Chapter

Synthesis and Optimization of Wind Energy Conversion Devices

Janis Viba, Vitaly Beresnevich and Martins Irbe

Abstract

An approximate method for the analysis of interaction between wind flow and rigid flat blades is considered. The method allows synthesis and optimization of wind energy conversion systems without using space-time-programming procedures. By this method, the action of wind flow on the blade is subdivided on frontal pressure and vacuum (depression) on leeward side. The method was tested by computer simulation and experiments in wind tunnel. Examples of optimization tasks are solved in application to blades with simple shape. New wind energetic device with controlled orientation of flat blades to air flow is developed. Theoretical and experimental analysis of blade's interaction with airflow is performed. Aerodynamic coefficients for blade's drag and lifting forces are determined experimentally in wind tunnel. Optimization of system parameters is made. To increase the efficiency of energy transformation, it is proposed to change, by special law, the orientation of blade's working surface relative to airflow during rotation of the rotor. It is shown that the optimal angular rotation frequency ratio between rotor and blade is equal to two. Serviceability and main advantages of the proposed method are confirmed by experiments with physical model of airflow device.

Keywords: wind energy conversion, rigid blades, airflow, experimental aerodynamics, simulation, optimization

1. Introduction

Extracting energy from wind flow is one of the most important renewable energy sources. Operation principle of wind devices is based on air flow action on blades mounted on special wheel and further transformation of air flow kinetic energy into the mechanical energy of wheel rotation [1, 2]. In order to increase the efficiency of wind energy transformation, it is proposed to change orientation of blades to air flow during rotation of main rotor. Position of blade relative to air flow is considered as an optimal, if resulting aerodynamic force gives maximal torsional moment about longitudinal axis of the rotor. This chapter considers solution of the problem stated by the theoretical and experimental analysis of blade's interaction with air flow in different aerodynamic conditions.

Solid body interaction with air flow is studied in many works. Lift and drag coefficients for flat plate interacting with air flow in the range of Reynolds number from 10^4 to 10^6 were analyzed by Haibo et al. [3]. It was shown that at small angles of attack lift–drag relation is parabolic, but at higher angles of attack, it is a circle with radius of unity. Stationary regimes with constant vectors of relative velocities are well researched and mathematically described (for example, see [4]).

Nonstationary regimes of interaction between continuous air flow and rigid body, as shown in [5], mathematically are more complicated. Such kind of interaction can be analyzed by numerical simulation with space time programming methods [6].

In this chapter, a simplified method for the analysis of interaction between air flow and rigid body is proposed. Method is based on separate consideration of flow-body interaction on pressure and suction (vacuum) sides.

2. Simplified model of air flow interaction with flat plate

To simplify the analysis, optimization and synthesis of wind energetic devices, it is proposed to use approximated model of flow-plate interaction without considering viscous effects of air medium. For this purpose, air flow interaction with the plate is subdivided on two phases: one interaction is on the pressure side and the other one-on the vacuum side (**Figure 1**).

To analyze air flow-plate interaction, the theorem on change of momentum of mechanical system in differential form, is used [7]. In accordance with this theorem, on the side of pressure the following equation can be written:

$$dmV\cos\beta = dNdt, \tag{1}$$

where dm is an elemental mass of air flow; V is a velocity of air flow; β is the angle between air flow direction and normal to the plate surface $L1$ (**Figure 1**); dN is the impact force in the normal direction to the plate surface $L2$; and t is time.

Elemental mass dm of air flow can be mathematically described by the equation:

$$dm = \rho VB\cos\beta\, dt\, dL \tag{2}$$

where dL is elemental length of plate's surface; B is width of the plate (in the case of two-dimensional task B = const); and ρ is the air density.

By the integration of Eq. (1), extra pressure and force along x-axis can be determined. Mathematically, the pressure distribution can be described by the expressions:

$$p_{L1} = V^2\rho(\cos\beta)^2 \tag{3}$$

$$p_{L2} = V^2\rho(\sin\beta)^2 \tag{4}$$

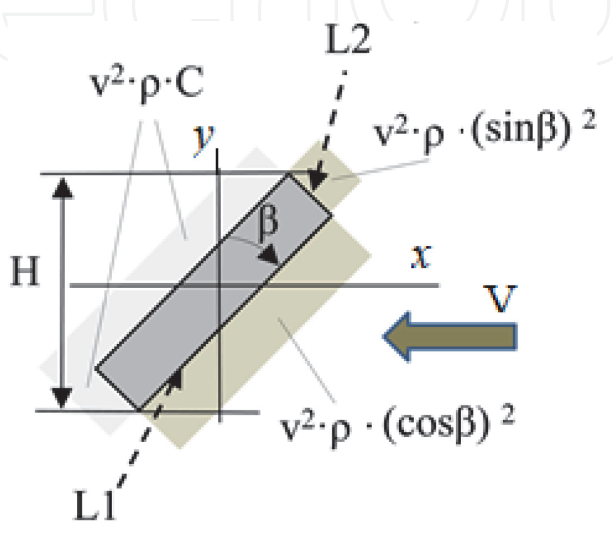

Figure 1.
Air flow interaction with rectangular flat plate.

Vacuum side of the plate is loaded by constant pressure, which can be determined by formula:

$$\Delta p_2 = +V^2 \rho\, C \tag{5}$$

where C is constant to be found experimentally or by computer simulation.

By this way, it is possible to find total force applied to the body in the air flow. For example, projection on x-axis of total force F_1 applied to the rectangular plate is described by the following equation:

$$F_{1x} = -HBV^2\rho\left[C + \frac{(\cos\beta)^3 + d\cdot(\sin\beta)^3}{\cos\beta + d\cdot\sin\beta}\right], \tag{6}$$

where d is the ratio of edges $L2/L1$; H is section height of the plate in the direction perpendicular to the flow (**Figure 1**, $H = L1\ \sin\ \beta + L2\ \cos\ \beta$).

As follows from the results obtained, an approximate analytical method can be applied to solve air flow and blade interaction problems. Validation of the results of analytical calculations can be performed using computer simulation and experiments. Examples will be discussed in the following sections.

3. Theory and simulation of plane motion of flat plate

To determine coefficient C, numerical simulations in Solid Works for flat plate interaction with air flow were performed [8, 9]. Modeling results for a rectangular flat plate were compared with analytical formula (6). It was shown that approximate value of coefficient C is about 0.5. The estimation of accuracy of formula (6) for C = 0.5 in comparison with simulation results is presented in graphical form in **Figure 2**.

From the analysis of **Figure 2**, it can be concluded that interaction force fluctuates within certain limits, and value of fluctuation is dependent on angle β. At smaller angles, the value of fluctuations is also small, but with the increasing of β fluctuation of interaction force becomes greater. The relative difference is not very large, and its mean value is about 3.6%.

