UDC 621.548(045)

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COMPUTER-AIDED DESIGN OF VERTICAL-AXIS WIND TURBINES

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Abstract**—***In the second chapter computer-aided system was offered for solution of the computer-aided design task. Two commercially-available computer-aided software, Kompas-3D and SolidWorks 2012, in combination with custom-developed "Rotor" program in Matlab environment were proposed to solve the task of preliminary vertical-axis rotor design. Aerodynamical aspects of vertical-axis wind turbines, as well as principle of action of lift-driven vertical axis wind turbines, were examined to formulate methodical basis for computer program.*

Index Terms—Vertical-axis wind turbine; computer-aided design.

I. INTRODUCTION

Wind energy is a very feasible and affordable source of renewable energy. Its rapid development worldwide is provided by research institutions and manufacturers that invest into green technology, trying to make it more efficient, simple, reliable, safe, versatile and cost-effective.

A lot multidisciplinary research was conducted in aerodynamics, aeroelasticity, flatter effects, strength of materials, composite technology, electromechanics, control systems, data acquisition systems aiming to improve service characteristics of wind energy stations.

In order to perform structural design, it was necessary to define the loads that act on a blade. This forced investigation of aerodynamics of vertical-axis wind turbine (VAWT) [1]. This study was only preliminary, and it overestimates the real performance of rotor. However, it makes possible to determine the amplitude- and sign-changing loads on a blade.

Vertical-axis wind turbines offer very simple control system solutions, can work at slow winds and accept wind from every direction, so this type of wind energy stations was selected for investigation in this work .

II. STATEMENT OF TASK FOR COMPUTER-AIDED VAWT ROTOR DESIGN

Design of VAWT is a complex and multidisciplinary task. VAWT functions due to complicated physical phenomena. Thus it is hard to calculate characteristics of such rotor directly. To easier the solution of task, computer-aided design software and calculation spreadsheets should be used.

The purpose of this work is to develop specific algorithms and program to manage calculations of VAWT rotor in steady-state mode. Aerodynamic, performance and structural aspects must be accounted. Level of complexity of algorithms and initial assumptions should be suitable for preliminary design of small-scale VAWT to be included into administrative buildings' electrical grid.

Input data:

– predefined rotor configuration with straight vertical blades mounted to the tower through support structure, consisting of struts or beams;

– definite airfoil data (wind-tunnel results and geometry);

– rotor diameter;

– blade geometry (span, chord, shape).

The result of work must include:

– preliminary calculations of rotor aerodynamics and performance in steady-state mode at prescribed conditions;

– calculations of blade loads;

– calculations of cross-sections of main structural elements of blade;

– calculations of the mass of blade;

– 3D-model of rotor;

– structural analysis of blade joints.

The task must be solved via specially developed software and/or available existing CAD software.

III. STRUCTURE OF COMPUTER-AIDED DESIGN SYSTEM

The design of wind tunnel is a complex multidisciplinary task, which involves aerodynamic, structural and performance calculations, 3D-modeling and 2D-drafting, preparation of material bills, technological process etc. This task cannot be directly solved by application of powerful CAD software without prior calculations of aerodynamics and structure. To solve the task it was decided to create spreadsheet, in other words "calculator" that will performed preliminary aerodynamic, structural and performance calculations, and then use CAD for 3D-modeling and mass calculations. After that 2D drawings can be created. SolidWorks was selected for 3D-modeling due to presence of skills and wide functionality of this software. Kompas-3D was use to make sketches and drawings from 3D-models exported from SolidWorks. Kompas-3D was chosen because it allows rapidly make drawings which satisfy all Power Standards of Ukraine requirements. "Rotor" program

http://ecs.org.ua

was developed in Matlab environment to perform preliminary VAWT rotor calculations. The structure of CAD complex, which solves the task of VAWT rotor design, is shown on Fig. 1.

