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Aerodynamic Protection of Wind Turbines

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Abstract: *In this work are presented the problems of aerodynamic protection of rapid axial wind turbines, with horizontal aggregate's shaft. There are investigated in detail the interaction phenomena of wind (fluid flow) with aerodynamic shaped blades of the turbine runner. It is calculated for the realized wind power plants (designed by "Politehnica" University of Timişoara) the attack angles of fluid flow on the blade airfoils at different runner radiuses. Also it is determined the operation reserve without separation of the flow from the blade in function of the wind velocity and / or the maximum angle of rotation of the runner blades in respect of blade shaft.*

Keywords: *horizontal axis wind turbines, flow separation from the blades, dynamic stall, three-dimensional flow in the runner, wind power aggregate protection.*

1. Introduction

Wind turbines are usually erected for maximum power production at around 15 m / s wind velocities. It is not economic to design and realize the turbines to withstand for much greater wind velocities. This is the reason why to limit the turbine's power in high wind conditions. If it is not made this protection, there are produced high runner speeds of rotation, overloading all mechanical ensemble and electric generator and sometimes producing catastrophic accidents.
In this article we focus on rapid axial horizontal axis wind turbine (HAWT) realized in two variant: with fixed runner blades and with mobile runner blades. In both cases the aerodynamic protection is realized limiting the absorbed power form the wind turbine, when the airflow separates from the runner blades. By wind turbines with the fixed blades the separation occurs when the wind velocity exceeds a definite value. Mobile blades wind turbine protection is assured through synchronous rotation of these blades around their axis at an external command and consequently producing the flow separation from the blades.

2. Fluid flow separation by rapid axial wind turbines

The aerodynamic protection of wind power plant is realized through a complex phenomenon of interaction of fluid flow (wind) with a solid aerodynamic shaped body in a rotation motion (wind turbine runner blade) by the separation regime of the fluid from the solid. The complexity is produced once by the character of the fluid flow (wind with direction and intensity variable in space and time, turbulence and gust) with three –dimensional structure in the boundary layer and second by the blade geometry (composed of aerodynamic profiles by different radiuses connected and twisted in space) and with its rotation motion. Wind turbine power control [2] through passive separation of the flow from the blade by stall - in a two-dimensional interpretation – takes place when the attack (incidence) angle of the blade constitutive profiles surpasses the stall critical angle and the lift decreases and shows fluctuating values. The advantage of this control system is that it didn't introduced solid mobile parts through the protection device. The disadvantage consists through the possibility of blade vibrations through the phenomenon of flutter. The majority of wind power plants, in operation nowadays, are using this type of control and protection. Wind turbine power control [3] through active separation of the flow is realized through the synchronous rotation of the wind turbine blades. By little wind velocities the wind turbine blades are put in the position of optimal power. When it is attaint the nominal (maximum) power and the tendency is to raise the power then the control device change action direction and induces a separation of the flow from the blades (stall). The advantage consists of the possibility to control the power especially by start and by gusts. Also at high wind velocities it is maintained the nominal power different from passive control, where the power decreases because of increase separation of the flow Fig. 1.

