Disadvantages in the structure of the most common rotary wind generators limit their use. This motivates the development of alternative types of wind turbines, the most promising of which are oscillating wind generators.

The object of the study is the structure of an oscillating type wind generator, which provides self-oscillating movement of the blade-wing. The design of the wind generator uses a modified wing shape to provide maximum lift. For this purpose, added elements are the tip and flap, which affect the shape of the wing, its angle of attack, and regulate the direction of the lifting force. The principle of attaching the tip and flap to the wing using spiral springs has been developed. The structure also includes locking magnets that affect the movement of the wing during a turn. The mechanism that drives the self-oscillating mode of operation of the wind turbine was described. This mode occurs under the action of the inertial force of the movement of the wing, the force of elasticity, the repulsive force of the magnets, and the pressure force of the air flow.

A computer simulation of the wind generator was carried out using the ANSYS CFX software package. The model of the flow around an absolutely rigid body at small values of the Reynolds number was applied. The resulting dynamics of the horizontal movement of the wing of the wind turbine make it possible to use it for energy generation already at a wind speed of 2 m/s. The low cost of the wing and the automatic regulation of its movement make it possible to install many wings to increase the power of the wind generator. Thus, the improved wind turbine is low-cost, harmless to birds, has self-regulation of wing movement and can use the low-speed component of the wind, which significantly expands the geography of its operation. It is possible to transfer the proposed technological solutions for the construction of hydroelectric generators

Keywords: oscillating wind generator, self-oscillating mode, blade-wing, angle of attack, low-speed wind component

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IMPROVING THE OSCILLATING WIND TURBINE MODEL

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1. Introduction

Wind energy is one of the most popular sources of clean energy. Traditionally, rotary turbines are used to extract this type of energy. However, serious shortcomings in the structure of the most common rotary wind generators limit their use. They are dangerous for birds and are characterized by significant noise impact on the surrounding ecosystem. In addition, most existing wind turbines produce energy with an efficiency of 30–35 % while the theoretical efficiency value (Betz limit) is 59.3 %. All this motivates the development of alternative, more advanced types of wind turbines. The task of devising new design principles for the operation of wind turbines to increase the efficiency of air flow energy conversion is also relevant. In practice, new structural solutions should lead to cheaper electricity obtained owing to wind energy.

Oscillating wind turbines are one of the promising directions for such developments. The most interesting of the first such developments is the wind generator built by Atelier DNA. The structure contained a large number of long elastic stems, which consisted of oscillating piezo electrics. In 2007, W2 Energy Development Corporation designed the first wind turbine that used the oscillating motion of a wing. In 2015, the Festo company tested the dual-bladed DualWingGenerator wind turbine, which imitated the movement of a bird's wings. Due to certain imperfections, these structures were not fit for industrial use. However, wind farms with oscillating wings had much better aerodynamic and energy characteristics compared to traditional ones. The potential efficiency of this type of wind turbines has been established.

Therefore, research aimed at searching for optimal solutions for the improvement of the oscillating type wind generator is relevant and will provide an opportunity for a wider and more effective use of the wind resource for the energy supply of humankind.

2. Literature review and problem statement

An overview of the current state of use of wind generators is carried out in studies [1, 2]. In [1], it is noted that one of the technological reasons that limits the service life of rotary type turbines is the wear that occurs in rotating parts (bearings and gears) due to stochastic wind load. Such turbines have a low efficiency of extraction of the kinetic energy of the wind stream, their work begins at a sufficiently high wind speed, and the speed at the ends of the blades can reach supersonic values. Wind turbines of the oscillating type are free of such disadvantages.

It follows from study [2] that various types of oscillating wind turbines are already used both on land and at sea. But purely marine or hybrid installations still have a significant priority. Among the original developments, a wind generator with a swinging sail, described in [3], should be noted. This paper proposes a new oscillating generator operating with a sail that swings horizontally in lateral wind flows. A calculation model of the oscillating process using quasi-stationary aerodynamic data of a flat plate is provided. But for the effective operation of such an installation, a wind speed exceeding 4 m/s is necessary.

In recent years, the oscillating-rotating type of installation described in article [4] has been experimentally tested on land. The work concept is based on the Coande effect, which uses the reciprocating motion (CoRe) of the turbine blades instead of rotation. The authors demonstrated that the CoRe system is capable of generating much higher torque than conventional rotary turbines, especially at low wind speeds. At the same time, for oscillating motion at low air speeds, it remains optimal to imitate the shape of a vertically moving bird's wings with turbine blades.

The latest models of oscillating generators with vertical blade movement are considered in works [5–9]. The conceptual structure of an oscillating wind turbine is provided in article [5]. On the basis of the developed computer code, a numerical simulation of the turbine motion takes place, taking into account its geometric and kinetic parameters. The results obtained by the authors for the generated power, as well as the power factor of the reference turbine, showed the effectiveness of using the proposed structure for harvesting wind energy. The problematic features of this model include the failure to take into account the inhomogeneity of the wind flow and the lack of a detailed description of the method of transferring the energy of the vertical movement of the wings directly to the electric generator.

