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Aerodynamic noise prediction of a Horizontal Axis Wind Turbine using Improved Delayed Detached Eddy Simulation and acoustic analogy

Masoud Ghasemian, Amir Nejat *

School of Mechanical Engineering, University of Tehran, Tehran, Iran

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ABSTRACT

This paper presents the results of the aerodynamic and aero-acoustic prediction of the flow field around the National Renewable Energy Laboratory Phase VI wind turbine. The Improved Delayed Detached Eddy Simulation turbulence model is applied to obtain the instantaneous turbulent flow field. The noise prediction is carried out using the Ffowcs Williams and Hawkings acoustic analogy. Simulations are performed for three different inflow conditions, $U = 7$, 10, 15 m/s. The capability of the Improved Delayed Detached Eddy Simulation turbulence model in massive separation is verified with available experimental data for pressure coefficient. The broadband noises of the turbulent boundary layers and the tonal noises due to the blade passing frequency are predicted via flow field noise simulation. The contribution of the thickness, loading and quadrupole noises are investigated, separately. The results indicated that there is a direct relation between the strength of the radiated noise and the wind speed. Furthermore, the effect of the receiver location on the Overall Sound Pressure Level is investigated.

1. Introduction

An increasing need for energy coupled with global warming has caused to exploring new alternatives to meet energy requirements [1]. One of the most promising renewable sources is wind energy [2]. In particular, there is an interest to develop small wind turbines for urban and suburban applications [3]. However, wind energy also has several disadvantages that stand in the way of wind turbine technology becoming popular. One of its major problems is societal rejection of wind turbines in developed areas due to acoustic pollution. Aeroacoustic noise from wind turbine may be a cause of annoyance from people living in the neighborhood of the turbines, particularly those neighborhoods with the low ambient noise level [4]. Noise emitted from an operating wind turbine can be divided into mechanical noise and aerodynamic noise. Mechanical noise originates from different machinery components, such as the generator and the gearbox. Aerodynamic noise is radiated from the blades and is mainly associated with the interaction of turbulence with the blade surface [5]. Machinery noise can be reduced efficiently by well-known engineering methods Such as vibration suppression, vibration isolation and fault detection techniques [4], whereas reduction of aerodynamic noise still represents a problem, and aerodynamic noise is the dominating noise mechanism. Therefore, it is important to identify and predict the most important noise sources.

Traditionally, noise prediction was performed using empirical or semi-empirical considerations. In recent years, because of the computational technology advances, the interest in the computational aeroacoustics has grown noticeably. The use of Computational Fluid Dynamics (CFD) for wind turbines has made it possible to achieve an accurate design tool, but this use has been limited to date because of the difficulties encountered by traditional Reynolds-Averaged Navier Stokes (RANS) turbulence models in accurately predicting the highly unsteady features that are key in the prediction of the noise of the wind turbine [6]. Large Eddy Simulation (LES) method has superiority compared with RANS. Unlike the RANS method, it resolves directly all the large scales, which contain the most energy. The small scales, or eddies behave in a universal way, and are simply modeled. However, LES is still computationally expensive for high Reynolds numbers and industry applications. This issue is tackled by using hybrid RANS-LES methods. The hybrid methods are a combination between the statistical RANS and LES methods. The basic principle in these methods is to model the boundary layer using a RANS turbulence model, whereas LES is used to resolve the detached eddies and separation regions in the farfield.

Tadamasa and Zangeneh [7] predicted the noise radiated from the rotating Horizontal Axis Wind Turbine (HAWT) blades. They used a RANS approach with Shear Stress Transport (SST) $k-\omega$

* Corresponding author.
E-mail address: nejat@ut.ac.ir (A. Nejat).

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Nomenclature

a_0	speed of sound (m/s)
C_p	pressure coefficient
d	distance to the nearest wall
f	frequency (Hz)
H	Heaviside function
k	turbulent kinetic energy (m^2/s^2)
l_{IDDES}	IDDES length scale
l_{RANS}	RANS length scale
M	mach number
$\acute{p}$	acoustic pressure (Pa)
P_{ij}	compressive stress tensor
r	distance to the receiver (m)
S_{ij}	strain rate
t	time (s)
T_{ij}	Lighthill stress tensor
U_j	velocity (m/s)
U_n	fluid velocity in the normal direction (m/s)
v_n	normal velocity of the integration surface (m/s)
y^+	wall unit

Greeksymbols

$\delta(f)$	Dirac delta function
μ	molecular viscosity (kg/ms)
μ_t	turbulent viscosity (kg/ms)
ρ	density (kg/m^3)
τ_{ij}	tensor of stress
τ	retarded time (s)
ω	rotational speed (rpm)

