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Influence of a rough surface on the aerodynamic characteristics of a rotating cylinder

The article considers the influence of the relative roughness of a cylindrical blade on aerodynamic characteristics. It is known that the operation basis of blades under consideration is the Magnus effect, which is characterized by appearance of a lifting force (Magnus force), when the cylinders rotate in a transverse flow. This force is used to rotate the wind wheel, similar to lifting force, but can have a much larger value when selecting optimal conditions, both geometric and aerodynamic. The authors conducted a comparative analysis of cylinder layout with a relative roughness (0.005 ÷ 0.02). Experimental studies of aerodynamics process of rotating cylinders were carried out in the aerodynamic laboratory using the T-1-M wind tunnel at an air flow value of 5 to 15 m/s. Graphs of dependences of rotating cylinder's lifting force and drag force on the changing air flow velocity and on relative roughness, k/d, are obtained. For further study experimental cylinder layout's aerodynamic parameters, the most optimal is the variant with a relative roughness value of 0.02, which had high indicators, was selected. In the course of experimental studies, graphs of the dependence of the values of lift and drag force on the angles of attack of a single rotating cylinder with a rough surface on the speed and angle of attack of the wind flow (0°, 30° and 60°) were obtained. It is established that the effective angle of attack is 0°, at which aerodynamic characteristics's maximum values were obtained.

Keywords: cylinder, aerodynamics, Magnus effect, wind tunnel, relative roughness, angle of attack, lifting force, drag force, air flow.

Introduction

The cylindrical body is classically an integral element of almost all aerohydrodynamic apparatuses and heat exchange devices. In the process of developing a multi-blade wind turbine with power elements in the form of rotating cylinders of variable cross-section at the initial stage, it was necessary to study the aerodynamics of cylinders of constant cross-section [1–3]. In particular, the aerodynamic phenomena and processes that are of interest arise when the cylinder flows transversely and the cylinder rotates simultaneously around its axis [4–9].

The Magnus effect, which was first described in 1853 by the German physicist Heinrich Magnus [10–13], occurs when the air flows around the rotating cylinders. The aerodynamics of a cylindrical blade operating on the basis of the Magnus effect was studied. The influence of the cylindrical blade shape on the Magnus force value is estimated using particle image velocimetry [8].

The two-dimensional transverse flow of a rarefied gas flow around a rotating circular cylinder was studied by means of calculations using the test particle method. A distinctive feature of the work is the identification of mechanisms for changing the sign in the values of the lifting force. The influence of the angular velocity of rotation on the pressure distribution in the cylinder is considered [9].

According to the results of another work, the main parameters of the rotating cylinders influencing the efficiency of the propeller are its speed of rotation and elongation, while at low settings it is the relative speed of rotation of the cylinder, such parameters are the Reynolds number, relative roughness of the cylinder surface and the degree of turbulence [10].

Comparative studies on the torque generated by improving the surface roughness of wind turbine blades based on the Magnus effect were conducted [14, 15]. The results showed that the torque coefficient generated by the sandpaper is 0.079–0.016, which is almost five times the value of the torque coefficient of a cylinder with a smooth surface. An additional advantage is that the roughness of the ground surface significantly increases the performance of the wind turbine up to four times based on the torque, compared to smooth surfaces.

These important data indicate that when using a rough surface, it is possible to optimize the aerodynamic parameters of the cylinders as much as possible.

The purpose of this work is to analyze the dependence of the aerodynamic parameters of a cylinder with a rough surface, as well as to determine the optimal value of the angle of attack of the air flow.

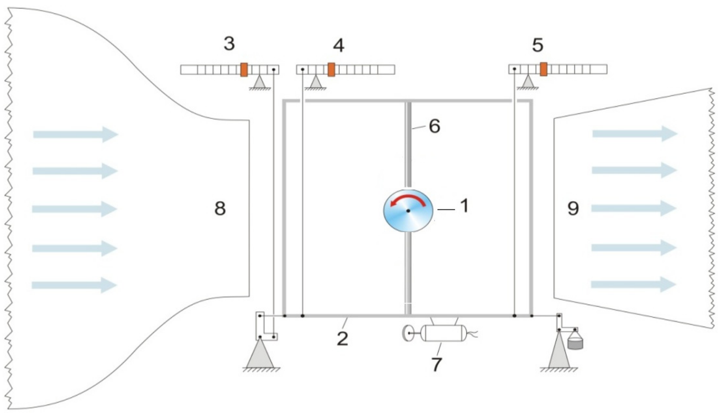
Experimental part

The study of the aerodynamic characteristics of the cylinder was carried out on a laboratory stand, which allows to measure the lift and drag force at different values of the cylinder rotation speed [13, 16].

