Numerical Aero-acoustics Assessment of Double-airfoil Vertical Axis Wind Turbine

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Abstract

In this work, the authors introduce an innovative design for lift-based vertical axis wind turbines (VAWTs) to reduce noise emissions. Each blade in the turbine consists of two airfoils. The aerodynamics of the new design has been investigated numerically to obtain the generated noise level. Unsteady Reynolds-averaged Navier-Stokes (URANS) equations have been used to obtain time-accurate solutions. The impact of the spacing between the two airfoils composing the blade has been studied at different tip speed ratios. The results indicate that the 60% spacing is the best configuration for the double-airfoil concerning noise emission, leading to a noise level reduced by 56%.

Introduction

Noise pollution from wind turbines is an important public health issue, and strict regulations are necessary regarding noise levels for nearby residents to a wind farm. The fact that more turbines lead to higher noise levels constitutes a problem. Indeed, more wind turbines are needed, but the nearby residents should not be affected. Noise levels can be measured objectively. However, as for most environmental issues, the public's perception of the noise impact of wind turbines is in part subjective. Vertical axis wind turbines are in principle suitable for implantation in densely populated city areas. Therefore, noise is a parameter of central importance. The origin of wind turbines noise is either aerodynamical or mechanical. This work considers only aerodynamic noise. Aerodynamically-generated noise is either narrow-band or broadband and is closely related to the geometry of the rotor, its blades, and their aerodynamic environment. In the next section, a novel blade design shown in Fig. 1 is presented to reduce noise generation of vertical-axis wind turbines.

State of the Art

Several methods are used to calculate sound propagation, ranging from simplified calculations that assume an hemispherical pattern, to complex computations that take into account the influences of terrain shape, barriers, wind speed and direction, atmospheric temperature profile, humidity, air and ground absorption... In this work, the authors consider fixed positions of the sound receivers at different locations to capture the patterns of the sound signal, as shown in Fig. 2.

M.J. Lighthill derived in a seminal work [1] equations to describe sound emissions, starting from the Navier-Stokes equations. He developed an acoustic analogy allowing a prediction of aerodynamic sound by using a stationary

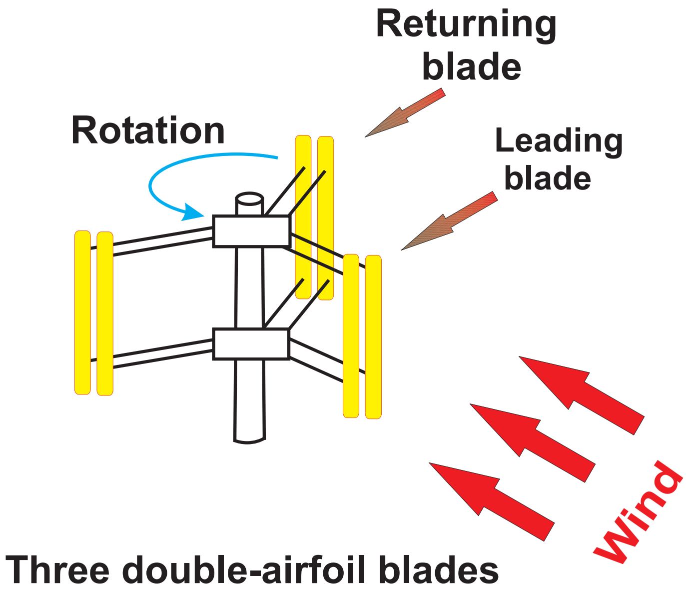

Abbildung 1: *New vertical axis wind turbine considered in this work*

wave equation, starting directly from modified versions of the mass and momentum conservation equations. Lighthill introduced the concept of a turbulent stress tensor that represents the radiation source terms per unit of volume coming from convection, shear and pressure. Those are modeled using an acoustic quadrupole. Normally, the influence of the Lighthill stress tensor focuses on small regions of the flow where perturbations could be introduced by solid surfaces. In the outer regions, any acoustic fluctuation is quickly damped out by the flow convection.

Starting from this description, J.E. Ffowcs-Williams, L.H. Hall and D.L. Hawkings included the influence of arbitrary moving surfaces, leading to the FH-W model [2]. The theory is derived similarly to Lighthill analogy over a scattering half plane. The same quadrupole term (Lighthill tensor) plus a dipole and monopole distribution result out of it. The conclusion of the FH-W model is that solid surfaces become acoustically equivalent to a distribution of monopoles and dipoles along that solid surface whose strength is equal to the local acceleration of the surface and the net force applied on the fluid, respectively. In the literature, the dipole term is often called loading noise, while the monopole term is usually denoted thickness noise.