"Rotor" program will perform calculations on the basis of next information:

– rotor dimensions (blade span, blade chord, rotor diameter etc.);

– mass estimate (guessed mass of rotor on the basis of statistical data)

– environmental conditions (wind speed, temperature, altitude etc.);

– parameters of motion (max. speed of rotation);

– strength of selected materials for each structural element.

SolidWorks CAD system will be used for 3D-modeling and checking of strength of separate parts using finite element method simulations. It will also give possibility to calculate mass precisely. If difference between mass estimate and calculated mass is big, calculations will have to be repeated and 3D-model to be corrected.

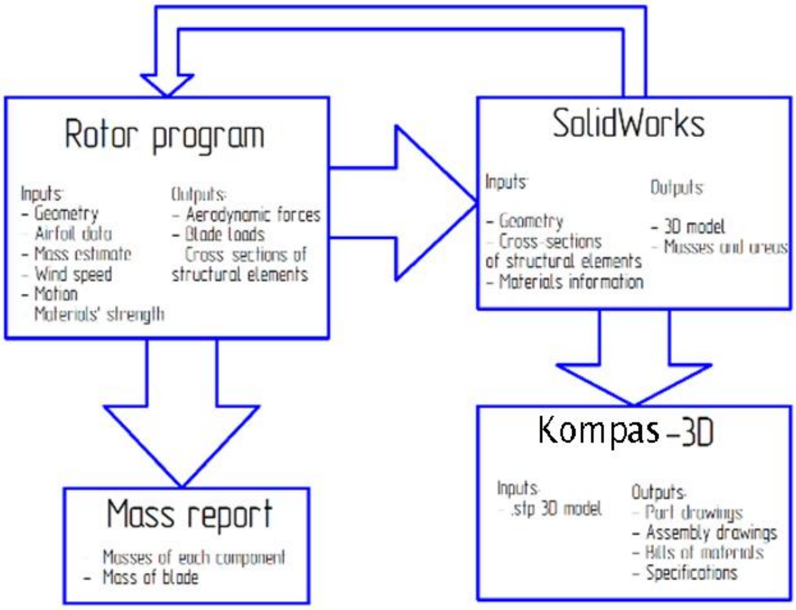

Fig. 1. Structural scheme of CAD system

After succeeding with 3D-model, it will be exported using one of universal CAD file formats, like .IGES or .STP. Kompas-3D will generate its own 3D-model out from exported file and help rapidly prepare drawings for each part and assembly.

Accounting mass of additional components (e.g. paint, glue) and using mass information from SolidWorks, the final mass report will be prepared.

Having all these steps done, one can start prototyping of VAWT rotor. All in all such combination of CAD software and custom-developed program will allow making quick preliminary design of VAWT. After that more complex and difficult research should be conducted on models, e.g. computational fluid dynamics (CFD) simulations, wind-tunnel tests, aeroelasticity study etc.

IV. Introduction to vertical axis wind turbines. Typical rotor constructions

This chapter describes the principle of work and aerodynamics of VAWT. For further investigation, it is necessary to define what factors to consider, and what can be neglected. So let's introduce several rules for the next chapters.

The task of automated design of VAWT rotor differs much from that of horizontal-axis wind turbine (HAWT) propeller-like rotors. Unlike the well-established theoretical and experimental basis for calculation of propeller-like rotors with axis of rotation parallel to wind direction, vertical-axis wind turbine blade are functioning more like a conventional wing of airplane than a propeller. Loads, acting on a blade of VAWT, try to bend it. Horizontal-axis wind turbine blades are mostly loaded by tension due to centrifugal forces. Central column of VAWT is loaded similarly to that of HAWT.

The design and development of VAWT is a multidisciplinary task, involving aerodynamics, aeroelasticity, dynamic response, structures, fatigue and acoustic studies. This thesis is mainly dedicated to preliminary design of VAWT and its' rotor calculation in steady-state working mode. Dynamic response and aeroelasticity are not investigated. Fatigue is examined partially for metal parts, mostly susceptible to cracks generation. Typical Darrieus-type wind energy station is illustrated below (Fig. 2).

