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Analysis of the Cabauw tower response under wind gust events

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1 Introduction

In the period between May 2019 and May 2020, the movements of the Cabauw observational tower have been monitored. This monitoring campaign was set up to monitor the behaviour of the tower before (period 1), during (period 2) and after (period 3) replacement of the stay cables. The observations during these periods have been reported in TNO report 2020 R11120A [1].

During the campaign some extreme wind events were registered by KNMI on site. KNMI has asked TNO to analyse the measured data at the tower during these extreme wind events. The goal of this analysis was to determine whether the tower showed different behaviour during these events, in comparison with the behaviour during normal wind conditions as described in TNO report 2020 R11120A [1].

Chapter 2 summarizes the set-up of the monitoring campaign. Chapters 3 and 4 each describe the analysis of a specific wind event. Chapter 5 gives the conclusions.

Annex A explains the applied procedure to synchronise the data sets obtained during the extreme wind events. Annex B gives values of the damping of the tower as determined from the measurements.

2 Measurement set up

In order to assess the dynamic behaviour of the Cabauw tower acceleration sensors have been installed at different positions on the structure.

An overview of the sensor locations is presented in Figure 2-1.

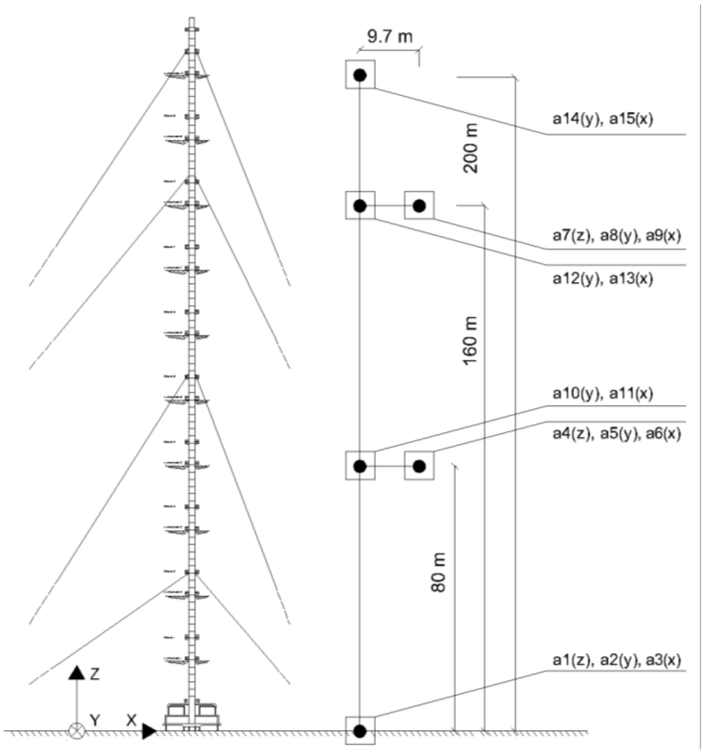

Figure 2-1: overview of acceleration sensor locations on the meteorological tower.

The sensors measure accelerations at the specified points on the outriggers (in X, Y and Z direction) and the mast (X and Y direction). The orientation of the outriggers with respect to the wind direction is shown in Figure 2-2.

The accelerations are sampled continuously at 200Hz. Data are stored on an hourly basis. The accelerations measured have been transformed into vibration velocities and vibrations displacements. These are computed by subsequentially integrating the accelerations. More information on the monitoring set up and performed analysis is given in TNO report 2020 R11120A [1].

In this report, the velocities of the outriggers during two extreme wind events are analysed to assess anomalies observed in the tower response.
To investigate the natural frequencies and the frequency content of the movements of the tower during these special events, Fourier transformation is applied to compute frequency spectra and spectrograms.

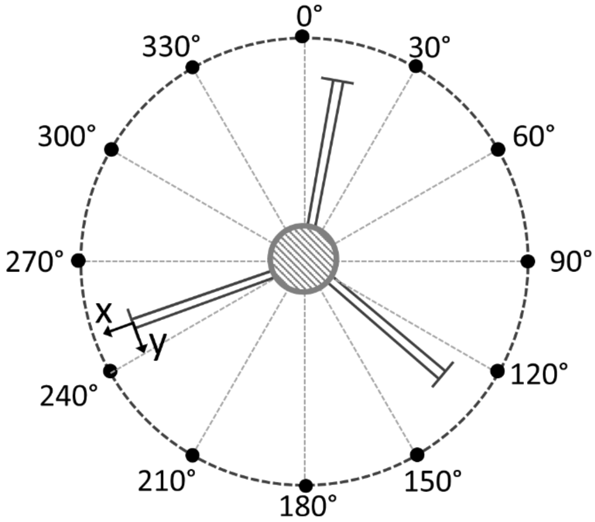

Figure 2-2: Orientation of outrigger with respect to wind direction and orientation of the local X and Y axes of the sensors.

2.1 KNMI datasets

The observations of the movements of the tower are compared with KNMI data. In TNO report 2020 R11120A [1], reference is made to the CESAR database, of which data have been used. The wind velocity data used are measured with cup anemometers, sampled every 3 seconds.
In addition, KNMI made data available, which were measured with a sonic anemometer at a rate of 10 Hz. The larger sampling rate of the sonic anemometer enabled a study of the short period peaks (shorter than 1 second) in the wind velocity.

3 Analysis of observations on 5th of June 2019

3.1 Wind measurements

On the 5th of June 2019, a local gust event was measured by the KNMI at the Cabauw site. Figure 3-1 shows contours of the maximum wind gust velocity over the Netherlands. A relatively high value of the wind gust velocity (around 35 m/s) was measured at the Cabauw site compared to values measured at other meteorological stations.

