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MASTER THESIS

Wind turbines - a study on the correlation between rotor size and noise characteristics

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Abstract

Wind power is a massively increasing energy source in the European Union, due to the 2020 goals that 20% of EU:s energy flow has to originate from renewable sources. Big wind turbines produce low frequency noise, which is a growing problem as the rapid technical development leads to larger and larger turbine. This master thesis aims to examine the frequency distribution of the noise emitted from wind turbines of different sizes with the ultimate goal to establish trends. Using sound recordings from Vestas V27, V42 and V90 turbines, the noise is divided into octave bands using MATLAB to study the amount of low frequency noise.

Due to a lack of accessibility to turbine sites, some site observed in the study suffer from a large amount of nearby noise pollution. However, a change in sound level in the region of the 63 to 250 Hz one-third octave bands is shown when comparing the V90 turbine data to the smaller sizes, correlating well with previous research in the field, but more research and measurements are needed to explain the occurrence on a more detailed level.

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1 Introduction

This is a master thesis in energy technology, written for Halmstad University's programme "Master in Renewable Energy Systems". Its content is approximated to cover 15 university credits and serves as a final examination of the students knowledge of the subject. Some of the references used in this report are written in Swedish.

1.1 Background

It is well established that wind turbines produce noise, but there is still a lot of information that has yet to be revealed in the field. Wind power is a massively increasing energy source in the European Union, due to the 2020 goal that 20% of EU:s energy flow has to originate from renewable sources [1]. In addition to this goal, the government of Sweden decided that 49% of Sweden's energy flow is to be from renewable energy and that 30 TWh of the power has to be produced from wind power [2]. In 2014 the wind power in Sweden produced 11.5 TWh (up from 9.8 TWh in 2013), which is roughly 8% of the Swedish total electrical energy flow that year [3], and is steadily increasing to meet the nation goal, averaging a growth of 15-20% in the last 10 years.

At a first glance, wind power is a pollution free way of generating electricity, there are no toxic emissions and there is no need for a fuel to power the generation. However the fact that noise is generated is something that has been met with great resistance in Sweden [4]. This has been a big problem for companies wanting to expand their activities in the wind power market and there is an apparent lack of knowledge about wind turbines and the effect that noise has. In order to be able to place the right wind turbine at the right place, further investigation and research has to be done to map how noise from wind turbines actually behave.

1.2 Purpose and Aim

This paper means to examine the frequency variations between different sizes of horizontal axis wind turbines, with sizes ranging from 225 kW to 2 MW. The purpose of this is to deduct how the frequency characteristics of the noise change with the scaling size and ultimately aims to find trends.

1.3 Question of interest

Does the frequency distribution of noise emitted from wind turbines become skewed towards the lower end of the scale when increasing the rotor size?

1.4 Boundaries

All wind turbines examined are designed and produced by Vestas, a limitation to narrow the possible uncertainties that can surface in the analysis. All turbines use an asynchronous generator with a gear box and Vestas own wing profile. The human annoyance factor will not be focused in this report and

weighting of this will not influence the analysis. To understand the content of this master thesis it is helpful to have some prior knowledge about sound and wave theory, but the underlying concepts behind the analysis will be explained.

1.5 Hypothesis

The sound frequency spectrum should tend to be more representative in lower frequencies as the size of the turbine increases. This hypothesis is based on the theory presented by Danish researchers [5] and the idea that larger turbines with wings of a larger mass would cause a larger displacement in the air, and thusly increase the change in pressure.

2 Theory

To be able to analyze the results of this study some basic knowledge about sound physics had to be acquired and explained. Following in this segment of the report is the theory that makes the foundation of the analysis. Some of this information can also be found in the previous bachelor thesis, but the basics are needed to understand new theory added in this master thesis.

2.1 General wave physics

Sound waves are pressure changes in a fluid, such as air or water. The change in pressure makes the human eardrum fluctuate and this is what we humans know as sound. These waves are all made up out of a wavelength (λ) and an amplitude (A_0) as shown below in Figure 1. These parameters in turn are determined by what fluid the wave is travelling in and how fast the pressure changes fluctuate. The amplitude tells us how much energy that is transferred in the wave and how far the fluid is displaced by the wave from its original position [6].

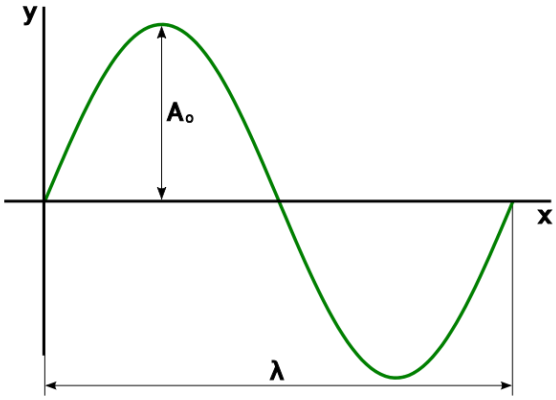

Figure 1 - The anatomy of a wave

The wavelength is determined by the formula $\lambda = \frac{c}{f}$, where f is the frequency [Hz] and c is the speed of sound [m/s] in the fluid which for air is 340 m/s [7]. This is the key to establishing frequencies, which in turn is what determines how the sound is perceived by humans. Large wavelengths thusly give low frequencies, which humans perceive as heavy, bass-like sounds.

The human ear can hear frequencies of about 20 - 20 000Hz, and wind turbines generally produce noise in the spectrum of 30 - 4000Hz depending on size. Sound below 20Hz is known as infra sound and can potentially be harmful to people [8]. However to produce infra sound it takes huge amounts of energy and is thusly not an issue for small turbines, but it might become a problem with the increasing size of modern turbines.

2.1.1 The unit Decibel

Sound is not measured in Pa, Pascal, even though it essentially is changes in pressure in a fluid. Instead the unit dB, Decibel, is used. Decibel is a logarithmic unit and is based on the human perception of sound. 0 dB means that no sound is emitted [9]. The unit is used for other things as well, like current, voltage and signal strength, but the common nominator in this is that a reference point is needed. Decibel can be described with the following formula, F1.

$$dB = 10Log\left({I}/{I_0}\right)$$

Sound intensity [F1]

In F1, I is the sound intensity, also sometimes called sound level and is given in the unit W/m^2. I_0 is the reference intensity in the fluid at hand and in air this value is 1 pW/m^2. Using this formula, F1, it can be shown that if we double the intensity, I, there is a change of 3 dB. However, when talking about sound it is important to separate sound level and sound pressure level. Where F1 describes the amount of sound emitted from a certain source I, F2 determines how the sound shows itself in readings. sound pressure level, or SPL for short is a mathematical representation of apparent sound, calculated in the unit Pa instead of W/m^2. The reference point in this instance is 20 μPa, and p describes the new, changed pressure level.

$$dB\ SPL = 20Log\left({p}/{p_0}\right)$$

Sound Pressure Level, SPL [F2]

However, it is important to note that outside of a laboratory, a change of 3dB is barely noticeable. Apparent sound is not the same as perceived sound, hence some guidelines have been determined to better describe perceived sound from a certain source [8].

- Changes smaller than 1 dB cannot be perceived
- A dB-change of 5 dB correlates with what most people recognize as a change in sound level
- A change of 6dB is equivalent with cutting the distance to the source in half, or the perceived measure of adding an identical source
- 10 dB is what most people would say is double the sound level.

Since the perception of sound differs depending on the frequency range, due to the logarithmic scale of the dB unit, a series of weightings are used. The most common weighting encountered in the field is dBA, which is an attempt to emulate human sound perception. Other common weightings are dBC and dBG, which are used for low frequency and infra sounds, thusly better representative for the lower regions of the frequency spectrum. A more uncommon, but still sometimes encountered weighting is the dBZ, which is a flat weighting over all frequencies [10].

All the data in the analysis will be given and referred to in Hz and dB/dBA/dBG.

2.1.2 Wave interaction

A perceived sound consists of multitudes of frequencies with different levels of intensity which are summarized with the following formula.

$$dB_{\Sigma} = 10 \cdot Log\left(\sum_{i=1}^{n} 10^{L_i/10}\right)$$

Sound summation law [F3]

This means that when frequencies of sounds are added together the sound pressure level is increased, to make a louder, complex sound. This is also true for adding several complex sounds with each other.

When several waves travel in the same space, they will interact and join together in a new sound, causing some frequencies to cancel each other out and some to empower through super positioning and amplitude modulation [11]. For example; When two waves of the same phase and frequency meet, they will add together and create a wave with the same length, but 3 dB stronger than each of the initial waves, as seen in illustration 1 below.

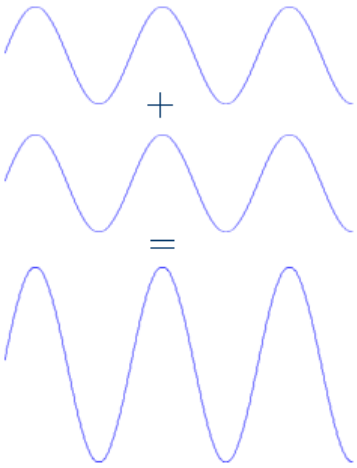

Figure 2 - Wave super positioning

Waves of the same length, but in 180º phase shift from each other will instead of add together, cancel each other out, causing the sound pressure level to return to the normal state of the space. This phenomenon is illustrated in illustration 2 below.

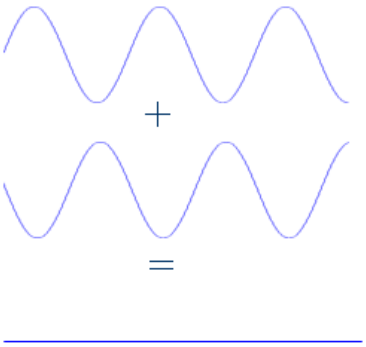

Figure 3 - Wave cancellation

This can be explained with the following formula, for all frequencies [11] where ϕ is the phase angle.

$$y\left(x,t\right) = y\,m\,sin\,(kx - \omega t\,) + y\,m\,sin(kx - \omega t + \phi\,) = 2\,y\,m\,cos\left(\frac{\phi}{2}\right) sin\,(\,kx\, -\, \omega t\, + \frac{\phi}{2})$$

Principle for superposition [F4]

However, when a much stronger wave encounters a lesser one, the stronger wave will simply consume the lesser and continue forward, called “Noise masking”. This is a common occurrence in nature, and when measuring noise from wind turbines near roads. Imagine having a conversation with a person vacuuming, having to raise your voice to be heard over the noise of the vacuum. This is based on frequency as well as intensity [12].

