Savonius rotors research for the self-generated power supply by land and by sea

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Abstract. For the first time the experimental investigation was carried out to evaluate the influence of zigzag-shaped wing flaps on a drag coefficient of half-cylindrically bladed Savonius rotor model. Drag coefficients depend on a turning angle of blades $\alpha$ relative to horizontal direction of an air flow and change on the close to the sinusoidal law. Existence of the flaps in the form of triangular zigzags allows increasing drag force of the blades on average by 1.5 times. In the presence of the zigzag-shaped wing flaps on external and internal outer generating lines the rotating speed of a Savonius rotor increases on average by 16%. Application of optimum geometrical ratios of parameters, such as relation of the blade height and the rotor diameter, the distance relation from an axle up to the blade edge to the radius of the Savonius rotor blade and the zigzag-shaped wing flaps will allow to reach the maximum capacity coefficient 0.32. The upgraded construction of a Savonius rotor offered by the authors can be quite competitive with wind-mill electric generating units (WMEGU) of other types. The introduced Savonius rotor of low power will be able to find rather broad application for power supply of independent / standalone objects by land and by sea.

1. Introduction
Savonius rotor is one of the vertically axial wind-mill electric generating units (VA WMEGU). It consists of one or two pairs of vertically located half-cylindrical blades. Advantages of a Savonius rotor cause such merits as simplicity and low cost of its design, a possibility to work at any wind direction and a big starting aerodynamic moment providing its self-run [1–9]. These qualities of a Savonius rotor make it an ideal source of low power for numerous independent consumers of mechanical energy, electricity and heat. Savonius rotor can be used not only by the land, but also by the sea for the water drive of small size vessels [10, 11]. However, most of the authors note that a Savonius rotor has wind power efficiency or power factor lower than at an H-darrieus rotor and wind wheel propeller type of horizontally axial wind-mill electric generating units (HA WMEGU) [4–12]. Improvement of a Savonius rotor design requires a research of blades aerodynamics and the geometrical and power characteristics.

The purpose of the work is the research of aerodynamic, geometrical and power parameters of Savonius rotors. The primary targets of the work are analysis of aerodynamic parameters of half-cylindrical blades of Savonius rotors and assessment of Savonius rotors geometrical and power parameters.
2. Analysis of the main aerodynamic parameters of a Savonius rotor
Rotation of a Savonius rotor is carried out at the expense of the difference of drag forces operating on the blades located on the different sides from a rotor axis. The key geometrical parameters of a Savonius rotor according to [9, 13] are diameters of the rotor wheel $D = 2r$, diameters of the end disks $D_1$, diameter of a shaft $d$, height of the blade $H$, the relative height of the blade $\lambda = H/D$, the central corner of segment of a circle $\theta$, distance from an axle up to blade edge $p$, rotor cross-sectional area $S$, cross-sectional area, wind tunnel $S_0$ and flow blockage factor $\sigma = S/S_0$ (see figure 1).

![Figure 1. The main geometrical parameters of a Savonius rotor.](image)

As it was already marked, rotation of a Savonius rotor is carried out at the expense of the difference of drag forces operating on the blades. However, the vortex current on the blades edges is the main reason of the big aerodynamic drag and loss of energy that reduce rotational speed and power factor of a Savonius rotor. One of the possible ways of low-to-high speed transition and power factor rise is enhancement of blades construction, for example, using original zigzag-shaped wing flaps. The authors made experiments on an impact assessment of zigzag-shaped flaps on a drag coefficient of half-cylindrically bladed Savonius rotor on the laboratory bench (see figure 2). The bench consists of the base 9 with the size of 0.70×0.40×0.020 m. Stands 8 are placed on it, to the upper part of which top and bottom shelves 3, 4 are connected (see figure 1a). On the top shelf the steel spring 1, a scale 2 of a spring 0.500 m long with the price of division of 1 mm is settled down. Units 5 from below are attached to the bottom shelf 4 up and down. Through units the nylon thread is passed that is connected on the top to the left end of a spring, and from below to a fork 7, rotating around an axis of a fork 6. The half-cylindrical blade 11 is connected to a fork 6 on a crosshead 10, which can be turned around an axis. On a stand for angle finder fixing 13 there is an angle finder 12 in the function of which the protractor with the division by 1º is used. In the middle of a fork 7 horizontal section the needle indicator 14 settles down, under that the scale of the needle indicator by the division of 1 mm 15 is settled down on the bench base 9. In a figure 2b the same bench is shown, the flaps of the half-cylindrical blade 16 are additionally mounted there.
Figure 2. The bench for determination of a drag coefficient of a Savonius rotor half-cylindrical blades: 1 – spring; 2 – spring scale; 3 – top shelf; 4 – bottom shelf; 5 – units; 6 – plug axis; 7 – frame; 8 – stands; 9 – bench base; 10 – cross head; 11 – half-cylindrical blade; 12 – angle finder; 13 – a stand for fixing of an angle finder; 14 – needle indicator; 15 – scale of the needle indicator; 16 – flaps of the half-cylindrical blade

