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ROTORS OF VERTICAL-AXIAL WIND TURBINES ASSEMBLED IN BEARINGS AND AERODYNAMIC CHARACTERISTICS OF A BLADE WITH UNCLOSED WING PROFILE

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Abstract:
In world practice, traditional blades used in high-speed wind turbines, both horizontal-axial and vertical-axial, have a wing-shaped profile. However, for horizontal-axial wind turbines, blades with such a profile have a fairly narrow range of operating values of the angle of attack of the incoming air flow and a low value of the moment of pulling from place. As for vertical-axial wind turbines, the self-starting of the rotor with wing blades is completely absent and additional devices are needed to start the rotor into operation. In order to ensure the self-starting of the rotor and the operation of the wind turbine at high and low wind speeds, a new shape of the blade profile was developed, called non-closed wing profile. The concept of the development is that the blade should have a configuration in which the pulling force is involved at the beginning of the movement, and then, with the establishing of the movement, a lifting force would arise, which acquires a prevailing character in the operating mode. The article presents the results of experimental studies of the aerodynamic characteristics of the developed non-closed wing blades. One of the results obtained is to determine the effect of the thickness of the blade profile on the range of values of subcritical angles of attack of the incoming air flow and the differences between the nature and range of changes in the coefficients of lifting force and pulling force in a traditional wing blade and a blade with a non-closed wing profile. Studies of the rotor model of a vertical-axial wind turbine with non-closed wing blades have confirmed the presence of its self-starting and operability even at low wind speeds.

Key words: *wing profile, wind turbine, blade, lifting force, pulling force, aerodynamic characteristics, angle of attack*

INTRODUCTION

Currently, the energy programs of many countries of the world, especially European ones, contain, as a rule, two main points aimed at improving the provision of energy [1]:

1) development of energy based on renewable energy sources;
2) improving energy efficiency.

The development of energy based on renewable energy sources is becoming increasingly important due to climate requirements. More than 170 countries have developed and adopted the Paris Climate Agreement, which calls for limiting the increase in average temperature to two degrees Celsius compared to the pre-industrial era. Programs for the transition of world energy to carbon-free have been adopted. Without a revolution in the field of energy, it will not be possible to fulfil the plan. According to IRENA analysts, the introduction of renewable energy sources is crucial for the planned transition. Wind energy occupies a large share in renewable sources, so according to the materials [2, 3, 4, 5] in 2019, the total capacity of wind generation in the world exceeded 651 gigawatts. According to the forecast of the International Renewable Energy Agency, by 2050 it is wind power that will provide more than a third of the world's electricity needs. Therefore, the development of equipment (in particular, wind plants, hereinafter referred to as WP) that converts wind energy into electrical and mechanical, taking into account the diversity of wind conditions around the globe, is of great importance [6-27].

An analysis of the current state of the global WP market shows that, horizontal-axial WP are basically offered. But recently, the share of vertical-axial WP has been growing, and this is logical from the point of view of their inherent advantages: the lack of a requirement for orientation to the wind, the twist of wing blades in scope, the possibility of placing energy-converting devices on the ground, low sensitivity to non-planarity of the wind.

LITERATURE REVIEW

Fairly complete information about the types of WP presented on the market is given in [28]. At the same time, it should be pointed out that the wind energy utilization coefficient of existing horizontal-axial and vertical-axial types of wind turbines does not exceed 0.4, and most often 0.3.

In wind turbines of vertical-axial WP, blades of different shapes and different principles of pulling force formation are used. The first type includes blades on which the pulling force arises due to the difference in head resistances when the blade moves into the wind and under the wind. These are WP with a cup rotor, with sailing blades, with a Savonius rotor, etc. The most common are WP with sailing blades and a Savonius rotor [2]. Due to the peculiarities of the process of transferring wind energy to the rotor, the speed of the blade along a circular trajectory in these WP cannot exceed the wind speed, i.e., the speed coefficient is is $\vartheta = U_b/U_\infty > 1$. Thus, the WP of the first type is classified by ϑ as slow-moving [1].

For low-speed WP torque has a predominant share in power generation due to the features of the workflow we have considered. As a result, these WP have a high value of the starting torque, which is equal to [1]:

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$$T = C_m \frac{\rho_a}{2} U_\infty^2 S \frac{D}{2},$$

where:

C_m is the torque coefficient, C_m,

S is the area swept by the rotor.

The great importance of the torque of starting causes such important advantages of low-speed vertical-axial WP as:

- the ability to self-start the rotor;
- the ability to work even at low wind speeds.

