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Numerical investigation on the effects of the aerodynamic shading between the tower and the blade of wind turbine generator with horizontal axis

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Abstract. The purpose of the current study is to evaluate the effects of the aerodynamic shading between the tower and the blade of NREL 5MW wind turbine generator. 3D models of the turbine and the tower are designed. They are reduced to plane models in order to simplify the convoluted, spatial aerodynamic interaction to a sequence of plane-2D problems. The plane models are numerically studied in Ansys Fluent, using dynamic-deformable mesh method. Visual and numerical results of the aerodynamic shading interaction are obtained. Force distributions on the blade and on the tower of NREL 5MW wind turbine generator are derived, for the exact moment when the aerodynamic shading occurs.

1. Introduction

In fluid dynamics, when two or more bodies are in a fluid dynamic interaction, and the bodies are close to one another, or passing close to one another, a phenomenon known as shading, occurs [1]. This phenomenon is characterized with deviations in pressure and velocity fields around the bodies, as well as a change in the aerodynamic forces, exerted on the bodies. Effects of this nature occurs between wind turbine generators in wind turbine farms, when a turbine`s aerodynamic wake shadows another turbine, resulting in less power of the second [2]. Similar aerodynamic shading can be observed in urban environment, building close to each other shadow one another [3].

While operating, the aerodynamic interaction between the wind and the wind turbine generator creates curtain pressure fields, close to the solid bodies (figure 1). They result in aerodynamic forces. When a blade of the turbine passes close to the tower of the structure, the pressure fields around the two bodies interact with each other, which result in deviation of the aerodynamic forces exerted on the bodies (figure 2). This interaction is associated with aerodynamic shading [4, 5].

Most of the traditional methods for analyzing the aerodynamic shading between tower and blade of wind turbine, such as Powles` method, Blevins' method are based on semi-analytical and experimental techniques [6, 7]. These methods are an approximation of the real physical medium and cannot guarantee adequacy of the numerical results. On the other hand the modern CFD softwares are capable of analyzing the aerodynamics of complex structures such as wind turbine generators, providing valuable and reliable numerical data [8, 9].

The purpose of the current study is a numerical evaluation of the effects the aerodynamic shading between the tower and blade of wind turbine generator with horizontal axis. All calculations are executed in Ansys-Fluent.

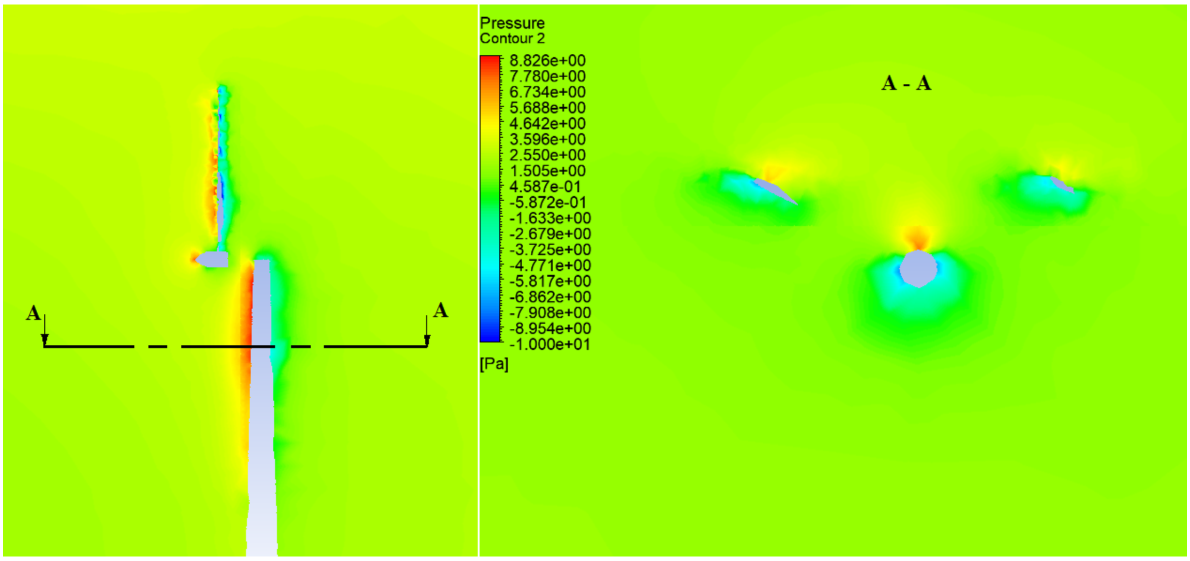

Figure 1. Pressure field distribution around the blade and the tower of an arbitrary wind turbine generator with horizontal axis.

