Wind Turbine Tower Resonance

Anders SJÖSTRÖM[1]; Colin NOVAK[2]; Helen ULE [3]; Delphine BARD[1]; Kent PERSSON[1]; Göran SANDBERG[1]

[1] Lund University, Sweden

[2] University of Windsor, Canada

[3] Akoustik Engineering Ltd, Canada

ABSTRACT

Wind turbine towers are large structures designed to withstand the unique loading conditions imposed on them by the turbine's nacelle and dynamic forces from the rotating blades. Observations and noise measurements of a particular wind turbine showed high noise levels at approximately 48 Hz, which could not be explained from the usual known potential noise sources. Correlated far field noise measurements and vibration measurements collected on the turbine tower, structural base and nearby ground have shown the source to be a resonance of the tower structure. Keywords: Wind turbine, Vibration, Sound I-INCE Classification of Subjects Number(s): 14.5.4, 21.2.1

1. INTRODUCTION

The interest for renewable energy have led to increasing increasingly large wind turbines. The acceptance for wind turbines from an acoustic perspective among the public is dependent on the manufacturers ability to produce turbines with low impact from noise and vibrations on the surrounding area (1, 2, 3). The noise from wind turbines is easily identified by humans and can be modulated due to varying meteorological conditions (4). Turbines with effects of 5MW are being installed and even larger turbines of 8MW and more are being projected. With increasing size of generators, longer blades and higher towers the dynamic effects on the coupled system that constitute the wind turbine becomes more complex (5). Although the largest wind turbines are projected for offshore installations large wind turbines with effects of 6.5MW are being installed onshore (6). With increasing height of the tower there is a need for better understanding of the behavior of the tower when subjected to dynamic loads, safeguarding against unwanted noise and vibrations.

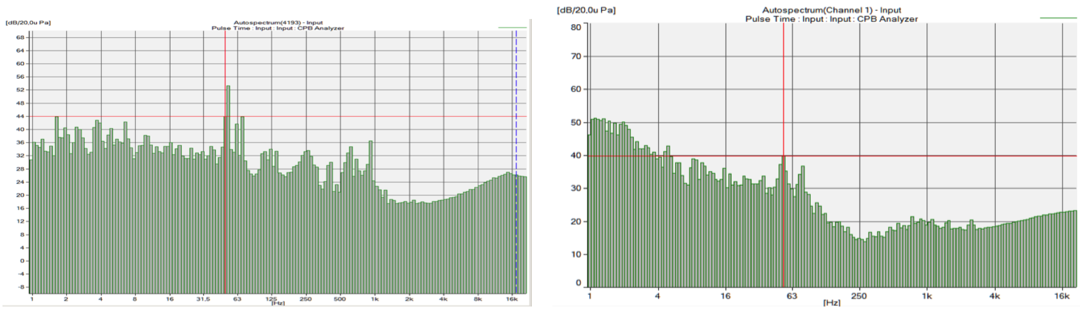
2. MOTIVATION

During a measurement campaign at a wind turbine in Skåne in south Sweden it was noticed that there was a persistent tone emanating from the wind turbine with a frequency of 48Hz. The tone was noticeable by humans as far away from the turbine as 400m. The tone also shifted in frequency during the measurements between 45Hz and 85Hz. In figure 1, showing the constant percentage bandwidth (CPB) in 1/24-octave bands, a peak at 48Hz is visible. The measurements have been performed at the distances 100m and 400m. The closest measurement were performed using a ground windscreen as specified in IEC-61400-11ed3, the furthest measurement was done using a simple foam ball (UA0237) wind screen resulting in higher noise in the lower frequency bands. The difference in sound pressure level (SPL) between the two measurements were 12dB. An additional measurement performed at 200m showed the SPL difference between the measurements at 100m and 200m to be 6dB, indicating that the source of the tone is indeed a point source. To investigate the source of the tone a more detailed investigation was performed during the first half of 2014 using both measurements and finite element modeling of the tower and ground. In this paper we describe the findings from that investigation.

3. MEASUREMENT SETUP

The measurement setup is outlined in figure 2. four accelerometers (Acc1-4) are used, Acc1 is on the tower at approximately 5m height, Acc2 is on the foundation, Acc3 is on the ground 3m from the foundation and Acc4 is on the ground 100m from the foundation. Acc3 is three-axial, all other accelerometers are single-axis. The accelerometers used are of types 4507, 4524 and 8344 from Brüel & Kjær. The microphones are placed

[1] anders.sjostrom@construction.lth.se



(a) 100m. (b) 400m.

