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Computational and experimental investigation of the aerodynamics and aeroacoustics of a small wind turbine with quasi-3D optimization

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ABSTRACT

Aerodynamics and aeroacoustics of a small horizontal axis wind turbine are investigated experimentally and computationally. The purpose has been to develop a procedure to predict and optimize the aerodynamic and aeroacoustic performance of such turbines. Aeroacoustic measurements are performed by an acoustic camera, while monitoring the plant's power output. In the computational analysis, an unsteady, 3D analysis is applied, modelling the turbulence by the Improved Delayed Detached Eddy Simulation (IDDES), and the aeroacoustics by the Ffowcs Williams and Hawkings (FW-H) approach. In the first part of the study, the original turbine blade is analyzed. A satisfactory agreement between the predictions and measurements is observed for the power conversion efficiency and the emitted sound. In the second part, the aerodynamics of the blade is optimized computationally, in the sense of a Quasi-3D approach, by a previously developed automated procedure. In this part, where a large number of 2D blade profiles are analyzed and optimized, a Reynolds Averaged Numerical Simulation approach is adopted for turbulence. In the third part, it is computationally verified (IDDES, FW-H) that the 3D blade, re-constructed based on the Quasi-3D optimization, exhibits a higher efficiency and lower sound emission. It is shown that the latter holds not only for the overall sound pressure, but also for the criteria pertaining to human perception of sound. Application of high-resolution methods with verification by on-site measurements, demonstration of the proposed Quasi-3D optimization procedure to lead to improved aerodynamic and aeroacoustic performance are innovative aspects of the present investigation. The presented, validated procedure can be applied to predict and improve the aerodynamic and aeroacoustic performance of small horizontal axis wind turbines.

1. Introduction

Wind energy is playing an important role in power generation out of renewable energy resources [1]. Beyond the on-shore or off-shore large wind turbines with large capacities (MW range), small wind turbines [2] with comparably small capacities (≤ 10 kW) are being increasingly used in residential areas, for a broader and more intensive utilization of the wind energy. Small wind turbines are also relevant in terms of decentralized power generation and power autarchy. An important issue concerning the installation of small wind turbines in residential areas is the aeroacoustic noise generation [3]. Currently, the design of small horizontal axis wind turbines do not necessarily rely on a refined analysis in this respect, in most cases, which leaves room for further investigation. This is a focus of the present investigation, where experimental and Computational Fluid Dynamics (CFD) based numerical methods are applied. The purpose is the development of a computational procedure to predict and optimize the aerodynamic and aeroacoustic performance of small horizontal axis wind turbines.

The present study consists of three basic phases. The first phase aims the validation of the applied computational procedures. Here, unsteady, 3D calculations as well as measurements are performed for an existing small wind power plant. Flow turbulence is treated by high-resolution methods such as Detached Eddy Simulation (DES) [4–6], which will be addressed in more detail below. In the second phase, an optimization of the blade is attempted, within a Quasi-3D approach, which is quite commonly applied in steam [7] and gas turbines [8]. In the present work, the approach is applied in a simplified form, as will be discussed below. Here, a representative number of two-dimensional, blade-to-blade sections are selected along the blade height, which are individually optimized, applying a previously developed optimization procedure [9]. Within the optimization loop, aiming an aerodynamic optimization, a steady-state approach is used (RANS: Reynolds

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Averaged Numerical Simulation). In the third phase, the 3D blade is reconstructed stacking the optimized 2D profiles, and its aerodynamic and aeroacoustic performance is computationally analyzed, for verifying the validity of the applied Quasi-3D optimization. In this phase, an unsteady, 3D CFD analysis is applied again.

Among the large amount of previous investigations on the aerodynamics and aeroacoustics of wind turbines, there is a large number of studies that deal with the aerodynamic optimization [10]. However, investigations that apply a CFD analysis to predict to the flow field are quite rare [11–13]. Chen and Agarwal [11], Riberio et al. [12] and Ju et al. [13] applied genetic algorithms for shape optimization of airfoils, combined with artificial neural network algorithms, where a CFD approach was employed for calculating the flow field. In the majority of the optimization studies [10] simplified methods were applied to calculate the flow field. Zhu et al. [14] presented a procedure for aerodynamic and structural integrated optimization of horizontal-axis wind turbine blades via genetic algorithms, using the Blade Element Momentum (BEM) method for the aerodynamic analysis. In the work of Pavese et al. [15], the purpose was the aeroelastic optimization of a swept wind turbine blade, where a gradient-based optimization procedure was used, along with an unsteady BEM to obtain the aerodynamic loads. Li et al. [16] presented a multi-objective optimization procedure via genetic algorithms, where the aerodynamic noise was considered as a parameter in addition to aeroelasticity. The flow field was computed by the XFOIL/RFOIL codes [16], which are based on inviscid linear-vorticity panel methods and can take viscous effects by superimposed sources into account. For the noise prediction, the NAFNoise code [16] was used, which is based on empirical correlations. In the investigations that apply a CFD analysis [11–13], which also differ from the present one as far as the applied optimization procedure is concerned, simpler, i.e. one-equation turbulence models were used in 2D formulations. In the present optimization, an essentially more accurate two-equation turbulence model is used. A further feature that distinguishes the present investigation form the previous ones [11–16] is the idea of Quasi-3D optimization, and the subsequent verification of the impact of the 2D optimization on the 3D blade geometry. To the best of the author's knowledge, this approach has not been applied before, in connection with small wind turbines. This constitutes an innovative ingredient of the present study.

