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IDENTIFYING SOME REGULARITIES OF THE AERODYNAMICS AROUND WIND TURBINES WITH A VERTICAL AXIS OF ROTATION

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The design of wind turbines with a vertical axis of rotation is quite simple, which successfully increases the level of efficiency. Existing vane wind turbines have a shortage of currents in the form of negative torque, and installations operating on the Magnus effect have a low lifting force. In this regard, the development and research of installations operating at speeds from 3 m/s, with combined blades with increased work efficiency is an urgent topic.

The object of the study is a wind turbine consisting of a system of rotating cylinders and fixed blades operating at low air flow speeds starting from 3 m/s. Numerical studies were carried out using the Ansys Fluent program and the implemented k-ε turbulence model. A special feature of the work is the combined use of two lifting forces: a cylinder and fixed blades, which made it possible to increase the output aerodynamic parameters. Calculations were performed for incoming flow rates of 3 m/s, 9 m/s, 15 m/s and cylinder rotation speeds of 315 rpm, 550 rpm, 720 rpm. It is determined that the period of change of the moment of forces T is 0.5 m/s, which corresponds to 2 revolutions of the wind wheel per minute. It was found that the cylinder rotation frequency in the range from 315 rpm to 720 rpm does not affect the period of change in the moment of forces, but the amplitude of the moment of forces increases with decreasing rotation frequency. The dependences of the rotation speed of the wind wheel on the velocity of the incoming flow, found by the method of sliding grids and 6DOF, are also obtained. It is determined that the installation begins to make revolutions from 3 m/s, with a positive torque of forces. The field of practical application of the numerical results will be useful for further research of wind turbines with combined blades

Keywords: combined blade, fixed blade, Ansys-Fluent, moment of forces

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1. Introduction

The climate agenda is becoming one of the most important challenges for the energy industry around the world and the new culture of humanity [1]. Ambitious goals for decarbonization and achieving carbon neutrality, stricter regulations and measures to limit CO_2 emissions, and the desire of investors to «green up» their portfolios in favor of sustainable development will have a significant impact on the fuel and energy complex of many countries [2]. As a result, energy from renewable sources is becoming an alternative, especially given the growing trend towards reducing the cost of building renewable energy plants [3], provided through constant technology development, growing demand from investors and economies of scale [4]. However, the share of electricity generation through renewable energy sources is still small, which does not meet the emission reduction goals approved under the Paris Agreement [5].

One of the rapidly developing renewable energy sectors is wind energy, which is aimed at combating climate change [6]. According to (GWEC) [7], by now the global wind power capacity reaches 837 kW, which prevents the emission of

1.2 billion tons of CO_2, equal to the annual emissions of South America. In the future, by 2027, it is planned that 557 GW of new capacity will be introduced, which is equivalent to 110 GW of new installations per year.

Despite the positive forecasts, the majority of densely populated territories have territories with an average wind potential of about less than 5 m/s, in which traditional wind turbines are ineffective. Traditional wind turbines are three-bladed installations with a horizontal axis of rotation, which are efficient due to the fact that they receive the full flow energy per blade area [8]. Nevertheless, such installations have a disadvantage in the form of orientation in the direction of the wind [9]. Along with the horizontal axis of rotation, installations with a vertical axis of rotation are also used in practice, the main advantage of which is independence from the wind direction and a relatively low level of noise and vibrations [10]. These wind turbines also have advantages such as good performance in weak and unstable winds, absence of noise, as well as aesthetic attractiveness for integration in urban areas [11].

Therefore, studies that are devoted to wind turbines operating on the basis of the Magnus effect, including the study of the aerodynamics of power elements, has scientific relevance.

2. Literature review and problem statement

In practice, the production of wind turbines with a vertical axis of rotation meets «carousel» – rotary (including the «Savonius rotor») and the «bladed» orthogonal ones are the Darye rotor [12].

Article [13] presents the results of a numerical study of the energy and flow characteristics for a Savonius rotor using the vortex particle method (DTVPM). It is shown that DTVPM makes it possible to effectively model the Savonius rotor without any empirical parameters. But there were unresolved issues related to determining the moment of force exerted on the wind wheel, which play an important role in the design of prototypes. The reason for this is the inefficiency of using this method in determining the moment of forces.