The air flow is created by the fan with a diameter of rotor wheel \( D = 0.45 \) m having 3 rotational speeds. The fan settles down at different distances from vertically located frame 7 where the half-cylindrical blade 11 or the half-cylindrical blade with flaps 16 with zigzag triangular shaped overhangs of 10 mm high is enshrined. The blade settled down under a certain angle \( \alpha = 0, 30, 60 \)–330º to the direction of an air flow. Average velocity was defined on the basis of samplings at three points by the digital anemometer at the level of the half-cylindrical blade axis 10. The average rate in the section of air flow was defined by results of these samplings. In case of switching the fan on the average airspeed \( V \) in section at a certain distance affected on the half-cylindrical blade by drag force (head resistance). At the same time the frame 7 together with the blade 11 was rejected to the right. For equilibrating of moment of drag force the moment of force expanding a spring 1 by value of \( \Delta X \) was used. This spring was expanded so that the needle indicator 14 returned on the initial zero mark on an indicator scale 15.

The drag coefficient of half-cylindrical blades was determined by the formula

\[
C_X = \frac{2k_g \Delta X L_1}{L_2 \rho D_b L_3 V^2},
\]

(1)
where \( k_G \) is the coefficient of spring rigidity, \( \text{Nm}^{-1} \); \( L_I, L_2 \) is the arm of force of a spring rigidity and front resistance, \( \text{m} \); \( \rho \) is the density of air, \( \text{kg m}^{-3} \); \( D_R, L_B \) is the diameter and length of model of the half-cylindrical blade, \( \text{m} \).

Two series of experiments by determination of drag coefficients of a half-cylindrical bladed Savonius rotor \( C_{x_0} \) and the half-cylindrical blade with triangular zigzag shaped wing flaps \( C_{x_1} \) have been conducted. Results of processing of experimental data on a formula (formula 1) depending on the average airspeed \( V \) and the blades \( \alpha \) angle rotation are given in tables 1 and 2.

**Table 1.** Drag coefficient of the half-cylindrical blade \( C_{x_0} \).

| \( \alpha, \ \text{deg} \) | 0 | 0.53 | 0.54 | 0.42 | 0.43 | 0.44 | 0.43 | 0.47 | 0.53 | 0.48 |
|----------------|---|------|------|------|------|------|------|------|------|------|
| 30             | 0.72 | 0.68 | 0.52 | 0.64 | 0.60 | 0.57 | 0.56 | 0.55 | 0.61 |     |
| 60             | 0.93 | 0.85 | 0.71 | 0.67 | 0.68 | 0.69 | 0.68 | 0.76 | 0.75 |     |
| 90             | 1.10 | 1.17 | 1.00 | 0.90 | 0.78 | 0.81 | 0.80 | 0.81 | 0.92 |     |
| 120            | 0.87 | 0.97 | 0.75 | 0.80 | 0.73 | 0.69 | 0.68 | 0.76 | 0.78 |     |
| 150            | 0.80 | 0.68 | 0.58 | 0.57 | 0.60 | 0.58 | 0.56 | 0.58 | 0.62 |     |
| 180            | 0.38 | 0.32 | 0.21 | 0.22 | 0.22 | 0.28 | 0.30 | 0.35 | 0.29 |     |
| 210            | 0.49 | 0.41 | 0.34 | 0.29 | 0.28 | 0.27 | 0.31 | 0.31 | 0.34 |     |
| 240            | 0.50 | 0.43 | 0.36 | 0.33 | 0.30 | 0.28 | 0.34 | 0.33 | 0.36 |     |
| 270            | 0.51 | 0.47 | 0.39 | 0.34 | 0.38 | 0.37 | 0.41 | 0.42 | 0.41 |     |
| 300            | 0.54 | 0.43 | 0.34 | 0.33 | 0.37 | 0.35 | 0.35 | 0.39 | 0.39 |     |
| 330            | 0.31 | 0.31 | 0.32 | 0.31 | 0.33 | 0.34 | 0.34 | 0.35 | 0.33 |     |

