NUMERICAL DETERMINATION OF THE NOMINAL POINT OF A WIND TURBINE

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Abstract: The aim of this paper is to determine the nominal point of a Darrieus vertical axis wind turbine. In this study, two methods have been used. The first case used the DOF method, which requires the designation of the degrees of freedom of the turbine to ascertain the optimal revolution of the turbine for a certain speed of the wind. The second method relies on the unsteady analysis of the turbine for different tip speed ratios. A circular shaped domain was created using ICEMCFD, which was further divided in two subdomains. The first subdomain, the rotor, incorporates the blades and the shaft, while the second subdomain, the stator, represents the outer environment. A structured mesh was chosen for this study. The grid was generated using the blocking method. The chosen parameters for this study have the purpose of capturing the flow around the blades, and especially the boundary layer. For both cases, the variations of the moment coefficient were computed. By multiplying the mean of the moment coefficient with the tip speed ratio, we get the power coefficient. The results of this paper will be tested in a wind tunnel, using an experimental scale model of the turbine.

1. Introduction

In an age when the effects of global warming become more and more obvious, through extreme meteorological events [1], combined with the rapid approaching depletion of fossil fuels [2], wind power offers a clean and inexhaustible source of energy to power the future [3].While the potential of wind was known for centuries, it only gained momentum in the past three decades [4], as governments supported the development of renewable energy through policies and tax breaks. The European Union wants a decrease in energy consumption of 20%, an increase of 20% of renewable energy generated and a 20% reduction in greenhouse gasses, with the aim of achieving all these objectives by 2020 [5]. This renewed interest and the substantial public funding of development, have made wind power the fastest growing energy resource in Europe and the world [6].

The benefit being environmentally and financially sustainable of wind energy power [7,8] gives it the potential of being the key asset in powering a better future for the generations to come. Also, the fact that it is a free source of energy, it can provide the necessary means for some countries to achieve energy independence, which plays a big role towards a stable economy.

Although, the free and limitless supply of power from the wind, seems to be the best alternative to conventional ways of producing energy, the current generation of wind turbines still fails to get anywhere close to their theoretical efficiency [9]. That is why, researchers around the globe, strive to come up with novel ways to shorten the gap between the current efficiency of wind turbines and the maximum theoretical efficiency, known as the Betz limit. The process of developing high efficiency wind turbines is a complex venture that requires extensive support from many branches of the industry, namely: manufacturing, testing, numerical analysis etc. This study is going to focus on facilitating the latter, by decreasing the necessary development time of the turbine.

Wind turbines can be classified by many factors, the most common ones are: the rotation axis (horizontal or vertical); the aerodynamic force that drives the turbine (lift –Darrieus; drag – Savonius; or a mix of both); and the power output. Since horizontal axis wind turbines (HAWT) seem to have reached their maximum potential in terms of power output, size and efficiency [10], this paper will focus on the vertical axis wind turbines (VAWT).

Though, less common, VAWTs have several advantages over the industry dominating HAWTs, i.e. more basic construction; they are able to work at wind speeds in excess of 200 km/h; the generator can be placed on the ground, significantly reducing weight; easily integrated on buildings, making it more adequate for urban settings; the direction of the wind does not influence their performance; and require less space to operate, having the ability able to achieve several times the power density of HAWTs if placed in farms [11]. But they are lacking when it comes to their ability of self-starting, and due to the extensive research, that benefited the HAWT, VAWTs have lower efficiencies.

The deficit in efficiency is the current centre of interest in research of wind turbines, focusing its resources in developing high performance VAWTs that can compete, or even outperform the current generation of HAWTs. At the current rate of development, with multi mega-watt VAWTs on the way[12], it is estimated, that VAWTs will outnumber and outweigh the HAWTs in terms of power generation somewhere in the next three decades.

There are a large number of studies that researched some of the factors that affect the aerodynamic performance of a wind turbine, in a bid to squeeze as much power as possible from wind turbines. Many of the studies involve computational fluid dynamics CFD analyses, and have focused on how the flow is affected by the geometry of the blade; the pitch of the blade [13];the solidity of the turbine [14]; and the effect of the shaft on the overall performance of the turbine [15]. Although, very useful, the results cannot be generalized, since making slight changes to the geometry of the turbine can often result in totally different flow patterns that will eventually have a big impact on the overall output parameters of the turbine, due to the asymmetric, periodic, unsteady and highly turbulent characteristics of flow around turbines [16]. This is the reason why there is a need of precise methods that assess the output performance of wind turbines. Although the experimental study of turbines in wind tunnels has the most accurate results, it often proves too expensive[17],involving manufacturing of scale models and requires a lot of time to set up the wind tunnel at the desired parameters. Experimental testing is still an invaluable resource, that is indispensable in any study, but it is mostly used as a mean to validate the results of a CFD case.