Because very little information on the acoustics of VAWTs is currently available, it is difficult to compare directly the noise generation characteristics of HAWTs and VAWTs [3]. Still, [4] contains information about the acoustics

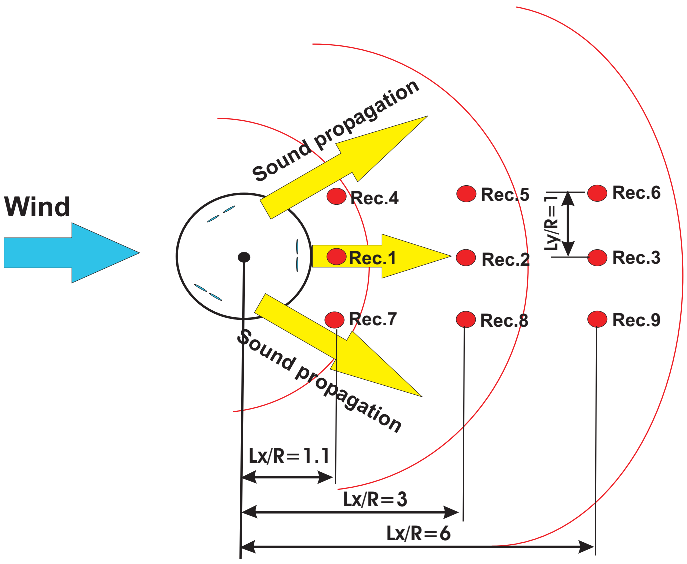

Abbildung 2: *Pressure wave propagation and position of the receivers.*

of a Vertical Axis Wind Turbine, investigating the effect of blade shape, tip speed ratio, solidity and distance between the noise source (here, a straight Darrieus turbine) and the receivers. The author found that the S1046 airfoil is the best airfoil to reduce noise generation. In addition, the results indicated that increasing the tip speed ratio increases the generated noise. Moreover, decreasing the solidity from 0.25 to 0.1 reduces the noise emission of the turbine by 7.6 dB. Overall, the average noise decay rate was found to be about 6 dB per unit distance from the source.

There is currently no detailed information available concerning aerodynamic noise sources associated with VAWTs [3]. Thus, to gain an understanding of the acoustics of this type of turbine, additional studies are needed. Therefore, the objectives of this work are (i) to introduce an optimum configuration to reduce the generated aeroacoustics from the vertical axis wind turbine; (ii) to evaluate the CFD ability to accurately predict vertical axis wind turbine noise. Achieving these objectives is important to improve VAWT acceptance, leading to a domestic turbine that could be installed near residential dwellings, since noise would not be a nuisance.

CFD Methodology

Due to the highly time-dependent nature of the flow around the vertical axis wind turbines, the CFD simulation of these turbines is a very difficult challenge. It is therefore necessary to check the full numerical model with great care. Thereafter, the resulting methodology must be validated. ANSYS-Fluent has been used in this work. Unsteady Reynolds-Averaged Navier-Stokes equations have been solved using the SIMPLE algorithm for pressure-velocity coupling. The finite-volume method has been used as a discretization procedure with second-order upwind scheme for all variables. Figure 3 illustrates all the details about the boundary conditions and the computational domain. One of the authors has validated this model and CFD procedure in a previous work [5].

The validation has been conducted between the present model and published experimental and CFD results concerning a H-rotor Darrieus turbine [5, 6]. The results indicated an acceptable agreement between the experiments and the present CFD model. Based on these studies, the power coefficient (turbine efficiency) is predicted by using the realizable k-ε turbulence model, as recommended in the scientific literature for rotating bodies. This recommendation has been confirmed by other studies considering rotating systems [7, 8] and airfoils as in [9, 10], showing that the realizable k-ε turbulence model is indeed suitable for such cases. The Sliding Mesh Model (SMM) is used to solve the unsteady flow. Five complete revolutions are always computed, using constant time steps equal to 1 ms. The flow properties are calculated by averaging the results during the last four revolutions. The acoustic signals for all receivers (Fig. 2) are obtained during the last revolution. Concerning boundary conditions, the inlet velocity is kept constant and equal to 9 m/s, while the pressure outlet is at atmospheric pressure (Fig. 3).

