Measurement at wind turbine near Waddinxveen

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Summary in Dutch

Op 1 februari 2016 heb ik een trillingsmeting uitgevoerd aan de fundering van en de bodem rondom een 3 MW windturbine in het Distripark Waddinxveen. De windsnelheid tijdens de meting was gemiddeld 15 m/s met pieken tot 23 m/s. Dit rapport beschrijft de meetopstelling, de postprocessing en de bevindingen. De meetopstelling bestond uit 6 versnellingsopnemers op de fundering en 12 versnellingsopnemers op de bodem. De versnellingen zijn geïntegreerd naar snelheden en verplaatsingen.

De hoofddoelstelling van de meting zijn bereikt:

- de beschikbare meetset van Deltares is geschikt om dit type metingen uit te voeren.
- het trillingsniveau op de fundering en in de grond is orde 1-2 mm verplaatsing en 1-2 mm/s snelheid.

De dubbele integratie naar verplaatsingen is mogelijk, maar behoeft nog wel aandacht. Door de lage frequentie van de rotor en de lage eigenfrequentie van het hele systeem is het lastig om de statische waarde goed weg te filteren. De bewegingen bij de frequentie 3 Hz zijn onverwacht groot. De horizontale verplaatsingen zijn onverwacht groot.

Contents

1 Introduction

The calculations of wind turbine response suggest that there are a few frequencies important for the wind turbine and thus the loading on the foundation. This refers to the eigenfrequencies of the tower-nacelle system. The following are important [e.g. Rodrigues dos Santos Costa 2014]

- first bending mode (0.3 Hz)
- first axial mode (1.0 Hz)
- second bending mode (3 Hz)

This means that conventional measurement set-up cannot measure these vibrations correctly, since these often use 1 Hz as lower cut off frequency.

The measurement equipment of Deltares uses piezo-electric acceleration transducers that are able to measure static and low frequency vibrations. Therefore, it seems a proper equipment for this purpose.

The first target of the measurements reported in this report is to judge the possibility of measuring the vibrations by the available equipment.

Once the equipment is mobilized, it is useful to get a first idea on the vibration level at the foundation, and in the soil, and propagation and decay of the vibrations in the soil around the foundation. This is the second target of this measurement.

2 Measurements

2.1 Wind turbine

The wind turbine selected for measurement is located in the Distipark in Waddinxveen. It is located along the Nijverheidsweg close to the company van Uden Logistics. Seen from the west it is the second wind turbine from in total four. The geographical position is (52.019564 NB,4.630586 OL) [Google Maps 2016]. This turbine is selected based on the distance to Delft, the accessibility and the fact that there is no water basin around the wind turbine and enough space to install the transducers at several distances.

Around the location some potential nuisance sources are available:

- The local road Nijverheidsweg. Several lorries passed with a rather high speed. The official speed limit is 50 km/h. The quality of the road is good there are no severe bumps.
- The highway A12. This carried continuous traffic with maximum speed of 100 km/h.

station	Cabauw	Rotterdam
Daily mean wind speed [m/s]	11.5	12.0
Maximum hourly mean wind speed [m/s]	16.0	14.0
Measured in hour division [h]	13	12
Maximum wind gust [m/s]	24.0	22.0
Measured in hour division [h]	13	13

Table 1 Wind data from two nearby stations at 1 February 2016 [KNMI 2016]

- The work field of van Uden (Transportweg 20 Waddinxveen). Close to the wind turbine some minor riding of lorries and other industrial carriages are done. The speed is always low (20 km/h)

The wind turbine has an axle height of 85 m. The rotor diameter is 90 m. The turbine is a Vestas V90-3.0 MW turbine [Windstats 2016].

It is founded on a concrete slab. The form of this slab is an octagon with a length per side of 6.9 m. The thickness is not known yet, but at least 1 m, since the top surface of the slab is about 1 m above the ground level. Based on general knowledge of the properties of the soil in this area, it is almost sure that the wind turbine is founded on piles.

2.2 Wind-conditions

The measurements are carried out Monday 01 February 2016. The general wind conditions was a wind speed of about 14 m/s with wind gusts up to 19 m/s. There were traffic warnings and some empty lorries were blown from the road.

Nearby weather stations are Cabauw located at (51 58' N.B. 04 55' O.L.) at about 19 km and Rotterdam airport Zestienhoven (51 58' N.B. 04 27' O.L) at about 15 km [KNMI 2016]. The wind speed is measured at 10 m height. Table 1 shows the results.

2.3 Equipment

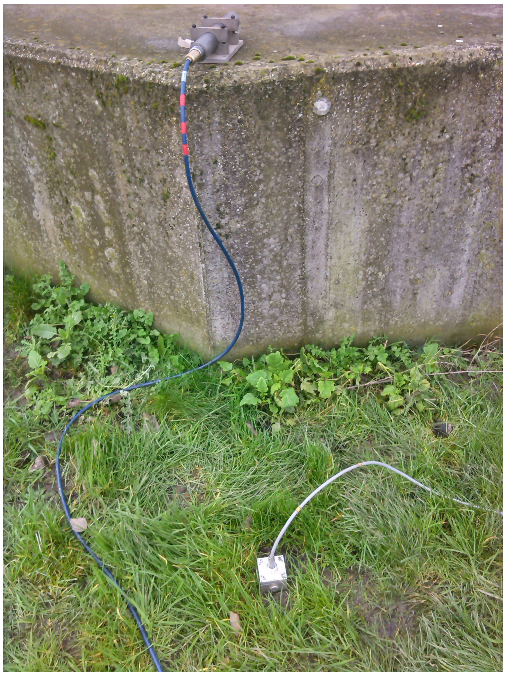
The equipment consists of four *turbocones*. these measure accelerations in three perpendicular directions. These *turbocones* are not pushed into the soil, but were laid on the soil and loaded by a block steel. The *turbocone* placed at the slab is placed in a special holder for this purpose.

Additionally 6 separated transducers are available. These are placed in special holders. These holders have a pin of about 20 cm, which facilitates a proper fixation into the soil. On the slab, the two holders are placed without any additional fixation. Figure 1 gives an idea of the field test.

(a) H10 and V11 on slab

(b) Overview from V6

(c) TC1 in the field



(d) TC3 and V5

Figure 1 Impression of measurement site and set-up

2.4 Measurement lay-out and recordings

Figure 2 shows a sketch of the measurements. Based on the limited targets of the measurement there has not been a lot of effort to create a very accurate determination of the position of the devices. The slab was accessible from one side only, therefore, all transducers are located at this side of the slab.

Based on some assumptions, the coordinates of the devices are estimated in Table 2.

The farthest transducer (V6) is just at the edge of the road (Nijverheidsweg).

The measurements started at 12:15 and stopped at 14:45, Table 1 shows that at that moment the highest wind speeds were found during that day. During the measurements some empty trailers were blown down leading to traffic jams.

During the measurement interval 12 measurements of 11 minutes (660 s) were recorded. The sample rate was 400 Hz. The equipment measures accelerations.

2.5 Test vertical transducers

A simple test of the transducers is switching of the 1-g compensation. The equipment has a special button for this purpose. Figure 3 shows the results. It is clear that all transducers show a -10 m/s^2 signal when the compensation was switched off.

