NEW DEVICES FOR ENERGY EXTRACTION FROM AIR FLOW

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Abstract. New devices for energy extraction from air flow are developed. The device consists of a central rotor and several plane blades, which are fastened to the rotor with the ability to change the orientation of their working surfaces relative to the direction of the incoming wind flow. Each blade is fastened to the rotor with a cylindrical axial hinge, which longitudinal axis is parallel to the rotor longitudinal axis. Axles of blades have kinematic connection with the central rotor; therefore the blades rotate as the central rotor rotates about its axis. It is considered that axis of the rotor is perpendicular to air flow and simultaneously has arbitrary angle against the horizon. Theoretical and experimental analysis of the blade interaction with the air flow is performed. Aerodynamic coefficients for the blade drag and lifting forces are determined experimentally in the wind tunnel ARMFIELD. Optimization of the system parameters is made using programs Excel and MathCad. It is shown that optimal angular rotation frequency ratio between the rotor and any blade is equal to 2. A physical model of a wind turbine with four blades is made. The experiments with the physical model confirm a serviceability of the device and its main advantages in energy extraction from air flow. The proposed method for energy extraction from air flow is patented in Latvia in 2015.

Keywords: air flow, rotor, blade, aerodynamic simulation, experiments.

Introduction

Wind installations are widely used in engineering during long time (wind mills, wind devices for water pumping, wind motors, etc.) [1; 2]. Operation principle of all these devices is based on air flow action on blades mounted on a special wheel and further transformation of air flow kinetic energy into mechanical energy of wheel rotation. But during operation of these devices there is no possibility for special change of the blade orientation relative to air flow; therefore, the position of the blade can be optimal only in specific time instants [3]. Due to this, at present, potential possibilities for effective energy transformation in wind devices are not used completely.

In order to increase the efficiency of wind energy transformation, it is proposed to change orientation of blades during rotation of the main rotor. Position of blade relative to air flow is considered as an optimal, if the resulting aerodynamic force gives maximal torsional moment about the longitudinal axis of the rotor. In this case maximal efficiency of wind energy transformation can be achieved. This paper considers solution of the problem stated by the theoretical and experimental analysis of the blade interaction with air flow in different aerodynamic conditions.

Investigation of air flaw interaction with flat blade

The model considered in this paper is shown in Figure 1. Flat blades 2 are hinged to the rotor 1, besides longitudinal axes O_1 and O_2 of the rotor and the blades are mutually parallel. Position of the blade 2 relative to air flow is given by angle α, but rotation of the rotor 1 is evaluated by angle φ. In order to increase the efficiency of wind energy transformation, it is necessary to find optimal relations between angles φ and α during operation of the system.

In accordance with aerodynamics theory [4], the flat blade 2 placed in air flow is subjected to action of the aerodynamic force R (Fig. 1). Force R can be resolved into two components: drag force F_x (acts along the flow direction) and lift force F_y (acts in the direction perpendicular to air flow). The following formulae are used to calculate these forces [4]:

$$F_x = \frac{1}{2} C_x S \rho V^2; \; F_y = \frac{1}{2} C_y S \rho V^2, \tag{1}$$

where C_x and C_y – dimensionless drag and lift aerodynamic coefficients;
S – area of the blade's working surface, m^2;
ρ – density of air medium, kg·m^{-3};
V – velocity of air flow, m·s^{-1}.