Figure 1 – Measured Sound Pressure Level at wind turbine

80m downwind from the tower. The microphones are all 1/2inch prepolarized infrasound microphones of type 4964 with low-frequency Adaptor UC-0211. All signals were measured simultaneously, unfortunately the rpm of the wind turbine and the windspeed could not be recorded during the measurement but only at the end of the measurement.

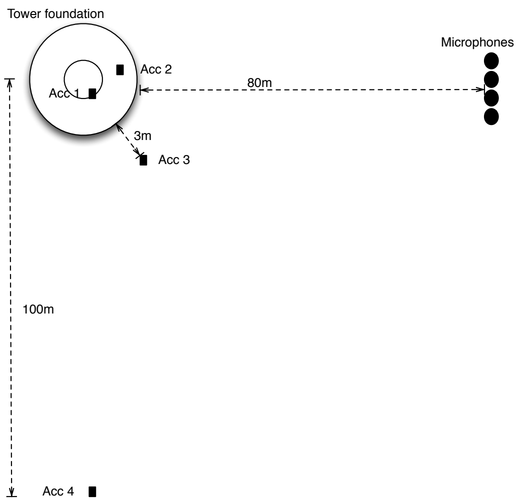


Figure 2 – Measurement set up.

4. RESULTS

The results are presented in three separate sections focusing on the vibrations, the SPL and the finite element simulations respectively.

4.1 Vibration measurements

In figure 3 the autospectrum from 40Hz to 160Hz of the measured signal from Acc1 can be seen. The red lines indicate the 45Hz and its harmonics and the black lines show the harmonics of the 50Hz. As seen in the figure the 48Hz peak is present in the signal, there is also a prominent peak at 80Hz.

In figures 4, 5, 6 and 7 the autospectrum of the measured signals from 0Hz to 200Hz is shown together with a more detailed plot of the frequency range from 70Hz to 110Hz. It is clear from figures 4, 5 and 6 that a large number of modes are excited in the structure from 80Hz to 100Hz. Especially there are large peaks at 80 and 85Hz. Looking in the lower end of the spectra, figure 6 show that the ground close to the foundation of the tower have a large response in the frequency range 40-50Hz which the foundation itself does not have. Comparing the near-field with the far-field vibrations it is clear that vibrations above 20Hz get dampened out quickly. However, the peak at 15Hz is very prominent at 100m from the tower. Notice that there is a large response at 15Hz in the ground close to the foundation and at 100m from the turbine. In table 1 the accelerations at the measurement points can be seen for the frequency 15.4Hz. The distinct peaks at 50, 100 and 150Hz in figures 4,5,6, 7 and 8 is the electrical main and its harmonics.

Figure 8 shows waterfall plots of the fft for the four accelerometers. As can be seen in the signat from the tower the mode at 80Hz only appears from 40s whereas the 90Hz signal is constantly present. Also notice that

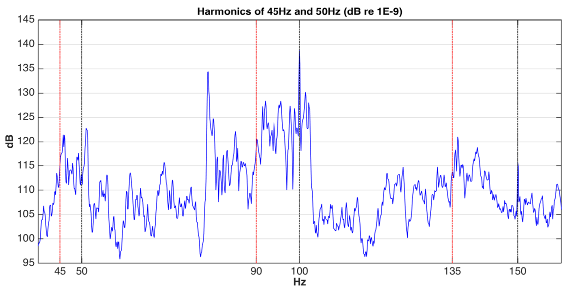
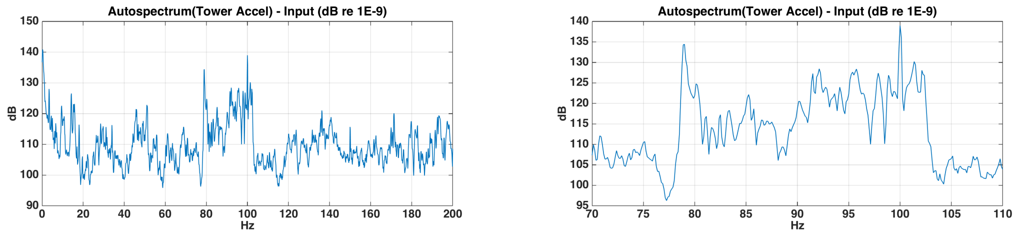