Nevertheless, the technological problem in the form of low efficiency and negative torque generated on the return blade limits its use in a large mastshab. The authors of the work [14] consider an increase in the power factor to be a solution to this problem by changing the blade profiles using optimization approaches based on modeling. It was also found that a change in the angle of inclination of the wind does not affect the output voltage of a wind turbine with a vertical axis of rotation, compared with the horizontal axis of rotation, which, when the angle of inclination of the wind changes, the output voltage decreases to 0 V [15].

The aim of the work [16] was to study the effect of using a profile with slots as a blade of wind turbines with a vertical axis of the Darrieus type. The work has studied and determined the operating and starting characteristics. The NACA 0018 profiles were used as the blade, which were subsequently optimized by changing the angle of inclination and dimensions.An interesting fact is that the slot in the profile delays separation at high angles of attack and, consequently, improves torque and power factor. However, the results of the study of the number of revolutions from the wind flow velocity have not been studied, and this installation also has a low starting torque, which makes it ineffective at low wind speeds.

The authors of the work [17] by changing the blade profile (shape, number, size and location of the blades) of the Darye wind turbine improved the power factor by 18 %. Numerical simulation is performed using nonstationary Navier-Stokes equations with Reynolds averaging (URANS), which were solved numerically in combination with the SST k-ω turbulence model. Nevertheless, the work does not present data on the moment of forces, the reason for this is a higher degree of nonlinearity, and therefore converges worse than the Realizable k-ε turbulence model, which takes into account these disadvantages.

In the world, more and more attention is being paid to the study of wind turbines operating on the basis of the Magnus effect [18, 19], which are effective at low wind speeds ranging from 3–4 m/s [20–22]. Numerical and experimental results in the study of wind turbines with cylindrical blades are presented in [18, 19]. The energy parameters of the installation are shown depending on the wind speed and the Reynolds number. But nevertheless, the results of determining the moment of forces are not available from time to time. In [20], the design of the Magnus wind turbine is optimized to ensure maximum energy efficiency. The authors have developed a control system for cylindrical blades based on a brushless DC motor. However, the results of determining the moment of forces are also not presented in the work. In [21, 22], the simulation results are presented in the form of an algorithm that allows determining the input data for the preferred software for optimizing the wind turbine design. However, there are no effects of adding a fixed blade to the cylinders, and how this effect affects the operation of the entire installation. Earlier, the authors of the work carried out theoretical calculations to study the addition of a fixed blade to a rotating cylinder, which showed an improvement in the aerodynamic characteristics of the entire combined blade [23].

But so far there is numerical and experimental data on the effect of the addition of a fixed blade on the entire system of wind turbines with a vertical axis of rotation of the Magnus type.

Based on the literature review, an unresolved issue is the identifying some regularities of aerodynamics of the combined use of a fixed blade with a cylinder as power elements of wind turbines operating on the basis of the Magnus effect.

3. The aim and objectives of the study

The aim of the work is to identify some regularities of aerodynamics around a vertical-axial wind turbine with combined blades, this will make it possible to create a fundamental basis for further research and creation of laboratory and prototype installations.

To achieve this aim, the following objectives are accomplished:

– obtain a system of equations to describe the air flow flowing around the wind wheel;

– perform numerical simulation, with the subsequent receipt of the results of dependence moment of forces on time and the rotation speed of the wind wheel on the speed of the incoming flow.

4. Materials and methods of research

4. 1. Object and hypothesis of the study

The object of the study is a wind turbine consisting of a system of rotating cylinders and fixed blades operating at low air flow speeds starting from 3 m/s.

The hypothesis of the study was to test the possibility of making a wind wheel of 30–40 rpm starting from 3 m/s, which would show the effectiveness of using combined blades as power elements of the installation.

The numerical simulation was carried out using the Ansys software, where the main focus is on the unsteady Navier-Stokes equation (finite volume method).

The system of equations is solved in the Ansys-Fluent package using the finite volume method and the sliding grid approach.

4. 2. Geometric model of wind turbines

Fig. 1 shows a wind turbine with three vertical cylinders rotating relative to their own axes.