Therefore, engineering analysis by the proposed method does not require a step by step space-time calculations to find interaction coefficient C. A new nonstationary flow interaction formula was obtained, and this formula includes the object shape, state, and flow rate direction parameters. Coefficient C is taken as C = 0.5. The efficiency of the proposed method is illustrated by the analysis of flat plate interaction with air flow.

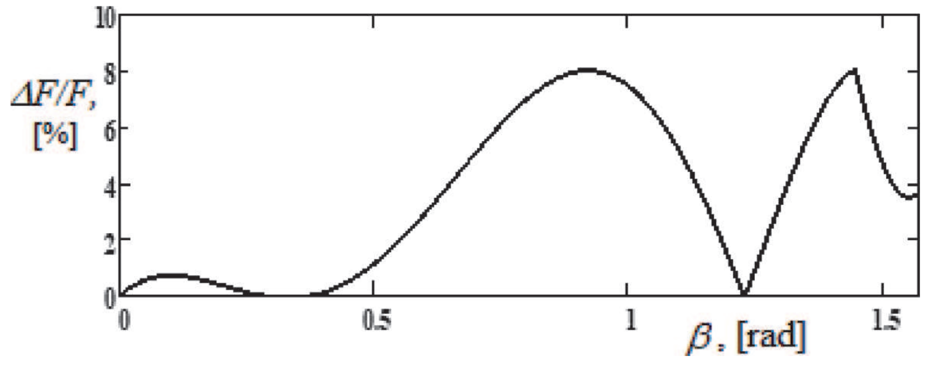

Figure 2.
The accuracy of formula (6) for C = 0.5 as function of angle β.

A two-dimensional (2D) model of translation motion of thin flat plate (thickness $d \sim 0$) in co-ordinate plane x–y is shown in **Figure 3**. The model includes linear elastic element with stiffness coefficient c and linear viscous damper with damping coefficient b.

In accordance with methods of classical mechanics [7], relative interaction velocity V_r must be taken into account:

$$V_r = V + v, \tag{7}$$

where V is velocity of air flow; and v is velocity of flat plate along x-axis.

In this case, differential equation of plate motion along x-axis can be written in the following form:

$$m\ddot{x} = -cx - b\dot{x} - A\rho\left\{\left[0.5 + (\cos\beta)^2\right]\cos\beta\right\}(V+\dot{x})^2 \text{sign}(V+\dot{x}), \tag{8}$$

where $A = LB$ is a surface area of the plate; ρ is the air density; β is plate angle against air flow; and m is mass of the plate.

The renewable energy is generated due to the action of damping force $(-b\dot{x})$. Therefore, momentary power can be determined by formula

$$P = b(\dot{x})^2. \tag{9}$$

The average power P_a during time t is determined by integration of Eq. (9):

$$P_a = \frac{\int_0^t b(\dot{x})^2 \mathrm{d}t}{t}. \tag{10}$$

By the analysis of Eq. (8), it can be concluded that five parameters can be used to control the efficiency of this system. These parameters are as follows: c, b, A, β, and V.

Mathematical simulation of Eq. (8) was performed with program MathCad assuming the following values of main system's parameters: $A = 0.04\ \text{m}^2$ (length $L = 0.2$ m and width $B = 0.2$ m); $V_0 = 10$ m/s; $\rho = 1.25\ \text{kg/m}^3$ (at temperature 10°C).

Results of simulation for control action by angle $\beta = \frac{\pi}{2.5}\sin(7t)$ are presented in **Figures 4** and **5**.

Average power P_a (**Figure 5**) is presented as percentage of maximal power, which can be achieved under the plate's velocity less than one third of flow velocity.

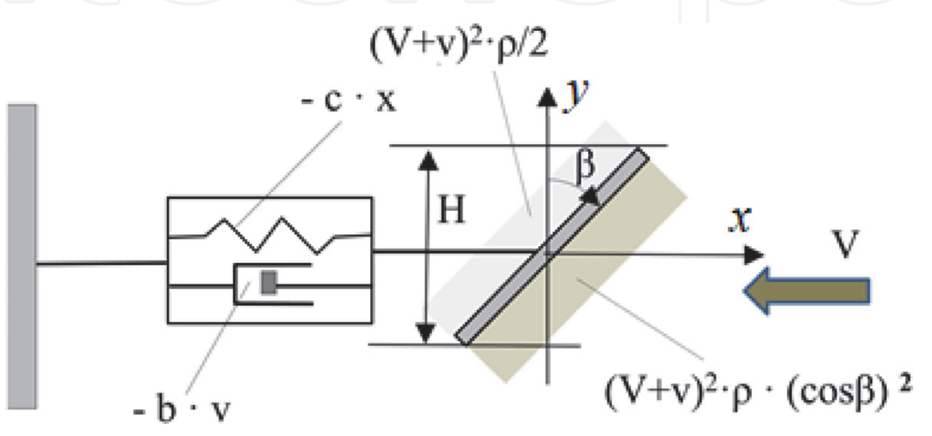

Figure 3.
Model of thin flat plate to obtain renewable energy from air flow.

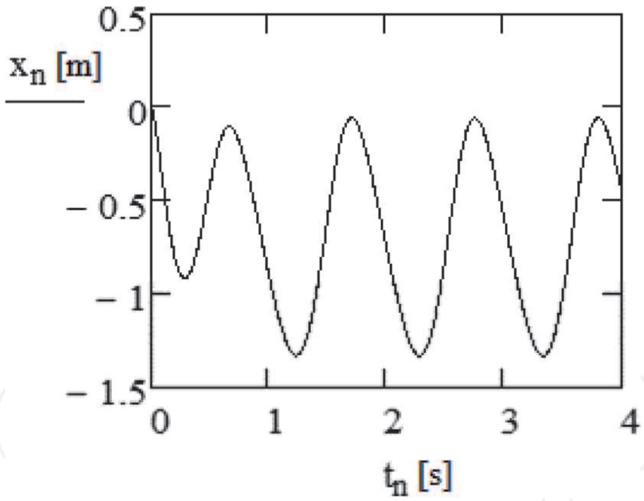

Figure 4.
Displacement x as function of time t.

