Aerodynamic study of a small horizontal-axis wind turbine

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Abstract: *The wind energy is deemed as one of the most durable energetic variants of the future because the wind resources are immense. Furthermore, one predicts that the small wind turbine will play a vital role in the urban environment. Unfortunately, nowadays, the noise emissions from wind turbines represent one of the main obstacles to widespread the use in populated zones. Moreover, the energetic efficiency of these wind turbines has to be high even at low and medium wind velocities because, usually the cities are not windy places. The numerical results clearly show that the wakes after the trailing edge are the main noise sources. In order to decrease the power of these noise sources, we should try to decrease the intensity of wakes after the trailing edge, i.e. the aerodynamic fields from pressure and suction sides would have to be almost the same near trailing edge. Furthermore, one observes a strong link between transport (circumferential) velocity and acoustic power level, i.e. if the transport velocity increases, the acoustic power level also augments.*

Key Words: *horizontal-axis wind turbine, CFD, aeroacustics LES, aerodynamic study, transport velocity.*

1. INTRODUCTION

It is well known that the wind resources are huge. For example, one of the most comprehensive studies showed that the retrievable wind power on land and near-shore is about 72 TW, which represents 5 times the world’s current energy use. Unfortunately, the noise inhibits the wide use of wind turbines in or near populated zones. Furthermore, the energetic efficiency of urban wind turbine has to be high even at low and medium wind velocities.

From these reasons, one clearly sees that it is useful to study both the aerodynamics and acoustics of a small horizontal-axis wind turbine in order to find out the ways to increase the aerodynamic efficiency and to minimize the noise. The aeroacoustics of this wind turbine is study using the Reynolds averaged Navier-Stokes (RANS) and large eddy simulation (LES) equations.

2. GOVERNING EQUATIONS

For a three-dimensional rotating Cartesian coordinate system, the unsteady Reynolds-averaged Navier-Stokes equations using the Favre averaging (a mass-weighted averaging) could be written in the conservative form as [1-2]

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(F_x-G_x\right)}{\partial x}+\frac{\partial\left(F_y-G_y\right)}{\partial y}+\frac{\partial\left(F_z-G_z\right)}{\partial z}=S \tag{1}$$

where

$$Q=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ \rho\left(e+\frac{W^2}{2}-\frac{\Omega^2 r^2}{2}\right)\end{bmatrix}\quad F_x=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ \rho uI\end{bmatrix}\quad F_y=\begin{bmatrix}\rho v\\ \rho vu\\ \rho v^2+p\\ \rho vw\\ \rho vI\end{bmatrix}\quad F_z=\begin{bmatrix}\rho w\\ \rho wu\\ \rho wv\\ \rho w^2+p\\ \rho wI\end{bmatrix} \tag{2}$$

If one assumes that the fluid is Newtonian and the thermal boundary layer is neglected, the diffusive flux G may be written as

$$G_x=\begin{bmatrix}0\\ \tau_{xx}^{tot}\\ \tau_{xy}^{tot}\\ \tau_{xz}^{tot}\\ u\tau_{xx}^{tot}+v\tau_{xy}^{tot}+w\tau_{xz}^{tot}+\alpha\frac{\partial T}{\partial x}\end{bmatrix}\quad G_y=\begin{bmatrix}0\\ \tau_{xy}^{tot}\\ \tau_{yy}^{tot}\\ \tau_{yz}^{tot}\\ u\tau_{xy}^{tot}+v\tau_{yy}^{tot}+w\tau_{yz}^{tot}+\alpha\frac{\partial T}{\partial y}\end{bmatrix}$$
$$G_z=\begin{bmatrix}0\\ \tau_{xz}^{tot}\\ \tau_{yz}^{tot}\\ \tau_{zz}^{tot}\\ u\tau_{xz}^{tot}+v\tau_{yz}^{tot}+w\tau_{zz}^{tot}+\alpha\frac{\partial T}{\partial z}\end{bmatrix} \tag{3}$$