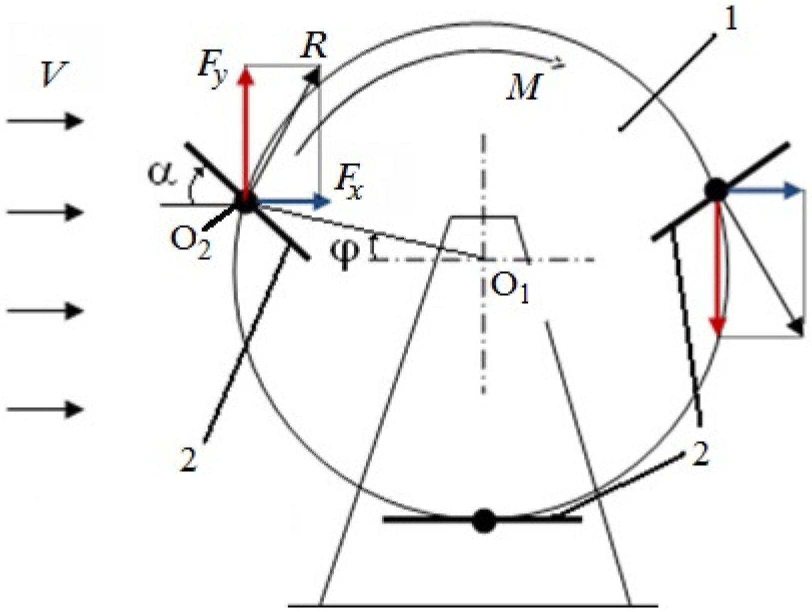

Fig. 1. **Principle model of wind device:** 1 – rotor; 2 – flat blade

Aerodynamic coefficients C_x and C_y are dependent on the blade geometry, its orientation relative to air flow and dimensionless Reynolds number [4]. Coefficients C_x and C_y for the considered flat blade were determined experimentally in the wind tunnel ARMFIELD. Principle diagram of the experimental setup is shown in Figure 2.

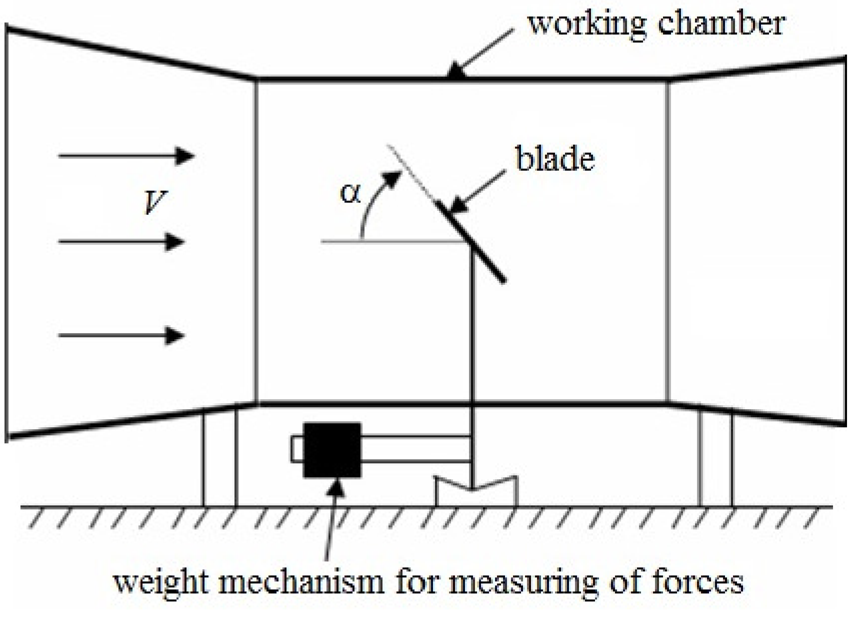

Fig. 2. **Diagram of experimental setup**

During the experiments, angle α between the air flow and the blade's flat surface was varied from 0º (working surface of the blade is parallel to air flow) till 90º (working surface of the blade is perpendicular to air flow), but the velocity V of wind flow – within the range of $5 \div 20$ m·s^{-1}. Aerodynamic forces F_x and F_y for different angles α and for the given flow velocity V were measured with the aid of weight mechanism (Fig. 2). After that, dimensionless aerodynamic coefficients C_x and C_y were calculated using formula (1).

On the base of mathematical processing of the experimental results, the coefficients C_x and C_y are plotted as functions of the angle α (Fig. 3 and Fig. 4, blue lines). To simplify the application of the experimental data in engineering calculations, approximation of the curves $C_x(\alpha)$ and $C_y(\alpha)$ is made (Fig. 3 and Fig. 4, red lines) using program EXCEL.

