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Noise directivity from a vertical axis wind turbine

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Summary

The directivity of wind turbine noise is of widespread interest and has received attention over an extended period. The reason for this is partly that noise optimization procedures can be implemented in order to increase the efficiency of the power output. Although directivity of horizontal axis wind turbines (HAWTs) are well understood, the directivity pattern around vertical axis wind turbines (VAWTs) are less well investigated.
This paper presents measurements of directivity on a 200 kW VAWT, a so called H-rotor, with variable speed and a tower height of 40 m. The turbine, which is situated in a flat agricultural landscape close to Falkenberg at the Swedish west coast, is one of the world's largest today operational VAWTs. Experimental results as well as a theoretical model based on the turbulent-boundary-layer trailing-edge (TBL-TE) noise suggest higher noise levels upwind of the rotor and the lowest noise levels in the perpendicular directions. Moreover, modulation analysis of the measurements indicates the presence of modulations but the results are inconclusive.

1. Introduction

The need for renewable energy has prompted the development of wind power. Wind turbines can be categorized by the orientation of their axis of rotation into two groups: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). Even though the HAWT has by far been the most successful concept, with the large and economically feasible turbines of today, the VAWT concept has advantages. VAWTs typically have fewer moving parts and a generator located at ground level, which could ultimately lead to higher availability and lower maintenance cost [1]. Furthermore, in [2] it has been indicated that the concept is more suitable for up-scaling than the HAWT concept. Also, the VAWT concept has potentially lower noise emission [1].

Noise is considered as one of the disadvantages with wind turbines. The definition of noise is simply unwanted sound [3]. Distinguishing noise from sound is to a large extent subjective, but sound from wind turbines is generally considered as unwanted and may therefore be referred to as noise. Extensive research has been presented regarding noise from wind turbines. For example, interesting work can be found in [4] where sound modelling, masking and propagation has been studied and in [5] where the human response to wind turbine noise has been investigated. However most research has been aimed at the more common HAWT concept and little attention has been given to the alternative VAWT which has shown potential for lower noise levels. Work that has been done regarding noise from VAWTs include [6] and [7] where numerical methods are used to simulate aerodynamic noise from VAWTs and which for both studies indicates lower noise levels compared to HAWTs. In [8] the noise characteristics of a model VAWT was investigated and the applicability of different noise prediction models was examined. Furthermore, the frequency distribution of VAWT noise was studied in [9].

Noise directivity, i.e. quantification of the noise distribution depending on direction, is of interest for wind turbines. For example, awareness of strong variation in directivity would allow for programing the turbine to operate in a less efficient mode with lower noise emission for certain wind directions. Directivity from HAWT noise has been studied in [10], where most noise seem to radiate upwind and downwind of the rotor. However, the swishing effect from amplitude modulation is most obvious in the perpendicular directions. Similar experimental studies on VAWTs are absent.

The VAWT we consider in this study is the so called H-rotor which is a Darrieus-type [11] turbine with straight blades. A 200 kW VAWT (hereafter referred to as the T1-turbine) was designed and erected by the company Vertical Wind AB in 2010. The turbine, which is located just outside of Falkenberg at the west coast of Sweden, is today owned by Uppsala University and the subject of research in a variety of fields. This particular VAWT has a direct drive permanent magnet synchronous generator which is mounted at the bottom of the tower and connected to the rotor by a steel shaft. The rotor consist of three 24 m long straight blades that are connected to the shaft by two struts each, both blades and struts are made out of fiberglass. The blades are fixed, but the variable speed of the turbine is used to control the stall effect so that the rated power can be obtained between the rated wind speed and the cut-out wind speed. This can be said to be a sort of active stall power control. Furthermore, it has a tower made out of laminated wood, which from the start was free standing, but after two years was complemented with support from three guy-wires. The T1-turbine is a first prototype and the noise level was not considered during design. If commercially produced, means to minimize noise would probably be taken, for example by altering the blade shape and choosing a blade profile developed to minimise noise rather than the standard blade profiled used for the T1-turbine.

