A novel method of vertical axis wind turbine noise prediction

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Summary
Vertical Axis Wind Turbines are becoming more commonplace in urban environments but to date there has not been much computational work done to quantify their noise outputs. The EU FP7 project: SWIP (New innovative solutions, components and tools for the integration of wind energy in urban and peri-urban areas) aims to deal with, and overcome, the main barriers that slow down the largescale deployment of small and medium size wind turbines. One of the outputs of the project is a novel, six bladed, vertical axis wind turbine rated at 2kW.
This work aims to predict aeroacoustic noise generated by the SWIP vertical axis wind turbine by means of a novel noise prediction method. Due to the high computational cost of LES an approach is proposed in which ANSYS Fluent is used to determine the transient flow solution, using unsteady RANS calculation, on a 2D section of the wind turbine undergoing rotation. Acoustic signals are calculated by employing a MATLAB code which uses the CFD solution as input data into a semi-empirical solver based a number of airfoil noise prediction algorithms. The 2D CFD data is interpolated onto a 3D model of the turbine using a quasi-steady time stepping approach. An estimate of the aeroacoustic noise of the turbine is established and the sensitivity of the code to changes in time step and discretisation is considered.

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1. Introduction

1.1. Vertical Axis Wind Turbines

Vertical Axis Wind Turbines (VAWT's) are a type of wind turbine used to convert kinetic energy from moving air into electrical power by means of lift producing blades. They differ to the conventional Horizontal Axis Wind Turbines (HAWT's) by having the main shaft transversely aligned with the wind direction. Vertical Axis Wind Turbines are seen as a viable solution to urban and peri-urban power generation requirements leading into 2020.

1.2. VAWT Aerodynamics

Wind turbines use standard airfoil sections to generate lift from an oncoming flow. As wind turbine airfoils rotate through clean air they produce noise from the interactions between the fluid (air) and the solid (turbine blade). The noise generated by the turbine blades is thus proportional to a number of aerodynamic parameters of the blades themselves and therefore it is advantageous to understand how the aerodynamic forces on the blades are produced and how to predict them.

Wind turbine aerodynamic performance can be predicted in a number of ways, each method outlined indicates an increase in computational effort in proportion to the fidelity of the model. As with any mathematical model there is a diminishing return of solution accuracy against computational effort.

- *Double Multiple Streamtube Model:* This model uses a number of streamtubes to predict rotor performance based on input data from a 2D airfoil polar. The method is used in the code QBlade [1]. The code, however, cannot solve for boundary layer velocity profiles or turbulent inflow parameters.
- *Unsteady 2D CFD:* By solving the Navier-Stokes equations for a rotating blade an estimate of its aerodynamic performance can be predicted. However, any 3D flow effects such as tip losses or cross flow would be negated in a 2D calculation.
- *Unsteady 3D CFD:* An extension of the previous method would yield better aerodynamic results, these results could be used to predict rotor power output.
- *DES:* Using a Deattached-Eddy Simulation (DES) should yield even more accurate results at a very

high accuracy. Results of these simulations would allow one to solve directly the Ffowcs-Williams Hawkings equations to propagate sound signals to a far field listener location. Similar work is done by Mohamed, 2014 [2].

As a single VAWT blade rotates around its own axis it experiences a number of different inflow conditions based on its azimuth angle. Figure 4 shows an example of a model of a single VAWT blade rotating about its axis. A full VAWT maxhine would consist of multiple equi-spaced blades. The blade encounters a series of dynamic stall events during rotation. From geometric considerations the resultant velocity that the blade experiences at any given azimuth angle (θ) is defined as W [m/s] (equation (1)), where U [m/s] is the freestream velocity and λ is the Tip Speed Ratio (TSR) (equation (2)). For equation (2) ω is the angular velocity [rad/s] and R is the radius of the turbine [m]. The effective angle of attack (angle between the blade chord and oncoming flow) of the turbine blade at any given azimuth angle is defined by α in (3).

$$W = U\sqrt{1 + 2\lambda cos\theta + \lambda^2} \quad (1)$$

$$\lambda = \frac{\omega R}{U} \quad (2)$$

$$\alpha = tan^{-1}(\frac{sin\theta}{cos\theta + \lambda}) \quad (3)$$

Figure 1 show the relationship between the effective inflow velocity and angle of attack for changes in the azimuth angle. It should be noted that even though the blade undergoes a geometric rotation of 360° it never experiences more than a certain *effective angle of attack* due to the velocity vectors acting on the blade. In the case of figure 1 the oncoming flow is a constant 8.41 m/s and the blade is rotating at 17.226 rad/s in a counter-clockwise direction.

