Effect of aerodynamic interference on the autorotation of pair of plates or Savonius rotors

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This work was devoted to investigation of the mutual dependence of processes of autorotation of two plates or two Savonius rotors.

At the beginning of this investigation a series of experiments to find the optimal relative position of the pair of auto-rotating plates and the fixed screen, which was located upstream from these plates, was carried out in the wind tunnel A-6 of the Institute of mechanics of the Moscow State University. The experiment was designed according with the scheme, shown in fig. 1, here $\mathbf{L_1}$ is the length of the fixed screen and **L** is the length of each of two plates. The distance between the centers of rotation of these plates is equal to **1,1 L**. The length of the fixed screen ($\mathbf{L_1}$) and the lengths of the rotating plates (**L**) are varied. The results of measuring of the angle speed of each plate's autorotation show that for several values of varying parameters the angular velocity of these plates in the direction shown in the fig. 1, exceeds the corresponding rate of autorotation of a single plate and the maximum speed of the synchronous autorotation for the pair of plates without the screen. For the optimal configuration of these 2 plates and the screen (when the speed of the autorotation reach it's maximum value) there was found that $L_1 \approx 0.7\,L$; $h \approx 0.125 L$, where h is the distance between the plane, including the fixed screen, and the plane, tangent to the area swept by two rotating plates and closest to the screen.