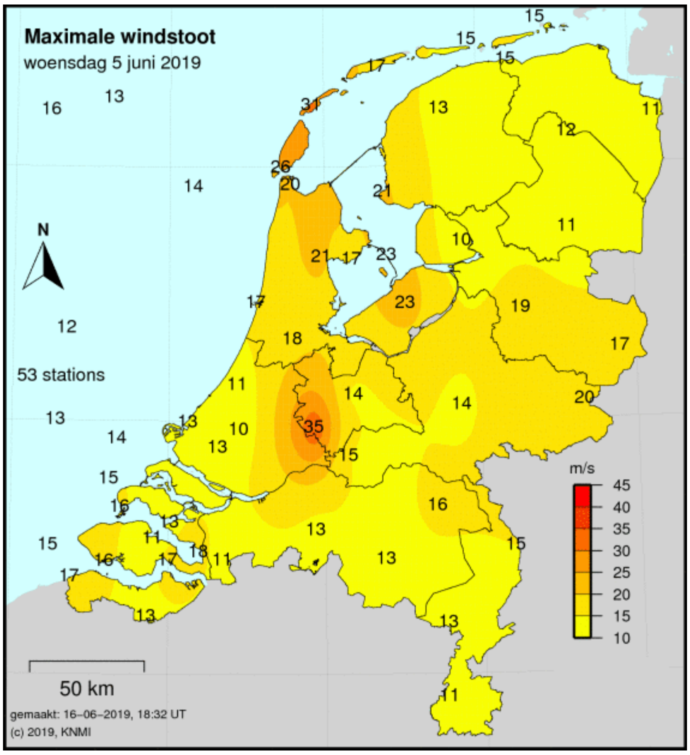

Figure 3-1 Contour of the maximum wind gust observed on the 5th of June 2019. The largest wind gust of 35m/s is recorded at the site of the Cabauw tower.

Figure 3-2 shows the time series of the wind velocity and the wind direction at the Cabauw site between the 21:00 and 22:00 (UTC time). This time series, which was provided by KNMI, was measured by a sonic anemometer (sampled at 10 Hz) at 180 m height.

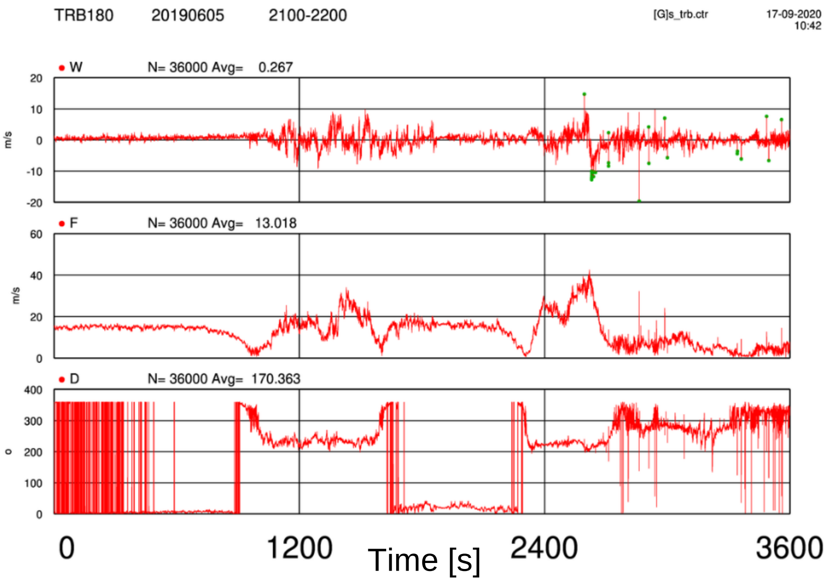

Figure 3-2 Time series measured by the KNMI on the Cabauw tower at 180m height on the 5th of June 2019, between 21:00 and 22:00 (UTC time): (top) vertical wind velocity, (middle) horizontal wind velocity, (bottom) wind direction of the horizontal wind velocity

3.2 Response of tower and outriggers

Figure 3-3, taken from Period A of the measurement report [1], shows the relation between the peak outrigger velocity (at 160m and 80m) and the square of the mean wind velocity measured by the KNMI (from cup anemometer data, as used in [1]). A linear fit was determined and given in the graph. In the figure a large outlier is visible at the mean wind speed squared of about 100 m^2/s^2. At this wind speed squared, a maximum outrigger velocity of 0.2 m/s was determined, a factor 4 to 10 higher than other values found at the same mean wind speeds squared. This outlier was recorded between 21:24 and 22:24 (UTC time) of the 5th of June 2019, and is therefore related to the gust event described before.

