ISSN 1454 - 8003
Proceedings of 2016 International Conference on Hydraulics and Pneumatics - HERVEX
November 9-11, Baile Govora, Romania

ASSESSING THE BLADE CHORD LENGTH INFLUENCE ON THE EFFICIENCY OF A HORIZONTAL AXIS HYDROKINETIC TURBINE

Rareș-Andrei CHIHAIA[1], Gabriela OPRINA[1], Sergiu NICOLAIE[1], Andreea EL-LEATHEY[1], Corina BABUTANU[1], Adrian NEDELCU[1]

[1] National Institute for R&D in Electrical Engineering ICPE-CA Bucharest, office@icpe-ca.ro

Abstract: *Hydro-kinetic turbines operate by using the kinetic energy of the water current in order to produce electric power. The kinetic energy is easily accessible on most rivers, triggering an increasing interest for such devices. Unfortunately, the low power density represents an important barrier to large-scale commercialization. Theoretical Betz law limits the extracted power coefficient to 0.59, but the real on site maximum values range from 0.4 to 0.45. However, a shroud placed around the rotor increases the power output by concentrating the flow from a larger surface and locally increasing the velocity. Thus, the design of the rotor blades is a very complex process due to the fact that the performance of these turbines depends on various parameters like number of blades, tip speed ratio, air foil type, blade pitch, chord length and twist angle along the blade.*
The paper aims to maximize the performance of a horizontal axis hydrokinetic turbine by assessing the blade chord length influence on the efficiency of such a turbine. The blade chord length and twist angle are firstly calculated, and then validated using Qblade software application. The computations and simulations are performed for a rotor provided with available data from previous tests achieved on site.

Keywords*: Chord, blade, hydrodynamic profile, hydrokinetic turbine*

1. Introduction

In order to avoid dam constructions, the river kinetic energy can be used directly using kinetic turbines. These types of turbines are easy to install; their operation is very simple while the maintenance costs are affordable. The water velocity of 1 m/s is characterized by an energy density of 500 W/m^2 on the cross section, but unfortunately only a part of it can be extracted and converted into useful mechanical or electrical energy. The parameters that influence the conversion efficiency are mostly related to the type of rotor and blades. The water velocity is particularly important. For example, from theoretical point of view, a double velocity determines an 8 times increase of the generated power.
The research is based on a previously developed rotor, [1], for which operational data is available (extracted power, rotational velocity, power coefficient curves). This rotor is used to compare the obtained results regarding the efficiency improvement achieved by varying chord length from hub to tip. Thus, the rotor geometry was reproduced by using the Qblade software application in order to evaluate its performance (power curve and power coefficient curve – C_p).
The simulation software uses the Blade Element Momentum (BEM) method in order to predict the turbine efficiency for the user-defined rotor geometry. The results were compared to the previously recorded data on site for this type of rotor. The differences between the simulations and in situ experimentation were insignificant, thus validating the software application and related computational method for this application.
Several chord lengths were determined using computation methods available in the literature which allowed the increase of the conversion efficiency in a given speed range for the turbine rotor. The variation of the chord length along the blade and the twist angle can be studied by simulation in order to choose the optimum blade shape for an increased efficiency. The characteristic data for the rotor was imported into the Qblade software resulting a 3D model. This type of graphic can be used for both simulations and for reduced scale experimental models on a compatible 3D printer in order to be tested on a dedicated testing stand.

2. Preliminary design features

The design stage started from a rotor geometry developed by the research team of ICPE-CA in a project conducted in 2006 (CEEX project no. X2C17/2016) [1]. Previously carried out tests showed a good capacity of the rotor to extract power from the water stream, e.g. a power value *P* of 28 W for a water velocity of 0.95 m/s. The micro-hydrokinetic turbine with constant cord length along the blades is shown in Fig. 1.

