Argumentation of the Optimal Hydrodynamic Profile of Blades of the Flow Microhydrostation Rotor's

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Abstract: *Insistent searches of authors have led to the design and licensing of some advanced technical solutions for outflow micro hydroelectric power plants. They are based on the hydrodynamic effect, generated by the hydrodynamic profile of blades and by the optimal blades' orientation towards water streams with account of energy conversion at each rotation phase of the turbine rotor. The selection of the optimal blades hydrodynamic profile is very important for functional optimization of micro hydro power plants. It will allow increasing the conversion factor (Betz coefficient) due to the hydrodynamic buoyant force. Due to the fact that the relative velocity of blades concerning the water currents is twice bigger, practically, at their motion against the water currents, the hydrodynamic lift force is relatively big, and the generated torque is commensurable to the one generated by the water pressure.*

Keywords*: Micro hydroelectric power plant, hydrodynamic profile*

1. Introduction

The inevitable increase of global energy consumption and the risk of a major environmental impact and climate change as a result of burning fossil fuels opens wide prospects for the exploitation of renewable energies. Hydropower, as a renewable energy source, will have an important role in the future. International research confirms that the emission of greenhouse gases is substantially lower in the case of hydropower compared to that generated by burning fossil fuels. From the economical point of view, the utilisation of half of the feasible potential can reduce the emission of greenhouse gases by about 13%; also, it can substantially reduce emissions of sulphur dioxide (main cause of acid rains) and nitrogen oxides.
Hydraulic energy is the oldest form of renewable energy used by man and has become one of the most currently used renewable energy sources, being also one of the best, cheap and clean energy sources. 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.

2. Conceptual diagrams

To avoid the construction of dams, it is possible to use the river kinetic energy by utilizing water flow turbines. This type of turbines can be mounted easily and are simple in operation. Their maintenance costs are rather convenient. The stream velocity of 1m/s represents an energy density of 500W/m^2 of the flow passage. Still, only part of this energy can be extracted and converted into useful electrical or mechanical energy, depending on the type of rotor and blades. Velocity is important, in particular, because the doubling of water velocity leads to an 8 times increase of the energy density. The section of Prut River is equivalent to 60 m^2 and its mean velocity in the zones of exploration is (1-1,3) m/s, which is equivalent to approximately (30-65) kW of theoretical energy. Taking into account the fact that the turbine can occupy only a part of the riverbed, the generated energy could be much smaller. There are various conceptual solutions, but the issue of increasing the conversion efficiency of the water kinetic energy stands in the attention of the researchers. The analysis of the constructive diversion of micro hydroelectric power plants, examined previously, does not satisfy completely from the point of view of water kinetic energy conversion efficiency. The maximum depth of blade's immersion is about 2/3 of the blade height *h* in a classical hydraulic wheel with horizontal axle (Figure 1). Thus, only this surface of the blade participates at the transformation of water kinetic energy into mechanical one. As well, the preceding blade covers approximately 2/3 of the blade surface plunged into the water to the utmost *(h''≈ 2/3h')*, that reduces sensitively the water stream pressure on the blade. The blade, following the one that is plunged into the water to its utmost, is covered completely by it and practically does not participate in the water kinetic energy conversion. Therefore, the efficiency of such hydraulic wheels is small.

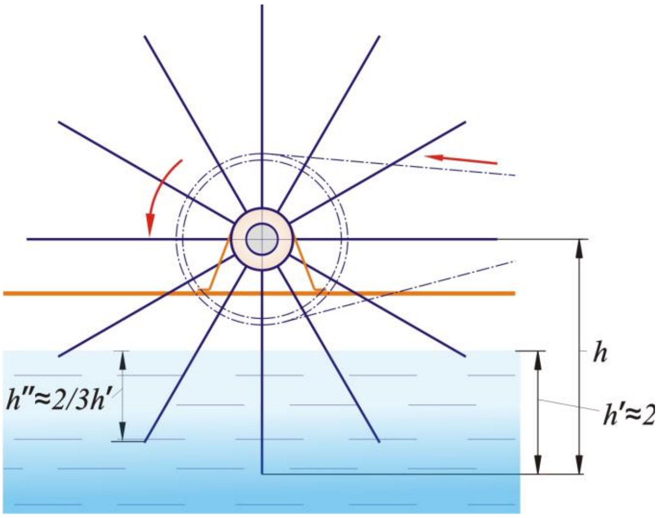

Fig. 1. Conceptual diagram of the water wheel with rectilinear profile of blades.