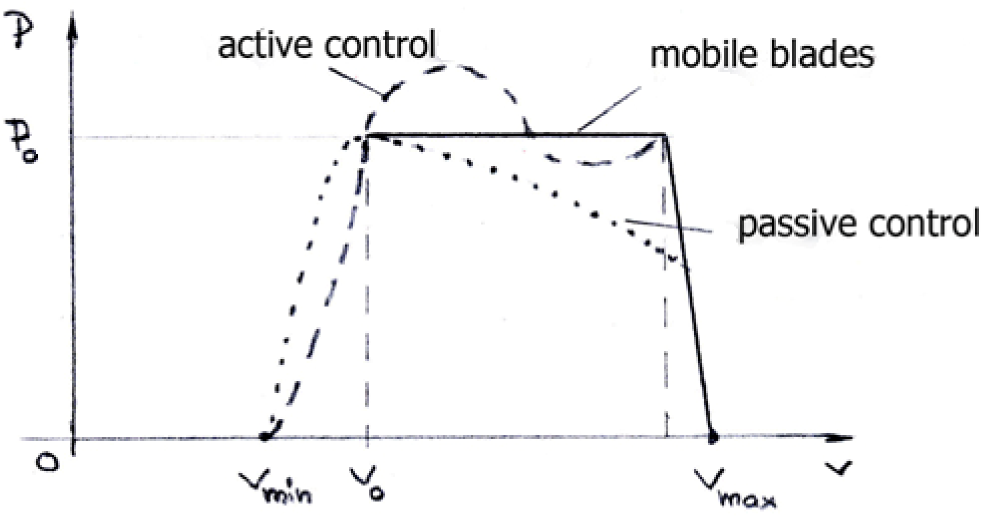

Fig. 1. Passive and active control of separation and control through blade rotation.
P_0 – nominal power; v_0 – nominal velocity

The 3D character of the flow structure in the wind turbine runner blade boundary layer of HAWT [4], is visualized in Fig. 2.

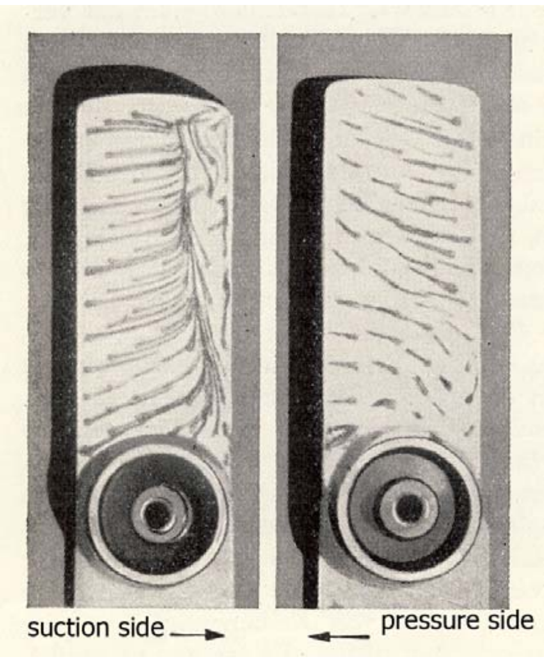

Fig. 2. Flow visualization in blade boundary layer of a turbo-machine [7].

From Fig.2 it is obvious that the fluid flow velocity has axial, tangential and radial components. So the separation investigations need to pass from a 2D analysis to a 3D analysis. Instead of a separation point it occur a separation line on the solid surface Fig. 3 [13].

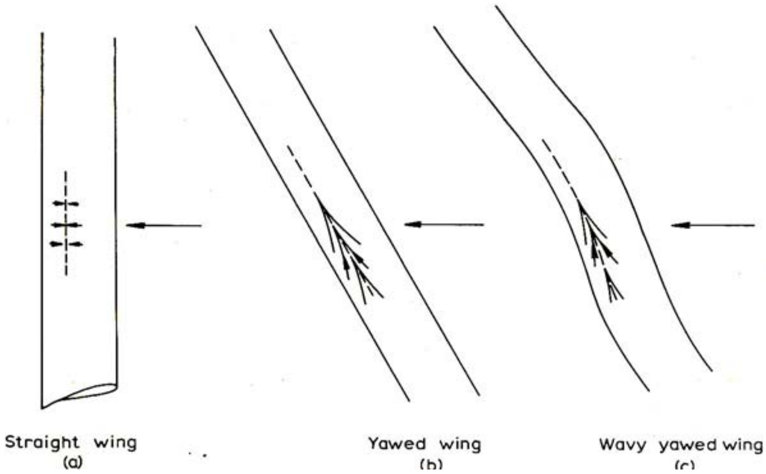

Fig. 3. Flow separation from a blade with different relative positions

Inclined separation comparative with transversal separation of the flow is postponed and occurs by higher wind velocities as it is seen in Fig. 3 qualitatively and this is the case by wind turbines. This kind separation is not so much investigated [13] as the 2D separation of a fluid flow from an airfoil Fig. 4 [5].