Fig. 1. Micro-hydrokinetic turbine developed in CEEX project no. X2C17/2016 [1]

In addition to the classical calculation and design methods applicable to such equipment, an open-source software application was used in order to run simulations that will determine the blade chord influence on mechanical and energy conversion performances. The objective of these tests is to identify a rotor with improved operating characteristic curves synthesized by $C_p = f(\lambda)$ and $P = f(n)$. The 3D geometry of the rotor imported in Qblade application is presented in Fig. 2.

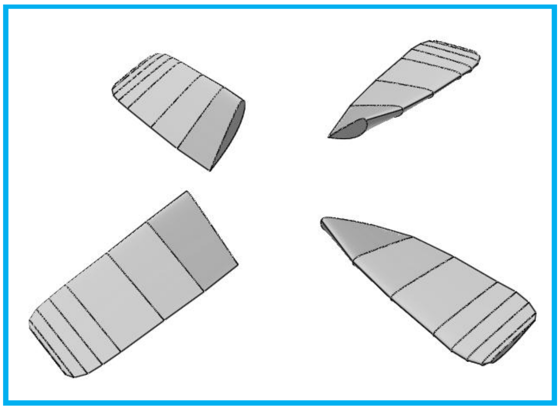

Fig. 2. 3D geometry of the rotor imported in Qblade application software

Based on recommendations suggested by literature and results obtained by successive simulations, an optimum rotor geometry was achieved, which allows the increase of the conversion efficiency by maximizing the power coefficient C_p for certain operating regimes. The improved rotor was chosen based on the study and simulation of several rotors solutions - with constant chord length along the blade chord, with variable cord length determined by calculation, with variable twist angle β along the blade length.
Aero-hydrodynamics profiles constitute basic elements in the construction of the turbine rotor blades. The aerodynamic profile represents a closed flat curve which determines the motion of a fluid around in order for it to have a low drag resistance and high lift. The profile of the blade is defined by the following geometry [2]:

- Chord, indicated by *C*, is the maximum distance between two profile points, coinciding to the segment bounded by the profile ends horizontally supported;
- Trailing edge - the point of the blade from the rear end;
- Leading edge - the contact point of the profile to the trailing edge and center of maximum radius;
- Rear of the profile - the half profile characterized by the greatest convexity located between the trailing and leading edges;
- Underside profile - the concave or the lowest convex part which is located between the trailing and leading edges;
- Thickness of the profile, denoted *d*, is the diameter of the circle-inscribed in profile; *d/C* is called relative thickness.

The blade profile related to the studied rotor is Gottingen 449. Thus, certain parameters specific to the profile could not be modified. Instead, the software application allows the modification of chord length and twist angle as shown in Fig. 3.