Insistent searches of authors have led to the design and licensing of some advanced technical solutions for outflow micro hydroelectric power plants. They are based on the hydrodynamic effect, generated by the hydrodynamic profile of blades and by the optimal blades' orientation towards water streams with account of energy conversion at each rotation phase of the turbine rotor (Figure 2). To achieve this, it was necessary to carry out considerable multicriteria theoretical research on the selection of the optimal hydrodynamic profile of blades and the design of the orientation mechanism of blades towards the water streams.

The main advantages of these types of micro hydroelectric power plants are:

- reduced impact on the environment;
- civil engineering works are not necessary;
- the river does not change its natural stream;
- possibility to produce floating turbines by utilizing local knowledge.

Another important advantage is the fact that it is possible to install a series of micro hydro power plants at small distances (about 30-50 m) along the river course. The influence of turbulence caused by the neighbouring plants is excluded.

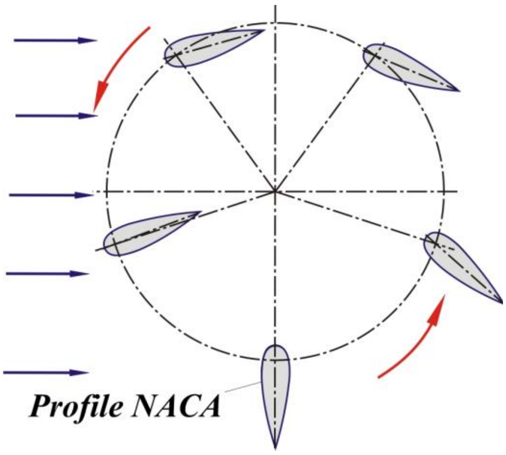

Fig. 2. Conceptual diagram of the water rotor with hydrodynamic profile of blades with its orientation towards the water streams.

The results of investigations conducted by the authors (on the water flow velocity in the selected location for micro hydro power plant mounting, on the geological prospects of the river banks in the location of installing the anchor foundation and on the energy demands of the potential consumer) represent the initial data for the conceptual development of the micro hydro power plants and the working element.

The conceptual development of the plant structures with hydrodynamic profile of the blades was performed on the basis of three conceptual diagrams:

- Micro hydropower plant with pintle and blades fixed on the vertical axles anchored by steel structure;
- floatable micro hydro power plant with pintle and blades fixed on the vertical axles;
- floatable micro hydro power plant with horizontal axis and blades fixed on the horizontal axles.

In order to increase the conversion factor of water kinetic energy (Betz coefficient), a number of structural diagrams of floatable micro hydro power plants has been developed and patented [1-3]. The micro hydropower plants comprise a rotor with vertical axis and vertical blades with hydrodynamic profile in normal section. The blades are connected by an orientation mechanism towards the water streams direction. The rotational motion of the rotor with vertical axis is multiplied by a mechanical transmissions system and is transmitted to an electric generator or to a hydraulic pump. The mentioned nodes are fixed on a platform installed on floating bodies. The platform is connected to the shore by a hinged metal truss and by a stress relieving cable.