Many lift-driven VAWT rotor configurations were developed, including:

– *O*-type Darrieus rotor;
– *H*-type rotor;
– Gorlov helical turbine;
– Savonius rotor;
– Multiblade giromill rotor;
– etc.

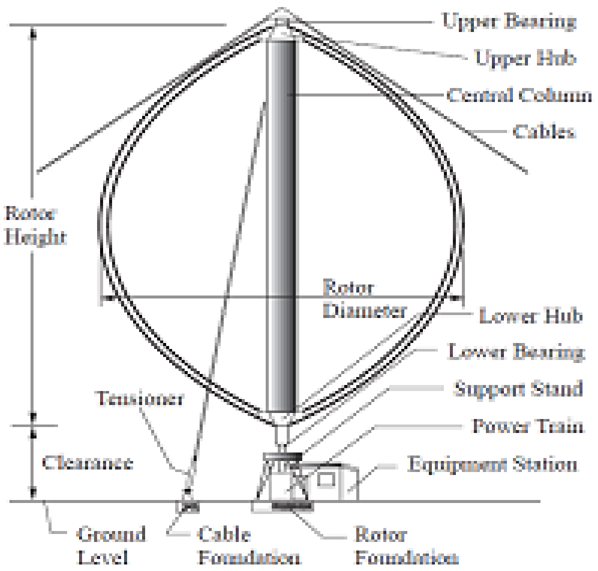

Fig. 2. Typical VAWT of Darrieus type

V. AERODYNAMICS OF VERTICAL-AXIS WIND TURBINES

Design assumptions

Design of wind turbine is rather difficult multidisciplinary task. Further design assumptions were taken to solve the task and finally make preliminary design:

1. Influence of the column on the airflow: obviously, the column generates wake, in other words – turbulent air stream, which influences the airflow around the blades. This factor is hard to account in the design of VAWT, so we will neglect it in further work. Wake from the column should be studied by means of CFD or in wind tunnel when performing detailed analysis of wind turbine.

2. Wake from the blades is neglected. This is rather rough assumptions, but it allows to solve the task without time-consuming and difficult CFD research or wind-tunnel tests. However, the performance of rotor will be overestimated.

3. Mass of blade is distributed uniformly along the blade span.

4. Rotation speed is assumed to be constant for each case. This corresponds to the case when wind turbine is connected to the general electric grid.

5. Turbulence is not considered in this work.

6. Aeroelasticity and dynamic behavior of structures are not investigated or accounted somehow, blades are assumed to be enough rigid in bending and torsion.

7. Air compressibility and wave drag are neglected, because blade airspeeds are low subsonic.

Airfoil and blade

Blade of VAWT drives the rotor due to lifting force, so airfoil solution is important aspect of rotor design. Because the blade has a positive angle of attack at the upwind side of the rotor and a negative angle at the downwind side, one has to use symmetrical airfoils like the NACA 0015 [2]. Important characteristics for selection of airfoil are maximal C_y/C_x, $C_{y\,\max}$, $\alpha_{\max}$ [3]. Let's examine the forces that act on the wing of infinite span.

Lift and drag forces **Y** and **X** compose total aerodynamic force **R**, which can be projected on chord line and on a line perpendicular to chord line passing through Aerodynamic Center (AC). Thus vector **R** can be expressed through sum of *N* and *T*, which are called normal and tangential forces respectively (Fig. 3).

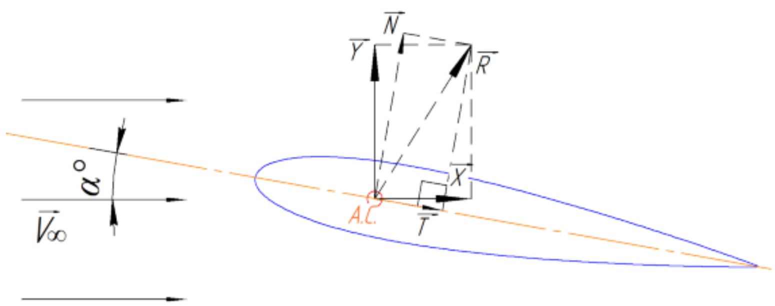

Fig. 3. Aerodynamic forces acting on the wing

Dynamic pressure is expressed as follows:

$$q = \frac{\rho V_\infty^2}{2}.$$

Lift and drag forces:

$$Y = C_Y qS; \qquad X = C_X qS.$$

Tangential and normal forces:

$$T = C_T qS = (C_Y \sin\alpha - C_X \cos\alpha) qS;$$

$$N = C_N qS = (C_Y \cos\alpha + C_X \sin\alpha) qS.$$

Pitching moment is calculated as follows:

$$M = C_m qSb; \qquad C^{\alpha}_{Y_{\alpha\infty}} = \frac{dC_Y}{d\alpha}.$$

Aerodynamic forces are applied in a point called Center of Pressure. However, for a symmetrical airfoil within average range of angles of attack Center of Pressure coincides with AC. Pitching moment of wing does not change relatively AC while the lift force changes linearly. Pitching moment is determined relatively leading edge of the wing in Soviet sources, in Russia, Ukraine etc., and relatively the point 0.25b rear from the wing leading edge in American and German sources. Center of Pressure coordinate can be calculated using next formula:

$$x_{C.P.} = \frac{C_M}{C_N} b = \frac{C_M}{(C_Y \cos\alpha + C_X \sin\alpha)} b.$$

For a given airfoil, aerodynamic properties are usually presented on plots $C_Y(\alpha)$, $C_M(\alpha)$, $C_Y(C_X)$ or in table form. These data corresponds to the wing of infinite span. Note the difference between the characteristics of wings having infinite and finite wing span (Figs 4, 5).

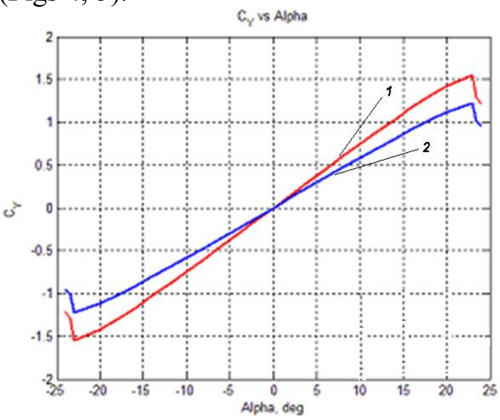

Fig. 4. NACA 0015 symmetric airfoil and wing lift curves at Re = 1.5·10^3: *1* is the Airfoil; *2* is the Wing, AR = 8

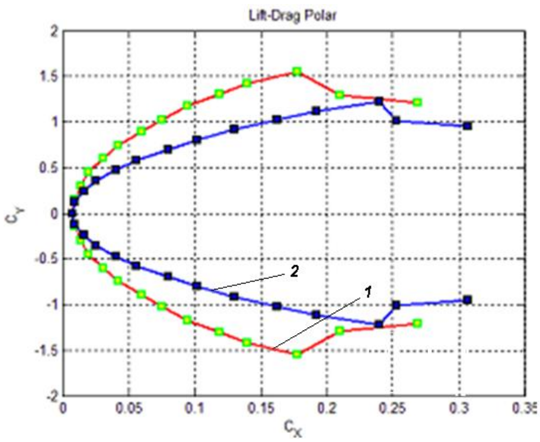

Fig. 5. NACA 0015 symmetric airfoil and wing lift-drag polars at Re = 1.5·10^3: *1* is the Airfoil; *2* is the Wing, AR = 8

Blade lift and drag

When rotor rotates the angle of attack α varies strongly (Fig. 6) and therefore the lift, the drag and the C_Y/C_X ratio vary strongly too. During the parts of the revolution where the blade moves about parallel to the wind there is only drag and the torque is negative, that means it is slowing down the rotor. Therefore the maximum power coefficient C_P is about 0.35 for big rotors [2].

