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Quantification of wind-induced coupled vibrations of a high-rise structure in urban context

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SUMMARY:
Vibration comfort is an important aspect of the design of high-rise structures. The prediction of wind-induced vibration amplitudes is based on a combination of models for structural components and wind load mechanisms. Estimated values need to be compared to comfort criteria. Data of long-term vibration monitoring on a high-rise building are presented here, focusing on the effect of coupled motion and the influence of neighbouring high-rise structures on the observed responses. Confidence levels are computed as elliptical shapes to assess the effect of coupled motion and study the in-wind and cross-wind responses. The analysis of nine years of data provides a statistical overview of dependencies to wind conditions and detailed insights into the shape of motion within single storm events. Based on the measured data, a significant influence of neighbouring structures has been determined and quantified.

Keywords: Vibration Comfort, High-Rise, Coupled Vibration

1. INTRODUCTION

Monitoring the wind velocity, wind-induced pressures, and wind-induced responses of high-rise structures is an important way to better understand high-rise physics in terms of aerodynamics, the resulting wind loading, and the interaction with mechanical behaviour. These effects involve significant randomness, which should also be treated appropriately for prediction purposes. For the structural design of high-rise buildings, a realistic assessment of the stochastic aerodynamic loading (especially in context with neighbouring structures) is usually based on wind-tunnel studies. However, models for empirical response prediction are widely discussed as well. Especially for early stages or structures in less complex surroundings, such models are essential. In this paper, we provide the results of a long-term monitoring campaign on a high-rise structure, the New Orleans Tower, located in Rotterdam, the Netherlands. Results of the structural properties have been published before (Bronkhorst and Geurts, 2022). The presented data aims to contribute to a future enhancement of the modeling process and to allow validation. In this context, two specific aspects are addressed based on our observations:

1. the influence of neighbouring high-rise structures on the observed responses,
2. the effect of motion coupling over two building axes.

Both aspects are not covered explicitly by models. This paper identifies the influence on the expected accelerations. Section 2 provides information on the building and the monitoring setup.

Section 3 shows the results of the statistical analysis performed on the measured acceleration data. Section 4 gives the main conclusion of the presented study.

2. BUILDING AND ON-SITE DATA

The high-rise building "New Orleans Tower" (NO Tower) is located in the centre of Rotterdam, on a small peninsula in the river "Nieuwe Maas". The structural height is $h = 158$ m, the depth and width are $d = b = 29$ m, respectively. Wind data is available from the nearby airport Rotterdam-The Hague (RTM) as hourly averages, and additionally, an anemometer is installed on top of the building, see Figure 1. Figure 1 also shows the location of the building in its near surroundings, indicating the wind directions with significant interference of nearby buildings. The measurement setup comprises external pressure sensors on the facade exterior at the 34^{th} floor, 2D accelerometers at three different heights, and an ultrasonic anemometer on top of the building Bronkhorst and Geurts, 2022. Signals are acquired with a frequency of $f_s = 20$ Hz. In the study presented here, the accelerometers are analysed and referenced to the wind speed conditions of RTM airport. All data has been transferred to a SQL database allowing for fast and reliable reduction of data, e.g., according to classes of wind velocities and directions. Such filtered accessibility of all data sets is a key condition for real data analyses, especially wind engineering. Structural responses like accelerations depend on wind loading and structural properties. The NO Tower has a squared cross-section. Previous analyses of data showed similar natural frequencies over both main axes of the building's cross-section ($f_x = 0.28$ Hz, $f_y = 0.29$ Hz, see Bronkhorst and Geurts, 2022). Such symmetric structural conditions are quite common for tall high-rise buildings. A coupling of both main vibration directions can be observed, which is neither represented by the mode shapes nor caused by a known wind load mechanism (gust loading, wake turbulence, vortex excitation). It is believed that this effect is caused by the proximity of the natural frequencies over both axes.

3. STATISTICAL ANALYSES

For all analyses, a filtering of wind direction sectors has been performed ($\Delta\Phi = \pm 10°$). Out of the complete data set (2012-2020), time-stamps for velocities above $v_{low} = 8$ m/s, measured at RTM airport with a sensor height of $h = 10m$ have been identified. For each time-stamp, detailed time-series with a length of 10 minutes (±5 minutes around the hourly timestamp) and a resolution

