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INVESTIGATION OF INFLUENCE OF INCLINATION ANGLES OF SAIL-TYPE BLADES ON THE STARTING TORQUE OF HORIZONTAL-AXIS WIND-WHEEL

The expediency of use of slow-speed (multiblade) wind-wheels with sail-type blades on the territories with low wind potential is substantiated. The structure of experimental prototype of horizontal-axis wind0wheel with sail-type blades is proposed. The technique of determination of blades inclination angles influence on the starting torque of the wind-wheel is presented. The obtained results are analyzed and the expediency and feasibilities of the wind-wheel largest sailing capacity ensuring with a view to obtain the largest starting torque under the small wind speeds are substantiated.
Key words: horizontal-axis wind-wheel, sail-type blade, starting torque, blade inclination angle, wind-wheel sailing capacity (windage).

Обґрунтовано доцільність використання тихохідних (багатолопатевих) вітроколіс з лопатями вітрильного типу у регіонах зі слабким вітровим потенціалом. Запропоновано конструкцію експериментального зразка горизонтально-осьового вітроколеса з вітрильними лопатями. Представлено методику визначення впливу кутів відхилення лопатей на пусковий момент вітроколеса. Проаналізовано отримані результати та обґрунтовано доцільність і можливості забезпечення якнайбільшої парусності вітроколеса з метою отримання максимального пускового моменту за малих швидкостей вітру.
Ключові слова: горизонтально-осьове вітроколесо, лопать вітрильного типу, пусковий момент, кут відхилення лопаті, парусність вітроколеса.

Introduction. At present stage of development of industry and manufacture, the tendency of searching energy-conservative technologies and alternative energy sources becomes more and more relevant [1]. This tendency is caused by the necessity of considerable reducing of production first cost, of improvement of ecological situation and of increasing of energy-independence of large amount of industry branches [1; 2]. The special role in this situation belongs to alternative energy sources and particularly to wind energy, which was successfully used in various spheres of human activity.

In accordance with the criterion of rotation axis placement, wind-wheels may be divided into two groups: horizontal-axis and vertical-axis [1]. The last ones were developed not so long ago, whereas horizontal-axis wind turbines have been successfully used already for over 200 years. Each wind turbine type has its advantages and drawbacks, which stipulate the expediency of its use in specific operational conditions. In the presented paper we'll consider horizontal-axis wind turbine and investigate the problem of expediency of its sailing capacity enlarging in order to obtain maximal value of starting torque.

Problem statement. One of the criterions of wind turbines classification is the type of blades: rigid or flexible [3]. The first ones are usually used in one-, two-, three- or four-bladed high-speed wind turbines, which are calculated and designed for operation in nominal mode when wind speed exceeds 10 m/s. Rigid blades have complicated geometric shapes with longitudinal helical-type twists, which stipulate the complicity of manufacturing technology and strict requirements to operating conditions (presence of accurate systems of anti-storm protection, of wind-wheel facing into the wind, of blades protection against ice formation etc.) [2]. Flexible blades have the opportunity of almost total self-adaptation to small changes of wind speed and direction due to their elasticity [4]. This allows to simplify the systems of regulation and wind-wheel facing into the wind and to cheapen its manufacturing. Also flexible blades allow increasing of covering coefficient (sailing capacity) of the wind-wheel without essential increasing of its mass [3]. This stipulates the increasing of starting torque and the opportunity to start the wind turbine under lower wind speeds (2–3 m/s). In this case the nominal operating mode of such wind turbine is ensured under the wind speeds in the range of 4–7 m/s, which are typical for essential part of the territory of intracontinental countries [2]. This allows to maximize the time of wind turbine operation and to minimize its idle time.

At the present time, only several production prototypes of wind turbines use sail-type blades. To a certain extent, this fact may be explained by insufficient substantiation of efficiency problems of such blades, used in wind turbines structures on territories with low wind potential. That is why the problems, related with investigation of efficiency of sail-type blades and development of the technique of their calculation and designing, are urgent at the present time.

Analysis of modern investigations and publications. The overwhelming majority of investigations on the subject of horizontal-axis wind turbines are dedicated to high-speed plants with small number of blades (1–4), the nominal operating mode (maximal efficiency) of which is reached when wind speed exceeds 10 m/s [1; 2; 5–10]. Unfortunately, the annual average wind speeds on the territory of Ukraine don't exceed 5 m/s [8]. This do not allow to use the advanced universal experience of designing and exploitation of wind-driven energy plants.

One of the ways of solving the problem of improvement of wind energy consumption on the territories with low wind potential consists in use of mutiblade slow-speed wind turbines [2; 8]. A great number of their structures are presented in numerous information sources of the middle of the past century. At that time wind power was considered to be one of the most prospective energy sources (not only for producing electric energy, but also mechanical, heat and other ones). Among the prospective spheres of wind turbines usage there were water supply of agricultural industries, irrigation of arable lands, electrification of the territories which are remote from centralized electric-power supply etc. [6; 7].