Table 1: Properties of the T1-turbine.

Rated power	200 kW
Turbine diameter	26 m
Tower height (incl. foundation)	40 m
Wing length	24 m
Swept area	624 m^2
Cut-in wind speed	4 m/s
Rated wind speed	12 m/s
Cut-out wind speed	25 m/s
Survival wind speed	60 m/s
Rotational speed	16-33 rpm
Power regulation	Stall
Rotation (seen from above)	Counter-clockwise
Wing/strut material	Fiberglass
Tower material	Laminated Wood

Figure 1: The T1-turbine.

2. Theory

Noise from operating wind turbines can be divided into aerodynamic and mechanical noise. Aerodynamic noise is of broadband character and occurs when the air flows around the blade and originates from various complex flow phenomena and generally increases with tip speed and hence the most sound is produced at or close to the tip of the blade. Mechanical noise originates from the relative motions of mechanical components in the gearbox, the generator, yaw drives, cooling fans, hydraulics and power electronics. For modern turbines the aerodynamic noise is generally dominant and in [12] it is shown that for a modern HAWT the most noise is created close to the wing tip when the blade travels downwards towards the receiver, a result of the directivity of aerodynamic noise emitted from a moving airfoil [3]. The characteristically swishing sound of a wind turbine is due to amplitude modulation and has been proven to be the sound feature from wind turbines that is the most annoying [3]. This mid frequency phenomena (400-1000 Hz) is created by the directivity of the trailing edge noise.

VAWTs usually has lower tip speed ratio (TSR) than HAWTs. The entire length of a VAWT blade travels at tip speed, which for a HAWT is only true for the actual blade tip. Since it has been shown that most of the aerodynamic noise from a HAWT is generated close to the tip [12], the blade velocity where noise is produced is lower for a VAWT then for a HAWT, an argument for lower levels of aerodynamic noise. However, the reality is more complex, mainly due to larger angles of attack and the unsteadiness of the flow. An additional difference is that VAWTs usually has support arms carrying the blades, a feature not needed for HAWTs. However, the support arms can be made streamlined, in which case they will not be expected to generate much noise. Furthermore the drive train of a VAWT can be located at ground level which limits mechanical noise propagation [1].

2.1 Noise directivity prediction model

Directivity of noise emitted from modern HAWTs has been studied quite thoroughly by Oerlemans et al [10, 12]. In general, aerodynamic noise from wind turbines are caused by both

inflow-turbulence and airfoil self-noise. However, in [12] it was found that the directivity pattern was only compatible with the trailing-edge self-noise directivity, in particular the turbulent-boundary-layer trailing-edge (TBL-TE) noise contribution. We assume here that the modelling presented in [10], based on the empirical model for airfoil self-noise of [13], may be relevant to VAWTs as well. For small VAWTs (low Reynolds numbers) laminar-boundary-layer vortex-shedding noise has been observed to be important [8], but for the current turbine the Reynolds number is of the order of $1 \cdot 10^6$, so the TBL-TE is expected to be dominant here.

A complication when considering VAWTs is that the angle of attack momentaneously becomes quite large, even during normal operation. For the optimal TSR of 3.8, and utilizing a simple model where the flow is unperturbed by the turbine, the angle of attack ranges up to 15°. A static situation with such a high angle of attack would imply a stalling airfoil. However, the angle of attack in the VAWT application is constantly changing, giving rise to a dynamic stall effect, which means that flow separation will effectively be delayed. The formulas of [13] refer to the static situation, and some modifications are expected to be necessary in order to apply these formulas to the current dynamic stall situation. The proposed modification is outlined and motivated below.

In [8] it was observed that the dynamic stall effect seems to constitute a measurable source of noise, probably due to large force fluctuations when the flow eventually separates. This was however only observed for low TSR, indicating that strong flow separation will not occur for the higher TSR of 3.8 considered here. In [14] dynamic stall was measured at different frequencies, and in particular a linear lift curve was maintained up to 15° at a reduced frequency k = 0.05, a frequency close to the one for the current situation (the amplitude of the oscillation was however larger in [14]). We therefore propose to use, as an estimate to account for dynamic stall, the low angle parametrization of the suction side δ^*, as defined in [13], for the entire range of angles of attack.

