The actuator cell model for the Darrieus wind turbine

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Abstract. Development of existing and innovative aerodynamic models for the Darrieus wind turbine has become very popular in recent years. Since research in the field of aerodynamics of the Darrieus concept is very limited, the development of simplified aerodynamic methods is very difficult. Therefore, the major objective of the present study is to present the concept of a new aerodynamic model for the Darrieus wind turbine – the actuator cell model (ACM). Aerodynamic loads are added to the unsteady incompressible Navier-Stokes equations as momentum source terms. The source terms are computed basing on instantaneous aerodynamic forces taken from the literature. The numerical results of wake structure computed by ACM are compared with the experimental data. Agreement between the numerical results of velocity profiles and the experimental data is reasonably good.

1. Introduction
Development of simplified aerodynamic models giving reasonable results of aerodynamic loads and wake structure for the Darrieus wind turbine is a challenge. The most popular aerodynamic model for the Darrieus wind turbine is the double multiple streamtube model (DMS) developed by Paraschivoiu [1]. Computations of aerodynamic blade loads basing on this model are very fast, however, its use is limited [2]. The DMS model fails for a large rotor solidity and for heavily loaded blades because the flow past the rotor is assumed to be quasi steady. Vortex models, based on vorticity equations, are another group of simplified aerodynamic models for the Darrieus concept. These models are computationally expensive and more accurate in comparison with momentum-based methods [3, 4]. Nowadays, Computational Fluid Dynamics (CFD) is becoming an important tool for calculating the complex unsteady flow around the rotor of a vertical axis wind turbine. CFD simulations of VAWTs are, however, very expensive and they are also limited [5-7].

A new trend in modelling of large onshore and offshore wind farms are CFD models that are combined with simplified aerodynamic models. CFD models allow modelling of complex terrain or complex forest environment whereas simplified models, such as, for example, blade element momentum method (BEM), can efficiently calculate aerodynamic blade loads. Such simplified CFD models allow a significant reduction of the computation time. The combination of the BEM code with the incompressible Navier-Stokes equations for aerodynamic analysis of wind turbine with a horizontal axis of rotation was performed by Mikkelsen [8]. The 3D Navier-Stokes equations with the large eddy simulation (LES) model combining with the actuator line technique were applied by Troldborg [9] for the analysis of wake behind horizontal axis wind turbine operating at various flow conditions. Rajagopalan and Fanucci [10] were among the first who performed the computations of a two-dimensional vertical axis wind turbine using a finite difference procedure where turbine blades were replaced by a porous cylindrical shell having a thickness of one volume control. A similar approach for the Darrieus concept was applied by Fortunato et al. [11]. The 2D actuator surface technique for a two-dimensional two-bladed vertical axis wind turbine has been used by Shen et al. [12]. In this approach, the two-dimensional Navier–Stokes equations are used with the k-ω shear stress
transport (SST) turbulence model and the turbine blades are modeled as body forces distributed on two rotating actuator surfaces.

In this paper, the concept of the new simplified aerodynamic model for the Darrieus wind turbine has been presented. The motivations for this topic are still growing demand for electricity causing that makes it necessary to look for alternative energy sources as well as high computing costs of typical full CFD calculations.

2. Darrieus-type vertical-axis wind turbine

2.1. Experimental model of a wind turbine
Numerical model of a one-bladed Darrieus-type vertical-axis wind turbine (VAWT) is developed based on the experiments conducted at Texas Tech University [3, 13]. The experiments were carried out in a water tow tank with a depth of 1.25 m, a width of 5 m and a length of 10 m. The choice of water as an operating fluid has some advantages, they are as follows: easier visualization of the flow field; a lower rotational speed of the rotor for a given Reynolds number and easier to measure aerodynamic forces because of lower blade inertial forces. During the experiment, the one bladed rotor made of aluminium with a NACA 0012 airfoil and a chord length of 9.14 cm was investigated. The diameter of the turbine rotor was 1.22 m. The towing velocity was 9.1 cm/s giving the tip to speed ratio of 5.0. The tip speed ratio is defined as the ratio of the tangential velocity of the blade and the wind velocity. During the experiments, the angular velocity of the rotor was kept constant and equal to 0.75 rad/s. Operating conditions of the rotor and its dimensions were chosen to give the blade Reynolds number of 40,000. The rotor solidity for the one bladed rotor, defined as the ratio of the chord length to the rotor radius, was 0.15. Because of the limited space, more details of the experiments are not presented in this paper, but they are available in the research reports [3, 13].

