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MATHEMATICAL MODELING IN RENEWABLE ENERGY CONVERSION SYSTEMS

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Abstract: *Research and elaboration of the systems for conversion of renewable energy sources (RES) as a research objective present great interest and importance. Wind and hydraulic energy currently are the most used, cheap and clean renewable energy sources. The main goal of this paper consists in the mathematical modeling of the aero/hydrodynamic profiles of blades and individualized orientation of the hydrodynamic blades. Using a high order panel method, the potential flow analysis is performed in order to compute the hydrodynamic lift and moment coefficients. The drag coefficient is computed through a boundary layer analysis. Increased efficiency is achieved by an optimum position of the blades with hydrodynamic profile.*
In order to increase the lift and reduce the drag forces for a blade segment with aerodynamic profile, a groove was created on its surface. The optimum location of the groove was determined by means of CFD analysis. Simulation results were compared to test results and the CFD analysis model was validated.
A new design and functional concept of a wind and hydraulic flow turbine with orientation of the hydrodynamic blades was proposed and elaborated.

Keywords: *Aero/hydrodynamic profile, wind and hydraulic turbine, water kinetic energy*

1. Introduction

Can you imagine life without television, cars or computers, without being able to prepare your food every day, without lighting in the house, without heating during the cold seasons of the year, etc.? But all this is the result of creative activity of scientists and inventors, especially during the last two hundred years. All this may disappear during the first half of the present century, following the drastic depletion of natural reserves of fossil fuels. Increased energy consumption leads to a continuous increase in the volume of extracting fossil fuels, which provides more than 85% of energy use today.
What energy sources are able to meet these requirements? Increasing power generation by burning traditional fossil fuels would further endanger the ecological impact. Expectancy of power engineering professionals is based on finding new solutions and processes that would meet the energy needs of mankind in the coming decades or centuries. At the forefront, nuclear energy solutions have been related to, but after the power failures (the U.S. Three Miles Island and Chernobyl in Ukraine), the need to develop alternative solutions environmentally friendly, has become an imperative.
One of the greatest challenges of the 21st century is to ensure the access of every citizen of the Planet to sustainable, non-polluting energy, which according to the UN Commission, means „*a development that meets the needs of the present, without compromising the capacities of future generations to satisfy their own n needs*". Looking visionary into the future, Freeman Dyson of the University of Oxford argues that technological changes fundamentally alter our ethical and social arrangements and that three new, rapidly developing technologies - renewable energy, genetic engineering and global communication - today have the potential to create more uniform distribution of global health.
The concept of energy efficiency (or energy optimization) became, at present, one of the main concerns of mankind on the whole world. With the first oil crisis of the early '70s, human society began to realize more than ever the need for a sustainable strategy by increasing the efficiency of energy use and implementing energy efficiency programs taking into account the depletion of fossil fuel reserves on Earth. Today, we speak of a global energy policy and a concerted strategy to reduce harmful emissions into the atmosphere, based on concrete economic and technical

solutions for rational use of fossil fuel reserves (which still have the main share of energy production) and valorization of renewable energy resources on a large scale, the so-called „*clean*" energy or non-conventional energy, as an alternative to the current system of fuel reserves on Earth. Renewable energies (solar, wind, hydro, etc.) are environmentally friendly but today they are not able to meet these ever-growing needs.

2. Mathematical modeling of wind and hydraulic rotors

Hydraulic and wind energies are the oldest form of renewable energy used by man and has become the most currently used renewable energy sources, being also one of the best, cheap and clean energy sources. The problem of the engineers is to develop hydraulic and wind energy conversion systems with higher efficiency, close to the theoretical limit of Betz (0,593).
The emergence of increasingly efficient computers and modern specialized software has made mathematical modeling an indispensable tool for researchers in various fields. Renewable energy conversion systems are one of these areas. In the Center for the Development of Renewable Energy Conversion Systems (CESCER) within the department „*Fundamentals of Machine Design"*, extensive scientific research is carried out regarding the optimization of the performance of the working bodies of the wind and hydraulic kinetic energy conversion systems, in particular, in the optimization of the profile of blades for wind and hydraulic rotors. A modern research has the following structure (fig. 1):

