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Simulation of orthogonal rotors with dynamic pitching blades

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Abstract. An adaptation of the mathematical model for the investigation of the parameters of orthogonal wind turbine has been performed. The simulation of Darrieus H-type rotor operating modes was performed and compared with experimental data. A kinematic scheme with dynamic blades was used for optimal tip-speed ratio. The results of numerical simulation with different deflection angles at fixed tip-speed ratio 1.6 showed that maximum rotor efficiency is reached for a blade pitch angle equal to 8 degrees. One can see that the use of the kinematic scheme, which allows changing the pitch angle of blades, leads to an increase in the efficiency of the rotor in the range from 12 to 50% (depending on the tip-speed ratio).

1. Introduction

According to conservation laws, the maximum achievable extraction of wind power by a wind turbine (WT) is 0.593 for ideal rotor of horizontal and vertical-axis WT. Different types of WT use the same effect of the lift of the flow around a special profile blade. Currently, the maximum achievable extraction of wind power by horizontal-axis WT is 0.4. The experimental investigation of Russian scientists shows, that the vertical-axis WT can obtain the value of the extraction of the wind power in a range from 0.4 to 0.45. Hence, the wind power extraction coefficients (Cp) for horizontal-axis, propeller, and vertical-axis WT are similar. However, Darrieus WT has the potential to obtain a higher value of Cp than horizontal-axis WT [1].

Currently, an experimental investigation is the main source of information when developed Darrieus WT. So, the most comprehensive experimental results, which allow an estimate of the effect of the main parameters of the rotor and the flow on energy efficiency of Darrieus WT with straight blades, have been studied in several previous works [2, 3].

The Small Hydropower Plants (SHP) of both submersible and floating types causes a great interest of scientists around the world. So, the fundamentally different types of turbines including orthogonal ones were investigated. For several years a technology platform of orthogonal hydraulic units is developed by JSC “Research Institute of Energy Facilities” (JSC “NIIES”). The obtained results show that adaptation of developed orthogonal turbine into SHP with low head (from 1 to 5 m) is possible. The model-unit of horizontal submersible SHP was developed and investigated by a group of scientists from Krasnoyarsk [4].

In modern vertical WT and rotors of hydraulic turbines, one usually uses motionless blades with fixed pitch angle that leads to simplifying the facility design and increases time of trouble-free operation but significantly restricts efficiency. Development of marine propulsion systems and aircraft cyclorotors, which have similar kinematics with Darrieus rotor, shows that it is necessary to apply controllable pitch angle in order to increase rotor effectiveness. For example, the study of research group from South Korea shows an increasing efficiency of orthogonal rotors of up to 70% by using turning mechanisms of the blades like an aircraft propellers.

Unfortunately, sufficient experimental data about investigation of H-type rotors in orthogonal hydraulic turbines are not presented in the literature. Thus, for validation of computation models, the data of WT studying were used. The study of WT, which was placed in a wind tunnel for different values of incident flow velocity and rotation frequency of the rotor, was presented in [5]. The vertical three-blades Darrieus H-type rotor with a diameter of 2.5 m and height of 3 m was investigated. The symmetric NACA 0015 with chord of 0.4 m was used as blades. Although geometric and consequently aerodynamic characteristics of the rotor are not optimal, a wide range of considered operation modes provides a reliable database for verification of computation models.

2. Methods

In this work a numerical simulation of interaction between revolving wind turbine rotor and incident flow was based on RANS (Reynolds-averaged Navier–Stokes) approach for incompressible flow in 3D unsteady approach. The two-equation k-ω SST model was used as a turbulence model. Rotation of the rotor and also the change of blades pitch angle for cases with the changes in the angle-of-attack over time were performed by user-defined functions, which allow using features of sliding mesh. The unstructured mesh comprised approximately one million nodes (see Fig. 1). For equation approximation, the second-order schemes were used. The time step was $\Delta t=T/120$ (here $T=2\pi/\omega$) and it corresponded to rotation of the rotor at 3 degrees. The steady-state periodic flow pattern was achieved during the calculation of ten complete rotor cycles, after that the averaging of the moment on the blades occurred for the next several cycles.