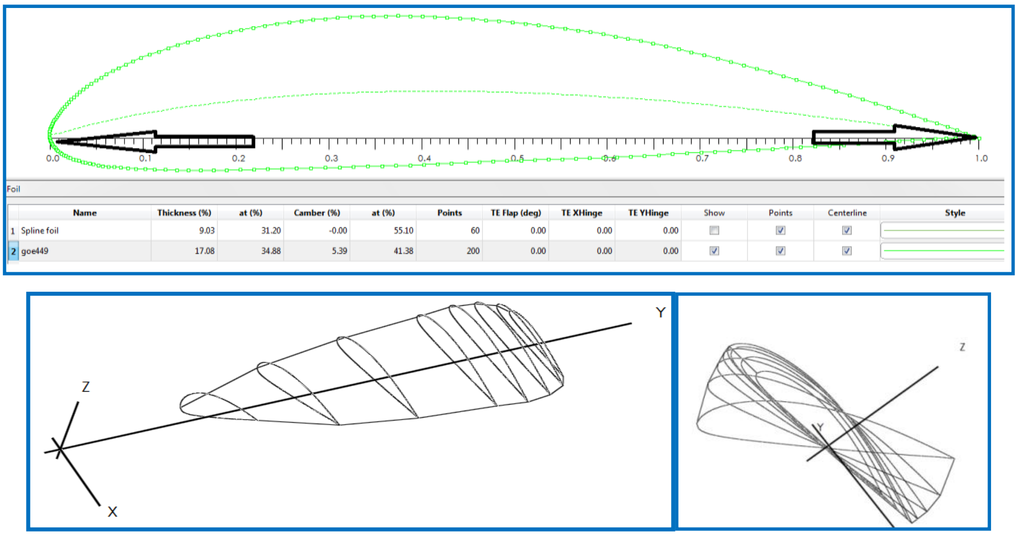

Fig. 3. Improvements in the structure of the rotor blades to determine the optimal geometry

3. Optimum chord length calculation for each section along the rotor blade

The chord profile, denoted by *C*, coincides to the segment bounded by the leading edge and trailing edge. The coordinates of the profile are determined based on the chord length *C* in the form *x/C* and *y/C* and define the main shape and thickness characteristics. The chord length *C* can be obtained by equalizing the torque of the rotor determined by the momentum theory to the torque obtained by applying the blade element momentum theory (BEM) and considering C_d – Drag coefficient other than zero [3]. Thus, *C* can be written as:

$$C = \frac{8a`r\lambda\pi\sin^2\varphi}{(C_L\sin\varphi - C_D\cos\varphi)B(1-a)} \tag{1}$$

Where *B* is the blades number, *α* – the angle of attack, *λ* – tip speed ratio (TSR) and $\varphi=\alpha+\beta$. The term *a* represents the induction factor and is defined as the fractional decrease of the water velocity between the freesurface flow and the rotor plane and can be determined using the folowing relation:

$$Cp = 4a(1-a)^2 \tag{2}$$

The momentum theory is valid only if $a < 0,5$. The term *a* represents the angular induction factor and can be defined as a fractional increase of the angular velocity based on momentum conservation principle. It can be determined using the following equation:

$$Tan\varphi = \frac{(1-a)}{\lambda(1+a`)} \tag{3}$$

C_L lift coefficient and C_D drag coefficient can be determined using the specific graphs for certain airfoil profiles. The most relevant polar diagrams are C_L/C_D or $C_L = f(\alpha)$ and $C_D = f(\alpha)$ [4]. Similar methods for calculating the hydraulic rotors and hence the length of the chord profile can be found in other papers [5], [6], proposing a simplified formula for calculating *C* as follows:

$$C = \frac{8\pi r \sin\varphi}{3BC_L\lambda} \tag{4}$$

Where *r* represents the radius for each profile section along the blade, φ is the angle between the water velocity vector and the plane of rotation, being calculated using the relation [7]:

$$\varphi = tan^{-1}(2/3\lambda) \tag{5}$$

The formula applies to the ideal rotor when C_p is 0.59 and a = 1/3. If the C_p value is expected to be lower, the formula is adjusted accordingly using the relation (2) which estimates the value of *a*. The above formulas allow the determination of specific elements characteristic to the design of a hydraulic rotor. The calculations were implemented in a spreadsheet. Firstly, it was necessary to determine the angle of attack based on Gottingen 449 polar diagrams. Thus, polar curves C_L/C_D and C_L/α were generated using the XFOIL application under GNU General Public License. The maximum value of Reynolds number considered for this application by taking into account the water velocity of up to 2 m/s is 200.000. The attack angle selection procedure based on polar diagrams is represented in Fig. 4.