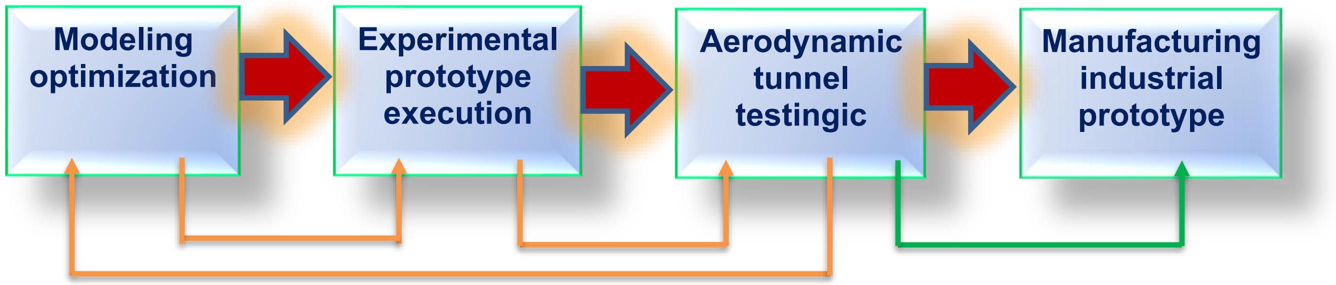


Fig. 1. The structure of modern research

CESCER is equipped with (fig. 2, 3): modern Workstations and performance simulation software ANSYS; 3D printers; aerodynamic laboratory tunnel GUNT HM 170; manufacturing laboratory; human potential.

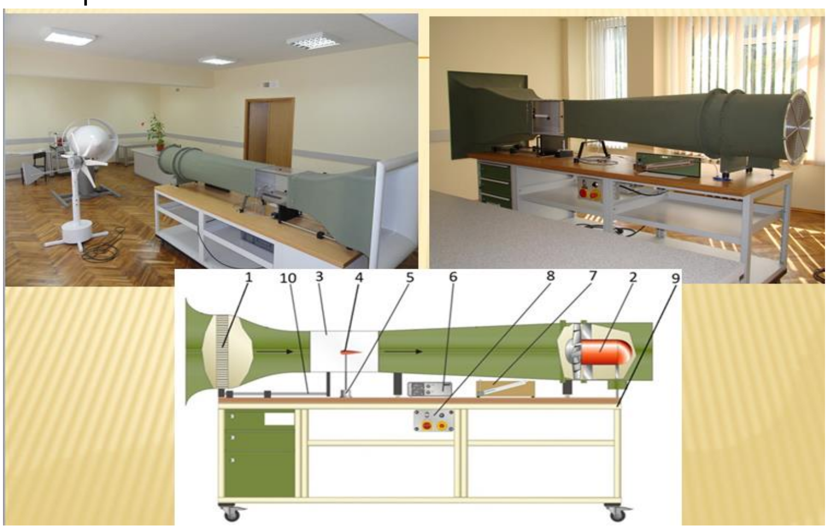


Fig. 2. Aerodynamic tunnel *GUNT HM 170*

Fig. 3. 3D printers for manufacturing

The stages of CFD simulation of the wind and hydraulic rotors are shown in ANSYS Workbench Project schematic (fig. 4).

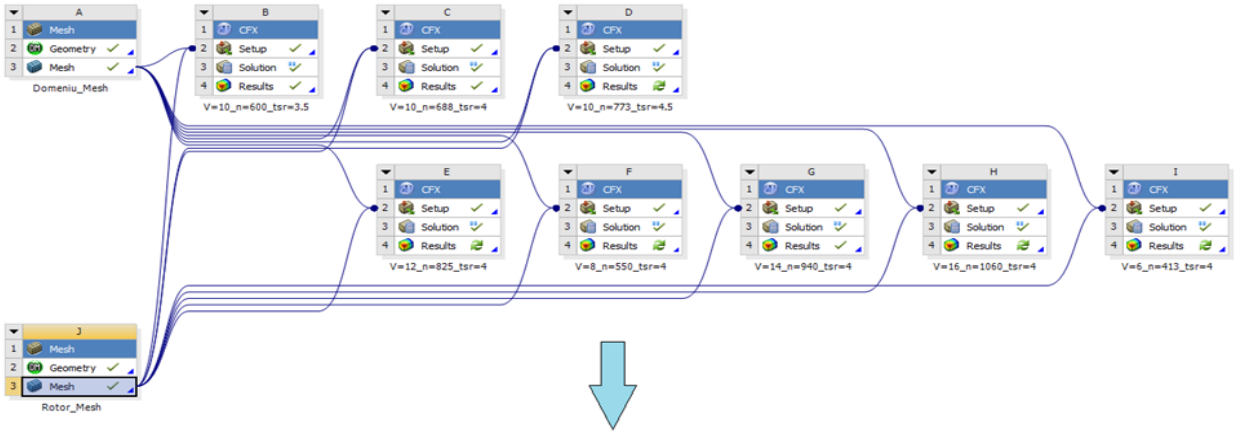


Fig. 4. ANSYS Workbench Project schematic

2.1 Mathematical modelling of hydraulic rotor

Hydraulic energy as a renewable energy source can be captured in two extra power forms:

– potential energy (of the natural water fall);

– kinetic energy (of the water stream running).