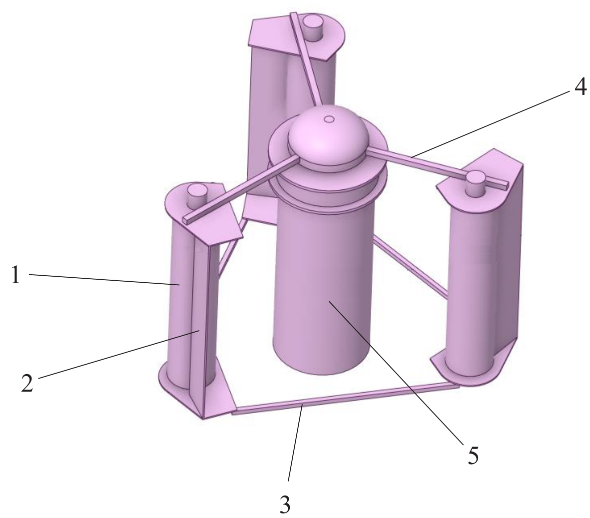

Fig. 1. Wind turbines with vertical rotating cylinders: 1 – rotating cylinder; 2 – vertical blade; 3, 4 – retaining rods; 5 – wind turbine support

The geometric characteristics of the wind turbine are presented in Table 1.

Table 1

Geometric characteristics of the wind turbine

Name	Sizes
Dimensions of rotating cylinders:	
Diameter	0.15 m
Height	0.69 m
Blade Dimensions:	
Thickness	0.005 m
Height	0.715 m
Width	0.1182 m
Dimensions of the retaining rods:	
Cross section of the upper rods	0.03×0.03 m
Cross section of the lower rods	0.015×0.015 m
The distance between the axis of the wind turbine support and the axis of the cylinder	0.5 m

Taking into account the above linear dimensions (Table 1), a mathematical model of a wind turbine with a vertical axis of rotation was created.

The initial data for the simulation are presented in Table 2.

With the above data (Table 2), a mathematical simulation of a wind turbine was performed.

Table 2

Initial data for modeling

Boundary conditions	
Inlet	
Type	Inlet speed
Initial pressure gauge (Pa)	0
Air flow velocity, m/s	3, 5, 7, 10, 15
Turbulence intensity (%)	5
Coefficient of turbulent viscosity	10
Outlet	
Type	Outlet pressure
Pressure gauge (Pa)	0
Reverse flow of turbulent intensity (%)	5
Coefficient of backflow of turbulent intensity (%)	10
Blade surface	
Type	Wall
Shift condition	No slipping
Periodic conditions	
Type	Rotation
The number of rotations of the blades (rpm)	315, 550, 720

4. 2. The main assumptions made in describing the flow of air flowing around a wind turbine

The main assumptions:

1. The air flow due to $M \ll 0.1$, i.e. the gas velocity to the local speed of sound has a low value, then it is described by equations valid for an incompressible medium.

2. Due to the large Reynolds numbers (the ratio of inertial forces to viscosity forces, $Re > 10^4$), the flow is turbulent.

3. Due to the low values of Mach numbers and insignificant temperature differences in the vicinity of the wind wheel, the current is isothermal.

5. The results of a numerical study of the aerodynamic characteristics of a wind turbine

5. 1. A system of equations describing the flow of air flowing around a wind wheel

To describe the flow around the sample by the wind flow, the following system of equations was used:

$$\frac{\partial u_j}{\partial x_j} = 0, \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} + \frac{\partial p}{\partial x_i} = \frac{\partial \tau_{ij}}{\partial x_j}, \tag{2}$$

where $\tau_{ij} = (\mu + \mu_t)\left[\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right]$ – stress tensor.

A turbulence model Realizable k-ε was used to describe the turbulent flow.

The equation of turbulent kinetic energy (3):

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho k u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon. \tag{3}$$

Equation of the specific velocity of turbulent energy dissipation (4):

$$\frac{\partial\rho\varepsilon}{\partial t}+\frac{\partial\rho\varepsilon u_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+$$
$$+\rho\varepsilon\left(C_1 S-C_2\frac{\varepsilon}{k+\sqrt{\nu\varepsilon}}\right). \qquad (4)$$

Production of turbulent kinetic energy $G_k=\mu_t S^2$, where $S=\sqrt{2S_{ij}S_{ij}}$ – modulus of strain rate tensor (5):

$$C_1=\max\left(0.43,\frac{\eta}{\eta+5}\right),\ \eta=S\frac{k}{\varepsilon},\ C_2=1.9. \qquad (5)$$