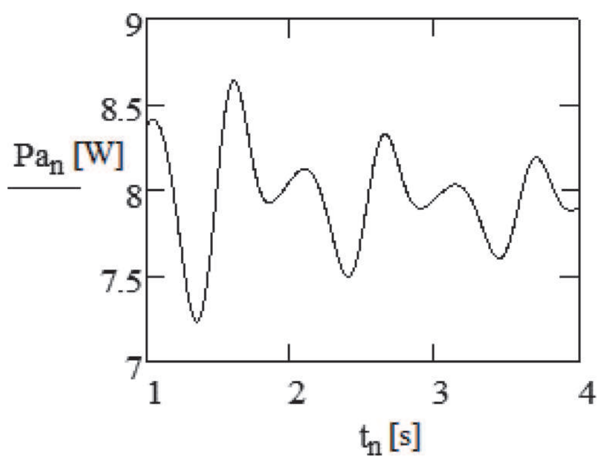

Figure 5.
Average power P_a of generator force $b\dot{x}$ during short transient process (t = 4 s).

Results of simulation for the case of control action on the system by harmonic variation of angle β (**Figures 4** and **5**) are as follows:

- stationary regime of motion occurs very quickly, practically within two to three cycles;
- it is possible to synthesize the optimal parameters of the system (for example, stiffness c, area A, frequency and amplitude of action, etc.), which would provide the maximum power within the given limitations;
- further increasing of the efficiency can be achieved by the use of more complex control variation of angle β (biharmonic, polyharmonic, etc.).

Results of simulation of plate's motion for the case of control action by velocity $V = V_0[2 - 0.5\sin(10t)]$ are presented in **Figures 6** and **7** (it is assumed that $V_0 = 10$ m/s).

As it is seen from the analysis of graphs presented (**Figures 6** and **7**), almost stationary oscillatory regime with maximal average power P_a can be achieved after some cycles of transient process.

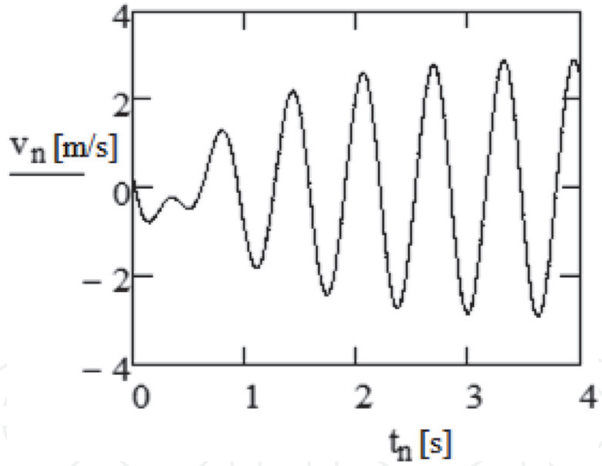

Figure 6.
Velocity v of plate's central point as function of time t.

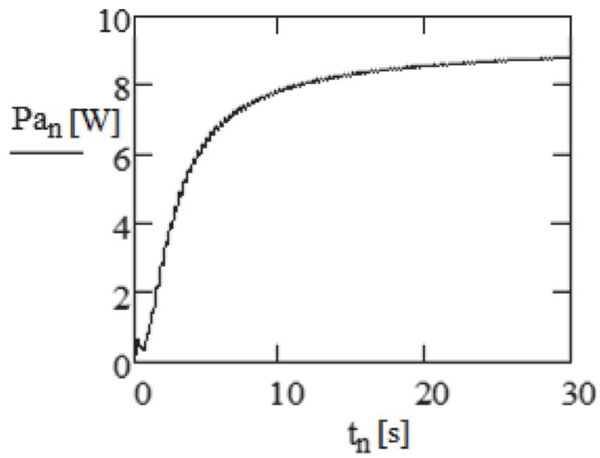

Figure 7.
Average power P_a of generator force $b\dot{x}$ during long transient process (t = 30 s)

Results of simulation for the case of control action on the system by harmonic variation of velocity V (**Figures 6** and 7) are as follows:

- a new opportunity to generate energy by the harmonic variation of flow rate is discovered;

- new variants of control action on the system by the flow rate variation using more complex laws (biharmonic, polyharmonic, etc.) are opened for the further research.

4. Parametric optimization of flat plate translational motion

The model of air flow interaction with flat plate is shown in **Figure 8**. In the given optimization problem, the power P generated due to action on the plate of air flow with velocity V is of interest. Parametric optimization aims to achieve maximum power P (criterion) providing plate's translational motion with constant speed u and in condition of braking with force Q (parameter).

In accordance with Eq. (6), the motion of a thin plate (d = 0) is described by the following differential equation:

$$m\ddot{x} = LB\rho(1+C)[V\sin(\gamma-\alpha) - \dot{x}\sin(\alpha)]^2 \cdot \text{sign}(V\sin(\gamma-\alpha) - \dot{x}\sin(\alpha))\sin(\alpha) - Q, \tag{11}$$

where m is mass of the plate; L and B are dimensions of the plate; α and γ are angles of flow and plate orientation against x axis.

The optimization task is solved under the condition of plate motion with a constant velocity $\dot{x} = u$. In this case, using Eq. (11), the braking power P of force Q can be expressed in the following form:

$$P = LB\rho(1 + C)[V\sin(\gamma - \alpha) - u\sin(\alpha)]^2 \cdot \text{sign}(V\sin(\gamma - \alpha) - u\sin(\alpha))u\sin(\alpha). \quad (12)$$

Parametric optimization problem was solved on the base of analysis of Eq. (12) with the aid of program MathCad. The aim of the optimization: to look for the parameters u, α, and γ that give the maximum power P at specified limits. The example of response surface for the criterion P as a function of plate angle α and velocity u is shown in **Figure 9**. In addition, **Figure 10** presents the section of this response surface corresponding to the constant velocity u = 8 m/s.

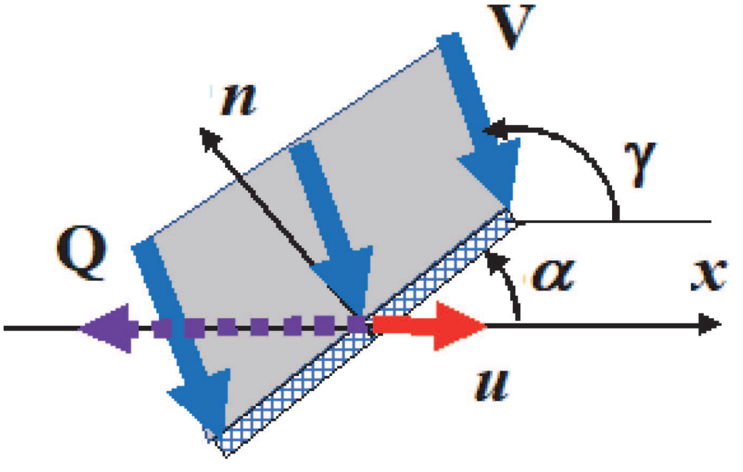

Figure 8.
Optimization model: V–air flow velocity; u–velocity of flat plate translation motion; and n–normal axis relative to plate.