Both extra power forms can be captured at different dimensional scales. Thus, the mechanical power of running water can be considered one of the oldest tools. Floating micro hydro power plants are of special interest. In terms of costs, floating micro hydro power plants are efficient because they do not include essential costs related to civil engineering [1,6].

In a classical hydraulic wheel horizontal axle (Fig. 3) [1] the maximum depth at which one of blades is sunk makes approximately 2/3 of the blade height h. Namely, only this area participates in the transformation of water kinetic energy into mechanical one. As well, the prior blade covers approximately 2/3 of the blade surface sunk utmost in the water (h''≈ 2/3h'). This fact reduces significantly the water stream pressure on the blade.

The insistent searches of authors lead to the elaboration and patenting of some advanced technical solutions for floatable micro-hydro power stations, based on the hydrodynamic effect, generated by the hydrodynamic profile of blades, and their orientation at optimum positions concerning the water streams with account of energy conversion in each phase of the turbine rotor rotation (Fig. 4) [1-4,6].

A very important aspect in the functional optimization of micro-hydro power plants is the selection of optimum hydrodynamic profile of the blades which allows increasing the conversion coefficient (Betz coefficient). Therefore, it was necessary to perform a large volume of multi-criteria theoretical research concerning the selection of optimum hydrodynamic profile of the blades and the design of the orientation mechanism towards the water streams.

The adopted technical solutions have resulted in an ample theoretical and experimental research carried out at the Centre for Renewable Energy Conversion Systems Design, Department of the Theory of Mechanisms and Machine Parts. To justify the constructive and functional parameters, supplementary digital modelling and simulation have been carried out by utilizing ANSYS CFX5.7 software. Subprograms developed by authors for the MathCAD, AutoDesk MotionInventor, etc. software, have been utilized, namely simulation of the interaction „flow-blade" of the floatable steadiness and also the optimization of blades hydrodynamic profile, with the purpose to increase the river water kinetic energy conversion efficiency for different velocities by using 3, 4 and 5 blade rotors. In the process of micro-hydro power plants design, the experience gained at research-design-manufacturing of the pilot plant was utilized.

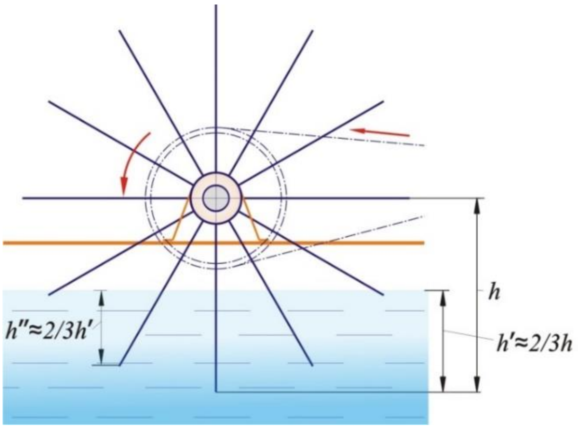


Fig. 5. Conceptual diagram of the water wheel with rectilinear profile of blades.

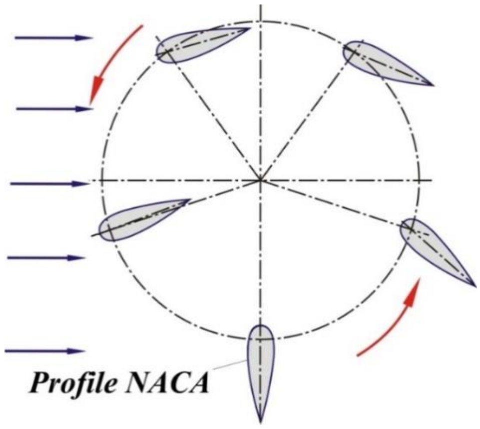


Fig. 6. Conceptual diagram of the rotor with hydrodynamic profile of adjustable blades concerning the water streams