1.3. Wind Turbine Aerodynamic Noise

Noise generated by Vertical Axis Wind Turbines is broadband in nature and is produced by two primary noise generation mechanisms: Inflow noise [3] and Turbulent Boundary Layer Trailing Edge (TBL-TE) noise [4].

Until present there has not been much need to predict the aerodynamic noise generated by VAWT machines as they have generally been considered to be *quiet enough*. It is, however, still imperative to quantify the noise that is to be generated by such devices in order to aid in the swift acceptance of building plans when designing a new turbine for an urban or peri-urban location.

Most manufacturers do not perform detailed noise studies of their designs and merely provide a single

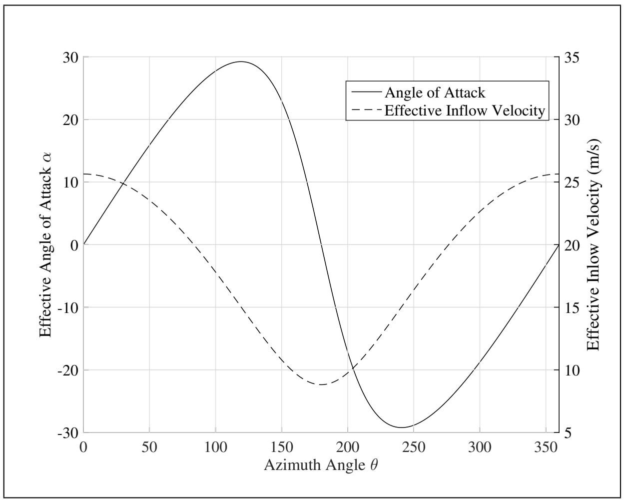

Figure 1. Relationship between angle of attack and effective inflow velocity with change in azimuth angle.

figure on their specification sheets saying that the devices adhere to requirements for noise levels in urban environments. Table I highlights the noise specifications given by some manufacturers of Vertical Axis Wind Turbines. The turbines selected are in the range 1.5 to 3 kW rated power save for the QR5 which was selected for the table due to the detailed noise measurements provided on their datasheet.

2. Prediction Model and Approach

The modelling approach used to predict noise from airfoils requires aerodynamic data from the wind turbine blades. Traditionally, low order prediction models will use rough estimates of aerodynamic forces on blades to provide input data to the relevant noise calculation modules of these particular types of codes [11]. The success of these codes lies in the assumption that the upstream blades have no effect on their downstream counterparts (a suitable HAWT assumption); however, during the rotation of a VAWT there is considerable interaction from upstream blade wake on downstream elements [12] that can be accounted for by performing a CFD calculation.

A novel noise modelling approach is proposed here which utilises aerodynamic data from CFD models as input data to a noise prediction algorithm based on two separate sets of semi-empirical airfoil noise codes. The CFD simulation provides a calculation for the boundary layer velocity profile and inflow turbulence parameters of a turbine blade undergoing rotation. This CFD data is written to ASCII files and is read by the noise prediction algorithm (developed in MATLAB).

This approach has been developed to predict the noise generated by the V2 VAWT which has been de-

Table I. Noise measurements of Vertical Axis Wind Turbines as provided by manufacturers

Turbine	Power Rating (kW)	Noise Level	Wind Speed (m/s)	Distance from Turbine (m)
Aerocopter [5]	2.0	<37 dB	-	-
Aeolos-V [6]	2.0	<45 dB	-	-
DS-3000 [7]	3.0	<40 dB (A-weighted)	-	-
P3000-AB [8]	3.0	-	-	-
QR5 [9]	6.5	57.9 dB (max)	10.0	22.5
VisionAir5 [10]	3.0	<38 dB	5.0	-