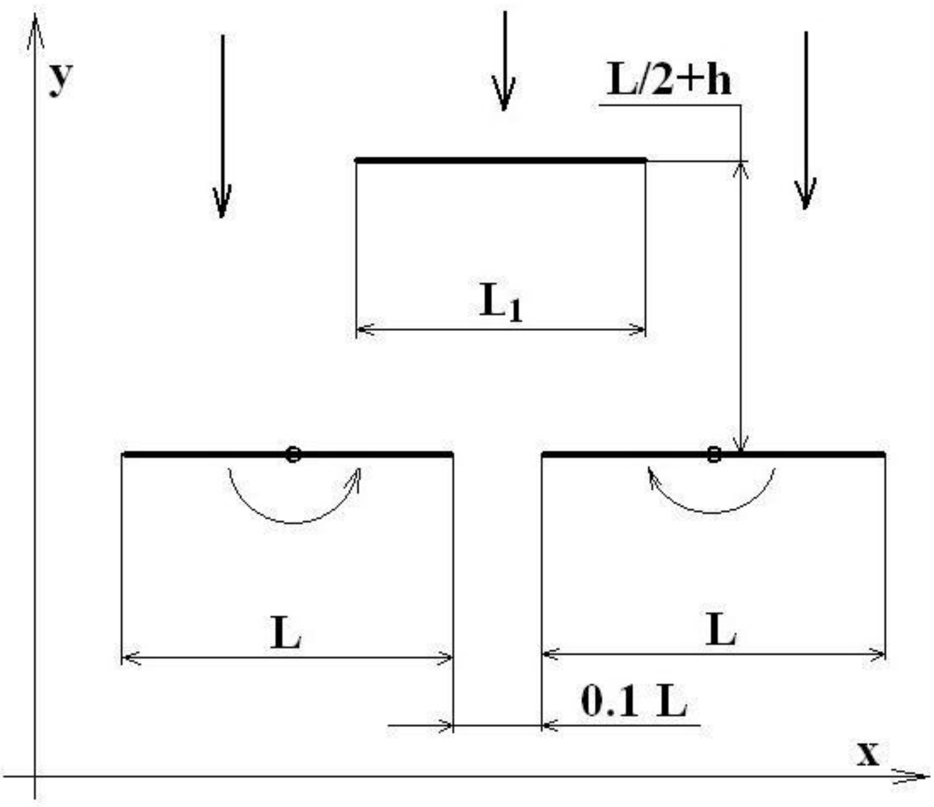


Fig. 1. The experimental scheme of location of two plates and the screen

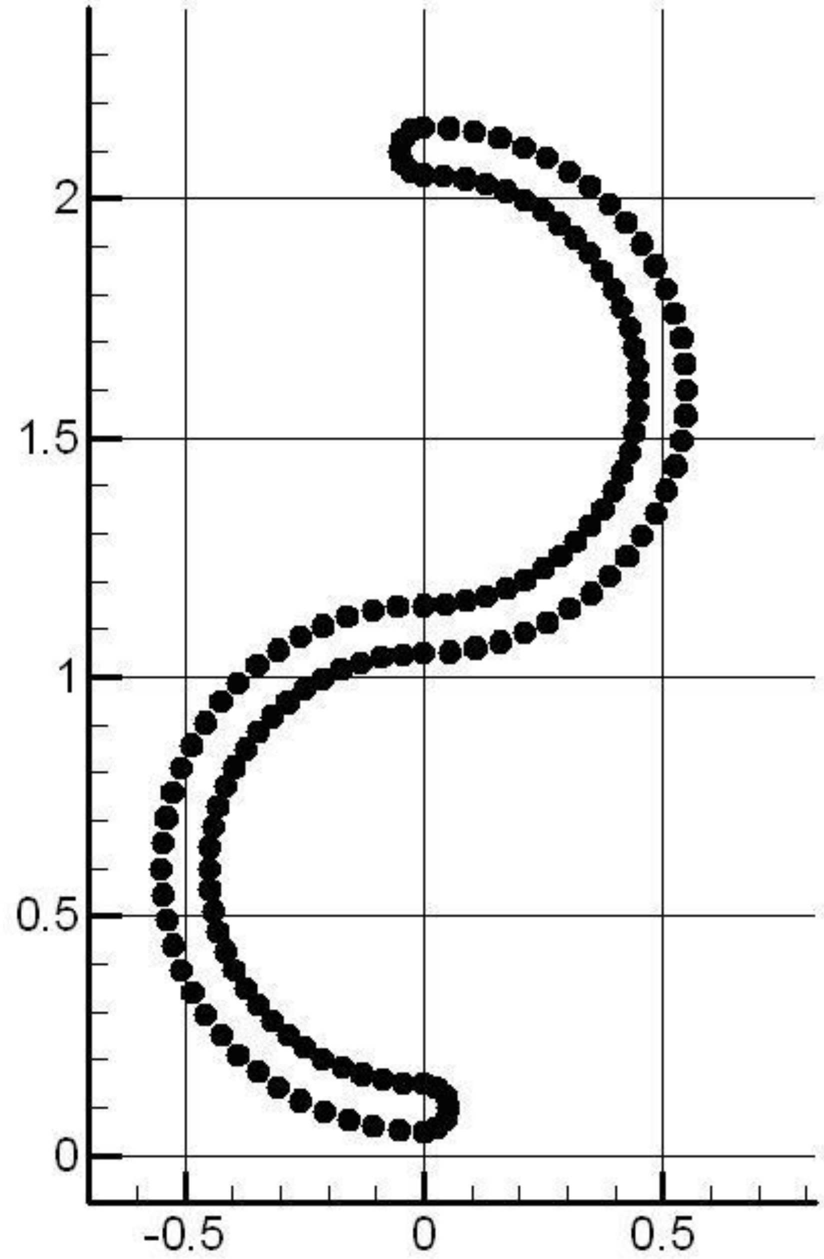


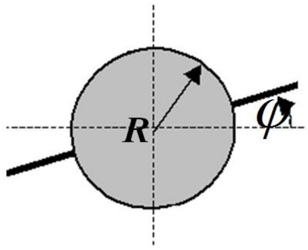
Fig. 2. The bilobed Savonius rotor

From the experiment [1] it is known that the two-bladed rotor wind wheel (the bilobed Savonius rotor; fig. 2) has a higher efficiency of using of the energy of the stream (up to 19%) and develops a greater speed than the three-bladed Savonius rotor and the four-bladed Savonius rotor.

For numerical simulation of the conjugate problem of dynamics and aerodynamics of auto-rotating body (the Savonius rotor) in this work we use the non-grid Lagrange numerical method which is called: "The method of the viscous vortex domains (VVD)". This method enables to calculate the motion of the body and of the fluid using the common system of equations. Similar description [2, 3] of the connected motion of the body and of the fluid is called "the vortical formulation of this conjugate problem" (1).