Subscripts

L	loading noise
n	component in surface normal direction
T	thickness noise
0	undisturbed condition

Abbreviations

CFD	Computational Fluid Dynamic
FW-H	Ffowcs Williams and Hawkings
FFT	Fast Fourier Transform
IDDES	Improved Delayed Detached Eddy Simulation
HAWT	Horizontal Axis Wind Turbine
LES	Large Eddy Simulation
NREL	National Renewable Energy Laboratory
OASPL	Overall Sound Pressure Level
PISO	Pressure Implicit with Splitting of Operator
RANS	Reynolds-Average Navier Stokes
SPL	Sound Pressure Level
URANS	Unsteady RANS
TKE	Turbulent Kinetic Energy
URANS	Unsteady RANS

based turbulence model for aerodynamic calculation and Ffowcs Williams-Hawking (FW-H) equation for aeroacoustics prediction. They investigated the effects of wind speed and rotational speed on the total noise radiation. Their results showed that the thickness noise increases continuously with increment in the rotational speed. Cho et al. [8] measured acoustic noise for a scaled model of NREL Phase VI wind turbine. They used a microphone array to identify the noise source position of the blade. Their results showed that the main acoustic noise source position moves toward the blade tip as the frequency increases and the noise level at low frequency below 2 kHz has much higher when the blade is in a stall condition. Chourpouliadis et al. [9] carried out a comparative study of the noise emissions from two interconnected wind farms. Their results showed that the predicted noise signals prove to be within the limits of recent regulations concerning the installation of wind farms. The aerodynamic and acoustic optimization process with decreasing the noise emission levels while increasing the aerodynamic performance can be found in study conducted by Göçmen and Özordem [10]. Their results show that redesigned airfoils have lower levels of noise emission and higher lift to drag ratios. Mo and Lee [11] numerically predicted the characteristics of aerodynamics noise generated from rotating wind turbine blades using incompressible large eddy simulation. The far-field aerodynamic noise for frequency below 500 Hz was modeled using FW-H analogy. They studied the aerodynamic noise due to the tip vortex-trailing edge interaction by local cross flows along the trailing edges. Lee and Lee [12] predicted aerodynamic noise from a 10 kW wind turbine using semi-empirical models. They found that trailing edge bluntness noise can be a dominant noise source for small wind turbines unless the wind turbine blades have very sharp trailing edges. Recently, Mohamed [13] carried out several noise evaluations of H-rotor Darrieus wind turbines. He studied the blade shape, the tip-speed ratio and the solidity effects on radiated noise. Results indicated that the higher solidity and higher tip-speed ratio rotors produce much more noise than the normal turbines. His study was based on a two-dimensional URANS (Unsteady RANS) simulation which neglected three-dimensional effects.

Several previous studies of the HAWTs noise used URANS approaches which these models tend to be overly dissipative and have been found to be poorly suited for prediction separated flow typically encountered at high wind speed. Furthermore, due to their inherent time-averaged nature, direct acoustic predictions derived from RANS are questionable. This study addresses some aspects of wind turbine noise generation and propagation not covered or not fully understood in the literature such as the role of thickness, loading and quadrupole noises at different frequencies and the effects of wind speed on flow separation and noise generation.

This paper has used Improved Delayed Detached Eddy Simulation (IDDES) to predict aerodynamic noise radiated from the NREL Phase VI wind Turbine. The current study is an accurate three-dimensional CFD unsteady simulation for aerodynamic noise prediction of the flow around the NREL Phase VI wind turbine. The IDDES turbulence model is conducted to obtain the instantaneous turbulent flow field. The noise predictions are performed by the FW-H acoustic analogy formulation. This paper focuses on the broadband noises of the turbulent boundary layers and tonal noises related to the passage of the blade. The surface pressure coefficients for three different inflow conditions $U_\infty = 7, 10, 15$ m/s were compared with the experimental data by [14]. The effect of distance and wind speed on the Sound Pressure Level spectrum and the Overall Sound Pressure Level (OASPL) is studied. Furthermore, the contribution of the thickness, loading and quadrupole noises were investigated, separately.

The purpose of this study is to evaluate the capability of the IDDES turbulence model in the aerodynamic prediction of wind

Table 1
The contribution of different sources in the total noise.

U_∞ (m/s)	Thickness and loading noises (dB)	Quadrupole noise (dB)	Total noise (dB)
7	46.7	49.3	51.2
10	53.5	58.6	59.8
15	60.7	64.6	66.1