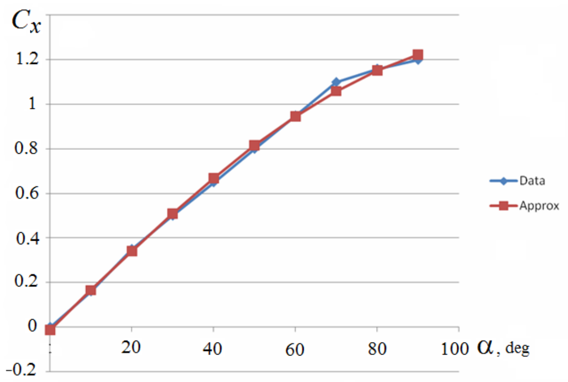

Fig. 3. **Drag aerodynamic coefficient C_x as function of blade's turning angle α**

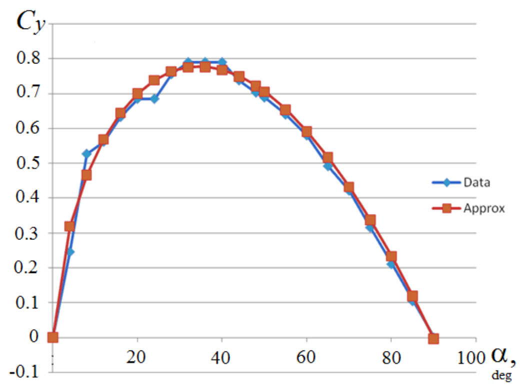

Fig. 4. **Lift aerodynamic coefficient C_y as function of blade's turning angle α**

Approximation functions $C_x(\alpha)$ and $C_y(\alpha)$ mathematically can be expressed with the following equations:

$$C_x(\alpha) = 1.31 \cdot \sin(0.0137\alpha) - 0.01; \tag{2}$$

$$C_y(\alpha) = -0.5094 \cdot \sin(0.00315\alpha - 0.28318) \cdot \alpha^{0.6143}. \tag{3}$$

Coefficient C for the resulting aerodynamic force R can be determined by the formula

$$C(\alpha) = \sqrt{[C_x(\alpha)]^2 + [C_y(\alpha)]^2}\ . \tag{4}$$

For each value of the rotor turning angle φ it is necessary to find an optimal position of the blade relative to the air flow (angle α). Angle α is considered as an optimal, if the resulting aerodynamic force R gives maximal torsional moment M about the longitudinal axis O_1 of the rotor (Fig. 5). But moment M is determined by projection R_τ of force R on tangent line τ. Therefore, angle α is optimal, if projection R_τ becomes maximal. To satisfy this condition, it is necessary to maximize a projection C_τ of the resulting aerodynamic coefficient C.

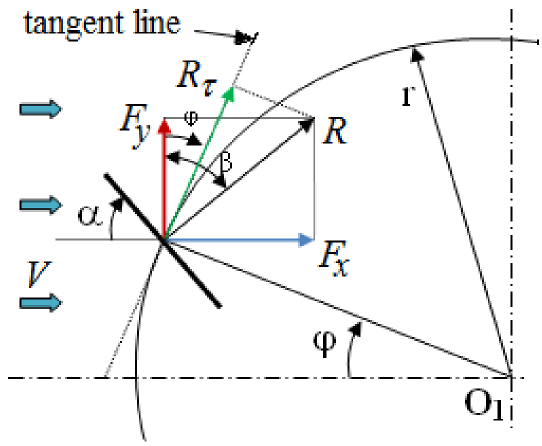

Fig. 5. **Decomposition of aerodynamic force R on components**

Projection of the resulting coefficient C on tangent line can be determined by formula (Fig. 5)

$$C_r(\alpha) = C \cdot \cos(\beta - \varphi), \tag{5}$$

where $\beta = arctg[C_x(\alpha)/C_y(\alpha)]$ is the angle between the vectors $\vec{R}$ and $\vec{F}_y$.

Optimal values of angle α were calculated with computer program MathCad using formulae (2-5). Calculations were made varying the turning angle φ of the rotor from 0º till 360º with the step $\Delta\varphi$ = 5º. The results of the calculations are presented in graphical form in Figure 6.