In this estimate the simplest possible approach is adopted regarding air flow and conditions along the blade span. The flow is assumed to be unperturbed by the turbine and no wind shear is taken into account. The basic empirical equation for the sound pressure due to the TBL-TE noise for an airfoil [12, 13] is

$$p^2 \sim \frac{\delta^* M^5 L}{r^2} \cdot \frac{2\, sin^2(\varphi/2)\, sin\theta}{(1 + M\, cos\theta)^4} \tag{1}$$

where δ^* is the displacement thickness of the boundary layer at the trailing edge, M is the blade Mach number, L is the blade span and r the distance from the source of observer. The angles are defined in [13], θ being, for example, the angle between the blade chord line and the source-observer line. When calculating r and the angles the motion of the air flow should be taken into account, using retarded coordinates for the source. In this estimate, however, retarded coordinates have not been used, but the error is expected to be small for the short distances and moderate wind speeds considered here.

There are three contributions to p^2, one from the suction side, one from the pressure side and one additional term due to the angle of attack. The last two contributions are proportional to the suction side displacement thickness, δ_s^*, which is much larger than the pressure side displacement thickness δ_p^* even at small angles of attack. We therefore use $\delta^* = \delta_s^*$ in (1) in the calculations, and the formula for δ_s^* reads ([13], untripped boundary layer, here used for all angles)

$$\delta_s^* = \delta_0^* 10^{0.03114\alpha} \tag{2}$$

where the angle of attack α is given in degrees, and δ_0^* is the displacement thickness for zero angle of attack, as parameterized in [13] as a function of the chord Reynolds number.

The turbine data used in this directionality calculation are given in table 2. Positioning the observer at a certain horizontal distance *D* to the hub, at different angles to the wind directions, the angles θ and φ, and source-observer distance *r* are determined as a function of the turbine dimensions and the blade azimuth angle β. The squared pressure (1) is then averaged over all angles β. The overall constant in equation (1) is not known (and not of interest in this directionality analysis); a constant is eventually fit in order to plot the result along with the measurement in figure 4.

Table 2: Turbine and wind data used in model

Hub height	40 m
Blade length	24 m
Blade cord	0.75 m
Radius	13 m
TSR	3.8
Wind speed at hub height	6 m/s

2.2 Measuring sound pressure level from a wind turbine

When recording noise from a wind turbine, the sound recorded $L_{p.rec}$ consists of the sound pressure level due to the wind turbine noise $L_{p.wt}$ as well as the background sound $L_{p.bg}$ which are related by [3]:

$$L_{p.rec} = 10 \cdot \log_{10}(10^{L_{p.wt}/10} + 10^{L_{p.bg}/10}) \quad (3)$$

Recording with the wind turbine sequentially turned on and shut down, (3) can be used to separate the wind turbine sound pressure level from the total sound pressure level, if the wind and background sound conditions are unchanged. In reality, the conditions are never unchanged. By keeping track on the wind speed and using long enough recordings, however, the effect of wind speed can be taken into account and the effect of background sound conditions will be evened out.

3. Setup and observations

3.1 Experimental setup

The microphones used were DBX-RTA-M measuring microphones normally used for reference measurements of wide bandwidth noise. These microphone is nearly omni-directional and has a very straight spectral response in the range of 20-20 000 Hz. The microphones were fitted with wind protection muffs and mounted on supports, 1.5 m above ground. The field recorder used were FOSTEX-2LE which samples with 24 bits sampling depth and at a speed of 44100 samples per seconds, which is sufficient to measure signals at the higher end of the hearable sound spectrum. The equipment was calibrated on site by recording the sound from a portable sound meter calibrator emitting 94 dB (±0.5 dB) at 1 kHz.

