Aerodynamics and aeroacoustics of a Vertical Axis Wind Turbine

L Brandetti[a], F Avallone[a], C J Simao Ferreira[a], D Casalino[a]

[a] AWEP Dept., Faculty of Aerospace Engineering, Delft University of Technology, Delft, the Netherlands

E-mail: l.brandetti@tudelft.nl

Keywords: Vertical Axis Wind Turbine, Aeroacoustics, Aerodynamics.

According to the orientation of the axis of rotation, wind turbines are classified in: Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs). Next to the most conventional and economically feasible HAWTs, VAWTs have advantages: the intrinsic omnidirectionality of VAWTs does not require the design of yaw motors; the location of the generator on the ground leads to easier access and, consequently, lower maintenance cost [1]; they are visually more appealing and suitable for the installation into urban environments. In order to be located in an urban environment, noise regulations must be respected. For operating wind turbines, it is possible to distinguish between mechanical and aerodynamic noise sources. The first one is caused by the dynamic response of the moving mechanical components while the latter is produced by the interaction of the airflow with the blades [2]. Nowadays, the major focus is on aerodynamic noise, proving that mechanical noise has been already optimized [3]. Aerodynamic noise can be divided in: turbulent-impingement (T-I) noise and airfoil-self noise. T-I noise occurs when the incoming turbulence interacts with the blade leading edge [4][5]. In literature, there is no agreement on how to model it. By comparing the analytical results of Botha [6] and Pearson [7] on the QR5 rotor, a mismatch up to 10 dB is found depending on the different correction factors applied. Airfoil-self noise, is generated by the interaction of a blade with the turbulence produced in its own boundary layer and near wake [8]. Depending on the flow conditions, five airfoil-self noise mechanisms [9] can be distinguished: Laminar Boundary Layer – Vortex Shedding noise (LBL-VS), Turbulent Boundary Layer – Trailing Edge noise (TBL-TE); Separation-Stall noise (SS), Trailing Edge Blunt – Vortex Shedding noise (TEB-VS) and Tip noise (TP). For HAWTs, which operate at high Reynolds number (i.e. larger than 5×10^5), TBL-TE broadband noise is the most relevant source of noise. This is caused by the scattering of the turbulent pressure fluctuations convecting over the sharp trailing edge [10]. Conversely for VAWTs, TBL-TE noise is not the primary source of noise. Pearson [7] and Botha [6] showed that, at low tip speed ratios, the blades of a VAWT are subjected to dynamic stall; under this condition, the shear layer separates, creating coherent vortices which generate tonal noise at low frequency (LBL-VS) [8]. When the tip speed ratio increases, the effect of the dynamic stall is less relevant and the major source of noise is T-I noise, i.e. interaction between the turbulent near wake of a blade and the following one. This mechanism is very similar to the blade-vortex-interaction noise experienced by helicopter in sideslip mode [11]. Pearson [7] also demonstrates that increasing the solidity of the rotor has a similar effect to increasing tip speed ratio because the induction factor is a function of both the solidity and the tip speed ratio. If small VAWTs are considered, low Reynolds numbers are experienced (i.e. lower than 5×10^5) and LBL-VS noise is expected to be the major source. Modelling the LBL-VS noise with the Brooks, Pope and Marcolini (BPM) approach [8], Pearson observed a tonal peak in the frequency range between 1×10^3 Hz – 2×10^3 Hz for a full-scale rotor. However, this trend does not match with the experimental findings of Dyne [12] because of the inaccurate assumption of steady and full-attached flow in the BPM model. Based on the previous discussion, an agreement on how to model the different noise sources for a VAWT as well as an accurate description of the flow close to the blade are needed. To this end, the current research investigates the aerodynamic and the aeroacoustics performance of two-bladed H-Darrieus VAWT using a multi-fidelity approach. First, Lattice-Boltzmann Very Large Eddy Simulations (LB-VLES) coupled with the Ffwocs Williams and Hawkings integral solution are carried out. This represents the first dataset where both the aerodynamic and the acoustic fields are retrieved using a single tool, thus allowing to link far-field noise with the unsteady aerodynamics. Then, the numerical results are used to validate a low-fidelity model, which is able to predict the performance of a VAWT with modest run time. The operating conditions of the turbine and its geometry are required to define the low-fidelity simulation. Steady, free-stream conditions under a quasi-steady time dependence are assumed. In order to analyse the aerodynamic performance of the turbine, the Actuator Cylinder (AC) model [13] is applied. The noise prediction methodology is based on the work of Botha [6]. First, by applying a mesh in the space domain, the single blade of the studied geometry is divided into single elements along the span. Next, a temporal discretisation is performed, which allows the blade to advance along its rotational path. The user can choose the angular discretisation, equals to the number of azimuthal position (θ) that will be evaluated during the simulation. For each of this grid point, the noise models are evaluated. The airfoil-self noise is simulated with the Brooks, Pope and Marcolini (BPM) model [8] while the turbulence-impingement noise is modelled following the approach of Buck et al. [14]. The result for a given noise model is an instantaneous acoustic signal at the retarded emission point. Thus, to account for the motion of the blades with respect to the stationary observer, the Doppler correction factor is computed [15] and the overall pressure signal at the receiver location is obtained by applying the methodology of Brooks and Burley [16]. Results show a good agreement between high-fidelity simulations and low-fidelity model at low frequencies, where turbulence-impingement noise is the most dominant noise source. At higher frequencies, laminar boundary layer–vortex shedding noise is the dominant source because of the low Reynolds number flow. For this noise source, a small disagreement between the high-fidelity and the low-fidelity results exists for the frequency of maximum noise. This is attributed to the presence of the struts, which largely affect the velocity perceived by the blades. It is concluded that, it is relevant to take into account their effects in the low-fidelity model to correctly evaluate the emitted noise.