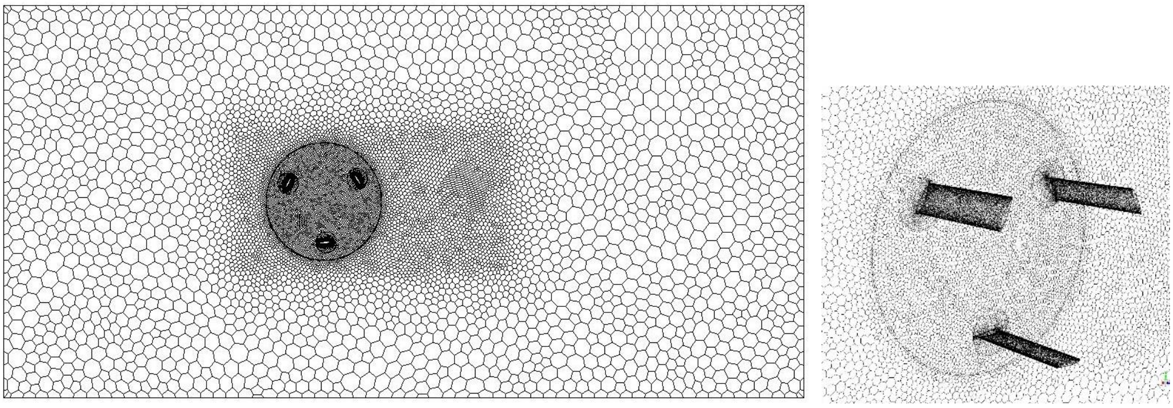

Figure 1. Example of unstructured computational grid for a cross-section (left) and on the rotor blades.

The efficiency of a WT is usually estimated in a dimensionless form, using the power factor Cp:

$$C_p = \frac{P}{\frac{1}{2}\rho u_{wind}^3 A}$$

here, P is the power produced by the WT.

In our calculations generated power estimated as:

$$P = \omega M$$

where ω - angular velocity of the rotor, M - mean moment of viscous and pressure forces affecting the blades surfaces relative to axis of rotor rotation. A - the effective area of the rotor.

The power factor is a function tip-speed ratio (the ratio between the velocity of the blade and the incident flow)

$$\lambda = u_{blade} / u_{wind}.$$

In our case u_{blade} corresponds to linear velocity of blade attachment point located at distance 25% of blade chord from the leading edge.

$$u_{blade} = \omega R$$

where R – radius of the rotor.

In order to provide the tip-speed ratio in the range from 1 to 2.2, the rotational speed of the rotor was varied in the range from 76 to 170 rpm, and the incident flow velocity was 10 m/s.

3. Results

The results of the numerical simulation show that the maximum magnitude of the investigated rotor efficiency is achieved for tip-speed ratio of 1.6, which is in a good agreement with the experiment. The calculated value of the rotor efficiency is more than experimental one (see Fig. 2), which is probably caused by absence of the rotor shaft and the blade mounting elements in the computation model. Nevertheless, one can observe a good correspondence between the experimental measured and simulated profiles. Therefore, the selected computation model is suitable for estimating the parameters of rotors of various designs.

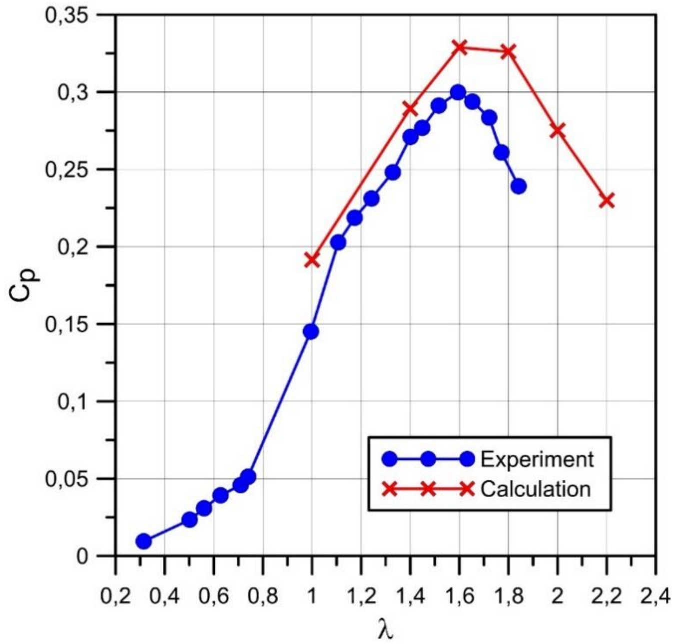

Figure 2. Comparison between the experimental data and numerical simulation.

In order to investigate the blades pitch angle effect, which is variable during the rotor rotation, the various kinematic schemes with a maximum pitch angle of ±6, ±8, ±10, and ±20 degrees were considered. Figure 3 shows the characteristic periodical dependence of the blade pitch angle on the blade orbital motion angle (maximum pitch is ±10 degrees). A certain value of the phase angle of the facility allows directing the flow behind the rotor in parallel to the incident flow.