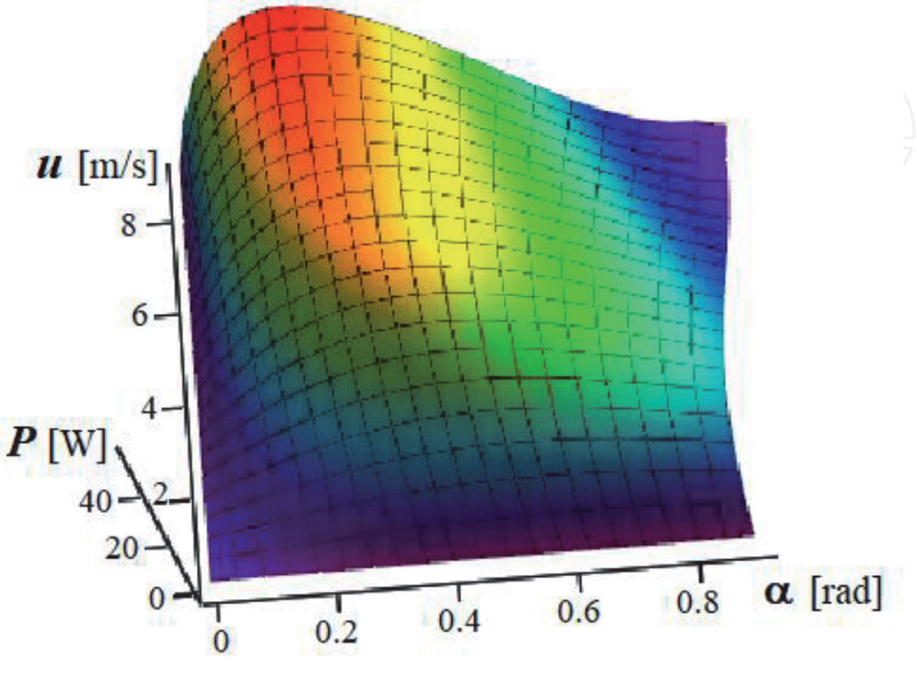

Figure 9.
Response surface for the optimization criterion P as a function of plate angle α and velocity u (for the case of L = 0.5 m; B = 0.5 m; ρ = 1.25 kg/m³; C = 0.5; V = 10 m/s; γ = π/2 rad).

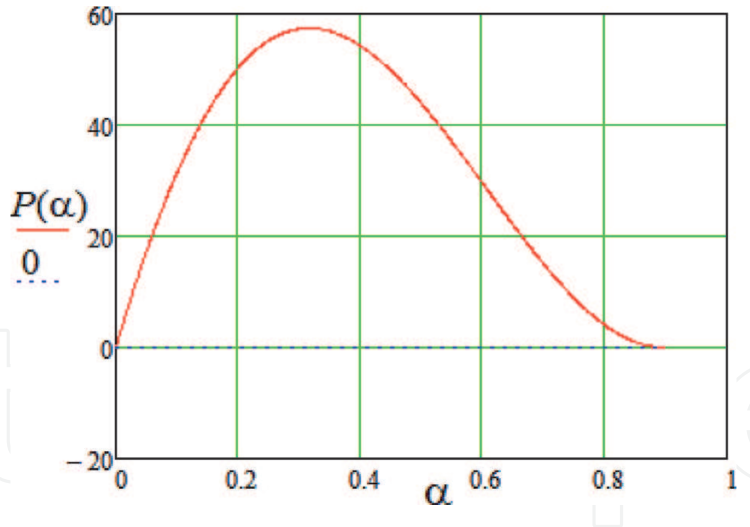

Figure 10.
Section of the response surface $P(\alpha, u)$ corresponding to the constant velocity u = 8 m/s.

The analysis of Eq. (12) shows that there is an extreme change of criterion P under the parameter u corresponding to the following condition:

$$u = \frac{V \sin(\gamma - \alpha)}{3 \sin(\alpha)} \tag{13}$$

Under the velocity u corresponding to the condition (13) the maximal power P is achieved:

$$Pmax = \frac{4C_0 V^3 [sin\,(\gamma - \alpha)]^3}{27}, \tag{14}$$

where $C_0 = LB\rho(1 + C)$.

For the other initial data, the optimal parameters must be sought numerically.

5. Wind energy conversion device with controlled orientation of blades to air flow

Efficiency of energy conversion at great extent is dependent on blade's orientation relative to air flow. In majority of existing air flow devices, there is no possibility for special change of blade's orientation relative to air flow during rotation of main wheel, and therefore, position of blade can be optimal only in specific time instants [2].

Special variation of flat blade's turning angle during rotation of main wheel is realized in the device described in [10]. But interrelation between turning angles of blade and main wheel are not optimal in this device. Due to this, potential possibilities to increase efficiency of energy extraction are not fully realized.

Theoretical analysis of air flow interaction with rotating flat blade in different aerodynamic conditions is considered in [11, 12]. It is shown that position of blade is optimal, if resulting aerodynamic force gives maximal torsion moment about longitudinal axis of main wheel.

This section deals with the determination of optimal control law for variation of blade's turning angle during rotation of central wheel.

5.1 Analysis of air flow interaction with flat blade

The considered model of air flow device is shown in **Figure 11**. Flat blades 2 are hinged to the rotor 1, besides longitudinal axes O_1 and O_2 of rotor and blades are mutually parallel. Position of blade 2 relative to air flow is given by angle α, but rotation of 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 [13], flat blade 2 placed in air flow is subjected to action of aerodynamic force R (**Figure 11**). Force R can be resolved into two components: drag force F_x (acts along flow direction) and lift force F_y (acts in direction perpendicular to air flow). The following formulae are used to calculate these forces [14]:

$$F_x = 0.5 C_x A \rho V^2;\ F_y = 0.5 C_y A \rho V^2 \tag{15}$$

where C_x and C_y–dimensionless drag and lift aerodynamic coefficients; A–area of blade's working surface; ρ–density of air medium; and V–velocity of air flow.

Aerodynamic coefficients C_x and C_y are dependent on blade's geometry, its orientation relative to air flow and dimensionless Reynolds number [13]. Coefficients C_x and C_y for the considered flat blade were determined experimentally in wind tunnel ARMFIELD. Principle diagram of experimental setup is shown in **Figure 12**.

During experiments, angle α between air flow and blade's flat surface was varied from 0° (working surface of the blade is parallel to air flow) to 90° (working surface of the blade is perpendicular to air flow), while the air velocity varies from 5 to 20 m/s. 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 (**Figure 12**). After that, dimensionless aerodynamic coefficients C_x and C_y were calculated using Eq. (15).