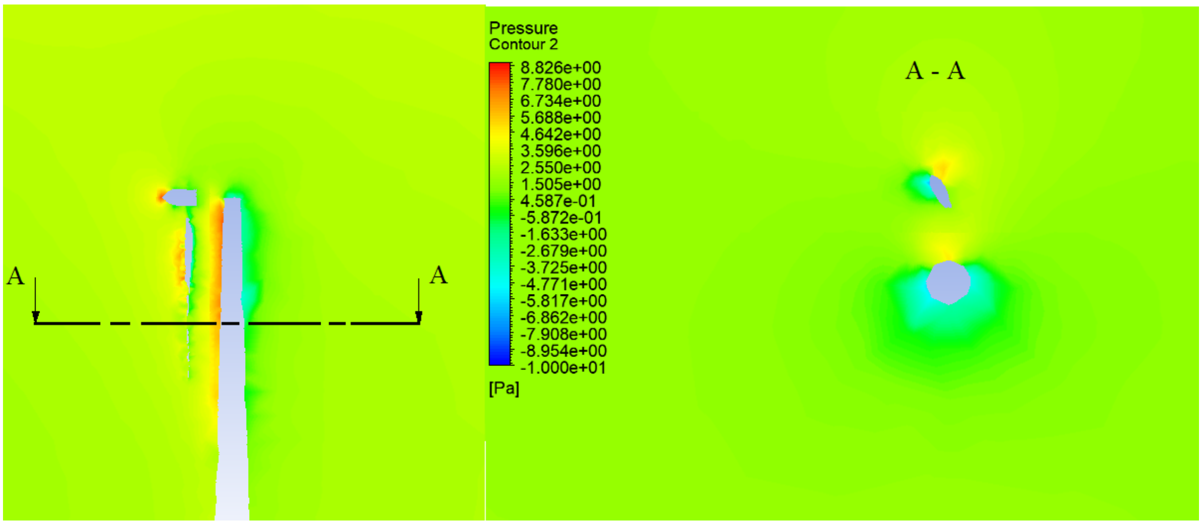

Figure 2. Pressure field deviation between the blade and the tower of an arbitrary wind turbine generator with horizontal axis caused by shading.

2. Model description

2.1 Wind model

In [10, 11] was shown that accounting for vertical wind speed gradient leads to significant fluctuations in the aerodynamic forces, especially for wind turbine generators of high class, like NREL 5MW [12]. In the current study, a logarithmic vertical wind speed distribution is chosen [13, 14] (figure 3).

$$u_0(z) = \frac{u^*}{k}\left[ln\left(\frac{z-d}{z_0}\right) + \psi(z, z_0, L)\right]. \tag{1}$$

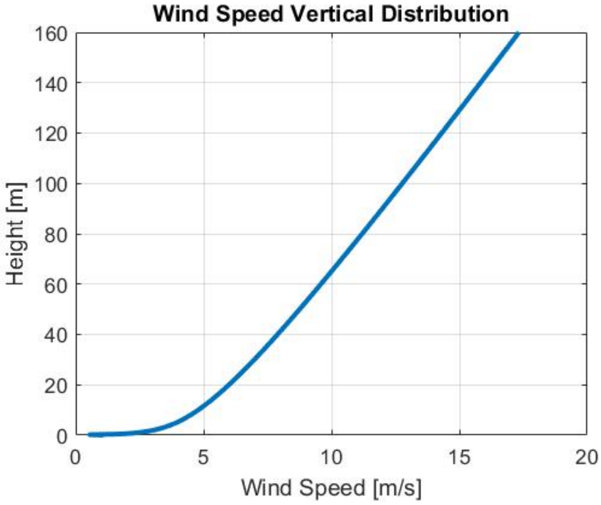

Figure 3. Wind speed vertical distribution.

2.2 Aerodynamics of the model

Considering the geometric dimensions of the generator [12], turbine diameter of 126 m and tower height of 87.6 m, a 3D transient numerical simulation of the turbine generator will cost a lot of computational time and may lead to inaccurate numerical values. In order to reduce the computational time and to improve the result accuracy, a 2D plane simulation is chosen. Similar to Blade Element Momentum (BEM) theory [15], the blade of the turbine is divided in finite cross sections. Each of the cross sections has 2 wind velocity components figure 4.

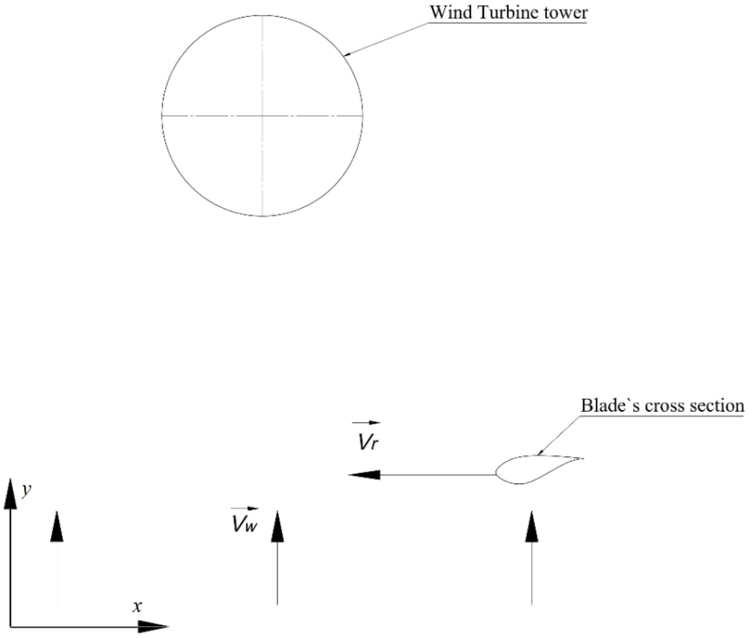

Figure 4. Aerodynamics of the model.