At the present time, the cost of traditional energy sources (electrical and heat energy, gas, coal, wood, fuel bricks etc.) is increasing year in and out [1; 9]. This stipulated the necessity of looking-for alternative variants of power supply of households of indigent segments of population. Unfortunately, wind turbines haven't won large popularity in this case. On the one hand, this may be explained by almost absolute absence of Ukrainian market of wind power transforming equipment, which is adapted to climatic conditions of our country. On the other hand, the cost of available wind turbines essentially exceeds the purchasing power (capacity) of and the average Ukrainian householder, whereas the average payback period of a wind turbine reaches sometimes to 5-10 years.

One of the ways of the stated problems solving consists in usage of slow-speed horizontal-axis wind turbines with sail-type blades [3; 4]. These blades ensure large sailing capacity (windage) of the wind-wheel and large starting torque under small wind speeds [5; 6]. This stipulates the opportunity of the wind turbine starting under the wind speed of 2–3 m/s and reaching the nominal operating mode under the wind speed of 5–6 m/s [7]. However, rather small number of publications are dedicated to investigations of slow-speed wind turbines with sail-type blades. Moreover, these publications are not systemized. At the present time, there isn't universal engineering technique (methodology) of calculation and designing of such wind turbines. Nevertheless, the necessity in such techniques is quite urgent at the present time, because there exists the exigency of development of comparatively cheap wind power transforming equipment, which may be efficiently used on the territories with low wind potential.

Formulation of the research purpose. The main purpose of the research consists in the following: to overview the structural and operational features of slow-speed horizontal-axis wind turbines with sail-type blades; to analyse the parameters which characterise wind-wheel operation; to substantiate the structure and to design the experimental prototype of the wind turbine; to develop the technique (method) of experiments carrying out; to make conclusions about the influence of blades inclination angles on the starting torque of the wind-wheel; to define the scopes of further investigations on the basis of presented research results.

Structural and operational features of slow-speed horizontal-axis wind-wheel with sail-type blades. Let us consider the structure of slow-speed horizontal-axis wind-wheel with sail-type blades (Fig. 1), designed by the authors of this paper in Lviv Polytechnic National University. The basic structural characteristic properties of this wind-wheel consist in horizontal placement of main drive shaft 1, absence of active system of facing of wind-wheel into the wind, large number of sail-type blades 3 (usually more than 6; in this case we take 8 blades), usage of the mechanism of blades folding up 4 as the system of anti-storm protection and power regulation.