Studies that show different models that can determine the aerodynamic capabilities of vertical axis wind turbines, have been conducted [18,19], but the results often have large error margins. However, CFD has proven to be the most reliable [20] and efficient, being able to adapt to a wide range of cases, being able to yield reliable results that closely match the experimental data [21]. The current problem with CFD analyses is that there are no set guidelines that ensure the validity of the results, since there are a lot of settings that can affect the outcome of each case.

Accurate CFD and experimental studies are crucial in the process of better understanding the VAWT, enabling researchers to evaluate the complex fluid dynamics around the wind turbine, in real world conditions, which further allows them to make correct assessments regarding what features are beneficial, and which are detrimental to the turbine. There are several CFD methods that can compute the output values of the turbine, but the common ones being used today, require extensive periods of time and several cases [22] to be conducted at different tip speed ratio (TSR) values, in order to determine the nominal point.

The aim of this study is to provide a method to numerically assess nominal point of a VAWT, along with the guidelines that ensure reliable results, without the need to undergo several cases. This method will employ the commercial CFD software Ansys Fluent to simulate the flow around the turbine. The Unsteady Reynolds Averaged Navier-Stokes (URANS) based model Sheer Stress Transport (SST) was chosen, which solves one for the equation for turbulence kinetic energy and the equation for the specific dissipation rate.

2. Theoretical approach

The theory that explains the fundamentals of the power extracted from a stream of wind by wind turbines, is a derived using the conservation of mass and the conservation of energy. As a result, equation (1) shows the maximum amount of power that can be extracted from a stream of wind, being an analogy of the Carnot cycle used in thermodynamics.

$$P_{\max} = \frac{16}{27}\frac{\rho}{2}V_1^3\frac{\pi D^2}{4} \tag{1}$$

The theory behind the efficiency of wind turbines was first introduced in 1919 by the German engineer Albert Betz [23], and applies to both vertical and horizontal axis wind turbines.

Unlike the Carnot Cycle from thermodynamics, which uses two temperatures, the analogy used by A. Betz relies on two speeds, V_1 andV_2. Through some assumptions, and deriving a relation between the two velocities, we get the Betz limit (2) [24], that states that the upstream velocity, V_1, is reduced to a lower, nonzero downstream velocity V_2.

$$Betz\ coefficient = \frac{16}{27} = 0.592593 = 59.26\% \tag{2}$$

The value of the coefficient corresponds to the maximum efficiency that a wind turbine can achieve, meaning that only 59.26% of the kinetic energy of a wind stream can be extracted, under ideal conditions. But, under real world conditions, due to factors like blade surface roughness, frictional losses, and blade tip losses the extracted power only reaches 35-40% of the total available power.

The efficiency of the turbine is defined by the power coefficient, and it is the ratio of the power extracted from the wind and the total power available in the wind stream.

$$C_p = \frac{P_t}{P} = \frac{P_t}{\frac{\rho}{2}\frac{\pi D^2}{4}V_1^3} = \frac{M\omega}{\frac{\rho}{2}SV_1^3} \tag{3}$$

The torque of the turbine is defined as:

$$M = \frac{\rho}{2}SV_1^2RC_m \tag{4}$$

From equations (3) and (4), the coefficient of power C_p is defined as:

$$C_p = C_m\frac{\omega R}{V} = C_m\lambda \tag{5}$$

From equation (3), the power output of the turbine can be expressed as [24]:

$$P = \frac{\rho}{2}V_1^3\frac{\pi D^2}{4}C_p \tag{6}$$

The dimensionless factor λ , known as the tip speed ratio (TSR), and it is defined as the ratio of the tangential speed of the blade and wind speed:

$$TSR = \lambda = \frac{v}{V} = \frac{\omega R}{V} \tag{7}$$

Another proposed model for calculating the performance of a wind turbine, is I. Paraschivoiu’s Double-Multiple Streamtube Model for Darrieus Wind Turbines [25]. This method relies on dividing a multiple-streamtube model in two parts: one that is modeling the upstream half-cycle of the rotor, while the other one is modeling the downstream half-cycle. This model involves calculating the upwind and downwind components of the induced velocities at each level of the rotor, was based on the principle of the two actuator disks in tandem.

Paraschivoiu’s model was a great breakthrough in the development of wind turbines, at the time, allowing analytical analyses to be performed on wind turbines with blades that had several curves, at the early design phase, due to their low computational cost.

