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# JUSTIFICATION OF AERODYNAMIC EFFICIENCY INCREASE METHODS IN GEARLESS HORIZONTAL-AXIS WIND TURBINES

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**Abstrakt.** *Theoretical and practical methods of improving aerodynamic efficiency in horizontal-axis wind turbines with gearless annular rotor by reforming the vortex air flow plane of rotation of the blades are highlighted.*

**Keywords:** aerodynamic efficiency, annular rotor wind turbine, reform vortex flows tail cone.

**Introduction**. One of the promising designs in horizontal-axis wind turbines (WT) is a gearless one, with no multistage mechanisms rpm. However, the establishment of standard generators directly on the shaft of WT is technically appropriate for a single wind turbine blades with a length of 1,5 m, and for counter rotating rotors two turbine systems up to 3 m. It is known [1] that increasing the length of the blades ensures the growth of power squared, but at the same time decreases inversely proportionally to the frequency of rotation of the shaft. Therefore, to increase the linear velocity of the electromagnetically active parts of the rotor gearless electric generator for constant rpm, it is necessary to increase the diameter, which it is possible according to [2] by its running as an open annular casing installed concentrically with the axis of rotation of the blades. The stator of the wind power generator is carried with an arched, fitted rotating rack. In this gearless design solving the problem along with more efficient electromechanical conversion of wind energy, the actual task is to provide high aerodynamic performance of WT.

**The problem state.** Among the modern methods of aerodynamic calculations of wind turbines with horizontal axis, e. g., [3] particular is focuse attention on determining the optimum blades geometric parameters for traditional designs, but a separate assessment of methods for improving the aerodynamic efficiency wind turbines with annular rotor is not considered. However, there are known theoretical studies [4], which can improve the aeromechanical efficiency of the system. Recently, wind turbines construction with of air input confuser dilution cones, have been proposed, which are estimated to have the best aerodynamic performance and greater reliability than the open-blade turbines. However, the theoretical and practical issues of improving the aerodynamic performance of structures with rotating concentric annular generator rotor has not been given sufficient attention, although the use of such structurally similar wind turbines used to be quite widespread, for example, [1] “wheel bicycle” type wind turbines as well as the known contemporary designs circular wind turbines.

**The purpose of the research** is to justify the methods of improving aerodynamic efficiency of gearless wind turbines with a rotor ring housing reform by vortex flow at the plane of the blades rotation.

**Research Methods** Theoretical analysis of aeromechanic system was implemented on the basis of the laws of aerodynamics, including the laws of motion and the attached free vortex flow. The effect of changes in vortex flow behind the blades with open concentric annular rotor and tail cone on laboratory models and the experimental setup is investigated.

**Studies.** The existing theoretical methods of calculating the actual wind turbines [3] are based on a number of assumptions made by the founders of the theory of the ideal windmill. For example, the circulation of airflow velocity around the blade profile is considered without taking into account the changes in the spatial and velocity vectors of the surface aerodynamic effects. A number of simplifications are also the basis of inference [3] that theoretically attainable maximum line aeromechanic efficiency be subject to the loss of one third of the initial wind speed as it passes through the plane of rotation of the rotor blade and reduce it by one-third at a certain distance from the plane of rotation of the blades. Under these conditions aeromechanical theoretically attainable efficiency, which is traditionally called Bettsa limit or the maximum use rate of theoretical wind flow should not exceed 16/27, or approximately 0,593. However, a simple analysis of primary power loss in wind flow under reducing its initial rate by two-thirds shows that this proportion may be somewhat higher. For example, supposing under these conditions the initial velocity of the wind flow to the plane of rotation of the rotor blade is 9 m/s, then in the plane of rotation of the blades fell by one third and was 6 m/s and at a certain distance from the plane of rotation is reduced by one third to 3 m/s. Then, subject to constant mass flow of wind flow, its available capacity, which depends on the cube of the speed decreases from $9^3 = 729$ relative units to the plane of $6^3 = 216$ in the plane of blades rotation is approximately 70 %, and finally to $3^3 = 27$ units at a certain distance from the rotation plane is approximately 96 %. In this example, obviously, one must also clarify how the modules of collinear wind flow velocity vectors in the plane of rotation of the blades were calculated or measured and under the classic phrase “at a distance” with them. The most likely cause of reduced translational velocity wind flow is its partial shift into rotational motion behind the plane of rotation of the blades. However, researching overall picture and quantitative parameters of vortex flows on the plane of rotation of the blades is still insufficient.