Table II. V2 Turbine Parameters

Parameter	Value
Chord	0.3 m
Pitch	-2.0°
Rotor radius	1.0 m
Blade span	4.5 m
Blade offset angle	90°
Number of blades	6
Airfoil	Data withheld
Rated power (operating point)	2.0 kW

Table III. Simulation Parameters

Parameter	Value
Wind speed (operating point)	8.41 m/s
Rotational velocity (ω)(operating point)	17.226 rad/s
Turbulence Model	k-ω SST
Turbulent Length Scale	11 m
Turbulent Intensity	20 %
Time Step	0.338 ms
Number of Rotations	6
Time Steps per Rotation	1 080

signed by the blades design group project partners on the SWIP project. The specifications of the V2 design are summarised in table II.

2.1. Aerodynamic Modelling

The approach used to resolve the aerodynamic forces for the suggested model of the given VAWT has been to implement a Computational Fluid Dynamics (CFD) model. As well as being used as input data to the aerodynamic solver this CFD data will also be used to fine-tune the model in the future. There is additional scope for finding an alternative aerodynamic model, but first an understanding of the existing conditions affecting the confluence between the blades needs to be achieved.

It is of fundamental importance to accurately predict the boundary layer velocity profiles at the trailing edge of the blades as well as predicting the turbulent inflow conditions at some location just ahead of the oncoming blade. A data probe writes out the required data for each time step, within a single rotation, along lines normal to both the pressure and suction sides of the trailing edge as well as a line protruding from the leading edge.

ANSYS Fluent is used as the CFD code to solve the Navier-Stokes Equations within the computational domain. A number of simplifying assumptions are imposed in order to speed up computational time without losing model fidelity. To model turbulence a k-ω SST turbulence model is selected. The selection thereof is due to Shear Stress Transport (SST) models showing success in predicting separated flows [13].

The computational domain is discretised into a grid consisting of about 220 000 nodes. The size of the domain is shown in figure 2 where C is a nondimentional measure of the airfoil chord length. The spacing of the nodes is more refined at the walls of the airfoils and less refined near the boundaries. The airfoil walls require more refinement in order to predict the large velocity gradient boundary layer flows in these regions. The time-step of the transient model is selected to provide sufficient numerical accuracy of results pertaining to the rotation of the turbine. It is decided to use a timestep of 0.338 $ms/timestep$ which corresponds to 1080 timesteps per rotation or 3 timesteps per azimuth rotation degree. Further refinement of the input data will be performed at a later stage to determine the sensitivity of the noise computations to the quality of the input data. Table III summarises the boundary conditions of the CFD simulation.

Figure 3 shows the thrust and normal force generated by a single blade of the turbine during rotation. This can be compared with other simulation data as it becomes available. As expected the turbine shows a large production of thrust for the first 120° of rotation to coincide with the increasing effective angle of attack of the blade (see figure 1). As the blade stalls it gradually generates less thrust until, at roughly 220° azimuth angle the blade actually produces a small amount of drag.

2.2. Acoustic Modelling

A quasi-steady approach is used to model the noise generated by the wind turbine. The length of a single blade is discretised into a number of strip sections, each representing a finite point source. The point

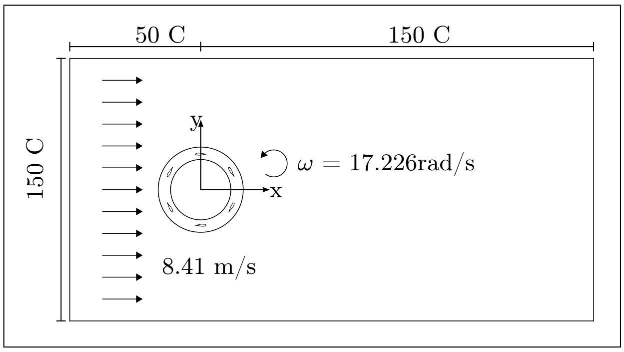

Figure 2. Computational domain and boundary conditions. Rotor size exaggerated for clarity.

