-peak acceleration divided by the standard deviation. Then the basic acceleration statistics can be described through a standard deviation and a peak factor. The peak factor values for all channels were found to have a median value of 4.2 with a standard deviation of about 0.5 [10].

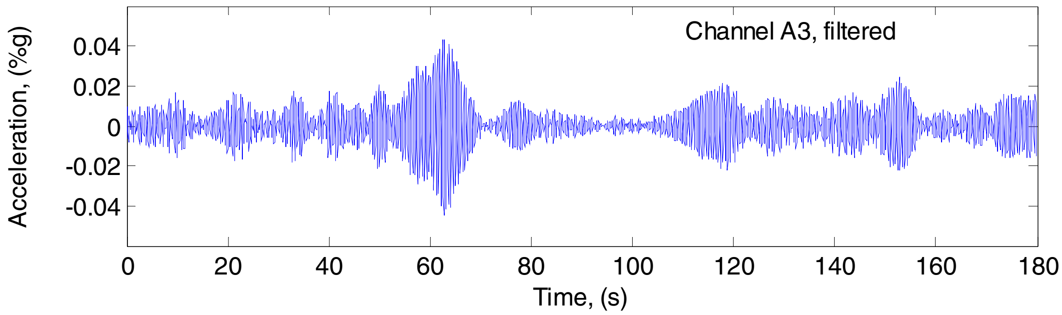


Figure 2. Example of multi-band-pass filtered acceleration record.

4 SYSTEM IDENTIFICATION USING WIND INDUCED RESPONSE

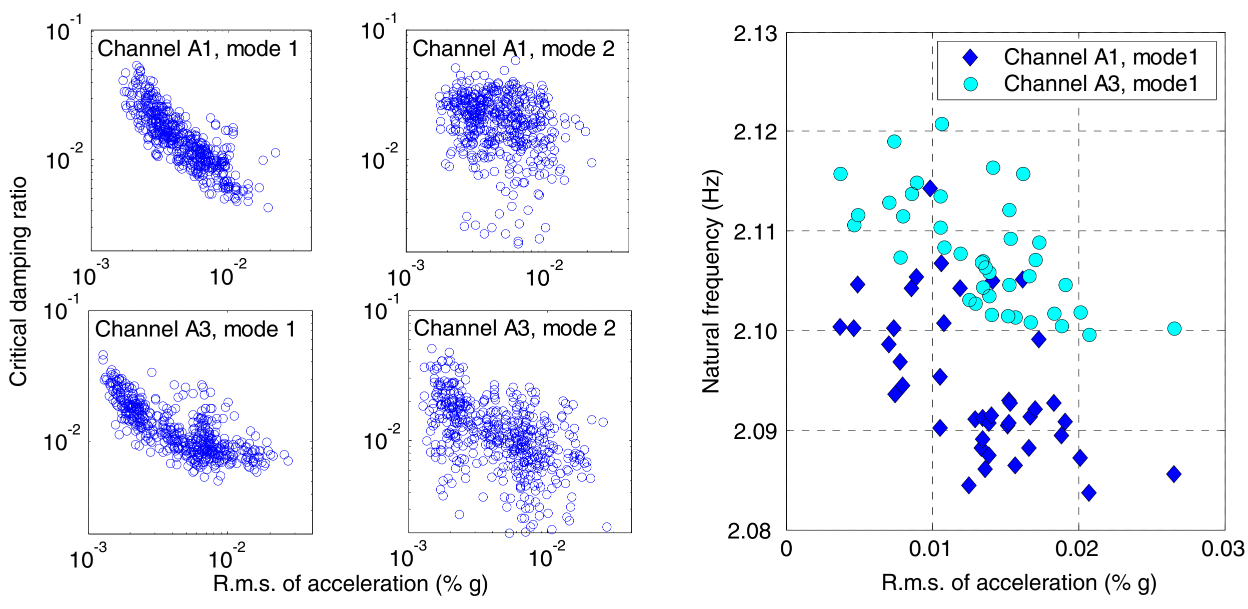
The recorded acceleration data was used for system identification of the building. The aim was, to estimate the natural frequencies and critical damping ratios for the three main modes of vibration identified in the spectral analysis and to explore the variability in the parameter estimation. For this purpose parametric methods were applied, using a state-space model identification (SMI) toolbox developed at TU Delft [4]. After proper pre-processing, only two parameters are required for an output-error model identification problem: the upper bound on the expected order of the system and the true order of the system to be extracted from the data. The upper bound on the expected system order was determined trough the Akaike criterion of an AR-SISO model of increasing order. To simplify the modelling procedure, it was decided to model only one mode at a time i.e., an equivalent SDOF system of which the true order is 2. Therefore, a sharp band-pass FIR-filter was applied to each time series filtering out data representing the three pre-identified modes of vibration. In order to facilitate the system identification and to imitate a more realistic SDOF response, Gaussian noise based on the base level power spectral density of an unfiltered signal using a constant spectral density assumption was added to the time series. A second sequence of Gaussian noise of the same variance was used as an input signal.