The "vortical" formulation of the conjugate problem of dynamics and aero-hydrodynamics is used

$$\begin{cases} \nabla \cdot \mathbf{V} = 0\,, \quad \mathbf{\Omega} = \mathrm{rot}\,\mathbf{V}\,, \\ \dfrac{\partial \mathbf{V}}{\partial t} + \Omega \times \mathbf{V} = -grad\left(\dfrac{p}{\rho} + \dfrac{V^2}{2}\right) + \nu\,\Delta \mathbf{V}\,, \qquad (1) \\ J\ddot{\varphi}\mathbf{e}_z + m\left(\mathbf{R}_\mathbf{m} \times \dot{\mathbf{V}}_\mathbf{m}\right) = \mathbf{M}_{ext} + \mathbf{M}_a\,, \quad m\dfrac{d\,\mathbf{V}_\mathbf{m}}{dt} = \mathbf{F}_{ext} + \mathbf{F}_a \end{cases}$$



$$\frac{\partial\,\Omega}{\partial\,\mathrm{t}} = \mathrm{rot}\left(\mathbf{V} \times \mathbf{\Omega} + \nu\Delta\mathbf{V}\right), \quad \mathbf{\Omega} = \Omega\,\mathbf{e}_z\,, \quad \mathbf{F}_a = -\frac{d\,\mathbf{P}_{fluid}}{dt}\,, \quad \mathbf{M}_a = -\frac{d\,\mathbf{K}_{fluid}}{dt}$$

$$\mathbf{P}_{fluid} = \rho \int\limits_{Sext} \mathbf{r} \times \mathbf{\Omega} ds - \rho \oint\limits_{L} \mathbf{r}_s \times \left(\mathbf{V}_s \times \mathbf{n}_s\right) dl \qquad \mathbf{K}_{fluid} = -0{,}5\,\rho \int\limits_{Sext} \mathbf{r}^2\,\mathbf{\Omega}\,ds + 0{,}5\rho \oint\limits_{L} \mathbf{r}_s^2 \left(\mathbf{V}_s \times \mathbf{n}_s\right) dl$$

- Hydrodynamic impulse of fluid (Lamb, 1947) ***- Rotary impulse of fluid (Lamb, 1947)*** ***- P.G. Saffman. Vortex Dynamics (1992)***

For non-vortical movements the theory is developed by Thomson, Tat, Kirhgoff (1869)

In our calculation (performed with help of software system [4]) it was found that in the presence of load (the viscous friction in the rotor axis; $k = 0.5$) the averaged angular velocity of the two-bladed rotor is equal to 0.56, and the dimensionless useful power (coefficient of using of the wind energy) is equal to 0,156. The difference between the results of our calculation and the results of the experiment [1] is about 18%.

The calculations of the flow near the two-, three- and four- bladed Savonius rotors show that two-bladed Savonius rotor is more efficient than three-bladed and the three-bladed rotor is more efficient than a four-bladed. This result is in qualitative agreement with experimental data [1].

After that there was investigated the effect of fixed screens located upstream from the rotors, and the influence of the interaction of vortex wakes (i.e., aerodynamic interference) on autorotation of Savonius rotors and on the efficiency of flow energy use. To calculate the dimensionless useful power (i.e., the coefficient of wind energy using) in the general case in the presence of two or more rotors (or screens), we used the formulae [5]:

$$\varepsilon = P / P_0\,, \quad P = k\sum_{i=1}^{N} \omega_{i\,cp}^2\,, \quad P_0 = 0.5\sum_{j=1}^{N_S} P_{0\,j}\,.$$

Here, the moment of load for the i-th rotor is:

$$M_{нагрузки\ i} = -k\omega_i\,,$$

P – total useful power, N – the number of rotors, P_0 – total capacity of the incoming flow, P_{0j} – the flow rate attributable to the j-th site of the wind-receiving surface, N_S – the number of the wind-receiving sites forming the whole wind-receiving area of the system.