**Table 2.** Drag coefficient of the half-cylindrical blade \( C_{x_1} \).

| \( \alpha, \ \text{deg} \) | 0 | 0.98 | 0.71 | 0.50 | 0.52 | 0.48 | 0.41 | 0.65 | 0.56 | 0.60 |
|----------------|---|------|------|------|------|------|------|------|------|------|
| 30             | 0.94 | 0.72 | 0.77 | 0.75 | 0.63 | 0.67 | 0.75 | 0.80 | 0.75 |     |
| 60             | 1.34 | 1.19 | 0.78 | 1.13 | 1.19 | 1.16 | 1.10 | 1.22 | 1.19 |     |
| 90             | 1.58 | 1.55 | 1.92 | 1.38 | 1.27 | 1.60 | 1.61 | 1.49 | 1.55 |     |
| 120            | 1.58 | 1.81 | 1.54 | 1.65 | 1.29 | 1.19 | 1.52 | 1.53 | 1.51 |     |
| 150            | 1.18 | 0.90 | 0.87 | 1.05 | 0.95 | 0.88 | 1.02 | 0.92 | 0.97 |     |
| 180            | 0.60 | 0.36 | 0.46 | 0.38 | 0.32 | 0.31 | 0.41 | 0.38 | 0.40 |     |
| 210            | 0.59 | 0.48 | 0.68 | 0.38 | 0.51 | 0.62 | 0.56 | 0.51 | 0.54 |     |
| 240            | 0.59 | 0.60 | 0.68 | 0.53 | 0.57 | 0.57 | 0.63 | 0.55 | 0.59 |     |
| 270            | 0.39 | 0.36 | 0.77 | 0.53 | 0.57 | 0.57 | 0.62 | 0.60 | 0.69 | 0.59 |
| 300            | 0.79 | 0.71 | 0.69 | 0.60 | 0.49 | 0.63 | 0.70 | 0.65 | 0.65 |     |
| 330            | 0.75 | 0.81 | 0.66 | 0.74 | 0.65 | 0.65 | 0.48 | 0.64 | 0.72 | 0.68 |

Apparently from tables 1 and 2 drag coefficients of model of half-cylindrical blades \( C_{x_0} \) of a Savonius rotor and half-cylindrical blades with triangular zigzag shaped wing flaps \( C_{x_1} \) practically do not depend on average rate of an air flow of \( V \) (oscillations of values are connected with a margin error measurements). They depend on a turning angle of blades \( \alpha \) relative to horizontal direction of an air flow. There are average values of drag coefficients blades for each of angles \( \alpha \) of \( C_{x_{1c}} \) (see table 1) and \( C_{x_{1c}} \) (see table 2). They change on the close to the sinusoidal law and reach the maximum values in case of angles 90° and 270°, i.e. in case of perpendicular to the direction of an air flow position of blades respectively concavity and convexity towards to a flow. Calculations on the relation of \( C_{x_{1c}}/C_{x_{0c}} \) show that the average is 1.5. Thus, existence of flaps in the form of triangular zigzags allows increasing drag force of blades. It will increase rotating speed and power factor of a Savonius rotor.

3. Analysis of the main geometrical and energetic parameters of a Savonius rotor

In case of a Savonius rotor rotation there is a flow lift-off from edges of blades. At the same time the powerful vortex current which depends on position of blades and rotational speed of a rotor is formed.
In publications we see that reduced models of a current which do not allow to evaluate real characteristics of a Savonius rotor are applied. Many works are devoted to the pilot study of a two-storey Savonius rotor. The complete results are given in the works [9, 13, 14]. The pilot studies conducted in a wind tunnel [13] showed that the flow blockage $\sigma$ coefficient increase from 5% to 20% doubles the power factor $C_p$. At the same time the maximum $C_p$ is reached in case of higher speed coefficient $Z$ that is equal to the relation of circumferential airspeed $V$. Changing of a flow blockage coefficient $\sigma$ from 0 up to 20% in condition of an optimum ratio between distance from an axle to the blade edge and at the radius of the driving wheel $p/R=0.20$ led to the $Z$ speed coefficient increase from 0.77 to 1.27, i.e. by 1.7 times. The author of the work [13] comes to the conclusion that the optimum Savonius rotor should have the following values of the geometrical parameters: $H/D = 0.77$, $p/R=0.20$, $\theta = 135^\circ$, $D/D_r = 0.75$ (see figure 1). This rotor in case of speed coefficient $Z = 0.79$ in an unlimited flow is capable to reach power factor /coefficient $C_p = 0.32$. However, the experiments executed in the hydropool in case of almost absent influence of the flow boundaries showed that Savonius rotor having size $R = 0.068$ m, $p = 0.015$ m ($p/R=0.22$), $H = 0.175$ m, $D = 0.26$ m ($H/D = 0.77$) and $\theta = 135^\circ$ [9], which are close to the recommended values [14]. At speed coefficient $Z = 0.65$ the maximum value of the power factor is reached and it makes $C_p = 0.20$. Thus, it is advisable to test the optimum geometry Savonius rotor in an unlimited air flow. At the first approximation such flow can be simulated by an air flow from the fan with a wheel of large diameter which by 2-3 times larger than diameter of a rotor. Besides, it is necessary to estimate the influence of triangular zigzag shaped wing flaps on the parameters of a Savonius rotor, in particular on the shaft speed.