Amplitude modulation is a phenomenon that occurs when an existing wave is modulated by a new, incoming wave, causing the new combined wave to sound "thumpy" or periodically swishing. illustrated below in Illustration 3.

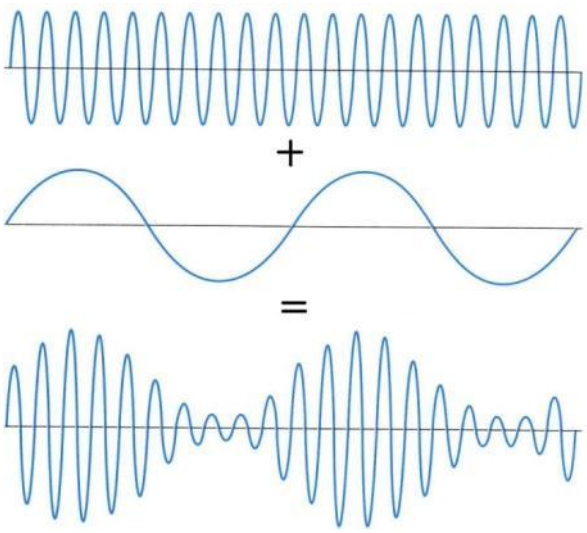

Figure 4 - Amplitude Modulation

2.1.3 Sound travels over distances

Given the information presented earlier in this report, there is a clear correlation between the wave length and how far said wave will travel. Sound pressure level declines with distance and is a direct function that ever repetition of the sound wave transfers energy to its surroundings in form of heat that is absorbed in the fluid it is travelling through [7]. The amplitude also has some effect on travel distance, however this is of minor importance since the amplitude only tells where the wave starts fluctuating.

When the wave in its propagation path hits an object, theoretically one of four things will happen;

- The object will absorb some or all of the energy
- The object will diffuse the wave
- The object will reflect the wave
- The wave will transmit through the object

The energy of the wave wants to be converted to heat, according to the laws of thermodynamics and thusly acts upon the object accordingly. The reality is that a combination of several or all of the four scenarios stated above happen, but mostly in nature the wave is either absorbed or diffused.

To describe absorption, a relationship between the wave and the mass of the object has to be uncovered. If the mass of the object is to big, the wave will not be absorbed, but will instead be reflected and no heat is transferred into the object. If the mass of the object is too small, the wave will simply pass through it and no heat will be transferred.

This relation is also dependant on the length of the wave. For all frequencies of waves or sounds, optimal absorption will occur when the object is half the length of the wave in thickness, i.e. $B = {}^{\lambda}/_{2}$, where B is the thickness of said object [7]. Thusly low frequency sounds are harder to absorb than high frequency ones, as these waves are very long.

Low frequency sounds are therefore more likely to diffuse or reflect in nature. Wave diffusion is a concept that describes what happens when a wave hits a complex surface of an object with a large mass. The wave will break up into smaller waves and later be able to be absorbed by new objects. The waves energy is being divided over a larger area than before, thusly lowering the sound level [W/m^2]. A good way to illustrate the concept is a wave breaker in a port, protecting boats inside by breaking the large waves, into smaller harmless ones. After a wave has been diffused, it can be absorbed as described earlier. This is why low frequency noise is a bigger problem than the rest of the spectrum. and why the terrain plays a big part in how the sound will behave at different locations.

2.1.4 Octaves and frequency bands

In order to assess the amount of low frequency noise in the recordings, so called Octave bands were generated. An octave band is a set of frequencies, divided as such that the upper limit of the band is twice the frequency of the lower limit. This is done in order to make the complex sounds recorded more compensable and manageable [13] [14].

When examining noise at a more detailed level, so called ”one-third octaves” are used to get more bands to analyze. One-third octaves are defined as a frequency band whose upper frequency is the lower frequency times the squared root of two [13]. The frequencies can be found in the tables, Table 1 and Table 2 below [14].

Band	Lower limit [Hz]	Mid frequency[Hz]	Upper limit [Hz]
1	11	**16**	22
2	22.1	**31.5**	44.2
3	44.3	**62.5**	88.4
4	88.5	**125**	176.8
5	176.9	**250**	353.5
6	353.6	**500**	707.1
7	707.2	**1000**	1414.2
8	1414.3	**2000**	2828.5
9	2828.6	**4000**	5656.9

Table 1 - Octave bands frequency distribution

Band	Lower limit [Hz]	Mid frequency[Hz]	Upper limit [Hz]
1	13.9	**15.6**	17.5
2	17.6	**19.7**	22.0
3	22.1	**24.8**	27.8
4	27.9	**31.5**	35.0
5	35.1	**39.4**	44.1
6	44.2	**49.6**	55.6
7	55.7	**62.5**	70.1
8	70.2	**78.7**	88.3
9	88.4	**99.2**	111.3
10	111.4	**125.0**	140.3
11	140.4	**157.5**	176.7
12	176.8	**198.4**	222.7
13	222.8	**250.0**	280.5
14	280.6	**315.0**	353.4
15	353.5	**396.9**	445.4

Table 2 - One third octave bands frequency distribution

The octave bands are characterized by the mid frequency, and will thusly only be given in that form in later chapters of this thesis. I.e. 63 Hz band = 44.3 - 88.4 Hz.

2.2 Wind turbine noise

In order to make the transition to a fossil free society, the expansion of all renewable power sources must be considered. Seeing that the wind power expansion thus far has met opposition, further research is needed to strengthen its market claim.

Noise emitted from wind turbines can generally be categorized into two parts: mechanical and aerodynamic noise. The later is produced by the airflow around the wings and has a characteristic swishing sound which has a lot of similarities with natural wind noise, often making aerodynamic noise hard to distinguish. These aerodynamic sounds are created by a form of Doppler effect when the blade is coming down towards the ground and when the blade passes by the tower in form of vortexes in the air [15]. This phenomenon is a product of amplitude modulation, described earlier in the theory section

Mechanical sounds on the other hand are often described as clunky and metallic noise and originate from, as the name implies, the mechanical parts of a turbine [16]. New technology and modern wind turbines have managed to reduce the amount of mechanical noise emitted. What can be found today in wind turbine noise is mechanical tones [17].

Noise is defined as "unwanted sound" and is thus already in the definition a matter of subjective opinions. Given this ambiguity and difficulty to determine an objective classification of what is considered noise and what is considered sound, three categories has been defined to evaluate how a certain sound affects the general population [8].

- Subjective aspects, like annoyance or irritation of a subject.
- Intrusion of activity, ex. speak, sleep or concentration
- Physical affect, hearing impairment, anxiety and tinnitus.

Sounds emitted from wind turbines are represented in the two first categories and modern turbines are almost exclusively found in the first category. The third category is rather a matter of distance to a sound source, than the sound itself. Examples for this third category are jet engines, rock concerts or explosions, but with the increasing size of turbines this might also be included in the future. It is therefore important to map how the noise behave depending on location, size and structure of a wind turbine.

2.2.1 Turbine size dependency on noise characteristics

Larger turbines generate more noise than small ones, this is due to that there are larger forces at work, but not only does the amount of noise change with the size, the noise itself changes. A Danish study, conducted at Aalborg University suggest that there is a downward shift in frequency is to be expected

when increasing the size of wind turbines, namely in the 63 – 250 Hz region [5]. This study was however conducted only with larger turbines, ranging 2 MW and upwards.

The same study also found evidence for increased levels of infra sound in the noise emitted from turbines rated at 3.5 MW and upwards, giving merit to the claim that infra sound emissions from future turbines will be a problem.

2.2.2 Low frequency and infra sound impact on humans

Low frequency noise is problematic because, as the rapid technical development leads to larger and larger turbine, the amount of noise pollution increases in nature and near civilizations. It has been proven that low frequency noise resonate with part of the human body, for example skull, chest cavity and bowels, causing medical distress [18]. In the same way you "feel music" when you are attending a concert, low frequency noise or even infra sounds can impact your body without you hearing it, causing hearing loss, heart arrhythmia and severe headaches [18]. Anxiety induced by noise is a common occurrence, and often brought up in debates regarding wind turbine noise. However the intensity of the noise have to be very high for these symptoms to appear, much higher than those found in the wind power sector today. In order for infra sounds to be detected by humans, a sound intensity of at least 90 dBG is needed, which is much lower than what is measured in recent projects [5]. In a project conducted in Germany, sound levels of 63 dBG (9 times lower than the limit) were detected at a distance of 100 meters from a 500 kW turbine, and 72 dBG (6 times lower than the limit) detected 100 meters from a 4.2 MW turbine [5].

Another response humans have to low frequency noise is drowsiness and losing the ability to concentrate over longer periods of time [19], making noise control an aspect that transcends the barriers of health. If not handled properly, low frequency sounds emitted by wind turbines in the future may affect the work discipline in society. The same study indicated that low frequency noise at 90 dBA, exposed for 30 minutes had about the same impact on a person as 1 cl of 40% alcohol [18]. Health aspects are a big part of this problem, but will however not be investigated in depth in this study.

2.2.3 Noise control in the wind power sector

There is a correlation between the speed of the blades tip and the amount of sound emitted, thusly if the speed is decreased, less sound will be produced [20]. Controlling the rotational speed is effective, but at the cost of produced power and is thusly financially undesired. Another thing that will affect the noise emissions at the expense of power is altering the wing profile, making it more sleek and thusly cutting through the wind better and creating less vortex induced noise.

For modern wind turbines, companies can use the pitch function of the blades. Pitching the blades means that the angle against the wind is changed so that more or less energy is transferred from the

wind to the turbine [21]. This method is mostly used to optimize the run time of the turbine and increase the amount of hours the turbine can produce power, but by changing the angle of the blades, less vortexes occur around the blades and thusly less noise is produced.

If a large turbine has to be pitch-controlled or speed regulated in order to control the noise, some of the purpose of having built a bigger turbine in the first place is lost. It is important to make sure that turbines can operate at rated power as much of the year as possible to obtain maximum fiscal efficiency. Therefore other methods of noise control have been experimented with, some with better success than others. Adding serrations to the blades is one of the more successful attempts at lowering noise emissions without affecting the power production to a wide extent.