The outlined procedure was applied to the acceleration data at hand. The variation in the damping estimates was found to be considerably greater than for the frequency estimates [10]. This is a common finding in system identification of civil engineering structures [5, 11]. In a statistical sensitivity analysis of modal parameters to measurement noise [7], Peterson et al. observed, that the absolute error in the modal damping ratio is approximately the relative error in the modal frequency. This implies that an identified model can have significant error in the damping ratio, even when the natural frequency is well resolved. Also of interest, is that the distributions of frequency estimates are centred at a specific number whereas the damping estimates, especially for the translational modes, have distributions that are skewed towards lower values. This reflects that, unlike structural mass and stiffness characteristics, damping does not relate to unique physical phenomenon.

Table 1, summarises the basic statistics of the analysis using only acceleration records that have standard deviation above 0.005% g. It should be noted that the choice of showing 3 significant digits is not to be interpreted as indicative of the accuracy of the estimates, but rather to stress the uniqueness of each value. The table presents several types of statistical averages. As expected, the choice of average value is not relevant for the natural frequency estimates, but it does matter for the damping. The rotational mode is not very prominent in the data except in the data from channel A3. Therefore, the damping values for the rotational mode are overestimated using the data from channel A1.

Table 1. Statistics for estimated natural frequencies and damping ratio's based on acceleration records that have standard deviation above 0.005% g. Mode 1 represents translational mode of vibration in the respective direction whereas mode 2 represents a common rotational mode of vibration.

Statistic	Natural Frequency (Hz)				Critical damping ratio (%)			
	Channel A1		Channel A3		Channel A1		Channel A3	
	mode1	mode 2	mode1	mode 2	mode 1	mode 2	mode 1	mode 2
median	2.102	2.803	2.118	2.819	1.001	1.890	0.875	0.817
mean	2.103	2.803	2.120	2.819	1.069	1.947	0.981	0.905
geom. mean	2.103	2.803	2.120	2.818	1.007	1.602	0.934	0.740
stand. dev.	0.012	0.027	0.030	0.051	0.381	0.985	0.353	0.515
maximum	2.146	2.879	2.266	2.954	2.683	5.817	2.731	2.609
minimum	2.057	2.716	1.985	2.659	0.428	0.023	0.503	0.016