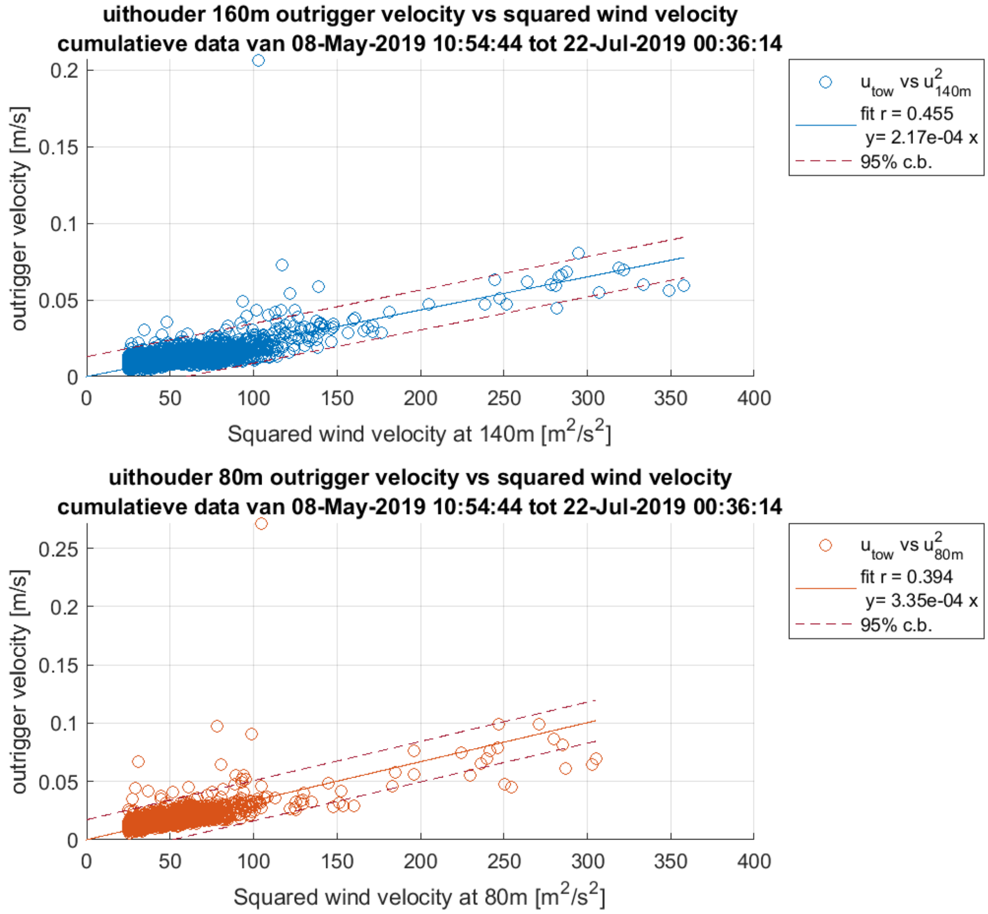

Figure 3-3 Maximum hourly outrigger velocity versus the squared mean wind speed for the period between the 8th of May 2019 and the 22nd of July 2019 for the outrigger at 160m (top) and the outrigger at 80m (bottom). The plot includes a linear fit (blue line) and a 95% confidence interval (dotted red lines).

To compare the wind velocity measurements by KNMI with the acceleration measurements by TNO, first a correction was made to account for the time lag between the recording time stamps.
After comparing the wind velocity time series, measured with the sonic anemometer at 180m, with the tower vibration time series, measured by the acceleration sensors, a time lag of 2.5 minutes was found. A detailed explanation of the time lag assessment and correction procedure can be found in Appendix A.

Figure 3-4 shows time series of the squared wind velocity from the sonic anemometer at 180m, and of the outrigger velocity in X direction. A comparison of these timeseries shows that a higher wind velocity leads to a higher outrigger velocity.

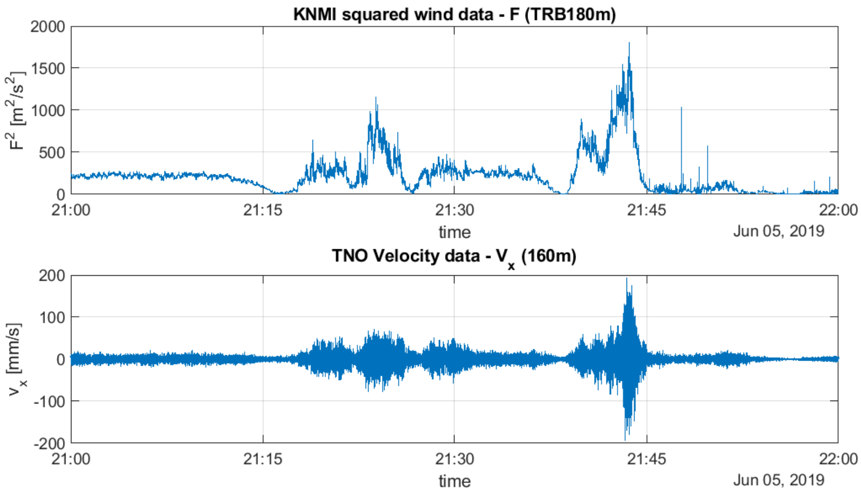

Figure 3-4 Timeseries measured in the gust event of the 5th of June 2019 (21:00 – 22:00, UTC time): (top) the squared wind velocity at 180m, and (bottom) the velocity in X-direction of the outriggers at 160m.

Figure 3-5 compares the magnitude of the velocity vector, $\bar{V} = \sqrt{V_x^2 + V_y^2}$, with the absolute values of the velocity in X and Y direction, V_x and V_y. Figure 3-5 shows that the velocity component in the X direction (along the outrigger axis) is larger than the Y component when the wind is coming from directions between 210 and 240 degrees which is near the orientation of the outrigger where the sensors are mounted (250 degrees). These wind directions occur for the periods with the highest wind velocity.