One component V_r corresponding to the rotation of the turbine blade, depending on the distance r from the cross section to the axis of rotation:

$$V_r = \omega r, \tag{2}$$

In the 2D case V_r is a translational velocity of the cross section. The second component V_w is the wind speed velocity itself. Its magnitude depends on wind speed vertical distribution (figure 3) and the cross sectional height from the ground. The frame of reference shown in figure 4 will be used to define the direction of the acting forces.

2.3 Numerical model

The described aerodynamic model is implemented in Fluent Ansys. The software solves numerically, the governing equations of fluid-dynamics: the Continuity equation (3), the Navier-Stokes` equation (4) and the Energy equation (5) [16], using Finite Volume Method (FVM) [17]. In the most general form, the equations are:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{V}) = 0 ; \tag{3}$$

$$\rho \frac{D\vec{V}}{Dt} = -\nabla p + \rho \vec{g} - \rho \vec{\omega} \times \vec{V} + g\rho T\vec{j} + \nabla\left(\mu \nabla . \vec{V}\right); \tag{4}$$

$$\frac{\partial}{\partial t}\left[\rho\left(e + \frac{V^2}{2}\right)V\right] + \nabla.\left[\rho\left(e + \frac{V^2}{2}\right)V\right] = \rho \dot{q} - \nabla.(p\vec{V}) + \rho(\vec{f}.\vec{V}) + Q`_{\text{viscous}} + W'_{\text{viscous}} . \tag{5}$$

Depending on the assumptions of the real physical system, the equations are modified in a more specific form. For the current study, the following assumptions are made:

- the air is assumed incompressible - with a constant density;
- the fluid is considered with isotropic viscosity;
- k-ω SST turbulence model is used [18]. The turbulence model adds two additional equations to the system of Partial Differential Equations (PDE);
- no heat transfer is considered.

The assumptions made, result in the following system of PDE

$$\left|\begin{array}{l} \nabla.\vec{V} = 0 \\ \dfrac{D\vec{V}}{Dt} = \vec{f}' - \nabla\left(\dfrac{p}{\rho}\right) + \nu \Delta \vec{V} \\ \dfrac{\partial k}{\partial t} + U_j \dfrac{\partial k}{\partial x_i} = P_k - \beta^* k\omega + \dfrac{\partial}{\partial x_j} + [(\nu + \sigma_k \nu_T)\dfrac{\partial k}{\partial x_j}] \\ \dfrac{\partial \omega}{\partial t} + U_j \dfrac{\partial \omega}{\partial x_i} = \alpha S_2 - \beta \omega^2 + \dfrac{\partial}{\partial x_j}[(\nu + \sigma_k \nu_T)\dfrac{\partial k}{\partial x_j}] + 2(1 - F_1)\sigma_\omega \dfrac{1}{\omega}\dfrac{\partial k}{\partial x_i}\dfrac{\partial \omega}{\partial x_i} \end{array}\right. , \tag{6}$$

where σ_ω=0.5, σ_k=0.85, η_0=4.38; β=3/40; β*=0.009, α=0.55 are coefficients of k-ω SST model [18].

Transient analysis is executed for physical time of 3.5 seconds with a time step of 0.0025 seconds. Dynamic mesh is used, in order to set linear velocity V_r of the blade`s cross sections. For this purpose, a UDF is compiled from a source file, using Microsoft Visual Studio [19]. The dynamic remeshing for different time steps of the DU40 airfoil calculation is shown in figure 5.