The example of the simplified qualitative analysis of power wind flow balance shows that there is certain reserve of aeromechanic improving the efficiency of the rotor blade. Theoretical calculations of such possibility were made by G. H. Sabinin [4], who took into account the additional effect of vortex solenoid and thus defined over the above mentioned Betts limit theoretically achievable value of the coefficient of wind flow, which was estimated about 0.687. That is, the refined picture of changes in direction of air flow with mostly linear motion collinear to the plane of rotation of the turbine rotating vortex flow at a certain distance from the plane and consideration of solenoid vortex tightening action. However, in practice, is still impossible to confirm the calculated by G.H. Sabinin theoretically achievable maximum utilization coefficient of wind flow is mainly due to the complexity of the picture of plane vortices by rotation of the blades. Besides, the parameters of the vortex motion also depend on the size of the rotor blade as in this case, as the diameter of the axial vortex channel also changes. Therefore, we can assume that the vortex flow behind the plane of rotation of different size blade rotor with horizontal axis will have different dilution rates in the axial direction, in accordance with the reduced [5] theoretical model of vortex flows. Another proof of the possibility of increasing the aeromechanic blade rotor design efficiency is modern counter rotating rotor horizontal-axis wind turbine, in which even the real value exceed aeromechanic efficiency theoretically achievable for mono rotor systems. This can be explained by the fact that oppositely rotating rear blades take kinetic energy of swirling blades airflow. This is a known method of increasing the capacity of air flow, for example, when set in front and behind the guide vane axial fan blade [5] that direct attached twisted mass of air in the axial direction. Another well known example of successful application of counter rotating rotors design is modern helicopters models. Obviously, a certain analogy can increase throughput and blade rotors of WT by redirecting air flow vortex in the axial direction behind the plane of rotation of the blades.

Let us analyze the conditions for the creation of vortex flow blades for horizontal-axis wind turbine with an open annular rotor electric gearless wind turbine shown schematically in fig. 1.

Similar schematic model of the mechanism of wind flow on the blade has often been seen before, for example, [1] to explain the theoretical methods of wind turbine calculating. However, in this case it is necessary to analyze the effect on airflow of concentric installed, for example, the front of the blades annular rotor gearless electric generator. As the speed of wind flow influencing the annular rotating body is relatively low (Mach number almost never exceeds 0,1), we can assume the density of air steady. However, the mathematical model of the complex relative motion of wind flow through the normal plane of the rotating ring is described with complex relationships, so with some simplifications the principle of superposition of individual simpler movements can be applied. The circulation of wind flow velocity around a fixed annular body profile, without surface effects is described with the formula:

$$\Gamma_{an} = V_2\,L_2 - V_1\,L_1, \tag{1}$$

where $\Gamma_{an}$ – over the surface of the annular body circulation speed, m$^2$/s; $V_1$, $V_2$ – wrap velocity by the inner and outer surface of the annular body profile, m/s; $L_1$, $L_2$ – length of line profile (circuit) of internal and external surfaces correspondingly, m.