2.2. Aerodynamic characteristics of wind turbine blades and wake structures
The flow past the Darrieus wind turbine is very complex because the angle of attack varies periodically with the azimuth from positive to negative values. A continuous change in the angle of attack causes unsteady induced velocities. Furthermore, depending on the operating conditions of the rotor and its geometry, blade-wake interaction and dynamic stall can occur. The operating conditions of the rotor are determined by the tip speed ratio TSR and the blade Reynolds number. The tip speed ratio is defined as

\[ \text{TSR} = \frac{\omega R}{V_0} \]

where: \( \omega \) is the angular velocity of the rotor; \( R \) is the rotor radius and \( V_0 \) is the wind speed. The geometry of the rotor depends on such factors as: the number of blades, the chord length, the rotor swept area, the rotor radius and the airfoil shape of the blade. Figure 1a presents the silhouette of the one bladed rotor investigated in this paper.

Aerodynamic characteristics of the wind turbine blades are aerodynamic forces exerted on a moving blade by the fluid. Figure 1b shows the cross-section of the Darrieus-type wind turbine rotating with an angular velocity \( \omega \). The relative velocity \( W \) is the sum of the local wind velocity \( V \) and the tangential velocity of the blade \( V_t \), defined as \( V_t = Ro \). An aerodynamic force having lift and drag components, \( L \) and \( D \) respectively, is projected to the chordwise and the radial directions, giving respectively the tangential and normal blade loads, \( F_T \) and \( F_N \). The local angle of attack \( \alpha \) is visible between the tangential velocity of the blade and the relative velocity \( W \). The normal and tangential loads, given by the dimensionless coefficients \( CFN \) and \( CFT \), are defined as:

\[ CFN, CFT = \frac{F_N, F_T}{0.5 \rho V_0^2 c} \]  

where: \( \rho \) is the medium density; \( V_0 \) is the medium velocity and \( c \) is the chord length.

Velocity profiles presented in this article are taken within one rotor diameter downstream of the rotor axis. The actuator cell model makes it possible to obtain two velocity components in the wake, streamwise \( V_x \) and lateral \( V_y \) (see Fig. 1c). The obtained results of velocities are compared directly with the experiment [13]. The velocity profiles presented in this paper are defined as:
\[
\begin{align*}
V_x &= \frac{V}{V_0} - 1 \\
V_y &= \frac{V}{V_0}
\end{align*}
\]

Figure 1. Model of a one-bladed vertical-axis wind turbine (a); aerodynamic blade loads, velocity vectors and angles (b); wake velocity measurement (c).

3. Method

3.1. Actuator Cell Model

Since the flow past a Darrieus-type wind turbine is inherently unsteady, a time-dependent approach is required. In this paper, unsteady flow past a Darrieus wind turbine is analyzed by using the actuator cell concept proposed by the author of this paper. The concept utilizes the sliding mesh model (SSM), available in ANSYS Fluent, to solve the unsteady Navier-Stokes equations. Aerodynamic blade loads are introduced into the model using momentum source terms.

In the ACM concept, the equations of mass and momentum conservation are solved. No turbulence model is used during simulations, therefore additional transport equations are not solved. The equations for mass and momentum conservation in an inertial reference frame for laminar flow as are follow [14]:

\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \tag{4}
\]

\[
\frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla (\rho \mathbf{V} \mathbf{V}) = -\nabla p + \nabla \cdot \mathbf{r} + \mathbf{S} \tag{5}
\]

where: \( p \) is the static pressure; \( \mathbf{r} \) is the stress tensor and \( \mathbf{S} \) are source terms (body forces).