3. Geometry and boundary conditions setup

The wind turbine on which this paper is based on, is a Darrieus type one with straight blades. The rotor has three blades that were designed using the NACA 0021 airfoil, and supporting arms, which are aerodynamically designed to reduce the negative effect of drag. The bearing system is also a part of the wind turbine assembly, consisting of a radial axial and a axial bearing mounted on a fixed shaft. Table 1 shows the geometric characteristics of the studied wind turbine.

Table 1. Wind turbine geometric features:

Parameters	Value	Units
Airfoil	NACA 0021	-
Blade chord	0.3	m
Turbine diameter	2.4	m
Turbine height	3.6	m
Number of blades	3	-
Design velocity	10	m/s
Design power	2000	W

The geometry of the wind turbine has been modeled using a commercial CAD software and it is shown in Figure 1, where the three blades and the supporting system can be observed.

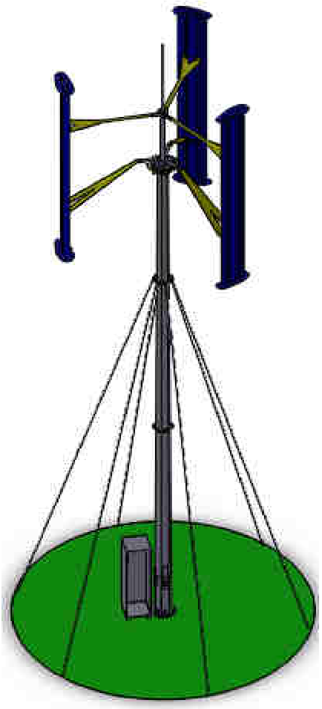


Figure 1. 3D Wind turbine model

Figure 2. Computational domain

For the numerical analysis, a 2D computational domain has been defined. The domain was further split in two subdomains, the rotor and stator. The former is the rotating part of the domain and incorporates the three blades and the shaft, while the latter is static and represents the environment around the wind turbine. An interface has been defined between the two subdomains, which connects the rotor to the stator and vice-versa. Figure 2 shows the computational domain with the two subdomains.

The grid was generated using the ICEM CFD software, by employing the blocking function, in order to have a structured grid with hexa elements. To resolve the probable issues around the boundary layer, the y^+ value has been set to no more than 1, and the growth ratio of the elements was set to 1.1. Figures 3 and 4 show the grid and the value of y^+, starting from the leading edge, all the way to the trailing edge.

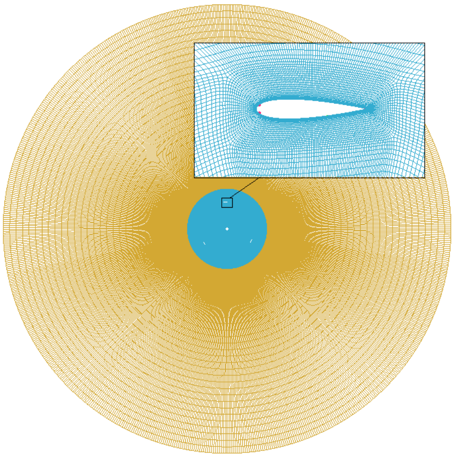


Figure 3. 2D Mesh of the wind turbine

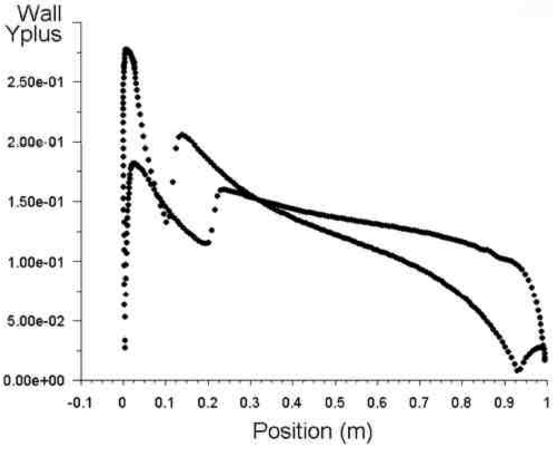


Figure 4. Blades y^+ value

The CFD numerical models work by solving the Navier-Stokes system of equations. This system is formed of the following three equations: the equation of continuity, conservation of momentum and conservation of energy. To simulate the flow around the wind turbine, the commercial software ANSYS fluent has been used. Table 2 shows the required input parameters of a CFD case.

