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Wind power equipment for small farms and households

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Abstract. This article deals with the development of small-sized wind power equipment as a viable solution for decentralized renewable energy production. To improve operational specifications of conventional turbine models with rotating blades, it is proposed to use a new design of wind power plant synthesized on the base of a closed loop conveyor equipped with flat-shaped blades. In this design, blades are mounted on a belt with an opportunity to move together with it in one straight line direction. Air flow interaction with flat blade that performs translation motion is studied by computer simulation using a superposition principle. In accordance with this approach, a fast-chaotic motion of air particles (Brownian motion) is separated from the slow-directed air motion, with the given average velocity. Dynamic analysis of flat blade interaction with air flow is performed for the stationary air flow with constant speed and also for non-stationary flows with wind gusts. Optimization of the system parameters is made using the generated power as a criterion. Simulation results confirm the serviceability and efficient operation of the proposed conveyor type wind power equipment. It can be mounted on the roofs of buildings or rooftops of vehicles, also device is befriended to nature and people.

Key words: air flow, belt conveyor, computer simulation, flat blade, optimization, power, wind turbine.

INTRODUCTION

Wind power is a sustainable and renewable energy source that holds significant potential for providing electricity to small farms and households. The use of wind turbines scaled for residential and agricultural applications has gained attention as a viable solution for decentralized energy production.

The design of small wind turbines plays a crucial role in optimizing energy conversion. Operational principle of conventional wind turbines is mainly based on air flow action on radial blades mounted on a special rotor and further transformation of air flow kinetic energy into the mechanical energy of wheel rotation (Le Gourieres, 1982; Manwell et al., 2009). But in modern commercial wind turbines with rotating blades, the speeds of blade ends increase significantly, and such engineering solution has a negative effect on the use of wind turbines due to high generated noise, increased vibration and dynamic stresses (especially, near the blades attachment to the rotor) resulted in damages and failure of wind turbines (Boller & Buderath, 2007). To prevent accidental situations, different methods of nondestructive testing and condition monitoring techniques are used (Ciang et al., 2008; Granados et al., 2023). This requires additional time and financial resources. Other problem of wind power turbines with rotating blades lies in rather high level of generated noise, which causes annoyance and mental stress in humans (Ambrose et al., 2012), as well these noises have negative affect on birds and animals (Knopper & Ollson, 2011; Park & Do, 2022). To decrease noise level, reduction of geometrical dimensions of blades and other elements of wind turbines would be useful size.

Recent research has emphasized the importance of aerodynamics, rotor design, and blade materials in enhancing the performance of small-sized wind turbines with rotating blades. Several works have been reported on small rotor wind turbines design (Singh & Ahmed, 2013; Chaudhary & Roy, 2015; Siddiqui et al., 2022) and performance optimization (Sanaye & Hassanzadeh, 2014; Scappatici et al., 2016; Umar et al, 2022). Insights into the aerodynamic characteristics of small wind turbines and the impact of various design parameters on energy extraction efficiency are given in (Kahsay & Nielsen, 2022). Paper (Khurshid et al., 2022) discusses the implementation of intelligent control algorithms to optimize the yaw and pitch angles of small wind turbines, thereby maximizing energy capture in variable wind conditions. A drag-lift hybrid wind turbine that can change the blade form adaptively according to the wind speed is proposed in (Gao et al., 2022). Innovations in materials and manufacturing techniques have contributed to the development of lightweight and durable components for small wind turbines (Mishnaevsky et al., 2017), highlighting their potential to improve strength-to-weight ratios and enhance overall system efficiency.

But despite above mentioned advantages in the development of small-sized rotor wind turbines, there is a principal limitation on further increasing of their power. In wind turbines with radial rotating blades, power extraction from air flow is proportional to radial dimensions of blades (Kulunk, 2011). But in small-sized wind turbines, opportunities for increasing of blade's radial dimensions are very limited, and due to this, there is an objective limitation on generated power.

Other drawback of conventional small-sized wind turbines lies in non-optimal orientation of radial flat blades to the air flow, and due to this, the potential possibilities for wind energy conversion in these devices are not fully used. Investigation of rotating flat blade interaction with air flow is performed in (Viba et al., 2016). And on the base of this research, new methods and devices for wind energy conversion with special regulation of blade's turning angle are developed (Viba et al., 2017; Viba et al., 2020). But these small-sized wind devices also have disadvantage which become especially noticeable as the number of blades increases. For example, it has argued in (Eltayesh et al., 2021) that operational efficiency of these devices is reduced with the increasing of number of blades. Specifically, for number of blades more than one, air vortexes are formed between the blades, which negatively affect the efficiency of wind energy conversion.

To overcome the objective shortcomings of existing wind equipment with rotating blades, it is proposed to realize in the turbine a new operational principle, based on the use of flat blade's translational motion excited by air flow. The motive for such motion transformation is due to the fact that during translational motion the velocities of all points on the side surface of the blade are the same (as opposed to conventional rotary-type wind devices}. This makes it possible to use the side surface of the blade more effectively than in known rotary devices (Kulunk, 2011). Efficient wind energy transformation in devices with translationally moving blades is confirmed by the operation analysis of the wind generator proposed in (Beresnevich et al., 2021). But this wind device is very complex in design and therefore not reliable enough. The present article focuses on the development of structurally simpler and more effective in operation wind power equipment with translationally moving blades.