Coefficient of turbulent viscosity:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon},$$

where

$$C_\mu=\frac{1}{A_0+A_s\dfrac{kU^*}{\varepsilon}},$$

$$U^*=\sqrt{S_{ij}S_{ij}+\Omega_{ij}\Omega_{ij}},$$

$$\Omega_{ij}=\overline{\Omega_{ij}}-\varepsilon_{ijk}\omega_k.$$

$\overline{\Omega_{ij}}$ – the vorticity tensor in a coordinate system moving with angular velocity ω_k:

$$A_0=4.04,\ A_s=6\cos(\phi),\ \phi=\frac{1}{3}\cos^{-1}\left(\sqrt{6}W\right),$$

$$W=\frac{S_{ij}S_{jk}S_{ki}}{\tilde{S}^3},\ \tilde{S}=\sqrt{S_{ij}S_{ij}},$$

$$S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right),\ \Omega_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right),$$

ε_{ijk} – components of the Levi-Civitt tensor.

Turbulent Prandtl numbers $\sigma_k=1$, $\sigma_\varepsilon=1.2$.

Boundary conditions.

The boundary conditions for the turbulent kinetic energy k on the wall are given as follows (6):

$$\frac{\partial k}{\partial n}=0. \qquad (6)$$

The boundary condition for the rate of dissipation of turbulent energy ε near a solid wall was set using the EWT model-ε.

Boundary conditions at the entrance to the region (7), (8):

$$u_x=V,\ u_y=0, \qquad (7)$$

$$\varepsilon=C_\mu^{0.75}\frac{k^{1.5}}{0.07D_h},\ k=\frac{3}{2}(V\cdot I)^2, \qquad (8)$$

where D_h – the hydraulic size of the entrance area of the area was assumed to be 1 m; I – the intensity of the turbulent pulsations was assumed to be equal 0.1.

Boundary conditions at the exit from the region:

$p=p_{ex}$.

Boundary conditions on the walls of the wind turbine:

$u_i=U(t,x,y)$,

where $u_i=U(t,x,y)$ – the speed of movement of the walls, depending on the speed of rotation of the working cylinders around its own longitudinal axis and the speed of rotation of the cylinders around the axis of the wind turbine.

5. 1. 1. The sliding grid method for solving systems of equations

The system of equations (1)–(8) is solved in the Ansys-Fluent package using the finite volume method and the sliding grid approach.

The entire region was divided into three types of nested subdomains (Fig. 2): fixed outer region 1, which is a ring with an outer radius of 2.5 m and an inner radius of 0.8 m; rotating region 2, which is a circle with a radius of 0.8 m; rotating regions around cylinders 3.

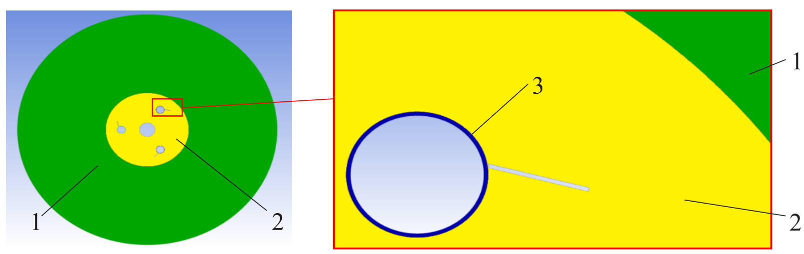

Fig. 2. Calculation area: 1 – external stationary area; 2 – rotating area of the wind turbine; 3 – rotating area of the cylinder

The calculations used a difference grid containing 24555 quadrangular cells. In the stationary region 1, 2771 cells were built, in the rotating region 2, 17836 cells were built, in the rotating region of the cylinder 3, 1316 cells were built.

The mesh was thickened near the walls of the cylinders, blades and supports.

To approximate the convective terms of the system of equations (1), (2), a countercurrent difference scheme of the second order of accuracy in space was used. The central difference scheme was used to approximate second-order derivatives. The Coupled scheme was used to coordinate the pressure field and the velocity field. Time derivatives were resolved with the first order of accuracy. The time step was set to $4\cdot10^{-4}$ s:

1. The rotation speed of the wind wheel was determined by the following algorithm.

2. The moment of forces acting on the wind wheel is calculated as a function of time $M(t)$, for a given rotation speed of the wind wheel N.