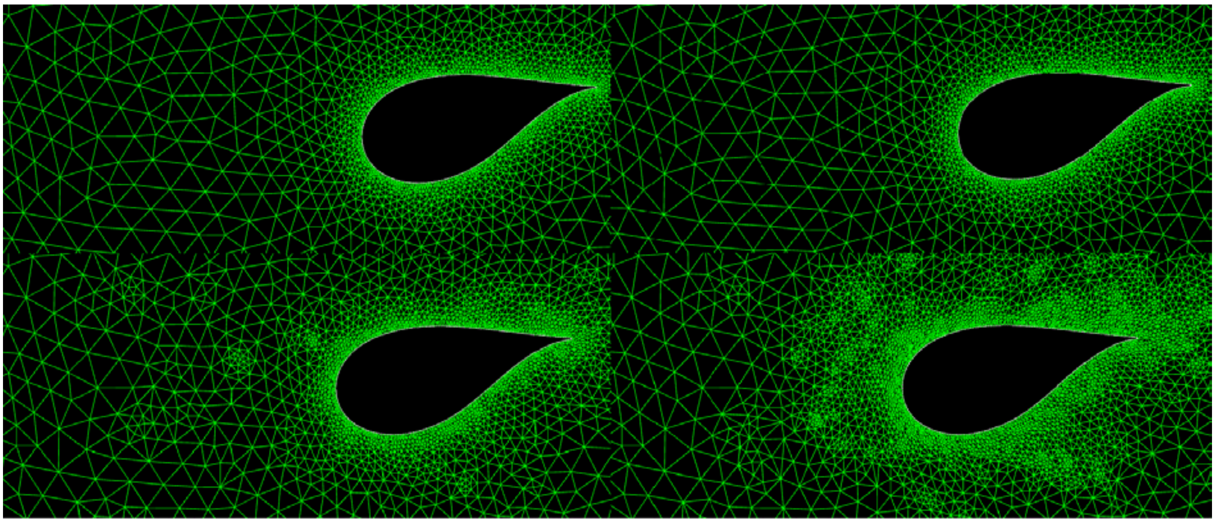

Figure 5. Dynamic mesh of the DU40 airfoil simulation for 1st, 3rd, 5th and 10th time steps of the calculation.

It is interesting to note the remeshed grid of finite elements, after the calculation finish (figure 6).

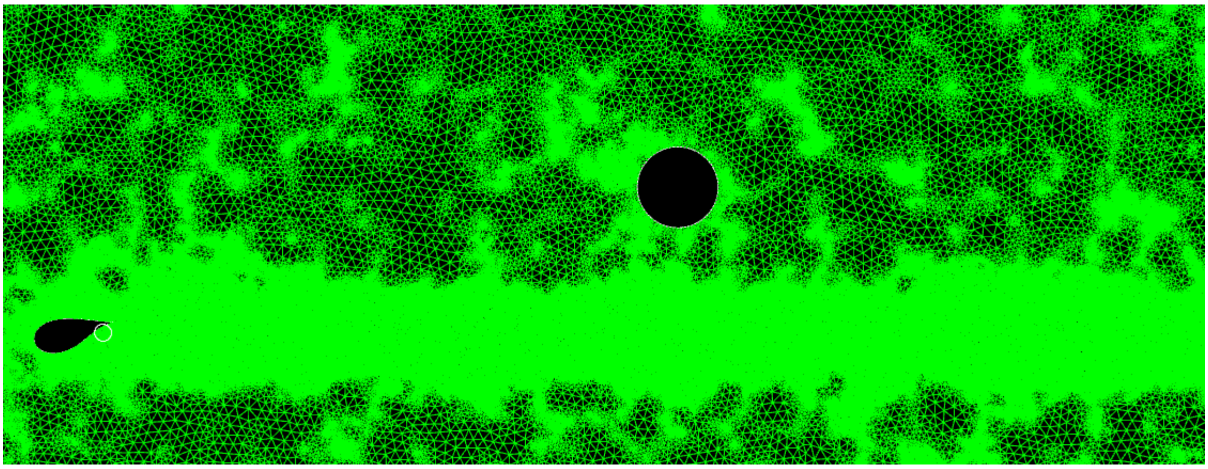

Figure 6. Finite element mesh at the end of the calculation.

The wind velocity V_w is set as inlet boundary condition. Multiple number of simulations are calculated for different cross sections of the blade. The purpose of the calculations is to define the behaviour of the pressure and velocity fields while the blade passes in front of the tower. Numerical values of the acting aerodynamic forces are obtain.

3. Results

As mentioned, calculations are made for multiple number of cross sections. The results show a certain pattern in the deviation of the aerodynamic parameters. In order to specify this pattern, the results for the DU30 airfoil are illustrated and analysed in details. The DU30 airfoil cross section is at distance of 24.05 m from the center of rotation. The two velocity components are V_w=10.5 m/s and V_r=30 m/s. The velocity and pressure distribution in the moment of a blade passing in front of the tower is shown in figure 7 and figure 8.