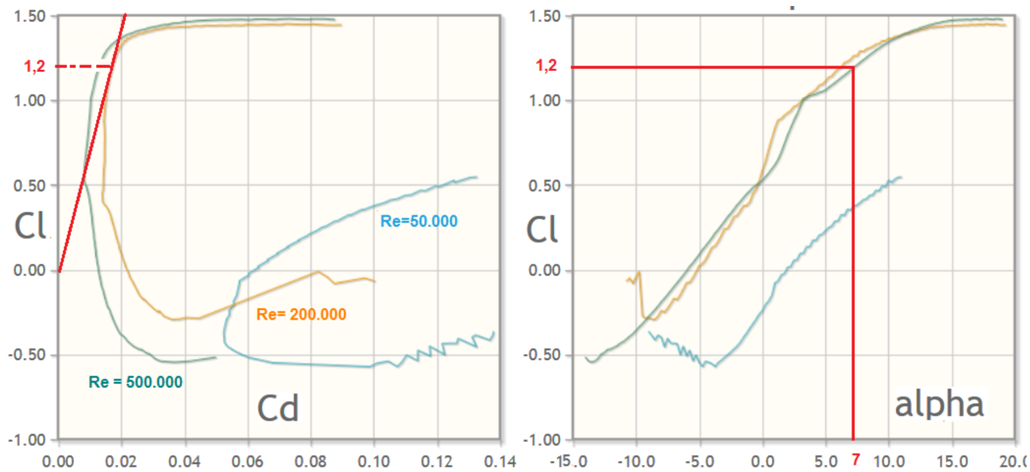

Fig. 4. The attack angle selection procedure based on the polar diagrams of the Gottingen 449 profile

Input data for the rotor computation consists of:

- Water velocity: 0.9 m/s;
- Rotor diameter: 0.5 m;
- Rotor blade length: 0.2 m;
- Hub Diameter: 0.1 m;
- Number of rotor blades: 4.

The obtained results were summarized in Table 1, wherein the input elements and the calculated parameters are represented for a rotor diameter of 0.5 m.

TABLE 1: Input and calculated parameters for a 0.5 m rotor

Input parameters					Calculated parameters			
ωR [m/s]	TSR (λ)	Attack angle α (degrees)	Lift coefficient C_L	Section radius r [m]	φ (rad)	φ (degrees)	Chord length [m]	Twist angle β (degrees)
2,36	2,62	7	1,2	0,25	0,308	17,66	0,049	10,66
2,12	2,36	7	1,2	0,225	0,340	19,48	0,053	12,48
1,88	2,09	7	1,2	0,2	0,379	21,70	0,059	14,70
1,65	1,83	7	1,2	0,175	0,427	24,45	0,066	17,45
1,41	1,57	7	1,2	0,15	0,488	27,95	0,075	20,95
1,18	1,31	7	1,2	0,125	0,567	32,48	0,086	25,48
0,94	1,05	7	1,2	0,1	0,672	38,51	0,100	31,51
0,71	0,79	7	1,2	0,075	0,815	46,70	0,116	39,70
0,47	0,52	7	1,2	0,05	1,010	57,86	0,135	50,86

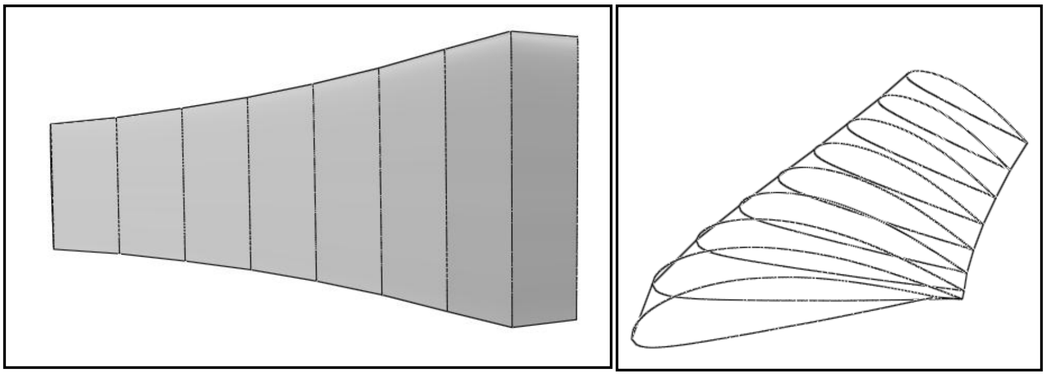

Fig. 5. Blade imported in Qblade application using the calculated parameters

When considering the blade construction, the most important data refers to the chord length for each section along the blade and the twist angle β. Computed values were imported into Qblade software for 3D construction in order to achieve the necessary simulations. The basic geometry of the blade is shown in Fig. 5.