METHODS USED FOR THE DYNAMIC ANALYSIS OF WIND ENERGY HARVESTING EQUIPMENT

Kinematic diagram of the proposed wind power harvesting plant with translationally moving blades is shown in Fig. 1. The device consists of a closed belt conveyor to which flat blades 1, 2, 3 and 4 are attached. In rectilinear movements of the conveyor belt, the upper section 1 and the lower section 3 may have several flat blades. Similarly, during operation of the device, the right rotation stage 2 and the left rotation stage 4 may have multiple blades. The considered electromechanical system consists of a conveyor belt kinematically connected to the right and left reverse pulleys, whose rotation axes Oz and O_2z are parallel. An energy harvesting generator is placed on the axis of the right pulley. The electromechanical system is positioned so that the wind flow velocity V_0 is perpendicular to the conveyor movement plane or parallel to the Oz axis. Accordingly, thin flat rectangular blades with height H and width L are attached to the conveyor belt. The blades are turned by an angle β to the direction of conveyor movement. The blades (flat plates) are attached to the conveyor belt by a truss-type system that is always perpendicular to the conveyor belt. If the plate is not perpendicular or parallel to the air flow V_0 (i.e., if $\beta \neq 0$ and $\beta \neq \pi/2$), the air interaction force moves the straight moving parts of the conveyor to the right and left, and rotates the pulleys. As a result, the generator turns on and accumulates energy.

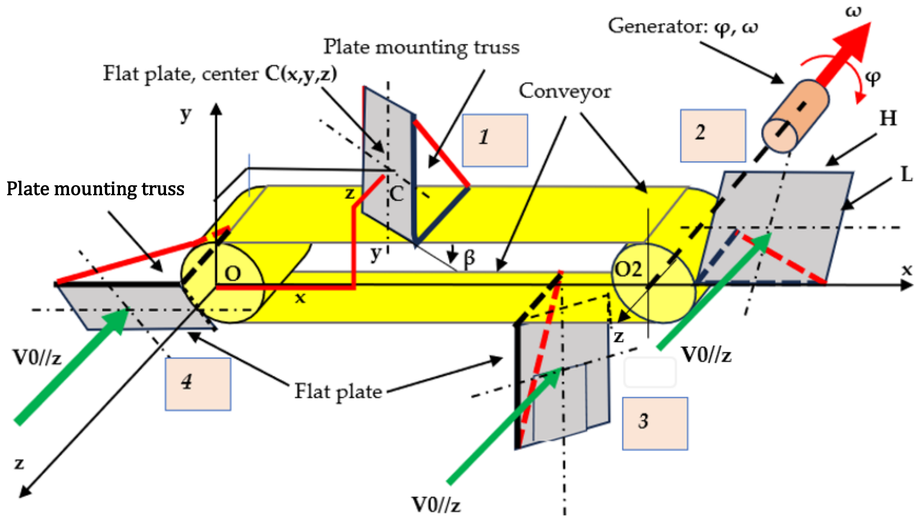


Figure 1. Kinematic diagram of the wind energy harvesting equipment.

Evaluation of the given electromechanical system (Fig. 1), in which the wind flow interacts with moving flat plates, leads to the conclusion that study of the system's movement is related to solving the spacetime task, using appropriate methods (Selyutskiy et al., 2013; Ederra et al., 2022). Among the methods encountered in practice, the method of applying drag and lift coefficients can be used (for example, it is used in the work (Selyutskiy et al., 2013)). The disadvantage of this method lies in the necessity to conduct preliminary experiments in a wind tunnel for the given real object in order to determine drag and lift coefficients. But values of these two coefficients can be determined only in the case of stationary flow and only for the rectilinear air flow. If the object would additionally rotate in real motion, it should be assumed that both drag and lift coefficients are not changed due to this rotation. Besides, experiments in the wind tunnel with the limitation of height and width dimensions do not reflect the real object's movement in nature.

An understandable and effective method for solving the spacetime task is numerical modelling with high-power computers, an example of such research is presented in (Ederra et al., 2022). This work explains the main problems in solving spacetime tasks. Of course, the numerical spacetime method will require a large amount of work in the calculation of the conveyor-type energy extraction system (Fig. 1).

As a third method, classical Newtonian mechanics approach based on the superposition principle should be mentioned (Viba et al., 2021; Viba et al., 2022). In this method, the stationary Brownian motion of air particles is separated from the additional non-stationary motion of air flow. As the result, a spacetime task is reduced to the solution of integral - differential problem, which finally gives the opportunity to solve ordinary differential equations (Meriam et al., 2016). The latter method is used here in this article to solve the problem stated above.

CALCULATION MODEL FOR AIR INTERACTION WITH BLADES

The proposed wind power harvesting device consists of several solid bodies (blades, rotor of generator) connected together by a flexible conveyor belt (i.e. kinematic link) and end pulleys (Fig. 2).