Special nets and devices installed in the channels of the wind tunnel made it possible to ensure a sufficiently uniform air flow in the working part over the entire cross-section. The flow rate varies in the range (5÷15) m/s.

Figure 1 (a, b) shows a sample of a cylinder with a rough surface, as well as a diagram of an experimental setup for studying the aerodynamics of a rotating cylinder in a flow. To conduct experimental studies on the aerodynamics of a rotating cylinder when flowing around the air flow, a model with a rough surface was made. The ram air velocity was measured with a Skywatch Atmos cup anemometer. The drag force and the lift force of the cylinder were measured using an aerodynamic balance. The angle of attack of the cylindrical blades was measured by comparison with rigid control (reference) instruments.

a) Sample of a cylinder with a rough surface



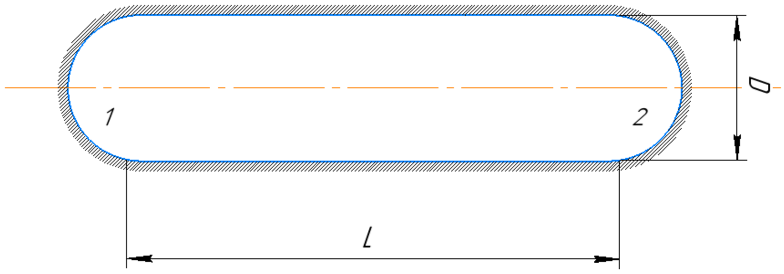
b) Scheme

1 - the study cylinder; 2 - the mounting frame layout with aerodynamics and weights;
3 - the scales that measure the force of drag; 4, 5 - the scales measuring the lift force; 6 - the rack mounting of cylinders; 7 - the motor for rotation of the cylinder; 8, 9 - the confuser and diffuser wind tunnel

Figure 1. Working part of the T-1-M wind tunnel

The diameter of the cylinder layout is 0.15 m, the length is 0.3 m. The manufactured cylinder with a rough surface is driven by a belt drive powered by an autotransformer of a variable-speed electric motor. The cylinder is easy to start, friction is reduced as much as possible due to special lubrication and a high degree of grinding of the axis of rotation and the inner surface of the cylinder.

The geometric scheme and size of the sample of the cylinder under study with spherical ends is shown in Figure 2.



1 — left hemisphere, 2 — right hemisphere, L = 300 mm, D = 150 mm

Figure 2. Geometric diagram of the sample, a rotating cylinder with spherical ends

The value of the relative roughness of the cylinder layout varies from 0.005 to 0.02.

The formula for determining the relative roughness:

$$\bar{k} = \frac{k}{d},$$

where k is the average height of the protrusions of the roughness of the cylinder surface, microns; d is the diameter of the cylinder, m. The roughness distribution over the cylinder surface is uniform. The surface grain density of the rough medium is 100–120 pcs/cm^2.

Results and discussion

Experimental studies of the aerodynamic parameters of a single rotating cylinder with a rough surface under different wind flow regimes and relative roughness values are carried out.

Figure 3 shows a graph of the dependence of the lifting force of a single rotating cylinder on the air flow velocity with relative roughness values of 0.005−0.02.

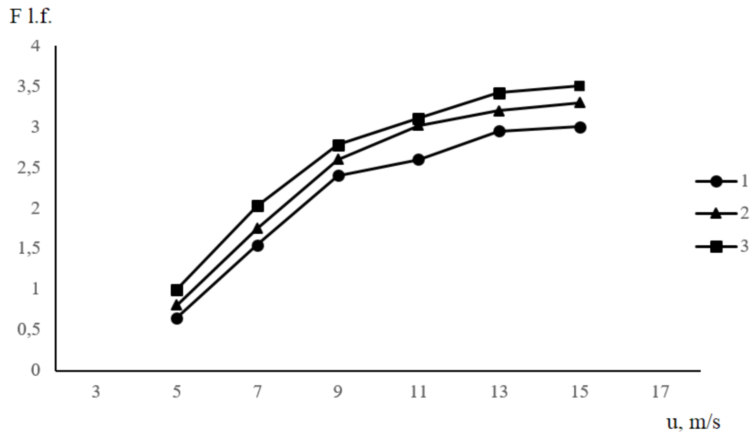


Figure 3. Graph of the dependence of the lifting force of the rotating cylinder on the change in the air flow velocity and on k/d: 1) 0.005, 2) 0.01, 3) 0.02.