The sliding mesh model is one of the most advanced CFD model available in ANSYS Fluent. In this concept, transient flow around the rotor can be analyzed using the rotating sub-domain mesh. The author of this paper created three cell zones A, B and C that are bounded by interface zones (Fig. 2). During the calculation, the cell zones B and C rotate relative to the cell zone A in discrete steps. The cell zone C does not move relative to the zone B.

In order to simulate aerodynamic blade loads, the momentum source terms \( \mathbf{S} \) (see Eq. 5) are applied to the smallest cell zone C (Fig. 2). The components of the source terms \( \mathbf{S} \) in a two-dimensional coordinate system are given by:

\[
S_x, S_y = -\frac{F_x, F_y}{V_c} \tag{6}
\]
where: $V_C$ is the volume of the cell zone $C$ consisting of one mesh cell; $F_x$ and $F_y$ are components of the aerodynamic blade load in the coordinate system presented in Fig. 1c. These components can be written:

$$F_x = F_N \sin \theta - F_T \cos \theta$$  \hspace{1cm} (7)

$$F_y = -F_N \cos \theta - F_T \sin \theta$$  \hspace{1cm} (8)

In this version of ACM model, the instantaneous aerodynamic forces $F_N$ and $F_T$ are taken directly from the experiment [13]. In this work, validation of ACM model is performed by comparing velocity profiles in the aerodynamic wake downstream behind the Darrieus-type rotor. The momentum source terms $S_x$ and $S_y$ are applied to the cell zone $C$ using the user defined functions (UDF). Values of $F_x$ and $F_y$ have been tabulated and stored in a separate file. Using the UDF code, the information about an actual position of the cell zone $C$ are taken from the ANSYS Fluent solver and then the appropriate values of $F_x$ and $F_y$ forces are interpolated from table data. Figure 3 presents non-dimensional components of the instantaneous aerodynamic force, $CF_N$ and $CF_T$, as a function of azimuth $\theta$.

![Figure 2. CFD model of the Darrieus wind turbine.](image)

![Figure 3. Non-dimensional components of the instantaneous the aerodynamic force, $CF_N$ and $CF_T$.](image)

### 3.2. Computational Mesh

A two-dimensional computational domain consists of three cell zones A, B and C (see previous Section) which are meshed independently using quadrilateral elements. Figure 4 shows the computational mesh for the actuator cell model used for all results presented here. The cell zone A contains only one mesh cell. The mesh density in the area behind the rotor is higher in order to obtain accurate results of velocity profiles. Computations are also performed using coarser mesh presented in Fig. 5. The results of velocity profiles at an example azimuth of 70 degrees obtained for the coarser and refined meshes are presented in Fig. 6. As it can be seen, the quality of the mesh does not affect the streamwise velocity component and only slightly affects the lateral velocity. Therefore, a distribution of mesh elements in a spanwise direction is an important factor. However, since the streamwise velocity is more important in comparison with the lateral velocity component, more mesh refinements have not been taken into account in these investigations. The number of mesh cells presented in Fig. 4 is 43,707.
3.3. Numerical scheme and boundary conditions
All simulations presented in this paper were obtained using the CFD code ANSYS Fluent 15. The pressure based solver with the SIMPLE pressure-velocity coupling scheme and a second-order spatial discretization of momentum and pressure was employed to solve the resulting set of equations. A physical time step size $\Delta t$ was established to be 0.00023 s. This value of the time step size corresponds to the increment of the azimuthal angle $\Delta \theta$ of 0.02º. In order to match the experimental set-up the following boundary conditions were chosen: velocity inlet at the domain inlet; pressure outlet and symmetry at the upper and lower sides of the computational domain. The symmetry boundary condition can be used in order to model zero-shear slip walls in viscous flows.

