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ON OUTPUT POWER FOR WAVE TYPE WIND TURBINES AND FOR AUTOROTATING FINNED CYLINDERS

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Abstract

New type of wind turbines – wave type wind turbines – is studied experimentally and theoretically. Two constructive schemes of such turbines are considered. It is shown that for some range of external load there exists attracting autorotation regime. Average angular speed and output power on this regime are estimated for different external loads. Comparison with autorotating finned cylinders is performed.

Key words

Media flow, autorotation, wind turbines.

1 Introduction

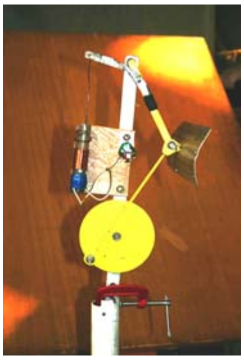


Figure 1. The breadboard model of WTWT.

One of the most important ways for increasing of power of wind turbines is creation of devices with large swept area. Example of such device is original Strekalov's wave type wind turbine (WTWT) [Strekalov, 1986; Strekalov, Misharev, Strekalova, 2004].

The principle of operation of the wave type wind turbine is based on the fact that when wind-capturing surface interacts with the wind, it begins to perform oscillations. This oscillatory motion is converted to rotational motion of the rotor which is then used for operation of electric power generator.

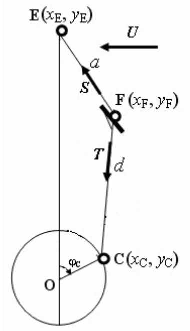


Figure 2.a. Wind turbine with fixed joint E.

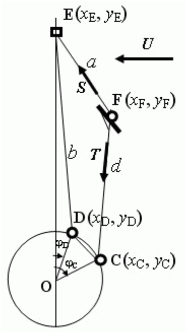


Figure 2.b. Wind turbine with mobile joint E.

2 Problem statements

A model flat problem of oscillations of wind capturing surface of the WTWT in free flow of viscous medium is studied (Fig. 2.a). Circles denote joints; thick line denotes the wind capturing surface (we assume it a weightless plate). The point O is the center of rotation of the rotor. OC, EF и CF are rigid weightless rods. The wind capturing surface makes with the rod CF constant pitch angle γ. Evidently, the system has one degree of freedom. Let the angle φ_C of rotation of the rotor be the generalized coordinate (angles are counted clockwise). Write down the motion equations of the considered mechanical system:

$$J\ddot{\varphi}_C\mathbf{e}_z = \mathbf{OC}\times\frac{\mathbf{CF}}{|\mathbf{CF}|}T \tag{1}$$

$$\left.\begin{aligned}
&m\ddot{x}_F(\varphi_C) = F_{ax} + \\
&+\frac{x_C - x_F}{\sqrt{(x_C-x_F)^2+(y_C-y_F)^2}}T + \\
&+\frac{x_E - x_F}{\sqrt{(x_E-x_F)^2+(y_E-y_F)^2}}S \\
&m\ddot{y}_F(\varphi_C) = F_{ay} + \\
&+\frac{y_C - y_F}{\sqrt{(x_C-x_F)^2+(y_C-y_F)^2}}T + \\
&+\frac{y_E - y_F}{\sqrt{(x_E-x_F)^2+(y_E-y_F)^2}}S
\end{aligned}\right\} \tag{2}$$

Here U is the flow speed; S and T are reactions in rods.

Besides this device, another construction was considered where the joint E can move along the vertical (fig. 2.b). Then equation (1) will take the following form:

$$J\ddot{\varphi}_C\mathbf{e}_z = \mathbf{OC}\times\frac{\mathbf{CF}}{|\mathbf{CF}|}T - \tag{1*}$$

$$-\mathbf{OD}\times\frac{\mathbf{DE}}{|\mathbf{DE}|}\frac{\cos(\angle\mathrm{OEF})}{\cos(\angle\mathrm{OED})}S$$

Dynamic systems (1-2) and (1*-2) are solved along with the following equations of hydrodynamics as conjugated problems in «vortex» statement:

$\nabla\cdot\mathbf{V} = 0$ (continuity equation);

$\dfrac{\partial\Omega}{\partial t} = -\nabla((\mathbf{V}+\mathbf{V}_d)\Omega)$ (equation of vorticity evolution equivalent to Navier-Stokes equations for the flat case).