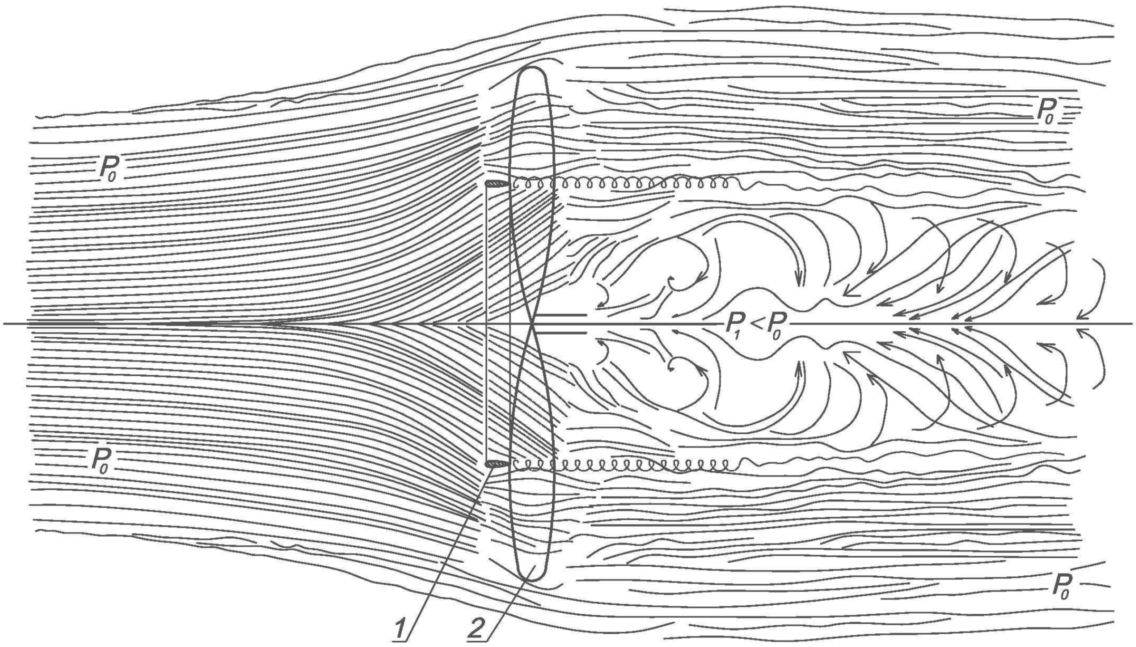


Fig. 1. Schematic representation of a possible movement of wind flow through the plane of rotation of the blades of the rotor annular electric generator: *1* – profile annular rotor body of rotor; *2* – blade

Formula (1) if $V_1 = V_2$ describes the ideal flow picture of perfectly symmetrical surface laminar air flow. However, in the inner and outer annular surface of body is in fact impossible to achieve the symmetry of the surface due to different values of the radii of curvature in normal to the direction of wind flow plane. Also almost it is impossible to provide equality condition of the air flow velocity at the site of their association on the back entire of the profile due to the actual presence of local and surface vortex motions. Thus, the most likely state of the airflow behind the elemental profile rings is chaotic vortex motion, within a relatively small air velocity is described according to the conclusions [5] with the relationship:

$$\partial\omega / \partial t = \nu\Delta\omega, \tag{2}$$

where $\omega$ – the angular velocity of the rotating motion of a single vortex relative to the initial direction of the flow, rad/s; $t$ – time; $\nu$ – kinematic viscosity of air, m$^2$/s; $\Delta\omega$ – Laplace operator for the function of the spatial angular velocity of the vortex axis. In a Cartesian coordinate system:

$$\Delta\omega = \partial^2\omega / \partial x^2 + \partial^2\omega / \partial y^2 + \partial^2\omega / \partial z^2.$$

According to [5] similar equations describe diffusion and heat conduction processes in a stationary environment, so the vectors projection of random vortices behind the blades are aligned in space with tendency of their distribution throughout the volume and gradual decay.

Significant impact on the process of wind flow passing through a plane annular body has a surface shape and the size of its internal and external profiles. For example, the known theoretical explanation [5] of the principles of Bord and Briks-Kort nozzles and special dilution profiles of gradually narrowed channels (confuser), which are widely used to increase the capacity of the stream. So, running the inner and outer annular surface of the rotor body enables to achieve maximum output even in a static mode. Hereby the formation of bound circulation vortex always moves to the side of less convex surface and lifting force under M. E. Zhukov rule action normal to a convex surface.

The described picture changes under the profile rotation of annular body with angular velocity $\Omega$. Then the direction of the wind flow will be determined by the contact angle of the flow, defined by analogy with the known [1] equation:

$$\gamma = \operatorname{arcctg} z_k,$$

where $z_k$ – rapidity annular rotor body,

$$z_k = V_0/\Omega R_k,$$

where $V_0$ – speed wind flow before the plane of rotation of the blades, m/s; $R_k$ – radius of the annular body of the rotor, m; $\Omega$ – angular velocity of the rotor, rad/s; $\Omega = 2\pi n/60$, where $n$ – rotational speed of the rotor, $\text{min}^{-1}$.