Table 2. Ansys fluent case setup

Models	Solver	Pressure Based	Unsteady	2D
	Viscous Model	k-ω SST		
Materials	Air	Density, constant		
Operating conditions	Pressure 101325[Pa]			
Boundary Condition	Inlet	Velocity inlet V_x=10m/s		
	Blades	wall		
	Shaft	wall		
	Interface	Interface rotor-stator		
	Rotor	Mesh motion		
	Stator	Stationary		
Solve	Controls	Solution	Courant nr=5	Discretization 2nd order upwind
	Initialize	Inlet, Velocity=10m/s		
	Monitors	Residuals	10^{-6}	
		Force	Momentum coefficient	
	Iterate	10^{6} Steps	0.001s time step size	
Report	Reference values	Inlet	Length=turbine radius	

4. CFD Simulations

Current CFD simulations of wind turbines, rely heavily on the mesh motion model, which works by selecting a set rotational speed for the rotor and performing several studies in order to determine the nominal point of the turbine. Although these studies have a decent accuracy, and have a relatively low computational cost, they do not provide any information regarding the self-starting capacity of the turbine, or the dynamic stall.

A numerical study by Amet et al. [26] on the blade-vortex interactions of Darrieus wind turbines, show that the flow pattern is highly dependent on the flow time history, not just the current flow characteristics that are being considered in constant rotational velocity CFD studies [27].

Another flaw of the mesh motion study, is the fact that the instantaneous rotational speed of the turbine is dependent on the torque, but the moment is non-uniform throughout a full rotation, making the constant rotational speed simulation less accurate [27].

To solve these issues, this study has been conducted using the degree-of-freedom (DOF) method of Ansys Fluent, which shows the time-dependent flow around the VAWT. The DOF study also accounts for the moment of inertia, and the self-starting characteristics of the turbine. The required input parameters of the simulation were the wind velocity and the moment of inertia, allowing the software to compute the characteristics of the turbine at every time step, until the simulation converged to the nominal point.

Due to the time-dependent characteristics of the simulation, the Unsteady Reynolds Averaged Navier-Stokes based model SST, was employed in this study, because of its successful history of accurately predicting the performance of wind turbines. This model is a combination of the standard k-ε model and the k-ω model, using k-ε for the free flow area, which is considered fully turbulent, and the k-ω model for the boundary layer. The transition between the two models is insured by the use of connecting functions, which have the purpose of activating each of the models, depending on the area of interest. These connecting functions have another role of introducing a diffusive term in the transport equation of ω.

The transport equation for the kinetic turbulent energy (k):

$$\begin{aligned}&\frac{\partial k}{\partial t}+\bar{u}\frac{\partial k}{\partial x}+\bar{v}\frac{\partial k}{\partial y}+\bar{w}\frac{\partial k}{\partial z}=\\&=\frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(\Gamma_k\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_k\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_k\frac{\partial k}{\partial z}\right)\right]+\tilde{G}_k-Y_k\,.\end{aligned} \tag{8}$$

The transport equation of the specific rate of dissipation (ω):

$$\begin{aligned}&\frac{\partial \omega}{\partial t}+\bar{u}\frac{\partial \omega}{\partial x}+\bar{v}\frac{\partial \omega}{\partial y}+\bar{w}\frac{\partial \omega}{\partial z}=\\&=\frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(\Gamma_\omega\frac{\partial \omega}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\omega\frac{\partial \omega}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_\omega\frac{\partial \omega}{\partial z}\right)\right]+G_\omega-Y_\omega+D_\omega\,.\end{aligned} \tag{9}$$

Γ_k, and Γ_ω are the terms that represent the effective diffusivities of *k,* and *ω,* respectively.