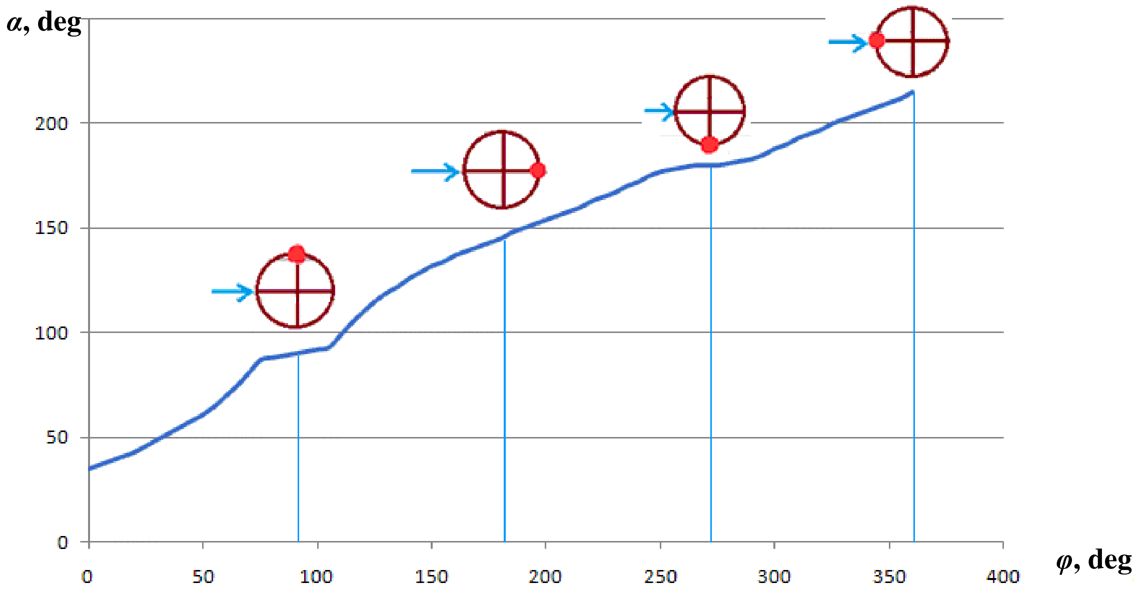

Fig. 6. **Relationship between optimal value of blade's angle α and rotor's turning angle φ**

Curve $\alpha = f(\varphi)$ can be used in designing of wind devices to determine optimal positions of the blade (angle α) for different possible values of the rotor turning angle φ.

Prototype model of air flow device

To achieve maximal efficiency of wind energy transformation, it is necessary to take into account the earlier determined optimal relations between the turning angles φ and α (Fig. 6). But the exact curve $\alpha = f(\varphi)$ is a nonlinear one, therefore, its practical realization in wind devices is very difficult. To simplify practical realization of optimal angles α in real mechanisms, it is proposed to use linear approximation of the exact (experimental) curve $\alpha = f(\varphi)$. The exact and approximated curves $\alpha = f(\varphi)$ are compared graphically in Figure 7.

