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DETERMINING THE AERODYNAMIC CHARACTERISTICS OF SAILING WIND TURBINE

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Wind turbines on the principle of operation can be divided into 3 types: sailing (Savonius), propeller and wing (Darrieus type) wind turbines. In paper the fundamentals of the theory of sailing wind turbines are outlined. The aerodynamic characteristics are determined: lift and drag coefficients, turbine power, use of wind energy, degree of speed, etc. A comparison of the calculation results with experimental data is presented. Satisfactory agreement of the calculation results with known experimental data is shown.

Keywords: Savonius, lift, drag, the degree of rapidity, utilization of wind energy.

Introduction

The general, robust growth of wind power around the world which goes hand in hand with further geographic diversification is very encouraging [1]. New world regions such as Latin America and most recently also Africa are playing an important role in this dynamic development. Obviously many governments have understood that wind power brings great benefits to their societies, as it is emission-free, cheap, domestic and accessible and offers a very attractive pathway to achieving the Paris agreement. However, signs of weakness in particular in Europe are a matter of concern. On Fig.1 shows the total energy consumption of wind energy in the world in 2013-2017.

Fig.1. Total installed capacity 2013-2017 (preliminary data), [1]

The European Union and its member states should urgently reinforce their efforts to deploy wind power as part of an overall renewable energy strategy and to work out a roadmap for a 100% renewable energy future [1]. All experts working in the field of renewable energy sources recognize that wind power has a great future in all respects. This explains the interest shown in the development of wind energy in many states.

There is a wide variety of wind turbine designs, but according to the principle of operation, they can be divided into three main types - sailing (Savonius), propeller (wind wheel) and wing (Darrieus type) [2-4]. The basis of our study selected sailing wind turbine. The advantage of our research is that the theoretical approach was correctly chosen to determine the main aerodynamic characteristics of a sailing wind turbine.

1. Construction of a four-blade sail-type turbine

Calculation of a sail - type turbine. As an example, let us consider the operation of a four-blade turbine, the design of which is sketched in Fig. 2a [2]. Each blade perceives the wind pressure to the full extent when rotating from the *OA* position to the *OB* position (see Fig. 2b).

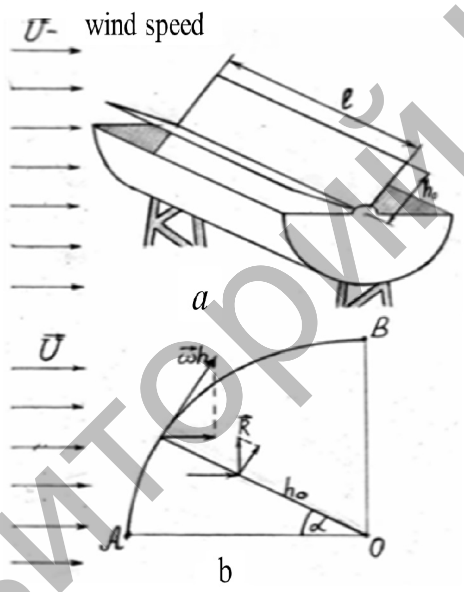


Fig. 2. The scheme of the simplest construction of a four-blade sail-type turbine

Behind the position of the *OB*, the angle of attack becomes negative and in addition the next blade appears which begins to obscure the previous one. Thus, the rotational moment is transmitted to each blade in the first quarter of the circumscribed circle. Accordingly, in this quadrant, the power transmitted by the wind turbine is registered. It is consumed for the work of lifting force $\vec{R}_x$ and overcoming the force of resistance of the blade $\vec{R}_y$.

2. Calculation of sailing wind turbines

Let us relate the coordinate system to a rectangular blade rotating in the direction of the wind movement, the area of which $S_0 = l\,h_0\ m^2$.

Then the velocity of flow on the blade will be equal to $|\vec{u}| = |\vec{U}| - |\vec{W}|\sin\alpha$, where $\vec{W} = \vec{\omega} h$ - linear velocity of the blade element at a distance *h* from the axis of rotation, $\vec{U}$ - wind speed. To find the resultant force of dynamic pressure, it is necessary to find the resultant vector of the relative velocity of the air flow. With this aim, we integrate the last expression over the surface $S_0 = l\,h_0$.

$$|\vec{u}_0| = \frac{1}{h_0}\int_0^{h_0} |\vec{u}|dh = |\vec{U}| - \frac{|\vec{W}_0|}{2}\sin\alpha \text{ , where } \vec{W}_0 = \vec{\omega}\, h_0 .$$

Dynamic wind pressure per blade

$$\frac{\rho u_0^2}{2} = \rho\frac{(2|\vec{U}| - |\vec{W}_0|\sin\alpha)^2}{8} \tag{1}$$

The resistance of the blade is determined by the known formula [5]

$$\left|\vec{D}\right| = C_x(\alpha)\delta_1 l \rho U_0^2 , \tag{2}$$

where $C_x(\alpha)$ - coefficient of resistance of a rectangular plate, is proportional to $\sin^2(\alpha)$ at small angles of attack $0^0 \le \alpha \le 20^0$ [6] and $C_x = 1.3$ at $\alpha = 90^0$ (see Table 1), δ_1 - the dimensions of the W vortex path behind the plate, the width of which $\delta_1 > h_0$ at $\lambda = \frac{l}{h_0} > 1$.