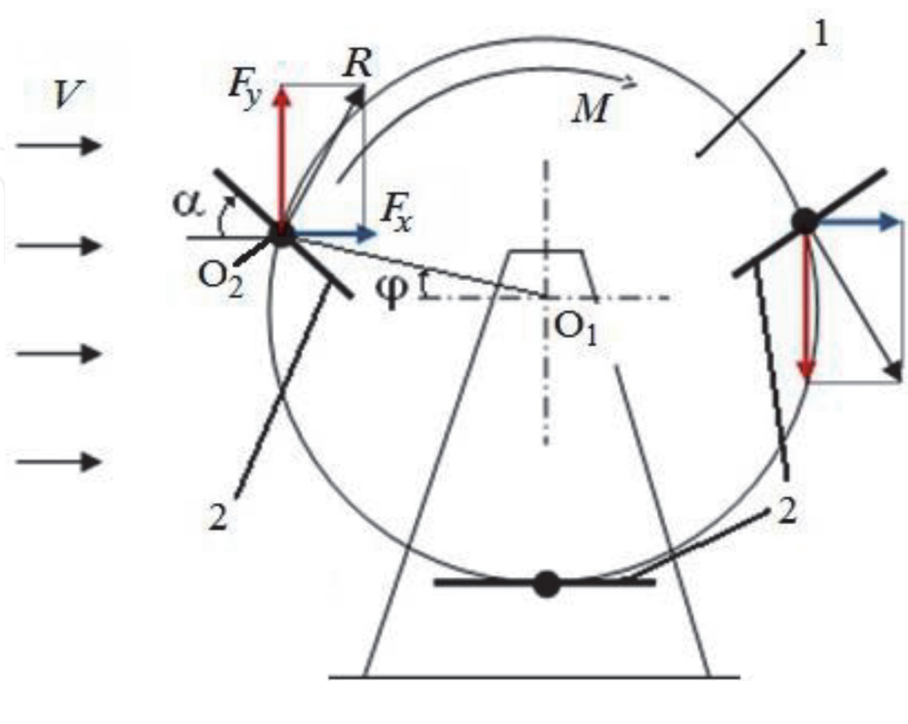

Figure 11.
Principle model of wind device: 1–central wheel; 2–flat blade.

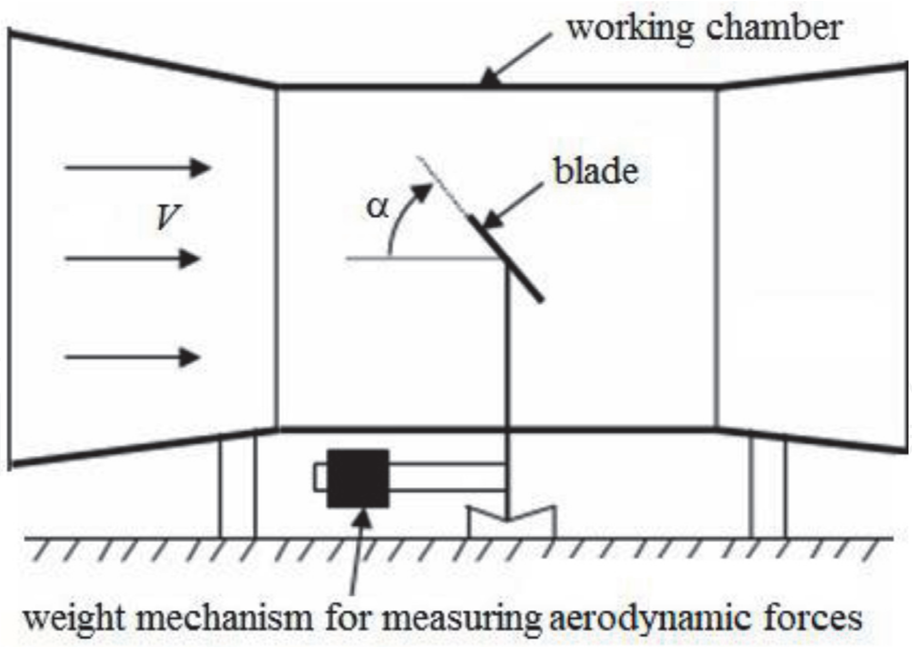

Figure 12.
Diagram of experimental setup.

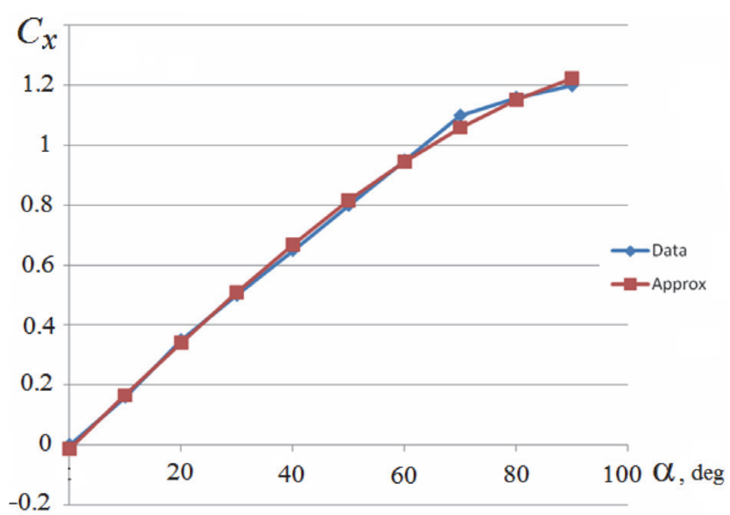

Figure 13.
Drag aerodynamic coefficient C_x as function of the incidence angle α.

On the base of mathematical processing of experimental results, coefficients C_x and C_y are plotted as functions of angle α (**Figures 13** and **14**, blue lines). To simplify the application of experimental data in engineering calculations, approximation of curves $C_x(\alpha)$ and $C_y(\alpha)$ is made (**Figures 13** and **14**, red lines) using program EXCEL.