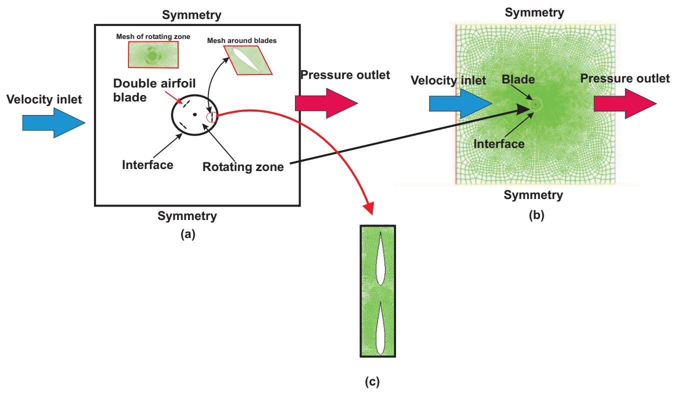

Abbildung 3: *CFD domain and mesh around rotating zone and blade; b) domain mesh; c) mesh around the double-airfoil blade*

Five revolutions for one specific configuration take about 6 hours of computing time on a standard PC. The adequate size of the computational domain has been studied in a previous work [5]. A mesh-independence test has then been carried out for one geometrical configuration. Several different two-dimensional, unstructured grids of increasing density and quality, ranging from 6 000 up to 135 000 cells have been scanned. This test showed that all grids involving more than 90 000 cells lead to a relative variation of the main output quantity below 1.2%. As a consequence, a grid range between 90 000 and 100 000 cells has been used for all further computations.

Regarding the acoustics calculation, the FW-H model is used in this work, this model being capable of predicting sound generated by equivalent acoustic sources (here, a vertical axis wind turbine) at an acceptable computational cost. Time-accurate solutions of the flow-field variables around the turbine, such as pressure, velocity components, and density on source surfaces, are required to evaluate the surface integrals. Time-accurate solutions can be obtained from unsteady Reynolds-averaged Navier-Stokes (URANS) equations. The FW-H acoustics model in ANSYS-Fluent permits to select multiple source surfaces and receivers. Sound pressure signals thus obtained can be processed using the fast Fourier transform (FFT) and associated postprocessing capabilities to compute and plot all acoustic quantities.

Results and Discussion

Only very few studies considered the aerodynamic noise of VAWT. Mohamed recommended in [5, 6] a design consisting of S1046 airfoils for straight Darrieus turbines. Later, he considered the acoustics of this turbine [4] and investigated the effect of some parameters on the generated noise. In this work, a double-airfoil blade (Fig. 1) is introduced as a novel idea to reduce the noise generated by a VAWT.

Impact of Tip Speed Ratio

First, the impact of the tip speed ratio has been studied. The tip-speed ratio λ is a dimensionless number defined as $\lambda = \omega R/U$, where R is the rotor radius (m), ω is the rotating speed (rad/s) and U is the flow velocity (m/s). Here, the double-airfoil blade is used with different spacings of 0%, 20%, 60% and 90% as shown in Fig. 4. Both airfoils involve the same profile (S1046) and a constant solidity of 0.1. The chord c is divided equally between the two airfoils. Nine receivers are used to collect the noise signals under different working conditions as shown in Fig. 3.

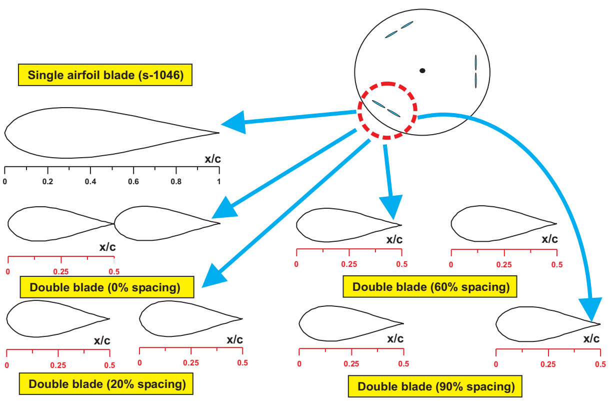

Abbildung 4: *Different configurations of the double-airfoil blade*

The results indicate that increasing the speed ratio increases slightly the noise from the VAWT. A sample of these results is shown in Fig. 5. Three different speed ratios have been studied ($\lambda = 3$, $\lambda = 5$ and $\lambda = 7$) for the same turbine solidity ($\sigma = 0.1$) and for all different spacing configurations of the double-airfoil turbine. For all receivers the results suggest that the rotational speed should be small to reduce noise generation. The average reduction of the sound amplitude is 15.5 dB when decreasing the speed ratio from $\lambda = 7$ to $\lambda = 3$. This reduction is a significant number, especially in residential areas.