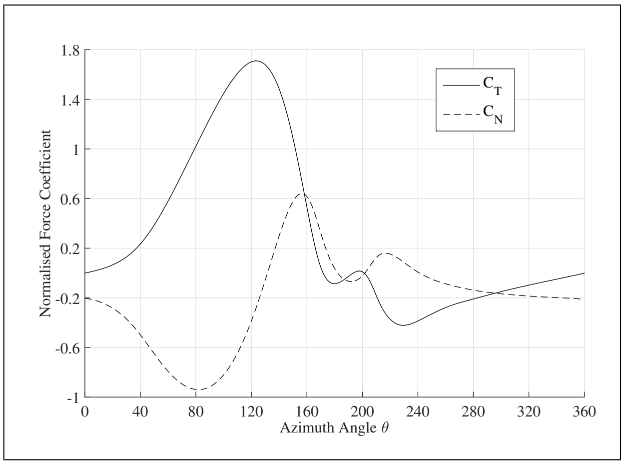

Figure 3. Relationship between angle of attack and effective inflow velocity with change in azimuth angle.

sources are all located at the trailing edge of the blade. The number of point sources and geometry of the blade *(blade span, pitch, chord length, angular offset, quarter chord location, hub radius)* can all be defined by the user but should correspond to the model used for the CFD input data. Figure 4 shows an example of the discretisation scheme employed for an arbitrary VAWT blade. In this figure the coordinate system corresponds with that of the CFD model and the angle θ is the azimuth angle of the source blade. The contribution of all the point sources along a single blade are averaged during each time step and then the contribution of the noise of all the blades is summed to obtain the total noise produced by a single rotation of the rotor.

At present the total aerodynamic noise generated by the turbine is modelled as the contribution from two major airfoil noise generating mechanisms; namely, Turbulent Boundary Layer - Trailing Edge and Inflow Noise. According to Moriarty et al. [14] most noise generated by wind turbines, especially at low frequencies, is dominated by inflow noise. Due to the location of the turbine being in a highly turbulent environment for the SWIP project this will be an important contributing factor to be modelled.

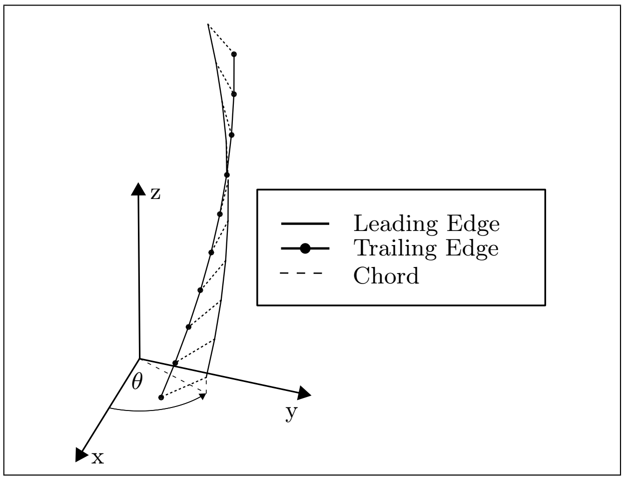

Figure 4. Model of single VAWT blade indicating coordinate system and point sources.

Secondly the most common noise generation mechanism will be from the TBL-TE noise will also be modelled. Additional contributions from other noise generation mechanisms will be outside the scope of the model for the moment.

Turbulent Boundary Layer - Trailing Edge (TBL-TE) noise is calculated using the empirical models from Brooks et al. [4] as seen in equations 4 - 6. The equations are summed to predict the TBL-TE noise for contributions from (as in the subscripts); s, the suction side of the airfoil; p, the pressure side of the airfoil and α the angle dependent airfoil noise contribution related to stall. Furthermore the equations are a function of; δ^*, the trailing edge boundary layer displacement thickness [m]; M, the airfoil mach number; L, the airfoil length [m]; $\bar{D}$, the directivity functions [1] (which are modified for high and low frequency corrections); r_e, the distance to the receiver; A, the spectral shape function for TBL-TE noise; St, the Strouhal numbers and; factors K, various constants.