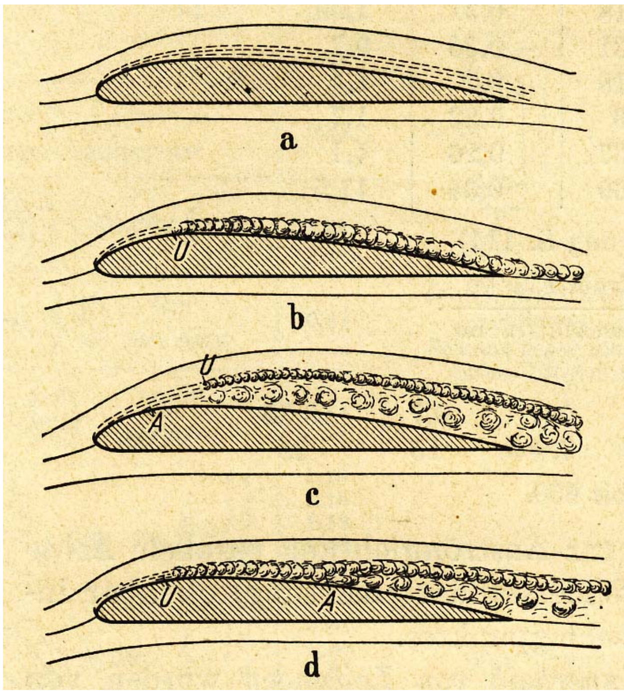

Fig. 4. Development of the boundary layer and the flow separation from a blade:
a – laminar boundary layer; b – laminar – turbulent transition; c – separation in the laminar zone;
d – separation in the turbulent zone; A – separation point ; U – transition point.

Separation from one or two points of the suction side of the airfoil depends from a lot of factors. So the geometry of the profile (and thickness, camber, roughness), fluid characteristics (pressure, temperature) and wind parameters (velocity, direction, turbulence, gust) are important. If the profile is a part from the blade it are added the variability of the profile shape with the radius, blade twist, variation of the attack angle with the radius, Reynolds and Mach numbers. All this elements made a difficult task to establish unique functional dependence of the conditions and power developed by the wind turbine at the stall limit in function of the wind.
The correlation is more like a zone with a definite degree of uncertainty Fig. 5.

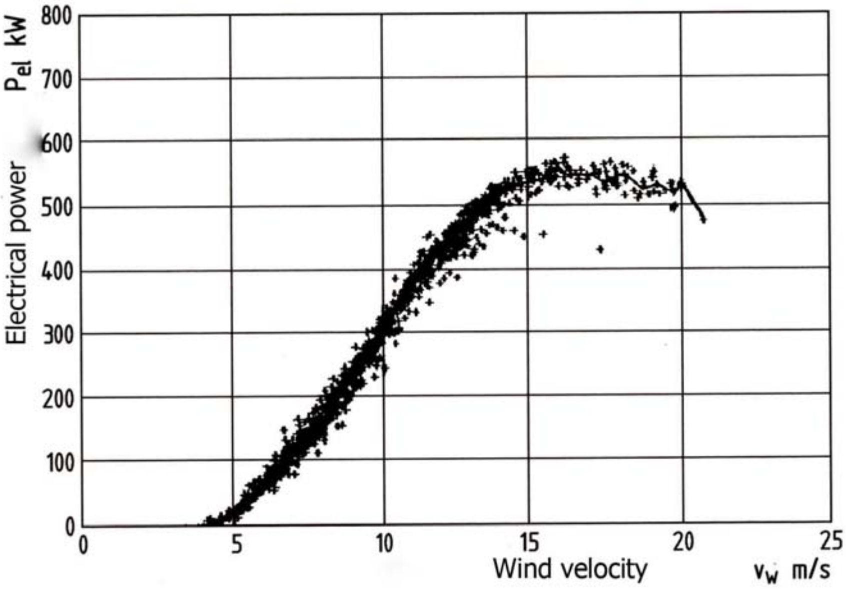

Fig. 5. Mean measurements, with 10 minutes rate, power in function of wind velocity at a wind turbine with fixed blades and with the limiting power through flow separation of the flow from the blade (stall).