Theoretical argumentation of the hydrodynamic blades profile in normal section

The geometric parameters of the hydrodynamic blades with profile NACA (0012, 0014, 0016, 0018, 63012, 63015, 63018, 66015, 66018, 67015 - about 40 profiles) was optimized [5]. It is considered the symmetrical profile of the blade, which is in a fluid current that moves evenly with speed V_∞ (Fig. 7) [1,2,6]. At the point of fixation *O'* of the symmetrical blade with the arm *OO'* we consider two coordinate systems, namely: the *O'xy* system with the *O'y* axis oriented in the direction of the vector speed V_∞, and the *O'x* axis normal in this direction; the *O'x'y'* system with the *O'y'* axis oriented in the direction of the *O'O* arm, and the *O'x'* axis normal in this direction. Point *A* corresponds to the flight board, and point *B* - the attack board. The angle of attack *α* is the angle between the rope *AB* of the profile and the direction of the velocity vector V_∞, and the positioning angle φ is the angle between the direction of the velocity vector and the *O'O* arm.
The hydrodynamic force *F* has the components in the *O'x* and *O'y* directions, called the load (lift) force F_L and strength (drag) force F_D:

$$F_D = \frac{1}{2} C_D \rho V^2 C_p, \tag{1}$$

$$F_L = \frac{1}{2} C_L \rho V^2 C_p,$$

(2)

where: *ρ* is the density of the fluid, *V* is the velocity of the current, $S_p = ch$ (*c* is the length of the cord *AB*, *h* is the height of the blade) represents the area of the lateral surface of the blade; C_L and C_D are the dimensionless hydrodynamic coefficients, called the lift coefficient (lift) and the coefficient of resistance (drag). The hydrodynamic coefficients C_L and C_D are functions of the angle of attack *α*, the Reynolds number *Re* and the hydrodynamic shape of the blade profile.
The components of the hydrodynamic force in the *O'x'y'* coordinate system are:

$$F_{X'} = -F_L \sin\varphi + F_D \cos\varphi, \tag{3}$$

$$F_{y'} = F_L \cos\varphi + F_D \sin\varphi. \tag{4}$$

Torque moment produced by one blade:

$$T_{r,i} = F_{X'} \cdot |OO'| \quad (5)$$

and total:

$$T_{r\Sigma} = \sum_{i=1}^{Nbl} T_{ri} \ , \quad (6)$$

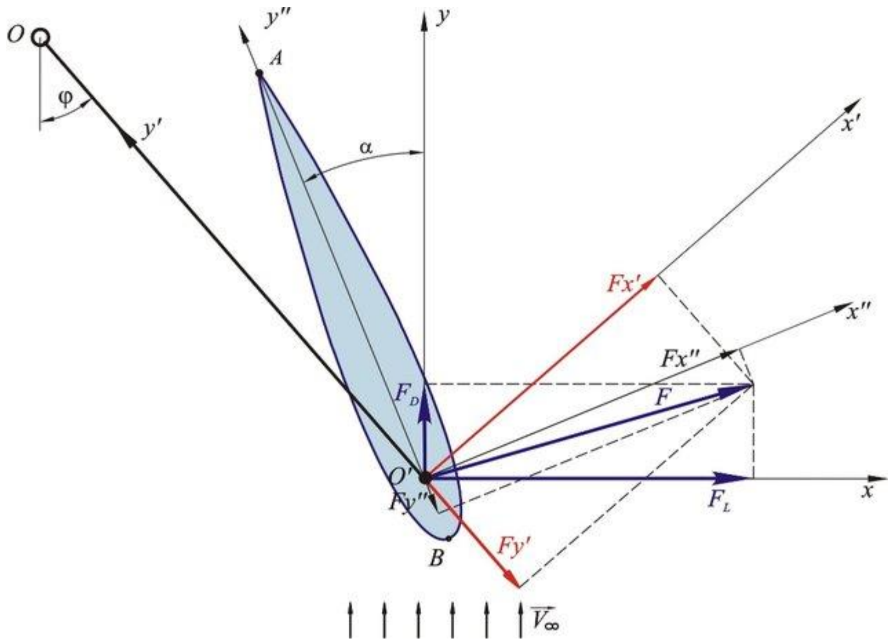


Fig. 7. Symmetrical profile of the blade in fluid current with speed $V\infty$

where: N_{bl} -number of blades.
Determination of the hydrodynamic lift C_L and moment C_M coefficients.

$$C_L = -F_x \sin\alpha + F_y \cos\alpha, \quad (7)$$

$$C_M = \sum_{j=1}^{N} C_{m.j.} \quad (8)$$

We apply the numerical calculation methods described above to calculate the coefficients C_L and C_D for the symmetrical profiles in the NACA aerodynamic profile library (0012, 0016, 63018 and 67015) with the chord length = *1,3 m*. The blade with computational domain was limited (fig. 8) and the streamlines and velocity distribution for angle of attack 18^o was determined (fig. 9). Based on the obtained numerical modeling results were determined: drag and lift coeficients as function of the attack angle *α* (fig. 10); hydrodynamic force *F* wich acting on the blade (fig. 11); torque moment *T* produced by 1 blade as function of the position angle (fig. 12) by all blade for 3 values of water flow speed (fig. 13).