The present authors maintained three modifications of the laboratory bench on the Savonius rotor frequency research (see figure 3). The laboratory bench with a Savonius rotor of optimum geometry (diameter $D = 0.185$ m) is presented in figure 3a. Four half-cylindrical blades 4 have height of $H = 0.140$ m, their disclosure angle is $\theta = 135^\circ$, diameter of $D_0 = 0.100$ m. The blades are attached to a shaft 2 by means of disks 3 with a diameter of $D = 0.246$ m. Rotating speed was measured by means of a mechanical frequency counter 1 with a margin error not more than 10 rpm. Air flow average velocity $V$ was determined on the basis of samplings in 6 points by means of a digital anemometer (margin error no more than 0.1 m s$^{-1}$). The same laboratory bench - Savonius rotor with the blades 4 having flaps 5 on the blade external generatrix is shown in figure 3b. In a figure 3c there is the same laboratory bench - Savonius rotor with the blades 4 having flaps 5 on the blade external generatrix and flaps 6 on the blade internal generatrix of is shown. All flaps have the form of triangular zigzags, their height 0.010 m. Three series of experiments were conducted:

- in rotating speed $n_0$ determination of a Savonius rotor with optimum geometry with half-cylindrical blades;
- in rotating speed $n_1$ determination of Savonius rotor with half-cylindrical blades with flaps on the blade external generatrix;
- rotating speed of $n_2$ Savonius rotor with flapped half-cylindrical blades (see table 3).

According to table 3 we see that increase in average airspeed $V$ from 2.1 up to 4.3 m s$^{-1}$, i.e. by 2.1 times leads to rotating speed increase $n_0$ from 100 to 260 rpm i.e. 2.6 times, rotating speed $n_1$ increases from 120 to 280 rpm., i.e. by 2.3 times and rotating speed $n_2$ is up from 140 to 300 rpm., i.e. by 2.1 times. Thus, rotating speed in all series of experiments increases practically in proportion to average airspeed. In the presence of triangular zigzag-shaped flaps of small height (10 mm) on external generatrix rotating speed increases on average by 8%, and the presence of triangular zigzag-shaped flaps on internal generatrix rotating speed increases additionally on average by 8%. Thus, existence of flaps on external and internal generatrix of half-cylindrical blades allows increase of rotating speed on average by 16%. This results from the fact that zigzag-shaped wing flaps significantly increase drag forces which are driving force in the Savonius rotors and promotes rotating speed increase. It will allow significant power and respectively energetic efficiency increase of geometrically optimum Savonius rotor. It is known that the useful output power and, therefore, energetic efficiency of any rotor engine is proportional to a cube of rotating speed $n^3$. Therefore the use of triangular zigzag-shaped flaps will allow to increase the electrical power factor of a Savonius rotor by $1.16^3=1.6$ times. The maximum possible
Figure 3. The laboratory bench on the research of Savonius rotor frequency:
a) with half-cylindrical blades;
b) with half-cylindrical blades and flaps on external generatrixs;
c) with half-cylindrical blades and flaps on external and internal generatrixs;
1 – mechanical frequency counter; 2 – shaft; 3 – end disks; 4 – half-cylindrical blades; 5 – flaps on extrados / external generatrixs blade; 6 – flaps on intrados / internal generatrixs of the blade 7 – top shelf; 8 – stands; 9 – base
Table 3. Rotating speed of Savonius rotor depending on blade construction and airspeed.