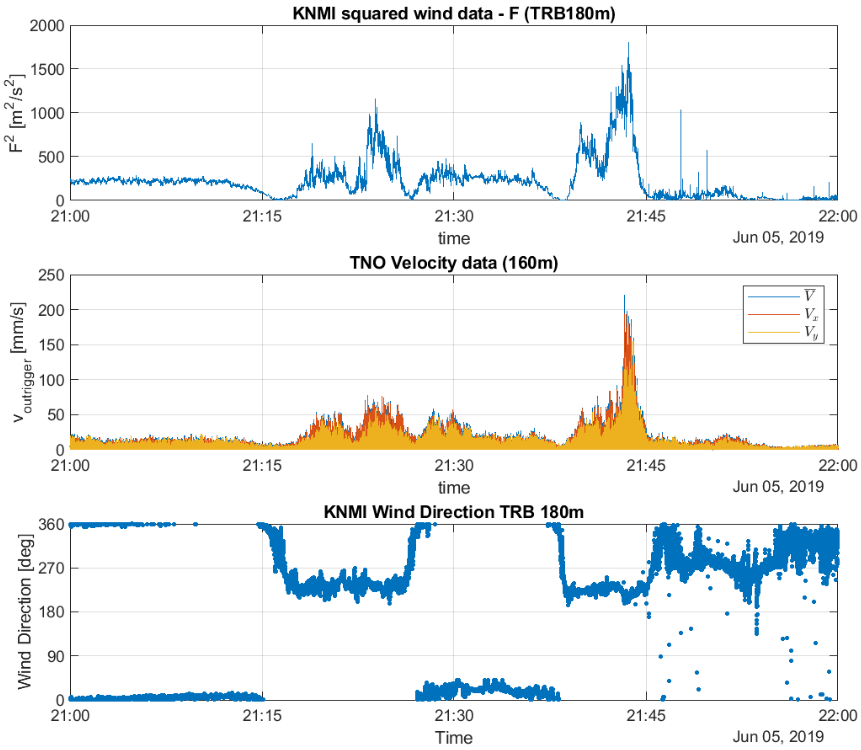

Figure 3-5 Squared wind velocity (top) and direction (bottom) measured from the KNMI sensors at 180m and the velocity of the sensors on the outriggers at 160m (middle) during the gust event of the 5th of June 2019 (21:00 – 22:00, UTC time).

The upper graph of Figure 3-6 shows 3 cross sections of the spectrogram of the outrigger velocity in X direction (bottom graph) for 3 separate time instances: before, during and after the passage of the gust event. An increase in the energy in the spectrum at the dominant frequencies is visible during the passage of the gust, due to the higher wind load on the tower, but there is no shift in dominant frequencies. This shows that the tower behaviour does not change during the passage of the wind event studied.

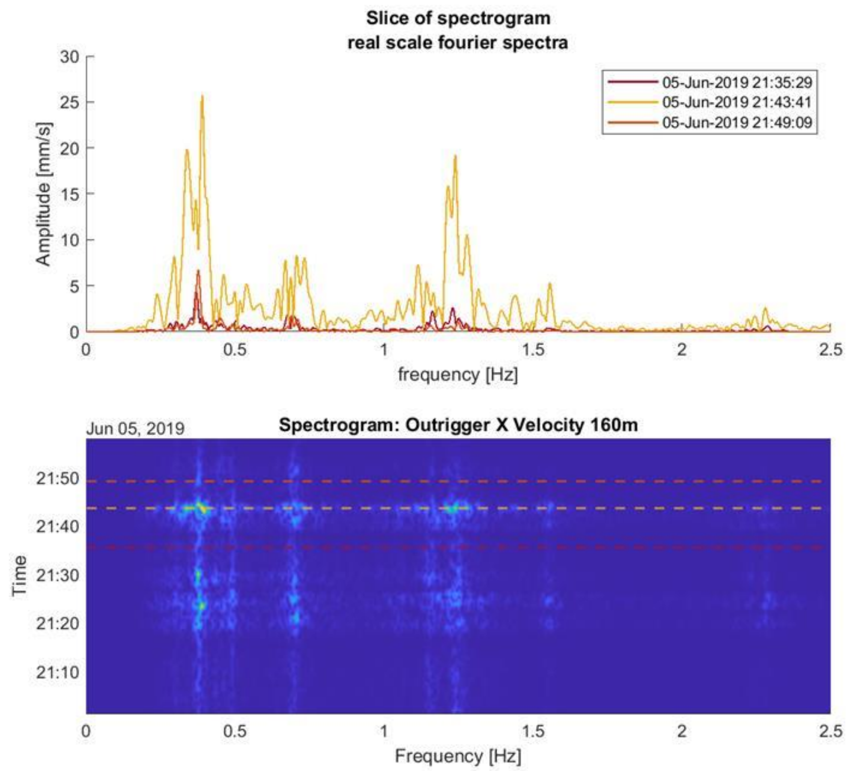

Figure 3-6 (bottom) Spectrogram of the outrigger velocity in X direction and (top) 3 cross section of the spectrogram: before, during and after the gust event. The spectrogram was obtained using time windows of 164 seconds to achieve a higher frequency resolution.

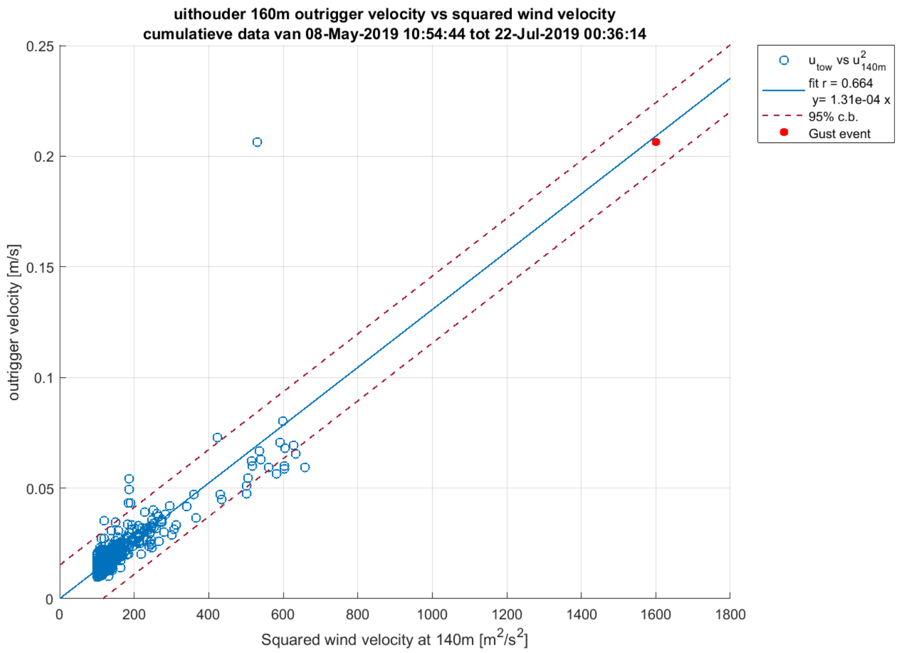

Figure 3-7 Maximum hourly outrigger velocity against the squared peak wind velocity for the period between the 8th of May 2019 and the 22nd of July 2019 for the outrigger at 160m (top) and the outrigger at 80m (bottom). The plot includes a linear fit (blue line) and a 95% confidence interval (dotted red lines). The blue dots use the peak wind velocities from

the KNMI cup anemometers at 140 m height; the red dot uses the peak wind velocity coming from the sonic anemometer at 180 m height.