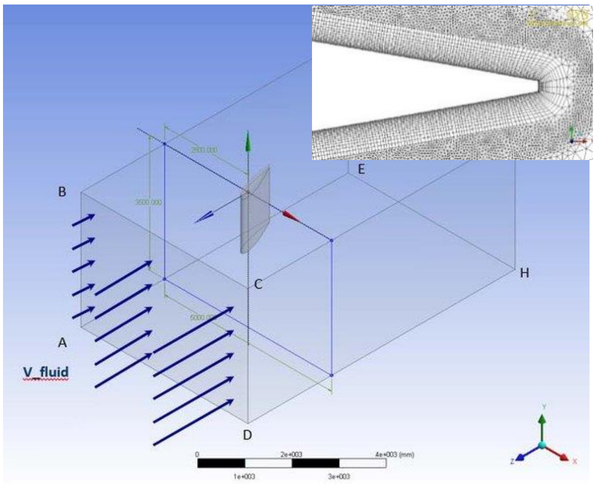


Fig. 8. Computational domain

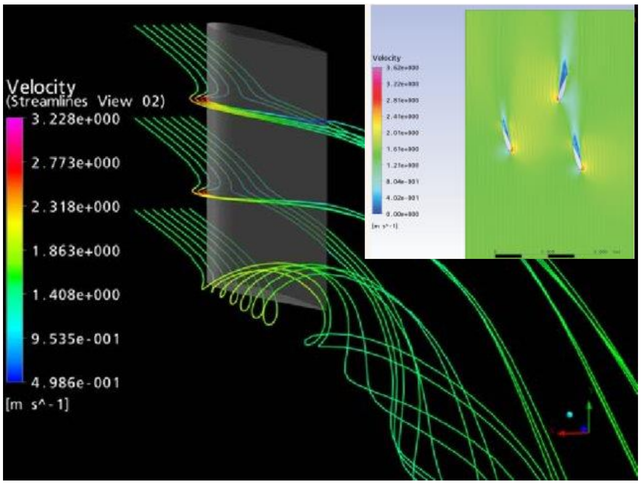


Fig. 9. Streamlines and velocity distribution for angle of attack 18º .

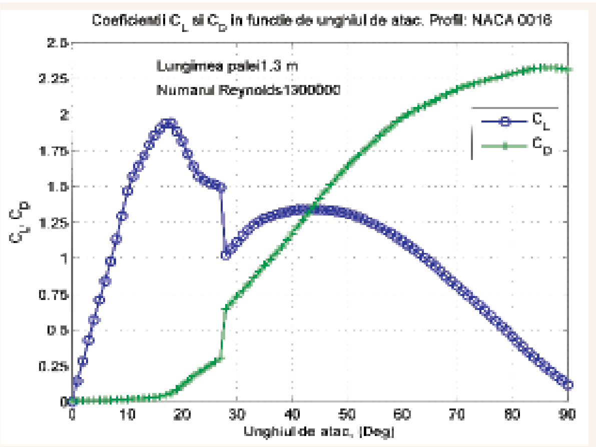


Fig. 10. Drag and lift coeficients as function of the attack angle *α*.

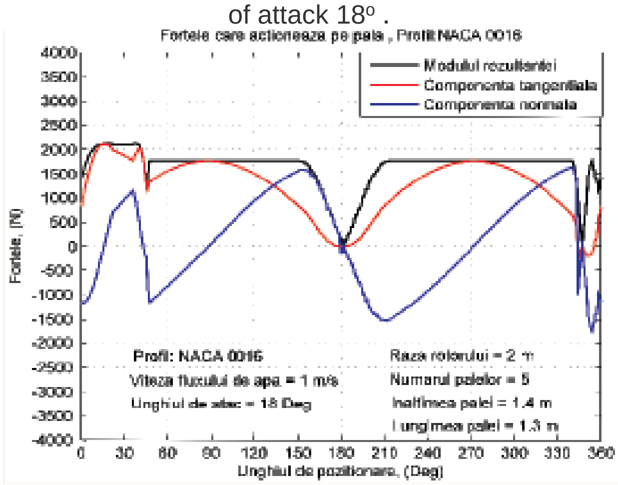


Fig. 11. Hydrodynamic force *F* wich acting on the blade.