By attaching saw tooth-like objects to the wind turbines blade, noise reductions of 2 to 10 dB were achieved in a research project called SIROCCO [22]. It was found that the serrations and optimized airfoils examined in the project worked very well at low frequencies, but did increase the amount of high frequency noise. Another method tested in the project was the so called “trailing edge fibres”, and by adding these 10-30 cm long fibres to the trailing edge of the blade, high frequency noise levels were reduced.

It was proposed that a function in the blades, like the pitch control we know today was to be added, making it possible to use both serrations and edge fibres, on the same blade, extending and retracting them automatically when needed. The SIROCCO project was so successful that companies designing turbines have begun producing prototypes with this functionality [22].

Another investigation was undertaken by researchers to correlate the noise emissions to exergy, opening new doors in the field. The main objective was to find a correlation between the SPL from the airflow around the blade, and the exergy destroyed in the fluid medium. The project is not yet finished, but if such a correlation could be found, it would be of big importance for the future of wind power, making it possible to pursue noise effective, but high power turbines [23]. Since the size of wind turbines are still growing, the amount of low frequency noise dependency on turbine size is of great interest.

3 Method and Material

This study is based on measurements conducted in the Halland county on the Swedish west coast, and for this study to be possible, measurement equipment of a certain standard is needed to guarantee a reliable and valid source of data for the analysis. In this segment of the paper said gear and methods of measurement will be described and explained.

In addition to the measurements conducted, essential information was gathered through a literature search with the help of the library database at Halmstad University and Google Scholar about current research on the subject. Furthermore information from the Halmstad University courses *ER4006, Wind power technology 7,5 hp (2013)* and *ER8002, Wind power planning and commissioning 7,5 hp (2014)* gave a good knowledge base to conduct the analysis in this report.

As mentioned in the earlier chapter "*Boundaries*", only one brand of wind turbines was used as research objects in order to narrow the possible errors in the analysis. All turbines observed in the study are designed and manufactured by Vestas and have similar wing profiles. All objects are equipped with gearboxes and asynchronous generator types.

3.1 Measurements

To ensure the validity of the measurements conducted, a standardized way had to be set up. All measurements had the same distance from the tower base to the microphone state in comparison to the height of said turbine, namely tower plus rotor radius or in other words one "total height" away. To establish where to set up the microphone station a simple, yet effective method was applied. Similar to the forestry method called "Yardstick method" [24], a ruler with a built in level, roughly one meter long was used to determine when the distance was equal to the total height of the turbine. By holding the "stick" in front of the eyes and walking toward or away from the tower until the tip of the stick is visually lined up with the top of the blades and the bottom of the stick is lined up with the bottom of the tower, the distance to the base of the tower is equal to the total height of the turbine.

Praxis when measuring sound from wind turbines is to perform these at 8 m/s measured at 10 meters height, and this is the wind speed that was aimed for when scouting for possible measurement days for this project. Weather forecasts and hourly wind data from nearby weather stations were used to track wind speeds during the day.

All measurements were performed downwind from the turbine, and all objects were measured during the same day in an attempt to have roughly the same wind speed in order to be able to compare them. All objects are located on similar sites; rural areas with few to no obstacles in the path from the turbine to the microphone.

Each recording is 15-30 minutes long in order to eliminate situational circumstances like singular passing cars or trucks on nearby roads, sudden gusts in the wind etc.

3.2 Equipment

The microphone and field recorder used for this project were borrowed from Halmstad University. The equipment was initially calibrated using a tone generator to ensure a reference point for the data gathered. The recorder used for the experiment was a FOSTEX-FR-2LE and the microphone was a DBX-RTA-M.

The microphone has a linear recording spectrum between 20 and 20 000 Hz and is almost entirely omnidirectional, meaning that it records equal amounts of sound from all directions. Additionally a muffler was used on the microphone to clear up wind distortions.

Figure 5 - FOSTEX-FR-2LE Field Recorder

3.3 Sites

All sites had to be within relative close proximity in order to be able to perform measurements in the same day, enabling attaining results with similar wind speed for all turbines. Halland county was chosen because of the abundance of Vestas turbines in the area as well as being the county where Halmstad University is located.

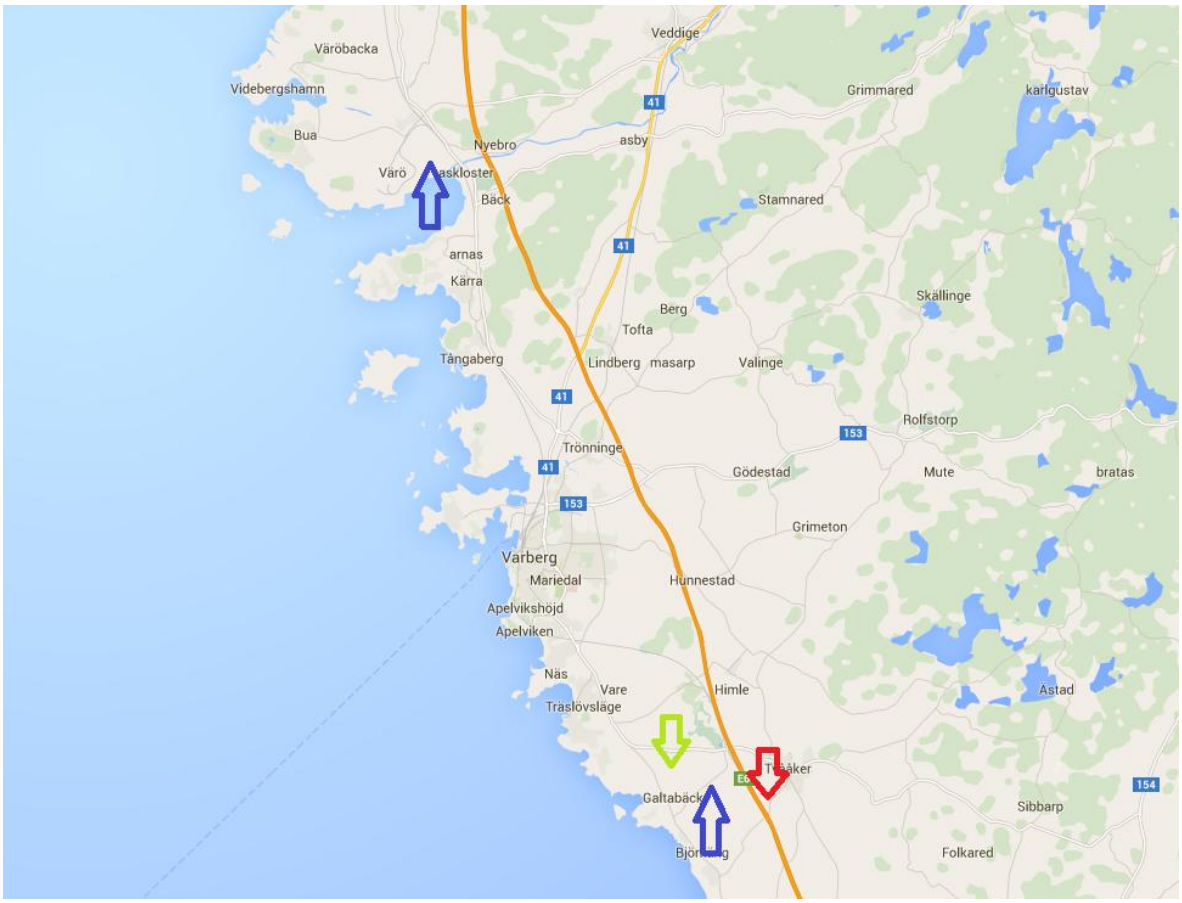

Figure 6 - Map over Varberg, Halland County

Figure 7 - Closer map over the Tvååker area

The arrows in the maps point to the sites used in the measurements, the colour coding remains through the analysis.

- Green; Vestas V27 225 kW
- Blue; Vestas V42 600 kW
- Red; Vestas V90 2 MW

3.3.1 Vestas V27 - 225 kW

Figure 8 - Wind turbine in Kistinge, Vestas V27

Tower Height: 31.5 m
Rotor diameter : 27 m
Rated power: 225 kW
Build material: Fiberglas and polyester wings, steel tower

Two sites were planned to be included in the analysis, but due to the fact that most of these smaller wind turbines are located on private land, both had to be eliminated. In a previous project comparing noise from small scale horizontal and vertical axis wind turbines [25], roughly 50 minutes of material was recorded at appropriate distance from a Vestas V27 turbine in Kistinge, and this material was well suited to be used in the analysis of this project. Also a backup V27 generator was found that could be used in the analysis

Figure 9 - Vestas V27 in Tvåker

3.3.2 Vestas V42 - 600 kW

Two sites were used for measurements. The first site is located in Tvååker, Varberg. The second site is located in Väröbacka, Varberg.

Figure 10 - V42 outside Tvååker, Varberg (left) and V42 in Väröbacka, Varberg (right)

Tower Height: 53 m

Rotor Diameter: 42 m

Rated Power: 600 kW

Build material: Fiberglas and polyester wings and steel tower.

3.3.3 Vestas V90 - 2 MW

Two sites were intended for this size as well, however when measurements were to be conducted one of the sites (Långås) was closed down for maintenance. Calls were made in order to clear up the confusion and the foundation for one of the turbines was cracked. Therefore the analysis only contains one V90-site, but with several recordings at two different wind speeds. The site used was only intended as backup as it is located right next to a highway.

Figure 11 - V90 site near Munkagård, Varberg

Tower Height: 95 m
Rotor diameter : 90 m
Rated power: 2 MW
Build material: Fiberglas and polyester wings, steel tower

3.4 Analysis

From the gathered data, an analysis using MATLAB was conducted in order to produce graphs for further examination. The MATLAB-program works in 3 stages:

- Quantifying recordings .wav
- Using theory described earlier, analyze the numbers
- Generating graphs

To explain the code in its entirety would exceed the bounds of this report, and thusly a simplified description follows.

The code is a modified version of a code used for the article "Noise propagation from a vertical axis wind turbine" [26], originally written by professor Lars Bååth, Fredric Ottermo and Erik Möllerström.

Alterations were made to better fit the scope of this project with additions of octave bands and one-third octave bands analysis. This part of the code convert the sound recordings to logarithms which later can be used to generate graphs and do calculations.

All graphs were generated using the MATLAB code, and the analysis following is made by observations based on previous knowledge and discussions with thesis supervisor Erik Möllerström.