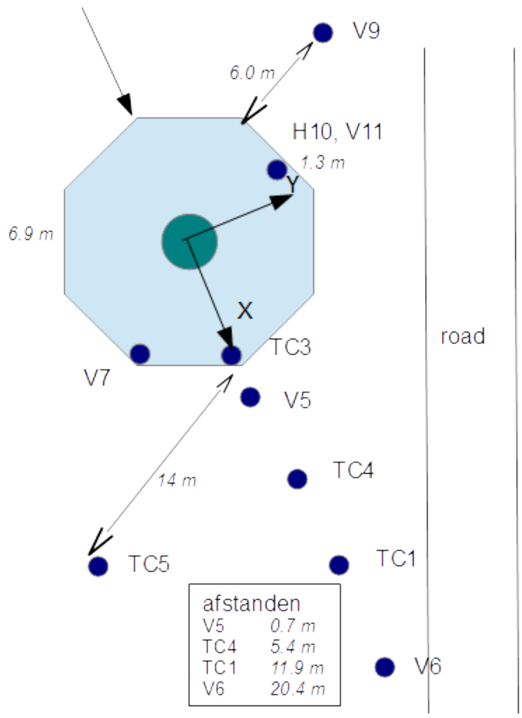


Figure 2 Lay out of measurement

channel field	channel program	transducer	direction	x [m]	y [m]	vertical	calibration $[(m/s^2)/V]$
0	1	TC1	-X	20.9	0.0	surface	0.901
1	2	TC1	+Z	20.9	0.0	surface	0.946
2	3	TC1	Y	20.9	0.0	surface	0.942
3	4	TC4	-X	14.4	0.0	surface	1.953
4	5	TC4	+Z	14.4	0.0	surface	0.913
5	6	TC4	Y	14.4	0.0	surface	0.923
6	7	TC5	-X	20.2	-8.4	surface	1.967
7	8	TC5	+Z	20.2	-8.4	surface	2.006
8	9	TC5	Y	20.2	-8.4	surface	0.874
9	10	TC3	-X	9.0	0.0	on slab	0.910
10	11	TC3	+Z	9.0	0.0	on slab	0.881
11	12	TC3	Y	9.0	0.0	on slab	0.926
12	13	V5	Z	9.7	0.0	surface	2.007
13	14	V6	Z	29.4	0.0	surface	2.017
14	15	V7	Z	6.4	-6.4	on slab	1.968
15	16	V9	Z	-8.7	11.9	surface	1.910
16	17	H10	X	-1.2	8.6	on slab	1.960
17	18	V11	Z	-1.2	8.6	on slab	1.996

Table 2 Global locations of transducers
Note: the channel number starts counting at 0

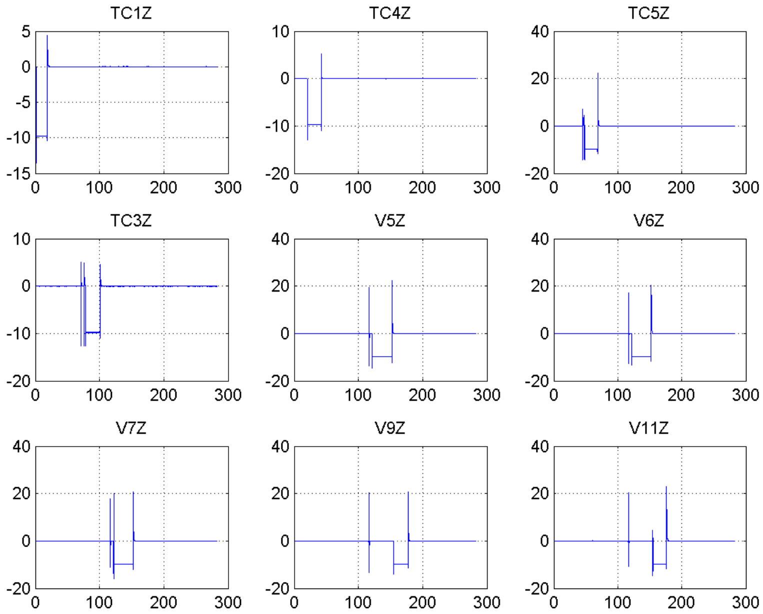


Figure 3 Test of vertical transducers

3 Results and processing

3.1 Wind turbine

At one moment the rate of the blades of the wind turbine had been counted. This had been done during 6 periods, the time of passage of the third is estimated (1,2,3 blades passing). A linear trend line shows that this takes 3.79 s. This means that he turbine is working at 0.264 Hz and a blade is passing along the tower with 3*0.264 = 0.792 Hz (or each 1.26 s).

3.2 Description of post-processing

The following steps are done during post-processing:

1. the acceleration on time signal is tapered with a cosine window over the first and final 30 s and a baseline correction is applied
2. the acceleration is transformed into the frequency domain
3. the frequency is filtered using a high cut filter (3.5-5.5 Hz)
4. for the velocity the acceleration is filtered with a band pass filter low pass 0-0.1 Hz and high-cut 14.5-14.6 Hz filter
5. this signal is integrated in the frequency domain and (after a baseline correction) an inverse Fourier transform is applied

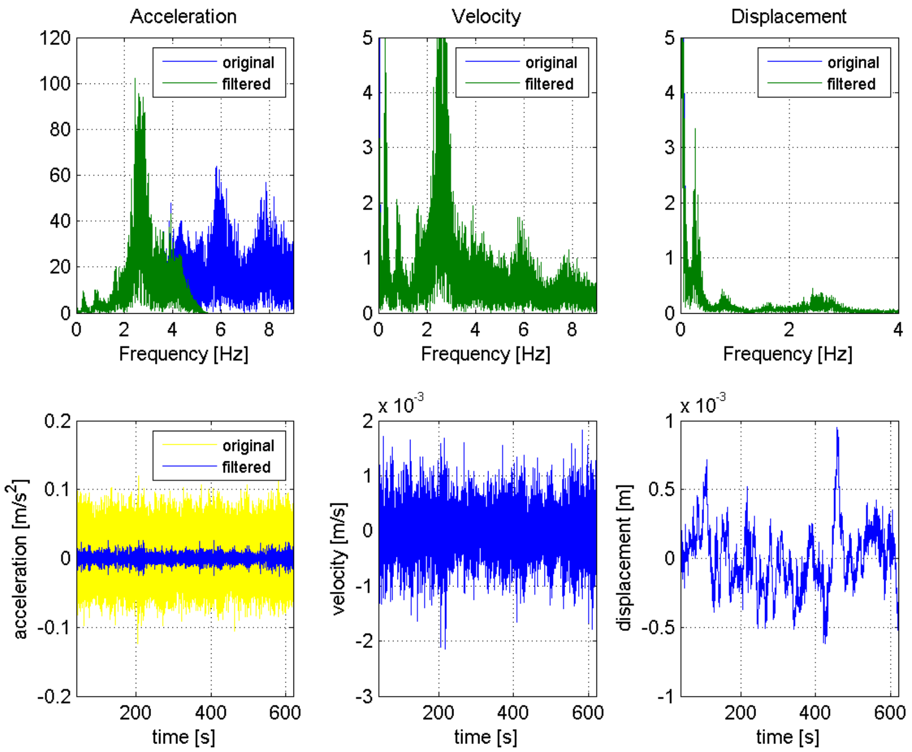


Figure 4 Acceleration, velocity and displacement of the slab (measurement 01)

6. for the displacement the velocity is filtered with a band pass filter low pass 0-0.1 Hz and high-cut 14.5-14.6 Hz filter
7. this signal is integrated in the frequency domain, a baseline correction is applied and inverse Fourier is done
8. the first and final 40 s of the displacement signal is removed. A linear fit is calculated and the results are presented relative to this fit

All results are completely presented in a separate appendix A. Six figures are shown. The top row shows the results in the frequency domain, the bottom row the results in the time domain. For the velocity and displacement these are back transformed results, for the acceleration (left column of figures) it is both originally measured as well as the back transformed result.

3.3 Measured motion of the slab

The measured motion of the slab is analyzed. Figure 4 shows the processed results. At top the frequency domain is shown, at the bottom the time domain data.