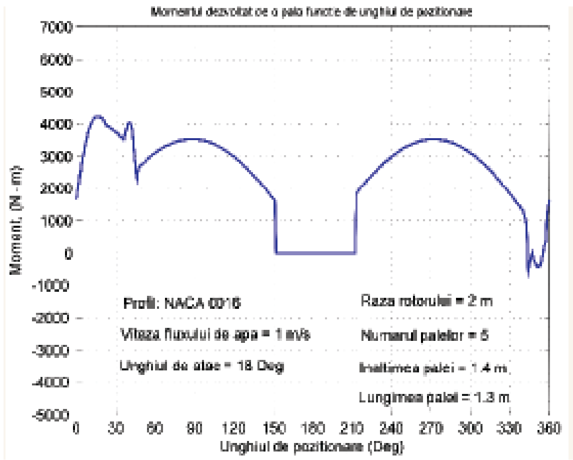


Fig. 12. Torque moment *T* produced by 1 blade as function of the position angle

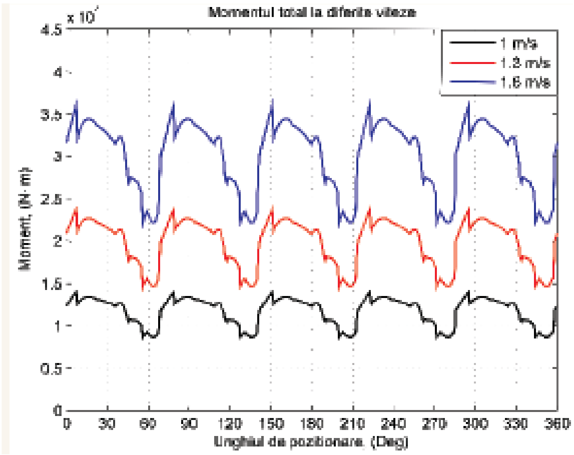


Fig. 13. Torque moment *T* produced by all blade for 3 values of water flow speed

Based on the results of the numerical modelling and the obtained patents [3,4], 3 types of micro-hydroelectric power stations with 3 and 5 blades rotor have been developed, designed, manufactured and tested [1, 5-6].

2.2 Mathematical modelling of wind rotor

In general, the mathematical modelling of the wind rotor is performed similar to the hydraulic one. Mathematical modelling included:

- aspects regarding the optimization of the aerodynamic profile of the blades;
- aspect regarding blade resistance.

2.2.1. Optimization of the aerodynamic profile of the blades

The velocity field around of the profile NACA4412 at the attack angle and Reynolds number given by:

$$Re = \frac{\rho c \vec{V}}{\eta} = \frac{c\vec{V}}{\nu}, \tag{8}$$

CFD modelling of the turbulence. An important problem in horizontal axis rotors is the reduction of the level of turbulence, which reduces the conversion efficiency. The results of measurements of air currents velocity and turbulence intensity in the field around the NACA 4412 profile are presented in fig. 14.

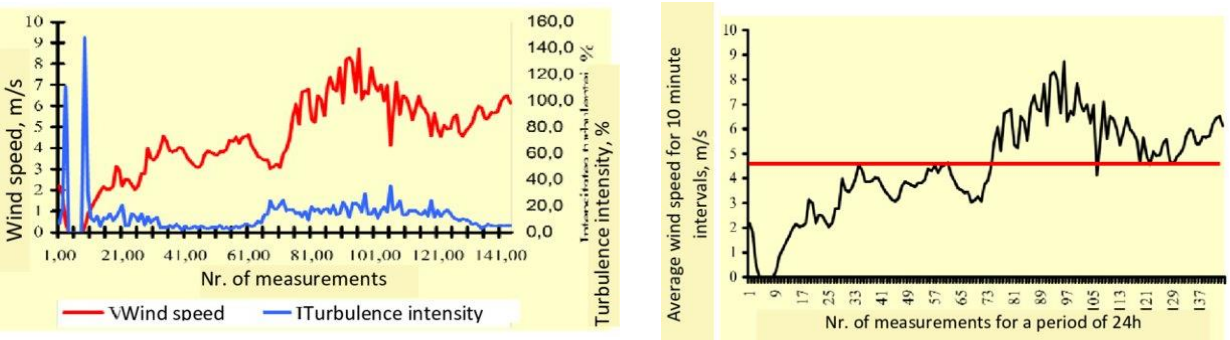
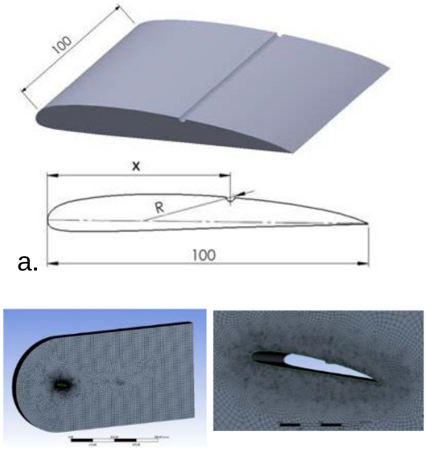