Other modalities to protect the wind turbines may be realized through ailerons, aggregate rotation or mechanical and electrical brakes.
Experimentally investigations about the 2 D stall on an airfoil, put in evidence in [7], is analytically studied on the base of Beddoes-Leishman , ONERA and MEXICO models in [8],[9],[10],[11],and [12]. Non-stationary character of the phenomena, measured from apparatus with high dynamic qualities, recorded in Fig. 6 showed the flutter of the airfoil.

Fig. 6. Polar curve of an airfoil recorded with high dynamic qualities.

The comparison between static and dynamic characteristics with hysteresis of an airfoil is represented in fig. 7.

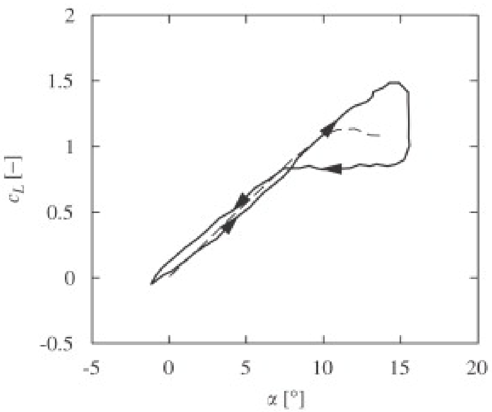

Fig. 7. Static and dynamic with hysteresis lift coefficient in function of attack angle by an airfoil.

The dynamic characteristics with hysteresis showed different aspect in function of the position of the profile along the radius of the blade and frequency of oscillation. Only one example with the hysteresis zone presented in detail is in Fig. 8.

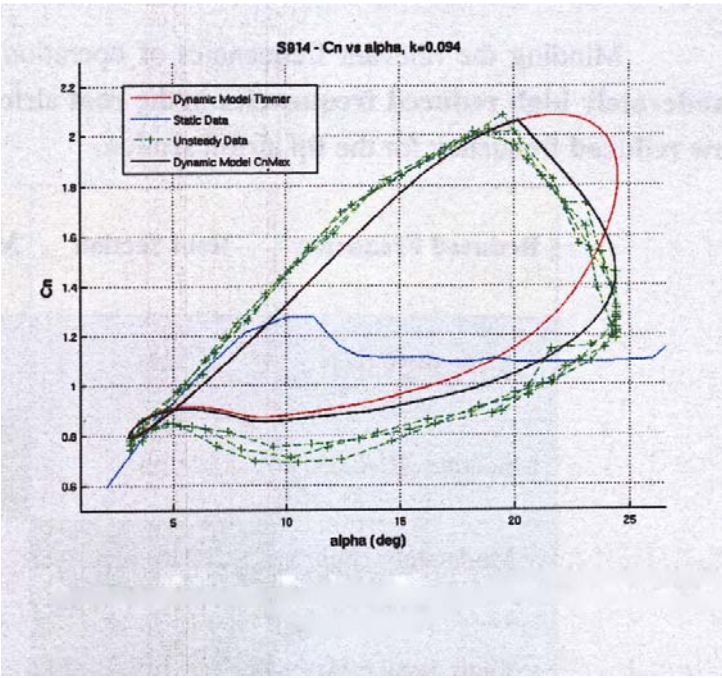

Fig. 8. Static and dynamic lift coefficient in function of attack angle at the root of the blade and with high frequency airfoil oscillation.

3. Protection calculus of the wind turbine from Ciugud

Aerodynamic protection of wind power plant from Marga and Ciugud were verified on the base of flow separation of the flow from the horizontal wind turbine blades through stall. Wind aggregates of 5 kW power in accord with the design [1] and rated wind velocity of v_0 = 8,5 m / s, and rated rotation speed of n_0 = 120 rev / min, for the constant speed of rotation and an interval of Δn_0 = 60 – 120 rev / min for the variable speed of rotation. Knowing the blades geometry through the coordinate of the aerodynamic airfoils at different runner radiuses and grid angles it is calculated the tangential velocity " u ", flow angle " β " and attack angle " i " of the airfoils with the formulas:

$$u = \omega \cdot r = \frac{\pi \cdot n}{30} \cdot r \qquad (1)$$

$$\beta = arc\,tg\left(\frac{v}{u}\right) \quad (2)$$

$$i = \beta - \varphi \quad (3)$$

From the 28 known sections of the wind runner blades there are chosen three representative sections for the hub, middle and outside zones. Data are extracted from [1] referring to breath of the blade (profile's chord) "b" and the complementary stagger angle of the profiles "φ". Results are given in Table 1.