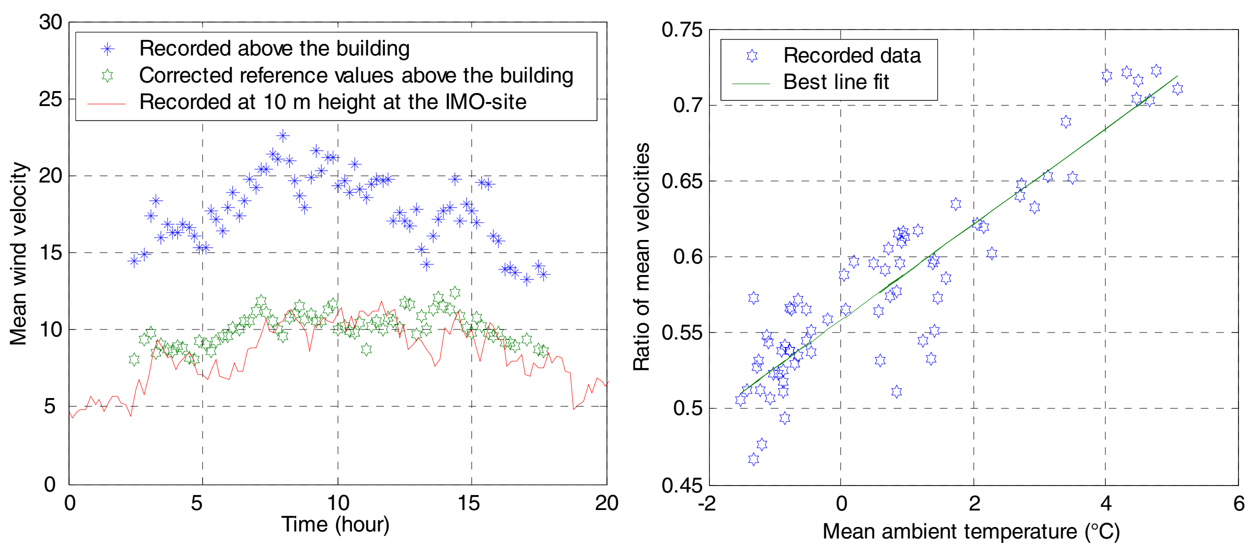


(a) (b)

Figure 3. (a) Estimated critical damping ratio as a function of standard deviation of acceleration at channels A1 and A3. Mode 1 represents translation in the respective direction. Mode 2 represents a common rotational mode of vibration. (b) Estimated natural frequency as a function of standard deviation of acceleration at channels A1 and A3. Mode 1 represents translational mode of vibration in the respective directions of each channel.

In Figure 3a, the damping estimates are plotted versus standard deviation of acceleration. The plots show a trend of reduced damping with increased standard deviation of vibration. This could be interpreted as an indication of a friction-type damping mechanism. A reasonable assumption for a reinforced concrete building of this type that would concur with the idea that friction can be assumed as the cause of significant energy losses [14]. However, the trend is not entirely true to the summation effect of many statistical stiction/friction mechanisms throughout a complex structure. It also contradicts the findings of Jeary [5], which suggest that damping in tall buildings is constant at low amplitudes, increases with amplitude for intermediate amplitudes and then levels of to a constant value for high amplitudes. The building in this case is not tall, and that may affect the damping characteristics. However, lack of resolution in the low amplitude data may also result in higher damping estimates i.e. errors, noise etc. produces artificial damping which result in overestimation of damping. It should also be noted that for Channel A3 the damping estimates are seen to level off for standard deviation above 0.005% g.

Figure 3b, which is based on records associated with a mean wind direction approximately perpendicular to the north face of the building, demonstrates that natural frequency estimates for reinforced concrete structures tend to decrease with increased amplitude of vibration [11].



(a) (b)

Figure 4. (a) The mean along wind velocity as a function of time. (b) The ratio of back-traced velocity values and recorded mean wind velocity above the building as function of temperature. The straight line shown is an estimated best line fit through the data set.

5 THE REFERENCE WIND VELOCITY

The mean along wind velocity recorded above the building, was discovered to be considerably higher than the mean wind velocity recorded at 10 m height at the IMO-site, some 720 m west of the building (Fig. 4a). The difference was of a factor 2 in many instances and could therefore neither be fully explained by difference in anemometer height, nor the expected speed up over the building. It was seen that the velocity difference between the two sites was dependent on both wind direction and temperature (Fig. 4b). This temperature effect is particularly evident for relatively low ambient temperatures (< 0 °C), commonly associated with northerly wind directions. This indicates that above the building there is a heat driven turbulence that affects the wind velocity recordings. Thermal diffusion may be created as the cold air stream comes in contact with the warmer building, especially the large shopping mall roof and the window surfaces of the office cubicle. The exhaust of the building ventilation system, located on the north side of the utility building on the roof, may also play a part. The fact that radiative thermal effects of buildings can have considerable effect on the flow around them has for example been demonstrated in [8].