The lower left figure shows that the equipment has a high noise level, which is easily removed by filtering high frequencies (above 80 Hz). The yellow line is the original signal, the blue line is the one after filtering at 4.5 Hz. At top the

time m:ss	time s	observation
0:05	05	car
0:58	58	lorry
2:35	155	lorry
3:06	186	lorry
7:27	447	van
8:10	490	lorry
9:41	581	lorry
9:50	590	lorry
10:16	616	car

Table 3 Noticed passages of traffic measurement 8

frequency domain data are shown. The low frequency peak at 0.32 Hz is in the acceleration already visible and in the displacement the most important motion. Other frequency peaks are found at 0.82 Hz, 1.6 Hz, 2.6 Hz, 5.9 Hz and 7.8 Hz. The frequency 0.82 Hz seems to be induced by the blades passing, that was counted to be 0.79 Hz (see Section 3.1).

This shows that the equipment is reasonably able to measure the low frequencies. It is possible to integrate these with respect to time to velocity of the transducer. Further integration with respect to time is more complicated, but with some additional effort reasonable results are obtained.

The measurement confirms the existence of important frequencies below the 1 Hz.

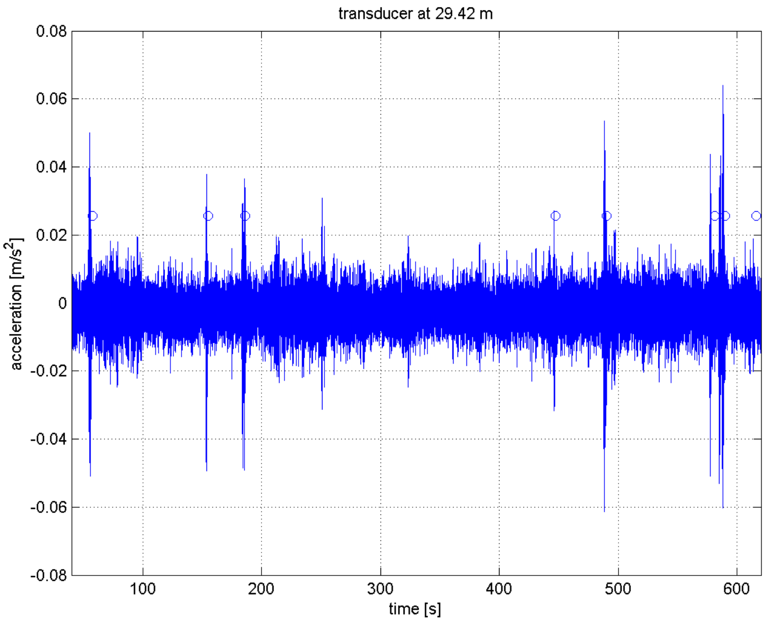
3.4 Influence of the lorries that passes

To study the influence of the lorries, measurement number 8 is further analyzed. Here, a lot of lorries did pass during the measurement. Table 3 gives an overview of the noticed lorries.

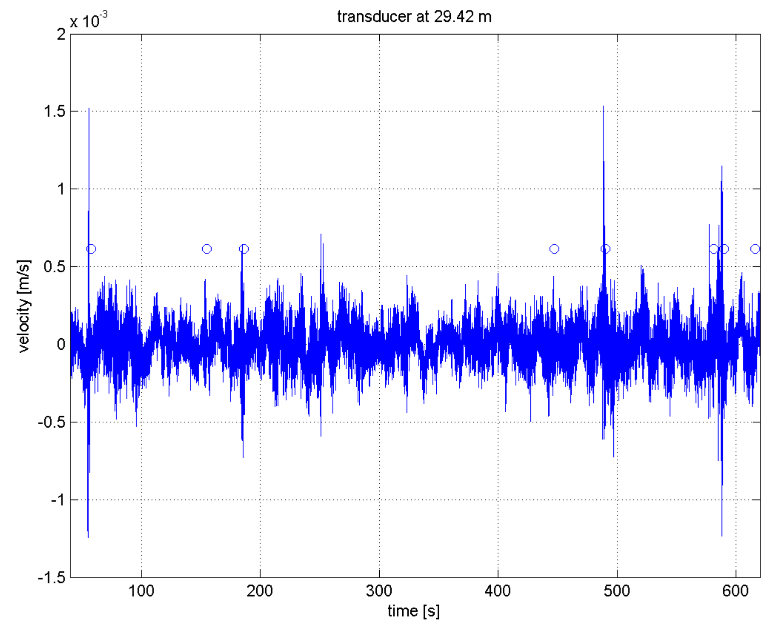
Figure 5 shows for measurement 8 the acceleration and velocity measured along the road with the written down passages of lorries, vans and cars. It is clear that the vibrations of the passing traffic is determining the extremes in these transducers.

This means that at least in the soil, the extremes are determined by the traffic and not by the wind turbine. To overcome this quandary, the measurements close to the road are inspected visually, and intervals without mayor vibrations are selected. The influence of cars is small and maybe not always clear.

Figure 6 and Figure 7 show the vibrations further away from the road. At the distance of the wind turbine these vibrations are just still visible. However, it

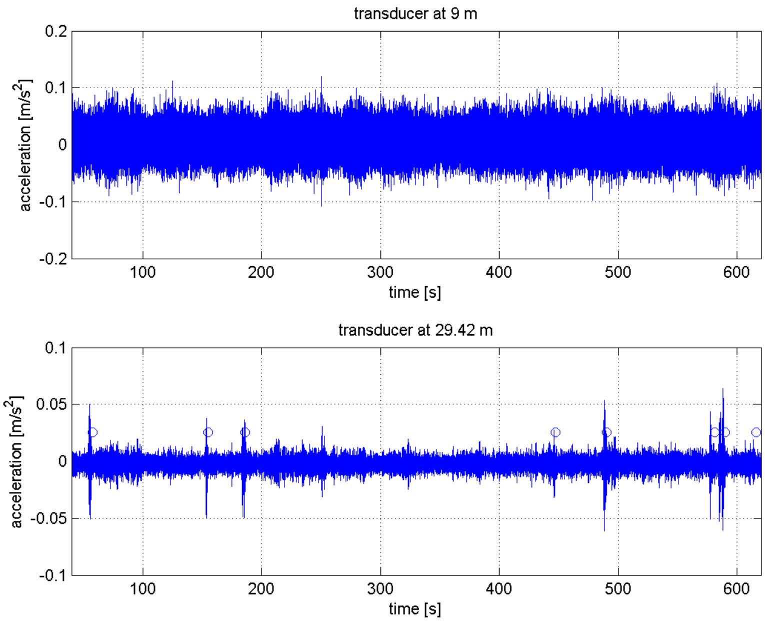


(a) Acceleration

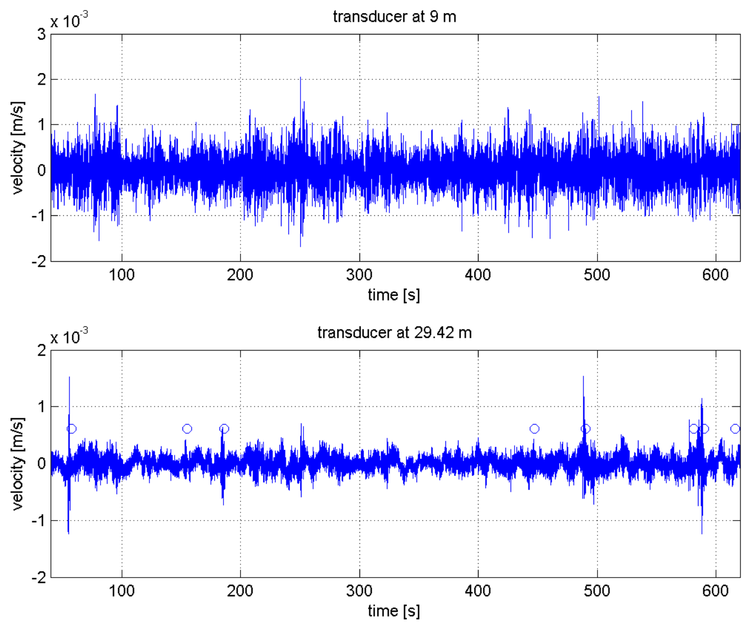


(b) Velocity

Figure 5 Results device close to the road with lorries passing. Top: acceleration, bottom: velocity