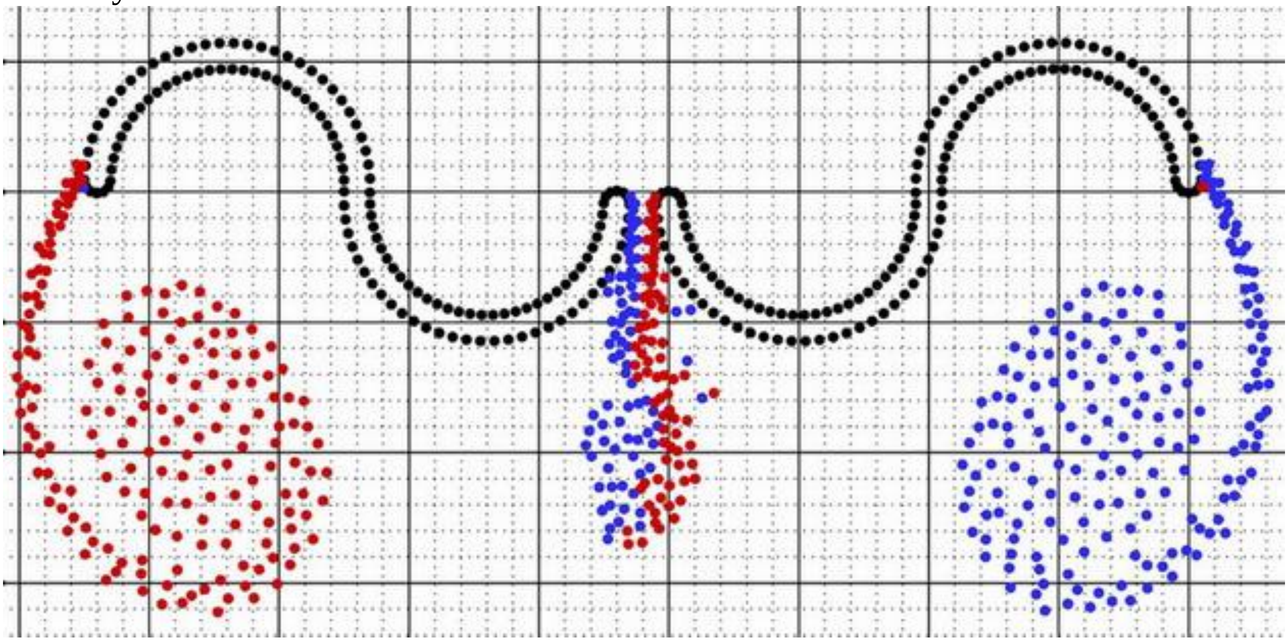


Fig. 3. Instant calculational vortex distribution in the process of autorotation of two Savonius rotors with concave wind-receiving parts located closer to the axis of symmetry between two rotors

To test the effectiveness of the interaction effect of vortex wakes for two Savonius rotors there was calculated the flow near two symmetrically arranged two-bladed rotors (fig. 3). The concave parts of wind-receiving surfaces are located closer to the axis of symmetry, so the direction of rotation is stable and speed of rotation is high.

The presence of two additional symmetrically arranged screens upstream (fig. 4) is helpful for synchronization of the process of autorotation of these 2 rotors.