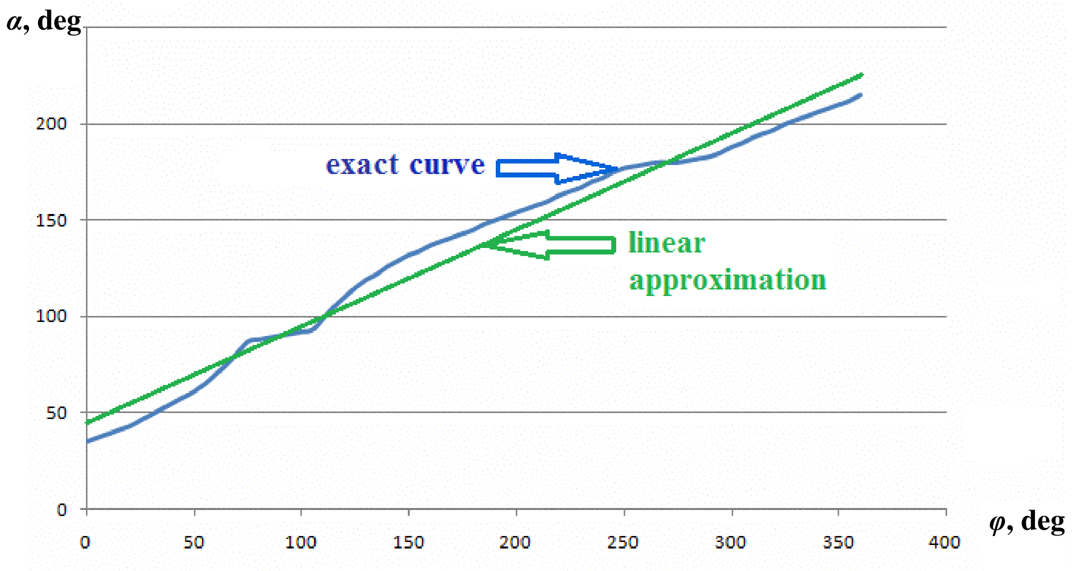

Fig. 7. **Linear approximation of relationship between angles φ and α**

Mathematically the linear relation between the angles φ and α can be described by the following equation:

$$\alpha = 45^\circ + 0.5\varphi = \pi/4 + 0.5\varphi. \tag{6}$$

As follows from equation (6), one revolution of the blade takes place after two whole revolutions of the rotor. Therefore, during one cycle both opposite working surfaces of each blade take up a running air flow in turn.

Calculation error on application of approximate linear function (6) has been evaluated. For this purpose, the values of angle α determined by formula (6) were inserted in the earlier used mathematical model (2-5). It was shown that in the most adverse case a relative error in determination of force R_τ does not exceed 10 %. Herewith, as follows from Fig. 7, approximate value of angle α during some stages of rotor motion is slightly smaller than the optimal one, but in some other stages – a little more of it. Therefore, on average in one revolution, the difference between the approximate and optimal values of the angle α (or between generated powers) will be very small.

Besides, application of linear approximation (6) makes it possible to simplify practical realization of optimal operation regime in the wind device. In accordance with equation (6), ratio of angular rotation frequencies between the rotor and blades must be constant and equal to 2. Such constant frequency ratio can be realized using simple transmission (gear, belt or chain). Taking account of these considerations, it has been found expedient to use a linear approximation (6) in designing of a wind device.

Kinematic diagram of the proposed air flow device is shown in Figure 8. The flat blade 2 is hinged to the rotor 1. Besides, longitudinal axes O_1 and O_2 of the rotor and blade are mutually parallel and kinematically connected to each other with belt transmission 3. Belt pulley 4 is attached to the blade 2, but pulley 5 – to the rotor 1. And in accordance with equation (6) angular rotation frequency ratio between the rotor 1 and blade 2 is taken as 2.

To follow possible changes of the air flow direction, the proposed device is equipped with the tail 6 fastened to the pulley 5. Due to the change of the air flow direction, the tail 6 is turned till becomes parallel to the air flow. Simultaneously the pulley 5 and rotor 1 are also turned, as the result the blade 2 takes optimal orientation to the air flow.