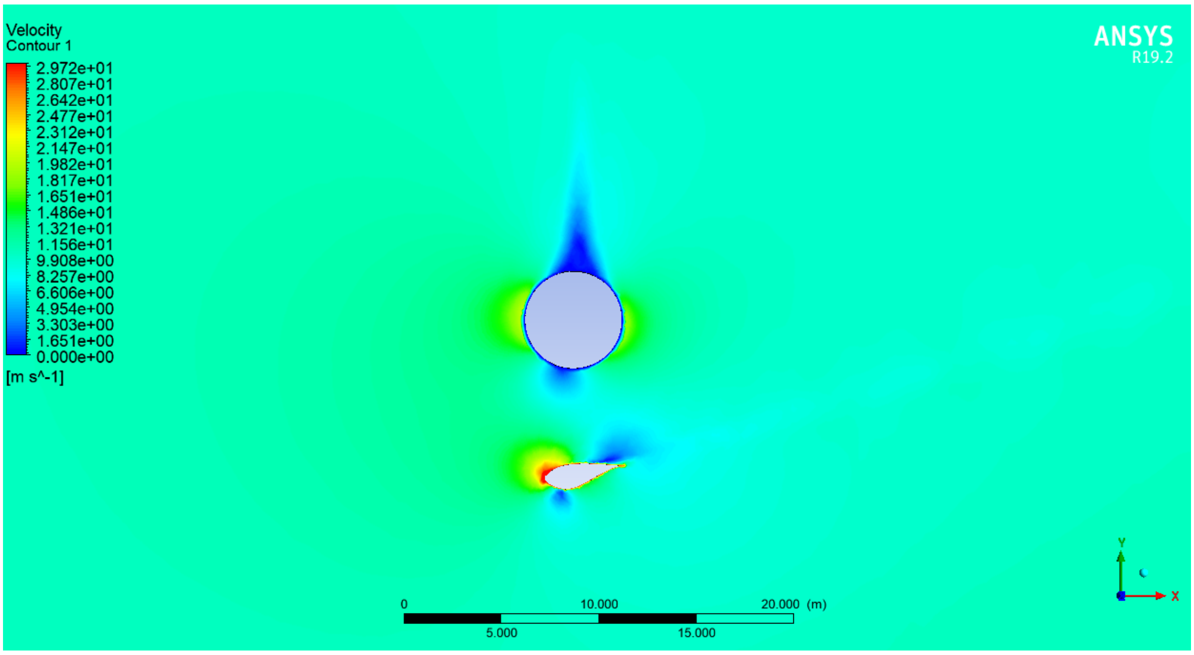

Figure 7. Velocity field of DU30 passing in front of the tower.

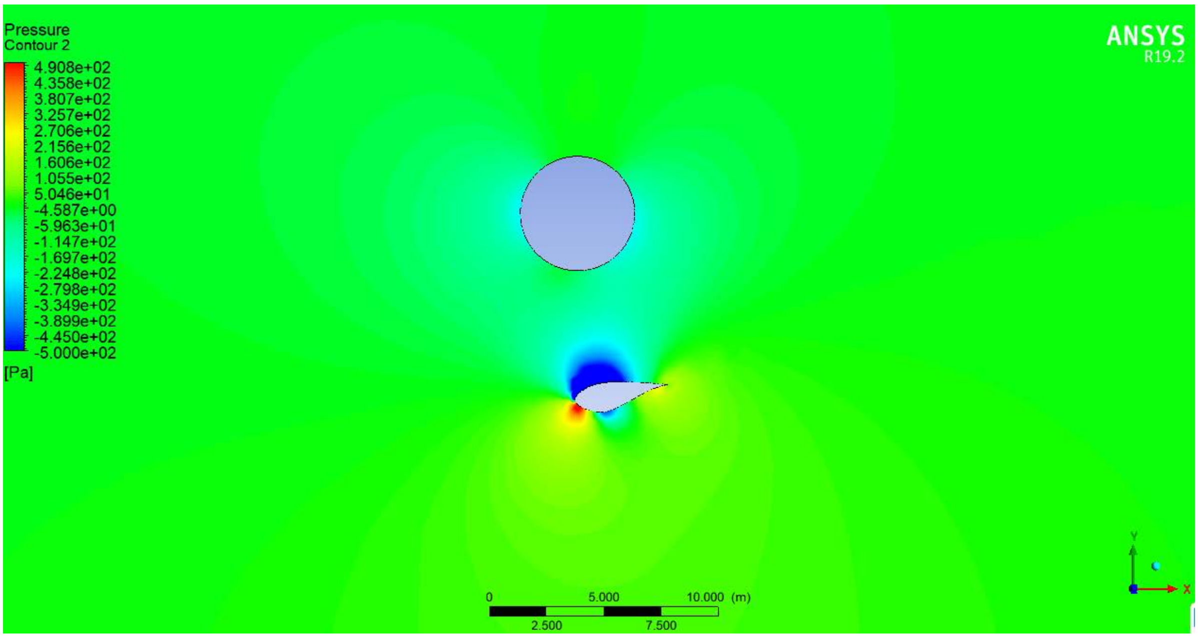

Figure 8. Pressure field of DU30 passing in front of the tower.

As expected, regions with relatively high speed occur close to the leading edge of the airfoil. This results in a low pressure close to the leading edge. The low pressure disturbs the pressure distribution around the tower, creating a region with low pressure in front of the tower. The effect of low pressure in front of the tower changes the direction of the drag force, exerted on the tower, from y positive direction (downstream) to y negative direction (upstream). The low pressure field close to the leading edge of the blade generates a lift force exerted on the tower. While the blade passes in front of the tower, the lift force changes its direction from x positive, to x negative. The numerical values of the tower drag and lift forces as a function of time are shown in figure 9 and figure 10.