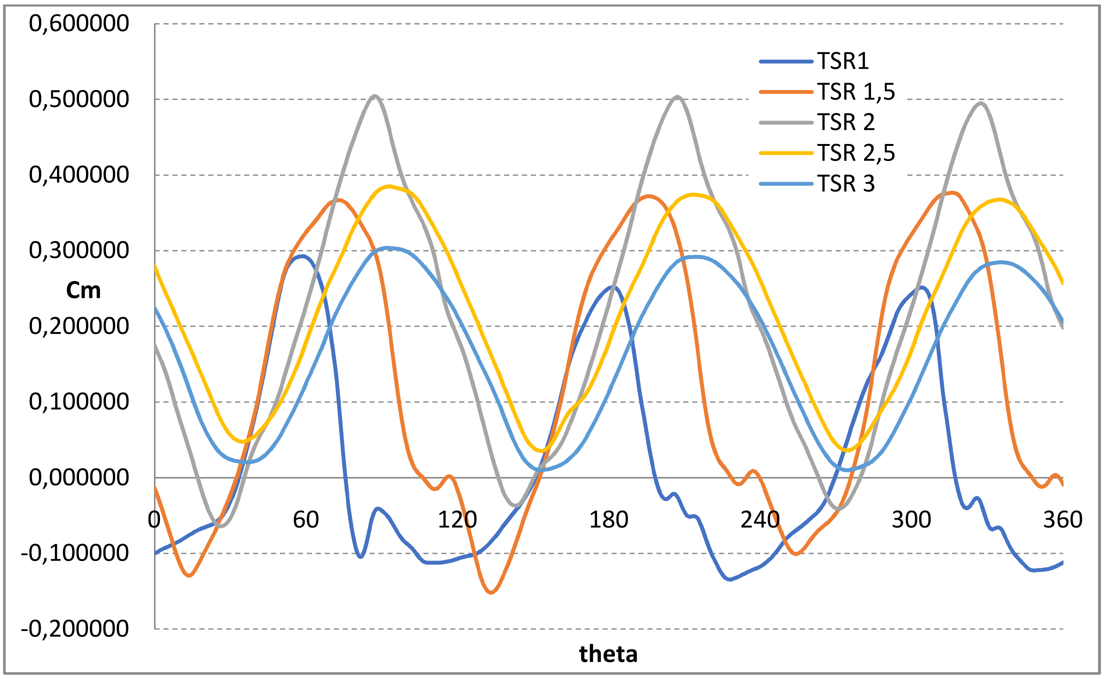
$$\Gamma_k=\mu+\frac{\mu_t}{\sigma_k},\ \Gamma_\omega=\mu+\frac{\mu_t}{\sigma_\omega}. \tag{10}$$

5. Results

In order to determine the optimal value of the TSR for this vertical axis wind turbine, several simulations were carried out, using the URANS model. It is a known issue that these turbines suffer in terms of self-starting capabilities, due to their aerodynamic equilibrium that simply makes them stop right away. Still, to estimate the efficiency of a wind turbine it is necessary to know the nominal point of the turbine, where the coefficient of power has the maximum value.

As results, the variations of the torque coefficient were plotted for a period of ($T=360^0$), and also the variation of the power coefficient as a function of TSR and employed method. The estimate the evolution of the turbine, the vorticity magnitude for different positions of the blade, has been plotted. This makes it easier to observe the recirculation areas that have a negative impact on the overall performance of the wind turbine.

