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ANALOGY BETWEEN A FLAPPING WING AND A WIND TURBINE WITH A VERTICAL AXIS OF REVOLUTION

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Based on an analysis of available experimental data, the hypothesis about an analogy between a flapping wing and a wind turbine of the Darrieus rotor type is justified. It is demonstrated that the torque on the shaft of the Darrieus rotor is generated by thrust forces acting on the blades in a pulsed flow. A conclusion is drawn that it is necessary to perform aerodynamic calculations of blades on the basis of the nonlinear theory of the wing in an unsteady flow with allowance for the airfoil thickness.

Key words: *flapping wing, wind turbine, Darrieus rotor.*

One of the promising research directions in wind power engineering is the development of wind-driven facilities with a wind turbine of the Darrieus rotor type [1]. Wind turbines of this type are substantially different from the traditional propeller-driven wind turbines, have a vertical axis of revolution, and can operate with all directions of the wind, i.e., no streamwise orientation of the system is required. In terms of their energy characteristics, such wind turbines approach the best propeller-type devices. For instance, the Vertikal Design Bureau (Miass, Russia) developed a facility with a two-tier rotor (Fig. 1) whose efficiency in test exploitation reached 40%.

Intense research of vertical-axis wind turbines was started in the early 1980s. In particular, methods of aerodynamic calculation of blades [2, 3] are under development. In most cases, such a calculation within the framework of the steady flow model fails to predict exactly the torque value and the flow energy efficiency ratio. The reason for this is essential unsteadiness of the flow near the rotating rotor. To explain the interaction between the blades of the rotating Darrieus rotor with the flow, a hypothesis about an analogy between the Darrieus rotor and a flapping wing was put forward in [4]. Let us consider the main elements of this hypothesis.

1. During its operation, the flapping wing and the blades of the Darrieus rotor experience the action of an unsteady flow. Such a flow generates a thrust force, which depends on the amplitude and frequency of flow oscillations, and also on the geometric parameters of the blade (wing). The thrust force acting on the blades generates an aerodynamic moment rotating the Darrieus rotor. In contrast to the Darrieus rotor, the torque of a propeller-type wind turbine is generated by lift forces acting on the blades; in this case, the aerodynamic calculation is performed within the framework of the steady flow model. It should be noted that no thrust force arises in the steady flow (the wing is affected only by the lift force and the drag force); therefore, the mechanisms of torque generation are principally different for the Darrieus rotor and the propeller-type wind turbine.

2. Propulsion in nature is mainly ensured by a flapping wing. Birds and most water inhabitants possess such wings. The efficiency of propulsion of this kind can be fairly close to unity. For this reason, migrating birds and insects can cover tremendous distances with small amounts of their “biological fuel” consumed. As there is an analogy between the Darrieus rotor and the flapping wing, we can naturally assume that the Darrieus rotor also has a high efficiency. The fraction of the kinetic energy of the flow that can be “captured” by the wind turbine is determined by the flow energy efficiency ratio η. For an ideal propeller-type wind turbine, the limiting value of this ratio is $\eta = 0.593$ [3]. A special experiment was performed with an ideal Darrieus rotor model (without support brackets connecting the blades with the vertical shaft) to see whether the flow energy efficiency ratio of the Darrieus rotor can be higher than that of an ideal propeller-type wind turbine. The model had three blades located

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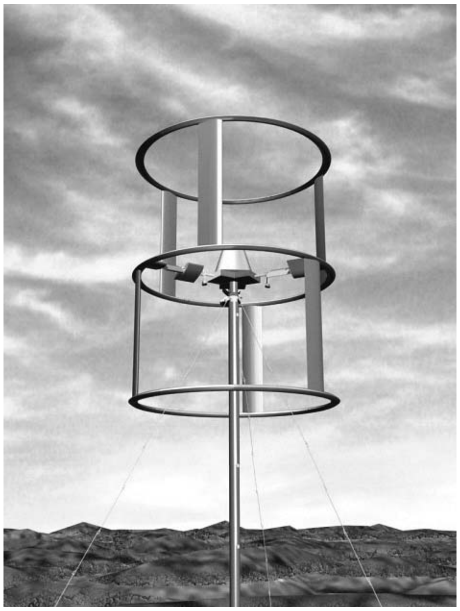

Fig. 1

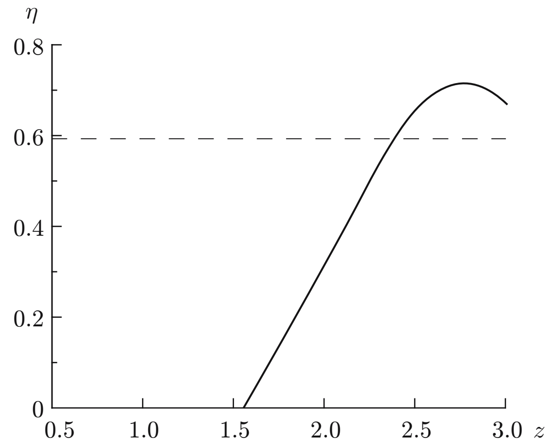

Fig. 2

Fig. 1. Prototype model of a two-tier Darrieus rotor.