In work [6], a computer simulation of the oscillating motion of the turbine blades, which has the shape of a bird's wing, was performed. Calculations of the draft project were carried out using the numerical method developed by the authors. It is shown, on the one hand, the ability of the method to qualitatively predict the behavior of the turbine. And the second is the theoretically high efficiency of this type of turbine. However, the work uses only conceptual and computational modeling of the motion of the wing blades without taking into account the peculiarities of their behavior in the generator structure.

A separate topic is the study of a wing-shaped foil oscillating in an air or liquid flow. In article [7], a new concept of an energy conversion system based on a completely passive oscillating foil wing is proposed and numerically analyzed. Analysis of the relationship between pitch and sway shows that the energy conversion system has a good ability to connect pitch and sway and simplifies the transmission system of oscillating motion. However, similar structures are more promising in liquid than in air. In addition, despite certain advantages, the low thickness of the wing has its disadvantages. In article [8], the flows around oscillating aerodynamic wings of different thickness were analyzed when using them as a device for collecting wind energy at a high Reynolds number. It is shown that the pressure difference between the upper and lower surfaces of a thick wing, which contributes to the generation of lift, can be much higher than that created by a thin aerodynamic wing (i.e., a foil wing). Therefore, oscillating wings with greater thickness can generate more power than wings with less thickness.

Calculations related to the operation of the Festo DualWingGenerator wind turbine are given in [9]. Two pairs of wings were used in the design of the wind generator, which moved vertically against each other. A spring that compresses during the lifting of the wing takes part in the change of position. When the wind blows, the wings move in opposite directions: the lower wings move up and the upper ones down, or vice versa. This motion is then converted into a rotary motion inside the column by means of two toothed belts and two wheels. The column in the middle also contains two servo motors and a sensor that sets the angle, amplitude, and frequency of the swing. At wind speeds of 4 to 8 meters per second, a 45 percent level of mechanical efficiency was observed. It has been shown that at low wind speeds (i.e., 4–5 m/s) the system has a higher level of energy production than rotary counterparts. However, the DualWingGenerator setup has some drawbacks. First, it is a forced change in the inclination of the wings, which is regulated by a special device. Secondly, during the upward movement of the wing, it is necessary to subtract the weight of the wing from the lifting force, which makes it impossible to move the wings at a wind speed of less than 4 m/s. In addition, the authors do not describe how the problem of orientation of the wings in the direction of the wind was solved.

The authors of work [10] also came to the conclusion that at low wind speeds (less than 5 m/s), a wind generator with an oscillating wing has a higher efficiency than a rotary generator. This conclusion was confirmed both by the results of computer simulations and on an experimental wind turbine. However, as in the previous work, the research was conducted for wind speeds greater than 4 m/s. The reason for this, most likely, is the loss of energy due to the forced adjustment of the angle of the flat blade when changing the direction of its movement. The author emphasizes that the studied model can be optimized to achieve a better result, but this was not the task of his work.

Thus, data from studies [5–10] allow us to state that oscillating generators are more efficient at low wind speeds than rotary generators. The ability to change the position of the wing depending on the direction of the wind gives them significant advantages. Eliminating the shortcomings of the existing structures and, above all, creating an auto-oscillating mode of movement of the wind generator blades should increase their efficiency. It is also desirable to reduce the wind speed at which the oscillating process begins and, accordingly, the energy generation process.

3. The aim and objectives of the study

The purpose of this work is to build a model of an oscillating type wind generator with an improved blade-wing structure and special components for its self-reversal. This will make it possible to ensure the self-oscillating mode of movement of the wing and increase the efficiency of the energy conversion of the air flow by the wing of the wind turbine.

To achieve the goal, the following tasks were set:

– to provide a structure of an oscillating type wind generator with a blade in the form of a wing that moves horizontally under the influence of the wind;

– to develop an improved structure of the blade-wing and justify the mechanism that ensures its self-oscillating movement;

– to conduct a computer simulation of the movement of the blade-wing and analyze the possibility of using the proposed design of the wind generator at low wind speeds.

4. The study materials and methods

The object of our study is the design of an oscillating type wind generator, which provides self-oscillating movement of the blade-wing. The hypothesis of the study assumes the advantage of using the self-oscillating mode to increase the efficiency of the energy conversion of the air flow by the wing of the wind turbine.

The movement of the blade-wing of the wind generator under the influence of the air flow was considered using the laws of aerodynamics relating to the wing of the aircraft. The lifting force of the wing is determined not only by the shape, profile and area of the horizontal projection of the wing, but also by the angle of attack. The lifting force reaches its maximum value at a certain angle of attack, the value of which is obtained according to the parameters of the wing from the reference data [11]. According to the corresponding parameters of the wing, the aerodynamic coefficient of lifting force C_y and the coefficient of aerodynamic resistance C_x were also found:

$$C_y = \frac{2Y}{\rho \cdot v^2 \cdot S};\ C_x = \frac{2X}{\rho \cdot v^2 \cdot S}, \tag{1}$$

where Y is the magnitude of the lifting force, X is the magnitude of the resistance force, ρ is the specific gravity of air; ν – air speed; S is the area of the wing.