$$SPL_p = 10log\left(\frac{\delta_p^* M^5 L\bar{D}_h}{r_e^2}\right) + A\left(\frac{St_p}{St_1}\right) + (K_1 - 3) + \Delta K_1 \quad (4)$$

$$SPL_s = 10log\left(\frac{\delta_s^* M^5 L\bar{D}_h}{r_e^2}\right) + A\left(\frac{St_s}{St_1}\right) + (K_1 - 3) \quad (5)$$

$$SPL_\alpha = 10log\left(\frac{\delta_s^* M^5 L\bar{D}_h}{r_e^2}\right) + B\left(\frac{St_s}{St_2}\right) + K_2 \quad (6)$$

[1] For the low frequency directivity function there is a pure dipole behaviour arising from the length scale of the turbulence and the chord of the airfoil being of comparable sizes. For the high frequency directivity a baffled dipole behaviour is seen.

In the VAWT prediction code, inflow noise is handled by semi empirical equations from Amiet [15] and reformulated by Lowson [3] as in equations 7 to 10. Where LFC is the low frequency correction, ρ_0 is air density [kg/m^3], c_0 is the speed of sound [m/s], l is the turbulent length scale [m], L is chord length [m], M is blade Mach number, u is turbulent velocity in the atmospheric boundary layer [m/s], I is turbulent intensity [%] and K is the wave number ($K = (\pi f L)/W$) [kg/m^3], $\bar{D}_h$ is low frequency directivity as before, S^2 is the Sears function and β is a Mach number correction ($\beta^2 = 1 - M^2$).

$$SPL_{Inflow} = SPL^H_{Inflow} + 10log\left(\frac{LFC}{1+LFC}\right) \quad (7)$$

$$SPL^H_{Inflow} = 10log\Bigg(\frac{\rho_0^2 c_0^2 l L}{2r_e^2} M^3 u^2 I^2 \frac{K^3}{(1+K^2)^{7/3}} \bar{D}_L\Bigg) + 58.4 \quad (8)$$

$$LFC = 10 S^2 M K^2 \beta^{-2} \quad (9)$$

$$S^2 = \left(\frac{2\pi K}{\beta^2} + \left(1 + 2.4\frac{K}{\beta^2}\right)^{-1}\right)^{-1} \quad (10)$$

A directivity correction is included to account for the propagation of each of the noise sources to the receiver. Both a high and low frequency correction based on the direction vector between the receiver and the point source in question are implemented.

The total noise generated by the device is calculated as the summed contribution of noise generated by a single blade throughout 360° rotation multiplied by the number of blades the turbine has.

2.3. Results and Comparisons

The code is run using an approximate model for the SWIP V2 wind turbine. A constant one dimensional flow field is used and the centre rotor is disregarded. The receiver is located at a distance 10m below and 10m upstream of the base of the turbine as per the coordinate system in figure 4. Results of the noise prediction are A-weighted and presented as the Overall Sound Pressure Level (dB) of the turbine.

It was observed that the noise prediction code was sensitive to the selected discretisation scheme for time stepping as well as the number of point sources along a blade length. This sensitivity can be seen in figure 5 which shows the average SPL produced by the turbine for changes in step size and number of point sources. It was observed that there was a negligible change in results with changes in step size beyond 200 steps. The number of point sources along the blade, however, did contribute greatly to results showing an increasing trend up until about 70 sources are selected.

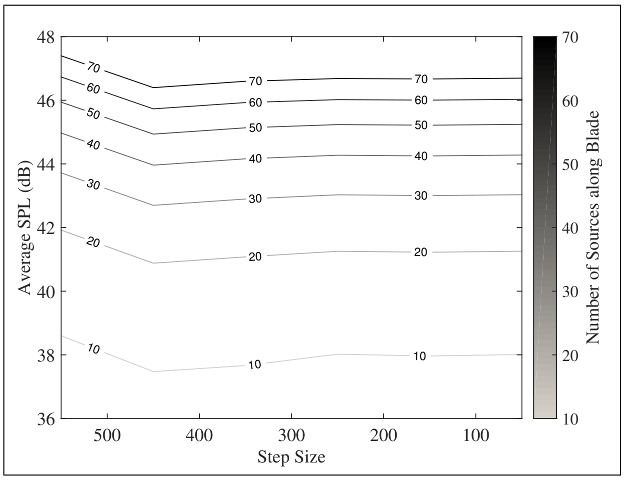

Figure 5. Convergence of the solution based on discretisation of time step and number of sources along the blade