The minimum operating speed is determined by the necessary value of the starting torque, depending on the design and mass characteristics of the rotor of a particular WP, as well as on aerodynamic resistance and workload. However, their wind energy utilization rate is low, up to 0.2.

The energy efficiency of the second type of vertical-axial WP with blades having a wing profile which using the lifting force that occurs when the blade profile flows around to form a torque is much higher (compared to low-speed WP). The most common among the second type of WP until recently was the rotor, proposed by Darrieus in 1925 [1], having a vertical shaft and blades curved from the shaft with a wing cross section. In the wind power industry, intensive research on the Darrieus rotor has been conducted since 1975. Currently, straight wing blades are also used, fixed to the shaft using horizontal or inclined traverses, the so-called Evans rotor [1].

The same traditional wing blades as for aviation are used in wind turbines of WP [29, 30]. For vertical-axial wind turbines, wing blades with a symmetrical profile are selected, since the torque is formed both on the windward and downwind sides [31]. The main aerodynamic characteristics of the blades are the values of the lifting force and the resistance force, respectively characterized by the coefficients C_y and C_x. Of course, the blade profiles are being improved in order to obtain the required aerodynamic characteristics.

However, vertical-axial WP with blades having a wing profile have a disadvantage – a sufficiently high value of the operating wind speed. It is known that according to the European Standard, the nominal wind speed is assumed to be 11.5...14.5 m/s. At a low average annual wind speed (less than 4.5 m/s), the use of high-speed vertical-axial WP is economically impractical, since in this case they have a working period of less than half the duration of a calendar year. For example, according to available data, in the conditions of the wind regime with average monthly wind speeds U_w from 3 m/s to 4.5 m/s, the working period of high-speed WP was from 25% to 45% of the duration of the calendar year. In addition, vertical-axial WP with blades having a wing profile do not have self-starting of the wind turbine, since the blades have a small starting torque. The WP must be put into operation by the promotion of special additional devices, which complicates and increases the cost of the design. Thus, it is logical to conclude that it is necessary to develop a new type of blades for vertical-axial WP.

Considering the above, for vertical-axial wind turbines it is advisable to create blades with a profile shape that ensures the fulfillment of the following requirements:

– self-starting the rotor;

– operation of the WP at low wind speeds.

Thus, the following concept was adopted for the development of a new shape of the profile of the blades of vertical-axial WP.

Self-starting of the rotor of the WP takes place with a sufficient amount of torque on the wind turbine when the wind flow acts on it at rest (the so-called starting torque), which can be achieved due to high head resistance and is inherent in slow-moving WP. In our case, the blade should have a configuration in which a resistance force is involved at the beginning of the movement, and then, with the development of the movement, a lifting force would arise, acquiring a prevailing character in the operating mode. The formation of the pulling force mainly due to the lifting force allows you to increase the C_p by at least 2 times compared with the use of head resistance. Based on the above considerations, a blade with a non-closed wing profile (type KN) was proposed, which was then proposed to be improved (modification KN-4). The essence of the development is that due to the open loop in the cavity of the blade, a kind of "trap" is formed, getting into which the air flow gives off part of the kinetic energy, launching the wind turbine. At the same time, on a large section of the circular trajectory, the difference between the pressure force from the cavity and the resistance force of the blade profile remains positive, directed in the direction of movement. When moving there is a lifting force occurs on the blades and becomes prevailing in the operating mode (with a speed coefficient of $\vartheta > 1$). It should be noted that the continuous flowing of the profile at certain angles of attack is facilitated by a quasi-stationary vortex formed in the "trap" [32, 33, 34]. In the rotor, the blade must be installed in a certain position, with the continuous side to the shaft, with a "trap" outside [32]. The proposed blade is designed to work at low wind speeds, which is relevant for the conditions of Ukraine, especially for the interior regions, since in many regions of Ukraine the average annual wind speed does not exceed 5 m/s. In order to confirm the correctness of the chosen concept, experimental studies of the aerodynamic characteristics of blades with a non-closed wing profile and models of wind turbines with them were carried out.

The purpose of the article is to show the aerodynamic characteristics of a new type of blades obtained in experimental studies and their comparative analysis with the aerodynamic characteristics of a traditional wing blade.

METHODS, RESULTS AND DISCUSSION

Physical model of prototype motion

The purpose of the experiments was to determine the coefficients of the lifting force C_y and the resistance force C_x of the blades with a non-closed wing profile (type KN) and a symmetrical profile when changing the angle of attack of the incoming flow α from 0° to 360° (the so-called "circular blowing"), while the relative thickness of the profiles was the same.