Correction coefficients for the wind velocity recorded above the roof were evaluated for different directional sectors. The correction coefficients were taken as linearly dependent on ambient temperature. The need for directionally dependant correction is at least partly caused by the asymmetric location of the anemometer mast on the roof. The corrected mean velocity values from above the building approached those recorded at the IMO-site fairly well, considering the distance between the two sites and other differences [10]. However, applying the mean wind velocities recorded at the IMO-site directly as reference was found to be inappropriate due to lack of synchronisation between recording intervals and time lag between events at each location.

6 ACCELERATION AS A FUNCTION OF WIND DIRECTION AND VELOCITY

6.1 *Analysis of current acceleration*

An interesting pattern is revealed in Figure 5a, by plotting the ratio of standard deviation of acceleration from the perpendicular directed channels A1 and A3 versus mean wind direction. The Figure demonstrates that the response at A1 is at least 60% larger than the response at A3 when the wind direction is approximately perpendicular to the east or west face of the building and vice versa when the wind direction is approximately perpendicular to the north or south face of the building. In other words, the along-wind acceleration dominates the across-wind acceleration by at least 60% when the wind direction is perpendicular to the building walls.

When the response is dominated by the resonant components it has been demonstrated [1, 3] that the r.m.s. of acceleration at the top of a tall building of given geometry in a stationary (synoptic) wind, can be approximated for the along- (σ_x) and across- (σ_y) response respectively by:

$$\sigma_{\ddot{x}} = C_x \overline{U}^{k_x} + D_x \quad \text{and} \quad \sigma_{\ddot{y}} = C_y \overline{U}^{k_y} + D_y \qquad (1)$$

Where, C_x, C_y, D_y are constants for a particular building, $\bar{U}$ is mean wind velocity at roof level of the building and k_x, k_y are exponents. The exponent for along-wind response, k_x, is greater than 2, since the spectral density of the wind velocity and the aerodynamic admittance function [2, 12] both increase at a greater power than two near the natural frequency. The exponent for cross wind response, k_y, is often around 3 but can be as high as 4. However, in this case the data seems to suggest that a power of 2.5 is the best fit for both along– and across-wind response.

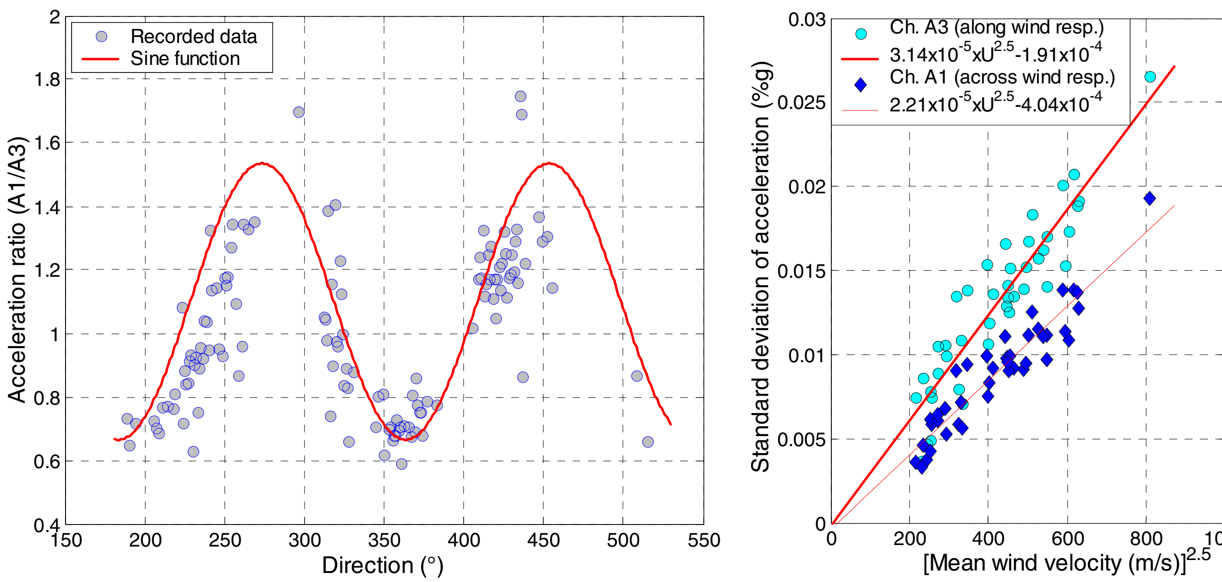
This is demonstrated in Figure 5b, for storms with mean wind direction approximately perpendicular to the north face of the building i.e., the acceleration recorded during theses storms represents the along- and across wind induced response. The power of 2.5 was chosen as a good representation through linear fitting of the data using zero acceleration at zero velocity as a bounding condition. The resulting relation is given for each channel in the legend of Figure 5b. It should be noted that in this context channel A1 represents the across-wind response and channel A3 the along-wind response.