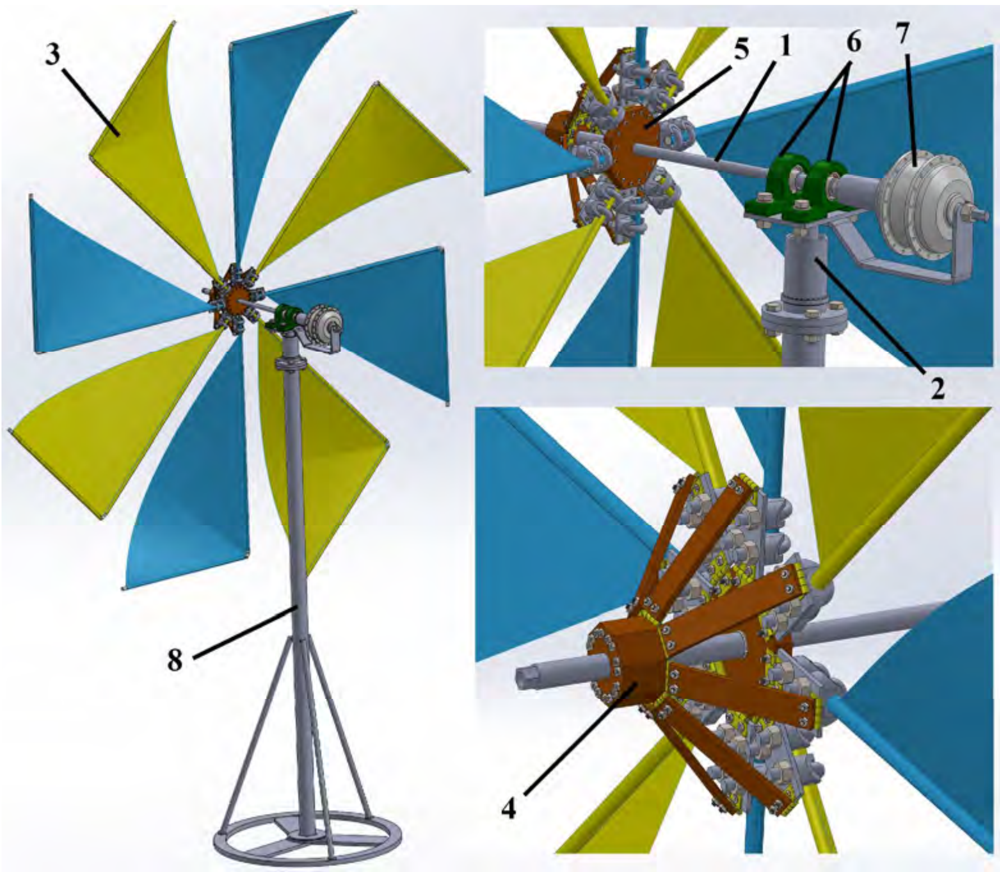


Fig. 1. Structural diagram of horizontal-axis wind-wheel with sail-type blades

The basic elements of wind-wheel structure are: axes and sails of blades 3, hub 5, hinges (joints) of blades attachment, main drive shaft 1, supporting bearings 6 of the main shaft, turning (rotating) unit 2 of the mechanism of facing of wind-wheel into the wind, mechanism of changing of blades inclination angle, formed by rocker, connection rod, slider and regulation spring (it is not presented in the Fig. 1), electric generator 7 and tower 8. The operation of the wind-wheel is carried out due to interaction between blades sails 3 and incoming airflow. The aerodynamic lift force causes rotation of blades axes 3 together with the hub 5 and main drive shaft 1, to which a loading device (electric generator, pump, compressor etc.) is connected. Taking into account the large sail area of such wind-wheel, it is expedient to face it into the wind by placing it behind the tower (so-called, down-wind orientation) and to ensure anti-storm protection by blades folding up (turning) in the bearing of apparent wind (similar to umbrella folding up principle).

Wind-wheels with sail-type blades have the opportunity of self-orientation (self-facing into the wind) without the necessity of use of additional systems, which appreciate their manufacturing and complicate exploitation. The anti-storm protection mechanism 4 with rocker, connection rod and slider (in this case, the mechanism of blades folding up) requires the existence of simple and, at the same time, enough reliable spring regulator, which is used for changing of blades position depending on airflow speed and, correspondingly, for power regulation, which is generated by the wind-wheel.

Parameters which characterize wind-wheel operation. At some distance from the wind-wheel, where the incident air-flow is uniform, the kinetic energy E of the air-flow mass m may be defined as:

$$E = \frac{m \cdot V_0^2}{2}, \tag{1}$$

where V_0 is the speed of the incident air-flow.

The value $m = \rho \cdot V_0 \cdot A$ in the cross-section before the wind-wheel is called mass rate of the air-flow, which is transmitted through wind-wheel swept area A per unit time, having the density ρ [10]. The wind-wheel swept area is geometrical projection of wind-wheel area on the plane perpendicular to the vector of wind velocity $\vec{V}_0$. In the case when the vector of wind velocity $\vec{V}_0$ is perpendicular to the swept area A, the value A equals $A = \frac{\pi \cdot D_b^2}{4}$ for horizontal-axis wind-wheels. Here wind-wheel diameter D_b equals the diameter of the circle, which is described by the most outer blades points about the rotation axis.

The total power N_{wind} of the air-flow, which approaches the wind-wheel (i.e., total kinetic energy of incident air-stream of the speed V_0 and of the area of cross-section which equals wind-wheel swept area) may be determined as [10]:

$$N_{wind} = \frac{\rho \cdot V_0^3}{2} \cdot A. \tag{2}$$

The wind-wheel takes off only some part of the air-flow energy and transfer it to the load, for example, electric generator. Let us write N_{ww} for the power of the wind-wheel. The ratio of wind-wheel power N_{ww} to total power of the air-flow N_{wind} is called the coefficient of wind energy usage (power coefficient) $C_p = \frac{N_{ww}}{N_{wind}}$. So mechanical power of the wind-wheel equals [10]:

$$N_{ww} = C_p \cdot \frac{\rho \cdot V_0^3}{2} \cdot A. \tag{3}$$

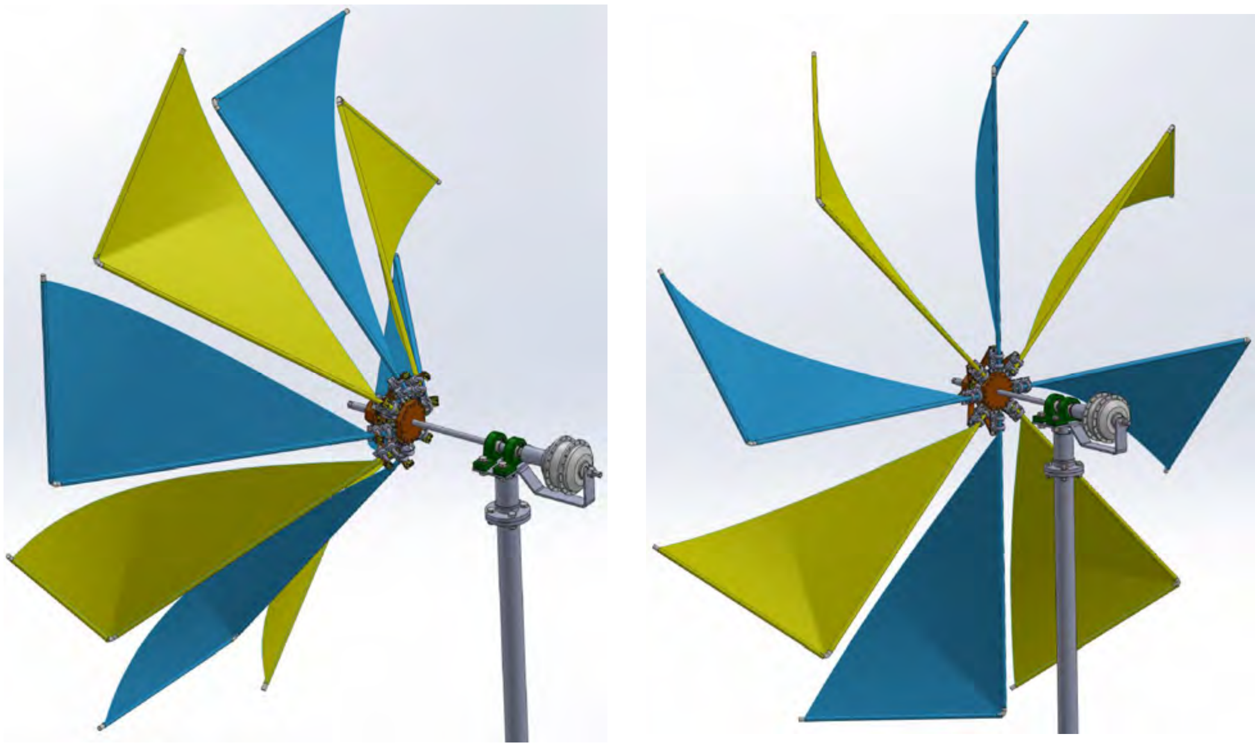
The ratio of peripheral (circumferential) speed U_R of the outer end of the blade to the speed V_0 of undisturbed incident air-flow is called the coefficient of specific speed, or the number of modules of the wind-wheel $Z = \frac{U_R}{V_0} = \frac{\omega \cdot D_b}{2 \cdot V_0} = \frac{U_R \cdot R_b}{V_0}$ [1]. Here $R_b = \frac{D_b}{2}$ is the outer radius of the wind-wheel (i.e., the distance between the rotation axis and blade outer end), ω – angular velocity of wind-wheel rotation.

If the relation between the torque, power and angular velocity of the wind-wheel is known $N_{ww} = M_r \cdot \omega$, we may determine wind-wheel torque with a help of the following formula:

$$M_r = C_M \cdot \pi \cdot R_b^3 \cdot \frac{\rho \cdot V_0^2}{2}, \qquad (4)$$

where C_M is the coefficient of wind-wheel torque which is related with the power coefficient by the following dependence: $C_p = C_M \cdot Z$.

In the presented paper we'll consider the influence of blades inclination angles on the starting torque of the wind-wheel under different air-flow speeds. On the basis of obtained results we'll analyze the dependencies of the wind-wheel starting torque $M_r(\alpha)$ i $M_r(\beta)$ as functions of the speed of incident air-flow V_0 and the dependency of the wind-wheel starting torque $M_r(V)$ as a function of blades inclination angles α and β. Here α is an angle between blade longitudinal axis and horizontal shaft of the wind-wheel (the angle is being changed during blades folding up in the bearing of apparent wind, as it is presented in the Fig. 2, a); β is and angle between blade plane and the plane of wind-wheel rotation, i.e., vertical plane perpendicular to wind-wheel shaft (the angle is being changed during blades rotation (turning) round their longitudinal axes, as it is presented in the Fig. 2, b).



а *б*

Fig. 2. Schemes of changing of blades position during their folding up in the bearing of apparent wind (a) and rotating (turning) round their longitudinal axes (b)

Structural features of the wind-wheel prototype and the technique of experiment carrying out. On the basis of designing results of horizontal-axis wind-wheel in the SolidWorks software (Fig. 1) the experimental prototype of horizontal-axis wind turbine have been manufactured in the scientific and research laboratory (NDL-40) of Lviv Polytechnic National University. The axes of blades have been manufactured using the bar of 10 mm diameter, which has been bended at a right angle. The sails have been manufactures using synthetics material (polyether). In order to ensure blades rotation (folding up) in the bearing of apparent wind, there are used articulated (hinge) joints between blades axes and wind-wheel hub. Blades position is being changed with a help of rocker-slider mechanism depending on wind speed and, correspondingly, aerodynamic ram pressure. Horizontal shaft of the wind-wheel is supported by two ball bearings on the supporting plate, which can rotate round vertical tower axis with a help of special supporting and turning unit. In this manner, wind-wheel self-orientation (facing into the wind) is ensured.