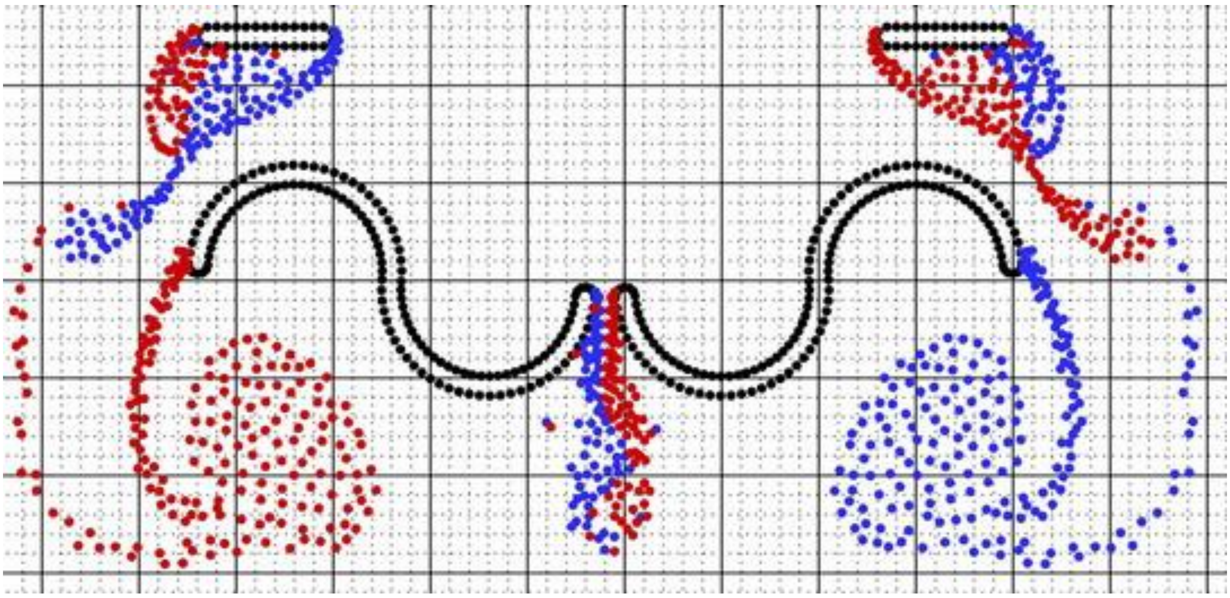


Fig. 4. Instant calculation vortex distribution in the process of autorotation of two Savonius rotors with concave wind-receiving parts located closer to the axis of symmetry between two rotors and with two additional screens before them