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

$$C_x(\alpha) = 1.31 \sin(0.0137\alpha) - 0.01 \tag{16}$$

$$C_y(\alpha) = -0.5094 \sin(0.00315\alpha - 0.28318)\alpha^{0.6143} \tag{17}$$

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

$$C(\propto) = \sqrt{[C_x(\propto)]^2 + [C_y(\propto)]^2} \tag{18}$$

DOI: http://dx.doi.org/10.5772/intechopen.90819

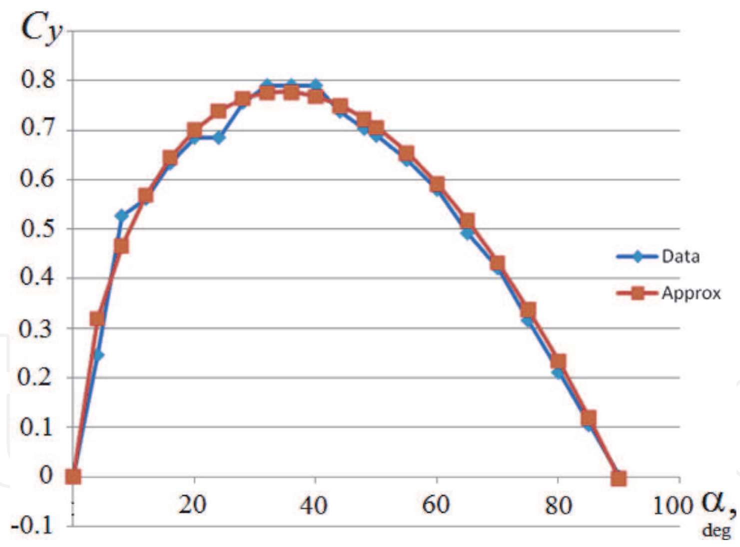

Figure 14.
Lift aerodynamic coefficient C_y as function of the incidence angle α.

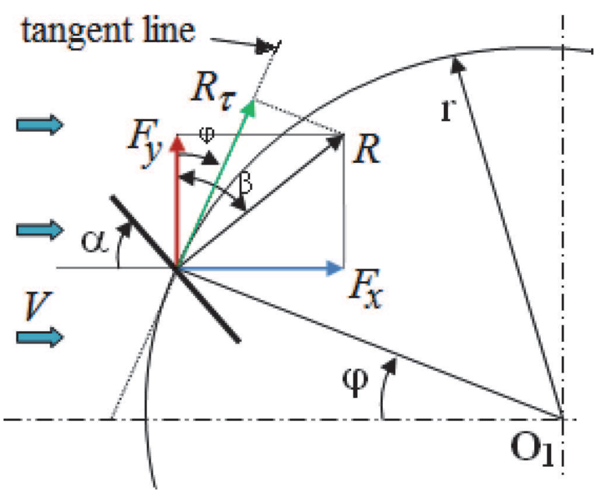

Figure 15.
Decomposition of aerodynamic force R on components.

For each value of rotor's turning angle φ, it is necessary to find the optimal incidence angle α. Angle α is considered as an optimal, if resulting aerodynamic force R gives maximal torsional moment M about longitudinal axis O_1 of the rotor (**Figure 15**). 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 resulting aerodynamic coefficient C.

Projection of resulting coefficient C on tangent line can be determined by formula (**Figure 15**)

$$C_r(\alpha) = C\cos(\beta - \varphi), \tag{19}$$

where $\beta = \mathrm{arctg}\left[C_x(\alpha)/C_y(\alpha)\right]$ the angles between vectors $\vec{R}$ and $\vec{F_y}$.

Optimal values of angle α were calculated with computer program MathCad using Eqs. (16)–(19). Calculations were made varying a turning angle φ of rotor from 0° till 360° with the step $\Delta\varphi$ = 5°. The results of calculations are presented in **Table 1**.

Using data of **Table 1**, a graph $\alpha = f(\varphi)$ is plotted (**Figure 16**). Curve $\alpha = f(\varphi)$ can be used in designing of wind devices to determine optimal positions of blade (angle α) for different possible values of rotor's turning angle φ.

φ[deg]	α[deg]	φ[deg]	α[deg]	φ[deg]	α[deg]	φ[deg]	α[deg]
0	35	90	90	180	145	270	180
5	37	95	91	185	148	275	180
10	39	100	92	190	150	280	181
15	41	105	93	195	152	285	182
20	43	110	99	200	154	290	183
25	46	115	105	205	156	295	185
30	49	120	110	210	158	300	188
35	52	125	115	215	160	305	190
40	55	130	119	220	163	310	193
45	58	135	122	225	165	315	195
50	61	140	126	230	167	320	197
55	65	145	129	235	170	325	200
60	70	150	132	240	172	330	202
65	75	155	134	245	175	335	204
70	81	160	137	250	177	340	206
75	87	165	139	255	178	345	208
80	88	170	141	260	179	350	210
85	89	175	143	265	180	355	212
90	90	180	145	270	180	360	215

Table 1.
Interconnection between rotor's turning angle φ and incidence angle α.

5.2 Prototype model of air flow device

To achieve maximal efficiency of wind energy transformation, it is necessary to take into account earlier determined optimal relations between turning angles φ and α (**Figure 16**). But exact curve $\alpha = f(\varphi)$ is a nonlinear one, therefore its practical realization in wind devices is very difficult.

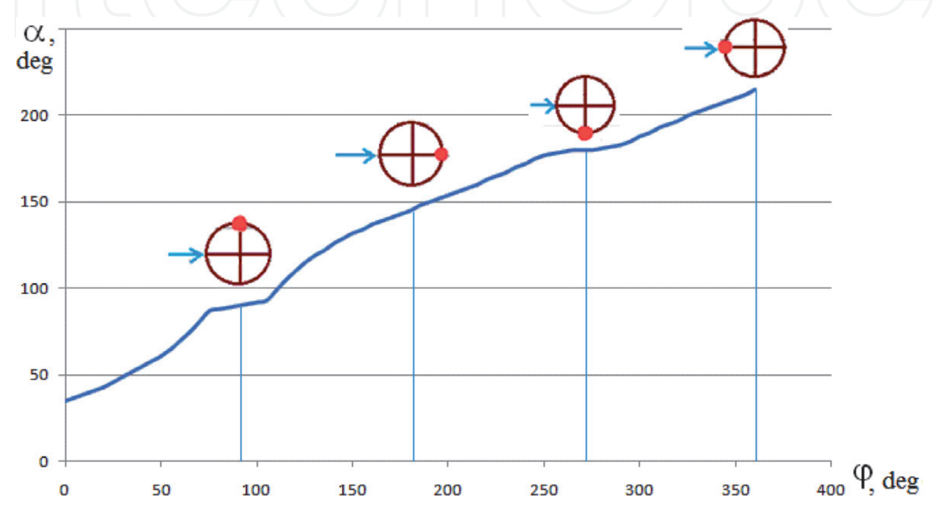

Figure 16.
The relationship between the optimal incidence angle α and rotor's turning angle φ.

To simplify practical realization of optimal angles α in real mechanisms, it is proposed to use linear approximation of exact (experimental) curve $\alpha = f(\varphi)$. Exact and approximated curves $\alpha = f(\varphi)$ are compared graphically in **Figure 17**.