TABLE 1

Rated values v = v_o = 8,5 m / s ; n_o = 120 rev / min.						
r [m]	b [m]	φ [^{0}]	Profile NACA	u [m /s]	β [^{0}]	i [^{0}]
3.5	0.355	4.2857	654415	43.982	10.938	6.6523
2.5	0.525	7.6000	654418	31.416	15.140	7.5401
1.5	0.695	15.3333	654421	18.850	24.272	8.9387

Analytic connection between profile's attack angle and blade radius is :

$$i = 11.99488 - 2.4207 \cdot r + 0.2555 \cdot r^2 \quad (4)$$

with the mean error : $\varepsilon_m = 4.6259 \cdot 10^{-18}$ (5)

For the wind turbines with variable speed it is considered the minimum speed in Table 2:

TABLE 2

Minimum speed values v = v_o = 8,5 m / s ; n_o = 60 rev / min.						
r [m]	b [m]	φ [^{0}]	Profile NACA	u [m /s]	β [^{0}]	i [^{0}]
3.5	0.355	4.2857	654415	21.990	21.1335	16.8478
2.5	0.525	7.6000	654418	15.7075	28.4197	20.8197
1.5	0.695	15.3333	654421	9.425	42.0459	26.7126

In this case the analytic connection between profile's attack angle and blade radius is:

$$i = 39.15383 - 9.7349 \cdot r + 0.9605 \cdot r^2 \quad (6)$$

with the mean error : $\varepsilon_m = 8.0954 \cdot 10^{-18}$ (7)

Comparative analysis of the results about the attack angles form Table 1 and Table 2 shows that runner speed decreasing produce the flow separation at the runner blade hub. Considering the accepted model for fluid flow structure in the runner wind turbines zone given by [2] and [3] it is possible to introduce the axial velocity correction a = 1/3:

$$v_a = v_o \cdot (1-a) \quad (8)$$

The vortex influence which occurs after the runner on the tangential velocity is introduced through the coefficient "a' ". It depends on the axial correction "a" and rapidity „λ":

$$a^{'} \cdot \left(1 + a^{'}\right) = \frac{a \cdot \left(1 + a\right)}{\lambda^{2}} \tag{9}$$

$$\lambda = \frac{u\left(R\right)}{v} \tag{10}$$

$$u^{'} = u\,(1 + a^{'}) \tag{11}$$

TABLE 3

Rated value n_0 = =120 rev / /min							
a **-**	**v_0** **[m/s]**	**u(R)** **[m/s]**	**λ** **-**	**a'** **-**	**v_a** **[m/s]**	**u'(R)** **[m/s]**	**λ'** **-**
1 / 3	8.5	43.982	5.174	0.0412	5.667	45.794	8.081

From Table 3 it is observed that the rapidity of the wind turbine is in the best operation interval of such type machine. Also the value of correction coefficient for axial velocity is considerable but the correction coefficient for tangential velocity is negligible.
Data from catalog NACA [6] gives characteristic curves of the profiles used in Fig. 9, Fig. 10 and Fig. 11.

