The optimal profile of wind generator blade modelling with CFD-method

Vadim Khudoyarov, Dmitry Samsonenko, Artyom Nikulin, Nikolai Barbashov and Leila Abdullina

Bauman Moscow State Technical University, Theory of machines and Mechanisms Department, 2nd Baumanskaya st., 5/1, Moscow, 105005, Russian Federation

E-mail: abdullina_98@mail.ru

Abstract. Using of renewable energy sources, instead of traditional oil, gas and coal, is the one of the ways by which it’s possible to hold global warming mechanisms. One of these sources is the wind energy and the device-transformer for it is the wind generator. This paper deals with the problem of the optimal wind generator blade design which allows getting the device efficiency maximum. The alternative wind generators realisations and their advantages are showed in the work. The numerical methods for fluid dynamic equations solving were applied for the optimal profile definition. The advantages of this way were showed, also the model, which was the best fitted for the concerned conditions, was chosen. Modelling was realized in ANSYS Fluent. The results were compared with the real wind generations data.

1. Introduction
In the modern world replacement energy of fossil resources by renewable energy is an important issue. This problem can be solved by using solar energy, geothermal energy, etc. One of such sources is the wind energy which converted to electric energy by wind generators. The wind energy has some advantages: it is weather independent, accessible, it doesn’t pollute the environment. The wind energy has been applied by people since ancient times. But the idea of the wind energy exploiting in order to extract electric energy was born in the end of XIX century by Charles F. Brush. It was the first wind generator and had power about 12 kW [1].

1.1. Current situation in wind energy
Nowadays wind generators achieve 8 MW and have rotor diameter above 120 meters. And it isn’t the maximum, specialists continue their researches and try to design wind generator with 20 MW of power. But there is a problem: the rotor weight promotes when we increase the wind farm capacity. This problem can be solved with modern materials, for example with composite materials. If such powerful generator will be designed it will be able to cover most of the European energy production [2].

According to World Wind Energy Association (WWEA) the overall capacity of wind turbines reached 597 GW in 2018. In figure 1 WWEA statistic of summary wind energy is presented [3].
Figure 1. Global wind installations. Growing of summary wind energy, wind turbines installed in 2015-2018 [4].

1.2. Types of wind generators
Wind generators are separated by their axis orientation on:
- Horizontal-axis wind generators (HAWG)
- Vertical-axis wind generators (VAWG)

In figure 2 typical schemes of HAWG and VAWG are presented.
And sometimes wind turbines are separated on the basis of their power:
- Industrial (>300 kW)
- Small turbines (1-300 kW)
- Micro turbines (<1 kW)

Usually HAWG are used as industrial because they have bigger the power efficiency coefficient than VAWG [6].

2. Aerodynamic in wind energy
In 1920 Betz showed that the wind turbines power efficiency can’t be more than 59.3 %. Figure 3 shows the scheme of air flow through wind wheel.

Now we can introduce drag coefficient (coefficient of wind velocity reducing) (1):

\[ C_p = \frac{1}{2} \rho v^2 C_{D} \]
\[ a = \frac{v_0 - v}{v_0} \]  

(1)

Where \( v_0 \) is wind velocity and \( v \) is rotor velocity.

So then we can determine wind power and power on the wind wheel as as \( P_w \) and \( P_u \) respectively (2) and (3):

\[ P_w = \frac{1}{2} \rho S v_0^3 \]  

(2)

\[ P_u = 2 \rho S a (1 - a)^2 v_0^3 \]  

(3)

Where \( \rho \) is air density, \( S \) is useful surface of wind blades.

Power coefficient can be defined as ratio \( P_u \) and \( P_w \):

\[ C_p = 4 a (1 - a)^2 \]  

(4)

This function achieves maximum of its value when \( a = \frac{1}{3} \). And this value is approximately 0.593. In figure 4 graphic of dependence \( C_p(a) \) is showed.

The fact of the power efficiency limitation can be explained by two opposing forces: the lifting force and the drag force. So it’s important to calculate the optimal shape (profile) of wind blade which accords to the power efficiency maximum. But it needs much of time and resources to investigate efficiency of each wind blade geometrical profile version. That’s why different methods of simulation are applied often while constructors design wind blades.

3. Theoretical aspects of simulation

3.1. Momentum theory

It’s necessary to solve the question of air flow around the blade for blade profile design, so it’s needed to solve the Navier-Stokes Equations with boundary conditions. The main way of its solving is the momentum theory, in particular the blade element momentum theory. The fundamental aspects of momentum theory are given in this section [2].

In its base momentum theory contains the following equations and laws: the law of conservation of mass, the equations of axial and angular momentum balance and also the law of conservation of energy (5-8):

\[ \oint \rho V \cdot dA = 0 \]  

(5)

\[ \oint u_x \rho V \cdot dA = \oint p V \cdot dA \cdot e_x \]  

(6)

\[ \oint u_\theta \rho V \cdot dA = T \]  

(7)

\[ \oint \left[ \frac{p}{\rho} + \frac{1}{2} ||V||^2 \right] \rho V \cdot dA = P \]  

(8)

where \( V = (u_x, u_r, u_\theta) \) is the velocity vector in the axial, radial, and azimuthal direction, respectively; \( \rho \) is the density of air; \( A \) denotes the outward-pointing area vector of the control volume; \( p \) is the pressure; \( T \) is the axial force (thrust) acting on the rotor; \( Q \) is the torque; and \( P \) is the power extracted from the rotor [2, 10].