Figure 5 shows the variation of the torque coefficient for different values of the TSR. The maximum value is obtain at TSR=2.5, where the value of the angle of incidence does not exceed the critical value of stall.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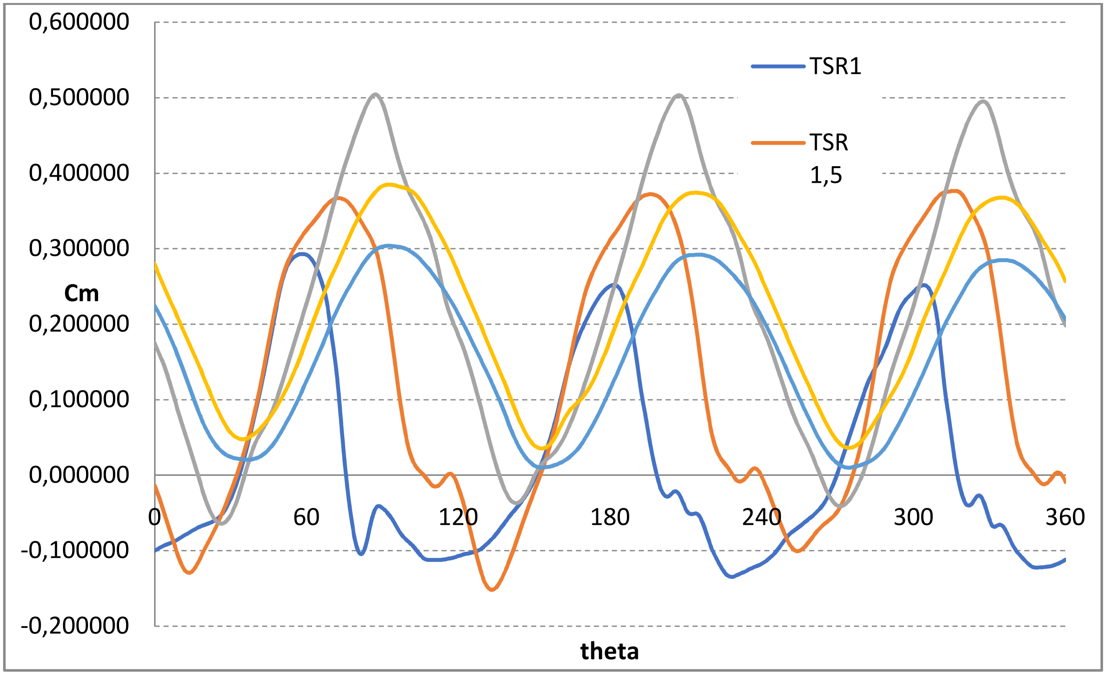
a)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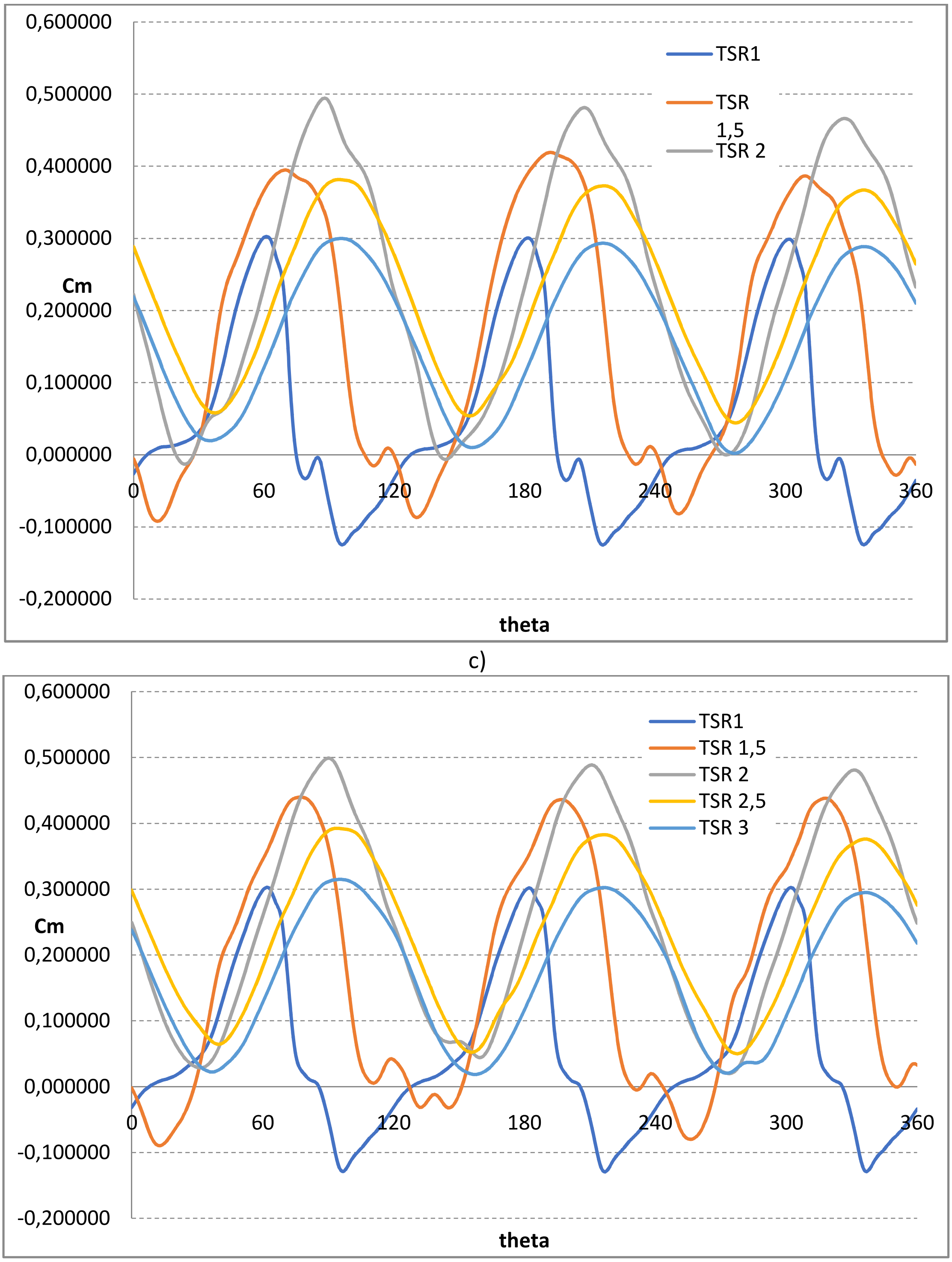
b)



c)

d)

Figure 5. Torque coefficient variation: a) V=6m/s; b)V=8m/s; c)V=10m/s; d) V=12m/s