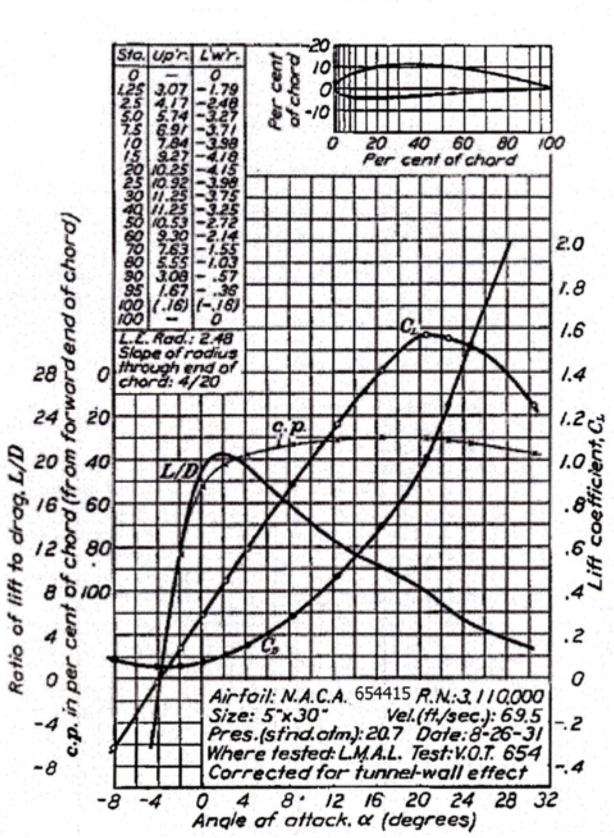

Fig. 9. Characteristic curves of the NACA 654415 profile

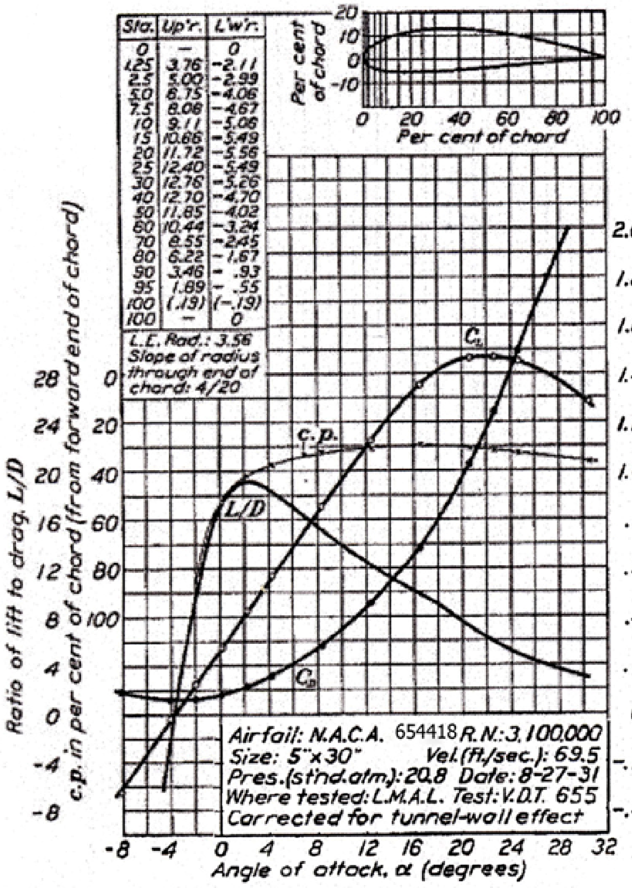

Fig. 10. Characteristic curves of the NACA 654418 profile

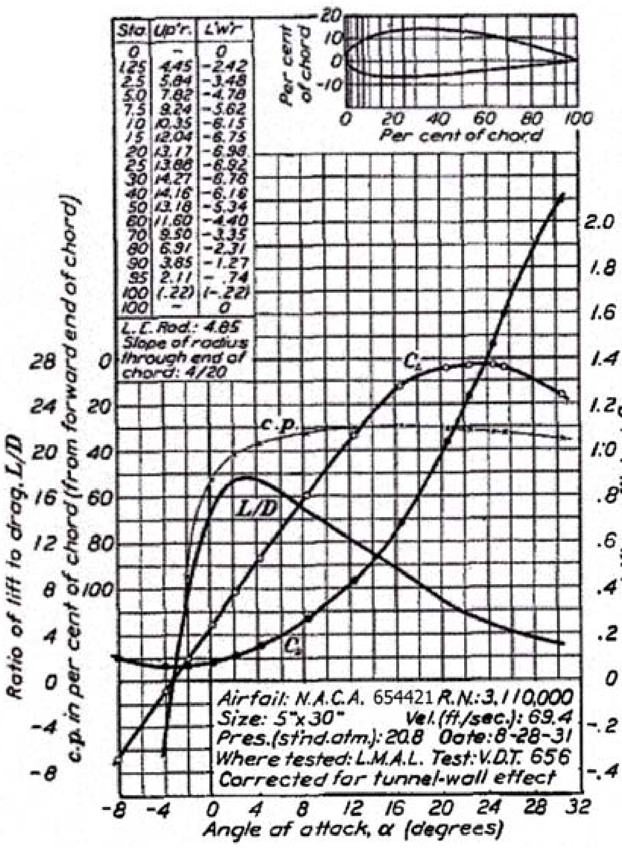

Fig. 11. Characteristic curves of the NACA 654421 profile

From these curves it is deduced the lift coefficient "C_L" corresponding to the attack angle "i" by different operation regimes, Also it is possible to determine critical attack angle values "i_{cr}" for maximum lift coefficient " C_{Lmax}" which assures the operation of the profile respectively the turbines blades without separation. See Table 4.

TABLE 4

Rated values v_o = 8,5 m / s ; n_o = 120 rot / min.				
Profile	**i [°]**	**C_L -**	**i_{cr} [°]**	**$C_{L\,max}$ -**
NACA 654415	6.6523	0.6	20.8	1.57
NACA 654418	7.54	0.8	22	1.47
NACA 654421	8.9387	0.85	24	1.38

Now it is possible to determine the blade axis rotation and the corresponding wind velocity by which the separation of the flow will occur based on the flow structure accepted model namely the interaction of the wind with the blades constitutive profiles.
The blade axis rotation angle Δφ, equal with attack angle modification Δi :

$$\Delta\varphi = \Delta i = i_{cr} - i \qquad (12)$$

The angle between the flow relative velocity with the opposite angle of the tangential velocity of the runner, β, is equal with:

$$\beta_{cr} = i_{cr} + \varphi \qquad (13)$$

and the maximum wind velocity, v_{max} , at the limit of flow separation from the blade surface :

$$v_{max} = u \cdot tg\beta_{cr} \qquad (14)$$

Results are given in Table 5:

TABLE 5

Rated values v_o = 8,5 m / s ; n_o = 120 rot / min.				
Profile	**u** [m / s]	**Δi** [°]	**β_{cr}** [°]	**v_{max}** [m / s]