Experimental investigations were carried out in the aerodynamic tunnel of Lviv Polytechnic National University. The wind-wheel 1 was placed in the working zone of aerodynamic tunnel 2 and was blown over by the air-flow of different speeds (Fig. 3). In order to register the starting torque of the wind-wheel under different blades inclination angles, the turning lever was rigidly attached to the main shaft by the one end. The other end of the lever interacted with the rod of spring-dial dynamometer. The indications of the dynamometer were read (registered) under different air-flow speeds and blades inclination angles. The air-flow speed was changed by means of changing of rotation frequency of ventilator 3 of aerodynamic tunnel 2 and was registered with a help of hand-held revolving-cup anemometer 4 (Fig. 3).

The results of presented investigations will be useful in the following situations: while developing the mathematical models for defining the wind-wheel starting process; for development of control system of blades positioning in the process of wind-wheel starting under various character of load attached to the driving shaft; for modelling of blades behavior while wind-wheel starting when using the mechanism of their folding up as a system of anti-storm protection and power regulation. If we use centrifugal mechanisms of blades folding up [7], which stipulate the increasing of wind-wheel sluggishness, it will be possible to use the results of presented investigations in order to analyze the possibilities and duration of wind-wheel starting under different air-flow speeds and loads attached to the driving shaft.

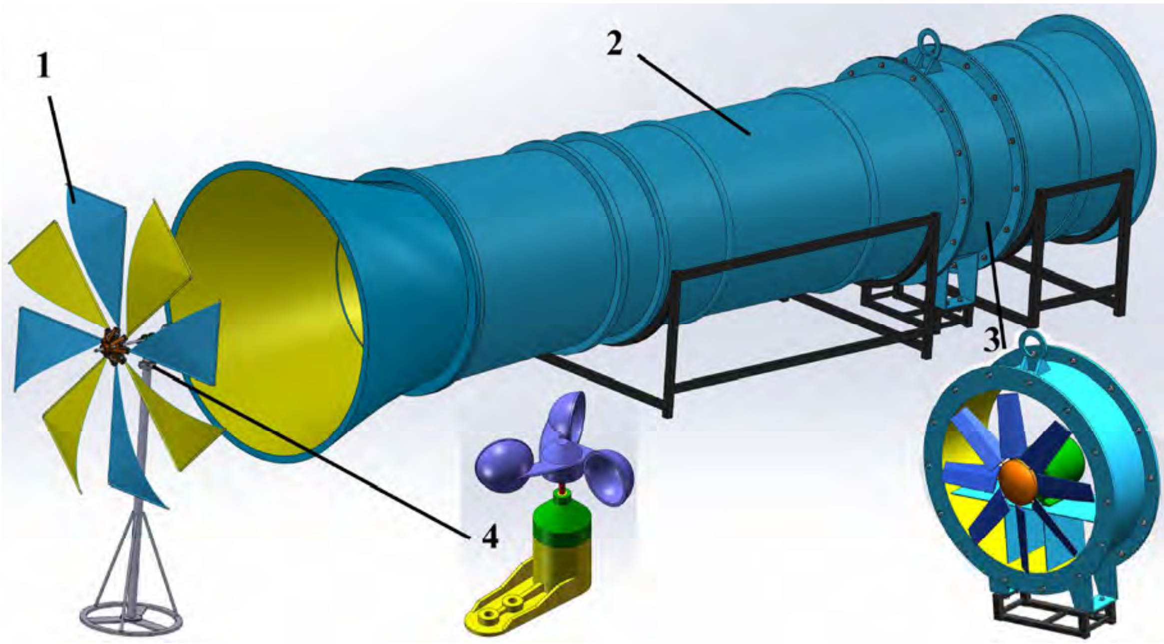


Fig. 3. The scheme of equipment placement during experimental investigations carrying out

The mechanism of wind-wheel starting torque measurement consists of the turning lever 1, which is rigidly attached to the wind-wheel main shaft 2 (Fig. 4). The other end of the lever interacts with the rod 3 of spring-dial dynamometer 4 (Mitutoyo No. 2358-50). The dynamometer 4 registers the magnitude of the rod 3 displacement, so we may determinate the magnitude of the force on the rod (in Newton) in terms of this displacement. If we know the length of the turning lever 1, it is not difficult to calculate the torque which is developed by the wind-wheel during its starting. The results of experimental investigations obtained during wind-wheel blowing over by the air-flow of different speeds are presented in Figs. 5–6.