Heisenberg equating the circulation created per unit time on the edges of a flat plate, located normally to the flow, circulation, carried by vortices, found that $\delta_1 / h_0 = 1.54$. In our case, when the breakdown of the vortices occurs only on one side of the plane blade, we assume that $\delta_1 / h_0 = 1.27$. The resistance coefficient of the thin symmetrical wing NASA profile 0006 in the range of the angle of attack $0^0 \le \alpha \le 20^0$ is well described by the empirical formula:

$$C_x(\alpha_1) = 0.001 + 0.5\sin^2\alpha . \tag{3}$$

There are no data for corners of attack «α» more than 20^0. At $\alpha \ge 20^0$ we can interpolate and write the dependence corresponding to large angles of attack $C_x = 1.3$ at $\alpha \to \pi/2$

$$C_x(\alpha_2) = 1.5\sin\alpha - 0.2 . \tag{4}$$

Thus, formula (2.5.2) takes the following form

$$\left|\vec{D}_1\right| = h_0 l C_x(\alpha_1)\rho\frac{\left(2|\vec{U}| - |\vec{W}_0|\sin\alpha_1\right)^2}{8} \tag{2'}$$

at $0 \le \alpha_1 \le 20^0$.

$$\left|\vec{D}_2\right| = 1{,}27\, l h_0 C_x(\alpha_2)\rho\frac{\left(2|\vec{U}| - |\vec{W}_0|\sin\alpha_2\right)^2}{8} \tag{5}$$

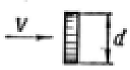
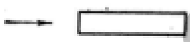
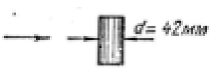
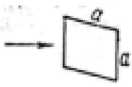
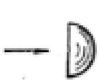
at $\alpha = \alpha_2$, $20^0 \le \alpha_2 \le 90^0$.

Lifting vector $\left|\vec{R}\right| = \frac{C_y}{l h_0}\frac{\rho u_0^2}{2}$ directed towards attack speed $\vec{V}$ at an angle 90^0 and the force, acting on the lifting of the blade is

$$h_0 l \vec{R}\sin\alpha . \tag{6}$$

Taking into account the fact that, for the plate, the coefficient of lift $C_y = 2\pi\sin\alpha$ in the interval $0 \le \alpha \le 20^0$ [2, 6] and $R = 0$ at $\alpha_1 > 20^0$, to determine the power transmitted to the turbine by the wind.

Table 1. The drag resistance C_x for different bodies

The name of the body	The form bodies	The ratio of the linear dimensions of the body	The speed of the experiment is v (m / s)	Reynolds number Re	The coefficient C_x
Round plate		–	–	$10.7 \cdot 10^4 \div 227 \cdot 10^4$	1.06÷1.28
Cone		–	10	$2.7 \cdot 10^5$	0.34
Cone with spherical base		–	10	$1.35 \cdot 10^5$	0.16
Also		–	10	$1.35 \cdot 10^5$	0.088
Cylinder		λ=7	$10 \div 30$	$10^5 \div 3 \cdot 10^5$	0.84
Cylinder with spherical bases		λ=7	$10 \div 30$	$10^5 \div 3 \cdot 10^5$	$0.28 \div 0.22$
Ball		–	–	$10^5 \div 4 \cdot 10^5$	$0.44 \div 0.10$
Cylinder		0.2 to 0.8	30	$8.8 \cdot 10^4$	$0.75 \div 0.65$
Square plate		–	–	$10.7 \cdot 10^4$ to $227 \cdot 10^4$	$1.06 \div 1.28$
Hollow hemisphere		–	–	–	0.33
Hollow hemisphere		–	–	–	1.34

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To do this, calculate the work done when moving the blade from the OA position to the OB position (see Fig. 2b). In this case, the point A passes the path equal to $\frac{\pi h_0}{2}$ with speed $\vec{W}_0$.

Accordingly, the power transmitted to the turbine will be

$$N = N_1 + N_2 , \tag{7}$$

where $N_1 = h_0 l \int_0^{\frac{\pi}{9}} \left(\vec{R} + \vec{D}_1\right)\vec{W}_0 d\alpha$, $N_2 = h_0 l \int_{\frac{\pi}{9}}^{\frac{\pi}{2}} \vec{D}_2 \vec{W}_0 d\alpha$.