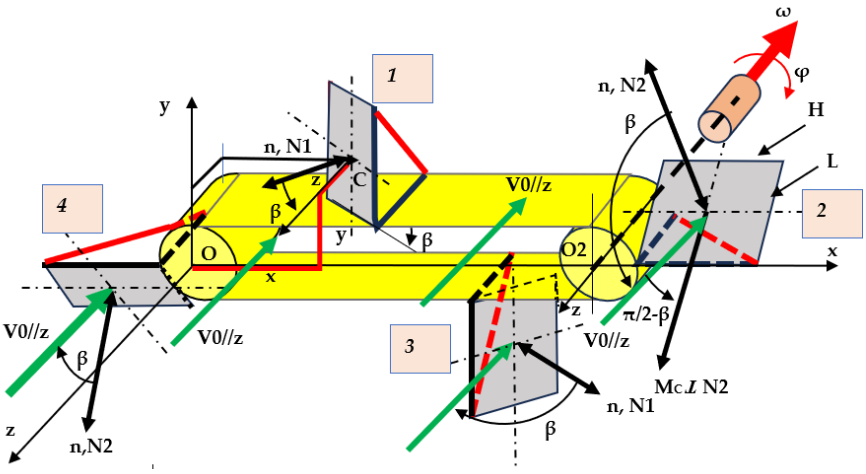


Figure 2. Calculation model for air interaction in four stages of a flat blade (rectangular plate).

A wind flow with a velocity V_0 parallel to the Oz (or O_2z) axis acts on the blades. Since air interaction forces are at work, in the general case the object under consideration is a system with distributed parameters. The number of degrees of freedom of the system tends to infinity. However, when applying the reduction method to the determination plate center C for air interaction, it is possible to reduce the number of degrees of freedom even to one.

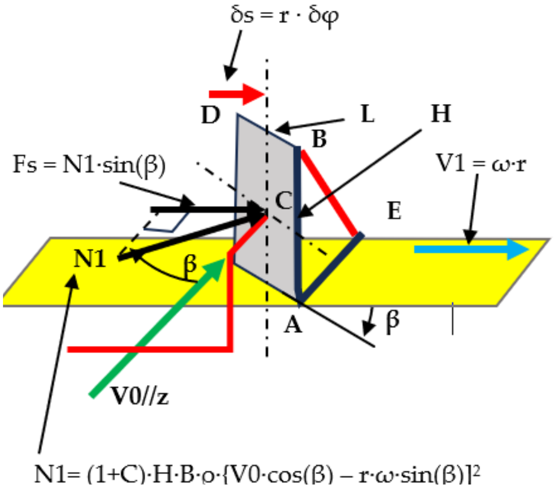


Figure 3. Calculation model of air interaction with flat blade in the translation stage 1.

To perform such reduction, for example, the turning angle φ of the generator's rotor can be used as generalized coordinate (Fig. 2). In this reduction, only the normal force N_1, caused by the air flow, will have to be found in stages 1 and 3 of the rectilinear translational movement (Fig. 3).

Accordingly, in stages 2 and 4 of the rotational movement, in addition to the normal force N_2, the moment M_C created by the air flow must be found, which in this case is perpendicular to the force N_2 (Fig. 4) (Viba et al., 2021; Viba et al., 2022). Pressure zone in the normal direction n is determined using the theorem of the change in the amount of movement of the air layer (Meriam et al., 2016). Accordingly, after integrating the interactions over the entire area of the rectangular plate, the resulting force of the pressure zone can be found.

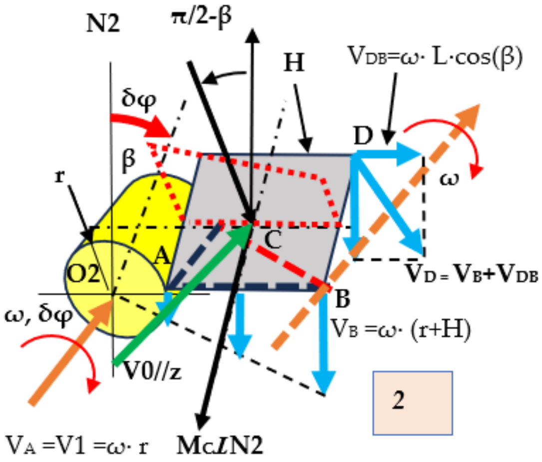


Figure 4. Kinematic diagram for the reduction of air interaction forces applied to one blade during its rotational movement (stage 2).

To determine forces N_1 and N_2, as well as a moment M_C, it is possible to use a calculation method described in (Viba et al., 2021; Viba et al., 2022; Meriam et al., 2016) in order to analyze non-stationary air flow interactions with flat blade. The essence of the method lies in the separation of air-blade interaction space into two zones: the pressure zone and the suction zone (Viba et al., 2022). By this method, the local forces of interaction in the normal direction, are obtained. After that, the interaction force in the suction zone is determined as a proportional value of the resultant force in the pressure zone. Finally, the total resultant normal force N_1 of the pressure and suction zones is obtained; this force is directed along the normal to the blade surface and its value can be calculated by the formula shown in Fig. 3.