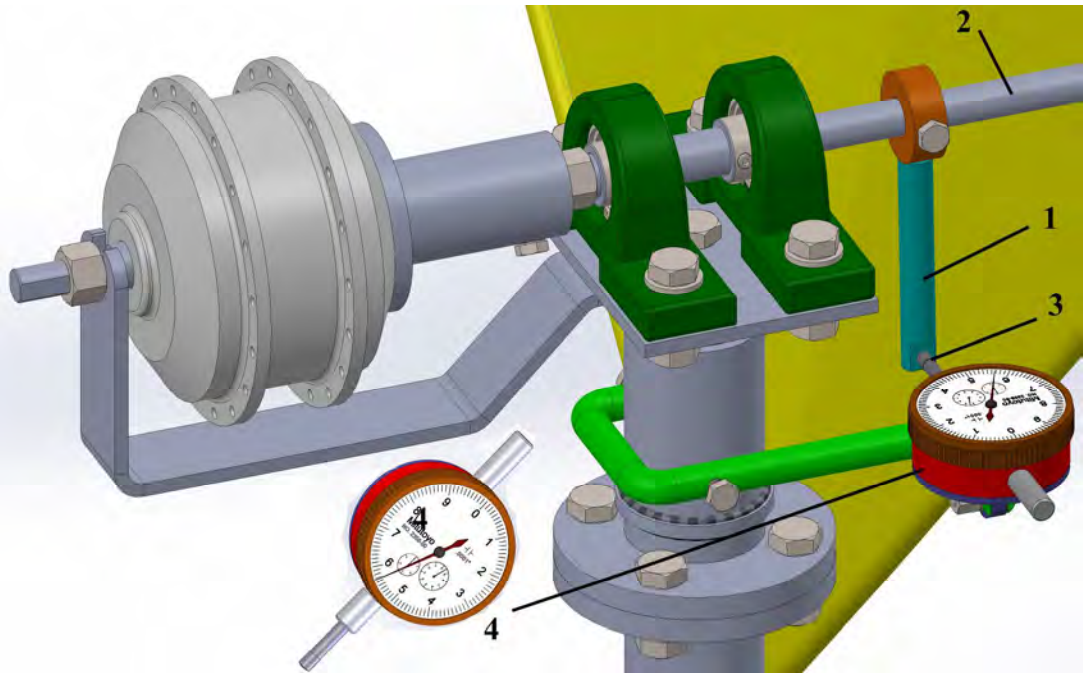


Fig. 4. The scheme of the mechanism of wind-wheel starting torque measurement

Results of experimental investigations. The investigations have been carried out under air-flow speeds of 5, 7, 9, 12 m/s. The angles β of blades planes inclination from wind-wheel rotation plane were adopted as 0°, 30°, 45°, 60°, 75° and 90°. The angles α of blades longitudinal axes inclination from wind-wheel horizontal shaft were changed from 30° to 90° with the interval of 15°. The air-flow speed was changed by means of changing of rotation frequency of ventilator 3 of aerodynamic tunnel 2 (Fig. 3). The angle β was changed by blades turning round their longitudinal axes and fixing with a help of special cramps (clamps). The angle α was changed by blades axes turning round the hinge, by which they were attached to the wind-wheel hub. In such a way, the blades were folded up in the bearing of apparent wind and the swept are of the wind-wheel was reduced. The results of experiments are presented in Tables 1–2.

On the basis of experimental investigations, the plots of starting torque as a function of blades inclination angles under different wind speeds are obtained (Figs. 5–8). By analyzing the influence of angle β of blade plane inclination from wind-wheel rotation plane (Figs 5–6), one may state that the starting torque with sharply decreases with the increasing of β from $0°$ to $90°$. First of all, this is related with reducing of wind-wheel sailing capacity, i.e., the area of active wind-wheel surface, which interacts with air-flow. That is why, in order to start the wind-wheel under lower wind speeds it is necessary to ensure the smallest angle of blades planes inclination from wind-wheel rotation plane.

Table 1

Results of experimental investigations of the influence of wind speed and the angle of blades planes inclination from the wind-wheel rotation plane on its starting torque M_r $(N \cdot m)$ when $\alpha = 90°$

	$V_0 = 5\ m/s$	$V_0 = 7\ m/s$	$V_0 = 9\ m/s$	$V_0 = 12\ m/s$
$\beta = 0°$	5.68	11.06	19.37	38.64
$\beta = 30°$	3.12	7.08	14.81	25.74
$\beta = 45°$	2.24	5.76	11.23	20.25
$\beta = 60°$	1.75	3.67	6.85	12.76
$\beta = 75°$	0.83	1.55	3.91	6.95
$\beta = 90°$	0.68	1.08	1.88	2.77

Table 2

Results of experimental investigations of the influence of wind speed and the angle of blades axes inclination from the wind-wheel shaft on its starting torque $M_r\ (N \cdot m)$ when $\beta = 30°$

	$V_0 = 5\ m/s$	$V_0 = 7\ m/s$	$V_0 = 9\ m/s$	$V_0 = 12\ m/s$
$\alpha = 30°$	0.77	1.24	1.68	2.35
$\alpha = 45°$	1.12	1.83	3.92	6.14
$\alpha = 60°$	1.81	2.71	5.87	11.47
$\alpha = 75°$	2.75	5.54	10.24	18.33
$\alpha = 90°$	3.12	7.08	14.81	25.74