The exact mathematical model of vortex flow behind a rotating annular rotor is difficult to describe, but by certain analogies it can be assumed that due to the viscosity of air circulation track of annular vortices forms an overall vortex solenoid with the same direction of rotation as that of the axial vortex behind the blade. At the same time, when going to the overall picture of vortex flow behind the plane of rotation of the blades, where [1] three groups of the most significant vortices, namely bound vortices around each blade helikoid free vortex flow from the flow through the ends of the blades and the axial vortex caused by twisting air axis wind turbine, which is to be added to the annular body formed by coaxial rotor vortex trail. In the theory of vortex flows [5] a similar example of such motion of two vortices in concentric circular trajectory around a common center. is considered. Then, due to the air viscosity, under the condition of keeping “moments of inertia” and “angular momentum” angular velocity of coaxial vortices should be synchronized. Since the minimum pressure is in a joint center of coaxial vortices channel behind the plane of rotation of the blades, it is likely that air will move from different directions, creating a reverse flow and increasing the overall viscosity resistance of the main stream. Direction of backflow movement caused by the difference of the minimum pressure at the plane of rotation of the blades and higher in the surrounding infinite mass of air. For the ideal uncompressed air enviroment with density axial vortex can be considered according to [5] for concentric circular trajectory with a certain circular velocity $V_c$, dependent on the radius $r$, which takes into account only the centripetal acceleration equal to $V_k^2/r$. Then the Euler equation for the projection of motion in radial plane shows the equation:

$$\rho\alpha_r = -\rho V_k^2 / r = -\partial p / \partial r,$$

where $\alpha_r$ – radial size of the vortex; $r$ – radius of rotation of the vortex air masses; $p$ – variable pressure.

Having assumed that the pressure in the surrounding airspace at a considerable distance from the center of the vortex is $p_0$, the pressure difference is described similar to that given in [5] the equation:

$$p_0 - p = \int_{\infty}^{r} \rho v^2 / r dr.$$

The analysis of the equation shows that the pressure decreases monotonically when approaching from a remote area to the center of the vortex. The equation solving shows that outside the vortex flow when $r \geq \alpha_r$ at constant density medium pressure change is described by epy relationship

$$p = p_0 - \rho\omega^2\alpha^2 2r^2.$$

Inside the air vortex when $r \leq \alpha_r$ is similar to the equation for an ideal fluid [5] pressure is determined by the locus with the formula

$$p = p_0 - \rho\omega^2\alpha_r^2 + 0,5\rho\omega^2 r^2.$$

The minimum pressure in the center of the vortex is described by the equation if $r = 0$

$$p_{\min} = p_0 - \rho\omega^2\alpha_r^2.$$

While analyzing this expression, we can see that the value of the minimum pressure in the center of the vortex at constant air density depends both on the size of the vortex and the angular velocity of the air mass inside it, and equally of these squares are mutually alternative options. Of course, the given relationships for the real air flow plane of rotation of the blades should to taking into account many factors which are not present in an ideal fluid, but the general patterns of pressure distribution in the axial vortex are also likely to be executed.

It is also important to analyze the probable direction of the air inside the vortex axial channel behind the plane of the blades rotation. It is indisputable that far behind the plane of the blade rotation pressure is equalized with the pressure around ambient air, while the lowest pressure is at the axis directly behind the plane of rotation of the blades. Thus the pressure gradient in the axial center of the vortex will be sent back from the plane of rotation of the rotor blade, which will cause movement of air in the vortex channel in the opposite direction, i. e. opposite to the wind direction to the plane of rotation of the blades. This, obviously, can explain the complexity of the use of vortex dilution solenoid estimated by G. H. Sabinin for vortex suction in the channel is not from the plane of rotation of the blades, but rather in the opposite direction. Since according to [5] is a vector vortex is solenoidal where $\operatorname{div}\omega = 0$ i $\operatorname{div} V = 0$, then the reverse flow moves along a closed path, i. e., first approaching the plane of the blades rotation, and then by centrifugal forces rejected in a centrifugal direction and mixing of air masses with new part can move in the vortex flow and partly re-exposed in the return flow of axial vortex channel.