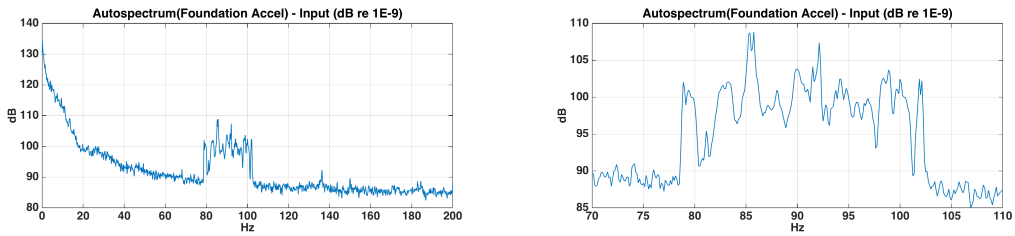
Figure 3 – Harmonics of 45Hz vibrations on the tower (red). Harmonics of electric mains at 50Hz are indicated (black)

the foundation and the ground close to the turbine both show this behavior. The peak at 85Hz can be seen in both the foundation and the ground near the tower, as in the case of the 80Hz signal, it is not present until after 60s.



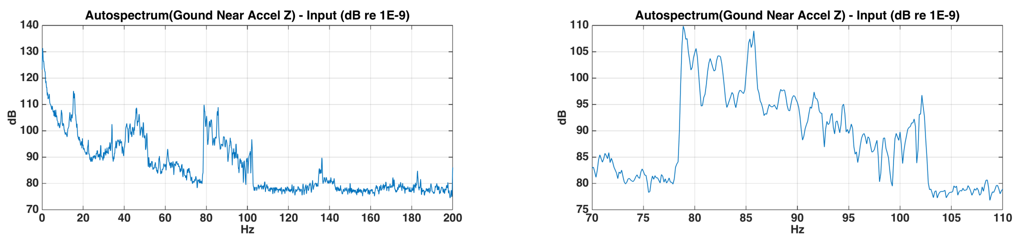
(a) Full spectra (b) Zoom 70-110Hz.

Figure 4 – Autospectrum of vibrations on wind turbine tower.



(a) Full spectra (b) Zoom 70-110Hz.

Figure 5 – Autospectrum of vibrations on wind turbine foundation.

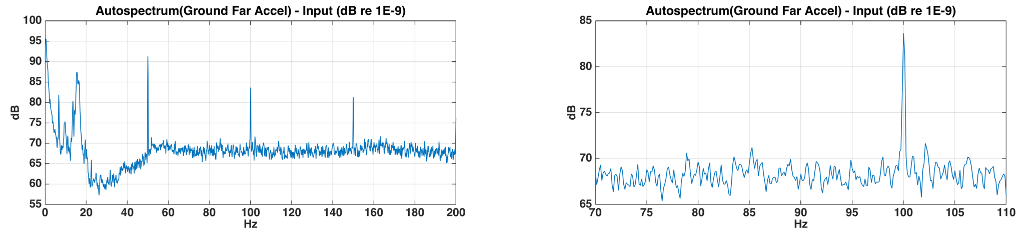


(a) Full spectra (b) Zoom 70-110Hz.

Figure 6 – Autospectrum of vibrations on ground 3m from wind turbine tower.

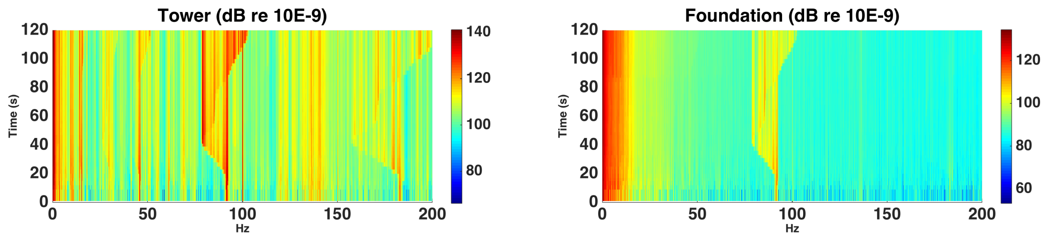
4.2 Sound pressure level measurements

The measurement setup for the measurement of the SPL can be seen in figure 2 and 9. During the measurement four different types of windscreens were used. Only data from two of the windscreens are