The main dimensionless variables, which are characterized wind turbine aerodynamics, are: the tip-blade speed ratio (9), the thrust coefficient (10) and the power coefficient (11):
\[ \lambda = \frac{\omega R}{v_0} \]  

\[ C_T = \frac{T}{\frac{1}{2} \rho S v_0^3} \]  

\[ C_p = \frac{P}{\frac{1}{2} \rho S v_0^3} \]  

where \( \omega \) is the angular velocity of the rotor, \( S \) is the rotor area, \( R \) is the radius of the rotor, and \( v_0 \) is the wind speed.

From relation (6) we can get the corrected thrust value conditioned by forces of 2 flows acting upon the rotor [2]:

\[ \Delta T = \rho v \Delta S (v_0 - v_1) + \Delta X \]  

where \( v_1 \) is the axial velocity in the wake, \( \Delta S \) is the area of the rotor disk on which the local thrust \( \Delta T \) acts, and \( \Delta X \) denotes the axial component of the force exerted by the pressure on the angular control volume:

\[ \Delta X = \oint p \mathbf{V} \cdot d\mathbf{A} \cdot e_x \]  

So, without details, we have restriction on the power coefficient:

\[ C_p = 4a(1-a) \left( \frac{a - \Delta X}{\Delta T} \right) \left( \frac{1}{(1 - \frac{\Delta X}{\Delta T})^2} \right) \]  

Where \( a \) depends on the ratio \( \frac{\Delta X}{\Delta T} \) too.

3.2. Blade Element Momentum theory

The blade element momentum (BEM) theory was developed by Hermann Glauert in 1926 as the tool for blade assay and design. The blade element theory is the wind turbine blade 2D analysis, which considers the construction and the number of blades for getting the torque and power. It is based on the rotor momentum theory. It’s suggested that forces on a blade element can be calculated considering so-called angle of attack, i.e. the angle between the air flow and the blade. The wind velocity components, the flow coefficients and the rotor rotation speed define the angle of attack [2].

The main suggestion of the blade element momentum theory is concluded in fact that the force of a blade element is responsible for change of axial momentum of air which flows through the circle space bordered by this element. It is thought that there are not radial interactions between contiguous rings.

Pass through derivation let’s go to the finish formulas, which define the blade profile [7].

\[ \frac{a}{1 - a} = \frac{C_L \cos \varphi + C_D \sin \varphi}{4(\sin \varphi)^2} \left( \frac{cN}{2\pi r} \right) \]  

\[ \frac{a'}{1 - a'} = \frac{C_L \cos \varphi + C_D \sin \varphi}{4 \sin \varphi \cos \varphi} \left( \frac{cN}{2\pi r} \right) \]  

Where coefficients \( C_L \) and \( C_D \) define actions of lift and drag forces respectively, \( c \) is the blade chord, \( \varphi \) is the angle of attack, \( N \) is the number of blades, \( r \) is the distance from the rotor centre to calculated blade element.
Equations (15-16) are used for wind turbine blades design by iteration process. The BEM theory is utilized for blade shape definition because it allows find an aerodynamic profile configuration for the required wind turbine specifics. As the results of this calculations can be profiles showed in figure 5.

![Figure 5](image)

**Figure 5.** Geometries of blade profiles calculated with the BEM theory [7].

**Figure 6.** Dependence between power coefficient and tip-blade speed coefficient as result of modelling.

4. CFD method

Computational fluid dynamic (CFD) is the section of science solving the heat and mass transfer questions in different technic and nature objects. The main purpose of CFD is numerical solving of the Navier-Stokes Equations describing fluids dynamic. Also different physical and chemical effects can be taken in account, for example combustion, turbulence or flows through permeable medium. These equations compose the math model of the heat and mass transfer. In this work CFD methods are utilized for review the efficiency of functioning rotor composed with designed blades.

Method has some advantages:

- CFD is faster and cheaper. Huge reduction of time and resources required for problems solving in comparison with traditional methods;
- CFD is the detailed solve allowed effectively analyse model in any place and any time;
- Due to modern achievements in technic, turbulent models and solving schemes numerical models of physical questions have high precision and reliability;
- In the most cases (except turbine) fluid flow prediction doesn’t require powerful computational station and PC power can be enough [8, 11-12].

Depending on solving question certain CFD model can be applied. That is some of them:

1. The standard $k$-$\varepsilon$ model is stable and has high precision for a greatly turbulent flow, i.e. for systems with the big Reynolds number, but can’t be applied for simulation with the rotation effect.
2. The RNG $k$-$\varepsilon$ model can be used for systems with the low value of the Reynolds number because with rotation effect the imitational precision rise in the high-speed deformation flow.
3. The realistic $k$-$\varepsilon$ model is more precise for prediction of speed and acceleration as well flat as volume flows but it imitates also non-physical turbulent viscosity due to it included as rotation as static zones of fluid medium [9].
4. The standard $k$-o$\omega$ model fits to flows with low Reynolds number, contractility and dispensing shear flows. It compares with experiments very well, can account remote trail problem, layers interflow and also flat, round and radial streams.
It’s obvious that in the current wind generator work simulation task flow is very turbulent, i.e. the Reynolds number is way to above 1. That’s why we use \( k-\varepsilon \) model.