A way to reduce the braking action of vortex flows conversion is their distancing from the blades rotation plane through the space localization air movement flow in the direction of increasing static pressure. For example, if you set the rotation plane behind the annular rotor blades and tail diffuser in the form of concentric shells lateral surface of the truncated cone (fig. 2), the brake flows away from the plane of rotation of the blades for the diffuser, and vanes for vacuum before the diffuser increases and causes additional air input suction flow through the annular plane of the rotor.

This rear diffuser also acts as the orientation of the plane of rotation of the blades perpendicular to the wind direction and increasing bandwidth, and therefore its power turbine. Coaxial shell cone establishment at a given distance from the plane of rotation of the blades of the rotor annular zone can delay chaotic vortex flows of the blades, reducing their inhibitory effect. Under these conditions, it is important to ensure coordination of shell size cone diffuser and annular rotor, such as diameter and angle of generators. Due to the complexity of the picture of translational motion of coaxial vortex flow around the outer conical surface and inside it, one could state hypothetically that the formed annular rotating of coaxial rotor vortex ring should take place on the outer surface, forming a kind of barrier for approaching return flow to the rear of the plane of rotation blades. Also important is the relative length and angle of the cone generatrix shell tail cone. The method of the previous experimental studies allows us to say that the highest capacity of wind turbine is achieved if equality ring rotor diameter and larger rear diffuser base of conical shell with its generatrix length equal to one third of the diameter of the angle of inclination $\pi/6$ relatively to the axis of rotation of the rotor. It is obvious that under such circumstances the diameter smaller of a front diffuser base of conical shell is one-third less than the diameters of the ring-shaped rotor and a larger rear base. The above ratio of geometric parameters were also obtained if the ratio of the size Middelev crossing of symmetric projection profile annular rotor body to its diameter as 1:30. Also an important geometrical parameter is the axial distance between the plane of blades rotation and parallel to the plane of the front of her lower base conical diffuser shell, which is a compromise value of the maxima of several functions and still needs further research. However, for these conditions it was experimentally determined that this distance should be half the diameter of the larger base cone or annular rotor. Based on theoretical calculations and the results of experimental research design was designed and manufactured in Bila Tserkva NAU with participation of Bila Tserkva engineering enterprises experimental gearless elektromechanical wind energy installation on wheeled platform, the image in the photo (fig. 3) and assigned to the field of energy and farming processes of agricultural production.