Fig. 2. Experimental dependence of the flow energy efficiency ratio η versus the specific speed for an "ideal" Darrieus rotor: the dashed curve shows the limiting value of the coefficient $\eta = 0.593$ for an ideal propeller-type wind turbine.

between two flat disks. Four sets of blades with different widths were studied. The experiment was performed in a hydrochannel with negligibly small influence of flow boundaries. Arrangement of the experiment and results are described in detail in [5]. The main result of this experiment is plotted in Fig. 2 as the flow energy efficiency ratio $\eta = 2M\omega/(\rho v^3 S)$ versus the specific speed $z = \omega R/v$ (M is the torque on the rotor shaft, ω is the circular frequency of shaft rotation, ρ is the fluid density, v is the flow velocity, S is the cross-sectional area of the rotor, and R is the rotor radius). The "ideal" Darrieus rotor considered in the experiment ensured the maximum value of the efficiency ratio equal to $\eta = 0.72$, whereas the maximum value for an ideal propeller-type wind turbine is $\eta = 0.593$ (see Fig. 2). These experimental data show that the propulsive characteristics of an ideal Darrieus rotor may be better than the corresponding limiting characteristics of an ideal propeller-type wind turbine.

It should be noted that the limiting value of the coefficient η for an ideal propeller was obtained theoretically within the framework of the model of steady motion of an ideal incompressible fluid, whereas the experimental study for the "ideal" Darrieus rotor was performed under conditions of unsteady motion of the medium. Under these conditions, the blades of the Darrieus rotor experienced the effect of the flow similar to that of a flapping wing, which is responsible for the greater value of the coefficient η.

3. The experimental study shows that the thrust force generated by a flapping wing depends substantially on the dimensionless thickness of the wing [6]. The most extensive study of this problem was performed by Cherkaz'yanov [7]. The experiments were performed with symmetric NACA airfoils with a dimensionless thickness $c = 0.06$, 0.09, 0.12, 0.15, 0.18, and 0.21, chord length $b = 0.15$ m, and aspect ratio $\lambda = 2$. The airfoils performed harmonic translational motions with amplitudes $A = b$ and $A = 0.7b$ perpendicular to the chord. The test results obtained in the present work for a circular frequency of wing oscillations $\omega = 2\pi$ sec^{-1} are plotted in Fig. 3 as the thrust force coefficient $C_T = 2R_T/(\rho S(b\omega)^2)$ as a function of the dimensionless thickness of the airfoil c (R_T is the mean value of the thrust force over the period of oscillations and S is the airfoil area).

An increase in the dimensionless thickness of the airfoil from 6 to 21% leads to a four-fold increase in the thrust force, which can only be attributed to the unsteady character of the flow around the wings. The maximum value of the thrust force is reached for the airfoil thickness $c = 0.21$. Note that this value coincides with the dimensionless thickness of the tail fin of a dolphin (18–20%).

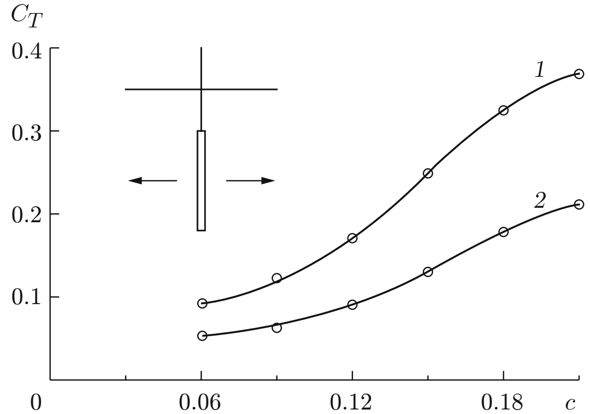

Fig. 3

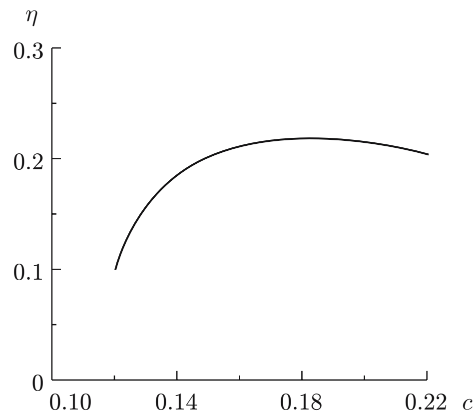

Fig. 4

Fig. 3. Thrust force coefficient versus the dimensionless thickness of the airfoil with crossflow oscillations of the wing in a "motionless" fluid: $A/b = 1$ (1) and 0.7 (2).

Fig. 4. Flow energy efficiency ratio η versus the dimensionless thickness of the blades of the Darrieus rotor [8].

A similar dependence of the thrust force on the airfoil thickness is observed for the Darrieus rotor. Figure 4 shows the experimental dependence of the flow energy efficiency ratio η on the dimensionless thickness of the blades of the Darrieus rotor [8]. For the Darrieus rotor, the torque is determined by the thrust forces acting on the blades; hence, the dependence $\eta(c)$ is similar to the dependence $C_T(c)$. The maximum value of the coefficient η is reached for the dimensionless thickness of the blade $c = 0.18$. As in the experiments with a flapping wing, the value of the coefficient η (thrust force) drastically decreases as the dimensionless thickness of the blade is reduced.

Conclusions. The results presented here allow us to conclude that there is an analogy between a flapping wing and the Darrieus rotor. Hence, the aerodynamic calculation for the Darrieus rotor should be performed on the basis of the nonlinear theory of the wing in an unsteady flow with allowance for the shape of the blade contour.

The explanation given for the mechanism of interaction of the blades of the Darrieus rotor with the wind flow allows some problems of practical importance to be solved [4, 5, 9], including obtaining high energy characteristics, restriction of the rotor circulation frequency, and rotor actuation.

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