A three-dimensional system of partial derivative Navier-Stokes equations was used, which describes the flow process of a viscous compressible gas. It takes the form [11]:

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \nabla\right)\vec{v}\right) = -\nabla P + \nabla \tau, \tag{2}$$

where P is the air pressure, ∇ is the Nabla operator, τ is the stress tensor, which is found from the following expression:

$$\tau = \eta\left(\Delta \vec{v} + \left(\nabla \cdot \vec{v}\right)^T - \frac{2}{3}\delta\left(\nabla \cdot \vec{v}\right)\right).$$

At the same time, η is the coefficient of dynamic gas viscosity, T is the temperature, and Δ is the Kronecker symbol.

The system of equations (2) is supplemented by the equations of continuity (3) and energy (4):

$$\frac{\partial(\rho)}{\partial t} + div\left(\rho \vec{v}\right) = 0, \tag{3}$$

$$\frac{\partial(\rho H)}{\partial t} + \frac{\partial P}{\partial t} + div\left(\rho \vec{v} H\right) = -div\left(\lambda \nabla T\right) + div\left(\vec{v} \cdot \tau\right) + A, \tag{4}$$

where λ is the thermal conductivity coefficient, H is the enthalpy, and A denotes the work of external forces.

During the simulation, a model was used to describe the motion of a flat rectangular wing for small values of the Reynolds number, which corresponds to the model in [12]. Two-dimensional air flow and movement of a wing-plate with a limited wingspan are considered. The wing moves horizontally in a uniform wind flow. In the Cartesian coordinate system, the direction of the air flow coincides with the OY axis, and the wing at zero angle of attack is located in the XOZ plane. The movement of the wing is periodic.

The Strouhal number for a flying wing is found from the following expression [12]:

$$S_t = f \cdot L / v,$$

where v is the wind speed, f is the oscillation frequency, and L is the movement amplitude. In this study, the value of S_t was significantly less than unity. That is, we are talking about laminar air movement.

Ansys CFX software package [13] was used for computer simulation of wind generator operation. The advantage of the chosen modeling platform is the availability of an application library for describing hydro- and aerodynamic processes. In addition, the language compiler works with complex mathematical models containing many equations.

The system of Navier-Stokes equations in this software package is solved using the method of control volumes, which uses the integral form of conservation laws. The method is implemented by dividing the entire calculated area into elementary volumes. However, for the form of elementary volumes, the integral form of conservation laws does not have strict conditions (limitations). Therefore, it is possible to perform calculations on both structured and unstructured grids. If the computational grid is unstructured, then it must contain a larger number of cells than the structured one. However, the unstructured grid has a significant advantage in the process of automated approximation for complex geometrical movement of the object.

During the solution of the research problem, a tetra grid was used, which had thickening in areas characterized by a significant gradient of parameters. This primarily applies to the upper and lower pivot points of the wing. In general, the number of calculation cells used in calculations was no less than 12 million.

The model took into account the movement of free air flow of a certain speed at the entrance, upper and lower borders of the blade-wing. The following approximations are used: there is a uniform static pressure at the inlet and outlet of the system; the model of flow around an absolutely rigid body is used at small values of the Reynolds number. Additional conditions included in the standardized software package are the equations governing the boundary conditions of the blade movement in the self-oscillating mode.

On the border of each computational area, the boundary condition Opening was set, which corresponded to the conditions of the process: for the components of the velocity vectors, for the values of the magnetic field, for the coefficient of elastic interaction, etc. The components of the velocity vector were located according to the given angle of attack.

Hooke's law was applied for the «Opening» boundary condition with respect to the elastic force.

For the boundary condition «Opening» with respect to the values of the magnetic field, the method of calculating the force of interaction of two rectangular permanent magnets, given in [14], was used. To find the magnitude of the force of interaction between such magnets, it is necessary to calculate the integral over the entire volume of both magnets, which leads to a very complex equation. To simplify the calculations, the force F_{m0} is determined when the magnets are in close contact. In addition, the effective distance d at which the force is equal to $F_{m0}/4$ is taken. As a result, the force $F_m(y)$ between the centered magnets is found as:

$$F_m(y) = \frac{d^2}{\left[C+d\right]^2} F_{m0}. \tag{5}$$

F_{m0} and d are functions of the magnetization and size of both magnets, but both parameters can be determined by establishing the strength of $F_m(y)$ in at least two distances. The corresponding values in this study are taken from the specification data of industrially manufactured magnets.

The surface of the wing blade was marked with the boundary condition «Wall». At this limit, the normal and tangential components of the velocity are equal to zero. Computer simulation of the wind generator was performed taking into account all the indicated boundary conditions. As a result, graphical dependences describing the operation of the wind turbine under study were constructed.

The procedure of converting the mechanical energy of the wing into electrical energy using a linear electric generator is discussed in detail in [15].

5. Research results of the improved wind generator model

5. 1. Structure of the wind generator

The principal diagram of the wind generator is shown in Fig. 1.