The experiments were carried out in the experimental hydrobasin of the Institute of Hydromechanics of the Academy of Sciences of Ukraine, the dimensions of which, respectively, were 50.77 x 7 x 2.5 m [32].

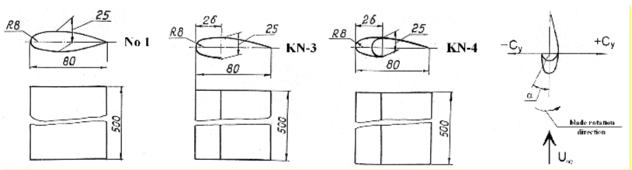


Fig. 1 Profiles of tested blade models

The objects of research were models of three blades (Fig. 1). One of them (No. 1) had a symmetrical wing profile with a chord of 80 mm, relative maximum thickness $\bar{c} = 0.3$, relative radius of rounding of the leading edge $\bar{r} = \frac{r}{b} = 0.1$, span L = 0.5 m.

The other two blades (KN-3 and KN-4) had a non-closed wing profile developed in the wind power laboratory of SumSU and differed from each other by the presence of a semi-cylindrical bridge in the cavity (KN-4). The geometry of the outer contour of the KN-3 and KN-4 profiles coincided with the symmetrical profile, except for the non-closed.

The installation scheme of a single blade model in a hydraulic basin is shown in Fig. 2. The model 1 was mounted vertically to the tubular axis 2, which could rotate in the upper ball bearing 3 and the lower rolling bearing 4. The bearing 3 was attached to the plate 5 by means of a bracket 6. The rolling bearing 4 was mounted on a two-component strain gauge 7, which made it possible to measure the longitudinal and transverse (relative to the direction of the incoming flow) components of the hydrodynamic forces acting on the blade model.

Axis 2 was fixed in positions corresponding to the specified values of the angle of attack α in the range from 0° to 360° with a minimum step of 5°. Fixation was carried out using a disk 8 and a pin retainer 9. The blade model was buried so that the distance from the water surface to the upper end of the model was 0.25 m. The installation was placed on a trolley towed in a hydraulic basin using a cable system and a hydraulic drive with smooth speed control in the range from 0 to 2 m/s.

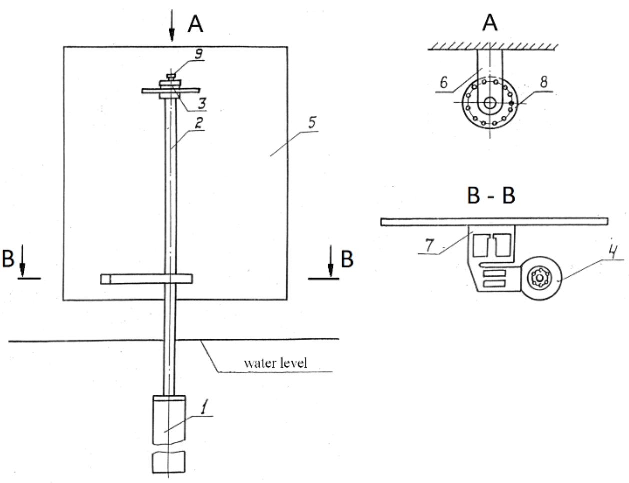


Fig. 2 Experimental unit for studying the blade model in a hydraulic basin

The water temperature in the hydrobasin was in the range of 15-20°C, the relative humidity in the room was 80 ± 15% (at 20°C). Before the start of the tests, the strain gauge device was calibrated to obtain a calibration curve, the serviceability and interaction of the measuring and recording equipment was checked. During the tests and after their completion, it was mandatory to monitor the characteristics of the equipment.

The measurement errors of aerodynamic forces, taking into account non-stationary (random) fluctuations in the readings of the instruments, were no more than three percent of the measured values. The average speed of the trolley during tests with a symmetrical closed profile (No.

1) was 1.7 m/s with a maximum deviation of 0.013 m/s (0.73%), during tests KN-3 and KN-4 the average speed was 1.71 m/s and 1.72 m/s with deviations of 0.007 m/s (0.41%) and 0.015 m/s (0.87%), respectively. The resistance of the submerged axis 2 (Fig. 2) was determined separately and subtracted from the resistance of a single blade. The value Re calculated from the blade chord can be assumed to be $1.23{\cdot}10^5$ for all three cases. The angle of attack α changed discretely in increments of 5-10°. In the course of the research, the lifting force F_y and the resistance force F_x were measured, while the coordinate system was current. Using the obtained values of F_y and F_x, the coefficients of the lifting force C_y and the resistance force C_x were calculated in the range of angles α from 0° to 360°. At the same time, it should be noted that the aerodynamic characteristics of the KN-3 blade were studied in the range of angles of attack 90 ≤ α ≤ 260, assuming that at the remaining angles the values of C_y and C_x coincide with the values for the KN-4 blade, since the influence of the semi-cylindrical bridge in these cases should not be any significant.

