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OPTIMAL SELECTION OF WIND TURBINE BLADE PROFILE

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Abstract*—The paperis devoted to vertical axis wind turbine combined rotor blade profile optimal selection. It includes the description of wind turbine optimization parameters, the statement of multicriteria optimization problem and the description of hybrid optimization algorithm.*

Index Terms—Combined rotor; wind turbine; vertical axis of rotation; blade profile; optimization.

I. INTRODUCTION

Modern wind energy is mainly based on the use of wind power plants (WPP) of the two main types with horizontal and vertical (VA) (or orthogonal) axis of rotation.

Vertical axis wind power installations are divided into two classes: Savonius and Darrieus rotors.

Darrieus rotor operates due to the torque from the lift of the blades. Therefore, the rotor can produce large enough power compared with rotors that use blades drag. Vector amounts of oncoming flow speed and the peripheral speed of blades rotation creates an angle of attack relative to the blade chord. Darrieus rotors peripheral speed exceeds the speed of oncoming flow. Since the blade must create lift when moving in both directions, its symmetrical profile shape is selected. According to this Darrieus rotor can't start on its own. Usually at small rapidity values Darrieus rotor has small or sometimes even negative torque [1] – [3] so it is necessary to create combined rotors.

II. PROBLEM STATEMENT

The efficiency of wind energy picking by Darrieus rotor blade depends on its lift coefficients C_x and C_y, which depend on blades geometrical parameters (thickness, chord and distance to the place of maximum profile thickness from the nose of profile):

$$C_y = f(c, b, x_c);$$

$$C_x = f(c, b, x_c),$$

where c is profile thickness; b is profile chord; x_c is distance to the place of maximum profile thickness from the nose of profile.

The optimum considered the values of C_x and C_y, which fulfill the following conditions:

$$C_y \Rightarrow \max,$$

$$C_x \Rightarrow \min.$$

There are many standard NACA asymmetric profiles, which differ in the relative profile thickness $\bar{c}$. For Darrieus rotors symmetric profiles from NACA 0006 to 0030 are used, where the last two digits indicate the relative thickness of profile as a percentage. Thus, the optimization problem is reduced to form the profile of optimal choice of relative thickness $\bar{c}^*$.

Then by setting subtasks have such optimization:

$$\bar{c}^* = \underset{\bar{c} \in C}{\mathbf{arg\,extr}}\ \mathbf{F}(\bar{c}), \qquad 0.1 < \bar{c} < 0.3,$$

where $\mathbf{F}(\bar{c})$ is criteria of profile optimization.

$$\mathbf{F}(\bar{c}) = \{C_Y, C_X\}^{\mathrm{T}}.$$

Following optimization criteria of Darrieus rotor blades profile are contradictory ($C_Y \Rightarrow \max$ and $C_X \Rightarrow \min$), this problem is also a multi-criteria optimization subproblem.

The value of lift coefficient can be obtained by solving the Navier–Stokes equations for given values of geometrical parameters:

$$\frac{\partial U_x}{\partial t} + \frac{\partial (U_x)^2}{\partial x} + \frac{\partial (U_x U_y)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[\nu_{eff}\left(2\frac{\partial U_x}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[\nu_{eff}\left(\frac{\partial U_x}{\partial y} + \frac{\partial U_y}{\partial x}\right)\right],$$

$$\frac{\partial U_y}{\partial t}+\frac{\partial(U_yU_x)}{\partial x}+\frac{\partial(U_y)^2}{\partial y}=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left[\nu_{eff}\left(\frac{\partial U_y}{\partial x}+\frac{\partial U_x}{\partial y}\right)\right]+\frac{\partial}{\partial y}\left[\nu_{eff}\left(2\frac{\partial U_y}{\partial y}\right)\right],$$
$$\frac{\partial U_x}{\partial y}+\frac{\partial U_y}{\partial x}=0, \quad (1)$$

where U_x, U_y are flow rates relative to the x and y coordinates, respectively.