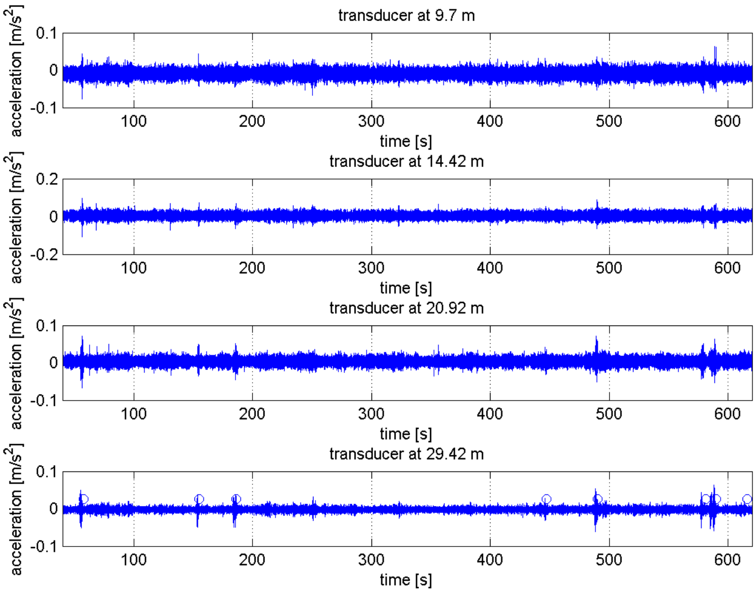


(a) Acceleration

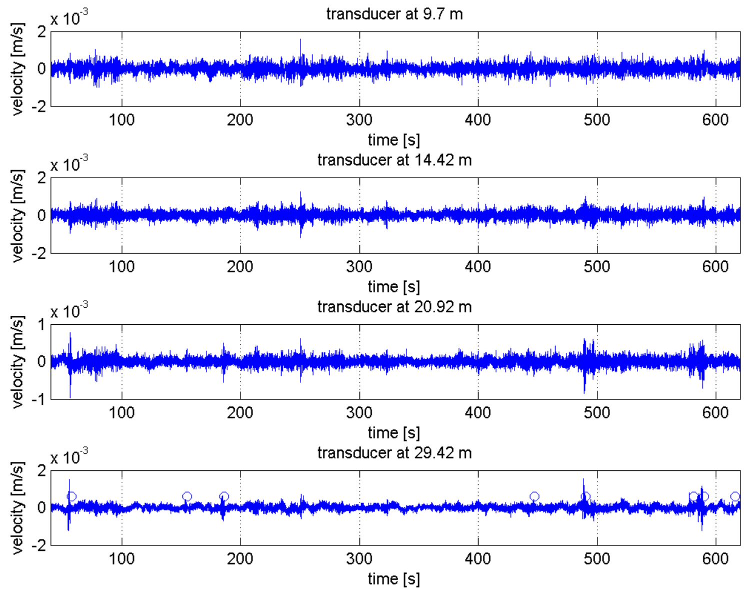


(b) Velocity

Figure 6 Results device TC5Z and V6Z with lorries passing (measurement 08). Top: acceleration, bottom: velocity



(a) Acceleration



(b) Velocity

Figure 7 Results device on ray x-axis with lorries passing (measurement 08). Top: acceleration, bottom: velocity seems better to limit the interval of the measurement to a interval without visible passages of lorries in transducer V6Z.

Figure 8 shows the results on the slab for measurement 08 on the slab. In the bottom figure the passages of the lorries are shown. These figures shows that on the slab the passages of the lorries are hardly visible. The variations in the measurement at the slab are thus essentially the variations in the wind and the response of the wind turbine itself.

3.5 Measurement in intervals without passing lorries

Table 4 shows the time limits used for next interpretations. Based on visual inspection of the accelerations in the transducer along the road, the longest interval without passing lorries is selected for each measurement. Maybe some vans and cars pass during these intervals. These generate minor vibrations.

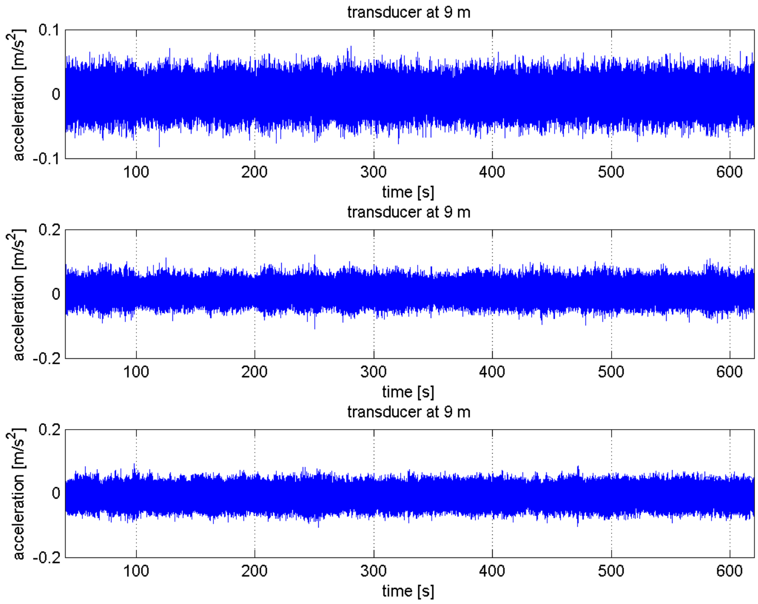
file	start	end	duration
1	240	520	280
2	120	420	300
3	250	520	270
4	220	620	400
5	180	570	390
6	200	330	130
7	300	620	320
8	260	440	180
9	40	620	580
10	40	620	580
11	40	360	320
12	40	340	300
13	40	570	530

Table 4 Limits of measurements without vibrations from Lorries [seconds]

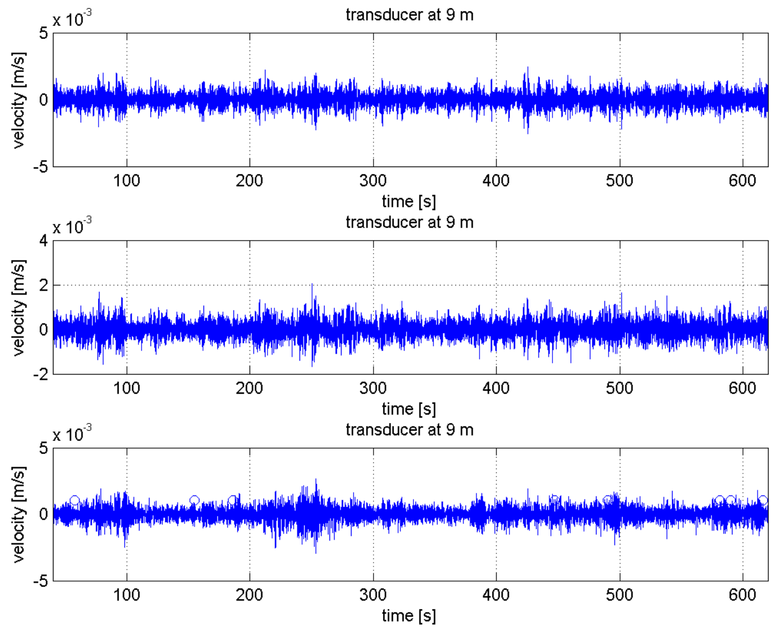
The results for these intervals are completely presented in a separate appendix B.