3.2 Data processing

Data recorded from each of the instruments was read into Matlab as a wav-file from the compact flash card used in the digital recorder. The calibration recordings were used to ensure correct mapping of the wav-data to sound pressure. Each microphone was time adjusted to become synchronized before representative background sequences and wind-turbine-turned-

on sequences were selected. Time segments with disturbing noise from trucks and other vehicles passing by the nearby road was excluded from the analysis. Sound pressure levels in dB(A) from the wind turbine was then calculated from the difference in mean sound power of the wind turbine and background sequences.

3.3 Observations

The T1-turbine is situated in a plain field with a heavy trafficked freeway 750 m to its southwest. Interfering noise from this freeway was evened out due to the distance and was approximately at the same level for all microphones during the entire recording. Furthermore there is an industrial recycling center located nearby with its access road just 70 m from the turbine. Interfering noise from trucks, cars and tractors passing by were cut out during data processing. Eight microphones sets were placed at 45° intervals at a distance of 40 m from the tower base. Then a recording was performed with the turbine first turned on for 30 minutes, then turned off for 30 minutes. Wind speed, wind direction and atmospheric conditions for both turbine and background recordings was measured with a 40 m high measurement mast situated 100 m from the turbine and logged together with the electrical output from the turbines own control system.

The experimental measurements were performed between 13:35 and 14:35, on 2015-01-20. The wind speed at hub height varied between 4 m/s and 9.5 m/s with a mean wind speed of 6.4 m/s when the wind turbine was turned on and 7.1 m/s when recording background noise. Recalculating for 10 m above ground the mean wind speeds were 5.2 m/s and 5.7 m/s for turbine and background segments respectively. The higher wind speed of the background recording will lead to a slight underestimation when calculating the portion of noise coming from the wind turbine. Since exactly the same time sequences are analyzed for all microphones, this will have a negligible impact on the relative results between the microphones and thus the directivity. The wind direction was close to eastern, with minute averages ranging from 79° to 83° (mean 81°) counting clockwise from north. The turbine was operating at the lower limit rotational speed, staying within 15.8-16.2 rpm during the entire operational time. The humidity was just above 100%, with moderate snowing. The temperature was within 0.5°C to 1.5°C and the pressure was steady at 101.2 kPa during the entire measurement.

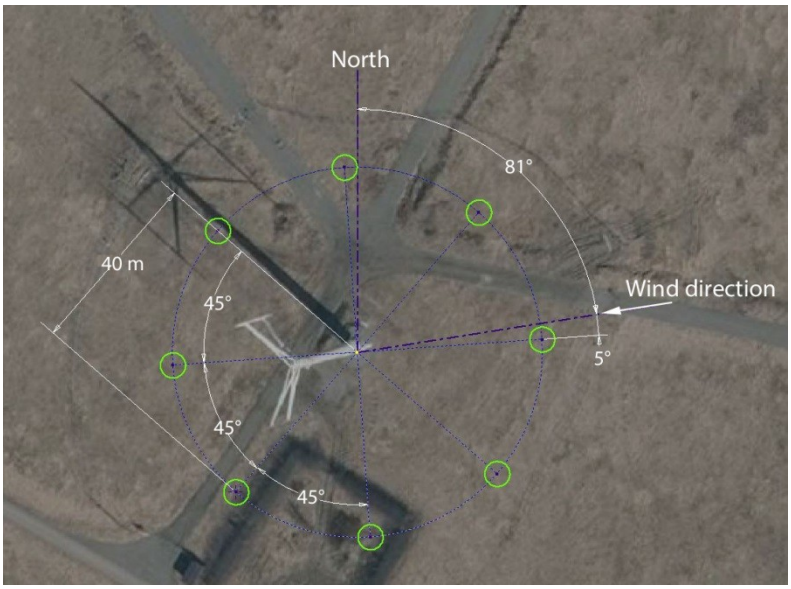

Figure 2: The microphones location relative the turbine base and mean wind direction during measurements. Note that the camera is not directly above the turbine, thus displacing the rotor from the base in the picture.