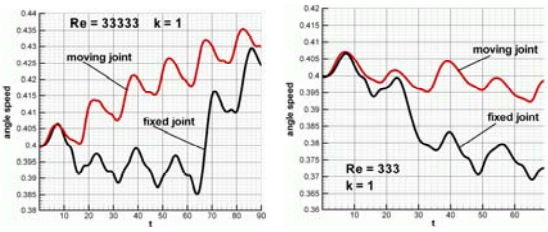
Here $\mathbf{\Omega} = rot\,\mathbf{V}$, $\mathbf{\Omega} = \mathbf{e_z}\,\Omega$ is vorticity; $\mathbf{V}_d = -\dfrac{1}{\mathrm{Re}}\dfrac{\nabla(\Omega)}{\Omega}$ is diffusion velocity of vorticity motion. Boundary conditions are given by adhesion condition V = VS. Aerodynamic force is expressed in terms of vorticity [Guvernyuk et al., 2005].

3 Calculation method

The principal tool for simulation of flows with intensive vertical structures the original Lagrangian numerical method of viscous vortex domains is used (VVD) [Dynnikova, 2004; Guvernyuk et al., 2006]. For verification of the applied computational technologies there is performed comparison with experimental data and with results of known calculations based on grid methods [Guvernyuk et al., 2005; Guvernyuk and Dynnikova, 2007].

4 Discussions of results

For Re = 50000 there was obtained the autorotation regime where the rotor rotates clockwise. Average value of the non-dimensional angular speed ω of the rotor is determined ($\omega = \dot{\varphi}_C\,|\mathbf{OC}|/\mathrm{U}$), and character of its change is analyzed. It is shown that for such Reynolds number (corresponding to airflow over a plate with width 0.07m at air speed 21.4mps) the leading role in the development of unsteady load is played by "edge" vortices, separation period of which is several times less than the period of full rotor revolution. It is shown that just "edge" vortices are "useful" for sustention of motion, while the secondary vortices are dissipative, that is, decelerate the motion. In order to check the operability of the new class of wind turbines and to verify the computation models there were performed experimental tests of breadboard models of WTWT in airflow. These experimental studies are carried out in subsonic airflows (characteristic model size up to 1 m, Reynolds numbers to 77000, Mach numbers in range 0,02–0,1). Unsteady angular motions of the plate are registered with the help of electromagnetic sensors of connecting rod displacements with subsequent computer processing of signals.



a) b)

Figure 3. Calculated angular speed

Experimental results for wind turbines with fixed joint E are compared with computation results. The computed average value of the non-dimensional angular speed is 0,108. In the experiment the non-dimensional angular speed is 0,083. This 30% disagreement between the calculation and experiment, probably, is due to the friction in joints. It is shown that the influence of the Reynolds number upon the Strouhal number (i.e., upon the non-dimensional angular speed) is insignificant. However, weak non-linearity of the dependence of the oscillation frequency on the flow speed is observed. In particular, for plate width 0,075 m the maximum (optimal) oscillation frequency is reached for flow speed 20 mps.

Comparison of numerical results for cases of fixed joint and mobile joint is performed. Power takeoff is simulated by viscous friction with coefficient $k = 1$ (Fig. 3). Note that for $Re = 33333$ the average angular speed of the device with moving joint steadily increases. As for the fixed joint case, the average angular speed slightly decreases at the initial stage, and then begins to increase. This result agrees qualitatively with preliminary experiments demonstrating that it is more difficult to speed up the wind turbine with fixed joint, than the one with mobile joint. This fact is clearly marked for small flow speeds. It can be seen that for $Re = 333$ the average angular speed decreases in both cases, but for mobile joint case this decreasing is not so fast.

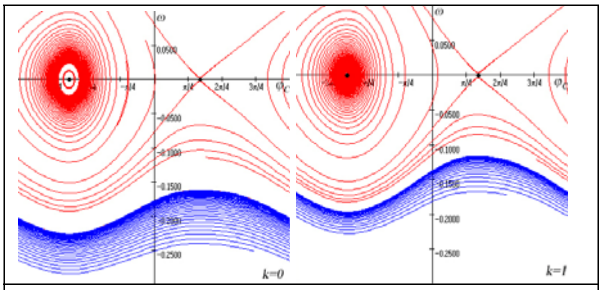


Figure 4. Phase plane structure

Simplified mathematical model of the WTWT is constructed for the fixed joint case. For description of the aerodynamic load upon the plate there was used the quasi-steady approach [Dosaev et al., 2007]. Parametrical analysis is performed, the structure of the phase plane for different values of the viscous friction coefficient k is studied (Figure 4 a,b). It is shown that there exists a stable equilibrium position. For small values of the coefficient k there exists also attracting limit cycle (autorotation regime). As the coefficient k increases, the average angular speed, as should be expected, decreases. If this coefficient exceeds a certain limit value, the rotational regime disappears.