4. Results and discussion
Numerical results of velocity profiles for two-dimensional rotor are compared with experimental results of Strickland et al. [13] and with the analytical results of these authors using a vortex model. Figure 7 shows the results of instantaneous streamwise and lateral velocity components for six different azimuth positions of the rotor. The dimensionless streamwise and lateral velocities, $u$ and $v$ respectively, given by equations 2 and 3 are shown as a function of the location $y$ normalized by the rotor radius $R$ (see Fig. 1). The calculated velocity profiles are also compared with numerical results of Rogowski et al. [6]. These authors carried out a full CFD analysis of the one-bladed wind turbine employing, among others, the RNG k-ε turbulence model. The level of agreement between the numerical results of velocity profiles obtained by the actuator cell model and the experimental results
by Strickland et al. [13] is reasonable. Velocity profiles given by ACM are also very similar to the full CFD results [6]. Figure 7 shows that wake characteristics downstream behind the rotor given by the vortex model seem to be underestimated.

**Figure 7.** Profiles of streamwise and lateral velocity components. The results obtained by the virtual cell model – black and red solid lines; experiment [13] – circles; vortex model [13] – dashed lines; RNG k-ε results – dotted lines [6].

Wake structure downstream behind the rotor is also analysed qualitatively by using streaklines. Streaklines were obtained by Strickland at al. [3] by means particles which flowed over the trailing edge of the rotor blade. The patterns of streaklines were recorded by using a camera. Numerical results of streaklines are obtained employing the discrete phase model (DPM) available in ANSYS Fluent. In the Euler-Lagrange approach the water phase (fluid phase) is considered as a continuum, while the particle trajectories are solved by tracking the particles through the computed flow field. In these investigations massless particles were injected to the main flow from the surface C (Fig. 2). The experimental results are compared with streaklines calculated by using the ACM model developed by the author of this paper. Figures 8a and 8b present respectively streaklines calculated by CFD and photographed by Strickland et al. [3]. The comparison between ACM and the experimental data is given in Fig. 8c. The comparison (Fig. 8c) shows good agreement in the area in which the dye pattern is not too diffusive. The streakline presented in Fig. 8 indicates the vortex sheet produced by the airfoil.
Figure 8. Streaklines computed by ACM (a); streaklines from the experiment [3] (b); streaklines – the comparison between ACM and the experiment [3] (c).

Figure 9 presents instantaneous static pressures computed by the actuator cell model. The obtained results are also compared with full CFD analysis presented by Rogowski at al. [6]. In the upwind part of the rotor (for the azimuthal angle range between 0º and 180º) overpressure areas are seen on the outer part of the airfoil. For the downwind part of the rotor (for azimuthal angles from 180º to 360º) the angle of attack changes the sign and overpressure areas are seen along the inner part of the airfoil. With increasing of the azimuthal angle up to θ=100º the static pressure increases because of the angle of attack increases and then decreases. In the downwind part of the rotor pressures are lower because flow velocity at the rotor is decreased. Pressure distributions obtained by ACM are similar to these given by the RNG k-ε turbulence model [6].

Figure 9. Instantaneous static pressure at three azimuthal angles – the comparison between ACM and full CFD simulation with the RNG k-ε turbulence model [6].
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5. Conclusions
The main purpose of the author is validation and verification of the simplified CFD model for the Darrieus wind turbine – the actuator cell model.

The presented results both instantaneous streamwise and lateral velocities obtained by the ACM model seem to be reasonable even for a coarse mesh.

The computational effort for the ACM is very low. In this work, only one processor (Intel Xeon x86_64) and 4GB of RAM were used. Simulations of 10 full revolutions of the rotor with very low time step size (corresponding to the increment of the azimuthal angle Δθ of 0.02º) took about one week. Full CFD analysis of the Darrieus-type wind turbine would take much longer.

A small number of mesh cells give results much quicker than the classical full CFD modelling. Therefore the ACM model can be coupled with momentum-based model in order to determine aerodynamic blade loads. In addition, the advantage of the presented model is the possibility of using it with a turbulence model to simulate a flow past a Darrieus-type rotor with shaft, struts or other rotor elements.

The presented studies are as a part of more extensive numerical research on a simplified numerical model for a Darrieus wind turbine.

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