3.6 Overview of the results

In total 13 measurements of 11 minutes each are done. This coincides with the standard usage of 10 minutes intervals in practice. For each interval the maximum value is selected. Figure 9 shows the results. The horizontal axis shows the device number, that is one higher than the channel number in Table 2. These figures give also some idea on the variation in these peak values. For the displacement,



(a) Acceleration



(b) Velocity

Figure 8 Motions in TC3 on slab in three directions for measurement 08

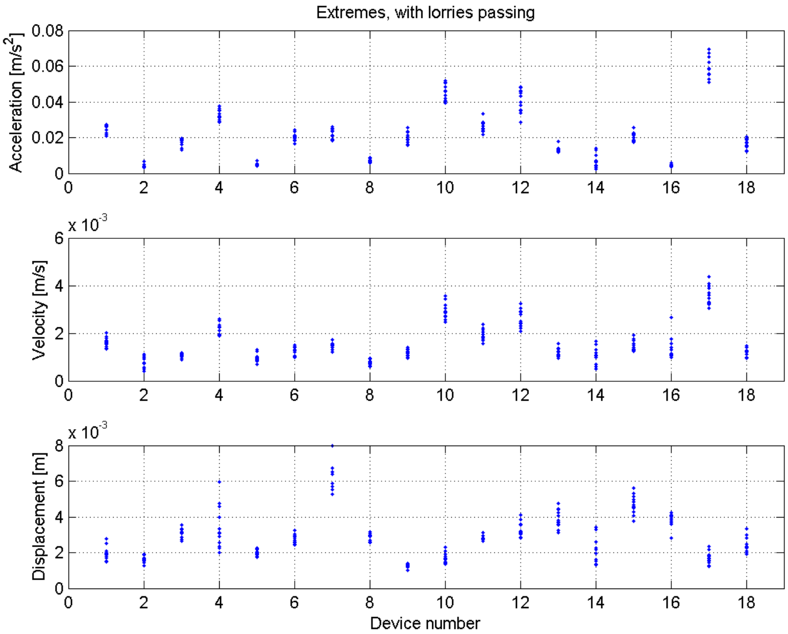


Figure 9 Maximum values in 10 min interval with lorry passages included
Top acceleration, middle velocity and bottom displacement

the data must be handled with care, since the integration method used might give some strange results.

Figure 10 shows the similar results as in Figure 9, but now limited to time intervals without clearly visible passages of lorries. Excluding the lorry passages leads to some minor changes in these plots, mainly in the locations close to the road and far from the wind turbine.

The channels 10, 11, 12, 15, 17 and 18 are located at the slab.

In the following sections the results are analyzed in more detail. The limited time intervals are used.

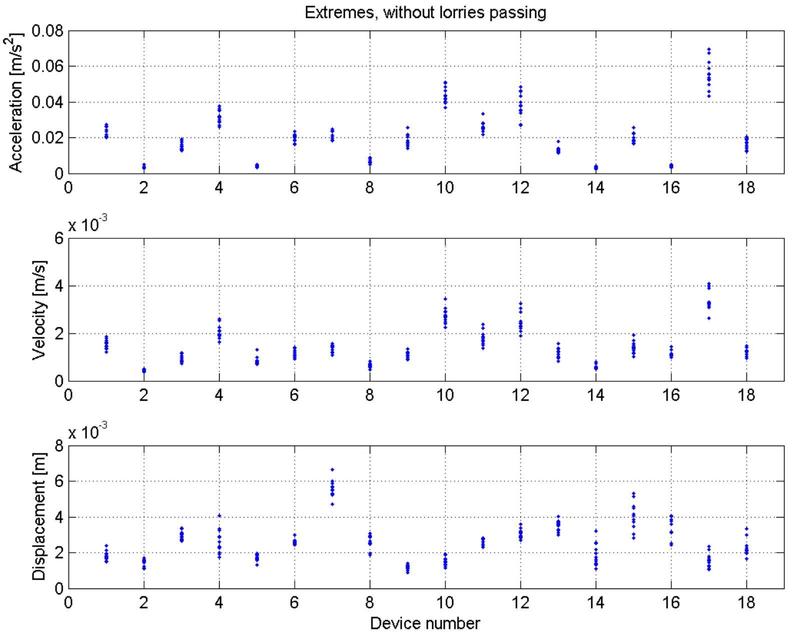


Figure 10 Maximum values in longest interval without lorry passages. Top acceleration, middle velocity and bottom displacement

4 Vibrations in the soil

In this section the measurements in the soil are further analyzed.

4.1 Vertical velocity along the x-axis

Measurement 9 is a proper measurement to analyze. The first lorry passed 643 s after start measurement. Visual inspection shows no extreme peaks in the transducer along the road.

Figure 11 shows the signals in the soil.

The top figure shows the time signals. The top row is the transducer on the slab. This shows that even without lorries passing the vibrations are irregular with periods of higher and lower peaks. The bottom row shows the vertical vibration along the road. No special vibrations that suggest lorry passage are observed. This signal suggests that one or two frequencies are dominating the response.

The bottom figure shows the results in the frequency domain. The response in the frequency domain show a very particular behavior.

- For low frequencies, say below 1 Hz, the soil has a clear response. The nearest transducer (at 9.7 m) is about 0.7 m from the transducer at the slab. Here the peaks at 0.3 Hz and 1 Hz are still visible. In the other transducers only

the static component is seen. In the farthest transducer the response seems to increase a bit. Maybe this is due to the fact that these low frequencies are transferred into the deep soil by the pile foundation and it takes some distance to propagate up to the surface.
- Between 1 and 2 Hz, no signal is observed at all.
- The peak at 2.5 Hz is strongly damped.
- The peaks at higher frequencies, 6 Hz and 8 Hz, are typical dynamic phenomena, these are propagating damped waves. Above 10 Hz minor vibrations are observed.

Figure 12 shows the same results, but now normalized on the vertical vibration measured at the slab. The first channel is therefore omitted. The strong peaks in the figure are due to the normalization. If the amplitude of the normalizing signal in one frequency is small, the value will be high. This is possible because there is no full causality in the signals: e.g. the vertical vibration in the slab is the summation of the rotation (ϕ_y) and vertical translation (u_z) of the slab. These two signals may cancel in the slab. However, they may propagate along different paths or different speed to the transducer. There the signals are not canceling. The quotient will be high.

The bottom figure shows the phase angle of the quotient. This is related with the propagation of waves. The top figure at 9.7 m is close to the transducer on the slab that is used for the normalizing. The phase angle is almost π or $-\pi = \pi - 2\pi$. This means that the signals are in anti-phase, while in-phase is expected and also visible in the time signals after strong magnification for 8 Hz signal, the frequency that dominates the velocity signal. At this frequency the there are many points in the phase plot for phase angle 0 rad.

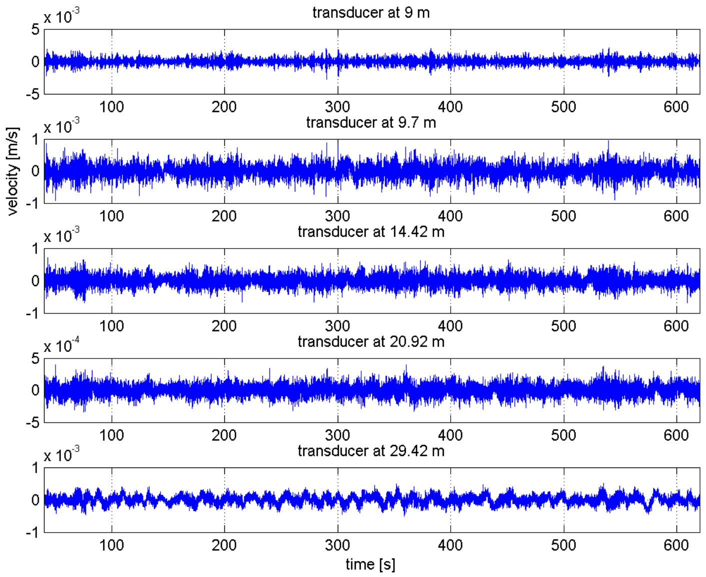
The transducers further away show more or less a band structure, which is typical for a propagating wave. From these bands the wave speed can be estimated, resulting is 40-50 m/s. This is a reasonable value for the soft top layer in Gouda.