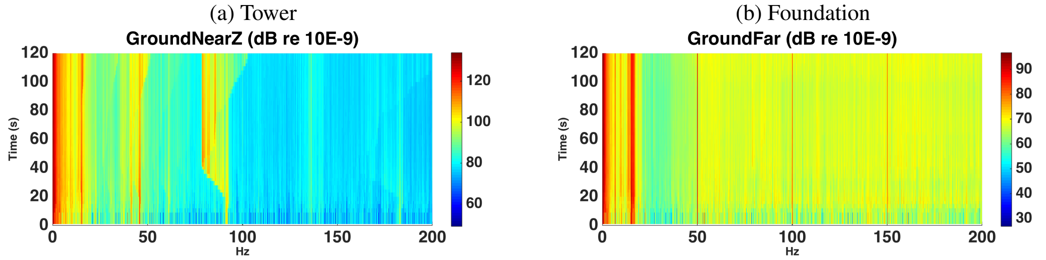


(a) Full spectra (b) Zoom 70-110Hz.

Figure 7 – Autospectrum of vibrations on ground 100m from wind turbine tower. Note the 50Hz and its harmonics.



(a) Tower (b) Foundation



(c) Ground near field (d) Ground far field

Figure 8 – Waterfall plot of FFT over time for vibrations.

presented here. For a more detailed investigation of the effect of different windscreens on the low-frequency and infrasonic SPL see (7). The microphone equipped with the UA0237 windscreen is placed at 1200mm height and the ground screen is placed at ground level. This height difference and the fact that the small windscreen is not constructed for low-frequency and infrasonic measurements results in the small windscreen being more affected by the wind noise especially in the low frequency and infrasonic part.

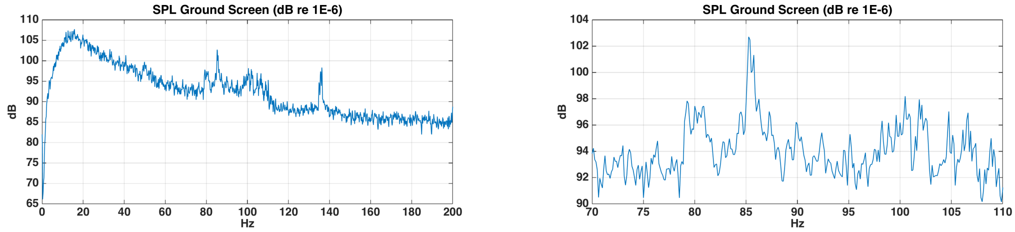
Figure 9 – Sound screens.

The SPL for the ground screen and the small screen can be seen in figures 10 and 11. There are large peaks at 85 and 136Hz in both measurements and for the ground screen there is also a peak at 79Hz. In the

Table 1 – Acceleration levels at low frequencies (dB re 1E-9).

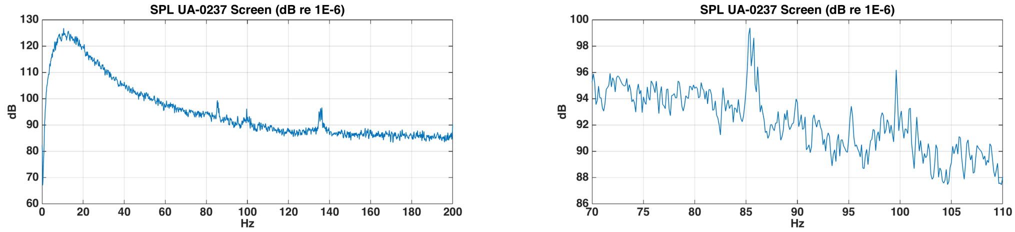
frequency (Hz)	Acc1	Acc2	Acc3	Acc4
15.4	123	106	105	87

low-frequency and infrasonic frequencies no prominent peaks are visible.



(a) Full spectra (b) Zoom 70-110Hz.

Figure 10 – Sound pressure level from wind turbine tower, ground screen.



(a) Full spectra (b) Zoom 70-110Hz.

Figure 11 – Sound pressure level from wind turbine tower, small screen.