Due to air interaction with flat blade, the following resultant normal force N_1 is applied in the center of the plate

$$N_1 = (1 + C)HL\rho \cdot (V_0 \cdot \cos\beta - \omega r \cdot \sin\beta)^2, \tag{1}$$

where C is a constant, H is the plate height, L is the plate width, ρ is the air density, V_0 is the air flow velocity, β is the angle of inclination of the blade relative to the direction of belt movement, r is the radius of the conveyor pulley, and ω is the angular velocity of the generator shaft. It should be noted here that the application of formula (1) and advices for the choice numerical values of the constant C are given in the co-authors' work (Viba et al., 2022) on the base of experiments in a wind tunnel.

In the rotational movement of one blade around the right end pulley of the conveyor (Fig. 4), the normal force N_2 and the moment M_C reduced to the mass center C are obtained in the following form:

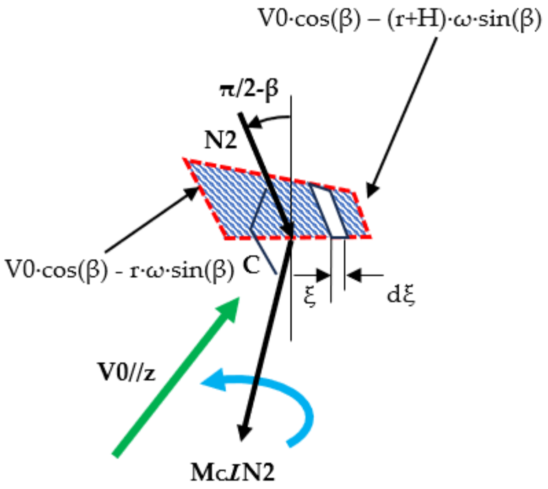


Figure 5. Calculation model of air interaction with flat blade in rotational motion: reduction of normal force N_2 and moment M_C to the mass center C of the blade.

$$N_2 = (1 + C)HL\rho \cdot \int_{-H/2}^{H/2} [V_0 \cdot \cos\beta - \omega(r + H/2 + \xi) \cdot \sin\beta]^2 \cdot \mathrm{d}\xi \tag{2}$$

$$M_C = (1 + C)HL\rho \cdot \int_{-H/2}^{H/2} [V_0 \cdot \cos\beta - \omega(r + \frac{H}{2} + \xi) \cdot \sin\beta]^2 \cdot \xi \cdot \mathrm{d}\xi, \tag{3}$$

where ξ is the radial coordinate of the blade element relative to the its mass center C.

As an illustration to the derivation of Eqs. (2) and (3), a calculation model is presented in Fig. 5.

By the integration of Eqs. (2) and (3), the following expressions for determination of normal force N_2 and reduced moment M_C are obtained:

$$N_2 = (1 + C)HL\rho \cdot \left\{H \cdot [V_0 \cdot \cos\beta - \omega \cdot \sin\beta \cdot (H/2 + r)]^2 + \frac{H^3\omega^2 \cdot (\sin\beta)^2}{12}\right\}, \tag{4}$$

$$M_C = \frac{(1 + C)L\rho H^4\omega \cdot \sin\beta \cdot [V_0 \cdot \left(2\sin^2\frac{\beta}{2} - 1\right) + \omega \cdot \sin\beta \cdot (H/2 + r)]}{6} \tag{5}$$

The obtained air interaction formulas (1), (4) and (5) can be used to form the differential equation of motion for the considered energy harvesting equipment. This problem is discussed in the next section.

DIFFERENTIAL EQUATION OF MOTION FOR THE SYSTEM UNDER STUDY

In compiling the differential equation of motion for the system with one degree of freedom, the dynamical virtual work method (Reddy, 2002; Meriam et al., 2016) is used. Here the turning angle φ of the generator's shaft is chosen as a generalized coordinate, and the virtual displacement of this coordinate can be presented by the variation $\delta\varphi$. The sum of elementary works δW of active forces, coupling reactions and inertial forces at the virtual displacement $\delta\varphi$ of the system should be determined by the following formula:

$$\delta W = (Q^A + Q^G) \cdot \delta\varphi + Q^R \cdot \delta\varphi + Q^{In} \cdot \delta\varphi \tag{6}$$

where Q^A is a generalized force of air interactions in stages 1, 2, 3 and 4 (Fig. 2), Q^G is a generalized force of generator, Q^R is a generalized force of coupling reactions, and Q^{In} is a generalized inertia force.