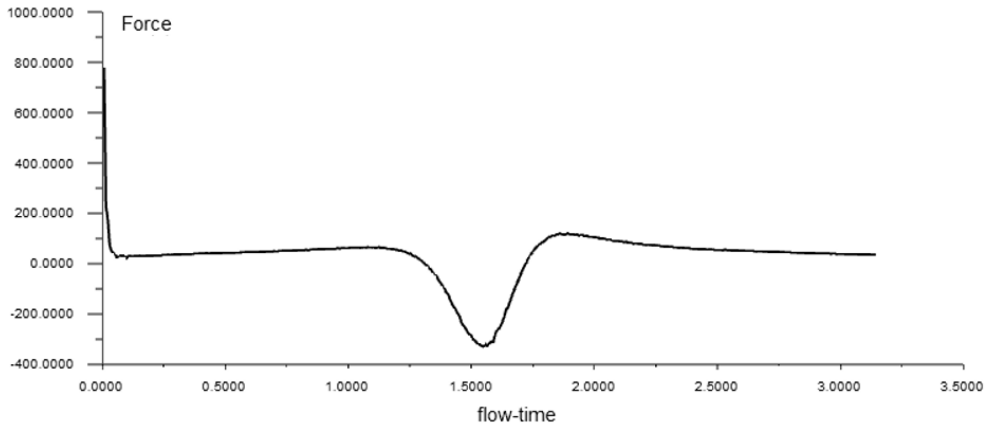

Figure 9. Tower drag force as a function of time.

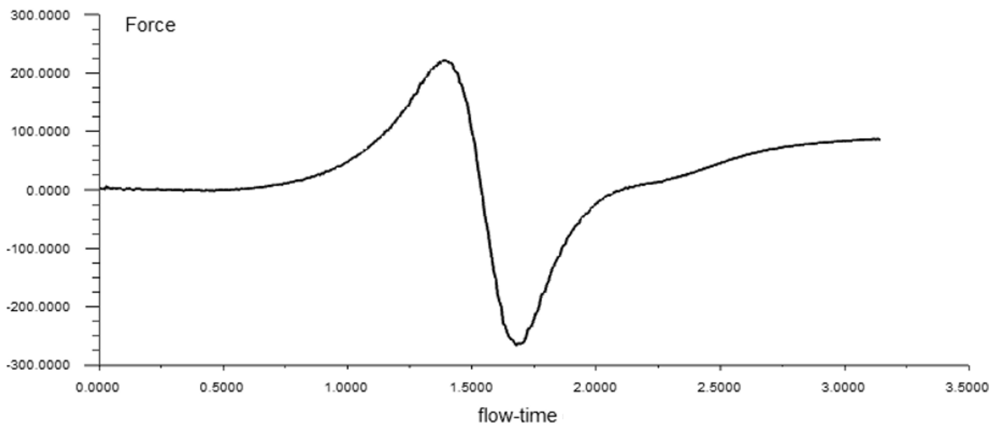

Figure 10. Tower lift force as a function of time.

The exact moment of time, when a blade is passing in front of the tower is 1.5 seconds. The aerodynamic shading influences the thrust (positive y direction) and the torque (negative x direction) forces exerted on the blade`s cross section. For the considered case, the drop in the thrust force is 15% and the drop in the torque force is close to 25%. The change in the magnitude of two forces is shown in figure 11 and figure 12.

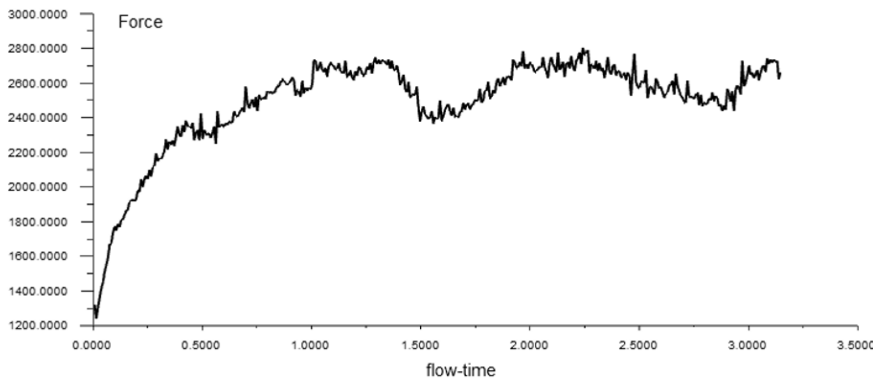

Figure 11. DU30 thrust force change in time.

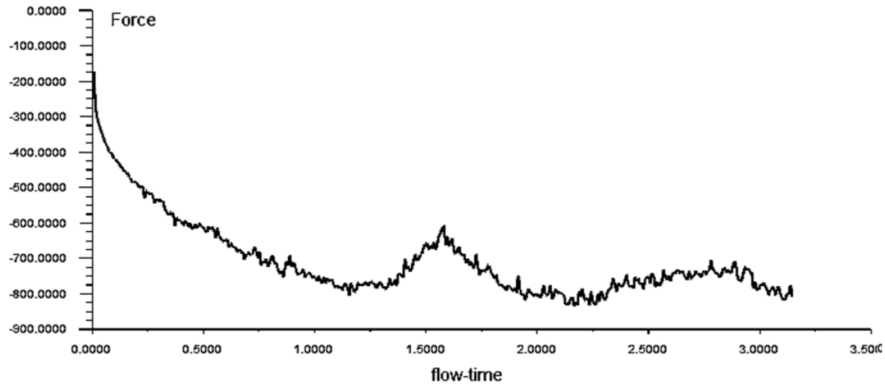

Figure 12. DU30 torque force change in time.