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

$$\alpha = 45° + 0.5\varphi = \pi/4 + 0.5\varphi \qquad (20)$$

As follows from Eq. (20), one revolution of blade takes place after two whole revolutions of 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 (20) has been evaluated. For this purpose, values of angle α determined by formula (20) were inserted into the earlier used mathematical model (16)–(19). 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 **Figure 17**, approximate value of angle α during some stages of rotor motion is slightly smaller than optimal one, but in some other stages–a little more of it. Therefore, on average in one revolution, the difference between approximate and optimal values of angle α (or between generated powers) will be very small.

Besides, application of linear approximation (20) makes it possible to simplify practical realization of optimal operation regime in wind device. In accordance with Eq. (20), ratio of angular rotation frequencies between 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 (20) in designing of wind device.

Kinematic diagram of the proposed air flow device is shown in **Figure 18**. Flat blade 2 is hinged to the rotor 1. Besides, longitudinal axes O_1 and O_2 of rotor and blade are mutually parallel and kinematically connected each other with belt transmission 3. Belt pulley 4 is attached to blade 2, but pulley 5–to rotor 1. And in accordance with Eq. (20), angular rotation frequency ratio between rotor 1 and blade 2 is taken as 2.

To follow possible changes of air flow direction, the proposed device is equipped with tail 6 fastened to pulley 5. Due to the change of air flow direction, tail 6 is turned till becomes parallel to air flow. Simultaneously pulley 5 and rotor 1 are also turned, as the result blade 2 takes optimal orientation to air flow. The proposed method for energy extraction from air flow and device for its realization are patented [15].

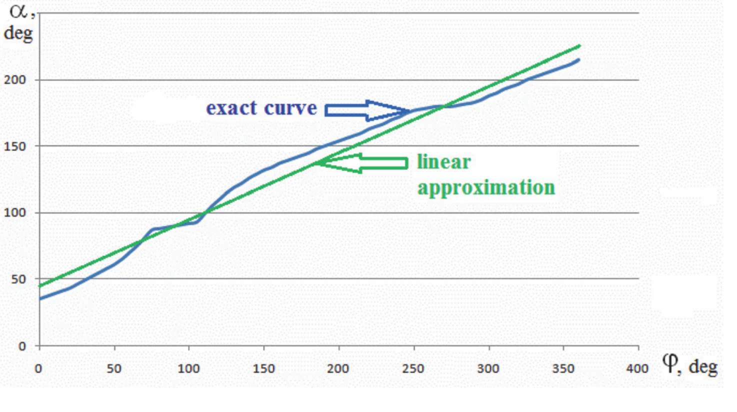

Figure 17.
Relationship between angles φ and α (experimental exact curve and its linear approximation).

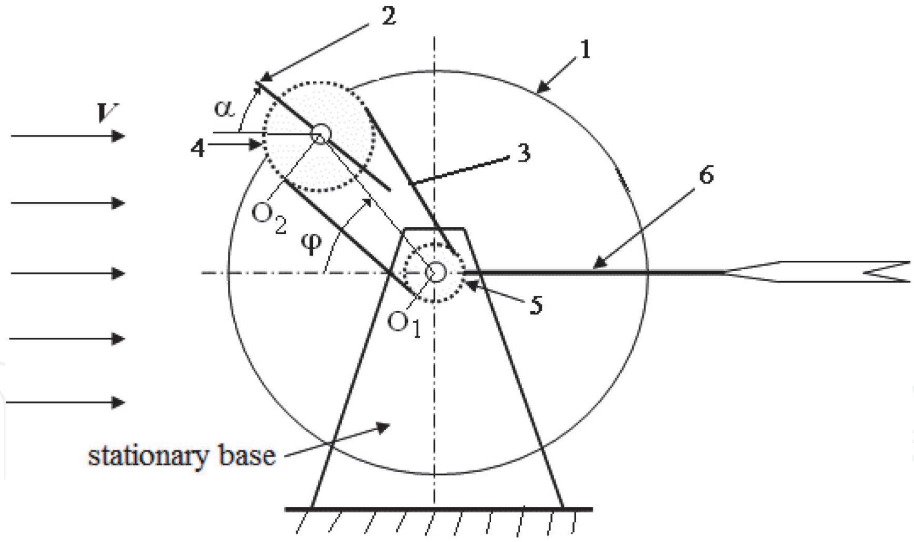

Figure 18.
Kinematic diagram of air flow device: 1–rotor; 2–flat blade; 3–belt transmission; 4 and 5–pulleys; 6–tail.

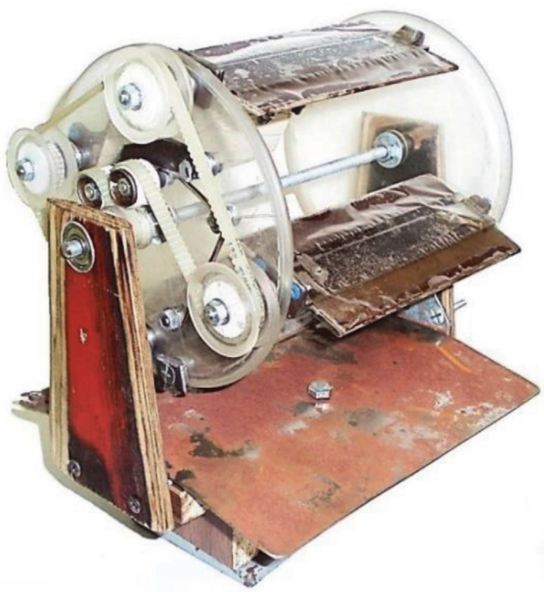

Figure 19.
Prototype model of wind energy conversion device.

In accordance with the proposed kinematic diagram, a prototype model of wind device is made (**Figure 19**).

Prototype model of wind device (**Figure 19**) contains four identical flat blades, which are kinematically connected with rotor by a toothed belt transmission. Ratio of angular rotation frequencies between rotor and blades is taken as 2; due to this the orientation of blades relative to air flow is changed in accordance with condition (20).

Experiments with prototype device are made in wind tunnel ARMFIELD (**Figure 20**). Stable and effective operation of the device is demonstrated for the range of flow velocities from 5 till 20 m/s.

Experimental investigations confirm the principal possibility to increase with the proposed method the angular velocity of central wheel and extracted power from air flow under the same wind velocity (in comparison with traditional air flow devices [14]).

Besides, experiments indicate on some shortcomings in operation of the prototype model shown in **Figure 19**. These shortcomings became especially evident with the increasing of number of blades. In such case the front blade (from the air flow side) can interfere for propagation of air flow to rearward blades. Air flow arriving to rearward blades can change its direction and intensity. Forming of air vortexes inside the space between blades has become possible. All these factors have negative influence on the efficiency of wind energy transformation.