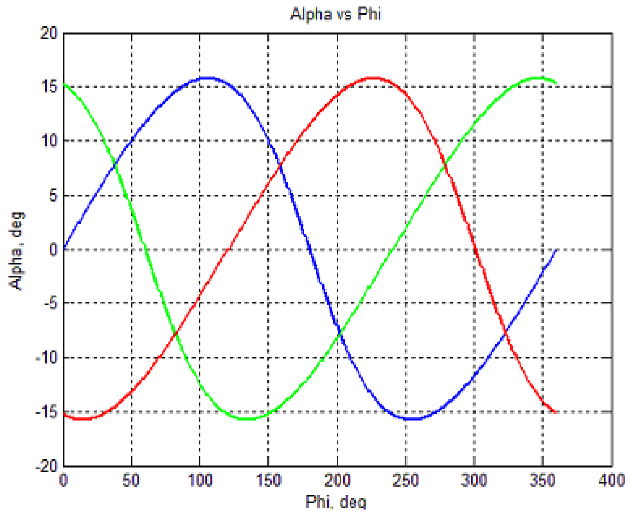

Fig. 6. Angle of attack oscillations on 3 rotor blades throughout complete revolution of rotor

Vertical-axis wind turbine blade has finite span. Due to this fact, induced drag (due to lift) adds to profile drag from table and the maximum lift of the blade is lower than that for airfoil. In this chapter for simplicity “the blade” term is changes to “the wing” because most of used formulas and dependencies come from aerospace literature.

NACA 0015 airfoil wind tunnel data

α	C_{Xf}	C_{Yf}	C_m
0	0,0077	0	0
2	0,0090	0,15	0,0360
4	0,0140	0,30	0,0715
6	0,0200	0,45	0,1070
8	0,0310	0,60	0,1430
10	0,0420	0,74	0,1760
12	0,0600	0,89	0,2120
14	0,0750	1,02	0,2430
16	0,0950	1,17	0,2790
18	0,1190	1,30	0,3100
20	0,1400	1,42	0,0338
23	0,1780	1,55	0,3690
23,5	0,2100	1,29	0,3670
24	0,2690	1,21	0,3630

Main geometric characteristics of wing are aspect ratio $\lambda_{AR} = \frac{l^2}{S}$, wing sweep angle χ and wing taper ratio $\eta = \frac{b_{tip}}{b_{root}}$ (ratio of wing tip chord to wing).

$$C_{Y_\alpha}^{\alpha} = \pi\lambda_{AR}\mu_k A; \qquad \mu_k = \frac{C_{Y_{\alpha\infty}}^{\alpha} b_{root}}{4l}.$$

Generally lift coefficients for wing of high aspect ratio can be calculates from airfoil data as follows:

$$C_{Y_W} = C_Y \frac{C_{Y_\alpha}^{\alpha}}{C_{Y_{\alpha\infty}}^{\alpha}}.$$

Induced drag is a function of C_Y [4]. Next equation describes blade's total drag coefficient:

$$C_{X_i} = KC_Y^2.$$

K is coefficient that accounts wing shape. It can be estimated using Oswald's span efficiency factor e [4, p. 299] for straight wing:

$$e = 1.78\left(1 - 0.045\lambda_{AR}^{0.68}\right) - 0.64;$$

$$K = \frac{1}{\pi\lambda_{AR}e}.$$

Total wing drag can be calculated by summing induced and profile drag at each angle of attack:

$$C_X(\alpha) = C_{Xf}(\alpha) + C_{Xi}(C_{Y_W}).$$

Blade rotary motion in airstream

Figure 7 illustrates how the flow stream direction is obtained by summing the vectors of wind speed V and linear speed of blade rotation U. Lifting force is decomposed in two components, Y_t and Y_n Namely Y_t provides torque for the rotor.