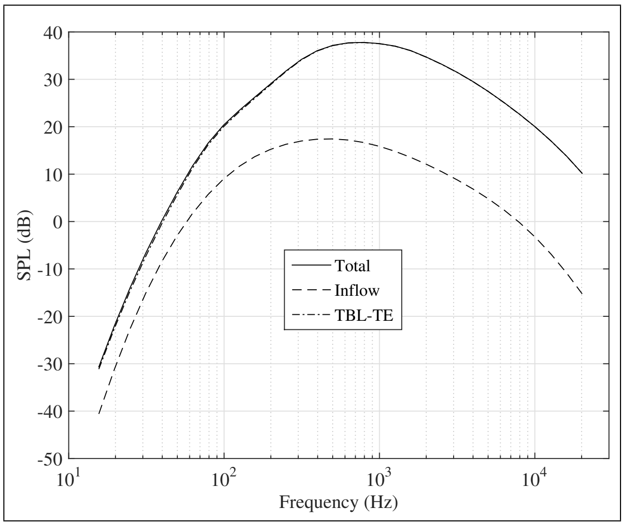

Figure 6. A-weighted overall sound pressure level during a single turbine rotation

Figure 6 shows the results of the noise prediction for a single rotation of the given VAWT machine. The averaged overall sound pressure level is a combination of the Inflow Noise (*27.19 dB*) and the TBL-TE noise (*46.96 dB*) providing a total average overall sound pressure level of *47.0 dB*. It is seen from the spectral analysis that the noise is broadband in nature (as assumed by the models used) and tends to be dominated by (TBL-TE) noise effects. This is attributed to the fact that, unlike in a horizontal axis machine, the rotation of the blades around their own axis causes a decrease of the length scale of the inflow turbulence.

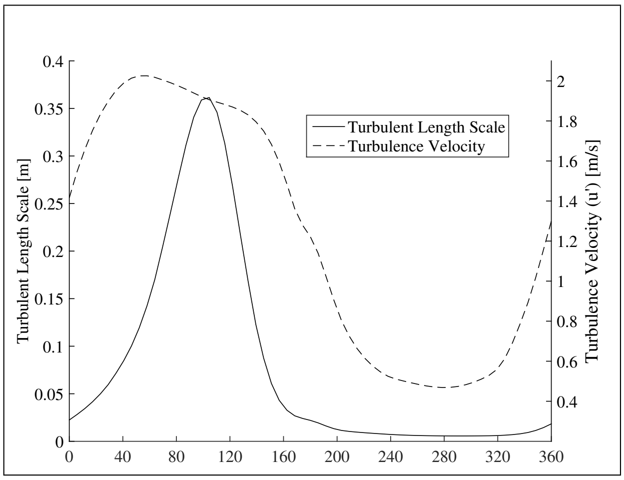

Figure 7. Turbulence during rotation

It is understood that, from the CFD simulation, the airfoils begin to generate their own turbulence during rotation. For the current simulation the inflow length scale is defined at the inlet as 11m but during turbine operation the length scale decreases considerably to the levels seen in figure 7.

3. CONCLUSIONS

A prediction code is developed to estimate the noise generated by a Vertical Axis Wind Turbine. The code requires a series of design parameters for a vertical axis wind turbine, a listener location as well as information with regards to the boundary layer profiles and airfoil inflow turbulence conditions (in this case from a CFD model). Two primary noise generation mechanisms are modelled for the source modelling. Subsequently the code returns the SPL produced by the turbine in the frequency domain.

The code is seen to be sensitive to the selection of the number of point sources along the blade but not overly sensitive to the selection of the step size. For the given configuration it was seen that noise generation was dominated by TBL-TE noise and that results from the code are of the same order of magnitude as those reported by manufacturers of turbines with similar power ratings.

It was of interest to see that Inflow noise had a considerably lower contribution to total noise than TBL-TE noise and this will be further investigated through experiments. Future work on the code will involve observing sensitivity to different types of input data from more refined CFD models.

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