For the low frequencies the phase angle is not clear, all values from $-\pi$ to $+\pi$ are observed. This is maybe due to the short distance between the transducers.

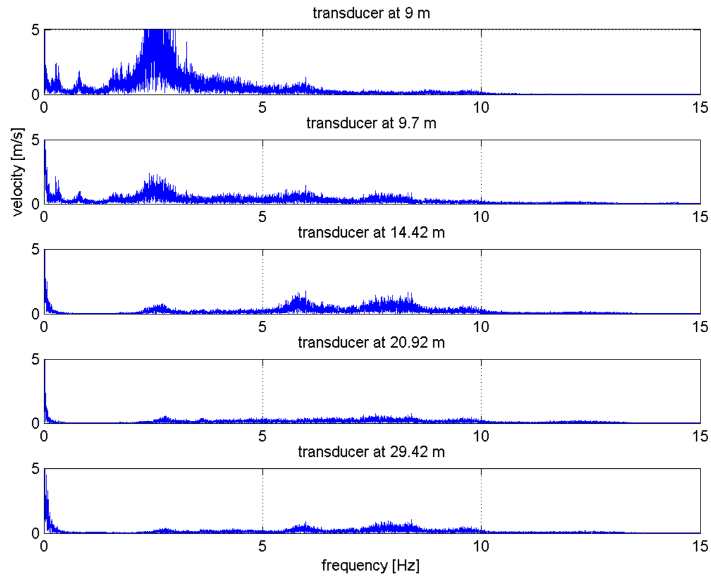
4.2 Horizontal motions in the soil

Three transducers in the soil measure horizontal accelerations. These are integrated to velocity and presented in this section. Again measurement 09 is considered. Figure 13 shows the results in the frequency domain.

The figures show a similar pattern as the vertical vibrations (shown in Figure 11b at page 19). However, the horizontal vibrations show less damping with distance for the frequencies under say 5 Hz.

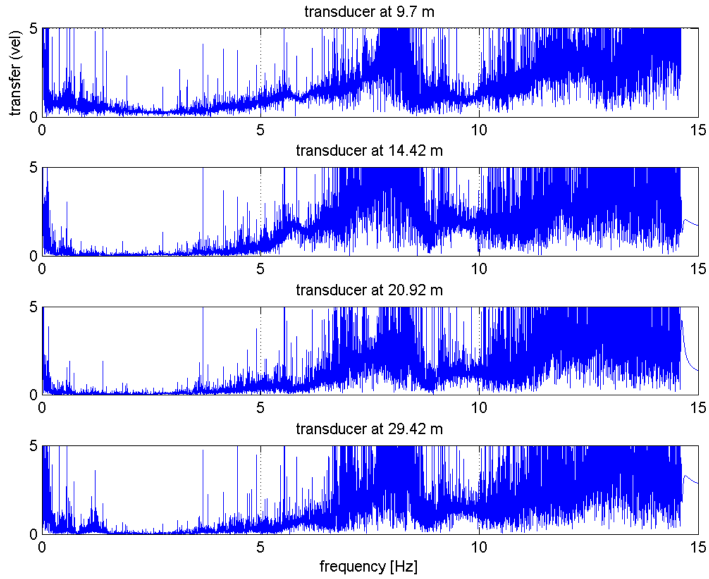


(a) Time domain solution

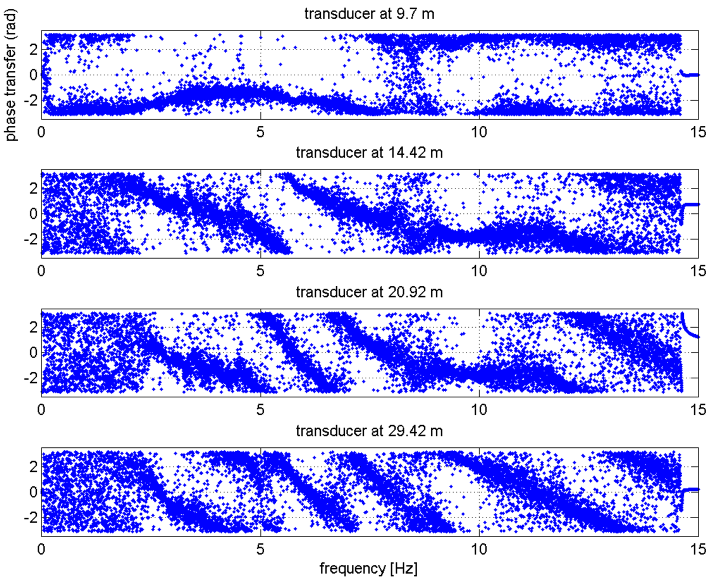


(b) Frequency domain transferfunction

Figure 11 Measurement 09, vertical vibrations measured on x-axis

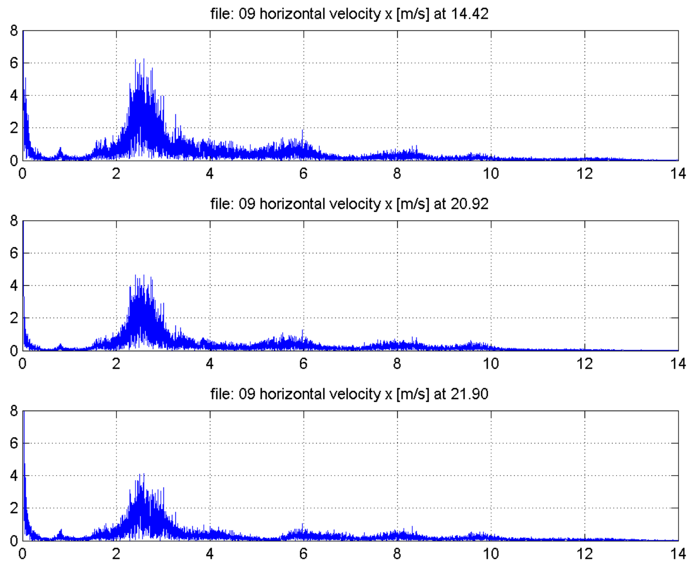


(a) Amplitude

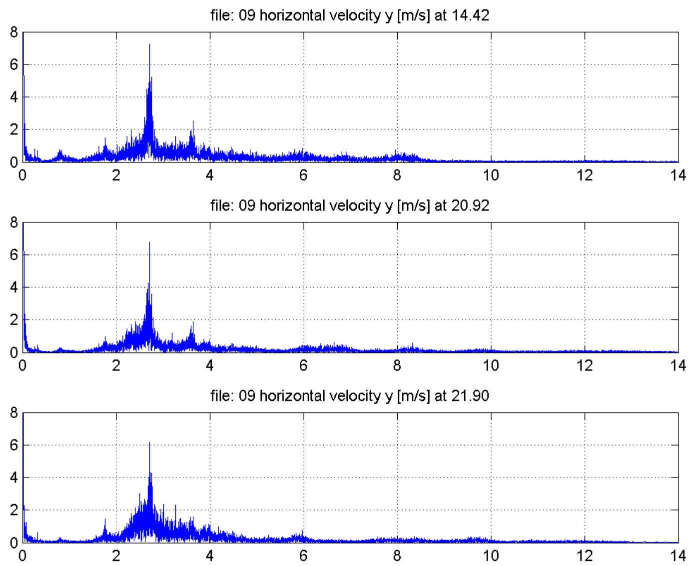


(b) Phase angle

Figure 12 Measurement 09, frequency domain transferfunction from slab to the vertical vibrations in the soil along x-axis



(a) horizontal in wind direction



(b) horizontal perpendicular on wind

Figure 13 Measurement 09, horizontal velocity in soil (frequency domain)

5 Slab motion further analyzed

The motion measured motion of the slab can be recalculated to the fundamental motions of the center of gravity. This section is made to show the possibility of this calculation using the measured signals. Due to the position of the transducers relative to the axes, this elaboration can be simplified. The calculations depends on differences between measured signals and measured positions. This might lead to a limited accuracy.