6.2 *Comparison with earlier acceleration observations and traditional models*

The relation given in Figure 5b, can be tested against recordings of wind and acceleration at the same site during a storm in 1991. The observed mean wind velocity was 17.5 m/s from the southeast. The anemometer was located in a mast at the edge of the southeast corner of the roof and should give reasonable along wind values for the mean wind direction in question. Applying the relations from Figure 5b, one can estimate the standard deviation of motion and compare with the values recorded 1991. This is done in Table 2. The predicted standard deviation values are similar to the uncoupled values recorded in 1991 [10], especially for the across-wind component. Since there is some rotational contribution in the along-wind component of the 1997 data, it is reasonable that the along-wind estimate is higher than the uncoupled value.

This further supports the validity of the correction used for the reference mean wind velocity from the 1997 full-scale experiment.

Parallel predictions have been made, for the above storm scenario, using the stochastic process model [13, 15], with the familiar model of mechanically induced turbulence. Predicted and observed values compared remarkably well (see Table 2) considering the approximations inherent in the numerical approach and the natural variability of the wind-induced response process.



(a) (b)

Figure 5. (a) Ratio of r.m.s. acceleration from channels A1 and A3. Directions of 180° and 360° are parallel to A3. Each circle represents an average ratio for each directional degree. (b) Standard deviation of acceleration as a function of corrected reference wind velocity to the power of 2.5. The wind sector is ± 10° from parallel to A3.

Table 2. Standard deviation for along- and across-wind response based on 17.5 m/s mean wind velocity.

Motion component	Values based on uncoupled recordings from 1991 (% g)	Values based on relations from Figure 5b (% g)	Values based on traditional stochastic models (% g)
Along	0.033	0.040	0.035
Across	0.028	0.028	

7 SUMMARY AND DISCUSSION

Natural frequencies and damping ratios of the structure have been identified by parametric system identification method to obtain robust estimates in the presence of mechanical noise in the building. The variation in damping estimates is found to be significantly greater than for the frequency estimates. It is observed that natural frequency estimates tend to decrease with increased amplitude of vibration.

Through continuous monitoring it is possible to investigate various relations that single storm data could not resolve. The analysis has revealed relationship of the vibration amplitude to wind velocity and direction, and to the estimated values of damping and natural frequency. A surprising feature is the suggestion of a relationship between the localized wind velocity above the building and the ambient temperature, which might be attributed to interaction between wind flow and the heat efflux from the building in the low temperatures of winter in Reykjavik, Iceland.

The ratio of perpendicular components of acceleration is found to follow an almost sine-like curve depending on the mean wind direction. The acceleration components are equal for an azimuth of about 45°, but the along-wind acceleration dominates the across-wind acceleration by at least 60% when the wind direction is perpendicular to the building walls.

The r.m.s. acceleration is found to follow a linear relationship to wind velocity to the power of 2.5 for both along- and across response.

Despite the special features noted, a conventional stochastic model of excitation by gusts is found to give an indication of the acceleration response, which may be adequate for assessment of subjective comfort, for which the criteria are rather 'soft'.

Comparing data recorded within the shear core of the building and data recorded at the building perimeter has shown that angular motion magnifies acceleration at the building perimeter, although not specifically presented herein. This may combine with visual cues to push the vibration into the perception range and add to the occupants' awareness or discomfort. It is therefore important at design stage to consider rotational effects in the structural behaviour.

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