To observe whether the tower response during the wind gust is in line with the measurements observed during Period 1, the TNO measurements are compared to the KNMI datapoints. In the main measurement report [1] the TNO measurements of the peak outrigger velocity are compared against the 10-minute mean values of the KNMI datapoints.

To assess the effect during the gust event, instead of the mean values, the peak values of the KNMI observations are compared to the TNO measurements of the peak outrigger velocity. Figure 3- shows in blue dots the squared peak wind velocity from the cup anemometers against the peak outrigger velocity together with a linear regression and 95% confidence intervals. In the figure, the outlier corresponding to the gust event of the 5th of June 2019 is still visible and outside the linear fit. The red dot on the figure corresponds with the same gust event when assigned the squared peak velocity of 1600 m^2/s^2 (i.e. peak velocity of 40m/s, as registered by the sonic anemometer) measured between the 21:00 and 22:00 (see Figure 3-4). The red dot in this figure is in line with the fit obtained with the cup anemometer data obtained during Period 1.

During the discussion on this event, it was discussed how large the damping in the structure is, and whether this could influence the response during a peak. Annex B provides the outcome of the damping estimates of the tower. The damping is larger than 2% which is rather high for a steel structure. It is therefore not expected that excessive resonance is occurring in the structure.

4 Winter storm: 9th of February 2020

During the 9th of February 2020, high wind velocities were measured during the whole day. Figure 4-1 shows the wind velocity measured with the KNMI sonic anemometer at 180 m height between 14:30 and 14:40 on the 9th of February 2020.

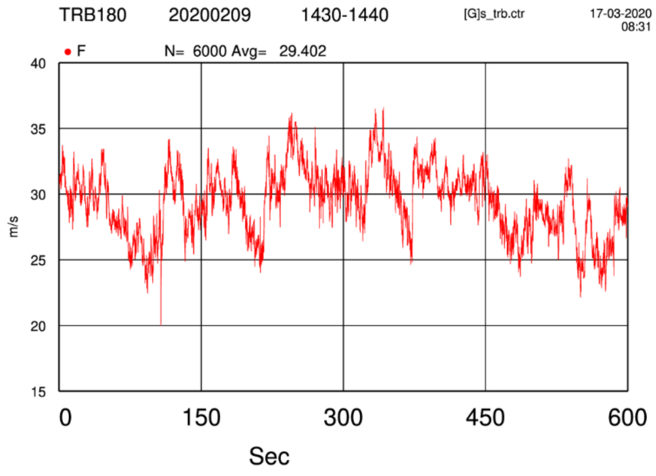

Figure 4-1 Horizontal component of the wind velocity measured by the KNMI sensors at the Cabauw tower at 180m height on the 9th of February 2020, between 14:30 and 14:40 (UTC time).

To illustrate the levels of wind velocity during this day, Figure 4-2 shows the outrigger velocity in X direction measured between 9:30 and 16:30 (UTC time).

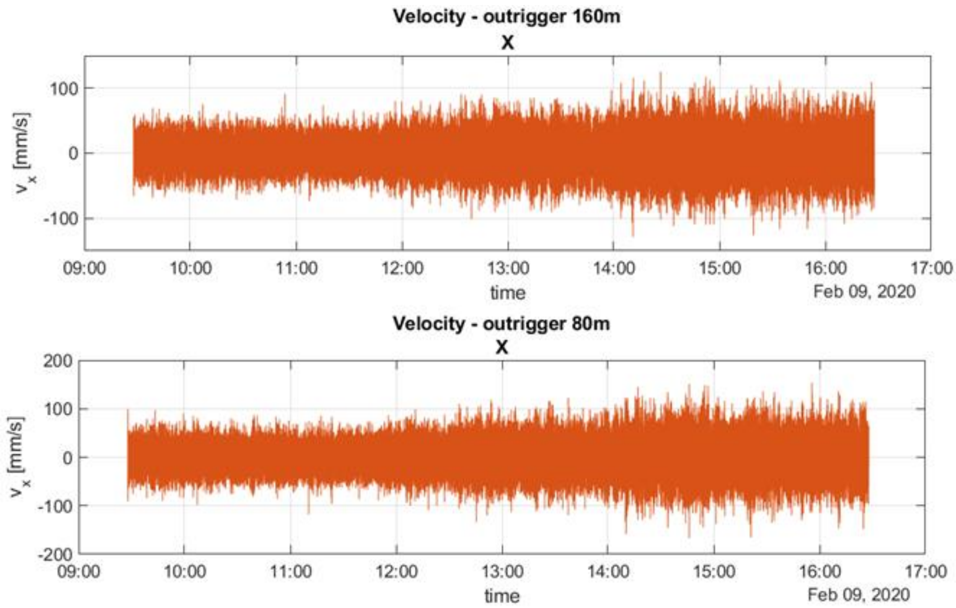

Figure 4-2 Outrigger X velocities at 160m (top) and 80m (bottom) between the 9:00 and 17:00 (UTC time) on the 9th of February 2020.

Based on this output, it was concluded that no special event occurred (compared to the event described in chapter 3).

The measured outrigger velocities have amplitudes larger than 100 mm/s, however no large out-of-trend velocity was observed as for the event on the 5th of June 2019 described in chapter 3.

The measurements of the 9th of February are the encircled datapoints in Figure 4-3 with the largest values on the upper right-hand side of the regression of Period 3 (see [1] for description). Other datapoints in the upper right-hand side of the regression are related to other winter storms that occurred on the 16th and 23rd of February 2020.