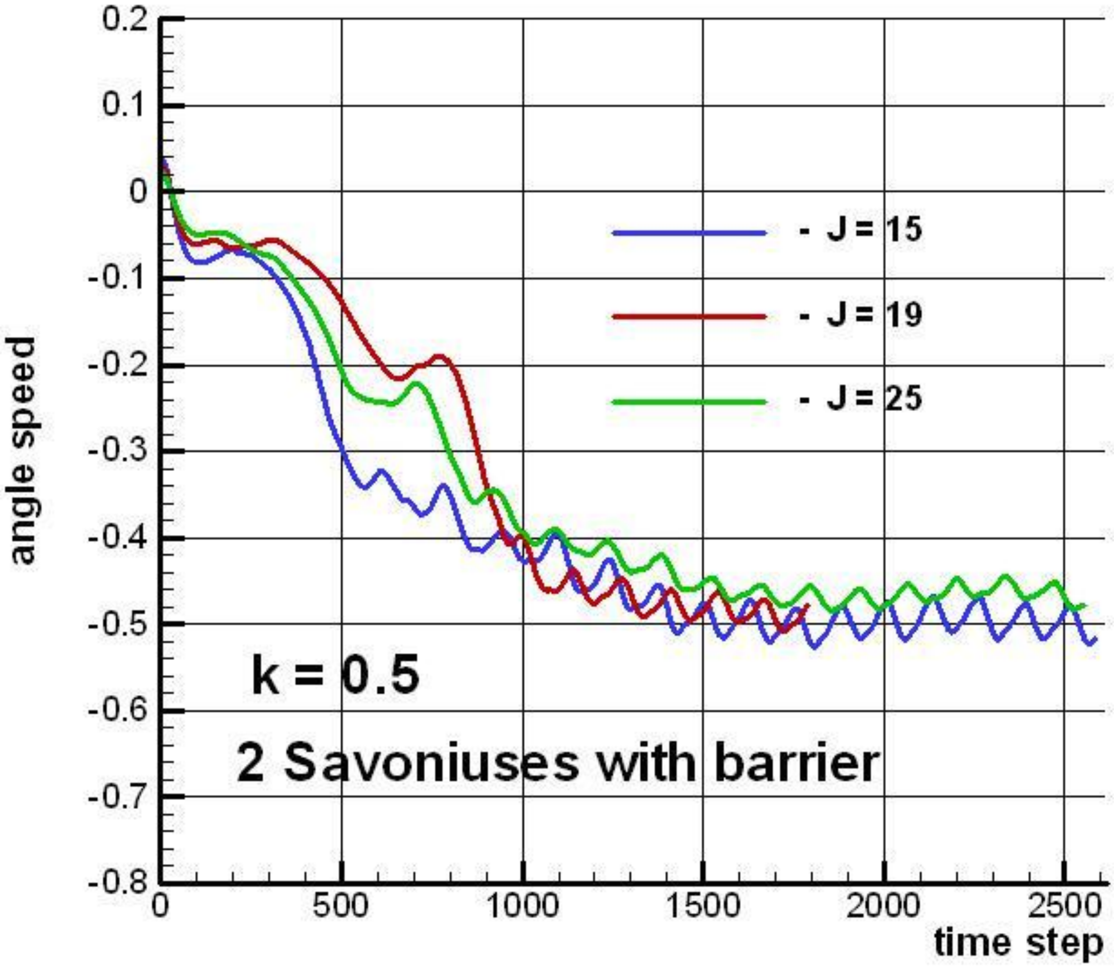


Fig. 5. The dependence on time of the angular velocity of autorotation of the pair of Savonius rotors at different values of their moments of inertia

Under the moment of load (k = 0.5) with increasing the moment of inertia of each of rotors there is not observed the increasing of angular speed of rotors (for the optimal configuration chosen in the experiment, fig. 1), fig. 5.

On the contrary, there is even a little decreasing of the autorotation speed with increasing the moment of inertia.