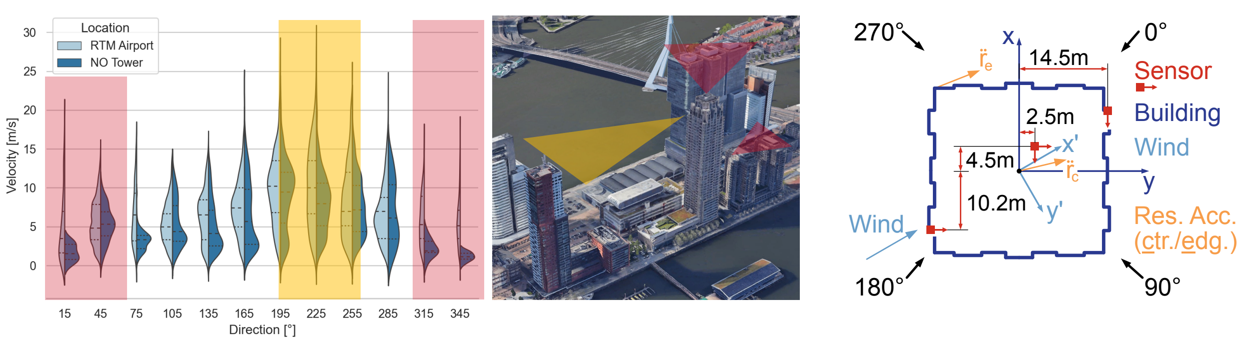

Figure 1. Left: Wind speed occurrences measured on top of the NO tower at $z = 160m$ and at RTM airport, middle: NO Tower and the surrounding with the two most relevant disturbed wind sectors, right: Position of sensors, definition of structural axes (x,y) and wind related axes (x',y'), and definition of wind directions.

of $f_s = 20$ Hz have been used for deeper statistical analyses. The above mentioned conditions are met for a set of 130 885 datasets within the complete measurement period, representing a coherent time period of 908 days, which is roughly 28% of the observation time.

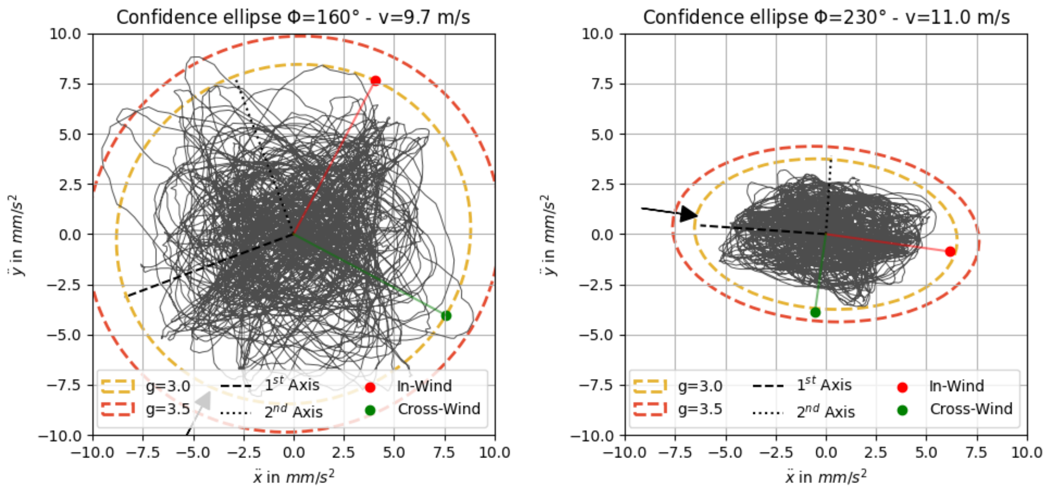

Figure 2. Examples of acceleration trajectories of 10 minute events. Dashed ellipses show two levels of confidence (Mahalanobis distances), marked dots represent in-wind and cross-wind amplitudes.