4 Results

4.1 Measurements

Due to the amount of data recorded, it is not feasible to show graphs for all measurements. Roughly 6 hours of material was recorded and processed, and following in the coming segments of the report are the data actually showing noteworthy findings. Comparing the days, the wind speed was similar and the graphs are thusly also similar. Therefore a selection of graphs to present was made to have all measurements within 1 m/s of each other. One exception is the measurement for V27 in Kistinge, which is from an old project and was conducted in April, 2014. Data for the days of measure follow below.

Day 1:
Date: 13/05/2015
Conditions: Clear skies
Wind speed: 6.8 - 7.5 m/s
Recordings: A01-A06 in figure 12 (A06 is the old recording from 2014 and is green due to the fact that the graph displays two separate recording channels.)

Day 2:
Date: 15/05/2015
Conditions: Cloudy with light drizzle in between measurements.
Wind speed: 7.1 - 7.6 m/s
Recordings: A07-A10 in figure 12

Approximate sound pressure levels for the recordings can be read on the Y-axis on the graphs in figure 10, but since the focal point of this thesis is on frequency distribution, it will be nothing more than a reference tool.

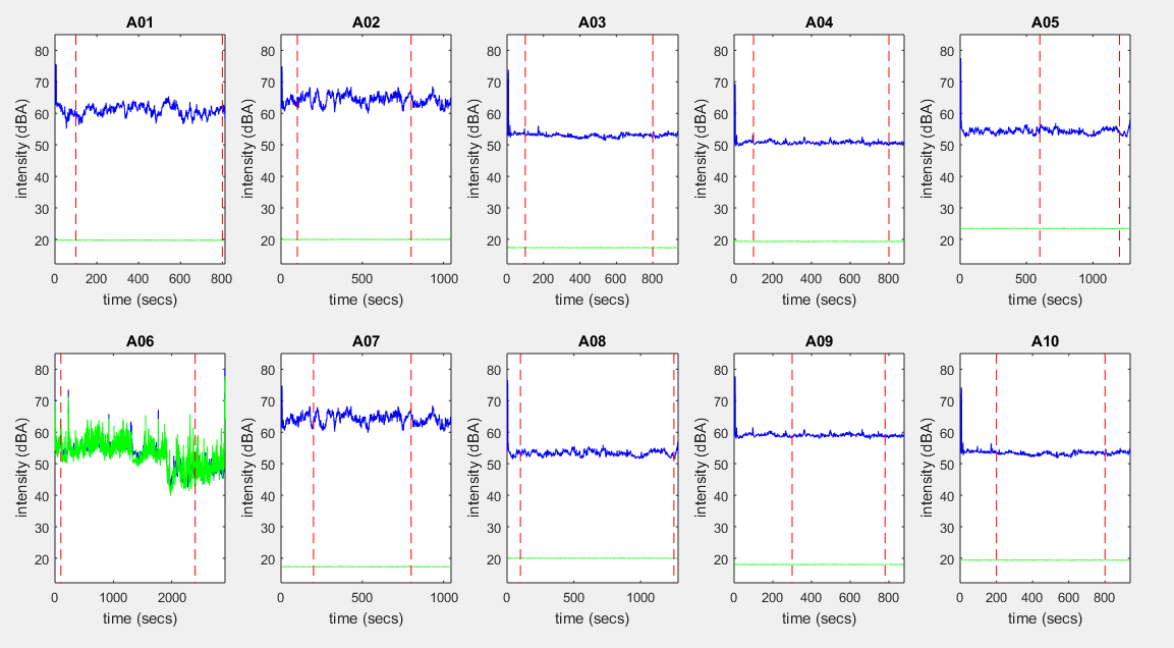

Figure 12 - All measurements used in the analysis

4.2 Octave bands

Following in this segment is a series of graphs generated with MATLAB based on the recordings done on the measurement sites. The graphs are divided into octave bands, ranging from 22 Hz to 2828.5 Hz (x-axis) with levels determined by the sound pressure level (y-axis). Frequencies below 22 Hz cannot be accounted for with the equipment used for this experiment and frequencies above 2800 Hz are deemed irrelevant for the study.

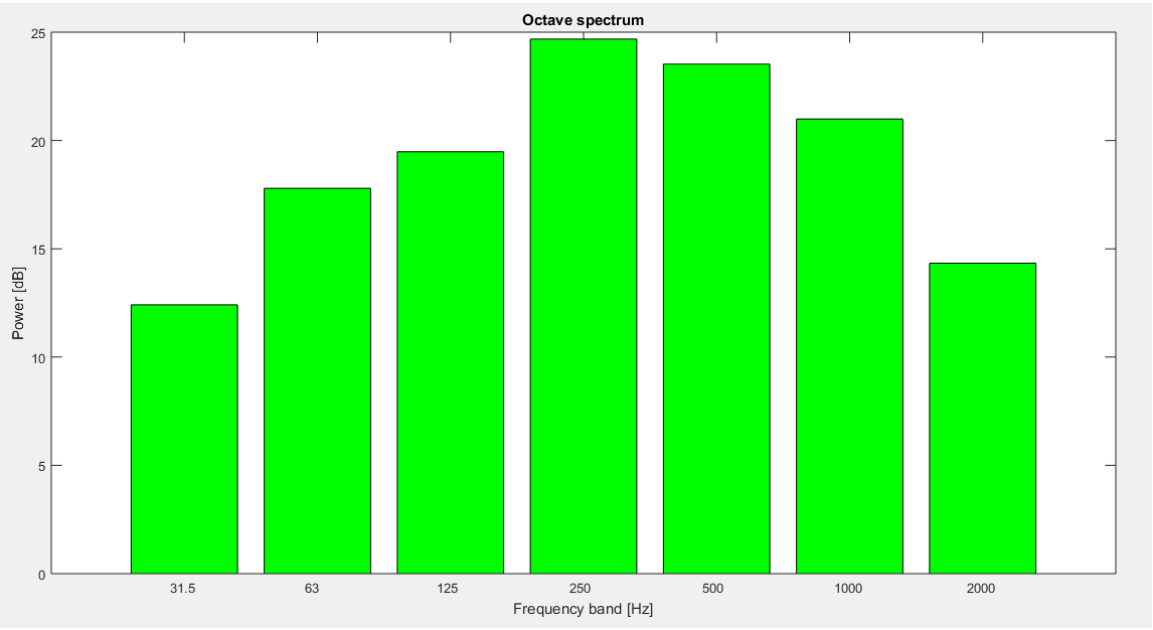

Figure 13 - Vestas V27 day 2 Tvååker Frequency distribution

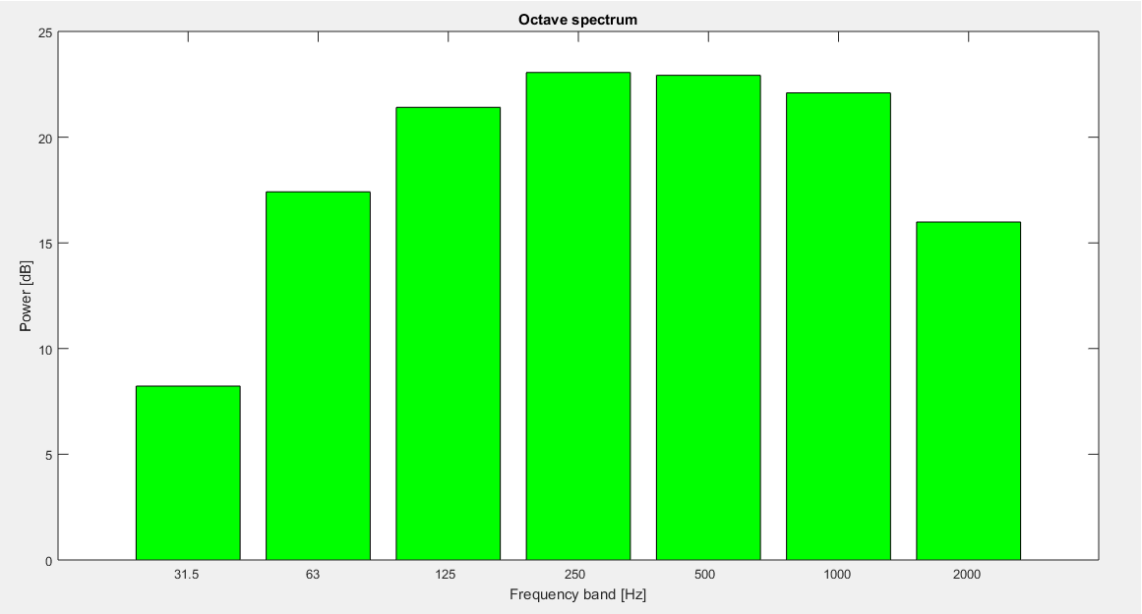

Figure 14 - Vestas V27 Kistinge Frequency distribution

The data from the V27 turbine, see figure 12, in Tvååker shows a dominant frequency distribution at the 250 Hz octave band (177 – 353.5 Hz). This measurement was the second of the day and the wind speed during this recording was 7.1 m/s. Figure 14 shows the frequency distribution collected from the 2014 recording mentioned earlier in this report. The distribution of the noise over the octave bands look similar to ones in Figure 12, with the same dominant frequency band. The wind speed during the recording in 2014 was 6.8 m/s.

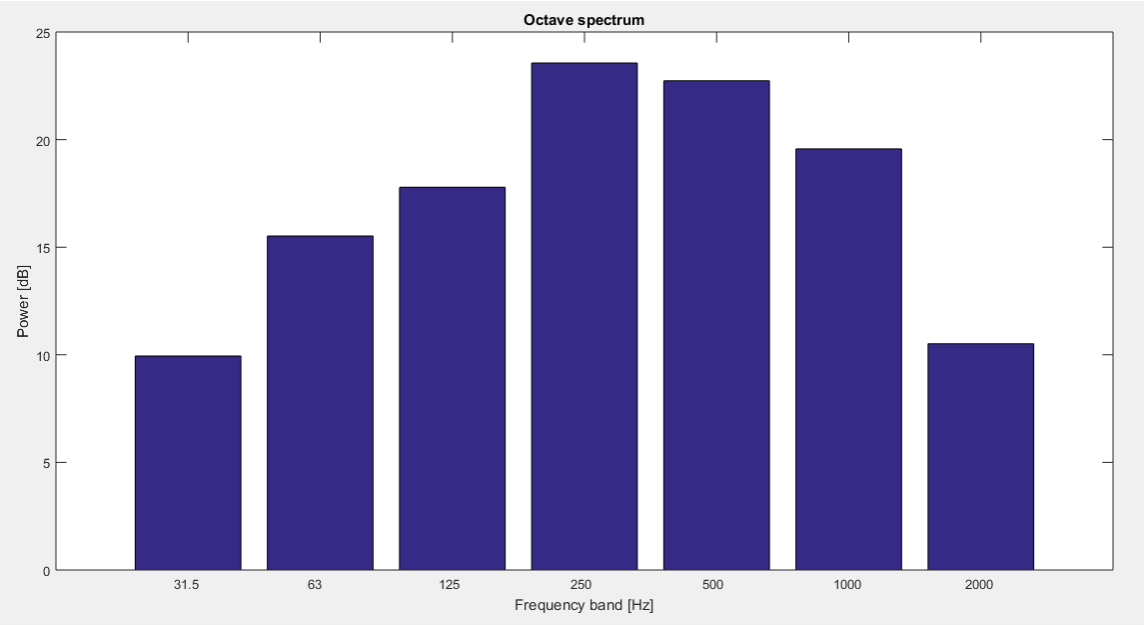

Figure 15 - Vestas V42 Tvååker day 1 Frequency distribution

The V42 turbine in Tvååker shows a frequency distribution very similar to the one found when examining the data from the V27 turbine in the same area. The measurements took place within 2

hours of each other and the wind data remained unchanged during the period. The wind speed was 7.2 m/s during this recording.