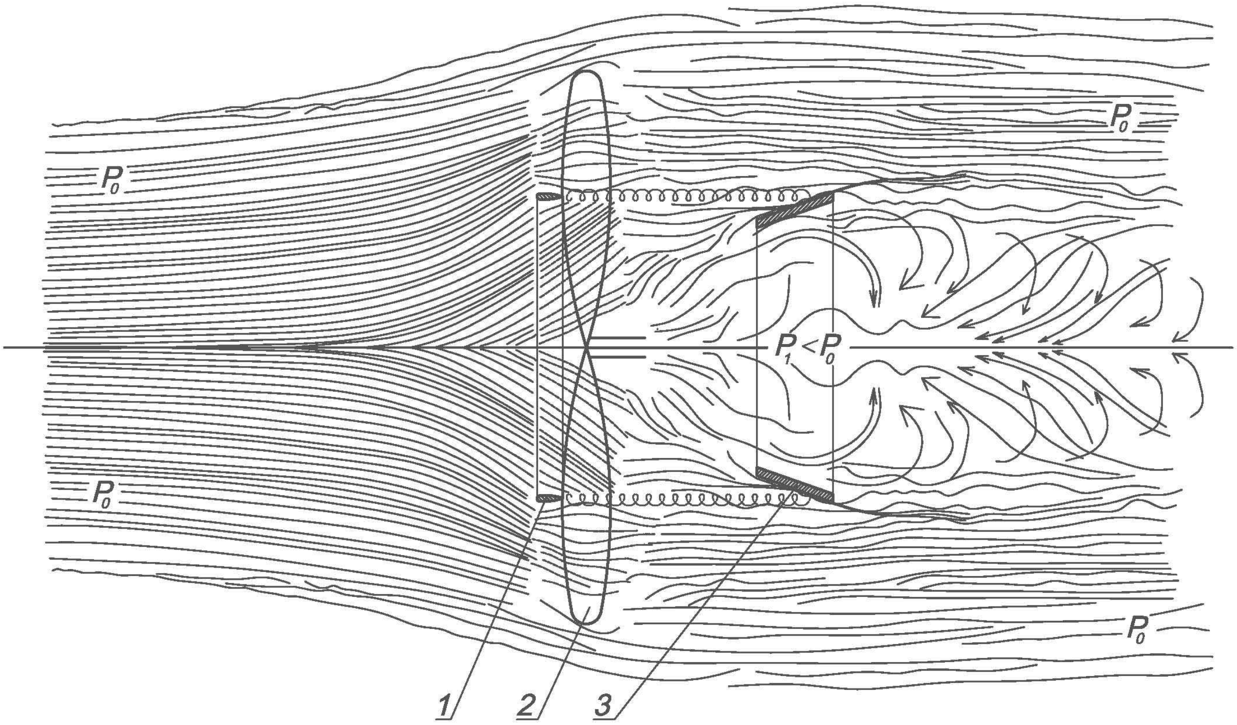


Fig. 2. Scheme of installation and performance of tail cone by a plane of rotation with the annular rotor blades: *1* – profile annular rotor body; *2* – blade; *3* – tail cone profile

Wheel platform with the dimensions: Length – 6400 mm width – 2500 mm height – 910 mm, equipped with four adjustable legs and bargain hook device for aggregation with class 9 or 14 kN tractors, which can transport wind turbines to the new long-distance site of the in the assembly or in nearby destination without a problem on flat terrain but fixed in assembled condition. On the platform installed reversible piramid-like base, height 2,2 m and liftable mechanism of lowering and raising is installed. Wind turbine with three main blades 3500 mm length and annular rotor diameter 2000 mm, fixed at six mounted unregulated blades is mounted on the vertical swivel counter 4100 mm length on a horizontal axis. Behind the plane of blades rotation cone-shaped tail diffuser mounted, geometrical dimensions are calculated by the method described above. Estimated wind turbines power at wind speed 8 m/s is about 7 kW. Versatile of wind turbine is its mobility and the possibility of simultaneous mechanical eccentric drive pumping units and gearless drive of electric generator. It is designed to provide immediate energy needs of field drip irrigation, the area of which has been rapidly increasing, as well as to power the electrified instruments in horticulture using a large capacity battery pack.


Fig. 3. Experimental model of gearless electromechanical wind energetic wheeled platformed installations: *1* – wheel loader; *2* – swivel bearing; *3* – coupling; *4* – the pyramid base; *5* – liftable mechanism; *6* – swivel stand; *7* – the main blade; *8* – body annular rotor; *9* – tail cone; *10* – generator

**Conclusions**

1. Urgent task is to develop methods to improve aerodynamic efficiency gearless wind turbines with annular rotor body on the basis of the use of the optimized shape of its profile and by installing coaxial tail cone in the shape of a shell truncated cone behind the plane of rotation of the blades.

2. The results of theoretical analysis and experimental research designed and produced an experimental gearless wind power plant with annular rotor and tail cone, mounted on wheeled platform designed to consumers energy technology in the field.

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**Обґрунтування методів підвищення аеродинамічної енергоефективності безредукторних горизонтально-осьових вітроустановок**

Описано теоретичні та практичні методи підвищення аеродинамічної енергоефективності горизонтально-осьових безредукторних вітроустановок з кільцеподібним ротором за рахунок реформування вихрового повітряного потоку за площиною обертання лопатей.

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**Обоснование методов повышения аэродинамической энергоэффективности безредукторных горизонтально-осевых ветроустановок**

Описаны теоретические и практические методы повышения аэродинамической энергоэффективности горизонтально-осевых безредукторных ветроустановок с кольцеобразным ротором за счет реформирования вихревого воздушного потока за плоскостью вращения лопастей.