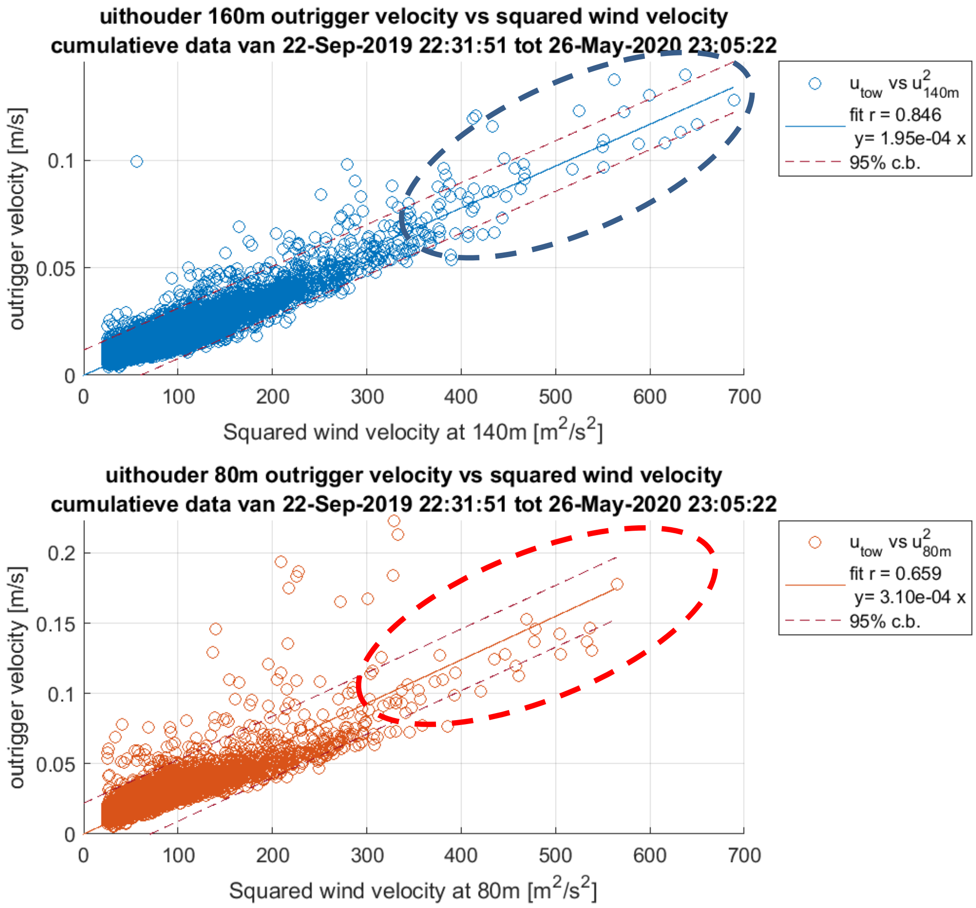

Figure 4-3 Maximum hourly outrigger velocity against the squared mean wind speed for the period between the 22th of September 2019 and the 26th of May 2020 after removing the outliers for the outrigger at 160m (top) and the outrigger at 80m (bottom). The plot includes a linear fit and a 95% confidence interval (dotted red lines).

For the outrigger at 80m, outliers are found for squared wind velocities between 100 and 300 m^2/s^2, with peak outrigger velocity larger than 0.15 m/s. The time-stamps related to these outliers together with the wind velocity and the error (the difference between the datapoint and the fitted value) are presented in Table 4-1.

Table 4-1 *properties of the outliers related to the peak outrigger velocity data between the 22nd of September 2019 and the 26 of May 2020 (measurement period 3).*

Physical quantity	**UTC Time (+/- 30min)**	**Value [mm/s]**	**Error [mm/s]**	**Wind velocity [m/s]**
Outrigger velocity 80m	10-Mar-2020 11:35:12	193.68	128.86	14.47
Outrigger velocity 80m	10-Feb-2020 04:57:52	223.13	121.36	18.13
Outrigger velocity 80m	11-Mar-2020 22:35:12	186.44	115.82	15.10
Outrigger velocity 80m	11-Mar-2020 23:35:12	183.33	113.61	15.00
Outrigger velocity 80m	23-Feb-2020 13:35:10	212.78	109.66	18.24
Outrigger velocity 80m	23-Feb-2020 07:35:10	175.04	107.62	14.75
Outrigger velocity 80m	10-Mar-2020 07:35:12	145.54	102.08	11.84
Outrigger velocity 80m	10-Mar-2020 08:35:12	129.45	87.13	11.69
Outrigger velocity 80m	09-Feb-2020 20:57:52	183.8	82.30	18.10
Outrigger velocity 80m	24-Feb-2020 14:35:11	165.03	80.77	16.49
Outrigger velocity 80m	10-Feb-2020 05:57:52	167.13	73.76	17.36

It is recommended to do an analysis comparable to the analysis done for the event described in chapter 3, to see whether there is a better correspondence with the actual peak velocities measured with a sonic anemometer.

5 Conclusions

This report describes a study of two extreme wind events which occurred during a monitoring campaign on the dynamic behaviour of the Cabauw observational tower in the period between May 2019 and May 2020. Velocity data measured with cup anemometers were used. During some extreme wind events, these data did not give a consistent relation with the measured tower response.

A comparison was made of the vibration measurements on the tower with wind velocity measurements performed with a sonic anemometer. This sonic anemometer measured velocities with a higher sampling rate than the cup anemometers. This comparison showed that the ratio between the peaks in the wind speed squared and the peaks in the vibration velocity for the extreme wind event on the 5th of June 2019 are consistent with the linear relation determined during normal wind conditions.

Analysis of the extreme wind event on the 9th of February 2020 resulted in several other events, for which a similar analysis as performed on the wind event of the 5th of June 2019 is recommended.