4. Results

4.1 Noise directivity

In figure 3 the noise directivity measurements are presented as a polar plot. In figure 4 the same results can be seen plotted together with the theoretical directivity pattern from “2.1 Noise directivity prediction model”. The experimental results follow the theoretical pattern reasonably well, with the highest sound pressure levels upwind of the rotor and the lowest levels in the perpendicular directions. With the exception of the upwind maximum value, the experimental extreme points are found at an angle slightly higher than that of the theoretical model. Furthermore, the minimum value found at approximately 270° is not as low for the experiments as the theoretical model.

The difference between the experimental results and the theoretical model is probably due to a combination of the limited amount of measurement data and the simplifications made in the theoretical model. For example, it would be interesting to include the turbulence inflow noise which according to [12] has a directivity that differs substantially from that of the TBL-TE noise modelled in this work.

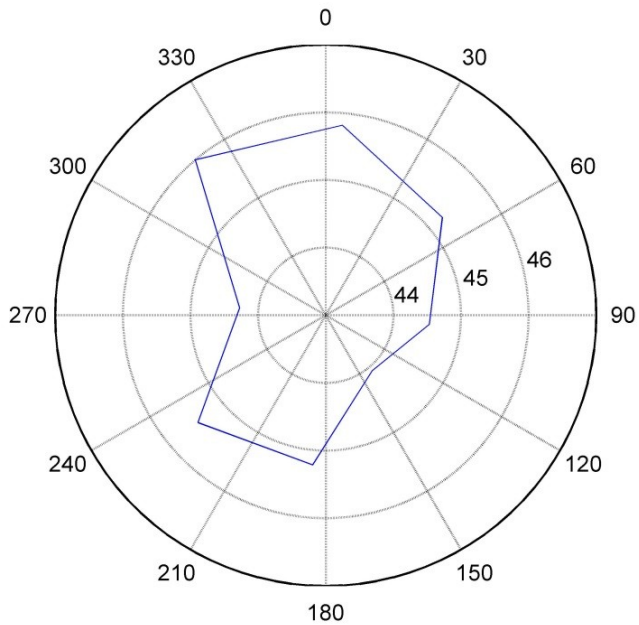

Figure 3: The noise directivity from the experimental measurements. Upwind is 0°. Radial axis unit in dB(A).

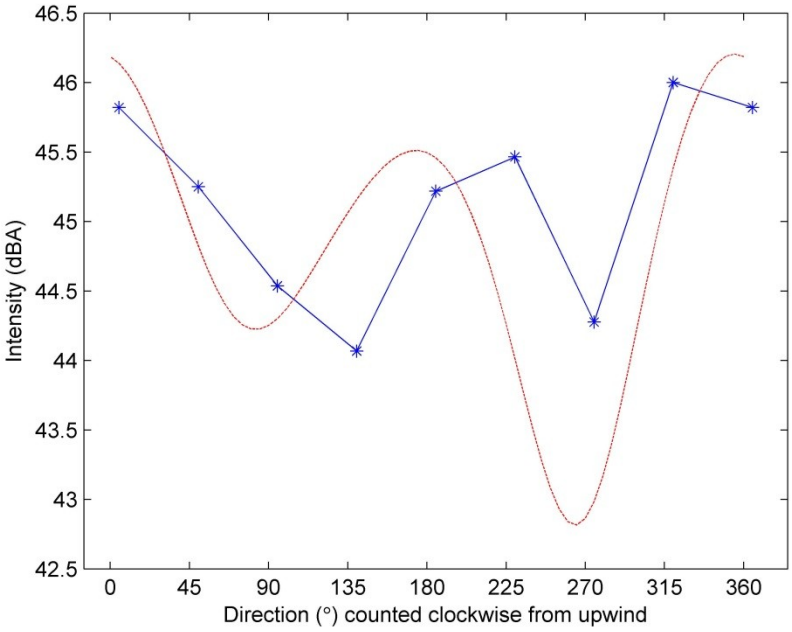

Figure 4: The noise directivity from experiments (blue) compared to theory (red)