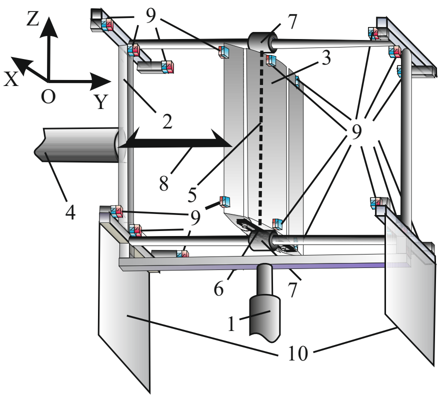

Fig. 1. Conceptual design of the wind generator: 1 — support pipe; 2 — frame; 3 — wing; 4 — linear cylindrical electric generator; 5 — axial rod; 6 — bearings; 7, 8 — holders; 9 — locking magnets; 10 — plates

The generator consists of the following main elements: vertical support pipe 1; frame 2 rotating around the axis of the support pipe; wing 3, and linear cylindrical electric generator 4. The wing is attached to the axial rod 5 on bearings 6 and can perform circular oscillating movements around the rod. The axial rod is attached to holders 7 using cylindrical linear bearings. Bearings slide along horizontal tubes in frame 2. Thus, the possibility of horizontal oscillating movement of the wing is ensured. In the middle of the axial rod on the bearing there is a holder 8 for transmitting the oscillating movement of the wing to the linear cylindrical electric generator. At the corners of the wing and the ends of the horizontal tubes of the frame, twenty-four neodymium magnets in a rubber shell 9 are installed as stops. Their magnetic orientation ensures that the magnets of the wing and the frame are repelled from each other. The support pipe can be attached to a vertical pole or to another base, which ensures the verticality of its location. Plates 10 are attached to the lower tubes of the frame, which ensure the orientation of the wing in the direction of the wind. The movement of the wind occurs along the OX axis, and the movement of the wing of the wind generator – along the OY axis.

The operation of the wind generator is based on the use of the lifting force of the wing in self-oscillating mode under the influence of the oncoming wind. This force provides the movement of the wing. The wing moves along a straight line with a periodic transition to the opposite direction of movement in the extreme left or right position. Such a transition is provided by a change in the profile and, accordingly, the angle of attack of the wing and occurs due to the redistribution of the lifting force along the plane of the wing. The wing profile change at the end points of its movement takes place under the influence of the inertial force of its movement and wind energy and ensures the self-oscillating mode. At the same time, a necessary condition is the symmetry of the wing shape with respect to its chord. Since the load on the wing is not very large, it can be made of materials with a low density to reduce its mass.

The starting angle of attack is set according to the value of the wind speed. Orientation to the wind is automatic.

5. 2. Structure and movement mechanism of a wind generator wing

5. 2. 1. Rotation of the wing as a result of changing its angle of attack

The corresponding process is shown in Fig. 1. For a wing of symmetrical shape at a zero angle of attack β, the lifting force is zero (Fig. 2, *a*). There is only the force of frontal resistance $\vec{X}$. As a result of the change in the angle of attack, there is a redistribution of the force of air pressure along the plane of the wing [16]. When a negative angle of attack β occurs, a force $\vec{Y}_1$, acts on the front part of the wing profile, and on the tail part – a force $\vec{Y}_2$, directed in the opposite direction (Fig. 2, *b*). The sum of the moments of these forces relative to the middle of the chord is not equal to zero and, with an unfastened wing, causes its further rotation. When the angle of attack changes from a negative value to a positive value, the forces $\vec{Y}_1$ and $\vec{Y}_2$ also change directions to the opposite (Fig. 2, *c*). A further increase in the value of the positive angle β leads to a shift of the points of action of these forces to the center of the wing chord.

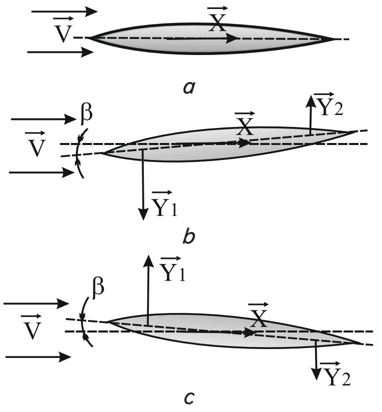

Fig. 2. Rotation of the wing as a result of changing its angle of attack: *a* — zero angle; *b* — negative angle; *c* — positive angle

This process can be made more effective as a result of the inclusion of a special part in the structure of the wing – the tip (pre-wing). Usually, in aviation, a tip with an adjustable angle of inclination relative to the wing chord is used in wings with a thin profile and a sharp leading edge to prevent airflow disruption at large angles of attack [16]. In the design of the wind turbine wing, the tip is used to change the shape of the wing. In Fig. 3, *a*, it is shown that when the direction of the tip coincides with the chord of the wing, the tip does not affect the shape and lifting force of the wing. If the direction of the tip does not coincide with the chord, this leads to a change in the length of the chord and a corresponding change in the angle of attack by $\Delta\beta$ (Fig. 3, *b*).