In order to improve the efficiency of wind energy extraction, new design of air flow device is developed. Computer model of this wind device is shown in **Figure 21**.

Wind device contains three identical flat blades, which are fastened on axes hinged in central wheel. Blade's axes are kinematically connected with central rotor by a system of cylindrical gear transmission. In accordance with the condition (20), ratio of angular rotation frequencies between central wheel and blades is taken as 2. Besides, it is proposed to move blades relative each other along their rotation axes. Thanks to this, it became possible to make around each blade free space in radial direction for air flow access.

During rotation blades do not interfere each other (**Figure 21**). Each blade has its own open channel for passing of air flow. Therefore, application of this device will

Figure 20.
Experiments in wind tunnel ARMFIELD.

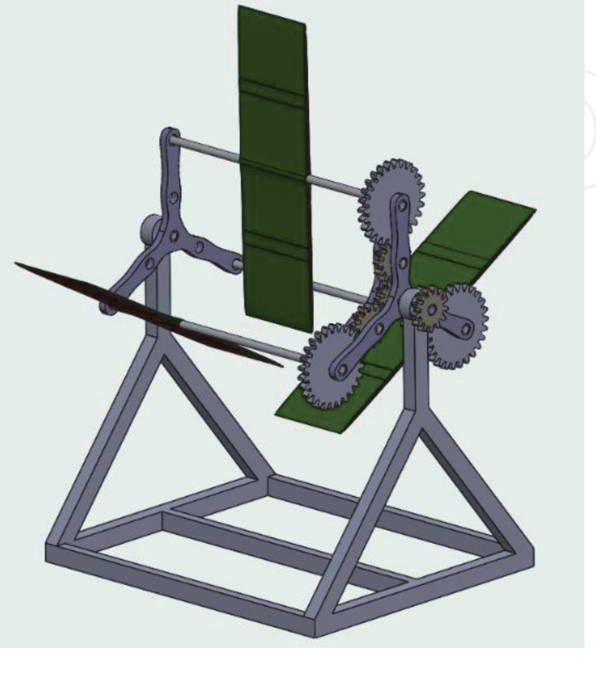

Figure 21.
New design of air flow device.

make it possible to increase the efficiency of wind energy transformation. More detailed quantitative analysis of operation of this device would be critical in the future.

6. Conclusions

New method for approximate analysis of air flow interaction with rigid body is developed. This method allows to solve problems of synthesis and optimization of wind devices in a simplified way, without using intensive and laborious space–time-programming procedures.

The aerodynamic drag and lift coefficients for flat blade are determined experimentally for different positions of blade relative to air flow.

Based on theoretical and experimental analysis, new designs of wind energy conversion devices with controllable orientation of flat blades to air flow are proposed.

A prototype model of the developed air flow device is given. Experiments confirm a serviceability of the device and efficiency of wind energy transformation.

Conflict of interest

The authors confirm that this section of monograph has no conflicts of interest.

Author details

Janis Viba, Vitaly Beresnevich* and Martins Irbe
Riga Technical University, Riga, Latvia

*Address all correspondence to: vitalijs.beresnevics@rtu.lv

References

[1] de Renzo DJ, editor. Wind Power: Recent Developments. Park Ridge, New Jersey: Noyes Data Corporation; 1979. 347p. ISBN: 9780815507598

[2] Dirba J, Levins N, Pugachevs V. Electromechanical Converters of Wind Energy (in Latvian). Riga: RTU Publishing House; 2006. 300p. ISBN: 9984320243

[3] Jiang H, Li Y, Cheng Z. Relations of lift and drag coefficients of flow around flat plate. Applied Mechanics and Materials. 2014;**518**:161-164. DOI: 10.4028/www.scientific.net/AMM.518.161

[4] Sears WR. Introduction to Theoretical Aerodynamics and Hydrodynamics. Reston: American Institute of Aeronautics and Astronautics; 2011. 150p. ISBN: 9781600867736

[5] Hossenfelder S. Is Space-Time Fluid? IAI News, Issue 59 [Internet]. 2017. Available from: https://iai.tv/articles/is-space-time-fluid-auid-897 [Accessed: 17 April 2019]

[6] Beal J, Viroli M. Space-Time Programming. Proceedings of the Royal Society A [Internet]. 2015. Available from: http://openmap.bbn.com/~jbeal/Publications/PTRSA2015-Space-Time-Programming-survey-preprint.pdf [Accessed: 15 April 2019]

[7] Meriam JL, Kraige LG, Bolton JN. Engineering Mechanics: Dynamics. 8th ed. New York: John Wiley& Sons; 2016. 736p. ISBN: 9781119044819 1119044812

[8] Tipans I, Viba J, Irbe M, Vutukuru SK. Analysis of non-stationary flow interaction with simple form objects. Agronomy Research Journal. 2019;**17**(S1):1227-1234. DOI: 10.15159/AR.19.083

[9] Vutukuru SK, Viba J, Tipans I, Viksne I, Irbe M. Analysis of flat plate vibrations by varying frontal area to the flow. In: Proceedings of 18th International Scientific Conference "Engineering for Rural Development". Jelgava: Latvia University of Life sciences and Technologies; 2019. pp. 1408-1414. DOI: 10.22616/ERDev2019.18.N147

[10] Elton LS. Windmill with Pivoting Blades. Patent US 7766602, USA, Int. Cl. F03D7/06/. Date of Patent: August 3, 2010

[11] Viba J, Eiduks M, Irbe M. Double pendulum vibration motion in fluid flow. In: Proceedings of International Conference "Engineering for Rural Development". Jelgava: Latvia University of Agriculture; 2015. pp. 434-439. ISSN: 1691-5976

[12] Viba J, Beresnevich V, Noskovs S, Irbe M. Investigation of rotating blade for energy extraction from fluid flow. In: Vibroengineering Procedia. Vol. 8. Kaunas: JVE International Ltd.; 2016. pp. 312-315. ISSN: 2345-0533

[13] Clancy LJ. Aerodynamics. New York: John Wiley & Sons; 1975. 610p. ISBN: 9780470158371

[14] Yanson RA. Wind Installations (in Russian). Moscow: Publishing House of Bauman MSTU; 2007. 36p. ISBN: 5-7038-2910-4

[15] Viba J, Noskovs S, Beresnevich V. Method for Control of Operation Condition of Wind Turbine and Device for Its Realization. Patent LV 15038, Republic of Latvia, Int. Cl. F03D7/06. Date of Patent: December 20, 2015