Considering that for a plate at $0^0 \le \alpha \le 20^0$, $C_y(\alpha) = 2\pi \sin\alpha$ [2, 6], and, substituting the expressions for $\left|\vec{R}\right|, \left|\vec{D}_1\right| u \left|\vec{D}_2\right|$, taking into account (3) and (4), we obtain

$$\begin{aligned} N = h_0 l W_0 \int_0^{\frac{\pi}{9}} \left(2\pi \sin\alpha + 0.001 + 0.5\sin^2\alpha\right)\rho \frac{\left(2|\vec{U}| - |\vec{W}_0|\sin\alpha\right)^2}{8} d\alpha + \\ +1.27\frac{lh_0}{8} W_0 \int_{\frac{\pi}{9}}^{\frac{\pi}{2}} (1.5\sin\alpha - 0.2)\rho\left(2|\vec{U}| - |\vec{W}_0|\sin\alpha\right)^2 d\alpha \end{aligned} \tag{8}$$

Integrals are tabular, easily taken. Performing simple operations, we find:

$$N = 0.027\rho l h_0 |\vec{W}_0| \left[7.17U^2 - 6.29\vec{W}_0\vec{U} + 0.082W_0^2\right]. \tag{9}$$

The coefficients of wind energy is found by dividing the power *N* transmitted by wind to the turbine by the own power of wind $N_в = lh_0 \rho \frac{U^3}{2}$.

$$\xi = 0.053\chi\left[7.17 - 6.30\chi + 0.082\chi^2\right] \tag{10}$$

Where the ratio of the translational velocity of the tip of the turbine blade to the wind speed is called the tip speed ratio (TSR), and is calculated as follows: $\chi = \frac{|\vec{\omega}| h_0}{|\vec{U}|}$ where χ is the TSR, and $\vec{U}$ is the free wind speed. Equating the first derivative $\frac{d\xi}{d\chi}$ to zero, find the maximum value of the wind power factor $\xi_{\max}$, as well as χ, at which $\xi_{\max}$ and $\xi = 0$ are achieved.

So, $\xi = 0$ at $\chi = 0$ and $\chi = 1.16$, and $\xi_{\max} = 0.11$ at $\chi = 0.58$.

Wind turbine power is determined by the formula

$$N = \xi \cdot lh_0 \frac{\rho U^3}{2}.$$

where *N* is power, *U*- wind speed, ξ *is* power coefficient, *l* - height, h_0 - blade width, ρ - air density.

3. Comparison of calculated and experimental data

Fig. 3 presents the experimental data of the P.P. Osipov [7] and calculated curves by the formula (10), as well as the results of calculations on the assumption that the blade does not rotate, but moves translationally with velocity $|\vec{\omega}| h_0$ in the direction of wind movement [6]. As can be seen in Fig. 3, the agreement between the calculated curve (10) and experiment is not more than 10-15%, while the maximum deviation of the dotted curve is much larger.

Light points - the experiments of P.P. Osipov. The solid line is calculated by formula (10). Dotted line - the results of calculation under the assumption that the blade does not rotate, but moves translationally.

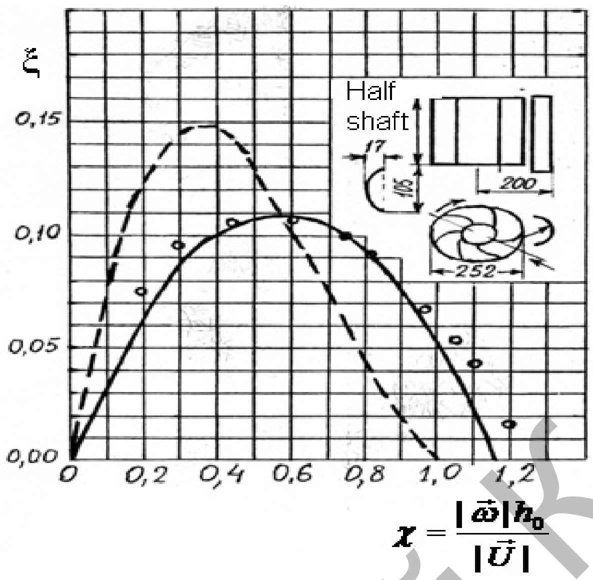

Fig. 3 Rotor power coefficient ξ as function of tip speed ratio χ. Here:
oooooo – the experiments of P.P. Osipov. ——— – is calculated by formula (10). — — — — – the results of calculation under the assumption that the blade does not rotate, but moves translationally.

Conclusion

A theoretical calculation of the main aerodynamic characteristics of a sailing wind turbine has been carried out. Our theoretical results were tested with known experiments [7]. Comparison with experiment showed good agreement. This gave rise to confidence in the correctness of the choice of methods for solving problems.

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