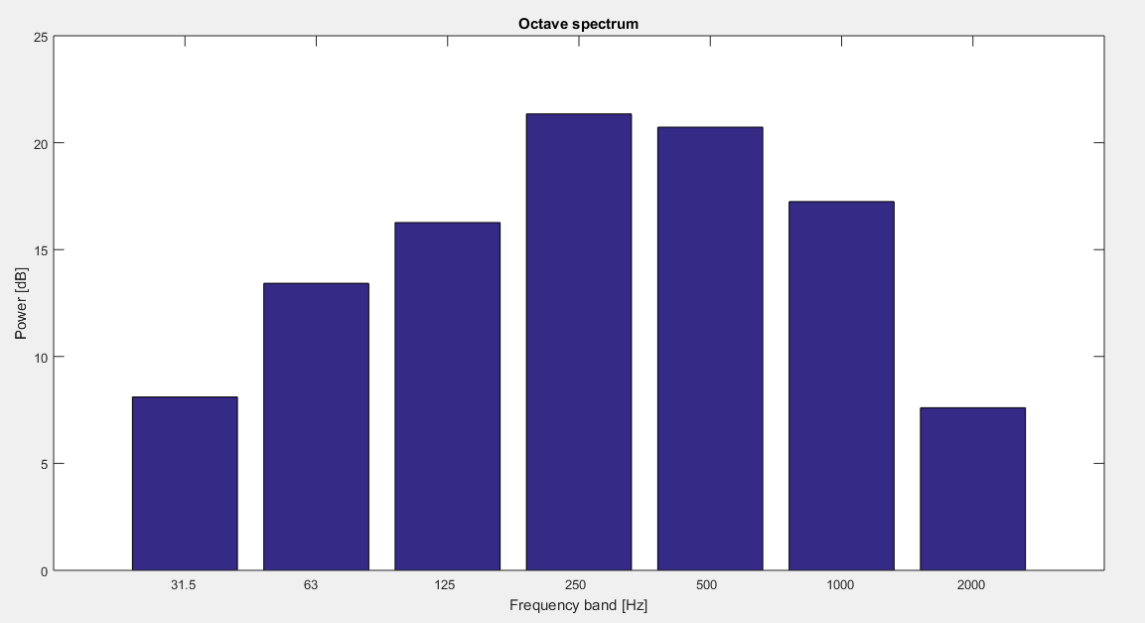

Figure 16 - Vestas V42 Väröbacka day 1 Frequency distribution

The turbine in Väröbacka, V42, show an almost identical frequency distribution to its twin in Tvååker, but at lower intensities. The wind speed during this measurement was 6.8 m/s, which was the lowest during the day.

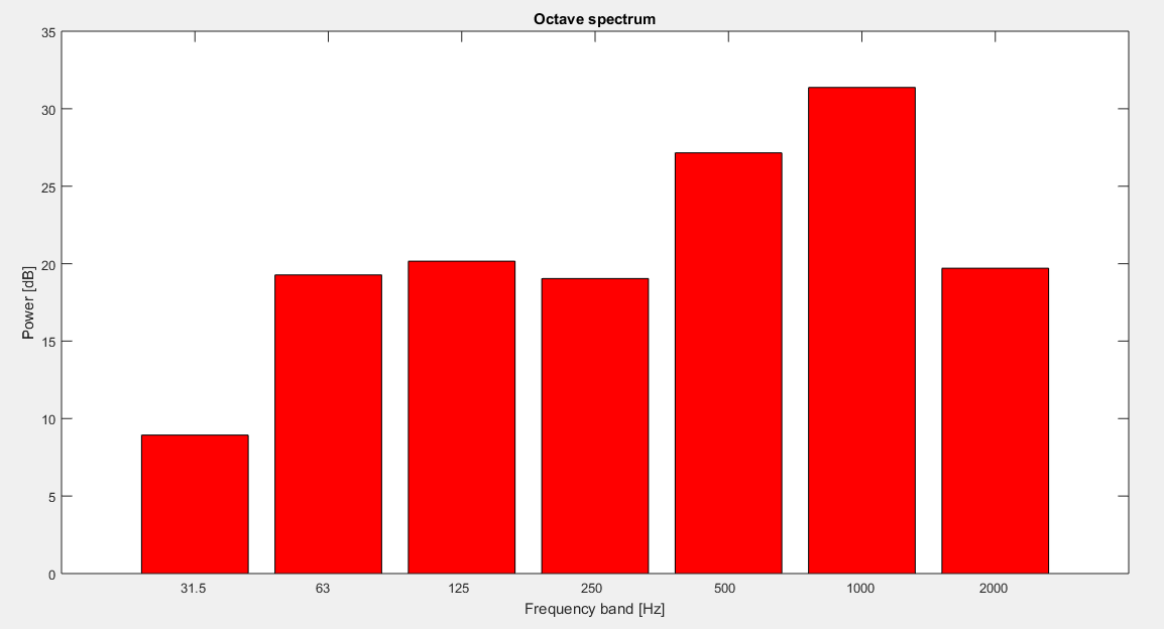

Figure 17 - Vestas V90 Munkagård, measurement day 1 Frequency distribution

This measurement show a very odd dominant frequency at the 1000 Hz octave band (707.1 - 1414.2 Hz). However in the lower frequencies it is noted that the 125 Hz band is more dominant than the previously dominating 250 Hz band, indicating some sort of noise anomaly at the site.

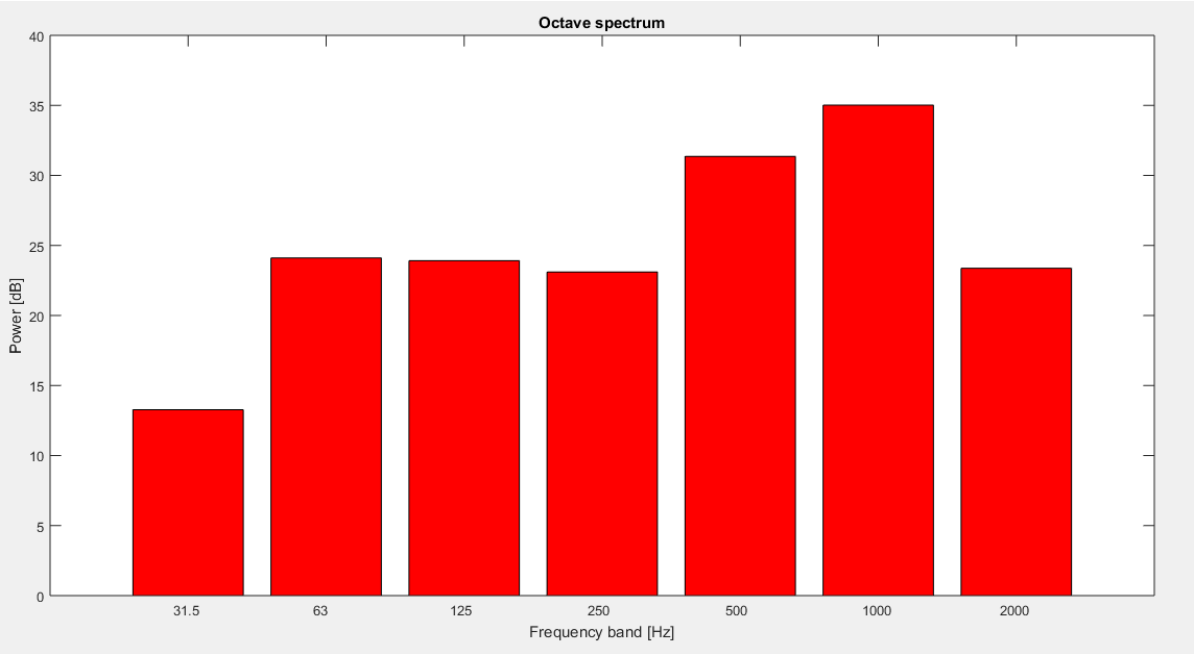

Figure 18 - Vestas V90 Munkagård, Measurement day 2 Frequency distribution

The same dominant frequency at the 1000 Hz band is shown in this measurement as well, further suggesting that there is something not accounted for at this site, or with the turbine model. However with the increasing wind speed between the two V90 measurements, the lower frequency trend keeps going. In the frequency range under 350 Hz, the 63 Hz band (44.2 – 88.4 Hz) is prevailing in this measurement.

The wind speed during the first V90 measurement was 7.3 m/s and 7.5 m/s during the second one.

4.3 One-Third Octave bands

What can be noticed in the graphs for the 2MW V90 turbines are anomalies starting to break the pattern at the 500 Hz octave band. After closer examination of the recordings and the site, this is determined to be road noise. The site is located right by the highway E6, which is producing a lot of noise, characteristically is 700 - 1300 Hz in bandwidth [27], correlating well with the abnormality shown in the graph.

To compare the turbine noise not heavily influenced by road noise, the focus has to be aimed towards the frequency bands below 700 Hz.. The following graphs, Figure 19 – 24, show the frequency bands for 22 – 420.5 Hz and are divided into one-third octaves instead of full octaves for a better resolution. Inspecting these graphs show an interesting phenomenon, the dominating octave band seems to shift to a lower band as the size increases.