It is concluded that a linear relation between oncoming wind and tower response is found when comparing the peak values. The tower does not behave different during short duration events compared to regular wind conditions.

These observations have been discussed by KNMI). Based on the observations we found, KNMI explains (quoted from email conversation with Fred Bosveld):

During rare events the normal relation between mean wind and maximum wind is lost. In such cases maximum outrigger movement is better analysed in relation to the wind gust. However the marked discontinuity algorithm implemented in the wind post processing at KNMI may hamper this application specifically for these rare events. KNMI is working on implementing a parallel wind data stream without this marked discontinuity.

6 References

[1] D. Moretti, C.P.W. Geurts, TNO Report 2020 R11120 “Monitoring vibrations of the KNMI Cabauw observation tower”

7 Signature

Delft, 27-11-2020

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A Synchronization KNMI-TNO sensors

To investigate the behavior of the tower in detail, the time-trace of the velocities of the sensors positioned on the outrigger at 160m between the 21:00 and 22:00 are plotted together with the squared wind velocity measured at 180m during the same time window. Figure A-1 shows that the amplitude of the tower response (top and middle) follows the wind excitation (bottom) however a time lag between the TNO and KNMI sensors is present.

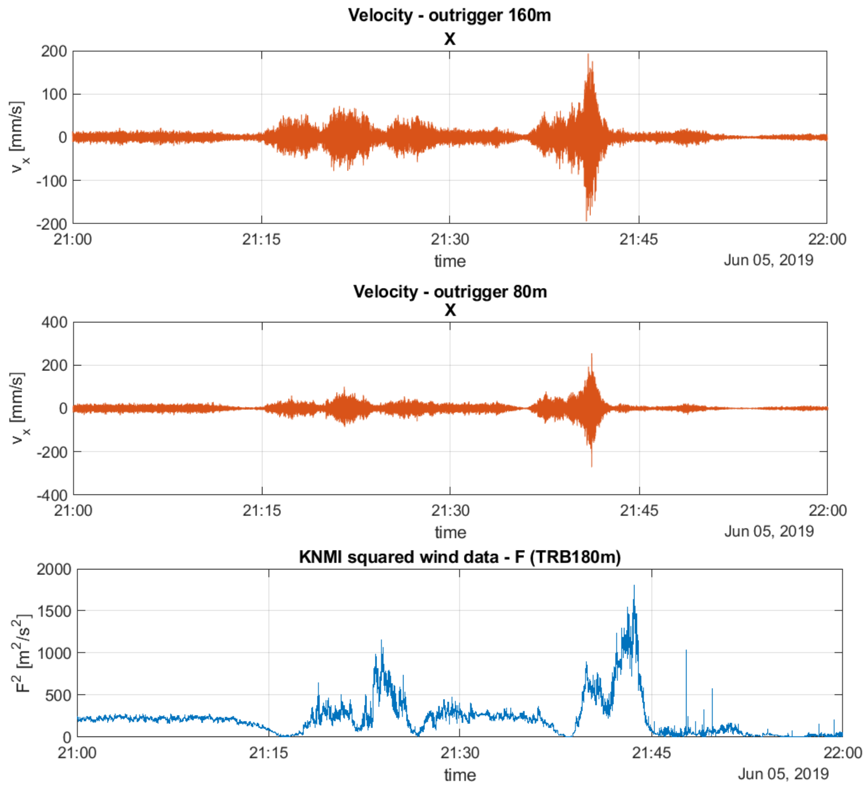

Figure A-1 Outrigger X-velocity at 160m (top) and 80m (middle) and squared wind velocity measured from the KNMI sensors at 180m (bottom) during the gust event of the 5th of June 2019 (21:00 – 22:00, UTC time).

To quantify the lag, the correlation between the inclinometer data at 180m and the acceleration in X direction of the outrigger at 160m is computed. The maximum correlation between the 2 time traces correspond to a delay of the KNMI sensor of 150 seconds (~2.5 minutes). The acceleration time-trace measured with TNO sensors are shifted 150 seconds to compensate for the time lag (orange line in Figure A-2, middle).