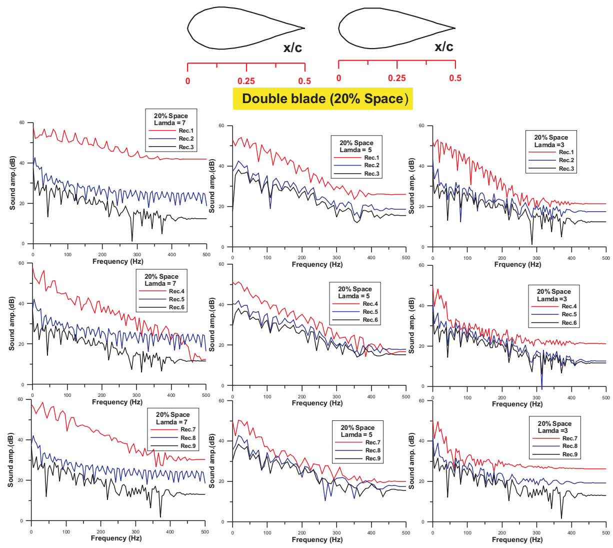

Abbildung 5: *Generated sound level of the double-airfoil turbine with 20% spacing at different speed ratios*

Impact of Double-airfoil Spacing

Mohamed [5] studied the effect of the airfoil shape on the characteristics performance of the rotor. The results indicated that S1046 is the best airfoil concerning performance. Now, the solidity $\sigma = nc/2R$ will be kept constant for all the spacings between the two airfoils, and is kept equal to 0.1. This solidity $\sigma = 0.1$ leads to the lowest noise generation for the standard design (single airfoil) as discussed in [4]. Based on the present study, it can be further concluded that the spacing between the airfoils is very effective to control the generated noise level, as shown in Fig. 6. By comparing with the single airfoil turbine (standard S1046), the new double-airfoil design with 60% spacing is the best configuration. Most receivers confirm that this configuration is better than the conventional design for all frequencies. Globally, it reduces the average sound level by 56%, as shown in Fig. 6. The average sound level is calculated at the last set of receivers ($L_x/R = 6$, involving receivers 3, 6 and 9). Therefore, the authors recommend the double-airfoil blade with 60% spacing for such a vertical axis wind turbines in order to reduce noise generation.

Sound Decay for the Optimum Configuration

As mentioned before, hemispherical wave fronts propagate in all directions from a point source or multiple sources. For the optimum configuration (60% spacing), the sound levels decay at the rate of about 3.7 dB per unit of distance of the receiver from the source (L_x/R) at a frequency of 200 Hz. It is interesting to note that the average decay rate is approximately constant. From this reduction rate, the noise radiation vanishing distance ratio (L_x/R) can be calculated as 10.1, showing that noise emissions will become negligible at a distance equal to roughly ten times the turbine radius.

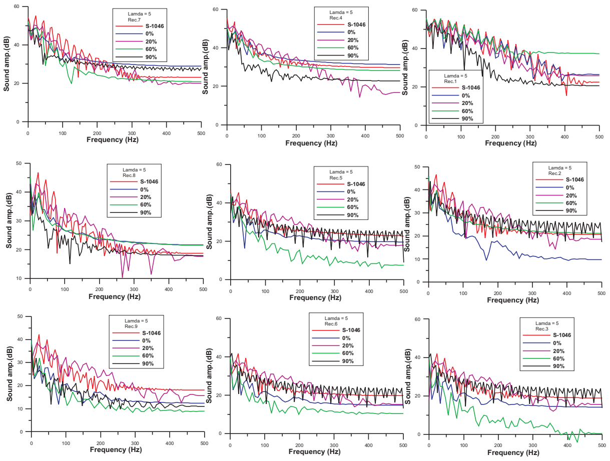

Abbildung 6: *Comparison of sound generation between the different configurations of the double-airfoil turbine and the conventional S1046 H-rotor*

Conclusions

Wind energy, undoubtedly, is one of the renewable energy sources that has undergone a remarkable and steady increase during the last decades. Vertical Axis Wind Turbines appear to be particularly promising for the conditions of low wind speed and residential areas, as well as for wind parks with low inter-turbine distances. Currently, there is almost no information about the aerodynamic noise of VAWT. An innovative design has been introduced in this work to reduce the generated aeroacoustics. The new turbine is constructed with three blades, each blade consisting of a double airfoil. The standard S1046 profile is used for each airfoil in the new design. The Ffowcs-Williams and Hawkings (FW-H) equations are used in this work to calculate the generated aeroacoustics from the new vertical axis wind turbine. The impact of the spacing between the double airfoils and of the speed ratio as well as the distance between the noise source (turbine blades) and the receivers have been investigated in this paper. The results indicate that increasing the tip speed ratio increases noticeably the noise generated by the H-rotor, both for the standard shape and the double-airfoil blade. Additionally, increasing the distance between the airfoils in the double-airfoil configuration decreases the noise emission at the same solidity. Most of the receivers indicated that the 60% spacing is the best configuration to reduce the noise from this wind turbine design. Moreover, the comparison between the conventional H-rotor and the new design (optimum configuration) shows that the new configuration reduces the average sound level by 56%, which is an impressive result. Finally, the authors believe that this work is interesting and delivers new insights concerning the acoustics of vertical axis wind turbines.

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