3. The time-averaged value of the moment of forces over a period of time is calculated T according to the formula $\langle M\rangle=\frac{1}{T}\int_0^T M(t)dt$. The time-averaged moment of forces is a function of the rotation speed of the wind wheel: $\langle M\rangle=f(N)$.

4. The rotation speed of the wind wheel is assumed to be found if the average moment of forces $\langle M\rangle$ it is equal to zero. The search for the rotation speed of the wind wheel is reduced to solving a nonlinear equation $f(N)=0$.

5. Solving a nonlinear equation $f(N)=0$ it was implemented using the secant method:

$$N_{k+1} = N_k - \frac{f(N_k)}{f(N_k) - f(N_k)}(N_k - N_{k-1}). \quad (9)$$

The chord method (secant method) is a numerical method for finding (one) solution (with a given accuracy ε) of a nonlinear equation of the form $f(N)=0$.

5. 1. 2. The 6DOF method for solving systems of equations

To determine the angular velocity of rotation of the wind wheel, the equation of rotation of a solid body is solved:

$$J\frac{d\omega}{dt} = \sum_{i=1}^{n} M_i, \quad (10)$$

where J – the moment of inertia of the wind wheel, ω – angular rotation speed of the wind wheel, M_i – moments of aerodynamic forces from the incoming flow, directed along the axis of rotation, acting on the elements of the wind wheel (cylinders, blades), $\omega = 2\pi N$.

In the present calculations, the moment of inertia J. The wind wheel was assumed to be equal to 2.5 kg·m^2. Moments of aerodynamic forces M_i they are calculated by the Ansys-Fluent program based on the solution of the system of equations (1)–(8).

5. 2. Calculation results of dependence moment of forces on time and the rotation speed of the wind wheel on the speed of the incoming flow

Calculations were carried out for incoming flow velocities of 3 m/s, 9 m/s, 15 m/s and cylinder rotation speeds of 315 rpm, 550 rpm, 720 rpm.

The value of the averaging time period T was selected from 3 s to 5 s, which is much longer than the period of rotation of the cylinders around their own axis at the lowest rotation speed of 315 rpm. To determine the rotation speed of the wind wheel according to the formula (9), it was required to perform from 2 to 4 iterations.

Fig. 3 shows the dependence of the moment of forces $M(t)$ acting on the wind wheel on time for the incoming flow velocity of 9 m/s and the rotation speed of the wind wheel of 120 rpm. This dependence is periodic in nature. The moment of forces is a vector product of the force applied to the point of application, to this force.

The period of change of the moment of forces T, shown in Fig. 3, is 0.5 m/s, which corresponds to 2 rpm of the wind wheel. As can be seen from Fig. 3, a–c, the cylinder rotation frequency in the range from 315 rpm to 720 rpm does not affect the period of change in the moment of forces, but the amplitude of the moment of forces increases with decreasing rotation frequency. The presence of four peaks depending on $M(t)$ in one period T is apparently due to the influence of rotating cylinders and a central support.

Fig. 4 shows the dependences of the wind wheel rotation speed on the incoming flow velocity obtained for cylinder rotation speeds of 315 rpm, 550 rpm and 720 rpm.

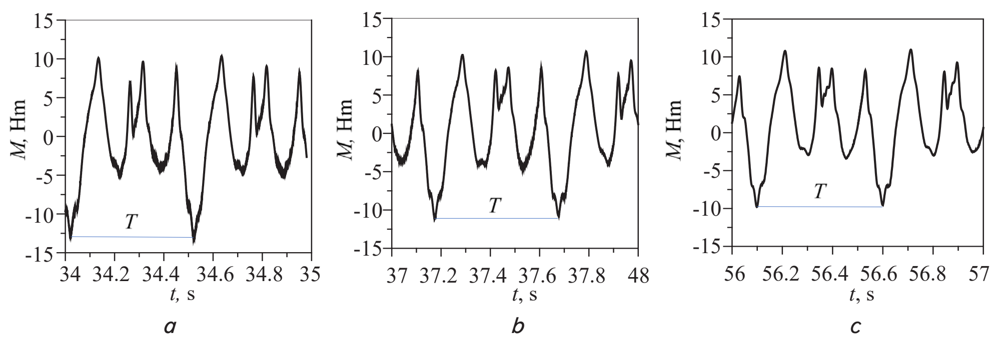

Fig. 3. Dependence moment of forces on time: N=120 rpm, V=9 m/s; a – n=315 rpm; b – 550 rpm; c – 720 rpm