According to initial conditions accepted parameters (U_∞, p_∞) undisturbed flow for the entire calculation area:

$$U_{0x}=U_\infty; \quad U_{0y}=0; \quad p_0=p_\infty. \quad (2)$$

Calculation of the wind turbine blade profile is conducted in CFX and is based on the method of solving NS equations (1) by the finite volume method (FVM) for hydrodynamics, such as continuity equation and the equation of momentum. Differential Equations (1) are integrated in each calculation volume. To calculate integrals using piecewise continuous functions describing change in the dependent variable (one of the components of velocity) between mesh nodes. As the result of differential equations sampling the algebraic equations are obtained:

$$b\mathbf{U}+n\mathbf{V}+m\mathbf{p}=\mathbf{G}. \quad (3)$$

where b, n, m are coefficients of the unknown elements matrixes **U**, **V**, **p**; **G** is the vector that is the right part of the equation due to set boundary conditions.

The coefficients of algebraic equations (3) are calculated using the Algebraic Coupled Multigrid (AMG) method, developed by M. Raw and G. Schneider. This method uses an implicit bound scheme for solving systems of linear algebraic equations. Computational cost of method linearly dependent on the number of calculation points. One of the important properties of FVM is that it uses the exact integral conservation of variables values such as mass and momentum of any calculation volumes group, and, consequently, the entire calculation area. This property is manifested in any number of key points. Thus, even rough grid solution meets the exact integral balances. When calculating fixed iteration process variations in time calculation process ends when it reaches the required level of convergence. The problem can be stated in two- and three-dimensional variants. In the simulation model, used viscous gas model with averaged turbulent characteristics (for Reynolds averaged Navier–Stokes incompressible fluid) (1). Parameters of flow and profile properties are set in program.

Variables are calculated for discrete angles of attack with turning profile to simulated incoming flow (Fig. 1). For undisturbed oncoming flow speed is taken normalized wind speed. In the optimization calculation step angle of attack (for example 1 °) is set in a range α = 0° ... 360° with iterative change of profile. In case of symmetrical profile use, it is enough to specify α = 0° ... 180°.

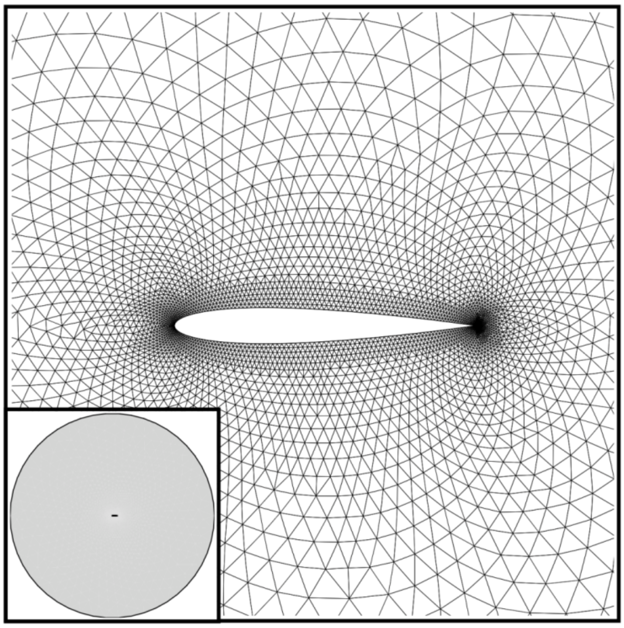

Fig. 1. Profile of the blade superimposed to calculate net flow in ANSYS CFX

The first order iterations allows to calculate pressure and export data to calculate the aerodynamic characteristics (ADC) (4), second order iteration change the angle of attack, third order iterations can change the conventional profile coordinates with restrictions on profile form parameters:

$$0.1<\frac{c}{b}<0.5; \quad 0.1<\frac{x_c}{b}<0.5.$$

III. CALCULATION ALGORITHM

Numerical calculations of the first order iterations are performed as follows. The influence of air on moving wing surface leads to appearance of continuously distributed pressure and shear stresses forces. According to this any aerodynamic force and moment can be represented as the sum of two components, one of which depends on the pressure distribution, and the other - from shear stresses. For each angle of attack obtained numerical values: C_T is longitudinal component of the aerodynamic force (ADF), acting on profile; C_N is normal component of ADF, acting on profile; M_T is moment of the longitudinal component of ADF relatively the profile nose; M_N is moment of relatively normal component of ADF at the profile nose; M_Z is total moment of ADF relatively to the profile nose, equal to $M_Z = M_N + M_T$. In addition, construction of pressure coefficient distribution diagrams on the profile surface, describing the nature of the flow. Aerodynamic coefficients of longitudinal and normal forces and aerodynamic moment determined by equations:

$$\left.\begin{aligned} C_T &= \frac{F_T}{q_\infty S}; \\ C_N &= \frac{F_N}{q_\infty S}; \end{aligned}\right\}, \quad m_Z = \frac{M_Z}{q_\infty S b}, \quad q_\infty = \frac{\rho V_\infty^2}{2}.$$

where S is characterized profile area, m[2]; q_∞ is dynamic pressure; ρ is the density of the air flow, kg/m[3].

For the resulting aerodynamic coefficients in a linked system of coordinates defined the relevant factors in the current coordinates by formulas:

$$\left.\begin{aligned} C_Y &= C_N \cos\alpha - C_T \sin\alpha; \\ C_X &= -C_N \sin\alpha - C_T \cos\alpha. \end{aligned}\right\} \quad (4)$$

According to the obtained values of C_X, C_Y and M_Z defined profile aerodynamic quality, center of pressure coefficient and the total wind power:

$$K = \frac{C_Y}{C_X},$$

$$\bar{x}_{\mu\partial} = \frac{-m_Z}{C_Y}, \quad C_R = \sqrt{C_X^2 + C_Y^2}.$$

ANSYS simulation package can replace physical experiments with measurement F_R and F_N using iterative drained profile blowing and deviations registration using dynamometers and / or pressure gauges connected to the drainage holes, perceiving pressure. In this case profile mounted on the rod is blown by the stationary flow that causes rotation acting on pressure gauges and dynamometers.

IV. Optimal Profile Selection Algorithm

The algorithm of the optimal profile includes the following steps.

1. Determine the angle of attack, such as: $\alpha = \Delta\alpha$.
2. For the geometric characteristics of NACA profiles 00 ** (** varies from 06 to 30) depending on the angle of attack calculate lift C_Y and drag C_X coefficients of profile.
3. By determined values C_X and C_Y decide whether they can be attributed to the Pareto optimal set.
4. Determine the angle of attack as $\alpha = \alpha + \Delta\alpha$.
5. Repeat steps 2–4 until the critical values of angles of attack are reached.

The result is the obtained Pareto front (Table I) of NACA optimal profiles, which are usable in the problem of optimizing the parameters of combined wind turbine rotor.

TABLE I

PARETO-OPTIMAL PROFILE SHAPES

NACA profiles	0008	0009	0010	0012	0018
C_Y	0.7840	0.9059	0.9624	1.2258	1.2311
C_X	0.00810	0.00892	0.00912	0.00961	0.01195

V. Conclusions

Optimization task statement shows, that the selection of optimal blade profile for Darrieus rotor blade is the multicriteria optimization task.

Proposed multicriteria optimization algorithm allows to increase the productivity of optimal profile selection for Darrieus rotor blade.

Use of finite volume method allows to solve the Navier–Stokes equation faster and easier with less time and computer performance requirements.

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В. М. Синєглазов, А. А. Зіганшин, М. П. Василенко. Оптимальний вибір профілю лопаті ротора вітроенергетичної установки

Розроблено алгоритм оптимального вибору профілю лопаті комбінованого ротора вітроенергетичної установки з вертикальною віссю обертання. У роботі наведено опис параметрів оптимізації ротора, поставлено задачу багатокритеріальної оптимізації та наведено гібридний алгоритм багатокритеріальної оптимізації.

Ключові слова: комбінований ротор; вітроенергетична установка; вертикальна вісь обертання; профіль лопаті; оптимізація.

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В. М. Синеглазов, А. А. Зиганшин, Н. П. Василенко. Оптимальный выбор профиля лопасти ротора ветроэнергетической установки
Разработан алгоритм оптимального выбора профиля лопасти комбинированного ротора с вертикальной осью вращения. В работе приведено описание параметров оптимизации ротора, поставлена задача многокритериальной оптимизации и приведен гибридный алгоритм многокритериальной оптимизации.
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