But the sum of the elementary works δW in the dynamics task, in accordance with (Reddy, 2002), is equal to zero:

$$\delta W = 0. \tag{7}$$

Choosing the variation of the generator turning angle φ as the virtual displacement $\delta\varphi$ (Figs. 3, 4) and using formulas (6)-(7), for the case $\delta\varphi \neq 0$ the following equation is obtained:

$$Q^A + Q^G + Q^R + Q^{In} = 0. \tag{8}$$

In the given mechanism, the generalized force of air interaction Q^A has three components

$$Q^A = Q_1^{N1} + Q_2^{N2} + Q_2^{MC}. \tag{9}$$

Using formulas (1) – (3), the following expressions for determination the generalized forces can be obtained:

$$Q_1^{N1} = k_1 N_1 \cdot \sin\beta \cdot r \tag{10}$$

$$Q_2^{N2} = k_2 N_2 \cdot \sin\beta \cdot (r + H/2) \tag{11}$$

$$Q_2^{MC} = k_2 M_C \tag{12}$$

where Q_1^{N1} is a generalized force of blade's normal force N_1 due to interaction with air, Q_2^{N2} is a generalized force of blade's normal force N_2 due to interaction with air, Q_2^{MC} is a generalized force of air interaction moment M_C, k_1 is a number of blades in motion stages 1 and 3, k_2 is a number of blades in the motion stages 2 and 4.

The characteristic of the energy storage generator can be assumed as a linear function of the angular velocity ω. In this case, the generalized force Q^G can be calculated by the following equation:

$$Q^G = -k_3 \cdot \mathrm{sign}(\omega) - k_4\omega \tag{13}$$

where k_3 and k_4 are positive constants.

Accordingly, the generalized force Q^R of coupling reactions depends on the structure and operation features of real mechanism. For example, this force could be considered as a fixed constant force or a force proportional to the velocity of the conveyor belt. For the last variant, the force Q^R can be determined by the following formula:

$$Q^R = -k_5 \cdot sign(\omega) - k_6\omega \tag{14}$$

where k_5 and k_6 are positive constants. It should be noted that the viscosity of the medium is not considered, but it can be taken into account in the formula (14) by proportional increasing the constant k_6 of the viscous resistance force.

In the considered system with one degree of freedom, which position is set by the turning angle φ of the generator's shaft, the generalized inertial force Q^{In} can be determined by the following formula:

$$Q^{In} = -(m_0 r^2 + J_{02}) \cdot \frac{\mathrm{d}^2\varphi}{\mathrm{d}t^2} \tag{15}$$

where m_0 is the reduced mass of translational motion of the conveyor belt and blades, J_{O2} is the reduced moment of inertia of rotational motion of the system around the axes Oz and O_2z.

By applying formulas (9) – (15), the following differential equation of motion of the electro-mechanical system under study is obtained:

$$\begin{aligned}(m_0 r^2 + J_{02}) \cdot \frac{d^2\varphi}{dt^2} &= (-k_3 - k_5) \cdot sign(\omega) - (k_4 + k_6)\omega + k_1 N_1 \cdot \sin\beta \cdot r \\ &+k_2 N_2 \cdot \sin\beta \cdot (r + H/2) + k_2 M_C.\end{aligned} \tag{16}$$

The differential Eq. (16) can be used to find the motion $\varphi = \varphi(t)$ for the system under study using the initial conditions given: $t = 0$; $\varphi(0) = \varphi_0$; $\omega(0) = \omega_0$. The minimal dimensions of the blade needed for the system to operate (run the generator) can be found out from Eq. (16), taking into account that the angular acceleration ε must be positive. For this purpose, the minimal number of blades k_1, k_2 and the interaction area LH in equations (1) – (3) should be selected.

Besides, on the base of the Eq. (16), parametric optimization tasks can be solved. For example, assuming generating power P as criterion, the following equation to optimize power P can be obtained:

$$P(t) = [k_1 N_1 \cdot \sin\beta \cdot r + k_2 N_2 \cdot \sin\beta \cdot (r + H/2) + k_2 M_C] \cdot \omega \tag{17}$$

Different optimization problems solved on the base of Eq. (17) are discussed below.

MOTION SIMULATION AND PARAMETRIC OPTIMIZATION OF THE SYSTEM UNDER STUDY

To solve a parametric optimization task, expressions (1), (4) and (5) for the forces N_1, N_2 and moment M_C are inserted into the Eq. (17). As the result, the following equation for the optimization criterion $P(t)$ is obtained:

$$\begin{aligned}&P(t)\\ &= \{k_1 \cdot (1 + C)HL\rho \cdot (V_0 \cdot \cos\beta - \omega r \cdot \sin\beta)^2 \cdot r\sin\beta + k_2 \cdot (1 + C)HL\rho \\ &\cdot \left\{H \cdot [V_0 \cdot \cos\beta - \omega \cdot \sin\beta \cdot (H/2 + r)]^2 + \frac{H^3\omega^2 \cdot (\sin\beta)^2}{12}\right\}(r + H/2)\sin\beta + k_2 \\ &\cdot \frac{(1 + C)L\rho H^4\omega \cdot \sin\beta \cdot \left[V_0 \cdot \left(2\sin^2\frac{\beta}{2} - 1\right) + \omega \cdot \sin\beta \cdot (H/2 + r)\right]}{6}\} \cdot \omega\end{aligned} \tag{18}$$

By the analysis of Eq. (18), it can be concluded that optimization of power P involves the need to vary up to 8 system parameters (variables): k_1, k_2, V_0, β, r, H, ω and geometrical constant $D = (1+C)HL\rho$. Some of these variables (k_1, k_2, V_0, H, D) will reach their maximum values during the optimization process, but quantities of β and ω will remain within the permissible limits. When optimizing the turning angle β of the blade, the separation of the flow above the blade should be observed in such a way that there is no overlapping of areas and there is always a translational movement through the flow excitation. Accordingly, after determining the values of β and ω, in solution of the differential Eq. (16) criterion (18) should be analyzed by the variation of other system parameters. Part of this numerical process is discussed here.