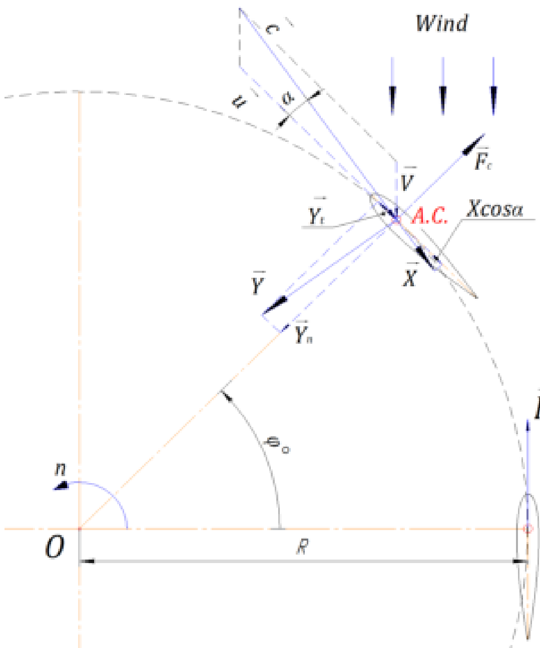

Fig. 7. Forces acting on VAWT rotor blade

Total tangential force transferred to the rotor column by the blade equals $Y_t - X\cos\alpha$.

The tip-speed ratio:

$$\lambda = \frac{\pi D n}{60V}.$$

Airflow velocity relatively blade varies by next dependence:

$$c = V\sqrt{(\lambda + \cos\varphi)^2 + (\sin\varphi)^2}.$$

Finally, the tangential force of rotor blade can be expressed as:

$$Y_t = Y\sin\alpha - X\cos\alpha$$

$$= \frac{\rho S c^2 \left(C_Y \sin\alpha - C_X \cos\alpha\right)}{2}. \qquad (1)$$

Angle of attack can be calculated as follows:

$$\alpha = \tan^{-1}\left(\frac{\sin\varphi}{\lambda + \cos\varphi}\right).$$

Let's substitute velocity c from (1) into formula:

$$Y_t = \frac{\rho S V^2}{2}\left(C_Y \sin\alpha - C_X \cos\alpha\right)$$

$$\times\left[(\lambda + \cos\varphi)^2 + (\sin\varphi)^2\right].$$

Torque of VAWT rotor as a function of rotation angle is calculated as follows:

$$T(\varphi) = \frac{DY_t(\varphi)}{2}.$$

Power and torque are connected as:

$$P(\varphi) = \frac{\pi n T(\varphi)}{30}.$$

Figure 8 illustrates general physical pattern of how torques of each blade vary during rotor rotation. The total rotor torque is obtained by superposition of torques of each blade. Figure 9 illustrates how aerodynamic forces act on a single rotor blade. Tangential component of lift force, Y_t, is the driving force for rotor rotation.

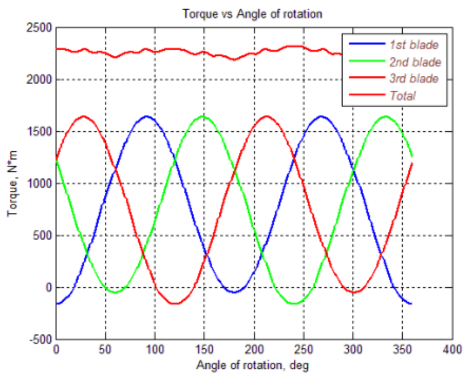

Fig. 8. Torque oscillations throughout full rotor revolution

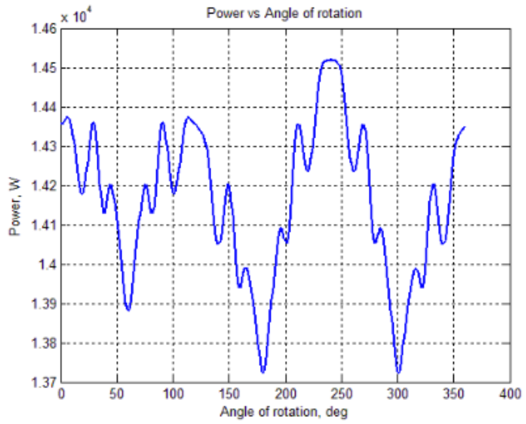

Fig. 3. 9. Example of power oscillations throughout complete rotor revolution

Figure 10 illustrates behavior of the velocities *V*, *U* and *C* which attack the blades of a VAWT rotor during a complete rotation around its vertical axis.