As can be seen from Figure 3, with an increase in the value of the relative roughness (surface roughness), the lifting force of the cylinder increases. This is due to the fact that during the rotation of the cylinder with an increase in the relative surface roughness the resulting boundary layer expands.

It is known [17] that the roughness provides a continuous flow around the cylinder, compared to the smooth surface of the cylinder. This is due to the stronger "grip" of the boundary layer with a rough surface than with a smooth one. The rough surface, most effectively captures the air particles moving around the wall area when the cylinder rotates, which in turn creates a rotational air flow, thereby increasing the efficiency of the work.

Figure 4 shows a graph of the dependence of the drag force of a rotating cylinder on changes in the air flow velocity and relative roughness. Hence, it can be concluded that the roughness also has a significant effect on the drag force by forming micro-roughness when flowing around the air flow. In the case of a turbulent boundary layer, the effect of roughness becomes stronger and earlier, the greater the relative roughness of the surface. The drag force of the rough surface will mainly consist of the resistance of the roughness bumps streamlined by the air flow.

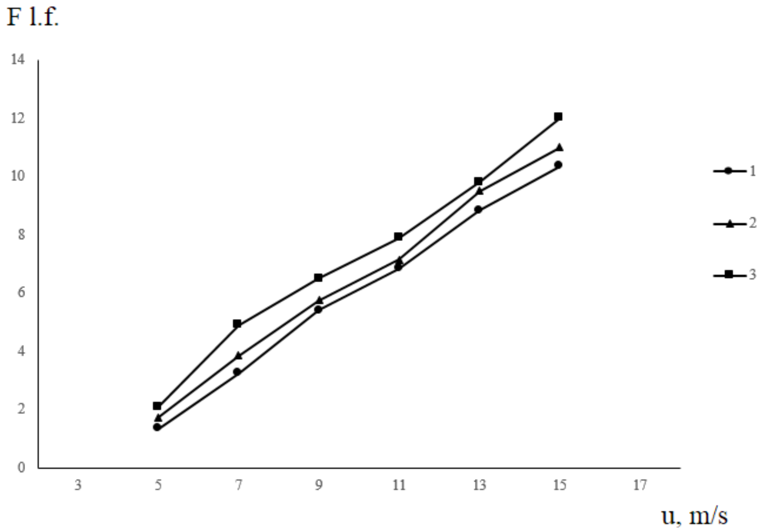


Figure 4. Graph of the dependence of the drag force of a rotating cylinder on the change in the air flow velocity and on k/d: 1) 0.005, 2) 0.01, 3) 0.02

To further study the aerodynamic parameters of the experimental cylinder layout the most optimal variant with a relative roughness value of 0.02 was selected, which had high indicators.

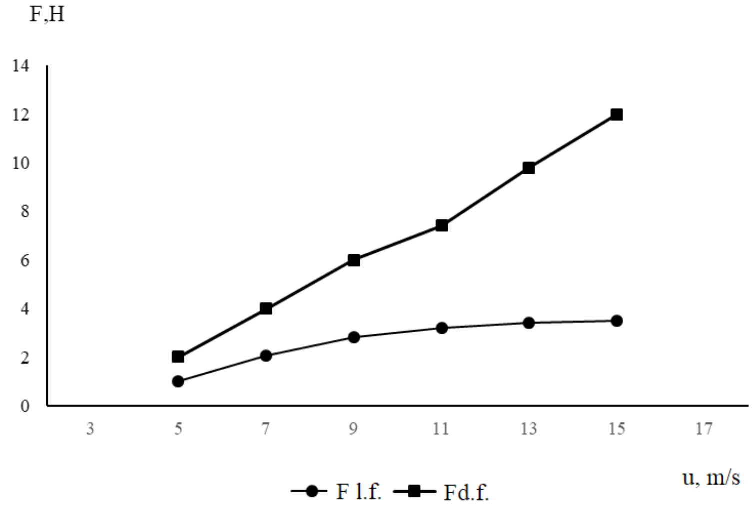
In the course of research, the dependences of the lifting force and drag force of a single rotating cylinder with a rough surface on the speed and angle of attack of the wind flow (0°, 30° and 60°) were obtained, and shown in Figure 5 (a, b, c).