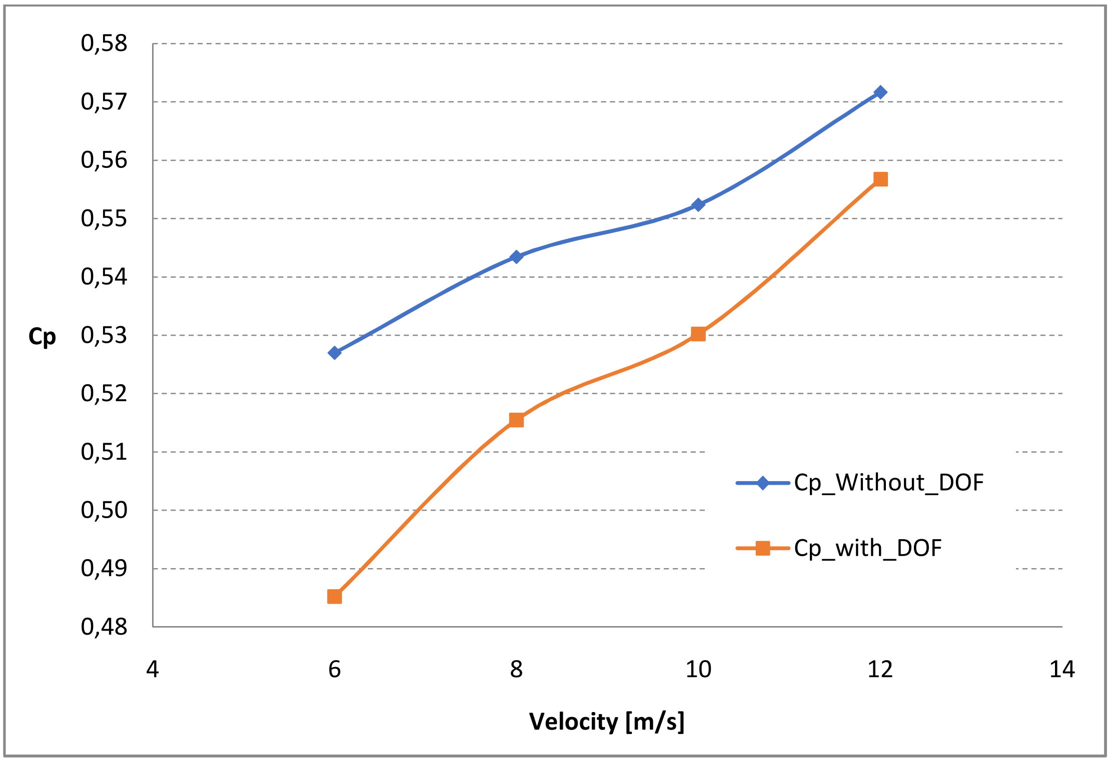
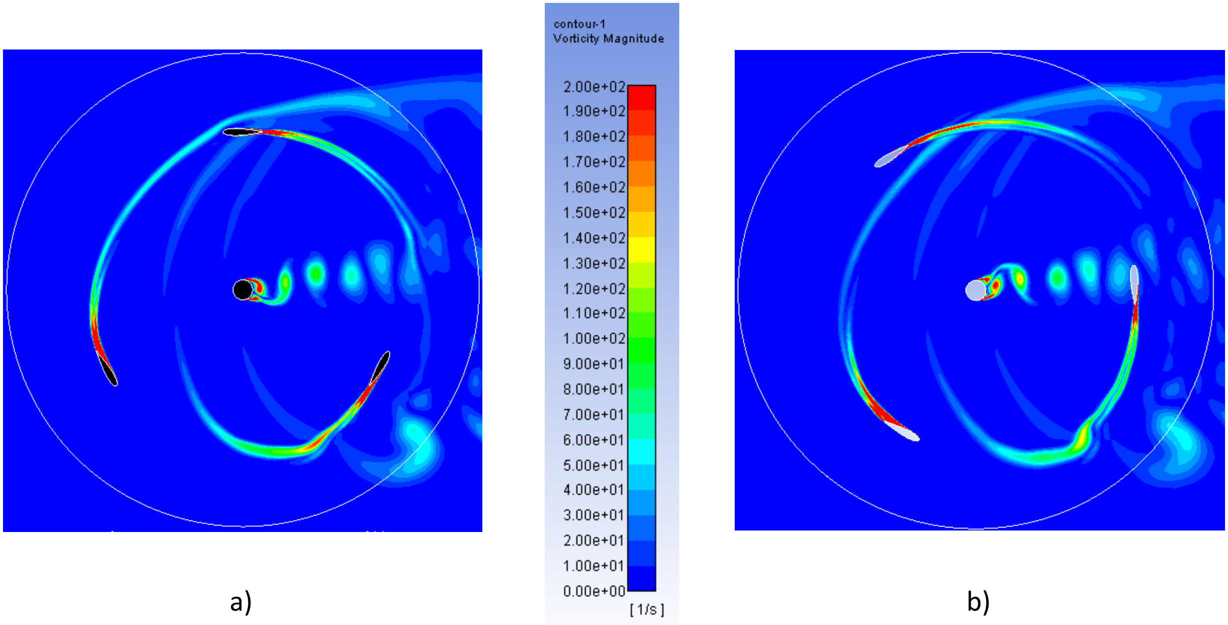