4. Evaluation of the hydrodynamic profile chord influence on the hydrokinetic turbine performance

Successive simulations achieved by Qblade software were performed in order to study the effect of the chord length for each section. The program generates specific curves to the computed parameters when one of the input data variables varies in the given range (attack angle, velocity, rotational speed). QBlade analysis, compared with a more complex CFD analysis, displays several limitations. One limitation worth mentioning consists in acceptable accuracy for high Reynolds numbers. Also, the effect of additional elements (the turbine shaft, nose cone) is not taken into account. Instead, the resulted curves and diagrams focus on the assessment of the extracted power and power coefficient C_p variation depending on the tip speed ratio. Thus, it is possible to simulate profiles and rotors in a short amount of time in order to select the proper blades based on an optimal mechanical energy output. In this case, the application was validated by using the rotor with Gottingen 449 airfoil type developed in the previously mentioned project [1]. The power diagram was generated for several water velocities (0.5m/s, 0.6m/s, 0.9m/s). The power curves are shown in Fig.6 and Fig.7 for comparative analysis.

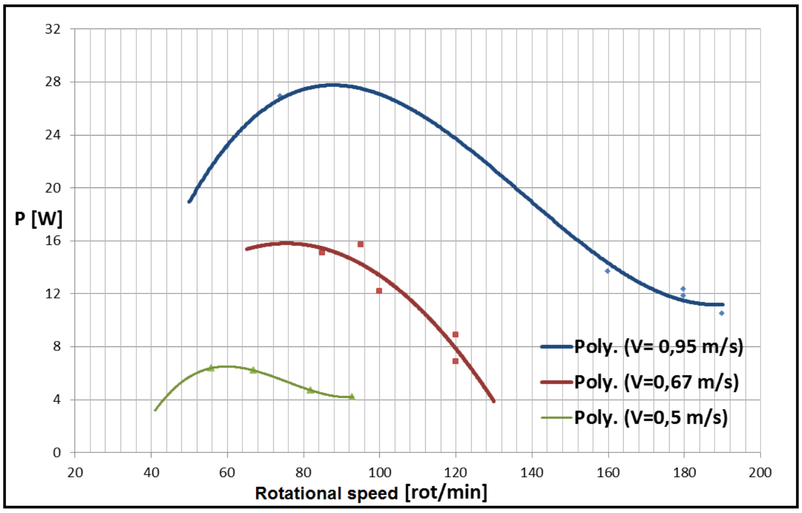

Fig. 6. The power curve for the Gottingen 449 rotor tested in situ

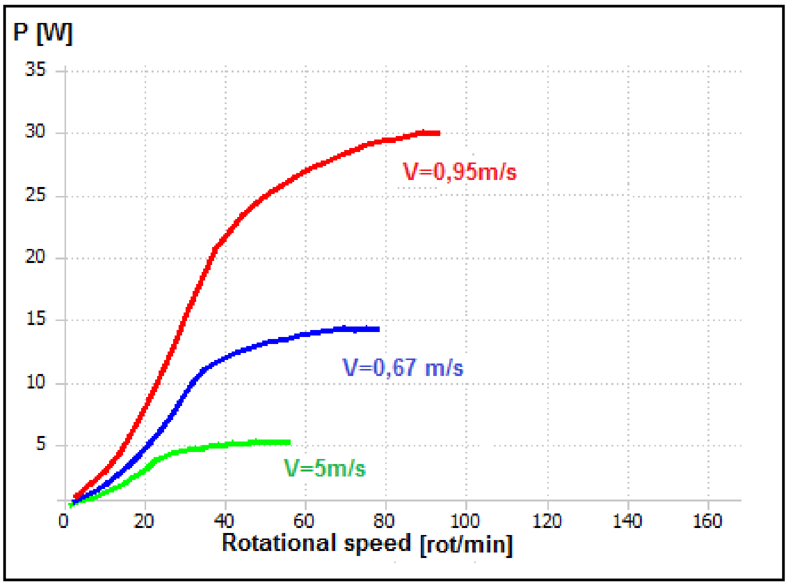

Fig. 7. The power curve for the Gottingen 449 rotor simulated in Qblade software application