The dependences $C_y = f(\alpha)$ and $C_x = f(\alpha)$ obtained in the experiments for profiles No. 1, KN-4, KN-3 are shown in Fig. 3, Fig. 4.

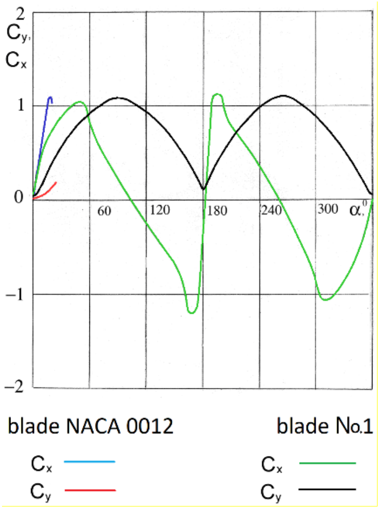


Fig. 3 Dependence of the aerodynamic characteristics of the blade No.1 and the blade NACA 0012 on the angle of attack α

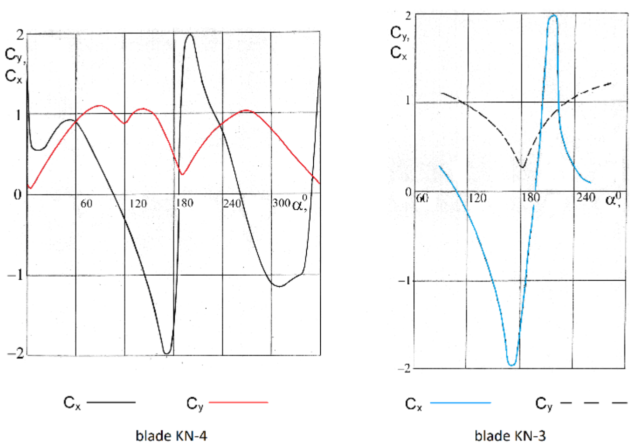


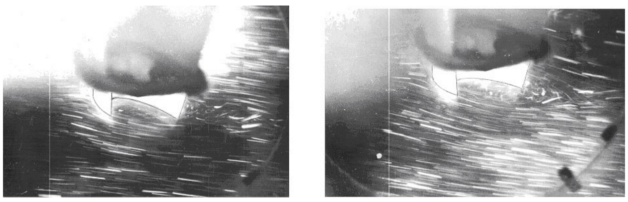
Fig. 4 Dependence of the aerodynamic characteristics of the KN-4 blade (a) and the KN-3 blade (b)on the angle of attack α

For comparison with traditional wing profiles, Figure 3 shows the aerodynamic characteristics of the symmetrical profile NACA 0012, which has a high aerodynamic quality [29] and a wing profile of greater thickness, the same with the thickness of KN. As you can see, the effect of the profile thickness is very significant. At $\bar{c} = 0.12$ (NACA 0012) the critical value of the angle of attack α does not exceed 18°, when the profile rise thickens to $\bar{c} = 0.3$ α reaches 50°, however, the aerodynamic quality is lower. With regard to the aerodynamic characteristics of a symmetrical wing profile with a thickness $\bar{c} = 0.3$ and an unclosed one of the same thickness (KN-4), the following can be noted: the nature and range of changes in their lifting force and resistance force coefficients are very different. Let's note the main differences.