Fig. 14. Wind speed and turbulence intensity

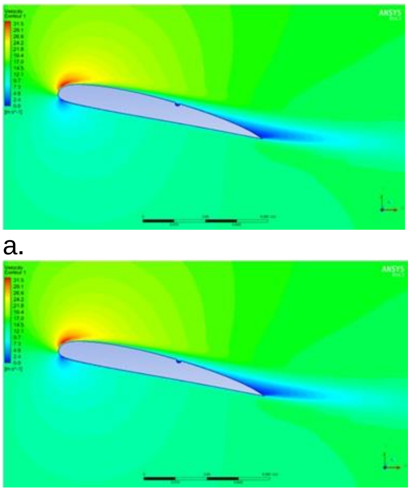
Wind turbine blade segment and domain was designed in SolidWorks and then imported into the ANSYS Workbench software. The dimensions of the blade segment were chosen taking into account the dimensions of the available wind tunnel measuring section (100 mm span and 100 mm chord). The size of the groove opening was accepted by 2.5% of the chord length as recommended in the paper [2]. Several CFD analyzes were performed in order to determine the optimum distance *x* from the leading edge to the center of the channel. Figure 15, *a* show the parameters of the simulated blade segment with airfoil NACA 4412. The dimensions of the computational fluid domain were chosen taking into account good practices and recommendations [3] so as to ensure free flow without influencing the boundaries of the field. Figure 15, *b* show considered fluid domain. Mesh was generated in the ANSYS Meshing Workbench integrated program. After importing the geometric model, the following regions required for computing were defined: (Inlet), (Outlet), (Walls) [5]. The basic dimensions of the mesh are specified by means of the minimum dimension Minimal size=0.22 mm and Maximum Max Size = 30 mm of the faces of the elements and the adjacent volumes. The surface of blade segment was meshed as *Mapped Face* with the mesh size 0.5 mm (Figure 15,*c*). The entire domain was meshed into approx. 1859600 finite elements. For a better understanding of the results the velocity contour and turbulence kinetic energy around the blade segment section was analyzed, Figure 16 and 17. From Figure 16, *b* we can see the delay effect of separating the boundary layer on the surface of the blade section with groove. In order to detect the influence of geometrical factors on blade's performance, turbulence kinetic energy is one of the indicators that helps identifying the regions of major turbulence that cause important energy flow losses.



a.

b. c.

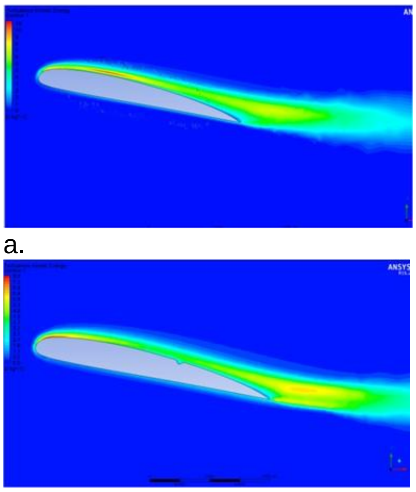
Fig. 15. Parameters of the simulated blade segment (a) meshed fluid domain (b) and around the blade (c)



a.

b.

Fig. 16. Velocity contour: *a* - smooth surface blade section; *b* - blade section with groove



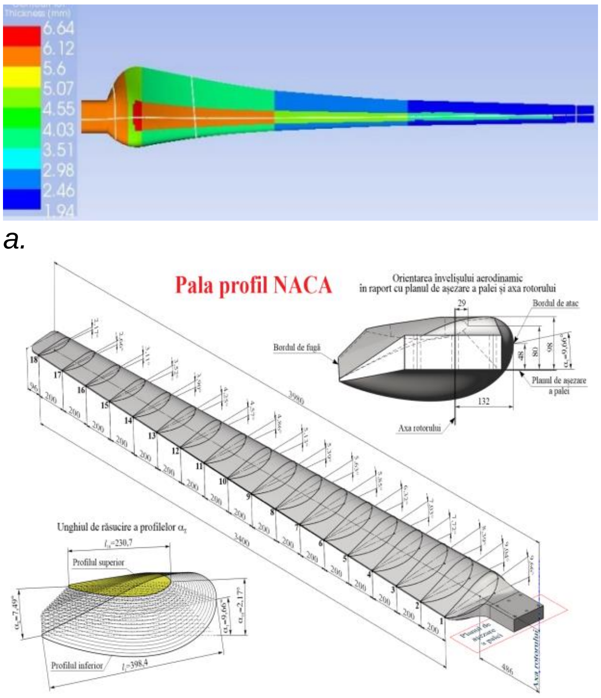
a.

b.