The numerical example considered here deals with the motion analysis of the simplest structural model of the wind power device, which includes only one blade in each stage ($k_1 = 2$, $k_2 = 2$). Accordingly, the other system parameters were chosen as follows: $k_3 = 0$; $k_4 = 0.25$; $k_5 = 0$; $k_6 = 0$; $H = 0.5$ m; $L = 0.5$ m; $C = 0.5$; $\rho = 1.25$ kg m^{-3}; $V_0 = 15$ m s^{-1}; $J = 100$ kg m^2; $\beta = 0.1\pi$ rad; $r = 0.5$ m. Computer simulation is performed with program Mathcad, and results are presented in graphical form in Fig. 6.

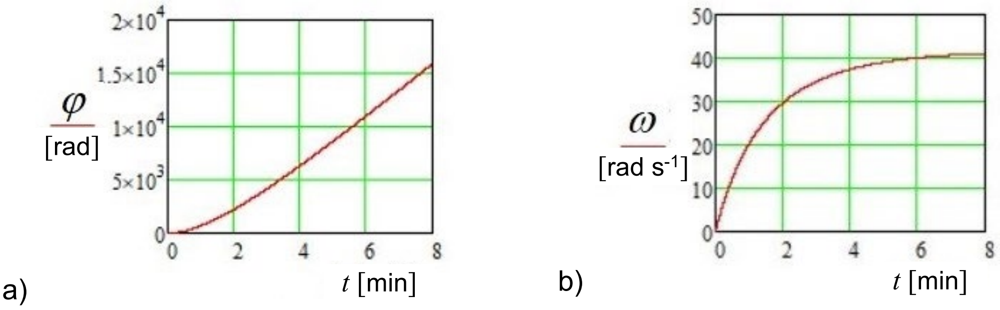


Figure 6. Kinematic characteristics of generator shaft in transient process as functions of time t: (a) Turning angle φ; (b) Angular velocity ω.

As follows from the analysis of the graphs presented (Fig. 6), a stationary rotation process of generator shaft occurs after about 8 minutes, starting from zero initial conditions conditions ($t = 0$; $\varphi(0) = 0$; $\omega(0) = 0$). Angular velocity in stationary operation regime is around $\omega = 40$ rad s^{-1}.

Power P accumulated by the generator is gradually increased during transient process, as it is shown in Fig. 7.

The resulting power P of generator (Fig. 7) includes two components: the air interaction power P_1 of two straight sections (numbered as sections 1 and 3 in Fig. 1) and the air interaction power P_2 of two rotary sections (numbered as sections 2 and 4 in Fig. 1). By the analysis of these graphs, it can be concluded that when approaching stationary motion ($\frac{d^2\varphi}{dt^2} = 0$; ω = const) the following relationship is approximately valid: $P = P_1 + P_2$. Additionally, one can also come to the conclusion that power P_1 obtained in the rectilinear movement stage of the blade is about four times greater than power P_2 obtained in the rotational motion stage of the blade. The main conclusion here is that the proposed wind power device (under the given system parameters) is able to generate a maximal power of about

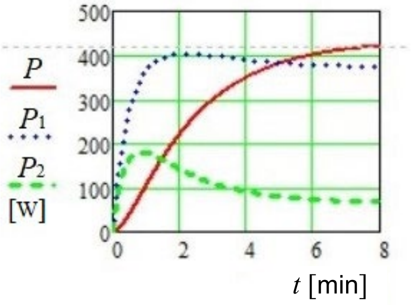


Figure 7. Growth of the power P accumulated by generator during transient process.

420 W. In this case, to increase the generated power *P*, the number of blades (k_1, k_2) should be chosen more and the tilt angle β should be adjusted.

COMPUTER SIMULATION RESULTS

The developed methodology makes it possible to simulate and parametrically optimize different operation conditions of the wind power device. Blade interactions with constant air flow speed V_0 can be analysed at different generator operation laws, for example, assuming $\boldsymbol{k_3 \neq 0}$, but $k_4 = 0$. Simulation results for this specific case (assuming $k_3 = 17.5$, $k_4 = 0$ and other parameters similar to those in section 5) are presented in Fig. 8. Computer simulation was performed with program Mathcad.

As follows from the simulation results (Fig. 8), the proposed wind power device (under the given system parameters) is able to generate a maximal power of 530 W.