These new graphs thusly represent the content of the first 4 bands in the previous segment, figure 13-18. In addition to these graphs, a frequency curve has been generated to further investigate if there is other disturbances than the nearby highway in the recordings. These will be displayed in figure 25-27.

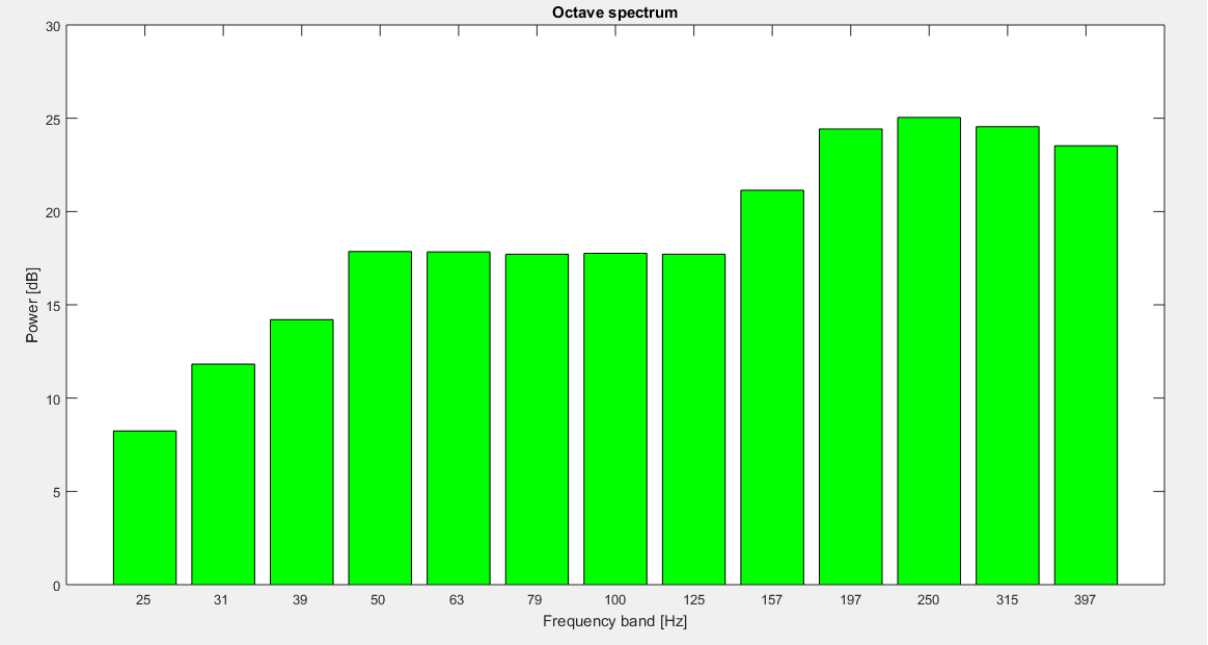

Figure 19 - Vestas V27, Tvåker One-Third Octaves frequency distribution under 450 Hz

What can be seen in figure 19 is that the octave band for 250 Hz is still the dominating one, and similar findings can be seen in figure 20, showing the higher resolution graph for the Kistinge recording. A minor difference is seen that, the 250 Hz bar is no longer the tallest and the 315 Hz and 157 Hz bands have increased.

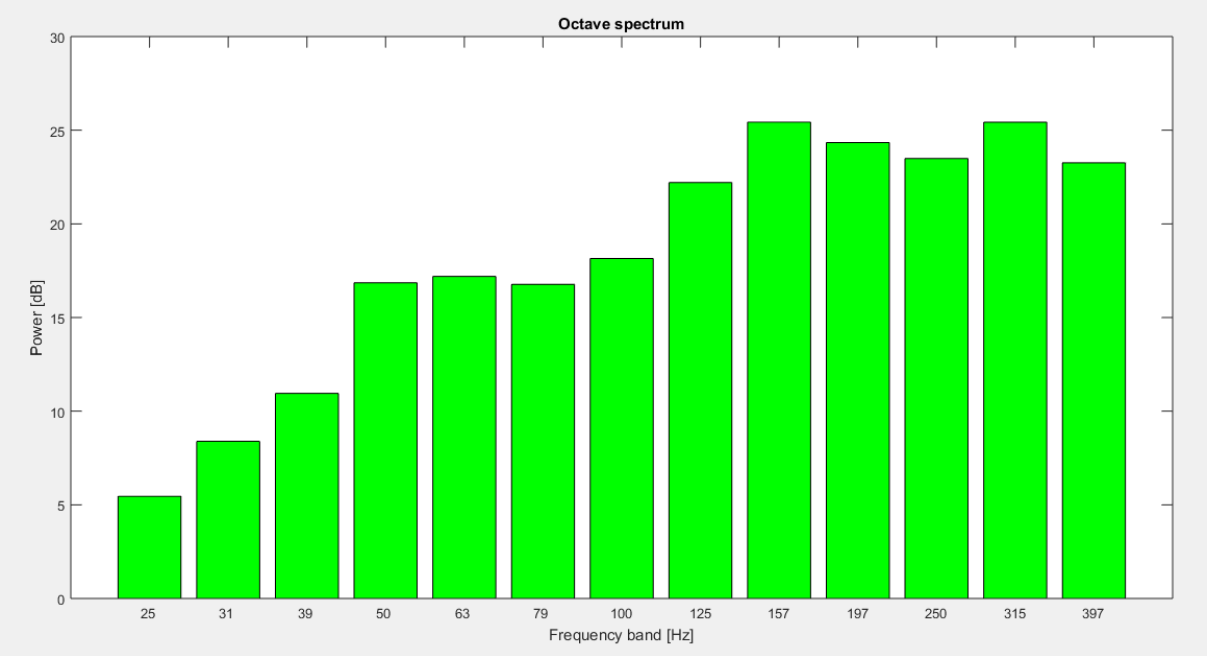

Figure 20 - Vestas V27, Kistinge One-Third Octaves frequency distribution under 450 Hz

In figure 21, showing the frequency distribution for the V42 turbine in Tvåker, it can be noted that the 250 Hz band no longer is the clearly dominating one, and that the noise is highly represented in all octaves from 197 Hz to 397 Hz.

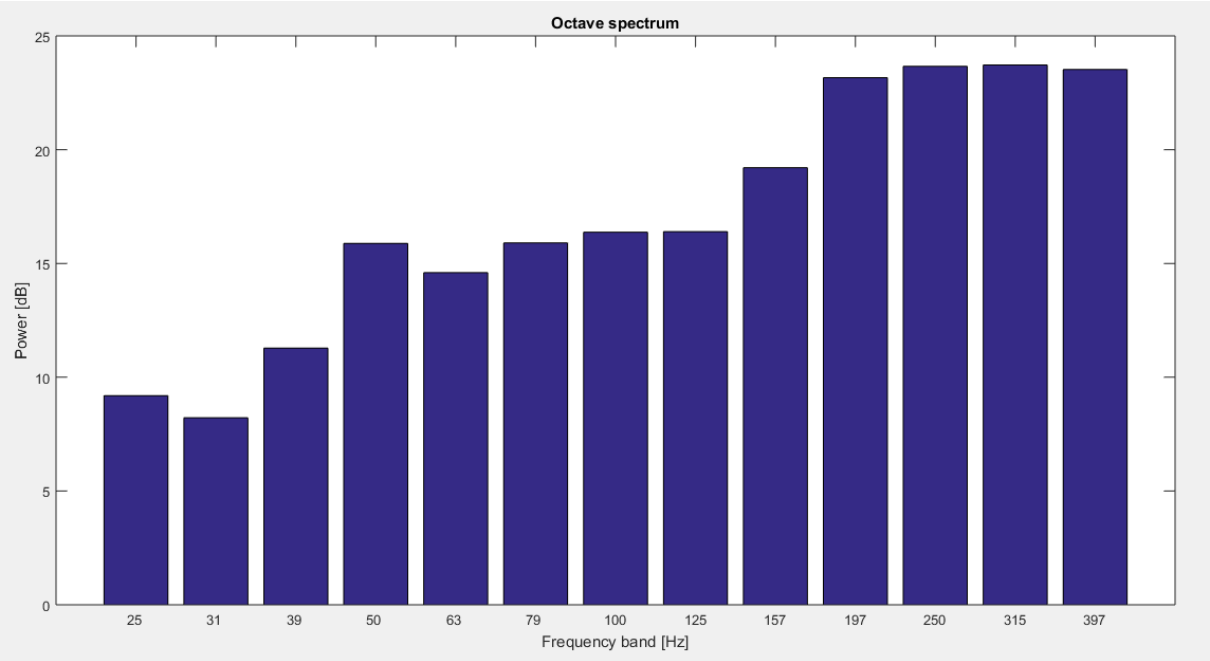

Figure 21 - Vestas V42 Tvååker One-Third Octaves frequency distribution under 450 Hz

Figure 22 shows an almost identical distribution over the octaves, with a general block of octaves all being highly represented, ranging from 197 Hz to 397 Hz.

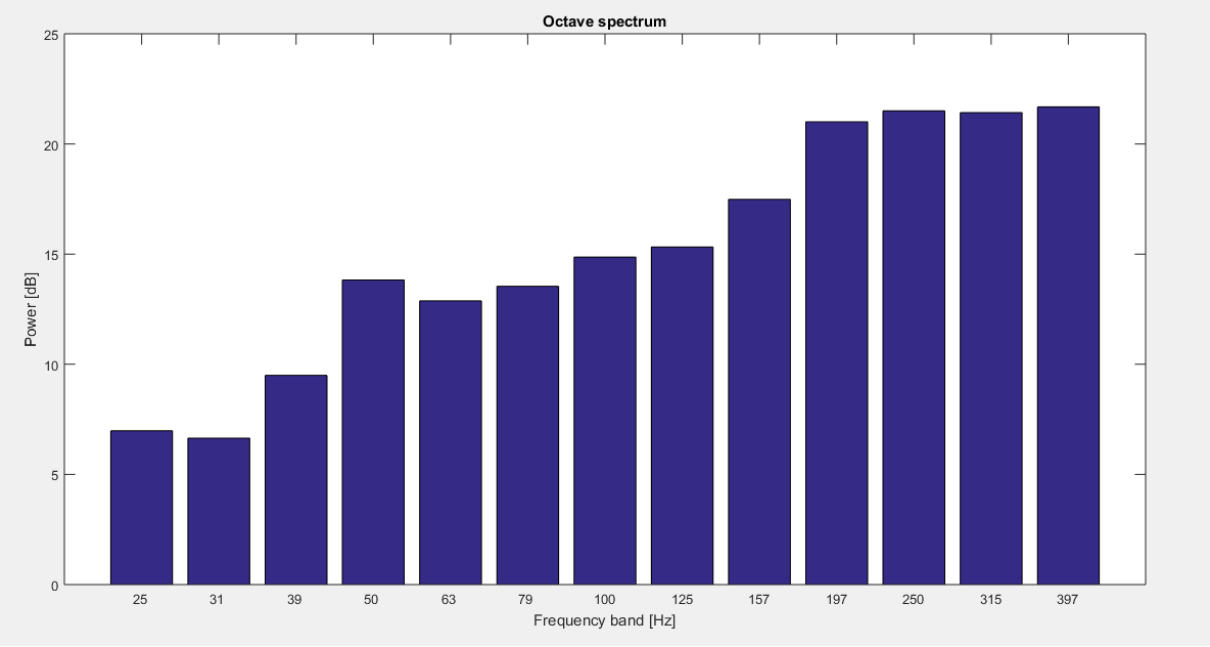

Figure 22 - Vestas V42 Väröbacka One-Third Octaves frequency distribution under 450 Hz

In Figure 23, an interesting occurrence can be seen. The dominant frequencies have shifted to a lower regimen of the octave bands. A part from the 397 Hz band, there is a clear trend that the octaves 63 Hz to 125 Hz have been increased, compared to their counter parts found in the V42 measurements.