As can be seen from the figure 5 (a, b, c), the amount of lifting force increases to a certain value of the cylinder rotation speed (in our case, u=11 m/s), with a further increase in speed a sharp increase in lifting force is not observed. When conducting a comparative assessment of these dependencies, it was found that with the direct transverse direction of the wind air flow (angle of attack of the flow α=0°) the maximum lifting force of 3.5 N is achieved with a flow speed of 15 m/s, almost 4 times more than with a similar speed value with an angle of attack α=60°. This is explained by the fact that at small values of the angle of attack up to 10° the flow pattern is attached, at angles of attack from 10° to 30° the character of the detached flow is symmetrical vortices, and at average values of the angles of attack 30° to 60° an invariable asymmetric vortex pattern occurs, in which transverse forces are formed, pressure on the cylinder is exerted [18].

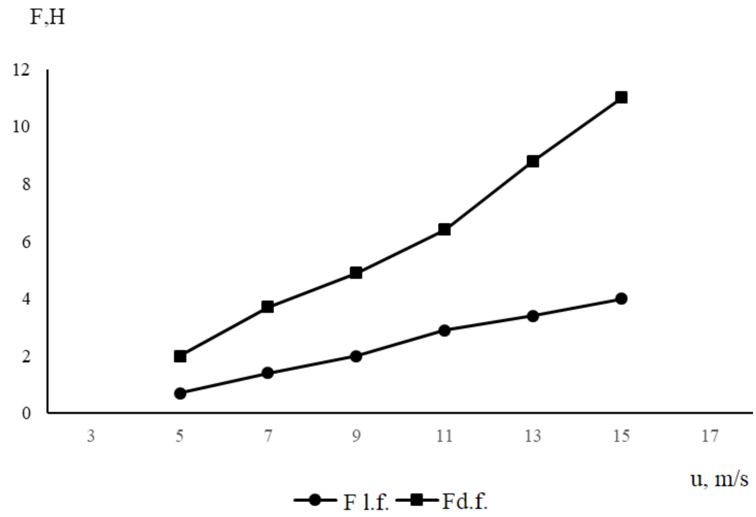
The measurement of the horizontal component of the aerodynamic force generated by the flow around the rotating cylinder makes it possible to determine the dependence of the drag force on the speed and direction of the air flow.

As can be seen from the figures, the qualitative nature of the presented dependencies at different angles of attack of the air flow practically repeat each other.

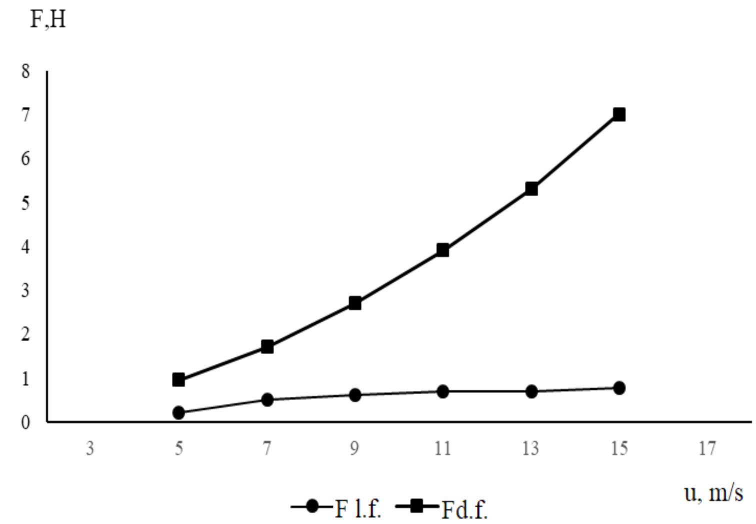
An increase in the values of the air flow velocity leads to an increase in the drag force of the rotating cylinder. As a result of the conducted studies the comparative efficiency of the rotating cylinder with a rough surface is shown, at the angle of attack of the air flow α=0°, with the direct transverse direction of the wind air flow, the flow velocity of 15 m/s-the maximum value of the drag force of the rotating cylinder is equal to 12 N.



a) at an angle of attack of 0 degrees



b) at an angle of attack of 30 degrees



c) at an angle of attack of 60 degrees

Figure 5. The dependence of the lifting force and the drag force of a rotating cylinder with a rough surface on the air flow velocity at an angle of attack of the wind flow (0°, 30° and 60°)

Conclusions

This paper presents the results of studies of the aerodynamic characteristics of cylindrical blades of a wind power plant. During the execution of the work:

– a comparative graph of the dependence of the lifting force and drag force on the change in the air flow velocity and the relative surface roughness is obtained. Based on the results of these studies, the optimal surface of the cylinder layout with a relative roughness ($\bar{k}$) of 0.02 was chosen, which gives a stronger adhesion of the boundary layer to the surface than other rough surfaces considered;

– the dependences of the lifting force and the drag force at the angles of attack of 0, 30, 60 degrees are obtained and analyzed. Comparing these dependencies, it was found that at a flow rate of 15 m/s, the maximum value of the drag force and lift force, 12 H and 3.5 N respectively, is achieved, which entails an increase in the efficiency and efficiency of the wind power plant (the angle of attack was 0°).