The sensors were located at a level 34 at a height of $h_{L34} = 114.6m$, while the top floor is located at $h_{L45} = 147.9m$. The measured accelerations have been scaled up to the upper floor level, assuming a linear mode shape in the upper third of the structure (Bronkhorst and Geurts, 2022). As none of the sensors was located exactly in the centre of the building structure, the measured signals showed a combination of translational and torsional components. Therefore, the acceleration data of the four accelerometer has been re-composed in the time domain to split the translational components $\ddot{x}(t)$, $\ddot{y}(t)$ and the torsional component $\ddot{\varphi}(t)$. Combining all sensors, the central transversal acceleration $\ddot{r}_c(t)$ and the combined transversal and torsional acceleration $\ddot{r}_e(t)$, valid for an unfavorable location on the building's edge, have been determined. The time series of $\ddot{r}_c(t)$ has been further decomposed into its in-wind and cross-wind components $\ddot{x}'(t)$ and $\ddot{y}'(t)$ respectively to allow reference to different underlying aerodynamic effects. The time series of $\ddot{r}_c(t)$ and $\ddot{r}_e(t)$ have been analysed with respect to their statistical properties (standard deviation, min, max, and 99.8%-quantiles). For each time period, the detailed x-y-trajectories have been analyzed for the shape of motion. It was found that the motion of the building showed significant interaction between both building axes, mainly ovaling or alternating between in-wind and cross-wind vibrations. The main axes of vibrations have been determined using Singular Value Decomposition (SVD). Figure 2 shows that the resulting 1^{st} and 2^{nd} axes can be, but are not necessarily aligned with the in-wind and cross-wind directions. For each acceleration shape, confidence ellipses (Mahalanobis distances, McLachlan, 1999) on two confidence levels have been determined, see Figure 2 to obtain characteristic values for the in-wind and cross-wind direction (p=98.9%), taking into account each course of motion. In Figure 3, the components of in-wind and cross-wind vibrations are plotted for all considered events of 10 minutes. In Figure 4 (left), the ratios of in-wind and cross-wind vibrations are plotted. Especially in this plot, a significant influence of the flow disturbance is visible for wind directions with upstream neighbouring buildings (see Figure 1). The torsional effect as ratio of $\ddot{r}_e/\ddot{r}_c$, plotted in Figure 4 (right), shows less influence by neighbouring structures.

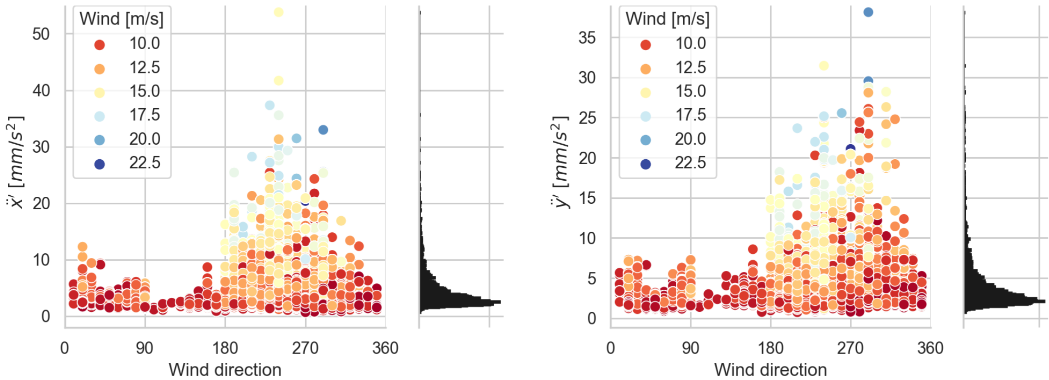

Figure 3. Left: In-wind acceleration $\ddot{x}'$ and right: cross-wind acceleration $\ddot{y}'$ dependent on wind direction and velocity

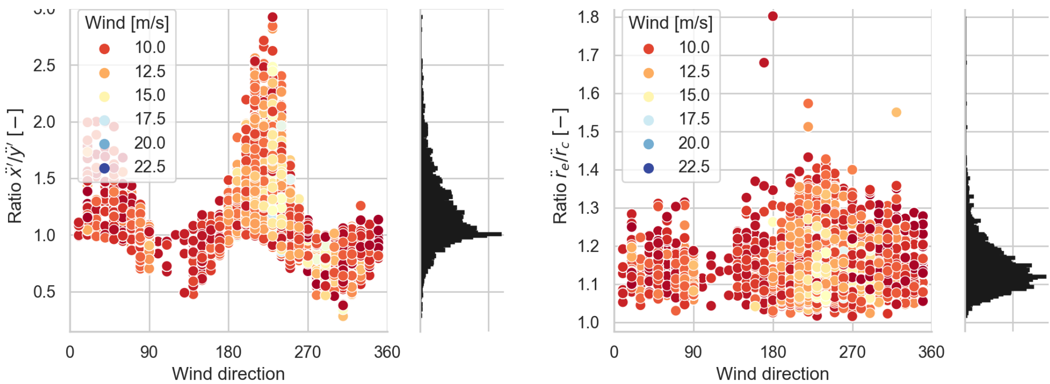

Figure 4. Left: Ratio $\ddot{x}'/\ddot{y}'$ and right: ratio $\ddot{r}_e/\ddot{r}_c$ dependent on wind direction and wind velocity

4. CONCLUSION AND OUTLOOK

For wind directions with upstream neighbouring structures, the measured accelerations are increased. Especially the ratio of in-wind to cross-wind amplitudes shows a significant dependency. Further investigations consider comparisons of accelerations and measured drag and lift force components (via pressure taps) and a comparison of analysed results with currently discussed models of the Eurocode standard and common comfort criteria.

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