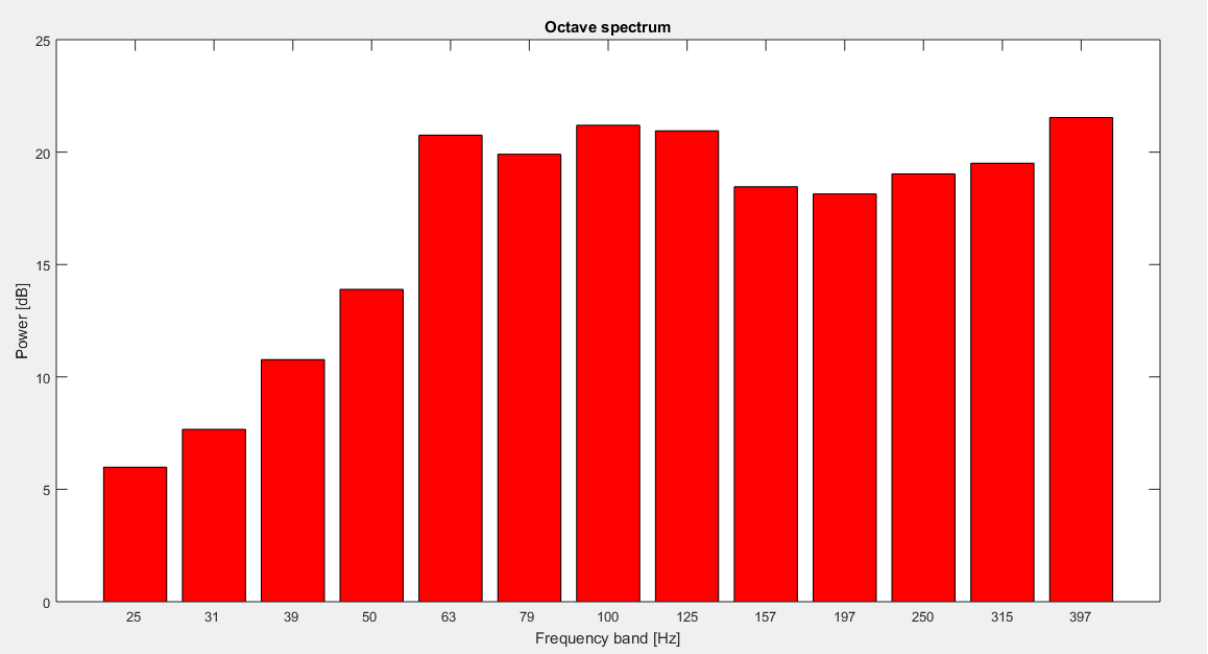

Figure 23 - Vestas V90-1 One-Third Octaves frequency distribution under 450 Hz

On the second day of measurements at the V90-site the same occurrence is found, as seen in figure 24, indicating that a trend is there to be discovered.

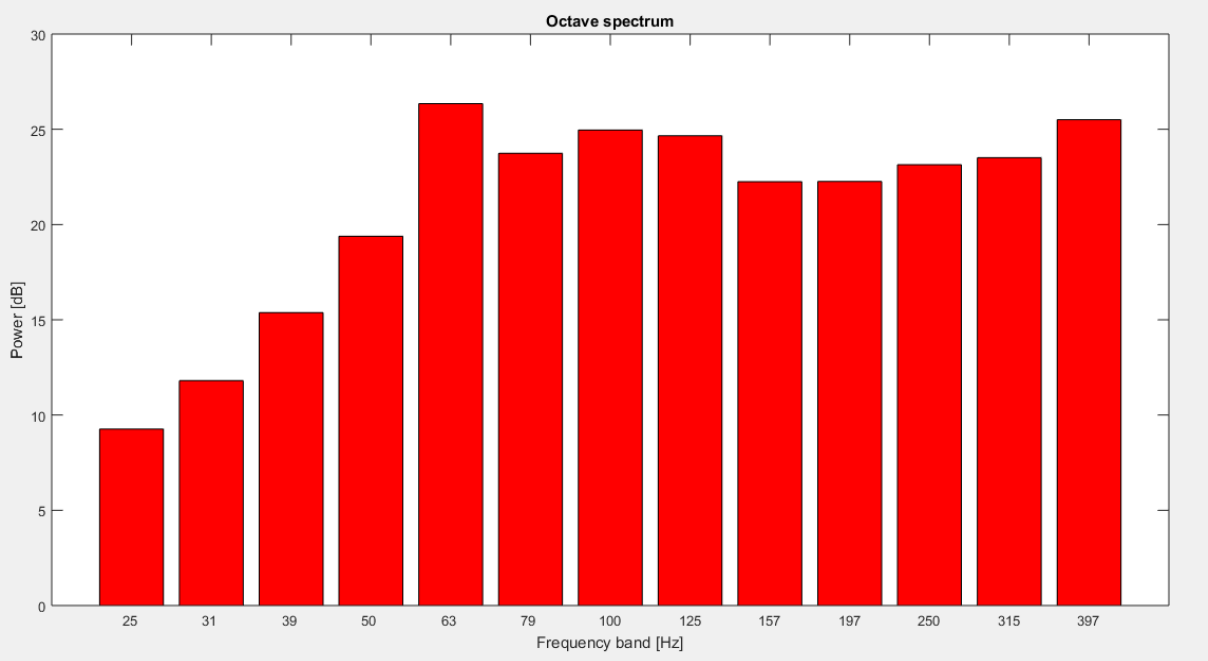

Figure 24 - Vestas V90-2 One-Third Octaves frequency distribution under 450 Hz

These graphs are quite narrow-banded and only display the allocation of frequencies within the low frequency range. Following is a series of graph to detect if there are any ongoing disturbances other than the road noise. These graphs are gives Intensity (y-axis) over frequency (x-axis)

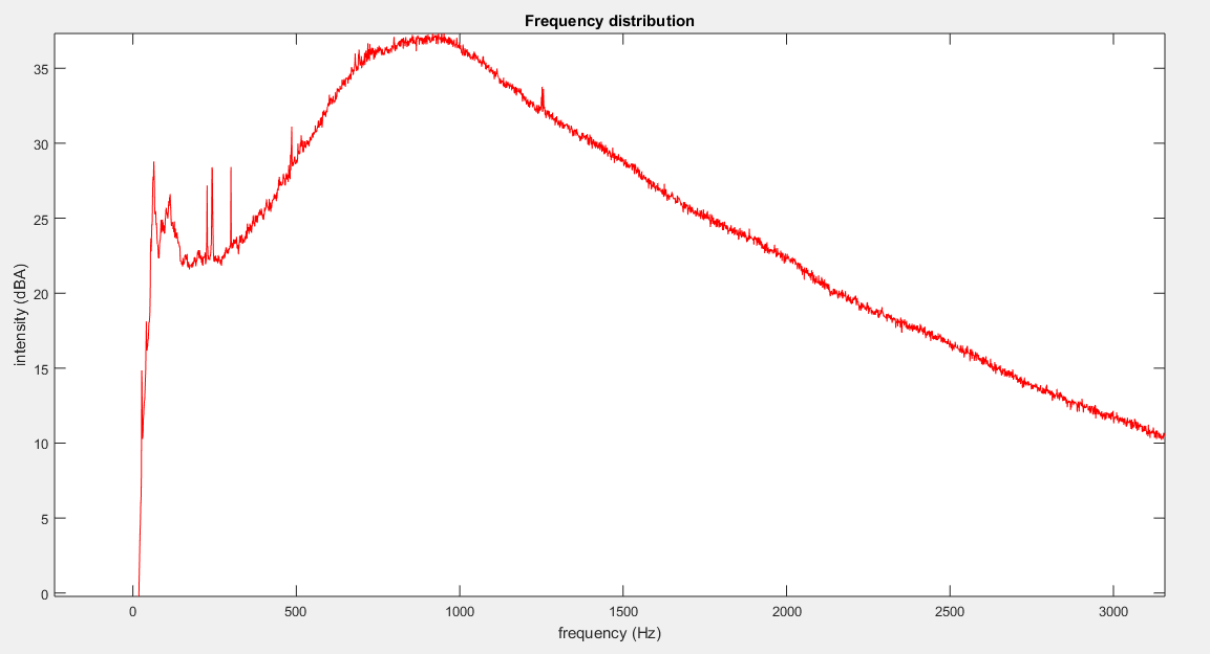

Figure 25 - V90 frequency curve

Figure 25 shows clearly the broad-banded road noise between 700 and 1300 Hz (x-axis), and that most of the sound recorded is being shadowed by the gargantuan amounts of noise. In figure 23, showing the frequency curve for a V42 turbine, there is a noticeable difference.