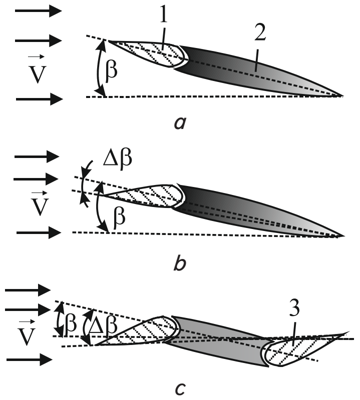

Fig. 3. The tip and flap of the deflecting wing:
a – the direction of the tip coincides with the chord;
b – the direction of the tip does not coincide with the chord;
c – wing with tip and flap; 1 – tip; 2 – wing; 3 – flap

To increase the value of $\Delta\beta$, you can also use a flap. Fig. 3, *c* shows a wing with a tip and flap, and how the tip and flap affect chord length and angle of attack.

5. 2. 2. Moving the wing

Horizontal movement of the wing is used in the operating mode of the wind generator. The main positions of the wing, which has a tip and a flap, are shown in Fig. 4.

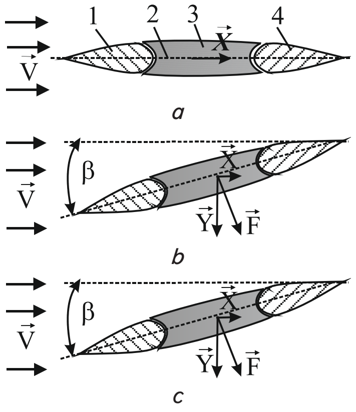

Fig. 4. Movement of the wing: *a* – neutral position;
b – positive angle of attack; *c* – negative angle of attack;
1 – tip; 2 – wing chord; 3 – wing; 4 – flap

Fig. 4, *a* shows a neutral position. It is implemented when the tip, flap, and chord of the wing are located along the direction of the wind. Under such conditions, there is no lifting force, but only the force of wind resistance $\vec{X}$. The movement of the wing occurs according to the positive value of the angle of attack β when the directions of the tip, flap, and wing coincide (Fig. 4, *b*) under the action of the force $\vec{Y}$. The resulting force $\vec{F}=\vec{X}+\vec{Y}$ is perpendicular to the chord. For a negative value of β (Fig. 4, *c*), a force $\vec{Y}$ directed in the opposite direction arises. The resulting force $\vec{F}$ also changes direction and is again perpendicular to the wing chord.

5. 2. 3. The mechanism of influence of the tip and flap on the change in the direction of movement of the wing

To connect the tip (flap), circular grooves are made in the wing with a diameter corresponding to the diameter of the rounding of the tip (flap). Cylindrical holes pass along the length of the wing along the length of the tip (flap), in which cylindrical tubes are placed centrally. These tubes are attached to the tip (flap) at several points with the help of bearings. Spiral springs are put on the tubes and rigidly connected to them. The number of springs is determined by the dimensions of the wing. Fig. 5 shows the intersection of tip 1 (flap) with spiral spring 3, which is mounted on aluminum tube 2. The springs connect the tip (flap) to the wing. The resulting connection makes it possible to perform elastic circular movements of the tip and flap relative to the wing.

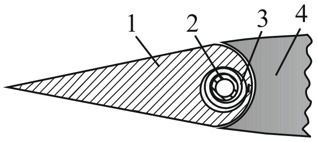

Fig. 5. Structure of the tip (flap): 1 – tip (flap);
2 – aluminum tube; 3 – spring; 4 – wing

When the tip or flap is bent, as shown in Fig. 6, under the action of the wind there is a force acting along the *OY* axis in the direction of this axis (Fig. 6, *a*) or in the opposite direction (Fig. 6, *b*).

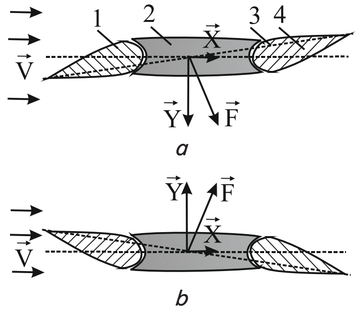

Fig. 6. The mechanism of influence of the tip and flap on the change in the direction of movement of the wing: *a* – force $\vec{F}$ coincides with the direction of the *OY* axis; *b* – force $\vec{F}$ is opposite to the direction of the *OY* axis

At this moment, the position of the wing is close to vertical. Such a situation occurs at the extreme right and extreme left points of the movement of the wing. The wing stops, while the springs are maximally twisted. The energy of their elastic deformation corresponds to the kinetic energy of the movement of the wing, obtained as a result of the force moving the wing. As a result, the wing changes the direction of movement to the opposite one under the influence of the elastic force of the spring and the force of the air flow.

5. 2. 4. Auto-oscillatory wing motion

The movement of the wing can be divided into two directions: along the direction of the OY axis and in the opposite direction of this axis (Fig. 1). Fig. 7 shows a cross-section of the wing, which, according to the stages, goes through the turning process at the location of the stops with neodymium magnets. In Fig. 7, *a*, the wing has not yet reached the stops. In Fig. 7, *b*, the tip touches the stop. In Fig. 7, *c*, the tip unfolds. Next, the wing rests completely against the stops (Fig. 7, *d*). At the last stage, the wing turned to the opposite angle of the chord (Fig. 7, *e*).