5.1 Rotation along horizontal axes

The vertical displacements of three points with coordinates (x_j, y_j) is measured. The measured signals are u_j. The motion of the slab is defined by its vertical motion u_o and rotation ϕ_x around the x-axis and the rotation ϕ_y around the y-axis.

The displacements of the three points can be calculated from (j is the point number)

$$u_j = u_o + \phi_x y_j + \phi_y x_j \tag{1}$$

From these three equations the displacements of the slab can be calculated from

$$\begin{bmatrix} 1 & y_1 & x_1 \\ 1 & y_2 & x_2 \\ 1 & y_3 & x_3 \end{bmatrix} \begin{pmatrix} u_o \\ \phi_x \\ \phi_y \end{pmatrix} = \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix} \tag{2}$$

Analytic inversion leads to

$$\phi_x = \frac{(x_3 - x_1)(u_2 - u_1) - (x_2 - x_1)(u_3 - u_1)}{(x_3 - x_1)(y_2 - y_1) - (x_2 - x_1)(y_3 - y_1)} \tag{3a}$$

$$\phi_y = \frac{(y_2 - y_1)(u_3 - u_1) - (y_3 - y_1)(u_2 - u_1)}{(y_2 - y_1)(x_3 - x_1) - (y_3 - y_1)(x_2 - x_1)} \tag{3b}$$

$$u_o = u_1 - y_1\phi_x - x_1\phi_y \tag{3c}$$

5.2 Rotation along the vertical axis

The two point with horizontal transducers are called B and C. Point B is TC3 with signal h_x^B (TC3X) and h_y^B (TC3Y) and coordinates $x^C = 9.0\ m$ and $y^B = 0$. Point C is the bloc with H10 and V11. H10 is here called h_x^C and has coordinates $x^C = -1.2\ m$ and $y^C = 8.6\ m$

The signals in the transducers are calculated from the motion of the slab ϕ_z, u_x and u_y

$$h_x^B = u_x \tag{4a}$$

$$h_y^B = x^B \phi_z + u_y \tag{4b}$$

$$h_x^C = y^C \phi_z + u_x \tag{4c}$$

Solving the block motions shows

$$u_x = h_x^B \tag{5a}$$

$$\phi_z = \frac{1}{y^C}(h_x^C - h_x^B) \tag{5b}$$

$$u_y = h_y^B - x^B * \phi_z = h_y^B - \frac{x^B}{y^C}(h_x^C - h_x^B) \tag{5c}$$

5.3 Resulting slab motions

Measurement 09 is elaborated. Figure 14 shows the results. Figure 15 shows the same results in the frequency domain.

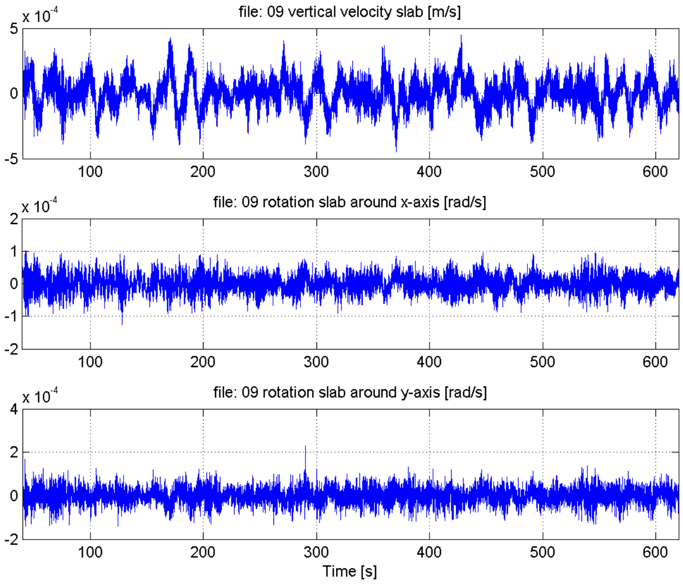
Figure 14 shows that the horizontal translations of the slab are 1 to 2 mm/s. The rotation velocities are 1 order smaller, but taking into account that the radius of the slab is order 10 m, the displacements at the location of the piles due to the rotation will be of similar order as the displacements.

Figure 15 shows that the differences in the frequency domain are larger. It is remarked that the scale for the horizontal displacements is a factor 4 higher than all other scales.

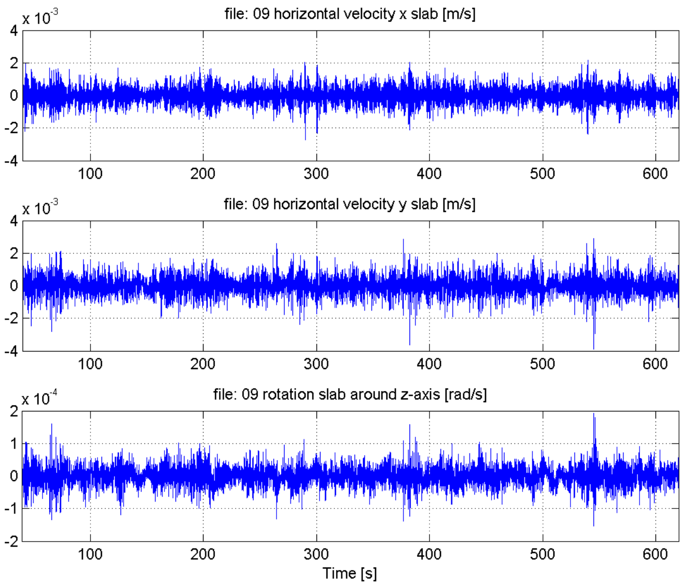
The 8 Hz frequency, that has already been observed in the soil is related to the vertical velocity of the slab. This might be due to the resonance of the system for axial loading of the tower. This degree of freedom is a independent mode, due to the symmetry of the structure (only the blades are asymmetric). This is a reasonably high frequency, since the axial stiffness of the tower is high, compared with the bending stiffness.

The horizontal motions are in the lower frequency range (0.1-6 Hz) dominant. These are coupled with the rotations around the x- and y-axis. The two fundamental modes are (1) rotation and (2) translation coupled with a rotation (the sway motion). For a thin slab, the coupling is weak.

The frequency content of the two horizontal motions are quite identical. Table 5 shows the position of the peaks (by cursoring in the Matlab figures). The lowest peak with frequency order 0.03 Hz and lower is not shown. Comparable frequencies are shown at one line. A risk for this elaboration is the fact that for higher frequencies more point are in a frequency band, leading maybe to some artificial