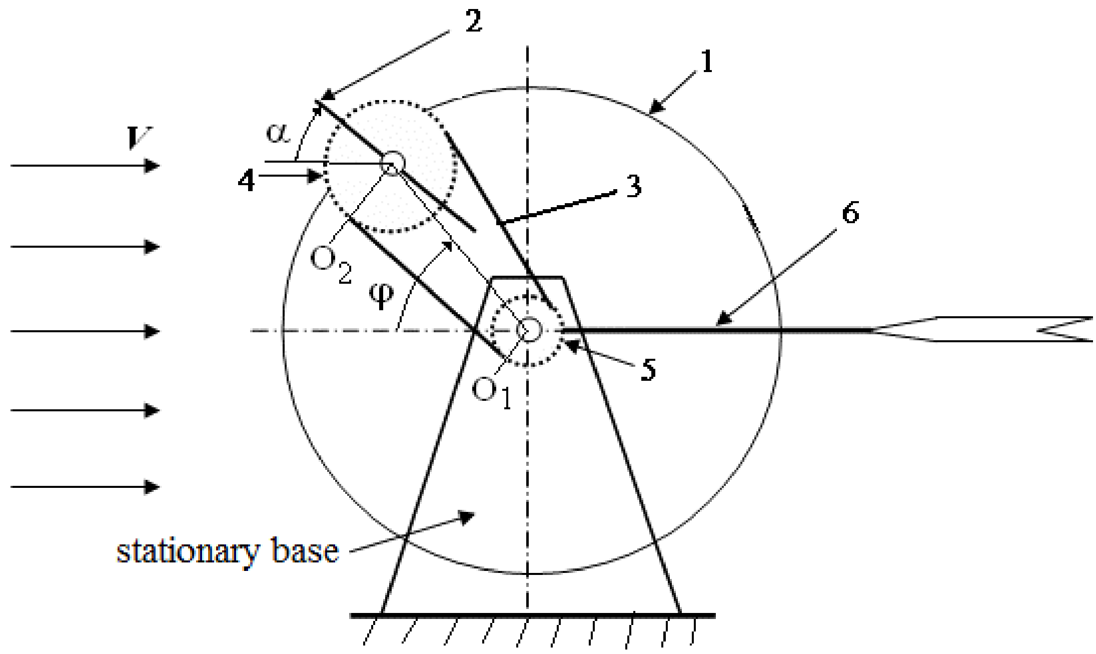

Fig. 8. **Kinematic diagram of air flow device:** 1 – rotor; 2 – flat blade; 3 – belt transmission; 4 and 5 – pulleys; 6 – tail

The proposed method for energy extraction from air flow and the device for its realization are patented in Latvia in 2015 [5].

In accordance with the proposed kinematic diagram, a prototype model of the wind device is made (Fig. 9). The device contains four identical flat blades, which are kinematically connected with the rotor by a toothed belt transmission. Ratio of angular rotation frequencies between the rotor and blades is taken as 2; thanks to this the orientation of the blades relative to the air flow is changed in accordance with condition (6).

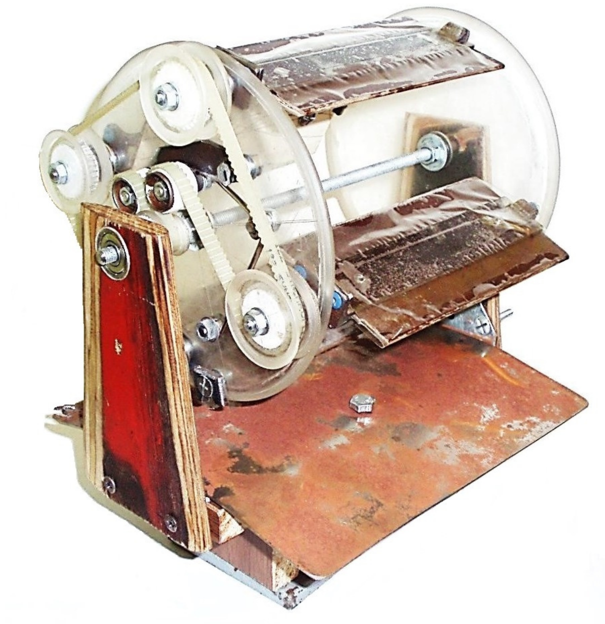

Fig. 9. **Prototype model of air flow device**

The experiments with the prototype device are made in the wind tunnel ARMFIELD. Stable and effective operation of the device is demonstrated for the range of flow velocities from 5 till 20 $m \cdot s^{-1}$. The experimental investigations confirm the principal possibility to increase with the proposed method the extracted power from air flow (in comparison with traditional air flow devices [3]). More detailed quantitative analysis of operation of the prototype device would be critical in the future.

Conclusions

1. Theoretical and experimental analysis of the blade interaction with air flow is performed.
2. Drag and lift aerodynamic coefficients for the flat blade are determined experimentally for different positions of the blade relative to air flow.
3. A new method for energy extraction from air flow is developed. The method is based on continuous regulation by the special law of the blade turning angle during rotation of the rotor.
4. It is shown that optimal angular rotation frequency ratio between the rotor and blade is equal to 2.
5. A prototype model of the proposed air flow device is made. During the experiments, stable and effective operation of the prototype device is demonstrated in the range of flow velocities from 5 to 20 $m \cdot s^{-1}$.

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