According to the Boussinesq hypothesis, the shear stresses τ^{tot} may be written as

$$\tau_{xx}^{tot}=\frac{2}{3}(\mu+\mu_t)\left(2\frac{\partial u}{\partial x}-\frac{\partial v}{\partial y}-\frac{\partial w}{\partial z}\right)\quad \tau_{yy}^{tot}=\frac{2}{3}(\mu+\mu_t)\left(2\frac{\partial v}{\partial y}-\frac{\partial u}{\partial x}-\frac{\partial w}{\partial z}\right)$$
$$\tau_{zz}^{tot}=\frac{2}{3}(\mu+\mu_t)\left(2\frac{\partial w}{\partial z}-\frac{\partial v}{\partial y}-\frac{\partial u}{\partial x}\right)\quad \tau_{xy}^{tot}=\tau_{yx}^{tot}=(\mu+\mu_t)\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right) \tag{4}$$
$$\tau_{xz}^{tot}=\tau_{zx}^{tot}=(\mu+\mu_t)\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)\quad \tau_{yz}^{tot}=\tau_{zy}^{tot}=(\mu+\mu_t)\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)$$

The eddy viscosity μ_t is computed with a turbulence model and for small variations of static temperature, the dynamic viscosity could be assumed constant.

For gases, the external force f_e due to the gravitational acceleration is very small, therefore it can be neglected.

Moreover, we can assume that the thermal conductivity is the single heat source.

If the Cartesian coordinate system is rotating about z axis with constant angular velocityΩ, source term S could be written as

$$S = \begin{bmatrix} 0 \\ \rho\left(\Omega^2 x + 2\Omega v\right) \\ \rho\left(\Omega^2 y - 2\Omega u\right) \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

For wind turbines, the velocities are small, therefore, the compressibility is negligible (ρ = const.). Furthermore, it is possible to neglect the energy exchange, i.e. one assumes that the static temperature is constant (T = const.) and one renounces to the energy equation.

In many practical applications involving turbulent flows (flow over airfoils, wind turbines etc.), noise does not have any distinct tones, and the sound energy is continuously distributed over a broad range of frequencies.

In those situations involving broadband noise, statistical turbulence quantities (turbulence velocity and length scales) computed with RANS and turbulence model equations can be utilized, in conjunction with semi-empirical correlations and Lighthill's acoustic analogy [3].

It is worthwhile to notice that, the turbulence model has to have at least two equations in order to can calculate the turbulence velocity and length scales.

For this reason, the algebraic and one-equation turbulence models cannot be used in conjunction with noise source models.

Unlike, the direct method [4] and the Ffowcs-Williams and Hawkings integral method [5], the broadband noise source models [6-8] do not require transient solutions to any governing fluid dynamic equations.

Therefore, the broadband source models require the least computational resources. Unfortunately, these source models do not predict the sound at receivers.

Furthermore, the noise source models are very sensitive to the grid and the mesh should be built so that y^+ is of order of 1 in order to properly capture the viscous sublayer of turbulent boundary layer.

3. NUMERICAL SIMULATION

The numerical simulations of the three-dimensional viscous flow were carried on a 5 kW horizontal-axis wind turbine [9], with an in-house code developed continuously by INCAS [10], which is based on finite volume method where each unknown takes an average value on each discretization cell.

The flow is assumed fully turbulent and we have used the shear-stress transport (SST) k-ω based model, which was developed by Menter [11] in order to combine the advantages of the robust and accurate formulation of the Wilcox k-ω model in the near-wall region with the free-stream independence of the k-ε model in the far field. To achieve this, the k-ε model is converted into a k-ω formulation.

At the left and right sides of computational domain, the rotational periodic boundary conditions are imposed and the blade wall has assumed adiabatic

Some results, at design tip speed ratio are given in Figs. 1, 2 and 3. One sees that although the angle of attack near the blade tip is small, the acoustic power level is high.

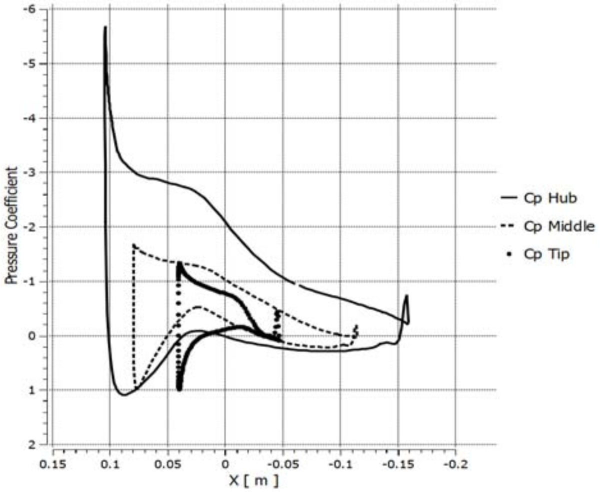

Fig. 1 – Pressure coefficient with respect to relative velocity, near hub, midspan and tip, at wind velocity of 8 m/s and tip speed ratio of 6, computed with in-house code, using RANS approach