Figure 6. Power coefficient variation with velocity

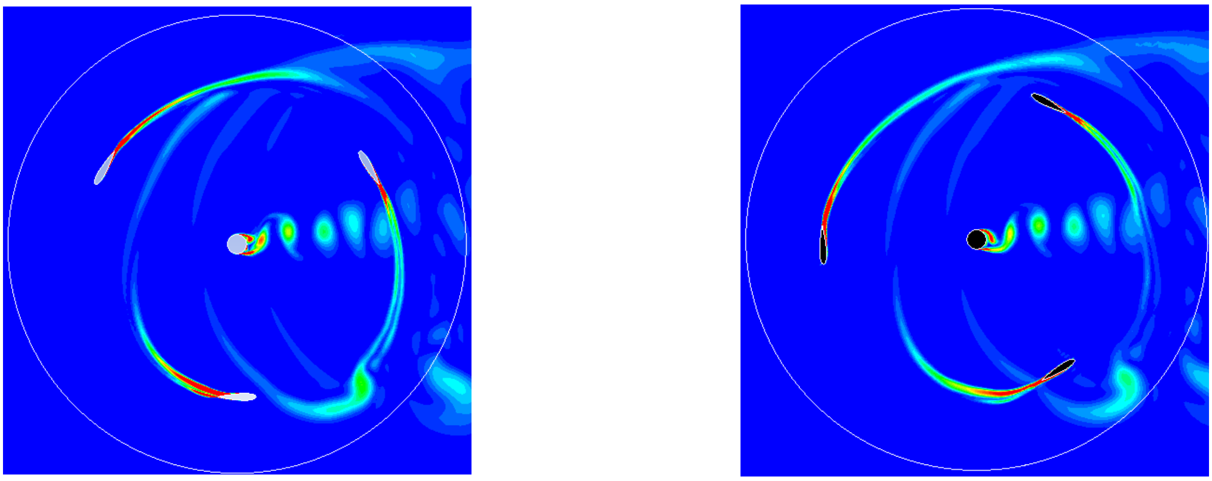
Figure 6 shows the variation of the power coefficient as a function of velocity. It can be observed that the DOF method, which takes in account the moment of inertia of the blades, estimates the output of the turbine by considering the role played by the mass of the assembly.

With the increase in value of the TSR, the vortices shown in the CFD simulation, change drastically. At low values of TSR, the separation of the boundary layer on the blades happens relatively fast, at high values, it tends to stay attached throughout a full 360 degree rotation. Figure 7 presents the vorticity at a wind velocity of 10 m/s, corresponding to a TSR value of 2.5.



a)

b)



c) d)

Figure 7. Vorticity magnitude contours: a) $\theta = 0^\circ$; b) $\theta = 30^\circ$; c) $\theta = 60^\circ$; d) $\theta = 90^\circ$;

6. Conclusions

In this article, the flow around a wind turbine has been numerically analyzed, with the use of CFD methods, in order to compute the nominal point of the turbine. For this analysis, the geometry of a vertical axis wind turbine, that can generate up to 2 kW of power at a wind velocity of 10 m/s, has been used. The analysis employed two methods of efficiency estimation for a wind turbine. The first method requires a fixed user defined value for the TSR, while the second one, requires the value of the moment of inertia, in order to determine the TSR. The analysis has shown that the method which employs the degree-of-freedom for the turbine, has estimated a lower efficiency, by taking in account the role played by the mass of the blades. As relevant results, the variations of the torque coefficient were chosen, for different TSR values (1; 1.5; 2; 2.5; 3) and wind speeds (6-12 m/s).The first method has estimated that the maximum efficiency is 57% for a value of the TSR of 2.5, while the DOF method yielded an efficiency of 55% for a TSR value of 1.9. The aforementioned values for efficiency are for the 2D case, where the 3D effects of the flow have not been considered.

7. Acknowledgement

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