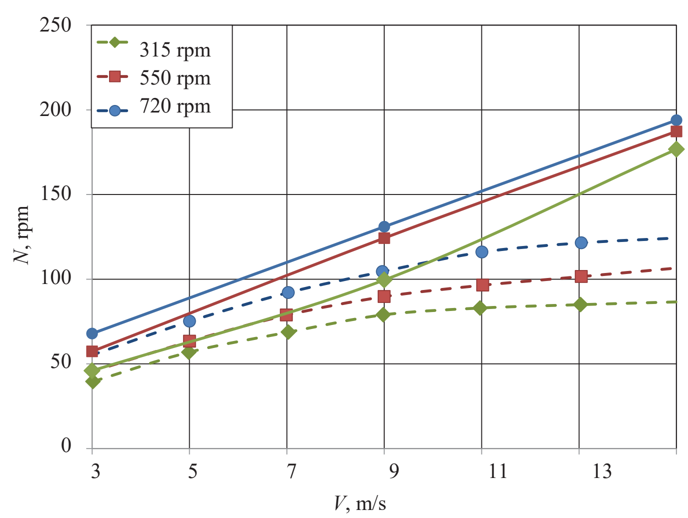

Fig. 4. The dependence of the rotation speed of the wind wheel on the velocity of the incoming flow obtained by the sliding grid method

The solid lines correspond to the results of a two-dimensional calculation model using the sliding grid method, and the dotted lines correspond to the results of experiments.

As can be seen from the figure, the error in determining the rotation speed of the wind wheel for incoming flow velocities from 3 m/s to 7 m/s is 16–24 % relative to the rotation speed obtained from the experiment. For incoming flow velocities from 9 m/s to 15 m/s, the numerical model used gives an overestimated value of the rotation speed of the wind wheel by 1.5–2 times.

As in the experiment, calculations show an increase in the speed of rotation of the wind wheel with an increase in the speed of rotation of the cylinders.

In contrast to the experimental results, which show that the increase in the speed of rotation of the wind wheel slows down with increasing wind speed, the calculation results give a dependence of the speed of rotation of the wind wheel on the speed of the incoming flow close to linear.

Fig. 5 shows the dependences of the wind wheel rotation speed on the incoming flow velocity obtained for cylinder rotation speeds of 315 rpm, 550 rpm and 720 rpm. The solid lines correspond to the results of a two-dimensional calculation model using the 6DOF method, and the dotted lines correspond to the results of experiments.

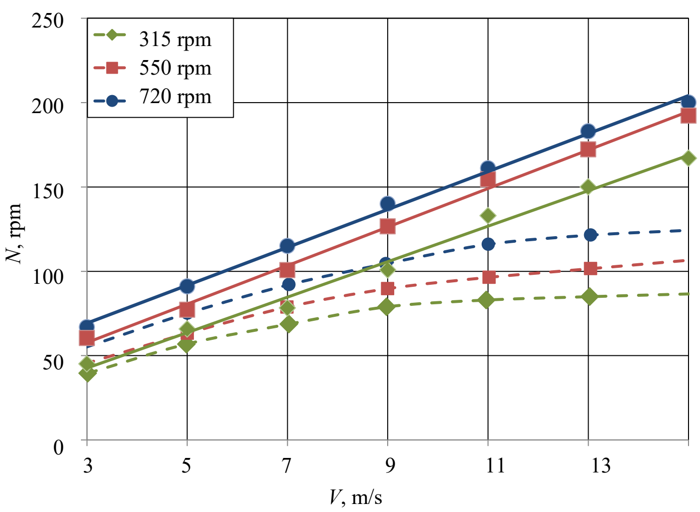

Fig. 5. The dependence of the rotation speed of the wind wheel on the speed of the incoming flow obtained by the 6DOF method

As well as for the sliding grid method, the 6DOF method allows to obtain the rotation speed of the wind wheel with an error of 16–24 % relative to the rotation speed obtained from the experiment for incoming flow velocities from 3 m/s to 7 m/s. For the incoming flow velocities of 11 m/s, 13 m/s and 15 m/s, the calculated speed of the wind wheel exceeds its experimental value by 1.5–2 times.