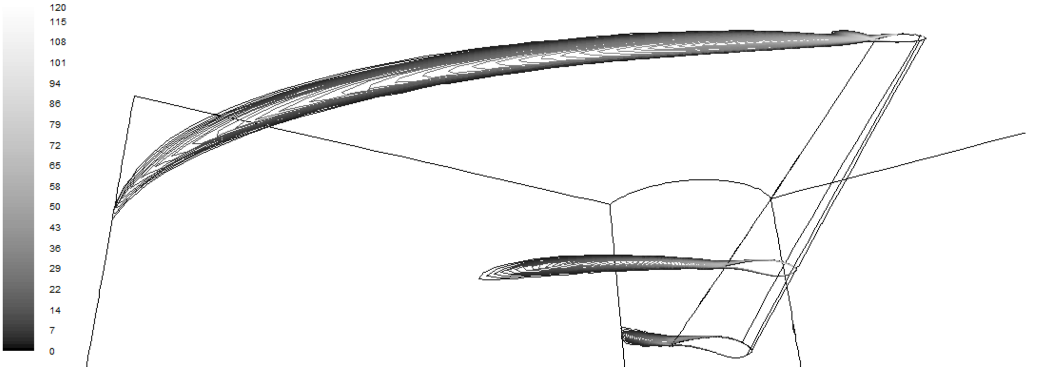

Fig. 2 – Isolines of acoustic power level (dB) near hub, midspan and tip, at wind velocity of 8 m/s and tip speed ratio of 6, computed with in-house code, using RANS approach

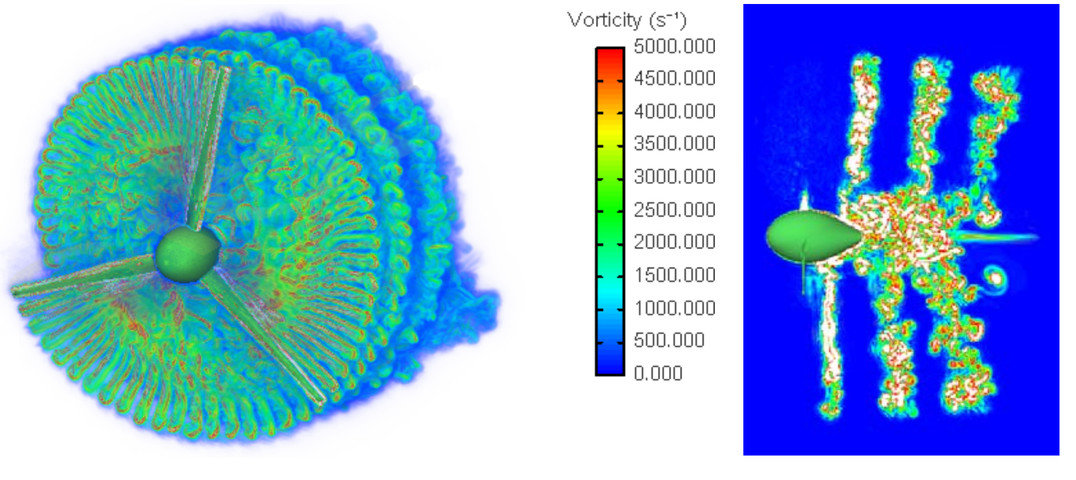

Fig. 3 – The evolution of vorticity after 1 revolution of wind turbine rotor, at wind velocity of 14 m/s and tip speed ratio of 6, computed with XFlow, using LES approach

6. CONCLUSIONS

The isolines of acoustic power level near hub, midspan and tip are shown in Fig. 2. As we expected, the wakes after the trailing edge are the main noise sources. In order to decrease the power of these noise sources, we should try to decrease the intensity of wakes after the trailing edge, i.e. the aerodynamic fields from pressure and suction sides would have to be almost the same in the vicinity of trailing edge.

Furthermore, one observes a strong link between transport velocity Ωr and acoustic power level, i.e. if the transport velocity Ωr increases, the acoustic power level also augments.

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