The described behaviour of the pressure and velocity fields, the drag and lift forces exerted on the tower, as well as the thrust and torque forces exerted on the blade is similar for all numerical calculations executed in the study. The accounting of all calculations and the coupling of all results, give us the following results. Figure 13 shows the drag force distribution on the tower of NREL 5MW wind turbine generator, without any consideration of aerodynamic shading. Figure 12 shows the deviation in the force, for the exact moment, when the blades 'shadows' the tower.

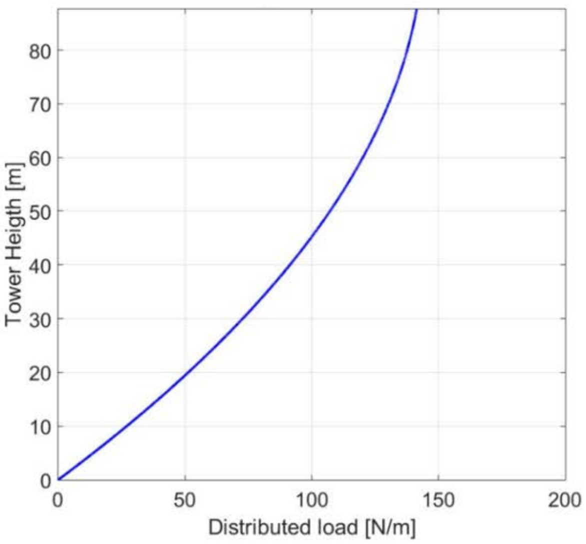

Figure 13. Tower drag force distribution without shading effects.

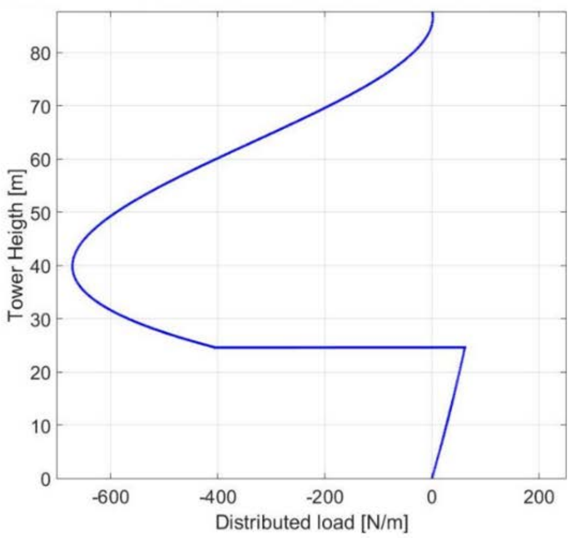

Figure 14. Tower drag force distribution with shading.

The rapid change in the distributed loads at a height of 25 m appears (figure 14), because no blade tip vortices are considered. In future researches, Glauert correction factor [21], associated with the tip loss, will be taken into account.

Figure 15 shows the thrust force distribution, exerted on the blade of the wind turbine for the vertical bottom position of the blade, without considering the aerodynamic interaction with the tower. Figure 16 shows the drop in the thrust force (normal to the plane of the wind turbine), when the shading is taken into account.

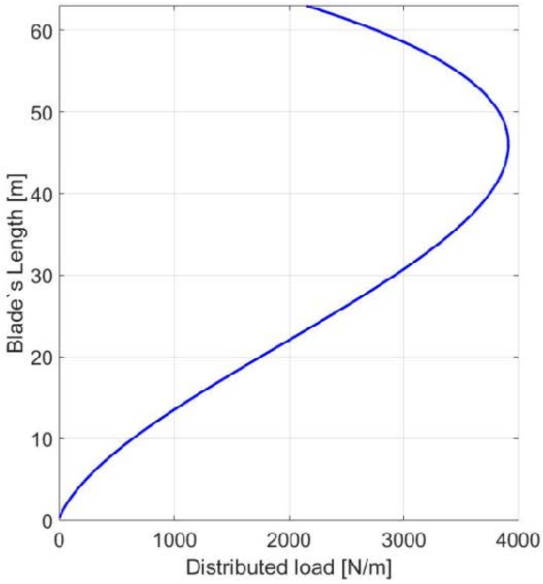

Figure 15. Blade thrust force distribution without shading effects.