4.2 Amplitude modulations analysis

Amplitude modulations of the wind turbine were estimated using the Lundmark calculation procedure [15], which has also been used by Larsson and Öhlund [16]. This procedure is based on an FFT algorithm of the sound levels ($L_{Aeq125ms}$) and calculates RMS values for different frequencies. Larsson and Öhlund used a threshold of RMS>0.4 [16] to detect thresholds and the same limit was used in this paper. In total 1600 segments (200 in each direction) were analyzed, in half of these samples the turbine was operational and the other half the turbine was still. The probability distributions of the maximum amplitude modulations in the frequency interval 0.6-1.7 Hz are shown in figure 5 for each direction separately. As can be seen lower amplitude modulations are probable when the turbine is off. The modulation threshold of 0.4 is exceeded for 22% of the segments when the turbine is on and 14% when the turbine is off. A nearby factory was causing audible impulsive noise at a 1 Hz modulation frequency which is probably responsible for the modulations in the sound when the turbine was not operating.

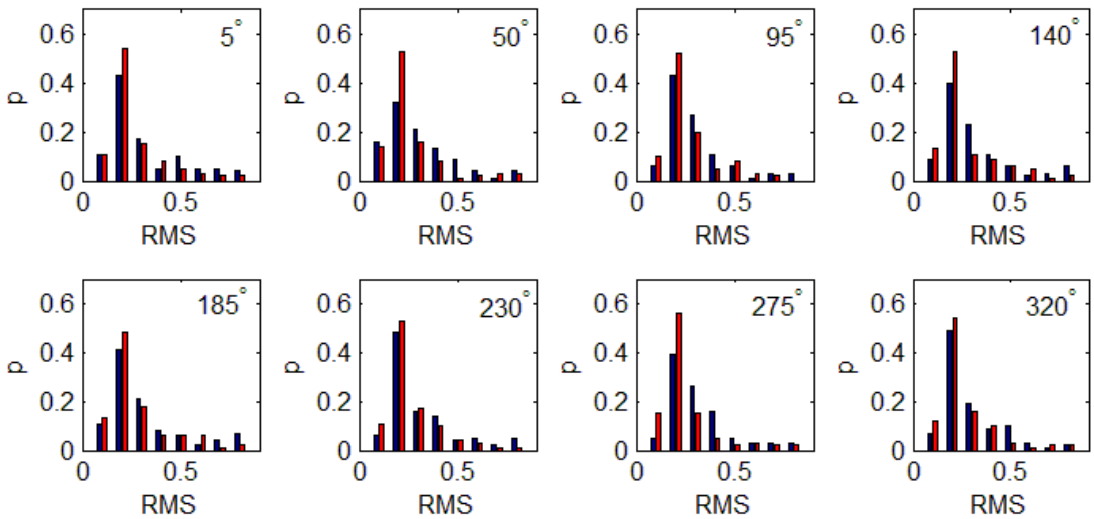

Figure 5: Probability distributions of the amplitude modulations in the eight directions, blue bars show the turbine turned on and red bars show the turbine turned off.

An ANOVA, comparing the distributions with turbine on/off, shows a statistically significant difference ($p<0.05$) for five directions indicating that the recordings contain amplitude modulations from the turbine. However, when examining the peak in modulation frequency only 100 out of 800 segments had the peak at the blade passing frequency (0.8 Hz) which indicates that the turbine is not the source of the modulations. Consequently, the amplitude modulation analysis show inconclusive results and would probably benefit from renewed measurements and further analysis before the presence of amplitude modulations from the vertical axis turbine can be confirmed or not.

5. Conclusions

The theoretical model of TBL-TE noise suggests higher noise levels upwind and the lowest noise levels in the perpendicular directions. This model is supported by the noise directivity measurements which follows this pattern. Analyzing amplitude modulations indicate the presence of modulations but the results are inconclusive.