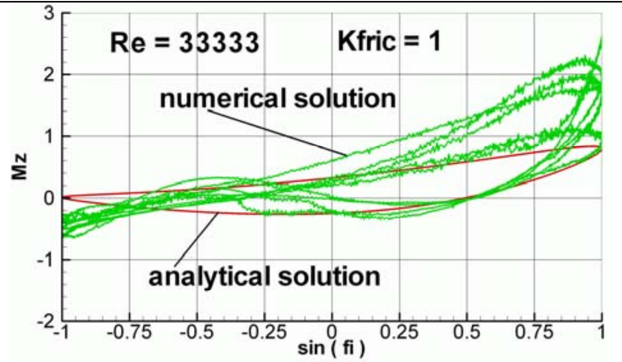


Figure 5. Aerodynamic torque vs. $\sin(\varphi_C)$

In the figure 5 the comparison of dependences of the torque acting upon the rotor of the WTWT on $\sin(\varphi_C)$ is given. The function obtained from VVD method is shown with the green curve. The function obtained from the quasi-steady approach is shown with the red curve. Evidently, the results are in qualitative agreement, but there exist quantitative differences. In particular, for VVD the amplitude of torque change is larger. This result suggests possible ways for the correction of these phenomenological models.

For comparison the efficiency of power takeoff for wave and rotor type wind turbines, the unsteady conjugated problem of autorotation of finned cylinder (vane) in viscous flow (analog of rotor type wind turbine) was solved. For numerical calculation the VVD method is used [Dynnikova, 2004; Guvernyuk et al., 2006]. For simultaneous determination of the angular speed and vorticity flow from the surface the one-step algorithm without subdivision of the coupled problem into dynamical and hydrodynamic components was used [Grigorenko, 2007]. In figures 6,7 the dependences of the average non-dimensional angular speed and output power coefficient on non-dimensional coefficient viscous friction are given for a vane with two fins. Evidently, for large and small values of k two-finned vanes are more efficient, while for intermediate values the WTWT is more efficient. Maximum power value for WTWT is reached for $k = 0.6$ and exceeds the maximum power for two-finned vane by 84% (figure 7).

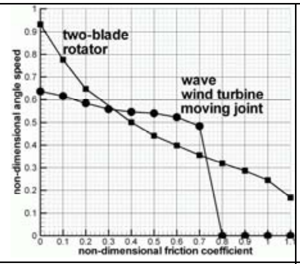


Figure 6. Non-dimensional angular speed vs. non-dimensional viscous friction coefficient

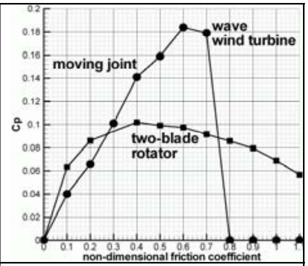


Figure 7. Non-dimensional output power coefficient vs. non-dimensional viscous friction coefficient

5 Conclusions

Operating capacity of WTWT of different types is confirmed experimentally. It is shown that starting up of WTWT with mobile joint takes place for lesser flow speeds, than for WTWT with fixed joint. It is shown that for some range of external load there exists attracting autorotation regime. Average angular speed on this regime is estimated for different external loads. Comparison between output power of autorotating finned cylinder and WTWT is performed.

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References

Dosaev M.Z., Kobrin A.I., Lokshin B,.Ya., Samsonov V.A., Seliutsky Yu.D. (2007). *Constructive theory of small-scale wind power generators*. MSU Publishing. Moscow. (in russian).

Grigorenko D.A. (2007). Programming realization of gridless numerical Lagrangian method for simulation of vortex flows. In *Proc. of the conference-contest of young scientists - 2006*. Moscow. Russia. pp. 116-121 (in russian).

Dynnikova G. Ya. (2004). The Lagrangian approach to solving the time-dependent Navier-Stokes equations. *Doklady Physics*. V49. N11. pp.648-652.

Guvernyuk S.V., Andronov P.R., Barannikov S.N., Gircha A.I., Grigorenko D.A., Zubkov A.F. (2005). *Modeling of unsteady loads for motion of bodies in viscous fluid*. Report of the Institute of mechanics of LMSU. N 4775. Moscow (in russian).

Guvernyuk S.V., Grigorenko D.A., Andronov P.R., Gircha A.I., Dynnikova G.Ya. (2005). *Algorithm of numerical simulation with methods of discrete vortices and viscous vortex domains*. Report of the Institute of mechanics of LMSU, N 4831. Moscow. (in russian).

Guvernyuk S. and Dynnikova G. (2007). Modeling the flow past an oscillating airfoil by the method of viscous vortex domains. *Journal Fluid Dynamics*. V.42. pp.1-11.

Strekalov S.D. Certificate of authorship N1240949, 30.06.86. Wind generator. Bulletin of inventions N 24.

Strekalov S.D., Misharev G.M., Strekalova L.P. (2004). *Wave technics*. Volgograd. (in russian).