1. At zero angle of attack on a non-closed wing profile, a large lifting (or lateral for this situation) force arises, directed from the non-closed side of the profile to the closed one and caused by the tearing off the flow on the non-closed side (Fig. 4). The possibility of such a phenomenon is confirmed by the information contained in the literature. On a symmetrical profile, this phenomenon is absent (C_y = 0, at α = 0°, Fig. 3), which corresponds to the classical flow pattern of symmetrical profiles. For non-closed profile (KN-4, Fig. 4) there is a sharp change of the coefficients of the lifting force on zero angle of attack C_y = 16.
2. Workspace for angles of attack (with a high enough C_y) to non-closed profile is broader than for closed, C_y has high values even at α ≥ |60|°, decrease it by increasing α over |60|° runs more smoothly (the angle α indicated in both directions from the zero angle of attack).
3. At angles of attack α ≈ 170° and α ≈ 200°, the C_y reaches a value of ±2, which is about twice as much as for a symmetrical profile (– 1.2 at α = 170° and 1.09 at α = 190°). In this position (as in the area of zero angle of attack), a jump in lifting force causes a sharp increase in radial force.
4. The minimum value of the resistance coefficient of a non-closed wing profile is about 1.7 times greater than the same value of the C_x of a symmetrical profile (0.075 and 0.045).
5. It should be noted that the maximum value of C_x for non-closed profile and closed profiles is almost equal: 1.1 at α = 90° for KN-4 and 1.13 for symmetric at the same α.
6. When comparing the characteristics of the KN-4 profile and KN-3 profile (Fig. 4) in the angle range 90 ≤ α ≤ 270, there is a difference in the characteristics of the curves $C_x = f(\alpha)$ for these profiles: this curve for the KN-4 profile has two extremes (1.1 at α = 90° and 1.06 at α = 140°). The presence of the second extremum on the curve can be explained by the influence of a semi-cylindrical bridge. When the WP rotor is self-starting and entering at the operating mode, as well as when working with low speed ($\vartheta \leq 1$), this character of the curve plays a positive role.

The dependences $C_x = f(\alpha)$ and $C_y = f(\alpha)$ obtained in the range of angles 90 ≤ α ≤ 360 for the KN-4 profile also make it possible to obtain the dynamics of the forces acting on the blade when blade moves along a circular trajectory in the turbine of a vertical-axial WP by calculation. However,

it should be noted a certain inaccuracy of the obtained results, due to not taking into account the mutual influence of the blades and, in particular, the braking of the flow.
It should be noted that the studied blades have an extended range of working angles α with a high value of C_y. The KN-type blades provided self-starting of the WP rotor and proved to be operable even at low wind speeds, as shown by studies of the rotor model with these blades [32, 35].
The extended range of working angles α with a high value of C_y without the tearing off of the flow on the surface, where the pulling force is formed, causes a high degree of adaptability of the blade to the flow conditions in the vertical-axial wind turbine, considered in [35]. The presence of self-starting of the wind turbine and the ability to work even at low wind speeds confirmed the correctness of the chosen concept of the blade shape.
However, due to the profile configuration, which determines the presence of tearing off of the flow even at zero angle of attack with the formation of a vortex wake, the KN-type blades have a relatively high resistance.



α = +10° α = −5°

Fig. 5 Visualization of the flow around the blade with the KN profile

Visual studies of the flow of the KN profile, conducted at the Institute of Hydromechanics of Ukraine at the same time as studies of aerodynamic characteristics, showed the presence of a vortex trace, Fig. 5.
Consequently, the KN-type blades cannot have a high aerodynamic quality, which, in turn, causes an insufficiently high wind energy utilization coefficient C_p. Further improvements in the shape of the profile increased its aerodynamic quality and wind energy utilization coefficient to 0.3, which was shown by relevant studies of wind turbine models [35].

CONCLUSIONS

1. A new shape of the profile (non-closed wing profile) of the blade, called KN, was developed to ensure the self-start of the wind turbine and the operation of the vertical-axial WP at both high and low wind speeds.
2. Studies of the aerodynamic characteristics of the KN-type blade have shown that the operating range of angles of attack (with a sufficiently high C_y) for a non-closed wing profile is wider than for a closed one, C_y has high values and when α ≥ |60|°, and decrease it by increasing α over |60|° runs more smoothly (the angle α indicated in both directions from the zero angle of attack).
3. The extended range of working angles α with a high value of C_y without separation of the flow on the surface, where the pulling force is formed, causes a high degree of adaptability of the blade to the flow conditions in the vertical-axial wind wheel.
4. Due to the profile configuration, which determines the presence of tearing off the flow even at zero angle of attack with the formation of a vortex trace, the KN-type blades have a relatively high resistance.
5. Visual studies of the flow of the KN profile, conducted at the Institute of Hydromechanics of Ukraine at the same time as studies of aerodynamic characteristics, confirmed the presence of a vortex trace.
6. An increase in the resistance of the KN profile compared to the wing one reduced the aerodynamic quality of the KN-type blades.
7. Further improvement of the shape of the KN profile improved its aerodynamic quality and increased the wind energy utilization coefficient of the wind turbine with KN-type blades to 0.3.

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