6. Discussion of the results of the study of the aerodynamic characteristics of a wind turbine

The advantage of using wind turbines with a vertical axis of rotation is the generation of electricity due to the possibility of self-starting and the absence of dependence on the wind direction on the example of the Savonius rotor [13]. But these installations have a disadvantage in the form of low efficiency, and the negative torque generated on the return blade limits its use in a large mastshab. Another representative is the Darrieus rotor [16, 17], the disadvantage of which is also the low starting torque. In this regard, the authors have created a mathematical model of a wind turbine with a vertical axis of rotation, with combined blades (cylindrical and fixed blades) (Fig. 1), the lifting force of which exceeds traditional wind turbines with cylindrical blades, due to the combination of two lifting forces: a cylinder (Magnus effect) and a fixed blade [23].

Studying the movement of the air flow flowing around a wind turbine under different conditions, it is quite difficult to determine the true values of each individual particle of aerodynamic characteristics. Therefore, it is more expedient to look for a solution to the systems of equations (1)–(8) describing the flow of air flowing around the wind wheel, describing the instantaneous state of motion, taking a number of assumptions that allow determining aerodynamic characteristics without loss of accuracy. Due to the low values of the Mach numbers (the ratio of the gas velocity to the local speed of sound, $M \ll 0.1$) the air flow is described by equations valid for an incompressible medium. Due to the large Reynolds numbers (the ratio of inertial forces to viscosity forces, $\mathrm{Re} > 10^4$), the flow is turbulent. Due to the low values of Mach numbers and insignificant temperature differences in the vicinity of the wind wheel, the current is isothermal.

The first objective is related to the development of a methodology for solving systems of equations (1)–(8). The resulting system of equations describes the aerodynamics around wind turbines based on the Magnus effect, compared with existing works devoted to the study of traditional wind turbines [24]. Currently, to solve the problem of flow around a rotating body, it is advisable to use numerical methods based on the Reynolds-averaged Navier-Stokes equations closed by the Realizable k-ε turbulence model and the sliding grid method. The Realizable k-ε turbulence model better simulates the flow of rotating elements around its axis, compared with the turbulence model (SST) k-ω models [17], which in its composition has a modified formula of turbulent viscosity for modeling the flow of wing-type blades. When using this method, the calculation model was divided into stationary and non-stationary components. The non-stationary component is the volume of air from which the volume equivalent to the wind turbine model is subtracted, with a given direction and speed of rotation. The stationary component is a fragment of the air environment with the object in question located in it.

The interaction of the stationary and non-stationary parts of the model was carried out through a grid interface. The main advantage of using this method is the possibility of working out the boundary layer both around the power elements and directly around the wind wheel itself. Also, to account for dynamic characteristics, such as the moment of forces acting on the wind wheel from time, the ANSYS FLUENT six degrees of freedom (6DOF) solver was used. Based on the conducted research, it is concluded that the method used can be used to assess the effect of rotation on the aerodynamic characteristics of a rotating body at low speeds.

The second objective was to obtain the results of numerical simulation. The dependences of the moment of forces $M(t)$ acting on the wind wheel on time for the incoming flow velocity of 9 m/s and the rotation speed of the wind wheel of 120 rpm at different speeds of rotation of the cylinders are obtained (Fig. 3, *a–c*). It was found that the cylinder rotation frequency in the range from 315 rpm to 720 rpm does not affect the period of change in the torque of forces, but the amplitude of the torque of forces increases with decreasing rotation frequency. The presence of four peaks depending on $M(t)$ in one period T is apparently due to the influence of rotating cylinders and a central support. The dependences of the rotation speed of the wind wheel on the velocity of the incoming flow are obtained, which are compared with the results of experiments obtained by the methods of sliding grids and 6DOF. It is determined that the error in determining the rotation speed of the wind wheel for incoming flow velocities from 3 m/s to 7 m/s is 16–24 % relative to the rotation speed obtained from the experiment, both for the sliding grid method and 6DOF. For incoming flow velocities from 9 m/s to 15 m/s, the numerical model used gives an overestimated value of the rotation speed of the wind wheel by 1.5–2 times. An interesting fact is that the overestimated values of the rotation speed of the wind wheel, obtained as a result of numerical modeling in a two-dimensional approximation using the sliding grid method and the 6DOF method, for incoming flow velocities of more than 7 m/s, which can be explained by the fact that the calculations do not take into account the resistance of the retaining rods, as well as the friction forces in the bearings of the wind wheel. It was also determined that 6-DOF has a much smaller deviation from the experimental results, almost 2 times less than the method with a movable grid [25].