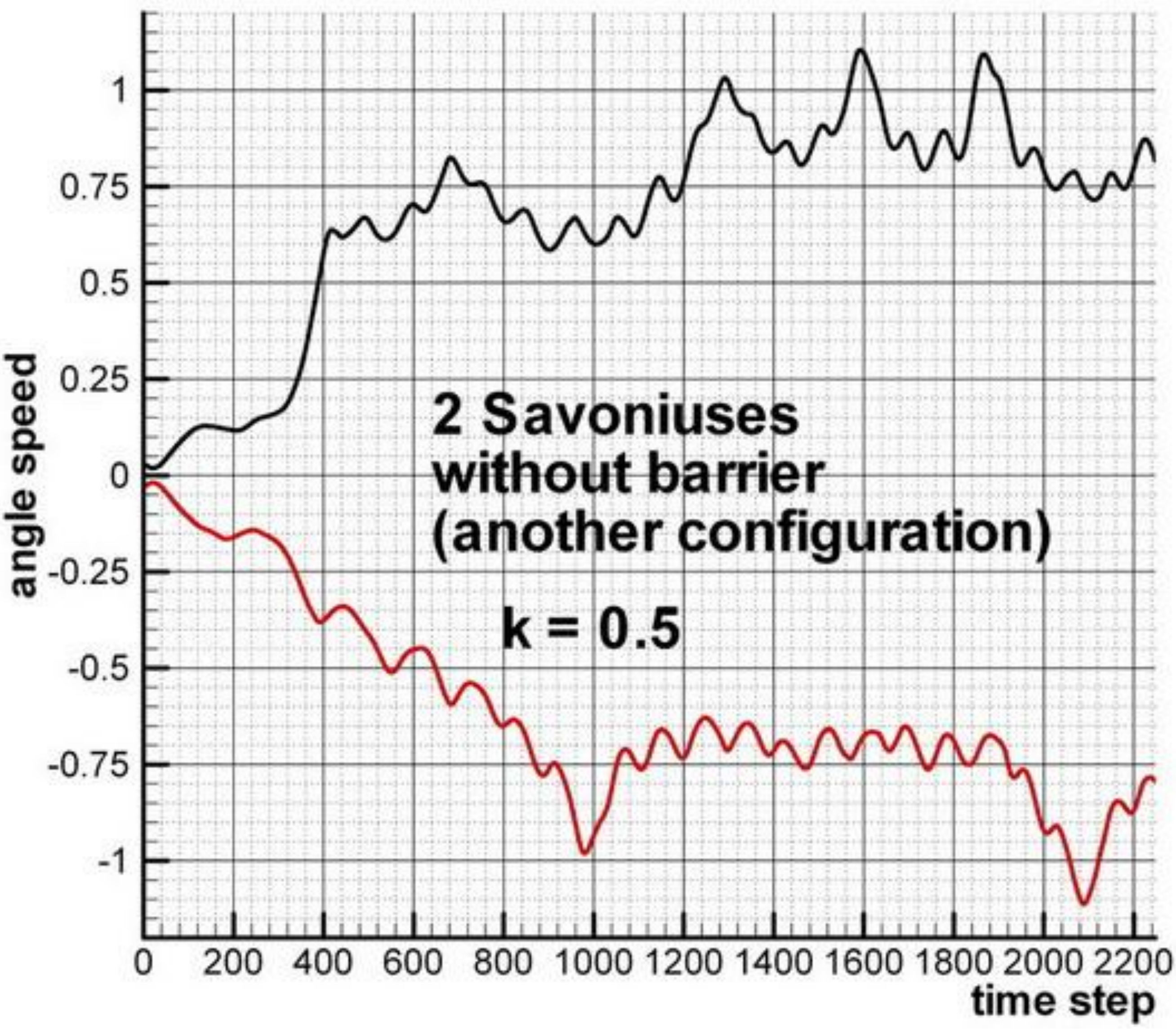


Fig. 6. The dependence on time of the angular velocity of autorotation of each of two Savonius rotors at the value of the friction coefficient in the axis equal to 0.5

Under the moment of load (k = 0.5) 2 Savonius rotors without barriers (with configuration, shown in the fig. 3) accelerated rapidly (fig. 6) than the one Savonius rotor without barriers, except that, the averaged angular velocity is significantly higher than the corresponding rate for 1 Savonius rotor without barrier.

Averaged calculated dimensionless useful power (coefficient of wind power using) for 2 Savonius rotors with two screens located upstream (fig. 4), is nearly 114% greater than the value of calculated dimensionless useful power (coefficient of wind power using) for 1 Savonius without any screen. The presence of 2 screens upstream enables to accelerate the autorotation of two Savonius rotors (fig. 7).