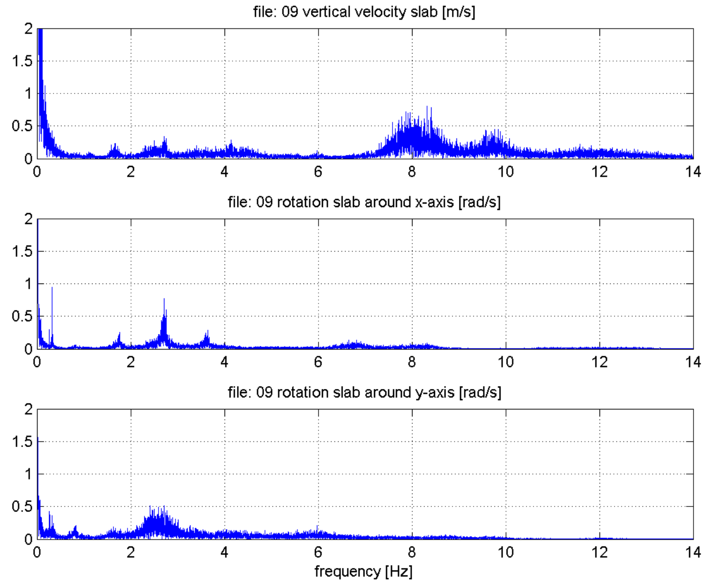


(a) from vertical motions

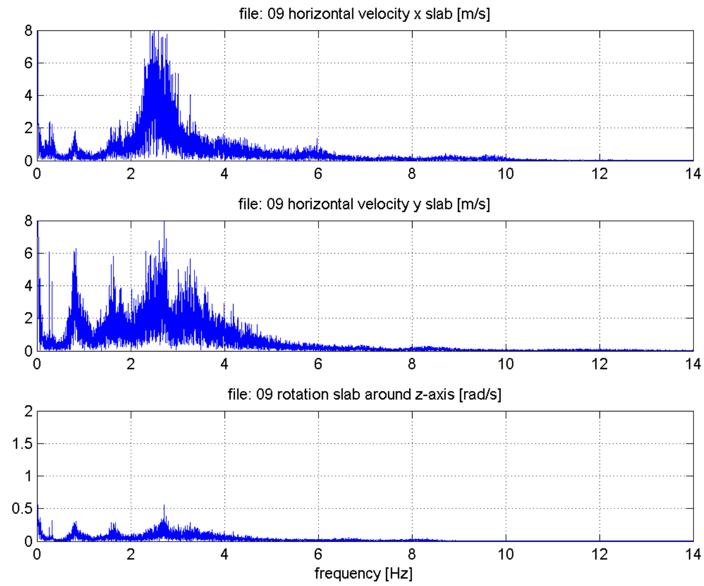


(b) from horizontal motions

Figure 14 Measurement 09, slab motion in time domain from the vertical vibrations



(a) from vertical motions



(b) from horizontal motions

Figure 15 Slab motion in frequency domain from the measured vibrations, measurement 09,

no.	f_x	f_y	remark
1	0.18	-	
2	0.28	0.27	rotor frequency
3	-	0.33	
4	0.80	0.80	three times rotor frequency
5	1.60	1.60	
6	1.76	1.80	
7	2.5	2.7	
8	3.3	3.3	

Table 5 Frequency [Hz] of peaks in translation in x- and y-direction for measurement 9

peaks. Checking other measurements the peaks 5 and 6 at 1.6 and 1.8 Hz might be one peak and peak 8 (at 3.3 Hz) might be not physical.

The final conclusion is that the lower frequencies (up to say 5 Hz) lead to important horizontal velocities. This is a bit unexpected for me, I installed mainly vertical acceleration transducers. I did not observed in the FAST calculations [Hölscher 2015].

5.4 Analysis of the discrepancy between calculated force and measured velocity

The unexpected importance of horizontal velocity at about 3 Hz can be explained by the difference between displacement and velocity. The first peak is seen at say 0.3 Hz, the second peak at say 3 Hz. This differs a factor 10, which might explain (part of) the difference. This section focus on this aspect.

Of course there might be other aspects: the frequency of the second peak, this might be in the range of frequency dependent stiffness; the distance between the piles is 18 m at a frequency of 3 Hz this relates to a wave speed of $3 * 18 = 54$ m. This is above the observed value. Or the stiffness of the foundation plays a role: if batter piles (slope 1:10) are used, the horizontal stiffness is 10 times lower then the vertical stiffness.

In order to evaluate the difference between displacement and velocity, I study the integration to displacement further for a limited frequency band. Measurement 9 is chosen, the horizontal slab motions are studied. These signals are shown in the two upper graphs in Figure 15b.

Figure 16 shows the results for the two frequency bands of interest. It is interesting to note that in both frequency bands the displacement and the velocity are more or less equal. The calculated forces in these two bands are quite different. This means at least that the response at the low frequency is determined by stiffness

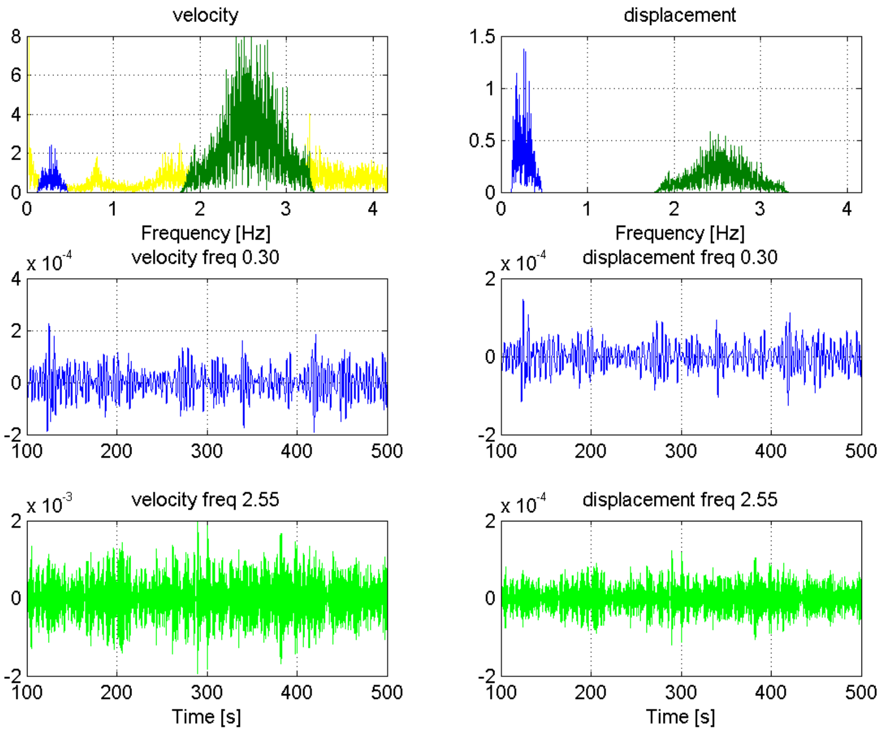


Figure 16 Measurement 9, horizontal motion of slab in x-direction, considered in limited frequency bands

and the response at the high frequency is determined by impedance, or the system behavior is strongly frequency dependent.

The low frequencies are close together. That might lead to a beat.

$$cos(\omega_1 t) + cos(\omega_2 t) = 2cos\left(\frac{\omega_1 + \omega_2}{2} t\right) cos\left(\frac{\omega_1 - \omega_2}{2} t\right) \tag{6}$$

with a beat frequency $f_{beat} = f_1 - f_2$. The two frequencies 0.28 and 0.33 Hz (see Table 5) lead to a beat frequency of about 0.05 Hz thus a period of about 20 s.

6 Conclusion and recommendations

The targets mentioned in Section 1 are reached:

- The equipment is useful for this type of measurements. The expected peaks in the low frequency range are clearly visible. Double integration with respect to time need some attention to get proper displacements.
- The vibration level at the slab has a displacement of order 1-2 mm and a velocity of order 1-2 mm/s.

- The vibration level in the soil has a displacement of order 1-2 mm and a velocity of order 1-2 mm/s.

The measurements showed some additional interesting results

- The horizontal vibrations are unexpected large.
- The vertical vibrations damp faster with distance then the horizontal vibrations.
- The motions parallel with the wind and perpendicular to the wind are quite comparable.
- The frequency band around 3 Hz is more important than the FAST calculations for a wind turbine suggested.
- The acceleration and velocity at the side of the smooth road generated by passing lorries are larger then the vibrations at 30 m from the wind turbine.

Based on this measurement it is recommended to

- Study the response of this type of foundation under horizontal load especially in the frequency range around 3 Hz.
- Improve the integration for displacement by using a higher (0.2 Hz) low cut filter and the influence on the behavior at the lowest two frequencies.
- Discussion on the need of a more extended measurement at e.g. the ECN test site in Wieringermeer

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