\( k-\varepsilon \) model is based on modified equations of the kinetic turbulence transfer \( k \) and speed of its dissipation \( \varepsilon \) [8, 13-18].

5. Results of modelling
The blade profile drawing and modelling of generator work with it were done to verify methods and model.

Modelling was completed in ANSYS Fluent [9]. Generator power efficiency values with different wind speed were collected in results of modelling. The generator power coefficient dependence from tip-blade speed coefficient is showed in figure 6.

This dependence is easy to analyse because variables \( C_p \) and \( \lambda \) are dimensionless but give complete representation of generator work. Noticeable that efficiency maximum is far from the Betz limit. It can be explain by corrective of power coefficient dependence described above. More complicated model shows that the real maximum of efficiency far below from the Betz limit.

6. Conclusion
Renewable energy sources implication will solve the limited sources of the planet problem and also will save the environment from pollution with vehicle emission.

But the efficiency of wind generators is limited, as was showed in this paper. So it’s necessary to solve the problem of wind generator blades profile design exactly to get maximum of energy.

To solve this problem it makes sense to use methods, which are implemented in computational soft already. One of these methods is computational fluid dynamic. As it was showed, CFD gives adequate results, its models can be adapt for different conditions of solving problem.

References
[1] Sørensen J N 2010 Aerodynamics aspects of wind energy conversion Annual Review of Fluid Mechanics 43 427–48
[2] Tande J J 2011 CFD Study of a 10 MW Offshore Horizontal Axis Wind Turbine Blade (Trondheim) p 117
[3] Web site of World Wind Energy Association Retrieved from: https://wwindea.org/blog/2019/02/25/wind-power-capacity-worldwide-reaches-600-gw-539-gw-added-in-2018/
[4] Web site of World Wind Energy Association. Retrieved from: https://library.wwindea.org/global-statistics-2018-preliminary/
[5] Web site about Wind Turbine. Retrieved from: http://vetrogenerator.com.ua/vetrogenerator/vertikal/148-chto-luchshe-vertikalnyy-ili-horizontalnyy-vetrogenerator-preimuschestva-i-nedostatki.html
[6] Wikipedia, The Free Encyclopedia. Retrieved from: https://ru.wikipedia.org/wiki/%D0%92%D0%B5%D1%82%D1%80%D0%BE%D0%B3%D0%B5%D0%BD%D0%B5%D1%80%D0%B0%D1%82%D0%BE%D1%80
[7] Mezaal N A 2018 Mathematical simulation of the wind energy device with 1.5 MW of power by CFD methods in ANSYS (Chelyabinsk) p 102
[8] Duran S 2005 Computer-aided design of horizontal axis wind turbine blades Graduate School of Natural and Applied Sciences of Middle East Technical University
[9] Fluent ANSYS FLUENT 12.0 Tutorial 9-11-12-23-28-29 2011 Turbulence and Discrete Phase Modeling
[10] Sørensen N N and Michelsen J A 2000 Aerodynamic predictions for the unsteady aerodynamics experiment phase-II rotor at the National Renewable Energy Laboratory Proc. on ASME Wind Energy Symposium (New York: ASME) pp 2000-37
[11] Versteeg H and Malalasakera W 1995 An Introduction to Computational Fluid Dynamics: The Finite-Volume Method (New York: Prentice Hall)
[12] Ferziger J H and Peric M 2020 *Computational Methods for Fluid Dynamics* (Berlin: Springer International Publishing)

[13] Benjanirat S, Sankar L N and Xu G 2003 Evaluation of turbulence models for the prediction of wind turbine aerodynamics *Proc. on ASME Wind Energy Symposium* (New York: ASME) pp 73-83

[14] Temis M Yu and Lazarev A P 2018 Influence of centrifugal forces on oil flow in journal bearing of planetary gear *Journal of Fluids Engineering, Transactions of the ASME* 140(2) 021109

[15] Mezhennaya N M 2018 Testing of embedding with margin for discrete random sequences *Prikladnaya Diskretnaya Matematika* 11 12-4

[16] Voronov S A and Veidun M A 2017 Mathematical modeling of the cylindrical grinding process *Journal of machinery manufacture and reliability* 4 394-403

[17] Vlasova E A, Mezhennaya N M, Popov V S and Pugachev O V 2017 The use of mathematical packages in the framework of methodological support of probabilistic disciplines in a technical university *Bulletin of the Moscow State Regional University: Physics and Mathematics* 4 114-28

[18] Sadykhov G S and Babaev I A 2016 Computations of the least number of objects necessary for the cyclical reliability testing *Journal of Machinery Manufacture and Reliability* 3 239-46