Besides the continuing interest in the numerical analysis of the aerodynamics of wind turbines, as recently demonstrated by Arpino et al. [17] and Ali et al. [18], who applied Unsteady RANS [17] and LES [18] analysis to vertical axis wind turbines, the computational analysis of the aeroacoustics of wind turbines is increasingly attracting the attention of researchers.

In [19], an aeroacoustic analysis was presented based on a RANS turbulence modelling approach. An Unsteady RANS based approach, but in 2D, was presented in [20]. Mo et al. [21] applied a Large Eddy Simulation (LES) based analysis to a horizontal axis wind turbine, whereas Ghasemian et al. [22] used LES to predict the aeroacoustics of a vertical axis wind turbine. Debertshäuser et al. [23] applied an LES analysis to a horizontal axis wind turbine, where the rotor blades were, however, not resolved. The latter were approximated as lines by the "actuator line technique" relying on tabulated airfoil data, putting the emphasis on the prediction of the wakes. A 3D Unsteady RANS (URANS) based approach was used to predict the aeroacosutics of a "wind-lens" turbine by Hashem et al. [24]. Caicedo et al. [25] performed an aeroacoustic analysis of wind turbine blade profiles for multiphase physics, namely, under icing conditions, applying RANS and LES analysis. However, the application of the latter may be seen to be debatable, since a 2D formulation was used [25]. In the present investigation, where turbulence is modelled by a DES approach accompanied by a transitional turbulence model, predictions are validated by field measurements. It has been postulated and proven that aeroacoustic behavior is connected with the aerodynamic performance, and an improved aerodynamics performance should automatically lead to noise reduction. These features can be regarded as the main distinguishing features of the present work, from the previous studies [19–25], as far as the prediction of the aeroacoustics is concerned. A further distinguishing feature of the present investigation from the previous work is a more detailed analysis of sound, from the perspective of "psychoacoustics" [26]. The latter describes the human perception of sound. This aspect is especially important, as far as the installation of small wind turbines in residential areas is concerned. The application of high-resolution methods with verification by on-site measurements, and the proposed automated Quasi-3D optimization procedure for improving the aerodynamic and aeroacoustic performance are innovative aspects of the present investigation. The proposed Quasi-3D optimization, which can be applied by less effort compared to a fully 3D optimization, makes the approach interesting for practical applications.

2. The considered wind power plant

The considered wind power plant is a small, horizontal axis wind turbine with three rotor blades and a nominal electrical power of 12 kW. The plant is installed and in operation near Husum, in northern Germany. The pole has the height of 30 m. The blades, each, have a length of 4.2 m with a radial extension of 4.4 m at their tip. The rotor speed is nominally 2 revolutions per second.

3. Experimental

The power output of the wind plant is continuously monitored. These measurements are used to validate the predicted aerodynamic efficiency of the turbine. For the measurement of aeroacoustics, an acoustic camera, i.e. the Bionic M-112 microphone array of CAE Software & Systems [27] is used, which consists of 112 MEMS-microphones with 24 bit resolution and sampling rate of 48 kHz in the frequency range 10 Hz–24 kHz with an operating range from 33 dB up to 120 dB. The wind velocity measurement is provided by an anemometer integrated to the plant. The microphone array is positioned according to DIN EN 61400-11 which is equivalent to IEC 61400-11. The signal processing is performed by the beamforming technique [28], which can quite accurately resolve noise sources to a localized area, when combined with a large number of microphones. Fig. 1 shows a photograph of the considered wind power plant and the positioned microphone array.

4. Modelling

The CFD modelling is performed within the framework of the finite volume method based general-purpose code ANSYS Fluent [29]. The Navier-Stokes equations coupled with the continuity equation are numerically solved, in combination with turbulence models, as will be described below. Constant air material properties at ambient conditions are used. An incompressible flow is assumed, which is quite realistic at the prevailing velocities, leading to maximum Mach numbers lower than 0.2.

The problem is formulated in a rotating frame of reference, which is a common approach in modelling turbomachinery flows [7,8]. The dimensionality is treated differently, in different phases, depending on the purpose. The original blade is analyzed using a 3D formulation. In the optimization phase, a 2D formulation is used, where a number of 2D blade-to-blade sections along the length of the blade are optimized, separately. The results are then used to construct the optimized 3D blade, in the sense of a Quasi-3D approach. In the presently applied approach, the 2D analyses are performed for blade-to-blade sections generated at constant-radius sections that are not necessarily aligned with meridional stream surfaces. This is unlike the classical Quasi-3D approaches that are usually applied in turbomachinery, where the meridional stream surfaces are used for this purpose. The improved 3D blade geometry is, then, obtained by stacking the optimized 2D airfoil