Fig. 17. Turbulence kinetic energy: *a* - smooth surface blade section; *b* - blade section with groove

Physically turbulence kinetic energy is produced due to the mean flow gradients, and is dissipated by viscous effects. For smooth energy is 10.5 J/kg (fig. 17,*a*). For blade with groove the maximum velocity is 31.5 m/s and turbulence kinetic energy is 8 J/kg (fig. 17,*b*).surface blade section the maximum velocity is 29 m/s and turbulence kinetic

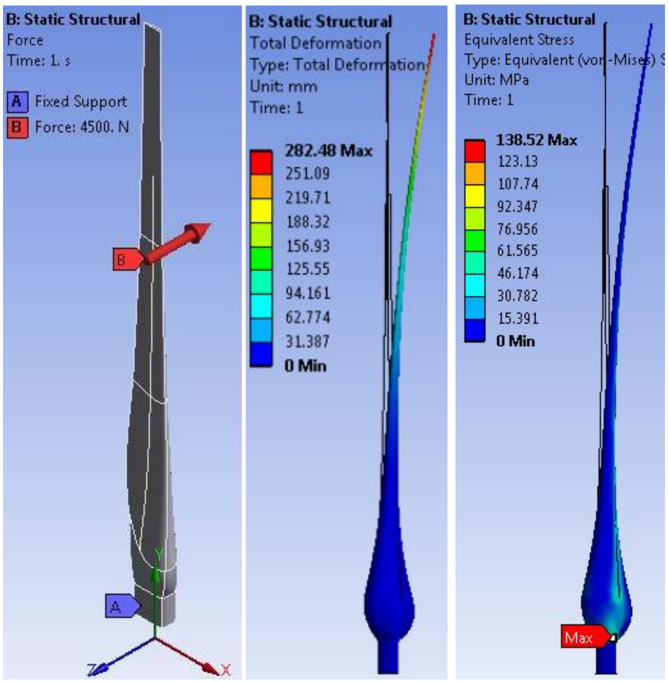
2.2.2. Numerical analysis of blade resistance



a.

b.

Fig. 18. The composite layer thickness (a) and components in layer schedule (b).



a. *b.* *c.*

Fig. 19. Flapwise bending: *a - axial loading, b – total deformation, c - equivalent stress*.

Along with the development of computer aided design (CAD) tools, design, analysis and manufacturing of wind turbine blades were made very cost effective and feasible. The following criteria have taken into account in the process of optimal blade design: minimize blade weight, does not exceed allowable stresses, minimize blade vibration and obtaining its modal frequency out of resonance. Blade mass and cost is mutually dependent and is related on the blade shell thickness. If the composite layer thickness for different blade section is at optimal level then we obtain the improvement of these parameters.
The load analysis of the blade consists of a 3D CAD model analyzed using the FE method (fig. 18). Regarding the dynamic behavior of the blade and the entire assembly of the wind turbine are imposed the following conditions: 1) the natural frequencies of the blade at 8 m/s wind speed must be above the ~2.5 Hz frequency of the turbine rotor (130 rpm) and 2) the natural frequency of the blade should be separated from the harmonic vibration of the tower (~1.16 Hz estimated first mod).
The blade was meshed entirely with 7539 layered shell elements and 7697 nodes in ANSYS Workbench. ANSYS Composite PrepPost (ACP) was used as a preprocessor for composite layups modeling as well as for post processing to check the stresses and the failure criteria that occur in the composite layers (Fig.18, *b*). To evaluate flapwise rigidity of the blade, this was constrained at the root end surface by fixing all six degrees of freedom and an axial force of 4.5 kN was applied on the blade surface as indicated in Fig. 19, *a*. The resultant deflection profile is illustrated in Fig. 19, *b*, from which it can be seen that the peak tip deflection is 282 mm (the distance from the blade tip to the tower is 480 mm) and the maximum compressive stress is 138 MPa, Fig. 19, *c*. To estimate the mode shapes and natural frequencies of the blade, a modal analysis was conducted in ANSYS Workbench. For a stopped rotor, the fundamental flapwise and edgewise vibrational modes occurred at frequencies of 7.5 and 15.23 Hz, respectively.

3. Conclusions

In conclusion, we state that micro hydropower plants ensure the transformation of 70...86 % of the flowing water potential energy into useful electrical energy transmitted to the hydrodynamic rotor. The basic advantages of micro-hydro power stations are as follows:

- small impact on the environment; it is not necessary to carry out civil constructions;
- the river does not change its natural course;
- the possibility to utilize local knowledge in order to produce floatable turbines;
- the possibility to mount a series of micro-hydro stations at small distances (approximately 30-50 m) because the influence of turbulence provoked by the adjacent installations can be excluded.

The value of the lift force of the blade segment fitted with groove was obtained approximately 6% lower than for the smooth blade segment. And drag force is decreasing with about 18% for blade segment fitted with groove.

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