The simulation results are similar to those obtained following the developed tests. The numeric application does not consider the influence of the hydraulic rotor hub and turbulences disturbing the flow, thus reflecting in insignificant differences between simulations and experimental testing.

Once the preliminary results for this type of rotor were established, it was possible to perform simulations on a new hydraulic rotor with chord lengths and twist angle β determined according to Table 1. The most relevant results were summarized in Fig. 8 (for water velocity of 0.9 m/s). The rotor was initially tested at a maximum water velocity of 0.9 m/s, so the simulations were carried out only up to that velocity in order to analyze the difference between the considered rotor and the optimized version.

Given the shaft size and the fact that the rotor has 4 blades, the maximum length of the blade has been limited to 0.105 m. It can be observed from Fig. 8, that the power extracted for the rotor provided with constant chord length is larger than in the case of the initial rotor for the 0 – 25 W and 0 - 60 rpm range. Instead, the rotor with variable chord length produces low power in this range, but brings a larger increase of the maximum power for up to 7-8% in the 70 - 120 rpm range.

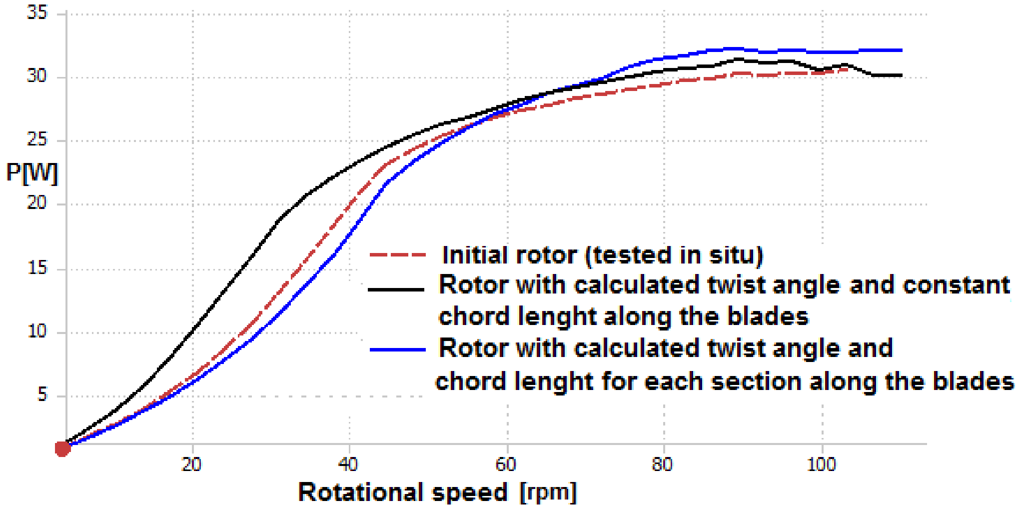

Fig. 8. Extracted power for the simulated rotors

The conducted research shows that the influence regarding the power generated could be assigned also to the chord length and twist angle. The simulations have shown that certain computational models contribute to a blade design with better conversion efficiency in certain speed ranges. The efficiency is expressed through the power coefficient C_p and reaches 0.45 according to simulations. Given the absolute maximum limit of 0.59 indicated by Betz theory, the results are satisfactory for the considered operation conditions.
For the next research stage, it is important to validate the simulation results suggested by Qblade software. In order to perform experimental testing for hydrokinetic turbines, special testing facilities have been designed [8]. Recently, ICPE-CA has acquired a modern facility for testing small scale hydrokinetic turbines, shown in Fig. 9. Thus, the research team benefits of the experimental stand which is equipped with all the necessary equipment for small scale models operating at water velocities of up to 1 m/s. A detailed description of the stand is described in [8].