5. CORRELATION BETWEEN VIBRATION AND SPL AIRBORNE MEASUREMENTS

Comparing the waterfall plots of the acceleration measurements in figure 8a and the acoustic measurements figures 13 and 12. The same pattern with an onset of a tone at 40s with a frequency of 79Hz and at 60s with a frequency of 85Hz. In figure 13 the increase in windspeed can be seen at 10Hz as an increasing intensity over time corresponding to the onset of the vibrations on the tower as seen in figure 8a at times 40, 60 and 100s with frequencies of 80, 85 and a range from 90 to 102Hz.

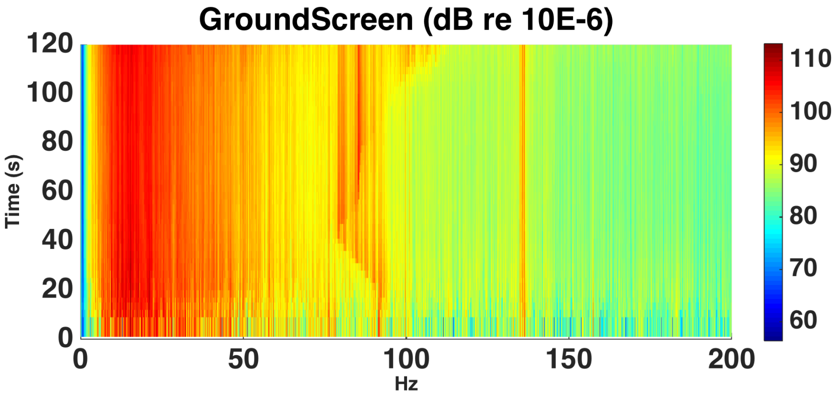


Figure 12 – Waterfall plot of FFT over time for the SPL measured with Ground Screen

6. SIMULATIONS OF THE WIND TURBINE AND GROUND

The tower and part of the ground has been modelled using the finite element model (FEM) The mesh of the model can be seen in figure 14. The model constitutes of the tower, the foundation and the soil. The excitation in the model is made at the top of the tower with 1N in x, y and z direction. The frequency response function (FRF) of the model can be seen in figure 15, note the clustering of eigenmodes around 80Hz. In the FRF only the bending modes are considered as the number of modes would be unmanageable otherwise. The mode shapes of the model corresponding to the FRF are shown in figure 16. The mode at 78Hz is the ground moving, forcing the tower to act as a rigid-body. there is also a strong coupling to the ground at 86Hz causing the ground to exhibit strong movements. As in the measurements, there is a clustering of modes between 75 and 90Hz. The modes in this region are very sensitive to changes in the stiffness in the soil and the foundation.