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Айналмалы цилиндрдің аэродинамикалық сипаттамасына кедір-бұдыр бетінің әсері

Мақалада цилиндрлік қалақшаның тиісті кедір-бұдырлығының аэродинамикалық сипаттамаларға әсері қарастырылған. Қарастырылатын қалақшалардың жұмысының негізі Магнус эффектісі екендігі белгілі, ол цилиндрлерді көлденең ағынмен айналдыру кезінде көтеру күшінің (Магнус күшінің) пайда болуымен сипатталады. Бұл күш жел доңғалағын айналдыру үшін қолданылады, көтергіш күшке ұқсас, бірақ геометриялық сияқты және аэродинамикалық оңтайлы жағдайларды таңдаған кезде әлдеқайда үлкен мәнге ие болуы мүмкін. Жұмыстың авторлары 0,005-тен 0,02-ге дейін өзгеретін салыстырмалы кедір-бұдырлы бетті цилиндрлердің макетіне талдаулар жүргізді. Айналмалы цилиндрлердің аэродинамика үдерісін зерттеу бойынша тәжірибелік зерттеулер ауа ағынының мәні 5-тен 15 м/с кезінде Т-1-М аэродинамикалық құбырын пайдалана отырып, аэродинамикалық зертханада жүргізілді. Айналмалы цилиндрдің көтеру күші мен кедергі күшінің ауа ағынының жылдамдығының өзгеруінен және тиісті кедір-бұдырлығынан тәуелділігінің графигі алынды, *k/d*. Цилиндрдің тәжірибелік макетінің аэродинамикалық көрсеткіштерін одан әрі зерттеу үшін, жоғары көрсеткіштерге ие болған, тиісті кедір-бұдырлығының 0.02 мәнімен ең оңтайлы нұсқа таңдалды. Тәжірибелік зерттеулер барысында жел ағынының жылдамдығы мен шабуыл бұрышынан (0°, 30° және 60°) беті кедір-бұдыр бір айналмалы цилиндрдің шабуыл бұрыштарынан көтеру күші мен кедергі күші мәндерінің тәуелділік графиктері алынды. Тиімді шабуыл бұрышы 0° екендігі анықталды және жұмыстың авторлары аэродинамикалық сипаттамалардың максималды мәндерін алды.

Кілт сөздер: цилиндр, аэродинамика, Магнус эффектісі, аэродинамикалық құбыр, тиісті кедір-бұдыр, шабуыл бұрышы, көтеру күші, кедергі күші, ауа ағыны.

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Влияние шероховатой поверхности на аэродинамические характеристики вращающегося цилиндра

В статье рассмотрено влияние относительной шероховатости цилиндрической лопасти на аэродинамические характеристики. Известно, что основой работы рассматриваемых лопастей является эффект Магнуса, который характеризуется появлением подъемной силы (силы Магнуса) при вращении цилиндров в поперечном потоке. Эта сила используется для вращения ветроколеса, аналогично подъемной силе, но может иметь гораздо большую величину при подборе оптимальных условий, как геометрических, так и аэродинамических. Авторы работы провели сравнительный анализ макета цилиндров с относительной шероховатостью, которая варьировалась от 0,005 до 0,02. Экспериментальные исследования по изучению процесса аэродинамики вращающихся цилиндров были проведены в аэродинамической лаборатории с использованием аэродинамической трубе Т-1-М при значении воздушного потока от 5 до 15 м/с. Получены графики зависимостей подъемной силы и силы лобового сопротивления вращающегося цилиндра от изменения скорости воздушного потока и от относительной шероховатости, *k/d*. Для дальнейшего исследования аэродинамических показателей экспериментального макета цилиндра был выбран наиболее оптимальный вариант со значением относительной шероховатости 0,02, который имел высокие показатели. В ходе экспериментальных исследований получены графики зависимостей значений подъемной силы и силы лобового сопротивления от углов атаки одиночного вращающегося цилиндра с шероховатой поверхностью от скорости и угла атаки потока ветра (0°, 30 и 60°). Установлено, что эффективным углом атаки является 0°, при котором авторы работы получили максимальные значения аэродинамических характеристик.

Ключевые слова: цилиндр, аэродинамика, эффект Магнуса, аэродинамическая труба, относительная шероховатость, угол атаки, подъемная сила, сила сопротивления, воздушный поток.

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