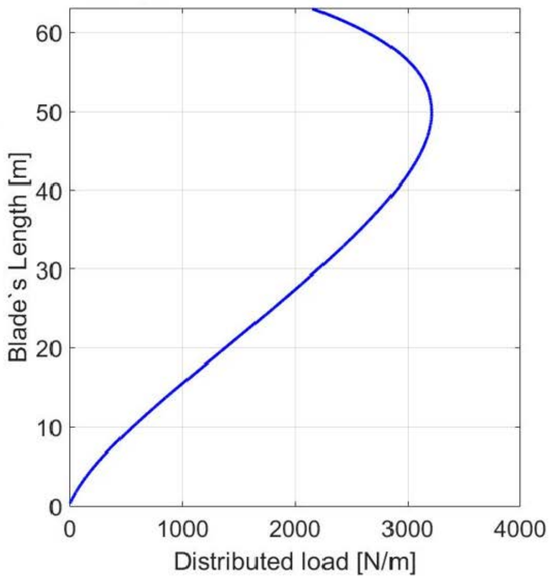

Figure 16. Blade thrust force distribution with shading.

As a confirmation of the numerical results validity, it is appropriate to mention that the aerodynamic forces, exerted on the blade`s cross sections, before the shading, correspond with lift and drag coefficients published in [20]. Before the shading manifests, the lift force on the tower is zero (figure 10).

4. Conclusion

The numerical studies made in this paper show the influence of the aerodynamic shading, which occurs between the blade and the tower of NREL 5MW wind turbine generator. Deviation in pressure and velocity fields is established, as well as change in the aerodynamic forces, exerted on the blade and the tower of the turbine generator. The drag and lift forces exerted on the tower change both their magnitudes and directions as shown in figure 9, figure 10 and figure 14. The analysis shows a drop in the blade thrust and torque forces between 15% and 25% compared to the primary values in figure 11, figure 12 and figure 16.

The paper suggests that the effect of aerodynamic shading is significant and should be analysed for every wind turbine design independently.

The obtained results could be used as inputs in a coupled dynamic model of the turbine and the tower in order to evaluate vibrations and fatigue of the constructive components. The model could be useful for the synthesis of a control system of the wind turbine to reduce loads and stresses on the components and to achieve better uniformity of torque and hence the quality of energy generated. The results could be used for verification of an analytical model of the aerodynamic shading, derived as a function of wind speed, distance turbine – tower etc.

Acknowledgments

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References

[1] Cummin R, Mason W, Marton S and McDoniel D 2015 *Applied Computational Aerodynamics* (Cambridge University Press) p 253

[2] Sørensen J, Mikkelsen R, Troldborg N, Okulov V and Shen W 2013 *The aerodynamics of wind turbines* (Springer)
[3] Michallef D and Bussel Gerard 2018 A review of urban wind energy research: aerodynamics and other challenges *Energies MDPI* **11**(9) 2204
[4] Leishman J2011 Aerodynamics of horizontal axis wind turbines *Advances in wind energy conversion technology* (Springer) pp 1–70
[5] Wang Y, Wang J Zhang J 2019 Effects of wind rotor tilt angle on aerodynamic power of wind turbine under typical periodic disturbances *Advances in Mechanism and Machine Science* (Springer) pp 3459–68
[6] Reiso M 2013 *The tower shadow effect in downwind wind turbines* (NTNU – Trondheim)
[7] Das S, Karnik N and Santoso S 2011 Time-domain modeling of tower shadow and wind shear in wind turbines *ISRN*
[8] Zahle F, Madsen A and Sørensen N. 2009 Evaluation of tower shadow effects on various wind turbine concepts *EFP-2007-II*
[9] Pinting Z, Shuhong H, Tao Y, and Jianlan L 2014 3D potential flow model of tower interference for upwind wind turbine *Advances in Mechanical Engineering* 612453
[10] Genov J and Angelov I 2016 Influence of vertical wind speed distribution on the dynamic loads in large wind turbines *Proc. Int. Sci. Conf. BulTrans-2016 (Sozopol, Bulgaria)* pp 136–40 (In Bulgarian)
[11] Genov J, Kralov Iv and Angelov I 2018 Dynamic loads of the turbine blades in high power class wind generators caused by the vertical wind turbulence *1st Inter. Conf. of Marine Eng. (Varna, Bulgaria)*
[12] Jonkman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-MW reference wind turbine for offshore system development, *Tech. Report NREL/TP-500-38060*
[13] Manwell J, McGowan J and Rogers A 2009 *Wind energy explained: theory design and application* (DNV – Global Energy Concepts, Washington, USA)
[14] Landberg L 2016 *Meteorology for Wind Energy - an Introduction* (John Wiley & Sons Ltd.) p 215
[15] Grant I 2011 *Wind Turbine Blade Analysis Using the Blade Element Momentum method*
[16] John D and Anderson J 1991 *Fundament of Aerodynamic* (University of Maryland) p 792
[17] Moukalled F, Mangani L and Darwish M 2016 *Finite Volume Method in Computational Fluid Dynamics* (Springer)
[18] SST k-omega model https://www.cfd-online.com/Wiki/SST_k-omega_model Accessed on: 15.02.2020
[19] *ANSYS Fluent Tutorial Guide 18* 2017 (ANSYS, Inc.)
[20] Moriaty P and Hansen A 2005 *AeroDyn Theory Manual* (NREL/TP-500-36881) p 47