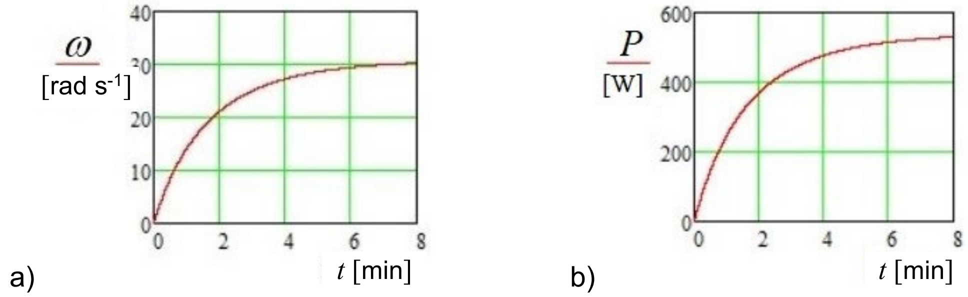


Figure 8. Simulation results for the transient process of generator shaft at the constant air flow speed $V_0 = 15$ m s^{-1} (assuming $k_3 = 17.5$, $k_4 = 0$): (a) Angular velocity ω; (b) Generated power *P*.

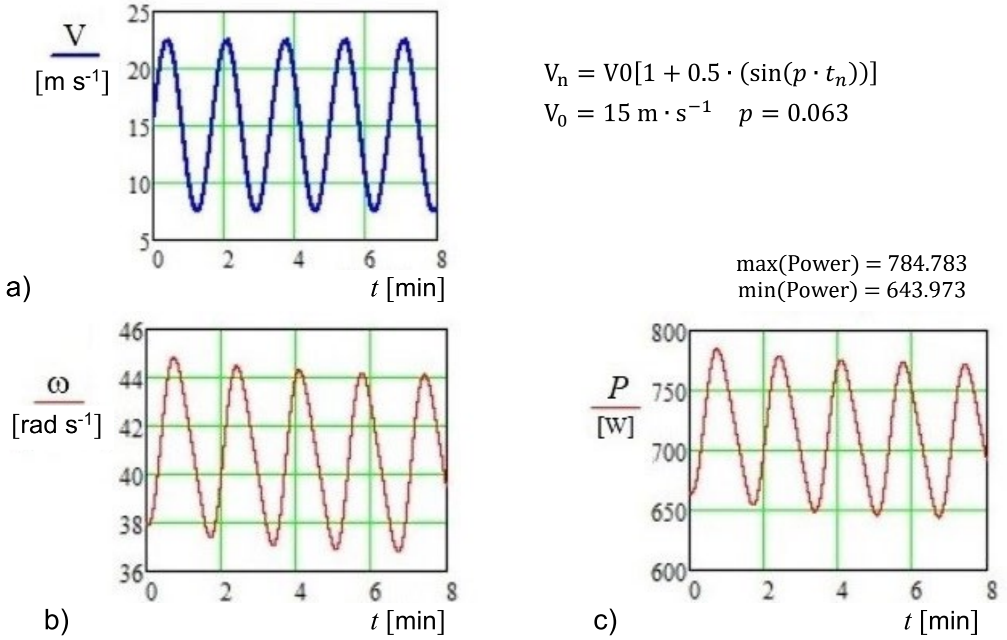
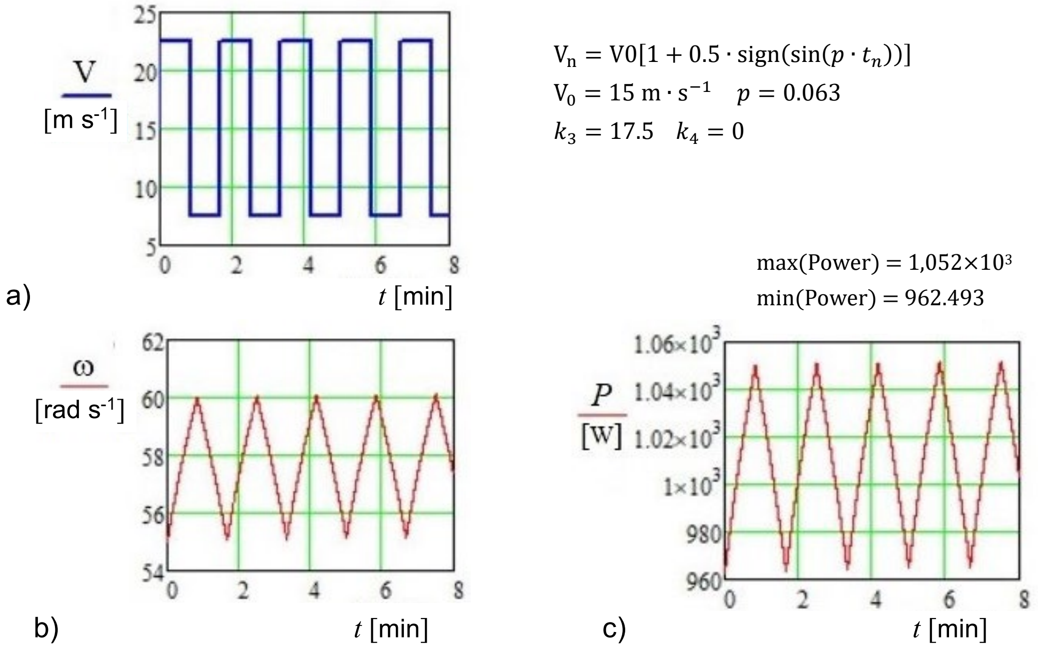


Figure 9. Computer simulation results for the wind flow with harmonic time-varying speed $V(t)$: (a) Harmonic time-varying law of wind flow speed *V*; (b) Variation in time of generator shaft angular velocity ω; (c) Generated power *P* as function of time *t*.