3.Theoretical justification of the hydrodynamic profile selection of the blade in normal section

Let consider the symmetrical profile of the blade placed in a fluid stream that moves uniformly at velocity $\vec{V}_\infty$ (Figure 3 [1]). In the fixing point *O′* of the symmetrical blade with lever *OO′* let consider two coordinate systems, that is: the system *O′xy* with axis *O′y* oriented in the direction of the velocity vector $\vec{V}_\infty$, and axis *O′x* - normal for this direction; and the system *O′x′y′* with axis *O′y′* oriented to the lever direction *O′O,* and axis *O′x′* - normal for this direction. Point *A* corresponds to the rear edge, and point *B* corresponds to the entering edge. The entering angle α is the angle between the chord *AB* of the profile and the direction of the velocity vector $\vec{V}_\infty$, and the positioning angle *φ* is the angle formed by the velocity vector direction and lever *O′O.*

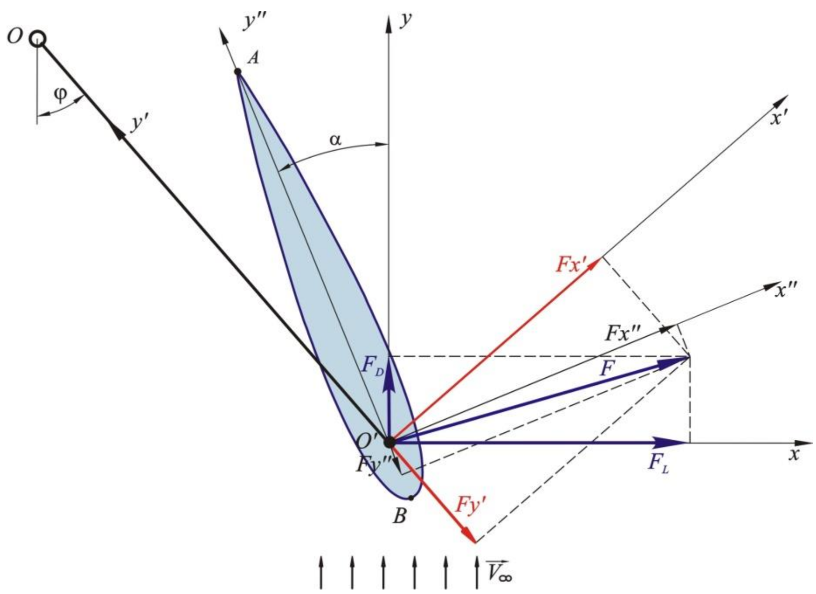

Fig. 3. Hydrodynamic profile blade.

The components of the hydrodynamic force $\vec{F}$ in the directions *O′x* and *O′y* are named the lift force and the resistance force:

$$F_L = \frac{1}{2} C_L \rho V_\infty^2 S_p, \tag{1}$$

$$F_D = \frac{1}{2} C_D \rho V_\infty^2 S_p, \tag{2}$$

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

$$\begin{aligned} F_{x'} &= -F_L \sin\varphi + F_D \cos\varphi, \\ F_{y'} &= F_L \cos\varphi + F_D \sin\varphi. \end{aligned} \tag{3}$$

The torque moment of the rotor spindle *OO′* developed by blade *i* is

$$T_{r,i} = F_{x'} \cdot \left|OO'\right|, \tag{4}$$

and the summary torque moment developed by blades is

$$T_{r\Sigma} = \sum_{i=1}^{Npal} T_{ri}, \tag{5}$$

where N_{pal} is the number of rotor blades.

Generally, the hydrodynamic force has no point of application in the origin of the blade axes system *O′* so as it produces a resulting moment. The produced moment is determined by comparing it to a certain point of reference. The point situated at distance ¼ of the chord from the entering edge *B* will be considered as point of reference. The moment, also called the pitching moment, is calculated according to formula

$$M = \frac{1}{2} C_M \rho V_\infty^2 c S_p, \tag{6}$$

where C_M is the profile number of turns.

4. Optimisation of NACA 0016 hydrodynamic profile

In order to maximize the moment of torsion produced by the micro hydro power plant rotor, the optimization of the hydrodynamic profile will be considered [4]. The moment of torsion depends on the lift and drag hydrodynamic forces given by formulas (7) and (8). The hydrodynamic forces through the hydrodynamic coefficients depend on the entering angle α, Re number and the shape of the hydrodynamic profile. The hydrodynamic shape of the profile was selected from the NACA library having as parameters (with account of the profile symmetry) only the maximal thickness. The entering angle constitutes the second parameter. The optimization aims at maximizing the lift force and, at the same time, does not allow the pitching moment and the resistance force to take very big values. The following issue of optimization should be considered:

Maximize $C_L = C_L(\theta, \alpha)$
with constraints imposed to the coefficients C_D and C_M , (7)

where θ is the maximum thickness and α is the entering angle.
The values of the inferior and superior borders are determined, as follows: the negative maximum value for the pitching coefficient will correspond to the solution for the entering angle 0. The maximum value for the resistance coefficient will correspond to the solution for the entering angle *α = 18˚.* Also, restrictions have been added to the optimization parameters $10\% \le \theta \le 20\%$ and $0^o \le \alpha \le 20^o$. To find the optimal values of function $f = f(x_1, \ldots, x_n)$ an iterative method is used:
As long as the demanded accuracy is not reached the solution will be,

$$B_i s_i = -\nabla f(x_i),$$
$$x_{i+1} = x_i + \alpha_i s_i, \tag{8}$$

where α_i are the multipliers and B_i are the definite positive approximations of the Hessian function f. The partial derivation of function f related to the component i is approximated with the help of the finite difference formulas:

$$\frac{\partial f}{\partial x_i}(x) = \frac{f(x + he_i) - f(x - he_i)}{2h}, \tag{9}$$

where e_i is the basis vector.
The optimization is done by the MATLAB optimization soft: *"Sequential quadratic programming algorithm with a line search and a BFGS Hessian update".* The quadratic sub-tasks are solved by modified projection method. The gradient of function $C_L = C_L(\theta, \alpha)$ is calculated by the finite difference formulas with the constant pitch $h = 10^{-4}$. NACA 0016 profile was considered as the initial profile (Figure 4). The result of optimization is presented in Figure 5.

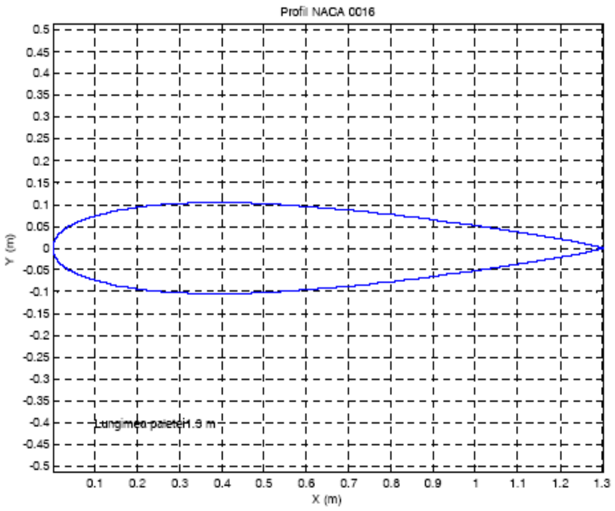

Fig. 4. NACA 0016 hydrodynamic rack profile standard.

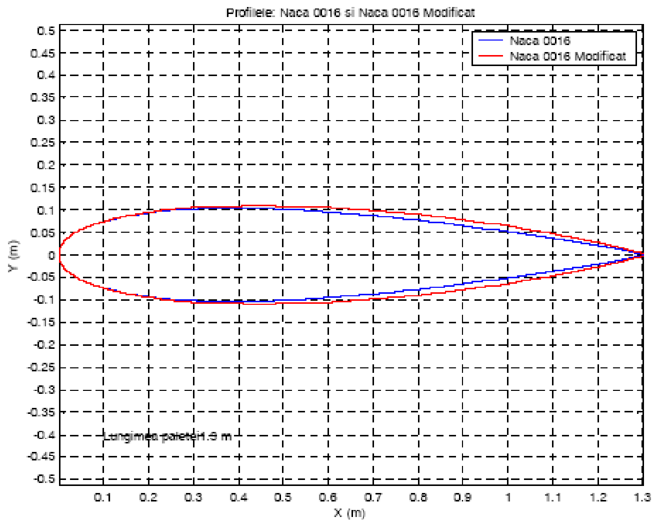

Fig. 5. NACA 0016 hydrodynamic rack profile standard and the optimised profile.