The mechanism of self-oscillating movement is determined by certain forces acting during a turn at each stage. Before the turn, the wing moved under the influence of the wind. Before the start of interaction with the stop, the movement of the wing with the tip and flap was uniform, which was automatically ensured by the mechanical load on the wing. As the distance between the tip magnets and the stop magnets 1 decreased, the force of repulsion increased. As a result, the movement of the tip slowed down. After the interaction of the tip with the stop, the tip spring was deformed. The angle of its inclination decreased and the position of the tip relative to the wing changed. That is, the elastic and magnetic interaction led to a change in the configuration of the wing.

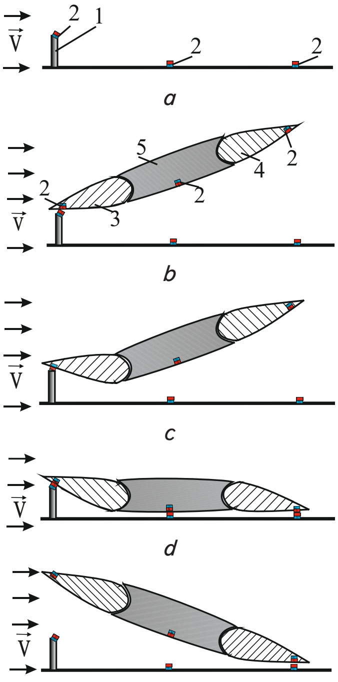

Fig. 7. Stages of self-oscillating movement: *a* – stops to the approach of the wing; *b* – the wing came to a stop; *c* – deployment of the tip; *d* – wing contact with all stops; *e* – wing reversal; 1 – emphasis; 2 – magnets; 3 – tip; 4 – flap; 5 – wing

By inertia, the wing and flap continued to move in the same direction. At the same time, the flap magnets and magnets 2 on the frame stop interacted. In addition, the flap spring was deformed. The flap changed direction. In the process of deformation of the flap spring, there was a change in the angle of inclination of the entire wing with a gradual transition of the angle of inclination to the opposite. Then the lifting force of the wind began to act. The wing straightened to its original shape and began to move under the influence of the forces of magnetic repulsion, elastic repulsion and the force of the wind. After the cessation of the action of the first two forces, the movement continued under the action of the force of the wind alone. When considering the overall balance of forces, the force of resistance to movement of the wing and the force of friction, taking into account the weight of the wing with the tip and flap, were also taken into account.

5. 3. Computer simulation of the movement of the blade-wing

For computer simulation of the movement of the blade-wing, the parameters given in Table 1 were used. The rectangular shape of the wing was used in the model. In order to minimize the mass of the wing, polystyrene foam with a bending strength higher than 0.35 MPa was chosen as the material for its manufacture. In addition to low density, this material also has a fairly low cost and is sufficiently fireproof.

The structure used magnets whose coercive force exceeds 2388 kA/m (these can be rated 30 EH, 33 EH, 35 EH, 38 EH). The values of the coefficients of the lifting force C_y and the aerodynamic drag force C_x were taken from the reference literature [16]. The angle of attack was determined by the pole of the wing.

Table 1

Parameters for modeling the movement of the wind turbine wing

Components	Value
Wing length	2.0 m
Wing chord	0.5 m
Wing area	1 m^2
PSB-S-50 polystyrene foam density	50 kg/m^3
Bearing mass LM60UU (2 pieces)	0.3 kg
Friction coefficient of LM60UU bearings	0.005
Length of thin-walled aluminum tubes 6×0.8 mm, AD31T5 alloy (2 pieces)	2 m
Mass of thin-walled aluminum tubes	0.076 kg
Total mass of the wing	3.2 kg
Wing movement amplitude	2.0 m
Airfoil	NASA-012
C_y	1.46
C_x	0.142
Angle of attack	20 degrees
Air density	1.21 kg/m^3
Air temperature	290 K
Coercive force of magnets	≥2388 kA/m
The coefficient of elasticity of a spiral spring	0.5

Based on the results of computer simulation, the dynamics of the wing position at low wind speeds were clarified, namely, the change in the position of the center of mass of the wing at air flow speeds of 2 and 3 m/s (Fig. 8). In addition, for different wind speeds, the numerical values of the efficiency of the energy conversion of the wind flow (Fig. 9, curve 1) and the power transmitted to the shaft of the cylindrical electric generator (Fig. 9, curve 3) were found.