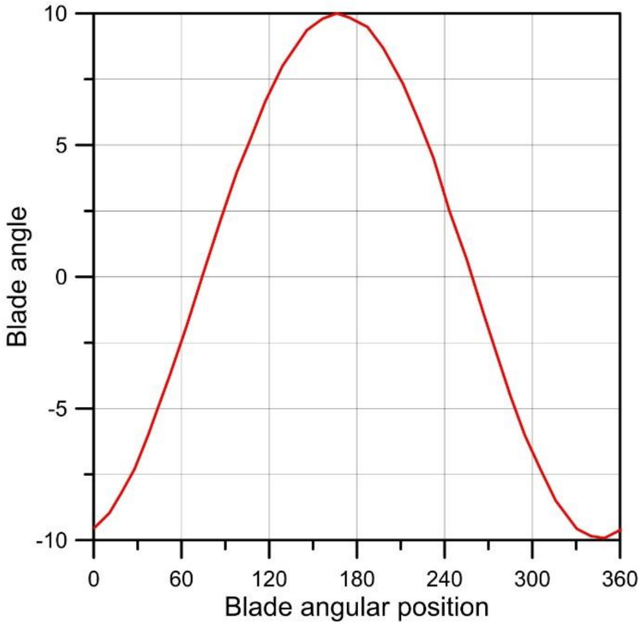

Figure 3. Dependence of the blade pitch angle on the blade orbital motion angle (for case ±10 degrees).

The results of numerical simulation with different pitch angles at fixed tip-speed ratio λ=1.6 showed that the maximum rotor efficiency is reached for a blade pitch angle equal to ±8 degrees (see Fig. 4).

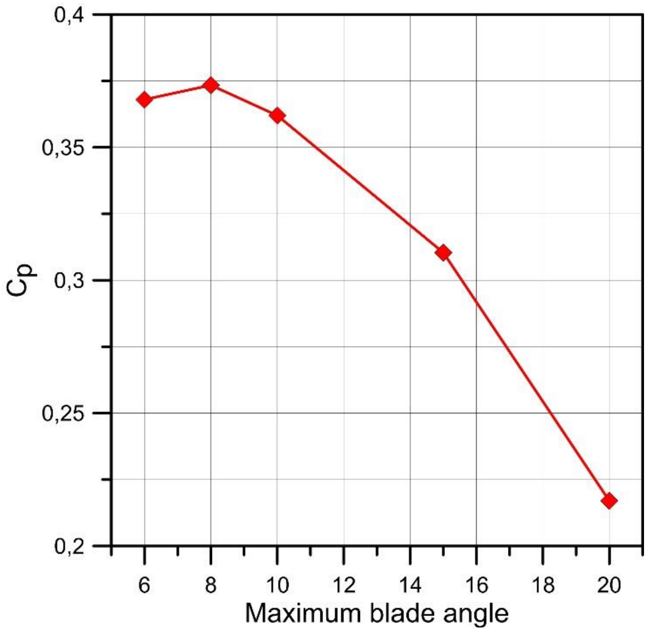

Figure 4. Dependence of the rotor efficiency on the blade pitch angle.

Furthermore, in addition, there was a series of numerical investigations of kinematic scheme with a dynamic pitch angle of ±8 for tip-speed ratio in range from 1.2 to 1.8. So Figure 5 shows a comparison (obtained by numerical simulation) of dependence of the power factor on the tip-speed ratio between the rotors with fixed and varied pitch angles of the blades. One can see that the use of a kinematic scheme, which allows changing the pitch angle of the blades, leads to an increase in the efficiency of the rotor in the range from 12 to 50% (depending on the tip-speed ratio).

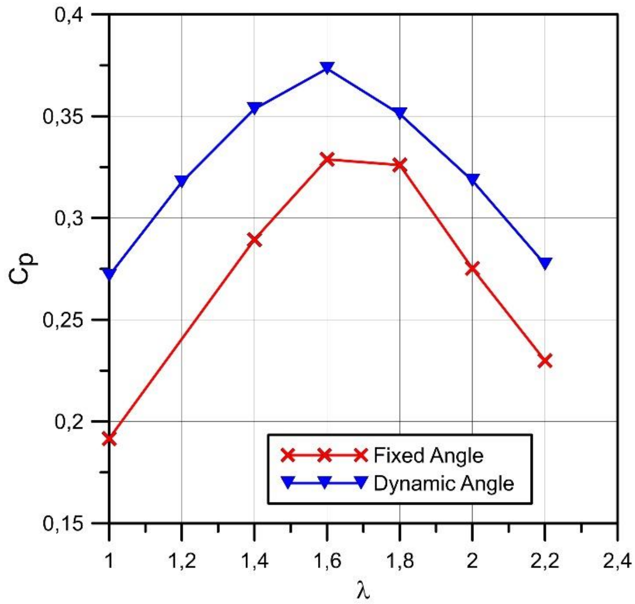

Figure 5. Comparison of the efficiency between the rotors with fixed and varied pitch angles of the blades.

Conclusions

Orthogonal rotors with variation of the blades pitch angles have been investigated by experimental and numerical approaches. The validation of computation models for numerical simulation of the characteristics of H-type rotors has been carried out and a good agreement between the calculated and experimental data is shown. The effect of the kinematic scheme, which allows a dynamic variation of the blades pitch angles, on the efficiency of the rotor has been evaluated. It is found that the maximum rotor efficiency is reached for a blade pitch angle equal to ±8 degrees. A significant positive effect of using the kinematic scheme has been shown by an example of the H-type Darrieus rotor with specific geometrical parameters.

Acknowledgment

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