5. Argumentation of the optimal hydrodynamic profile of blades

The selection of the optimal blades hydrodynamic profile is very important for functional optimization of micro hydro power plants. It will allow increasing the conversion factor (Betz coefficient) due to the hydrodynamic buoyant force. As well, conversion increase is achieved by ensuring the optimal position of blades towards the water streams at various phases of rotor revolution, employing an orientation mechanism of blades. Thus, practically all blades (even those blades which move against the water currents) participate in the generation of the summary torque. Moving in the water currents direction, for torque generation the blades use both the hydrodynamic forces and the water pressure exercised on the blade surfaces. Moving against the water currents direction the blades use only the hydrodynamic lift force for torque generation (figure 6). Due to the fact that the relative velocity of blades concerning the water currents is twice bigger, practically, at their motion against the water currents, the hydrodynamic lift force is relatively big, and the generated torque is commensurable to the one generated by the water pressure.

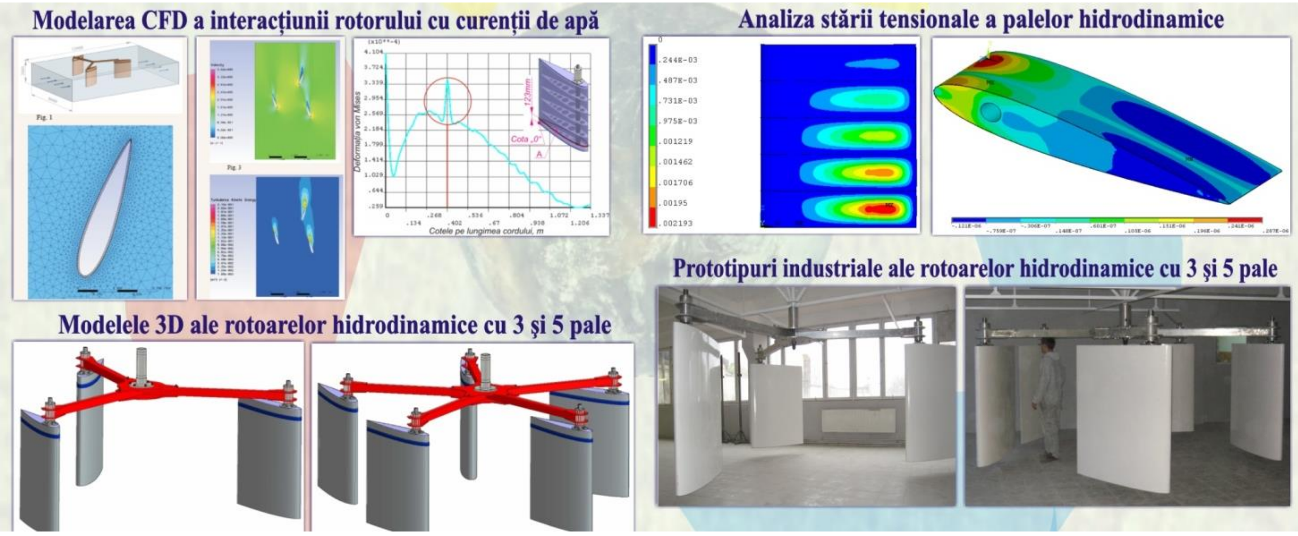

Fig. 6. Argumentation of the optimal hydrodynamic profile of blades.

This effect makes the basis of all patented technical solutions. The technical solutions of micro hydro power plants comprise various basic nodes and conversion principles that have been patented. These technical solutions allow essential increasing of the river water kinetic energy conversion coefficient. Full description of the most representative technical solutions and brief description of the conceptual diagrams of micro hydro power plants properties are given below.

4. Conclusion

Hydrodynamic rotors provide kinetic energy conversion of river water into mechanical or electrical energy without building barrages. Increased efficiency is provided by blades aerodynamic profile and their optimum position for efficient conversion of water kinetic energy.
To ensure the floating stability of the micro hydro power plants the rotor is mounted on the main structure with displacement *e* against the water stream. Thus, the micro hydro power plants designed to be anchored on the left bank cannot be anchored on the right bank.

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