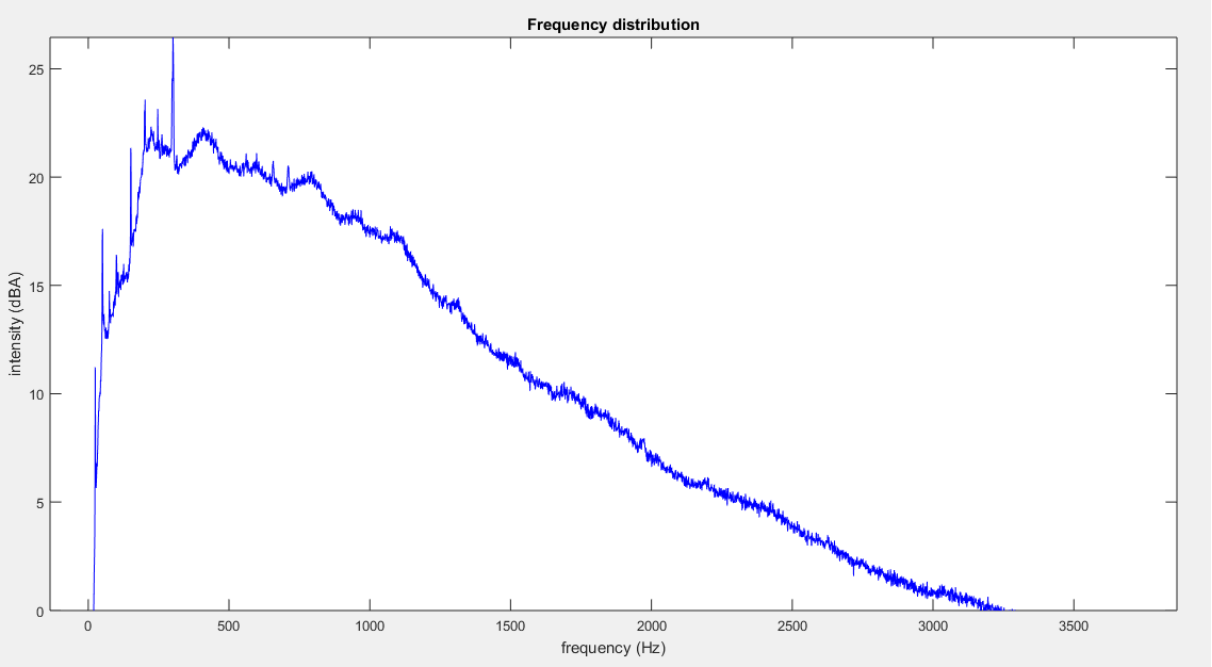

Figure 26 - V42 Frequency Curve

In figure 26, the frequency peak at around the 250 Hz band is noticeable, and following that is a steady declination over the forthcoming frequencies. Where as in figure 25, there is a sudden rise in intensity due to the road noise pollution.

For comparison a graph, figure 27, for the V27 frequency curve was also generated.

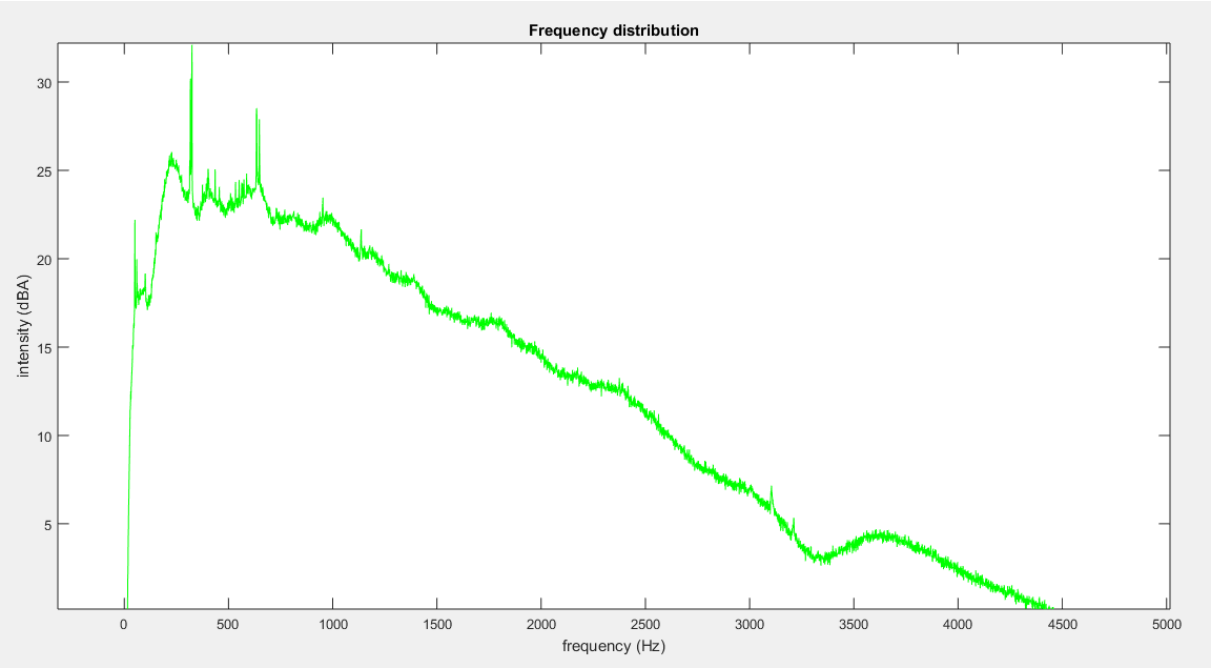

Figure 27 - V27 frequency curve

Minor differences are apparent, something that looks like a tone at around 800 Hz (x-axis), but in most aspects identical to the curve in Figure 26.

5 Discussion

The aspect of low frequency noise becomes a great one, seeing that our demand for power increases every year. Larger turbines are inevitable to support the future society, and in combination to the problems to solve this electrically, lowering the impact on humans while producing said power is paramount.

5.1 Generally about the project

During this project several problems have been encountered, but the biggest ones have been the inaccessibility to the sites intended to be included in the experiment and the unpredictable nature of the wind. The first problem can be fixed by having the support of a major wind power company, thus getting access to a larger quantity and variety of sites. However, the wind is of constant concern when conducting this sort of experiment and the only way to counteract it is to simply allocate more time for measurements and to be ready to go out in the field during all hours of the day if need be. Another, albeit smaller, problem is that the wind speed is constantly changing. A larger team of people is needed to make simultaneous measurements possible at several sites. something to consider for future experiments, to minimize possible interactions between frequencies. Alternatively, larger amount of noise measurement data together with data of measured wind speed can be used so that noise from different turbines can be compared for the same wind conditions. Measurements during the night, when the traffic load on the nearby roads is also something to consider for future experiments, to minimize possible interactions between frequencies.

It would be interesting to include more sizes of turbines in the study, however the size range of Vestas turbines in Halland was quite limited, with only a total of three sizes being available for observation (225 kW, 600 kW and 2 MW). There are Vestas models to fill the gaps, but this would increase the area of the experiment, and it would not be possible for a single individual to perform the measurements.

5.2 Discussing the data

When analyzing the graphs it is important to understand what the data is saying. Relying on the theory described earlier in the thesis it is possible to make some deductions. When standing near the sites during the measurements, and what was heard at all sites was the characteristic swishing amplitude modulation from the wind turbines, i.e. the aerodynamic sounds. Therefore it is likely that the change in frequency noted in the recordings is a change in the aerodynamic sounds, not the mechanical.

It is possible that the increase in size will put more stress on the mechanical parts and the structure of the turbine tower and thus produce low frequency noise at higher sound levels, but there is no support for this in either the data, or from listening done at the sites during the recordings. Mechanical sounds

are most likely represented in the spikes present for all sizes of turbines in figures 22-24, and does not change in frequency when comparing the graphs.

In the One-third octave analysis of the turbines observed in this study, it can be noted that the 63 Hz band is more than 6 dB louder, i.e. twice as high according to theory presented earlier, in the noise from a V90 than what was observed with the V42, indicating that something is happening with the frequency spectrums lower regions as the rotor size is increased. This is however impossible to prove as a trend without more data to support the theory. But when comparing these findings with those found by the Danish researchers in Aalborg, signs of the downward shifting trend is the same even in these smaller turbines examined in this project.

However, it is assumed that the change does not apply to turbines smaller than 600 kW, since the frequency distribution in all V27 and V42 turbines studied in this project were almost identical.

5.3 Future work and further research

The limitation to only observe turbines in rural areas might have to be reconsidered in the future, as these areas often are near roads and houses. If a more comprehensive study is to be made, turbines in forest areas should also be included to get a better idea of how the terrain impacts the frequency distribution.

Regarding the method of measurement in consideration to the background noise, namely road noise, some changes have to be made if further studies are to take place. The traditional way of performing noise measurements is to perform site measurements both with and without the turbine running. However this cannot be made unless the company operating the turbine is on board with the project. The company operating most of the turbines included in this study was kind enough to allow access to some closed sites, but since measurements took place on days with good wind speeds with the turbines producing their rated power level, it would be an economical setback to stop the turbines.

It would also be interesting to compare different technologies, for example with or without gearbox, different wing profiles, same turbine at different tower heights etc. It is know that the gearbox is a significant source of noise in wind turbines, as well as structural noise in form of vibrating parts etc. This would on the other hand make the project far too large for a single person to conduct.

6 Conclusions

It is concluded that sound frequency spectrum does change with the increased size of turbine rotors, and while showing signs of the trend found in previous research, the data amount gathered is insufficient to completely accept the hypothesis that the change would be specified to the lower frequencies.

When comparing the V90 turbine data with those of the V42 and V27, it is noted that there is a change in aerodynamic noise in the 63 - 250 Hz one-third octave bands. The V90 measurement shows a sound level twice as high in the 63 Hz band compared to the V42 and V27, but the amount of data is insufficient to claim a trend. The changes found in the experiment correlates with the findings in earlier research.

It is also concluded that the changes in frequency distribution does not happen with turbines smaller than 600 kW, as all data below this show the same distribution.

Further research is needed, with some alterations to the method of experimentation. It is recommended that future studies include more types of turbines, with a larger range of power ratings.

The question of interest in this thesis can be answered with the following statement; The frequency spectrum of the aerodynamic noise does become skewed when the turbine size is increased, but more research is needed to further determine exactly how.

7 Acknowledgements

First of I would like to thank everyone that has helped and supported me during this master programme at Halmstad University. It would not be possible to keep the motivation up without my family, my friends and my teachers, and for this I thank you.

This master thesis gave me yet another opportunity to combine my interest for sound and noise aspects with my studies in energy technology, which has been rewarding and fun. A special thanks to professor Jonny Hylander and my supervisor Erik Möllerström for the help during this project, and for supplying the material and base idea for this thesis.

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