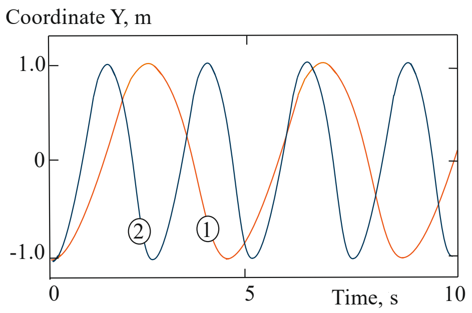

Fig. 8. The dynamics of the wing position at low wind speeds: 1 — v=2 m/s; 2 — v=3 m/s

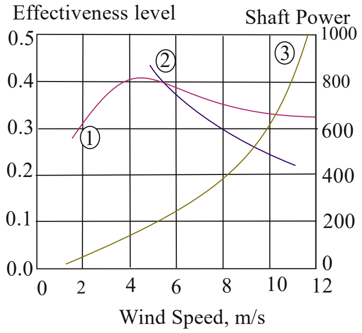

Fig. 9. Characteristics of the movement of the wing of the wind generator: 1, 2 — efficiency of wind flow energy conversion; 3 — power transmitted to the shaft of the cylindrical electric generator; 1, 3 — generator improved in this work; 2 — DualWingGenerator [17]

For comparative analysis according to work [17] in Fig. 9 (curve 2) we also show the dependence on the wind speed of the wind flow conversion efficiency for the prototype DualWingGenerator wind turbine.

6. Discussion of results of computer simulation of the wind turbine

As shown in Fig. 1, 3, in the structure of the wind generator, a transformed wing shape is used to ensure its self-oscillating movement and maximum lifting force. For this purpose, added elements are the tip and flap, which affect the shape of the wing, its angle of attack, and regulate the direction of the lifting force (Fig. 3, 4, 6). In addition, a special attachment of the tip and flap to the wing is used using spiral springs (Fig. 5) and locking magnets that interact with the magnets of the tip, flap and wing during its reversal. As a result, the self-oscillating mode occurs under the action of the inertia force of the wing movement, the force of elasticity, the force of repulsion of the locking magnets, and the force of the pressure of the air flow (Fig. 7).

Computer simulation of the movement of the blade-wing (Fig. 8) shows that, taking into account all the forces of resistance and friction acting on the wing, its self-oscillating motion begins when the wind speed v is 1.6–1.7 m/s. At values of v from 2 m/s and more, the resulting dynamics of the wing allow the device to be used as a wind generator. The value of the wind speed, which is necessary for the initial movement of the wing, is lower than that of analogs, in which the working process starts with a speed of 4 m/s [9, 10, 17]. This is due to the horizontal movement of the wing, which does not require additional force to lift its natural weight.

It is known that the average wind speed in Ukraine is less than 4 m/s. Although the low-speed component of the wind is low-energy, it significantly expands the geography of the wind turbine's use. In addition, the low cost of manufacturing the wing allows you to install a dozen wing blades to increase energy production.

The efficiency of the energy conversion of the wind flow by the wing of the wind generator is maximum at a wind speed of about 4 m/s (Fig. 9, curve 1), which is determined by the set angle of attack of the wing. When the force of the wind decreases, it decreases as a result of the increase in the influence of frictional forces. When increasing the value of v, the level of efficiency also decreases somewhat, which can be corrected by setting the angle of attack that corresponds to the force of the wind.

The value of the coefficient of efficiency of the use of wind energy by the wing of the installation reaches 41 %. At a wind speed of about 5 m/s, this value is somewhat lower than that of the DualWingGenerator wind generator (curve 2 in Fig. 9). However, at higher wind speeds, the DualWingGenerator wind flow conversion efficiency is lower, and at values of v=4 m/s and less, it is no longer possible to use it. But the wind turbine model improved in this study can work.

The value of the power on the shaft of the electric generator, which is provided by the movement of the blade-wing, is shown in Fig. 9 by curve 3. It can be seen that the wind turbine reaches a power of 1 kW at a wind speed greater than 10 m/s. However, the simulation was performed for a single wing blade. Installation of ten blades will make it possible to obtain a power of about 2 kW even at a wind speed of 5 m/s. In addition, the presence of an auto-oscillating mode greatly simplifies the control system to achieve the maximum efficiency of electricity generation. Thus, the proposed improvements increase the aerodynamic and energy performance of oscillating wing wind farms. Such power plants can be used in almost all geographical regions. The low cost of the wings and the absence of additional devices to regulate their movement will lead to a decrease in the cost of the wind turbine and the cost of electricity.

However, computer simulation cannot take into account all the factors affecting the movement of a wing blade. Only the construction of a working model of an improved wind turbine will make it possible to fully determine its working characteristics. At the same time, based on expressions (1) to (4), it can be stated that the increase in the density of the medium increases the lifting force of the wing. This constitutes the prerequisites for the transfer of the obtained technological solutions for the aquatic environment, that is, for coastal marine hydroelectric generators.

7. Conclusions

1. An improved design of an oscillating type wind generator with a blade in the form of a wing has been provided. The operation of the wind generator is based on the use of the lifting force of the wing under the influence of the oncoming wind flow. The movement of the wing is horizontal and occurs in self-oscillating mode. The structure of the wind turbine includes a linear cylindrical electric generator, locking magnets and plates, with the help of which automatic orientation to the wind takes place.

2. To ensure the self-reversal mechanism of the wing, it is proposed to use two additional components – the tip and the flap, which affect the length of the chord and the angle of attack of the wing. Their connection with the wing has been

designed, which makes it possible to perform elastic circular movements of the tip and flap relative to the wing. The self-oscillating mode is implemented with their help under the influence of the inertia force of the wing movement, the force of elasticity, the repulsion force of the locking magnets, and the force of the air flow.