Fig. 9. Experimental stand for testing axial hydraulic turbine models

The blade resulted from the design stage can be easily exported to the 3D printer and can be produced from ABS for testing. For the moment, the influence of the chord length variation along the blade has been demonstrated.
The use of computational models and recent developed software application based on numerical analysis allowed the design of a hydraulic rotor with increased performance. Furthermore, the experimental results could be compared to the computational model and simulation software in order to validate each design stage.

5. Conclusions

The computational model and simulations were performed starting from previous available data recorded on site during another research project. The tested rotor was developed in a previous project [1]. The performed tests provided very good results for certain operation conditions. The design of the rotor blades is a very complex process due to the fact that the performance of these turbines depends on various parameters like number of blades, tip speed ratio, air foil type, blade pitch, chord length and twist angle along the blade.

The paper intended to investigate the design elements which improve furthermore the conversion efficiency for the hydrokinetic rotors. Based on the experience of the research team, new contributions in the field and modern simulation techniques, it has been shown that changes in chord length along the blades and variation of the twist angle have a great impact regarding the power output. The most favourable values were chosen for the design of an optimum hydrokinetic rotor with a maximum diameter of 0.5 m in order to maintain permanent comparison to the initial rotor. The objective of the paper has been met by identifying means to maximize the performance of a horizontal axis hydrokinetic turbine and the blade chord length influence, respectively.

Acknowledgments

This work was financially supported by ANCSI, Romania, under the scientific Programme NUCLEU 2016-2017, Contract PN 16 11 01 06, no. 14N/2016, research theme 5106/2016.

References

[1] “Hydro power systems for conversion-storage-distribution of renewable energies, dedicated to ecological River transport, on protected areas” - CEEX project no. X2C17/2016;
[2] A. Badea, H. Necula, V. Cenusa, M.C. Cioban, C. Dinca, C. Ghita, C. Ionescu, D.O. Kisch, C. Marculescu, A. Morega, B. Popa, R. Porumb, C.A. Safta, I.Tristiu,” Surse regenerabile de energie”, Editura A.G.I.R., 2014, ISBN 978-973-720-469-1;
[3] E. Chica, F. Perez, A. Rubio-Clemente, S. Agudelo, “Design of a hydrokinetic turbine”, WIT Transactions on Ecology and The Environment, Vol. 195, 2015 WIT Press, ISSN 1743-3541, doi:10.2495/ESUS150121;
[4] S.S. Michael, D.M. Bryan, “Wind tunnel tests of six airfoils for use on small wind turbines”, Journal of Solar Energy Engineering 126(4), January 2004;
[5] E. H. Lysen,” Introduction to wind energy”, CWD 82–12nd edition, The Netherlands, 1983.
[6] J.F. Manwell., J.G. Macgowen, A.L. Rogers “Wind turbine energy explained: theory, design and application”, England: John Wiley and Son Ltd, 2002;
[7] M. Anyi, B. Kirke, “Hydrokinetic turbine blades*:* Design and local construction techniques for remote communities”*,* Energy for Sustainable Development, Volume 15, Issue 3, September 2011, Pages 223–230;
[8] T.C. Popescu, R. Radoi, M. Blejan., S. Nicolaie et al.,”Considerations on the Experimental Testing Means of Axial Hydraulic Turbine Models”, Conference: 15th International Multidisciplinary Scientific Geoconference (SGEM) Location: Albena, BULGARIA Date: JUN 18-24, 2015, Energy and Clean Technologies, Book Series: International Multidisciplinary Scientific GeoConference-SGEM, Pages: 137-144, 2015.