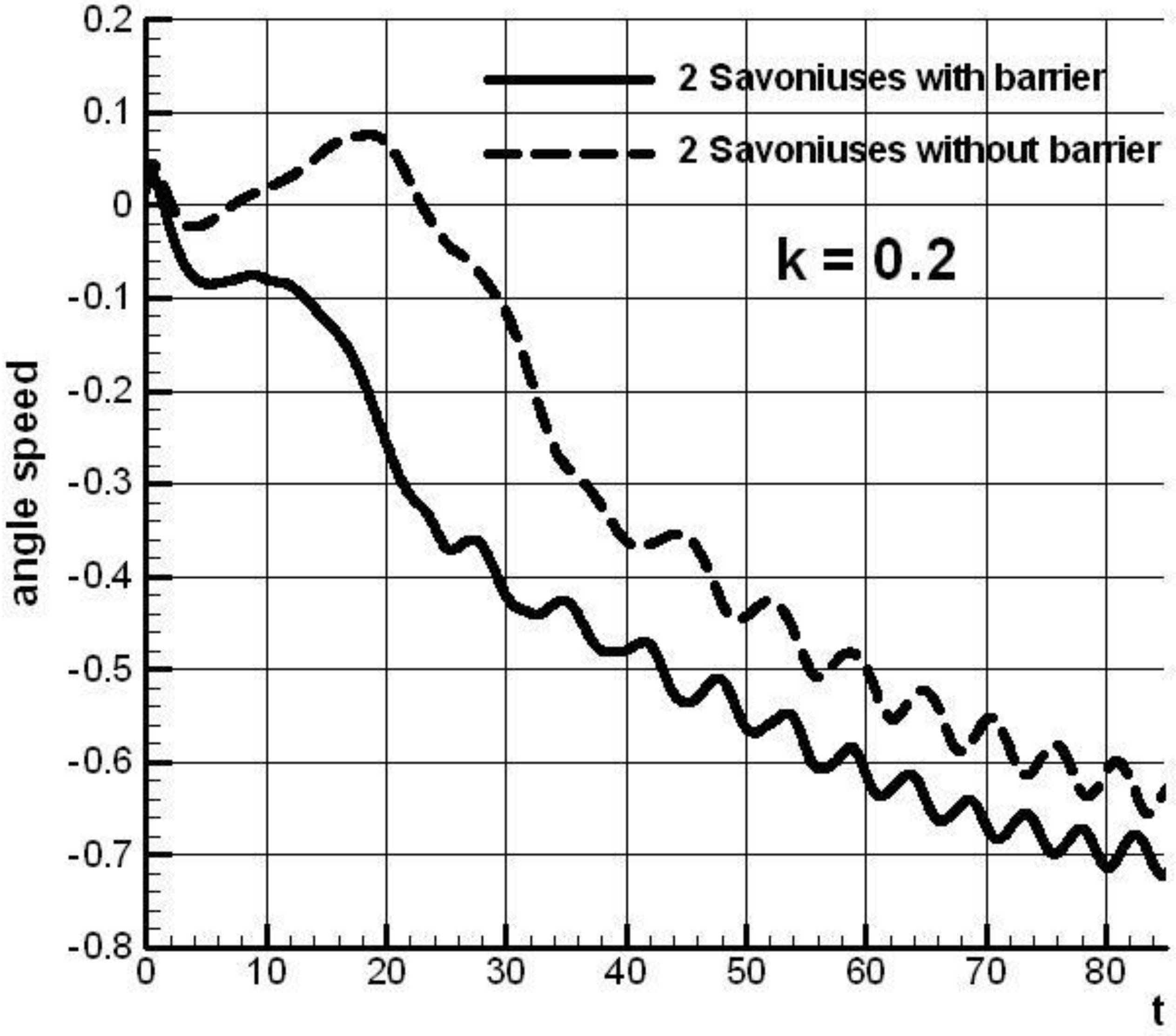


Fig. 7. The dependence of the angular velocity on time for autorotation of the pair of Savonius rotors at the value of the friction coefficient in the axis equal to 0.2

Conclusion

Thus, if someone want to increase the efficiency of wind turbines of rotor Savonius' type it is appropriate to use 2 two-blade rotors and position them so that the concave sections of the wind-receiving surfaces are closer to each other than convex sections. With such arrangement two rotors generate two powerful synergistic vortices by concave parts of their surfaces, and these vortices give more effective contribution to auto-rotation of the rotors than one vortex because of partial consolidation of these interacting vortices and formation of the common area with low pressure. As a result, the useful power of this system of rotors significantly increases in comparison with the case of 2 usual independent two-blade Savonius rotors. Through the using the system of two rotors instead of independent 2 rotors the averaged coefficient of the wind power using increases more than by 100 percent. Through the using two consecutive pair of rotors the averaged coefficient of wind energy using increases more than by 69% in comparison with the single Savonius rotor, but less than one pair of Savonius rotors.

Thus, the optimal from all investigated in this work basic configurations of Savonius rotors is a pair of two-blade rotors, arranged in such a way that the plane, including two axes of rotor's rotation, is perpendicular to the vector of the flow velocity at the infinity, and the concave sections of the wind-receiving surfaces are nearby. This configuration is shown schematically in fig. 3. Each of the rotor's blade in fig. 3 is formed by two semicircles. The gap between the nearest edges of the two rotors is 40% of the radius of the semicircle. For optimal configuration averaged calculated dimensionless power (coefficient of wind energy using) is more that 115% greater than the value of the calculated dimensionless power (coefficient of wind energy using) for 1 Savonius rotor.

In addition, it was found that the synchronization of rotation of pair of rotors can be achieved using a couple of screens located upstream (fig. 4). The size of each screen is equal to 1.4 of the radius of semicircles forming the rotor blades. Distance from the line connecting the centers of rotation of the rotors to each screen is 2.5 of the radius of the semicircles forming the rotor blades.

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