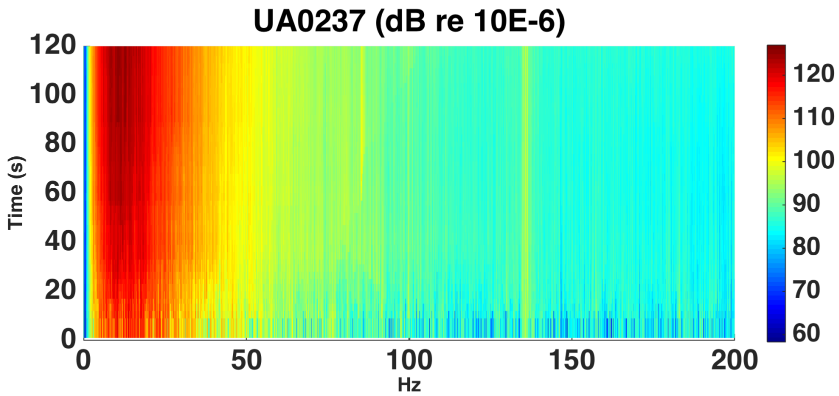


Figure 13 – Waterfall plot of FFT over time for the SPL measured with UA0237

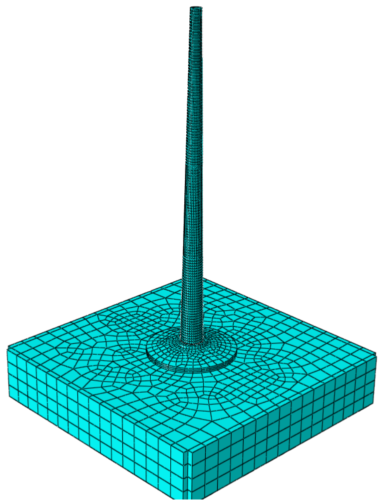


Figure 14 – Finite Element Model of the wind turbine and ground

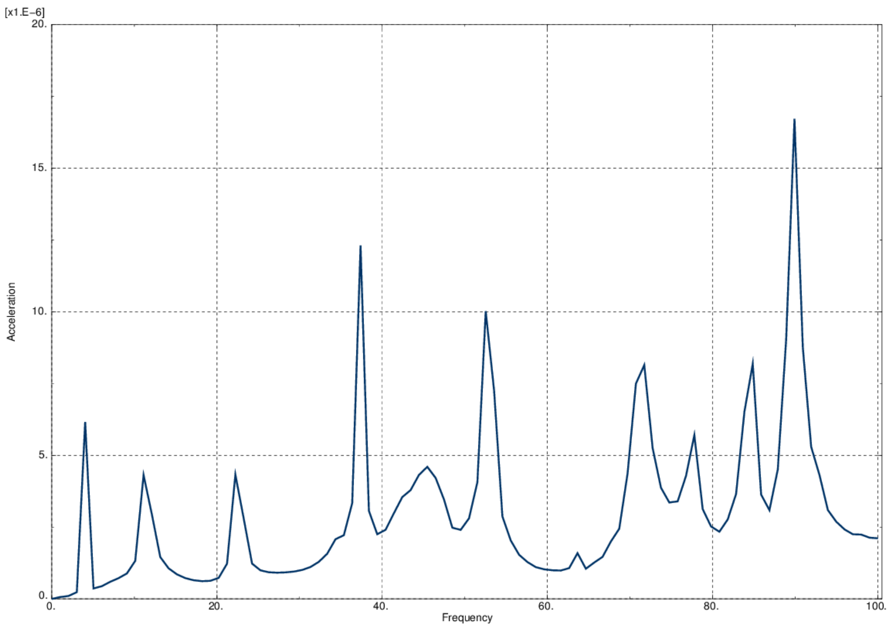
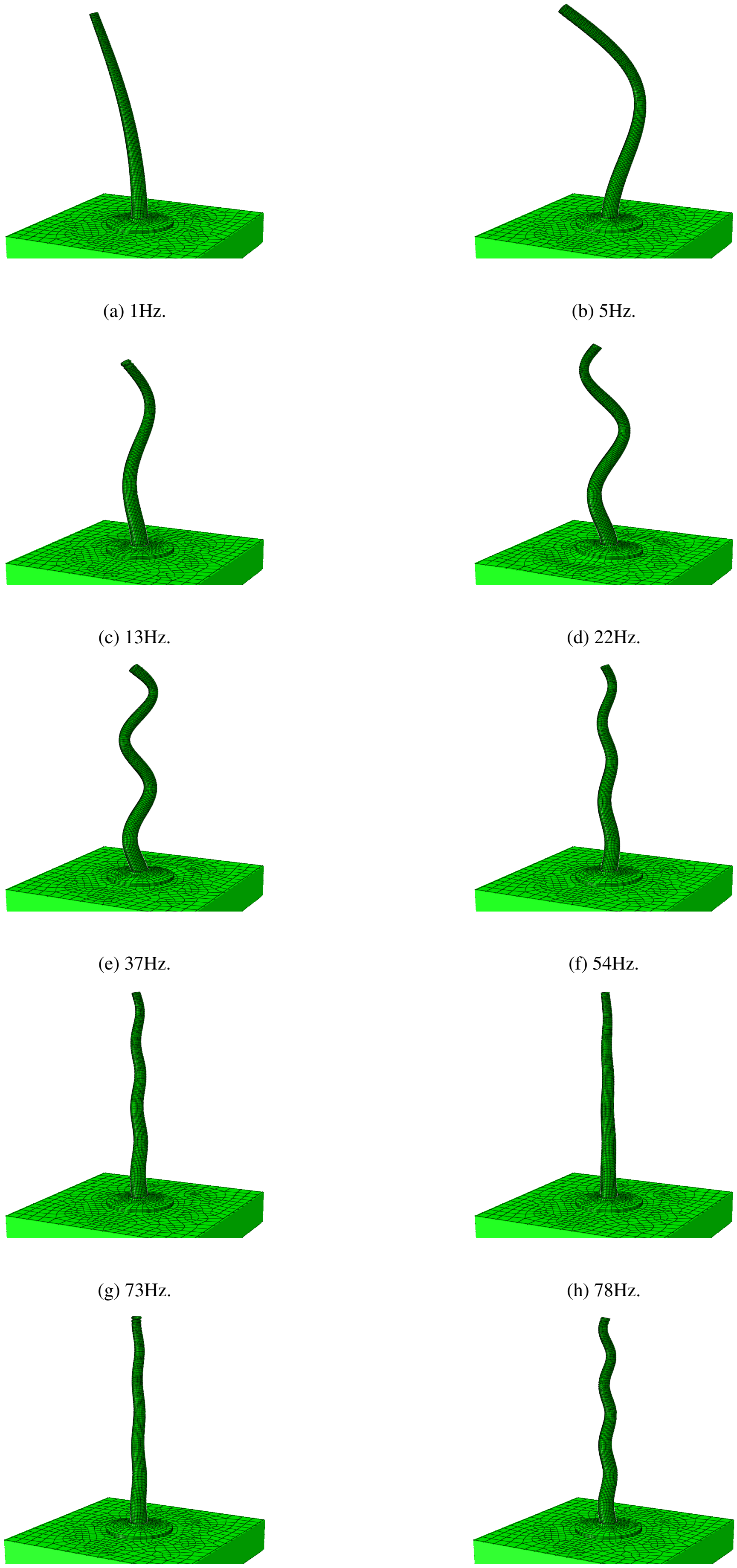


