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# An implementation of an aeroacoustic prediction model for broadband noise from a vertical axis wind turbine using a CFD informed methodology

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ABSTRACT

This paper presents an enhanced method for predicting aerodynamically generated broadband noise produced by a Vertical Axis Wind Turbine (VAWT). The method improves on existing work for VAWT noise prediction and incorporates recently developed airfoil noise prediction models. Inflow-turbulence and airfoil self-noise mechanisms are both considered. Airfoil noise predictions are dependent on aerodynamic input data and time dependent Computational Fluid Dynamics (CFD) calculations are carried out to solve for the aerodynamic solution. Analytical flow methods are also benchmarked against the CFD informed noise prediction results to quantify errors in the former approach. Comparisons to experimental noise measurements for an existing turbine are encouraging. A parameter study is performed and shows the sensitivity of overall noise levels to changes in inflow velocity and inflow turbulence. Noise sources are characterised and the location and mechanism of the primary sources is determined, inflow-turbulence noise is seen to be the dominant source. The use of CFD calculations is seen to improve the accuracy of noise predictions when compared to the analytic flow solution as well as showing that, for inflow-turbulence noise sources, blade generated turbulence dominates the atmospheric inflow turbulence.



## 1. Introduction

Small Vertical Axis Wind Turbines (VAWT) can be easily integrated into urban and peri-urban environments as a means to generate power in these locations. There has been very little work reported to quantify their noise output as it is generally considered that small VAWT's should be *quiet enough* given that their deployment in urban areas means that their noise output rarely exceeds that of their surroundings [1]. However, early stage noise source prediction is still necessary during turbine design in order to approve designs for integration into urban environments.

Small Wind Turbines (SWT's) are defined, according to IEC 61400-2:2013, an International Standard published by the International Electrotechnical Commission regarding wind turbines, as having a swept area of less than 200 $m^2$. This corresponds to a Horizontal Axis Wind Turbine (HAWT) with a diameter of around 16 m. For a VAWT with an equivalent swept area, this corresponds to any machine with a diameter of less than 5 m and span of 10 m.

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Preliminary design of SWT's almost exclusively incorporates the use of low- or reduced-order prediction tools to make early performance estimates. Popular design tools such as QBlade [2] utilise methods such as the Double-Multiple Streamtube (DMS) [3] approach for aerodynamic performance estimates. Noise estimates may subsequently be made based on these preliminary flow calculations.

Wind turbines generate noise from both mechanical and aerodynamic sources. Mechanical noise is produced by gearboxes, yaw mechanisms and other instruments required to convert wind power into electricity. Small turbines, however, have very few moving parts and very often incorporate direct drive generators instead of gearboxes. The noise from these components is either very low or can easily be treated through the use of acoustic liners within the nacelle.

The primary noise generation mechanism present in modern SWT's is aeroacoustic noise [4]. This noise source is produced by the aerodynamic effect of turbine blades interacting with incoming flow. The individual components of this noise source can be separated into a number of categories, namely: low-frequency noise, inflow-turbulence noise, tonal noise and airfoil self-noise. Prediction of these noise sources, as applicable to turbine blades, is repeatedly accomplished by implementing codes [4-9] based on semi-empirical methods by; Brooks et al. [10] for airfoil self-noise, and analytic methods by Paterson and Amiet [11] for inflow-turbulence noise sources. These methods discretise a 3D turbine blade geometry into a number of 2D airfoil strip sections in space and then apply the models in a spanwise manner in time to account for blade rotation. Low-frequency noise is not of major concern for wind turbines with an upwind configuration (blades ahead of tower) [12]. Furthermore, the blade passing frequencies of modern VAWT's are of the order of several hertz, thus falling into the lower end of the audible noise spectrum - this noise source is probably not applicable to small turbines due to their lower relative operating speeds. Several studies have been performed to validate the aforementioned flow and noise prediction codes for their applicability to the problem of HAWT noise and continue to show good agreement with experiment [4,13]. Such codes continue to be used in HAWT development.

VAWT blades undergo highly unsteady flow fluctuations as they rotate about their own axis [14,15]. Unsteady forces act on these turbine blades due to geometric effects and blade-blade aerodynamic interactions; causing unsteady power generation with rotation. Unsteady flow will generate unsteady aeroacoustic noise generation and the effect of these unsteady parameters on noise generation has not yet been explored in a prediction study.

Time dependent 2D and 3D Computational Fluid Dynamics (CFD) calculations have been seen to provide more detailed flow solutions for VAWT aerodynamics when compared to rudimentary stream tube models. CFD calculations can be used to quantify the anisotropy of turbulent fluctuations within the rotor. Furthermore, wind tunnel testing of assembled VAWTs is difficult to perform and only a limited number of experimental results are available [16,17]. Experimental campaigns are mostly used to study overall performance as opposed to looking at detailed flow structures. Li et al. [16] performed a thorough investigation of the flow features around the blade of a VAWT, verifying CFD calculations against wind tunnel test data and showed that CFD calculations performed well when an appropriate turbulence model was applied. There are, however, some outstanding issues to be addressed when using CFD for VAWT aerodynamic prediction [18]. An example of this is the matter of grid dependency such as the study by Almohammadi et al. [19] showing the sensitivity of the power/torque calculations to mesh types and the time step/Courant number.

The primary objectives of the present study are concerned with the development of a validated computational method for the prediction of noise generated by a VAWT. Additionally the new methods will make use of CFD calculations as input data to existing noise models since CFD calculations can be used to efficiently (and more accurately) predict detailed flow features including turbulence parameters which are important inputs required for noise prediction models. Models for inflow-turbulence and self-noise sources are implemented. This approach would realise the applicability of a hybrid noise prediction method for aerodynamically generated VAWT broadband noise sources. This study will aid in determining the location and mechanism of dominant noise sources arising from aerodynamically generated VAWT noise as well as understanding the effect that turbulence has on overall VAWT noise. The method is verified against an existing test case in order to establish its applicability to the present problem. Finally the method is used to study the effect of parameter variations on noise production for the SWIP V2 turbine, A 2 kW VAWT developed by the consortium of partners working under the EU directive FP7 project, SWIP[1].

## 2. Airfoil noise models

For this study, four noise prediction models were implemented. Two models were implemented to predict self-noise and another two for the prediction of inflow-turbulence noise. The results from each noise model will be compared in order to determine each ones' applicability to the prediction of VAWT noise.

A limitation of these noise models is that specific aerodynamic interaction between following blades is not considered - the blades are modelled in isolation. It is also assumed that the self-noise produced by the wind turbine blades is produced under steady flow conditions. In summary; the formulations assume steady, free stream, conditions under a quasi-steady time dependence.

[1] The overall objective of the SWIP project is to develop, implement and test innovative solutions and components for tackling the current barriers that wind turbines encounter, opening the way for a successful market uptake in the near future [20]. This objective follows an EU directive to improve onshore wind power penetration with a goal of achieving 20% penetration by 2020.