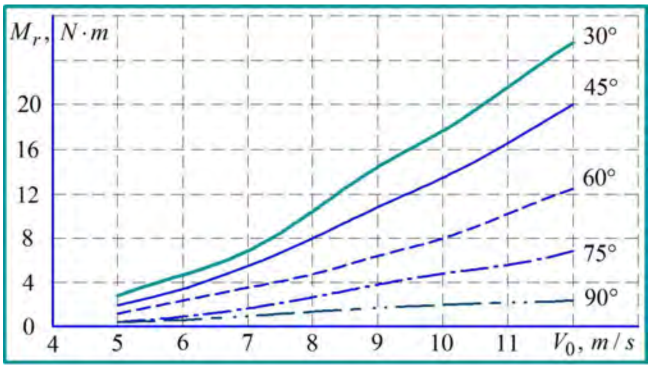


Fig.5. Plot of wind-wheel starting torque M_r as a function of the speed V_0 of incident air-flow under different β angles of blades planes inclination from wind-wheel rotation plane when $\alpha = 90°$

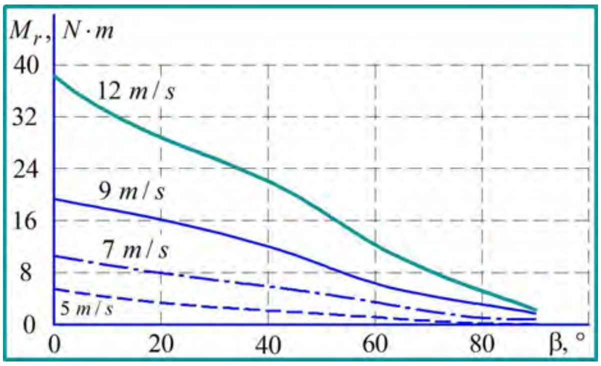


Fig. 6. Plot of wind-wheel starting torque M_r as a function of β angle of в blades planes inclination from wind-wheel rotation plane under different speeds V_0 of incident air-flow when $\alpha = 90°$

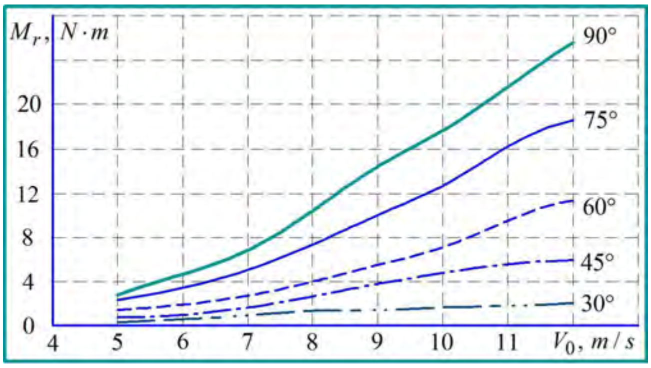


Fig. 7. Plot of wind-wheel starting torque M_r as a function of the speed V_0 of incident air-flow under different α angles of blades longitudinal axes inclination from wind-wheel horizontal shaft when $\beta = 30°$

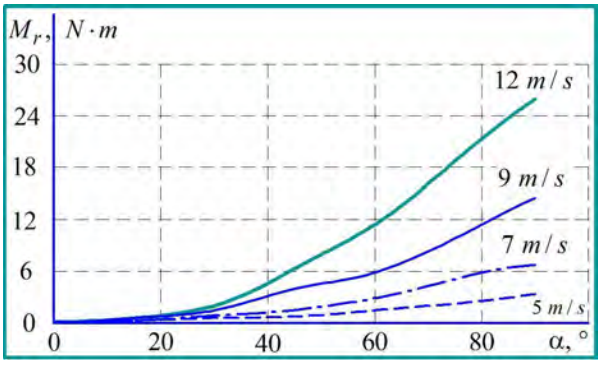


Fig. 8. Plot of wind-wheel starting torque M_r as a function of α angle of blades longitudinal axes inclination from wind-wheel shaft under different speeds V_0 of incident air-flow when $\beta = 30°$

By analyzing the influence of angle α of inclination of blades longitudinal axes from the wind-wheel horizontal shaft, one may state that the starting torque of the wind-wheel sharply increase with increasing of α from 0° to 90° (Figs. 7–8). First of all, this is related with increasing of wind-wheel swept area and, correspondingly, of its sailing capacity, i.e., the area of active wind-wheel surface, which interacts with air-flow. That is why, in order to start the wind-wheel under lower wind speeds it is necessary to ensure the largest angle of blades longitudinal axes inclination from wind-wheel shaft.