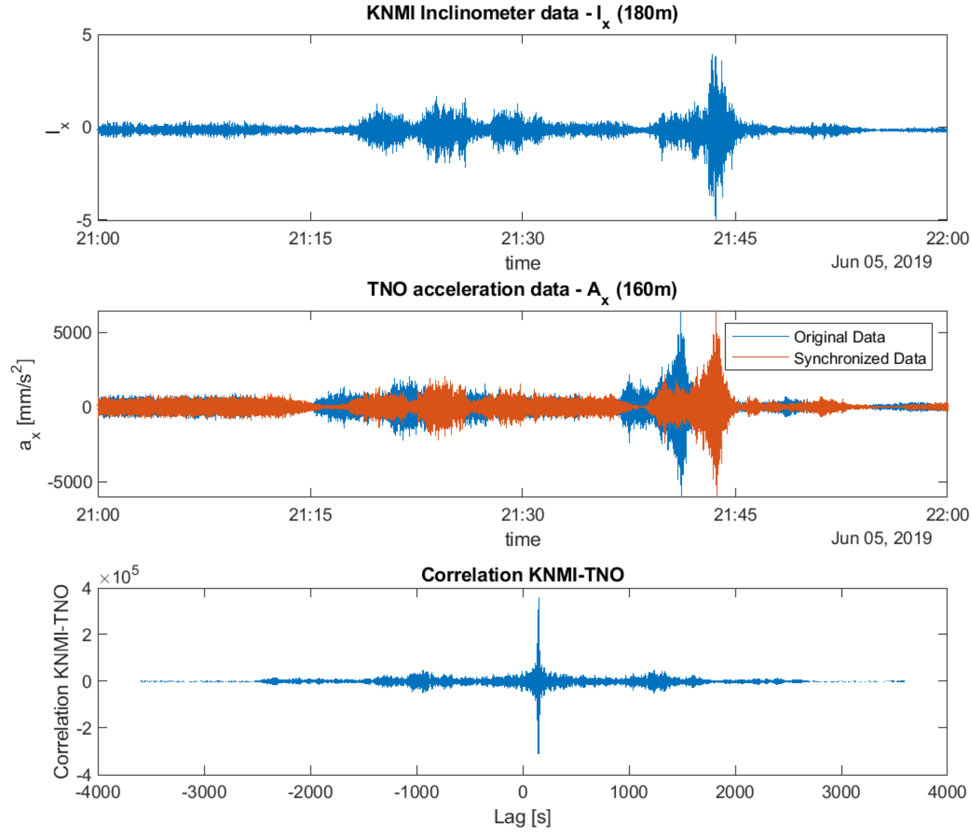

Figure A-2 Inclinometer data measured from the KNMI sensors at 180m (top), X-acceleration of the outriggers at 160m (middle) original (blue) and synchronised (orange) and the correlation between the inclinometer data and original acceleration data (bottom) during the gust event of the 5th of June 2019 (21:00 – 22:00, UTC time).

B Damping estimation (Period 1)

Figure 3-4 and Figure 3-5 show that the lag between the peak in the wind velocity and the peak in the tower response is relatively small for such a slender structure and the tower oscillations are damped quite quickly. To estimate the damping percentage of the tower related to dominant natural frequency (thus to the first vibration mode), the half-power band width method has been applied to each 1-hour measurement of Period1 (before replacement of the guides). The results are shown in Figure B-2.

The half power bandwidth method is a technique to estimate the structural damping by following these steps (see also Figure B-1):

- Determine from the spectrum at which frequency a peak occurs;
- Take the height of the peak response amplitude (A_{max}) at that frequency and divide this value by $\sqrt{2}$. The value found corresponds to half the power of the maximum value.
- Measure the width of the peak at that half-power value (that is the bandwidth between f_1 and f_2).
- Compute the damping ratio of the structure, ξ, by the (approximated) expression:

$$\xi = \frac{(f_2 - f_1)}{2 * f_n}$$

Where f_n is the central (natural) frequency within the bandwidth and f_1 and f_2 are, respectively, the upper and lower bounds of the bandwidth.

The damping ratio is defined as the ratio between the actual damping and the critical damping in the structure, which is the damping at which a structure returns to its equilibrium without oscillation.

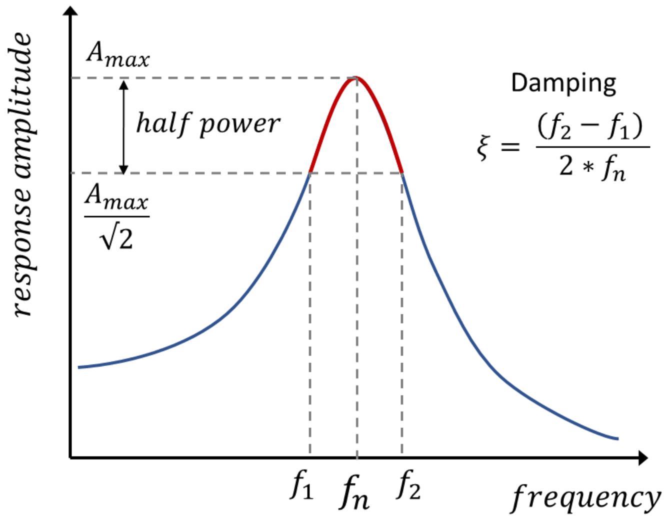

Figure B-1 Graphic representation of the half-power bandwidth method for structural damping estimation.

The value of the damping does not depend on the wind velocity, unless the structure behaves different at different vibrations amplitudes. This was not further investigated here.

From the figures, a damping between 2.3% and 3.2% (with median value around 2.7%) was estimated. For steel structures, normally damping values around 1% are applied. The relatively high damping for such a slender structure can be explained by e.g. the presence of bolted connections along the tower body, the anchors between the cables and the tower.

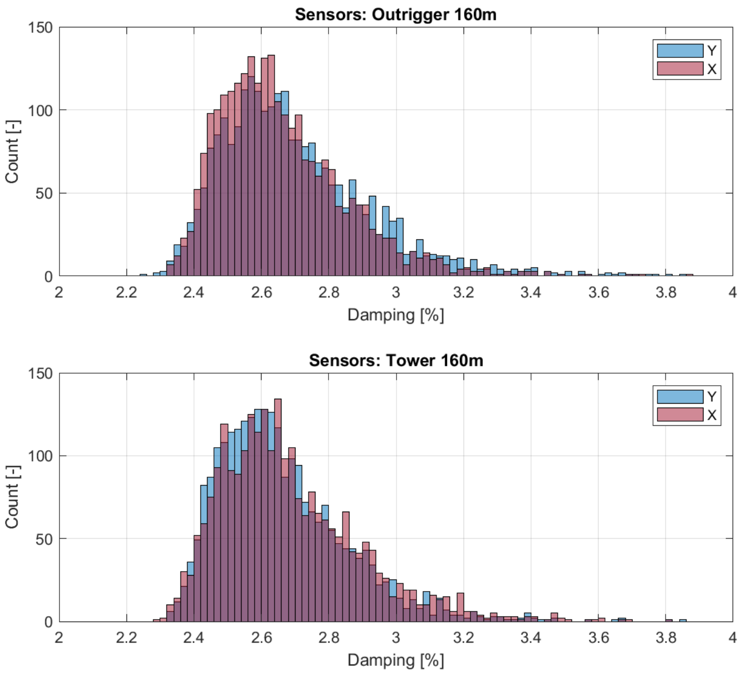

Figure B-2 Damping percentage estimated with the half-power bandwidth method for each of the measurement of Period 1 for the sensors on the outrigger (top) and the tower (bottom) at 160m in X and Y direction.