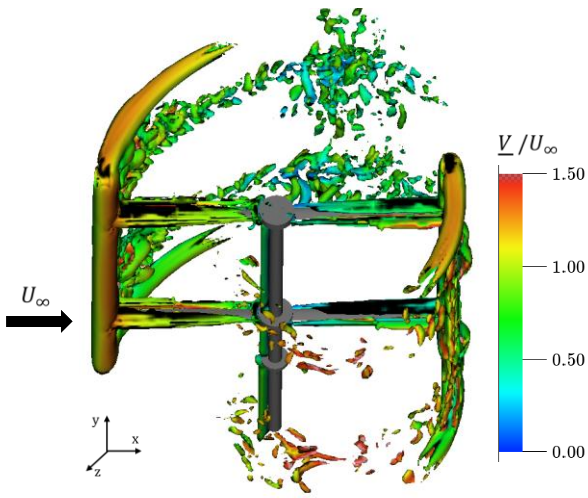

Figure 1 View of the instantaneous flow field visualized through the λ2 criterion for vortex visualization colour contoured with the non-dimensional velocity magnitude V.

Bibliography

[1] Eriksson S, Bernhoff H and Leijon M 2008 *Renewable and Sustainable Energy Reviews* **12** 1419–1434.
[2] Manwell J F, Mcgowan J G and Rogers A L 2009.
[3] Wagner S, Bareiss R, and Guidati G 1996.
[4] Rogers A L, Manwell J F and Wright S 2006.
[5] Kim J W, Haeri S and Joseph P F 2016 *Journal of Fluid Mechanics* **792** 526–552.
[6] Botha J D M 2018.
[7] Pearson C 2013.
[8] Brooks T F, Pope S, and Marcolini M A 1989 1–142.
[9] Van den Akker H and Mudde R F 2014.
[10] Ffowcs Williams J E and Hawkings D L 1969 *Philosophical Transactions of the Royal Society of London* **264** 321–342.
[11] Lowson M V and Ollerhead J B 1969 *Journal of Sound and Vibration* **9** 197–222.
[12] Dyne B K 2007.
[13] Madsen H A 1982.
[14] Buck S, Oerlemans S and Palo S 2016 *Journal of Sound and Vibration* **385** 219–238 2016.
[15] Ruijgrok G J J 1993.
[16] Brooks T F and Burley C 2004 *Journal of the American Helicopter Society* **49** 28–42.