Scopes of further investigations. Further investigations on the subject of the paper consist in development of mathematical models of wind-wheel starting and accelerating to nominal rotation frequency taking into account working conditions and operational features of specific loads powered by the wind-wheel. In this case, mathematical model of aerodynamic subsystem of the wind-wheel (i.e., the system of interaction between air-flow and blades) should be complemented with equations of motion of its separate elements during power regulation and wind-wheel facing into the wind (i.e., with mathematical model of mechanical subsystem of the wind-wheel). The last stage in development of mathematical model of the wind-wheel, which is considered as combined aerodynamic-mechanical-electrical system, consists in complementation of mathematical models of aerodynamic and mechanical subsystems with equations which describe the operation of electrical subsystem, i.e., of the load powered by the wind-wheel. On the bases of developed mathematical model of wind-wheel combined aerodynamic-mechanical-electrical system, one would be able to form the technique of wind-wheel calculation and designing.

a *b*

Fig. 9. Structural diagrams of horizontal-axis wind-wheel with air-flow concentrator

One more prospective scope of investigations related with the subject of the paper is modernization of the systems of anti-storm protection and power regulation of horizontal-axis wind turbines with sail-type blades. It is believed that the most efficient method of power regulation of horizontal-axis wind-turbines is blades turning round their longitudinal axes (so-called, pitch regulation). However, taking into account the large sailing capacity of the wind-wheel with sail-type blades and the expediency of usage of the system of wind-wheel self-facing into the wind (by placing the rotor behind the tower), in such wind turbines it is possible to use structurally simple mechanisms of blades folding up in the bearing of apparent wind (so-called, mechanisms of "umbrella" type). In order to enlarge the accuracy of power regulation and the reliability of the mechanism operation under gale winds, it is possible to use combined mechanisms, in which the simultaneous use of mechanisms of blades folding up and turning is ensured [2; 8].

Also it is necessary to mention the expediency of usage of the experimental results, presented in this paper, during the modelling and analyzing of operation efficiency of wind turbines with air-flow concentrators or, so-called, confusers (Fig. 9). They allow to entrain the larger air-flow area and guide (direct) it to the wind-wheel blades, enlarging in this manner the torque on the driving shaft. The confuser should be rigidly attached to the wind-wheel nacelle with the opportunity to face into the wind together with the wind-wheel. The confuser may be designed as one-piece solid bogy (Fig. 9, *a*) or may be formed by many separate plates (Fig. 9, *b*), which may change their position with respect to the bearing of apparent wind by turning round the hinges, by which they are attached to the confuser frame. In such a way the changing of confuser sailing capacity (windage) may be carried out.

Conclusions. The article substantiates the expediency of usage of slow-speed multiblade horizontal-axis wind turbines with sail-type blades on the territories with low wind potential. The structure of the wind-wheel is proposed and its operational features are considered. In particular, it is emphasized on the advantages of usage of the system of wind-wheel self-orientation (self-facing into the wind) by placing it behind the tower (so-called, downwind placement). Also the expediency of usage of the mechanisms of blades folding up in order to ensure anti0storm protection and power regulation of the wind-wheel.

The main operational parameters which characterize wind-wheel operation, in particular, power, torque, specific speed etc., are overviewed. The analytical dependencies for their calculation are presented. The dependence of wind-wheel torque on the angle between blade longitudinal axis and horizontal shaft of the wind-wheel (the angle is being changed during blades folding up in the bearing of apparent wind) and the angle between blade plane and the plane of wind-wheel rotation, i.e., vertical plane perpendicular to wind-wheel shaft (the angle is being changed during blades rotation (turning) round their longitudinal axes) is substantiated.

The structural feature of wind-wheel prototype ae overviewed and the technique of experimental investigations carrying out is proposed. The structure of the mechanism of wind-wheel starting torque measuring with a help of dynamometer is developed. On the basis of results of experimental investigations the plots of the starting torque as a function of blades inclination angles under various wind speeds are presented. By analyzing the obtained dependencies, the conclusion about the expediency of ensuring the largest wind-wheel sailing capacity (windage) in order to obtain the largest starting torque is made. It is necessary to ensure the perpendicularity of the planes of blades to the plane of wind-wheel rotation and the perpendicularity of blades longitudinal axes to wind-wheel horizontal shaft.

The prospects of further investigations on the subject of the paper are overviewed. In particular, it is emphasized on the expediency of development of universal engineering technique of calculation and designing of the wind turbine as combined system which consists of aerodynamic, mechanical and electrical subsystems. The results of investigations presented in the paper may be used during the development of corresponding mathematical models of wind turbine subsystems. It is also mentioned

about the possibilities of usage of combined mechanisms of blades folding up and turning as wind turbines systems of anti-storm protection and power regulation in order to increase operation accuracy. Three-dimensiona diagrams of the proposed mechanisms are presented. The expediency of usage of air-flow concentrators in order to entrain the larger area of air-flow and guide (direct) it to wind-wheel blades, enlarging in this manner the torque on the driving shaft.

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