NACA 654415	43.98	14.1477	25.0857	20.588
NACA 654418	31.415	14.46	29.6	17.846
NACA 654421	18.849	15.0613	39.333	15.446

This table shows the safety of the wind turbine against air flow separation from the runner blades. Namely approximately 14 degrees of blade axis rotation at wind aggregates with mobile blades and for wind velocities approximately of 15 m / s both cases in the situation of zero azimuth angle. After the 14 degrees rotation the separation begins at the out side of the blade (Profile NACA 654415) and the hub zone (NACA 654421) at wind velocities 1.76 times greater than the rated 8.5 m / s velocity.

4. Conclusions

a) Air flow separation from the rapid axial wind turbines blades is complex. The complexity consists on the interaction from three-dimensional fluid flow with a profiled solid body in a rotation movement. Restrictions refers to dynamic stall phenomena namely the aerodynamic separation of the air flow, viscous fluid, two – or three – dimensional, incompressible, stationary and subsonic. Separation from the blades occurs in constant speed of rotation and zero azimuth angles.
b) Analytic and numerical models which describe the separation of the fluid through the interaction of the flow with runner blade surface are perfectible.
c) The three-dimensional structure of the fluid flow occurs because the air velocity has on the vicinity of the blades an axial, a tangential and a radial component and this delays the separation of the fluid from the blade.
d) Wind power plants protection against flutter calculated through two-dimensional model is secure.
e) The proposed method applied to power plants Ciugud and Marga demonstrates its validity and utility.

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