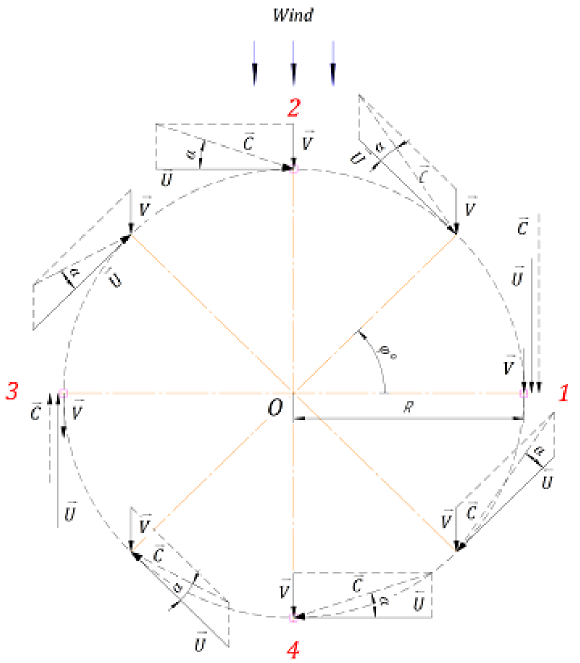

Fig. 10. Behavior of the velocities *V*, *U* and *C* which attack the blades of a VAWT rotor during a complete rotation around its vertical axis

VI. Conclusions

The task of computer-aided design of vertical axis wind turbine was solved by using a combination of available commercial software and custom developed program in Matlab environment. The program performs preliminary calculations of 3-blade VAWT rotor, including aerodynamics, performance and strength, on the basis of information about rotor geometry, airfoil aerodynamic properties, structural materials and environmental conditions. Performance is overestimated due to neglecting of blade wake, effects of tower and blade support structure.

The developed computer-aided system is suitable for initial sizing and preliminary design of VAWT rotors. Detailed design of rotor was performed in CAD software SolidWorks 2012. Drawings can easily be generated in Kompas-3D in correspondence with Ukrainian standards.

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Received 25 May 2014.

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А. В. Кульбака. Автоматизоване проектування вітроенергетичних установок з вертикальною віссю

Запропоновано автоматизовану систему для вирішення завдання автоматизованого проектування. Розв’язано задачу попереднього конструювання ротора з вертикальною віссю використовуючи комерційно доступне комп’ютерне програмне забезпечення Компас-3D і SolidWorks 2012, у поєднанні із спеціально розробленою в середовищі Matlab програмою «Ротор». Розглянуто аеродинамічні аспекти та принцип дії вітроенергетичних

установок з вертикальною віссю, які працюють від підйомної сили, і сформульовано математичні основи для комп'ютерної програми.
Ключові слова: вертикальна вісь вітроенергетичної установки; системи автоматизованого проектування.

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Освіта: Національний авіаційний університет, Київ, Україна (2011).
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А. В. Кульбака. Автоматизированное проектирование ветроэнергетических установок с вертикальной осью

Предложена автоматизированная система для решения задачи автоматизированного проектирования. Решена задача предварительного конструирования ротора с вертикальной осью используя коммерчески доступное компьютерное программное обеспечение Компас-3D и SolidWorks 2012, в сочетании со специально разработанной в среде Matlab программой «Ротор». Рассмотрены аэродинамические аспекты и принцип действия ветроэнергетических установок с вертикальной осью, которые работают от подъемной силы, и сформулированы математические основы для компьютерной программы.
Ключевые слова: вертикальная ось ветроэнергетической установки; системы автоматизированного проектирования.

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