3. Ansys CFX software package with an application library for describing aerodynamic processes is used for computer simulation of the wind generator wing. A rectangular wing model and a laminar air flow approximation were used. The results showed the possibility of using the proposed design of the wind generator starting from a wind speed of 2 m/s and its greater efficiency compared to existing analogs. The low cost of the wings and the presence of an auto-oscillating mode of their movement allow increasing the number of wings in the wind generator to increase its power. Installation of ten blades will make it possible to obtain a power of about 2 kW at a wind speed of 5 m/s.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

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

References

1. Roga, S., Bardhan, S., Kumar, Y., Dubey, S. K. (2022). Recent technology and challenges of wind energy generation: A review. Sustainable Energy Technologies and Assessments, 52, 102239. doi: https://doi.org/10.1016/j.seta.2022.102239
2. Rehman, S., Alhems, L. M., Alam, Md. M., Wang, L., Toor, Z. (2023). A review of energy extraction from wind and ocean: Technologies, merits, efficiencies, and cost. Ocean Engineering, 267, 113192. doi: https://doi.org/10.1016/j.oceaneng.2022.113192
3. Hosseini, R., Roohi, R., Ahmadi, G. (2019). Parametric study of a novel oscillatory wind turbine. Energy Equipment and Systems, 7 (4). 377–387. doi: https://doi.org/10.22059/EES.2019.37713
4. Garzozi, A., Dunaevich, L., Greenblatt, D. (2020). High-Torque Oscillating Wind Energy Generator. Journal of Physics: Conference Series, 1618 (4), 042004. doi: https://doi.org/10.1088/1742-6596/1618/4/042004
5. Dehghani, M. (2021). Conceptual Design and Initial Analysis of an Oscillating Wind Turbine. 7th Iran Wind Energy Conference (IWEC2021). doi: https://doi.org/10.1109/iwec52400.2021.9466989
6. Hosseinie, R. (2019). Deriving Approximate Criteria for Design and Analysis of a Novel Oscillatory Wind Turbine Using Linearization. Iranian Journal of Science and Technology, Transactions of Mechanical Engineering, 45 (4), 1115–1122. doi: https://doi.org/10.1007/s40997-019-00339-3
7. Jiang, W., Wang, Y. L., Zhang, D., Xie, Y. H. (2019). Numerical investigation into power extraction by a fully passive oscillating foil with double generators. Renewable Energy, 133, 32–43. doi: https://doi.org/10.1016/j.renene.2018.09.094
8. Sun, X., Zhang, L., Huang, D., Zheng, Z. (2017). New insights into aerodynamic characteristics of oscillating wings and performance as wind power generator. International Journal of Energy Research, 42 (2), 776–789. doi: https://doi.org/10.1002/er.3865
9. Fenercioglu, I., Zaloglu, B., Ashraf, M., Young, J., Lai, J., Platzer, M. F. (2015). Flow around an Oscillating Tandem-Wing Power Generator. 53rd AIAA Aerospace Sciences Meeting. doi: https://doi.org/10.2514/6.2015-1751
10. Liu, T., Ramasamy, R. V., Radermacher, R., Liou, W., Salazar, D. M. (2018). Oscillating-wing unit for power generation. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 233 (4), 510–529. doi: https://doi.org/10.1177/0957650918790116
11. Anderson, J. D. (2016). Fundamentals of Aerodynamics. New York: McGraw-Hill Education, 1154. Available at: https://aviationdose.com/wp-content/uploads/2020/01/Fundamentals-of-aerodynamics-6-Edition.pdf
12. Wang, S., Zhang, X., He, G., Liu, T. (2015). Evaluation of Lift Formulas Applied to Low-Reynolds-Number Unsteady Flows. AIAA Journal, 53 (1), 161–175. https://doi.org/10.2514/1.j053042
13. Ansys CFX. Available at: https://www.ansys.com/products/fluids/ansys-cfx
14. Schomburg, W. K., Reinertz, O., Sackmann, J., Schmitz, K. (2020). Equations for the approximate calculation of forces between cuboid magnets. Journal of Magnetism and Magnetic Materials, 506, 166694. https://doi.org/10.1016/j.jmmm.2020.166694
15. Politykin, B. M., Shtanko, O. D., Litvinova, M. B., Karpova, S. O. (2017). Energy recovery device for the internal combustion engine. Naukovyi visnyk Natsionalnoho Hirnychoho Universytetu, 3, 82–89. Available at: http://nvngu.in.ua/index.php/en/archive/on-the-issues/1435-2017-eng/contents-3-2017/power-supply-technologies/4005-energy-recovery-device-for-the-internal-combustion-engine
16. Houghton, E. L., Valentine, D. T. (2017). Aerodynamics for Engineering Students. Butterworth-Heinemann. Available at: https://www.academia.edu/28792229/Aerodynamics_for_Engineering_Students
17. DualWingGenerator. Festo. Power generation with the wingbeating principle. Available at: https://www.festo.com/PDF_Flip/corp/Festo_DualWingGenerator/en/files/assets/common/downloads/Festo_DualWingGenerator_en.pdf