The originality of the results obtained is the dependence of the moment of forces for wind turbines operating on the basis of the Magnus effect, containing combined blades. Unlike the existing results, which represent only the dependences of aerodynamic forces [26] or torque [27] affecting the entire design of a wind turbine, in this paper the results obtained give a complete picture of the change in the moment of forces depending on time, obtained by the 6DOF method and the sliding grid method.

The practical significance of the results obtained is determined by the possibility of using combined bodies, which is a complex system of a cylinder and a fixed blade, to solve numerical problems in the development and creation of prototypes of wind turbines with a vertical axis of rotation.

As a disadvantage of the study, there is no picture of the pressure distribution of the wind turbine by the air flow, since it shows the formation of a lifting force that characterizes the efficiency of the installation.

In future studies, it is planned to study the impact of the application of the considered numerical methods for determining aerodynamic coefficients. When studying wind turbines with combined blades, the limitations are the air flow velocity at which the studies were conducted, from 3 to 15 m/s, above 15 m/s in stormy winds, electromagnetic braking of the entire installation is triggered in the installation, based on this, further speed increase is not advisable. Also, there is almost no scientific literature on the study of the aerodynamic characteristics of wind turbines with combined blades in the form of rotating cylinders with a fixed blade to compare the results with other authors, since the installation created by the authors is a new invention.

7. Conclusion

1. A method for solving systems of equations has been developed to describe a wind wheel containing cylindrical blades. Based on the developed methodology for modeling the parameters of the wind wheel, using well-known theoretical provisions, a mathematical calculation model based on the dependence of the equation has been developed. Its feature is to take into account the speed of movement of the walls depending on the speed of rotation of the working cylinders around its own longitudinal axis and the speed of rotation of the cylinders around the axis of the wind turbine. Thanks to this, it is possible to fully reproduce the aerodynamics around wind turbines based on the Magnus effect at the numerical stage. Unlike the existing equations, which mainly describe traditional winged wind turbines.

2. Numerical modeling was performed, followed by obtaining the results of the dependence of the moment of forces on time and the speed of rotation of the wind wheel on the velocity of the incoming flow. The period of change of the moment of forces T corresponds to 2 revolutions of the wind wheel per minute. This phenomenon is explained by the fact that, due to the geometry of the wind wheel under study and the presence of three combined blades, it leads to deviations from uniform rotation: the wind wheel periodically accelerates slightly to maximum values during rotation and slows down to minimum torque values. The explanation for this is the influence of the rotating cylinders and the central support.

Numerical simulation of a turbine with three combined blades demonstrates the nature of the dependence of the aerodynamic characteristics of the turbine on wind speed and angular velocity of rotation of the turbine, as well as on changes in geometric dimensions that determine the design of the turbine. The proposed approach makes it possible to determine the conditions of optimal rotation, as well as to estimate the amplitude of pulsations of the torque of the wind turbine depending on the angular velocity of rotation, wind speed for the considered models of wind turbines.

From the dependence of the rotation speed of the wind wheel on the speed of the incoming flow, it was found that with a minimum wind speed of 3 m/s, the wind wheel makes 50 rpm, which exceeds conventional wind turbines operating on the basis of the Magnus effect by almost 7–10 %, thanks to the use of combined blades.

A distinctive feature of the previously known results, this approach is the ability to study dynamic operating modes that allow to optimally configure the control system in order to increase the energy efficiency of both a wind turbine with a combined blade and a hybrid station as a whole.

Conflict of interest

The authors declare that they have no conflicts of interest in relation to the current research, including financial, personal, copyright or any other that could affect the research and the results presented in this article.

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Data availability

All data is available in the main text of the manuscript.

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