| No | $V$, ms$^{-1}$ | $n_0$, rpm. | $n_1$, rpm. | $n_2$, rpm. | $n_3/n_0$ | $n_4/n_1$ |
|----|----------------|-------------|-------------|-------------|------------|------------|
| 1  | 2.1            | 100         | 120         | 140         | 1.20       | 1.17       |
| 2  | 2.3            | 120         | 140         | 160         | 1.17       | 1.14       |
| 3  | 2.9            | 140         | 160         | 170         | 1.14       | 1.06       |
| 4  | 3.1            | 160         | 180         | 190         | 1.13       | 1.06       |
| 5  | 3.3            | 190         | 210         | 220         | 1.11       | 1.05       |
| 6  | 3.4            | 210         | 220         | 230         | 1.05       | 1.05       |
| 7  | 3.7            | 220         | 230         | 240         | 1.05       | 1.04       |
| 8  | 4.1            | 240         | 250         | 260         | 1.04       | 1.04       |
| 9  | 4.3            | 260         | 280         | 300         | 1.08       | 1.07       |

Average value 1.08 1.08

The value of electrical power factor can reach $C_p = 0.20 \cdot 1.6 = 0.32$ that matches the maximum possible value of power coefficient $C_p = 0.32$, received [13]. Thus, it is expedient to supply half-cylindrical blades of a geometrically optimum Savonius rotor with triangular zigzag-shaped flaps. Further on the influence of flaps with various-shaped and sized overhangs on the electrical power factor of Savonius rotors will be studied more in detail.

The authors of the article [15] showed the maximum possible for HA WMEGU $C_p = 0.45$ is reached only in case of coincidence of wind speed to a rotor spin axis. The existence of control systems does HA WMEGU "sluggish" because of long response to the change of the wind direction. As a result the average wind power utilization coefficient at HA WMEGU can decrease to 0.25-0.30 and become lower than at VA WMEGU on the basis of Savonius rotor with the maximum possible 0.32. Therefore the upgraded constructions of a Savonius rotors offered by the authors can be quite competitive with HA WMEGU. Savonius rotors of small power from 1 up to 16 kW will be able to find rather broad application for the mechanical energy, electricity and heat support of independent objects. They can be also applied to the needs of water-supply and power supply as well as to the drive of small size vessels and they can start an H-darrieus rotor [2, 10, 16].

In future it is expected to study and optimize more in detail geometrical parameters of Savonius rotor flaps and it is also suggested to specify aerodynamic and energetic parameters of a Savonius rotor not only in a laboratory, but also in field-use conditions.

4. Conclusion

1. The pilot experimental investigation studies on an impact assessment of the influence of zigzag-shaped wing flaps on a drag coefficient of a half-cylindrically bladed Savonius rotor are for the first time executed. Drag coefficients practically do not depend on the average airspeed. They depend on a turning angle of blades $\alpha$ relative to horizontal direction of an air flow. They change on the close to the sinusoidal law and reach the maximum values in case of angles 90° and 270°. The existence of triangular zigzag-shaped flaps allows to increase drag force of blades on average by 1.5 times.

2. In the presence of triangular zigzag-shaped flaps of small height (10 mm) on external generatrixs rotating speed increases on average by 8%, and in case of existence of flaps on external and internal generatrixs of half-cylindrical blades allows increase of rotating speed on average by 16%. This results from the fact that zigzag-shaped wing flaps significantly increase drag forces which are driving force in the Savonius rotors and promotes rotating speed increase.

3. Application of optimum geometrical ratios of parameters, such as relation of the blade height and the rotor diameter $H/D = 0.77$, the distance relation from an axle up to the blade edge $p$ to the radius of the blade $p/r=0.20$, the central angle of circular arcs $\theta = 135^\circ$ in a Savonius rotor and the use of triangular zigzag-shaped flaps will allow to reach the maximum possible va of power factor $C_p = 0.32$. Thus, it is expedient to supply half-cylindrical blades of a geometrically optimum Savonius rotor with triangular zigzag-shaped flaps.

4. The maximum possible value for HA WMEGU $C_p = 0.45$ is reached only at coincidence of wind speed to an axis of rotation. Existence of wind orientation control systems reduces the actual power.
factor to 0.25–0.30. Therefore the modernized design of a Savonius rotor suggested by the authors with the maximum possible value of power factor 0.32 can be quite competitive with HA WMEGU. The presented Savonius rotor of small power will be able to find rather broad application for power supply of autonomous objects by land and by sea. It can also be used to start an H-darrieus rotor in the combined VA WMEGU.

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