The developed methodology makes it possible to simulate and optimize some other, more complex aerodynamic problems, when blade of the device is subjected to action of wind flow with time-varying speed V. The computer simulation results for one such case (wind flow variation by harmonic law) are presented in Fig. 9. Analysis is performed assuming $k_3 = 17.5$, $k_4 = 0$ and other parameters similar to those in previous section.

As follows from the simulation results (Fig. 9), harmonic time-varying wind flow causes cyclic time pulsation of generated power P. In stationary operation regime of the device, maximal generated power is 785 W, minimal – 644 W and mean value – 714.5 W. Therefore, amplitude of power pulsation is 70.5 W or about 10% from mean value.

Computer simulation results for other characteristic case of air flow condition, when operation of the device is accompanied with wind gusts, are presented in Fig. 10. In the case considered here, wind gust mathematically is described by the rectangular law (mathematical expression of the used rectangular law and its main numerical parameters can be found in Fig. 10).



$$\mathrm{V_n} = \mathrm{V0}[1 + 0.5 \cdot \mathrm{sign}(\sin(p \cdot t_n))]$$

$$\mathrm{V_0} = 15\ \mathrm{m \cdot s^{-1}} \quad p = 0.063$$

$$k_3 = 17.5 \quad k_4 = 0$$

max(Power) = 1,052×10³

min(Power) = 962.493

Figure 10. Computer simulation results for the air flow accompanied with wind gusts: (a) Rectangular time-varying law $V(t)$ of wind gusts; (b) Variation in time of angular velocity ω of generator shaft; (c) Generated power P as function of time t.

As follows from the simulation results (Fig. 10), the proposed air flow device can stably generate power even in condition of intensive wind gusts. In the considered example, variation of wind speed in gusts was taken from 7.5 till 22.5 m s^{-1} or 50% relative to mean value of $V_0 = 15$ m s^{-1}. And in such condition, the device stably generates power within the range from 962 to 1,052 W (pulsation of generated power is about 5% relative to its mean value).

DISCUSSION

The main result of the article lies in the methodology for studying the interaction between moving solid objects and surrounding air medium. This methodology is adopted and modified to analyse interactions of solid bodies with air flow in conditions of variable air flow and wind gusts. Applicability of the methodology has been confirmed by solution some practical numerical examples.

The methodology is based on the hypothesis of dividing interactions into pressure and suction zones. The laws of mechanics on the reduction of interactions are used in the pressure zone. Accordingly, the hypothesis applied in the suction zone is that the interaction can be described in proportion to the air flow velocity in the pressure zone. The methodology allows to simplify the solution of spacetime tasks by transforming the description of the object to the solution of the ordinary differential equation.

It should be noted that in the calculation of the considered energy harvesting equipment, the existence of the applied theory should be checked for the rotation stages, where there should not be a suction process at the end point of the blade, or the rule according to the following inequality should be fulfilled:

$$V_0 \cos\beta - \omega \cdot (r + H) \cdot \sin\beta > 0 \tag{19}$$

where notation is the same as above in the Eq. (1).

If condition (19) is not satisfied, the proposed methodology cannot be applied and the spacetime task must be solved. Such a case is not considered here due to the scope of the article.

In addition, it should be noted that the hypothesis of energy conservation in the process of transition from rectilinear motion to rotational motion is assumed in the calculation. This process is also not subject of research here, because it is related to the occurrence of an impact in the transformation. Impact softening is considered constructively in the work (Viba et al., 2022), where a plate conveyor is used instead of a belt conveyor.

CONCLUSIONS

The main key points to be emphasized in this article can be summarized as follows:

- The analytical method for studying the interaction between air flow and a thin plate when the plate moves in a straight-line direction or rotates around a fixed axis is proposed.
- The proposed method allows to simplify the solution of spacetime problems in fluid dynamics, even in the cases of time-varying flow rates, for example due to pulsation of flow velocity by a harmonic law or because of wind gusts.
- Computer simulation results confirm the serviceability and efficient operation of the proposed conveyor type wind power equipment. It is shown that proposed device can stably generate power even in conditions of air flow variations and intensive wind gusts.
- The proposed energy harvesting equipment can be placed not only horizontally, but also vertically or obliquely, as the flow direction does not influence its operation.
- The results obtained can be also applied for the development of small-sized hydropower equipment, with the possibility of their use in shallow river waters.

- Experimental studies of the proposed small-sized aerodynamic equipment in wind tunnel will be the subject of further research and can be presented in the next articles.

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