Noise origination from VAWTs is more complex compare to that of HAWTs, and the less explored nature of VAWT noise makes it more difficult to predict. For example, lack of empirically established modelling of the displacement thickness δ^* during dynamic stall ads uncertainty. Addressing VAWTs, the static relations commonly used when evaluating HAWT noise are clearly inadequate as the displacement thickness and thereby also the sound levels gets exaggerated.

The noise characteristics of VAWTs needs to be investigated further and the 200 kW VAWT creates an opportunity doing so utilizing arguably the largest operational VAWT existing today. In addition of further investigation of the noise directivity, examples of future work on the T1-turbine could be quantification of the aerodynamic noise sources using a microphone array.

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References

[1] S. Eriksson, H. Bernhoff, and M. Leijon, “Evaluation of different turbine concepts for wind power,” *Renewable and Sustainable Energy Reviews,* vol. 12, no. 5, pp. 1419-1434, 2008.

[2] F. Ottermo, and H. Bernhoff, “An upper size of vertical axis wind turbines,” *Wind Energy,* vol. 17, no. 10, pp. 1623-1629, 2013.

[3] D. Bowdler, and H. G. Leventhall, *Wind Turbine Noise*: Multi Science Publishing Company, Limited, 2011.

[4] K. Bolin, “Wind Turbine Noise and Natural Sounds: Masking, Propagation and Modeling,” Ph.D. thesis, Royal Institute of Technology, 2009.

[5] E. Pedersen, “Human response to wind turbine noise: Perception, annoyance and moderating factors,” Ph.D. thesis, The Sahlgrenska Academy, University of Gothenburg, 2007.

[6] A. Iida, A. Mizuno, and K. Fukudome, “Numerical simulation of aerodynamic noise radiated from vertical axis wind turbines,” in Proceedings of the 18 International Congress on Acoustics, Kyoto, Japan, 2004.

[7] H. Dumitrescu, V. Cardos, A. Dumitrache, and F. Frunzulica, “Low-frequency noise prediction of vertical axis wind turbines,” *Proceedings of the Romanian Academy,* vol. 11, no. 1, pp. 47-54, 2010.

[8] C. Pearson, “Vertical axis wind turbine acoustics,” Ph.D. thesis, Cambridge University, 2014.

[9] E. Möllerström, S. Larsson, F. Ottermo, J. Hylander, and L. Bååth, “Noise propagation from a vertical axis wind turbine,” in inter.noise2014, Melbourne, Australia, 2014.

[10] S. Oerlemans, and J. Schepers, “Prediction of wind turbine noise and validation against experiment,” *International journal of aeroacoustics,* vol. 8, no. 6, pp. 555-584, 2009.
[11] G. J. M. Darrieus, *Turbine having its rotating shaft transverse to the flow of the current*, Patent no. 1835018, U. S. P. Office, 1931.
[12] S. Oerlemans, P. Sijtsma, and B. Méndez López, “Location and quantification of noise sources on a wind turbine,” *Journal of Sound and Vibration,* vol. 299, no. 4–5, pp. 869-883, 2/6/, 2007.
[13] T. F. Brooks, D. S. Pope, and M. A. Marcolini, *Airfoil self-noise and prediction*: National Aeronautics and Space Administration, Office of Management, Scientific and Technical Information Division, 1989.
[14] K. Gharali, and D. A. Johnson, “PIV-based load investigation in dynamic stall for different reduced frequencies,” *Experiments in Fluids,* vol. 55, no. 8, pp. 1-12, 2014.
[15] G. Lundmark, “Measurement of swish noise, a new method,” in Fourth International Meeting of Wind Turbine Noise, INCE/Europe, Rome, Italy, 2011.
[16] C. Larsson, and O. Öhlund, “Amplitude modulation of sound from wind turbines under various meteorological conditions,” *The Journal of the Acoustical Society of America,* vol. 135, no. 1, pp. 67-73, 2014.