Figure 15 – FRF of the tower model, normalized acceleration.



(a) 1Hz. (b) 5Hz.

(c) 13Hz. (d) 22Hz.

(e) 37Hz. (f) 54Hz.

(g) 73Hz. (h) 78Hz.

(i) 86Hz. (j) 90Hz.

Figure 16 – Modeshapes for FE-model of wind turbine tower.

7. DISCUSSION

The motivation for this work was to investigate the source of the tone at 48Hz measured during the previous measurement campaign. Although the 48Hz tone could not be detected in airborne sound, it was shown to be present as a vibration in the structure. It was shown that the vibrations in the tower were dependent of the wind speed and could be detected in the airborne sound. The low-frequency vibrations did not give rise to measurable low frequency sounds, but were shown to propagate well in the ground. FEM simulations of the structure showed that the interaction between the soil, the foundation and the tower give rise to a clustering of frequencies between 70 to 90Hz which was also seen in the measurements as a clustering between 80 to 100Hz. The interaction between the soil, the foundation and the tower needs to be investigated further. The propagation of the low-frequency vibrations in the ground is also an area of future research.

8. ACKNOWLEDGEMENT

The authors wishes to acknowledge Brüel & Kjær for assistance with measurements. Kraftringen for providing access to the wind turbine and Mats Ingvarsson for providing access to the fields surrounding the turbine.

REFERENCES

1. Pedersen E. Human response to wind turbine noise-perception, annoyance and moderating factors. Inst of Medicine. Dept of Public Health and Community Medicine. Göteborg; 2007.

2. Bakker RH, Pedersen E, van den Berg GP, Stewart RE, Lok W, Bouma J. Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. Science of the Total Environment, The. 2012 May;425(C):42–51.

3. Baath LB. Noise spectra from wind turbines . Renewable Energy. 2013 Jan;57(C):512–519.

4. Larsson C, Öhlund O. Amplitude modulation of sound from wind turbines under various meteorological conditions. Journal of the Acoustical Society of America. 2014 Jan;135(1):67–73.

5. Pao LY, Johnson KE. A tutorial on the dynamics and control of wind turbines and wind farms. Proceedings of the American Control Conference. 2009 Jun;p. 2076–2089.

6. Leung DYC, Yang Y. Renewable and Sustainable Energy Reviews. Renewable & Sustainable Energy Reviews. 2012 Jan;16(1):1031–1039.

7. Novak C, Ule H, Sjöström A. An investigation of Different Secondary Noise Wind Screen Designs for Wind Turbine Noise Applications. In: Proc. 43rd International Congress on Noise Control Engineering (INTERNOISE 2014); 2014. .