THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI
FASCICLE XIV MECHANICAL ENGINEERING, ISSN 1224-5615
2006

CONCEPTUAL DESIGN OF THE ELECTRICAL MICRO-HYDRO-POWER STATION FOR THE CONVERSION OF FLOWING WATER KINETIC ENERGY INTO MECHANICAL AND ELECTRICAL ENERGY

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ABSTRACT

The engineering complex study of the triad “gear-technology-transmission” has permitted to elaborate a new type of precessional transmissions with multicouple gear. In this paper, the authors present the mathematic model of the multicouple gear. A computer program for doing this it is also elaborated. It is shown a block-scheme of the algorithm of the program modules including the calculus modalities exposed in the paper.

1. Introduction

In order to avoid the construction of barrages, river kinetic energy can be utilized with the help of water stream turbines. This type of turbines cab be easily mounted, simply operated and their maintenance costs are convenient. The water stream rate of 1m/s represents an energetic density of 500W/m^2 of the crossing section, and only one part of this energy can be extracted and converted into electrical energy. This depends on the type of rotor and blades which are the objectives of our research. The speed is especially important, because a double increase in the water speed will result in an 8 times increase of the energetic density. Prut river has an equivalent section of 60 m^2 and an average water speed of 1,0 m/s in exploitable zone, which is equivalent with a theoretical energy of approximately 30 kW. But, taking into account that the turbine can occupy only one portion of the riverbed the generated energy can be much smaller. There are different conceptual solutions for the elaboration of this type of turbines. The positive aspects of these turbines are: reduced impact on the environment; there is no need for civil constructions; the river is not changing its original course; it is possible to make use of local knowledge to produce floating turbines. Another advantage is the fact that it is possible to mount tens of micro-hydro-power stations on the river course by excluding the influence of the turbulence from the neighboring stations.

The results of the undertaken research on the water flow rate in the place chosen for the micro-hydro-power station mounting, geological prospecting of the river banks in the place of the anchoring foundation and potential consumers needs represent initial data for the conceptual elaboration of the micro-hydro-power station and the working element.

Conceptual elaboration of the micro-hydro-power station construction has been done on the basis of three conceptual designs:

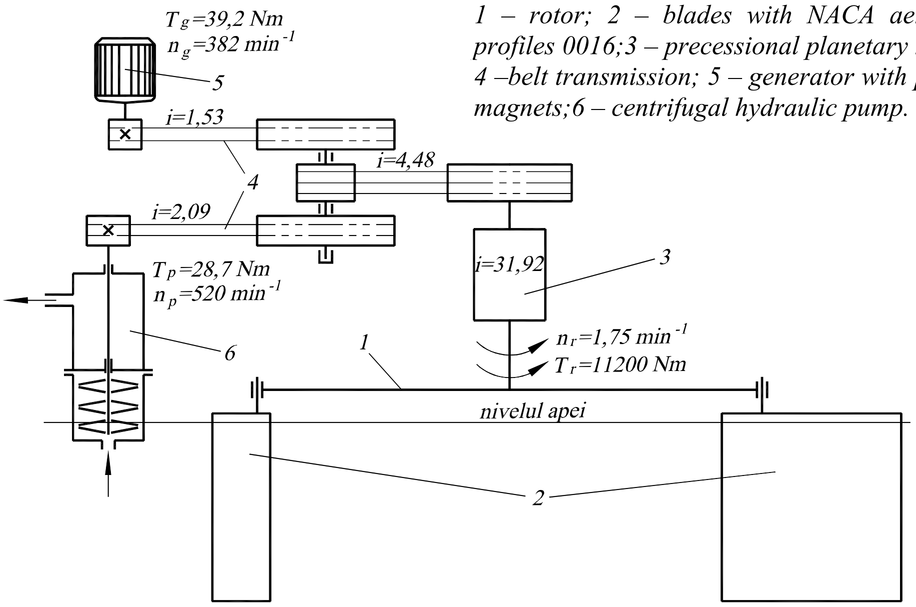
- micro-hydro-power station with pintle and blades fixed on horizontal axles;
- micro-hydro-power station with pintle and blades fixed on vertical axles;
- floatable micro-hydro-power station with horizontal axle and helical turbines.

2. Elaboration of kinematic diagram of the micro-hydro-power station

Starting from the double destination of micro-hydro-power station – conversion of flowing water kinetic energy into electrical and mechanical energy for water pumping, the kinematic diagram was elaborated (see fig.1.) [1,2,3]. At water flow rate $v=1 m/s$ the moment of torsion of the rotor shaft is T_r=11200Nm and the angular frequency is $\omega_r=0{,}18 s^{-1}$. With account of the mechanical efficiency and reduction factor of mechanical transmissions we get:

- moment of torsion of the pump shaft T_p=28,7*Nm*;
- frequency of revolutions of the pump shaft n_p=523*min*$^{-1}$;
- moment of torsion of the electromotor shaft T_e=39,2*Nm*;
- frequency of revolutions of the electromotor shaft n_e=382*min*$^{-1}$.

The carried out research has demonstrated that the utilization of the energetic potential of flowing water is up to 15...18%**.** As consequence, this concept of micro-hydro-power station can be utilized only for the conversion of kinetic energy into mechanical energy that is useful for irrigation works.



1 – rotor; 2 – blades with NACA aerodynamic profiles 0016;3 – precessional planetary multiplier; 4 –belt transmission; 5 – generator with permanent magnets;6 – centrifugal hydraulic pump.

Fig. 1. Kinematic diagram of the micro-hydro-power station

3. Theoretical research and elaboration of rotor with blades with NACA aerodynamic profile

On the basis of preliminary research the construction of rotor with 3 blades with NACA profiles, has been elaborated. The blades are oriented at a setting angle ***α,*** which is variable concerning the action line of the flowing water speed vector (fig.2).

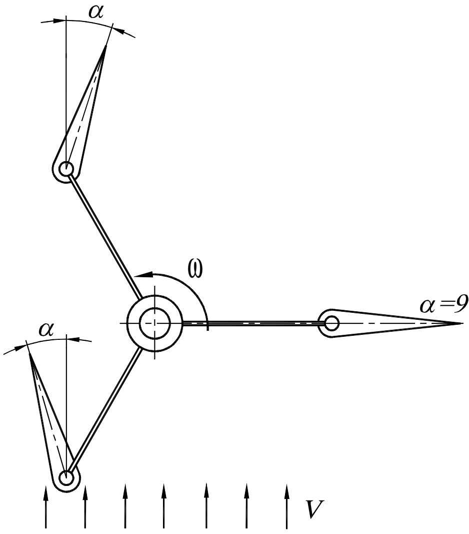


Fig. 2.

Consider a symmetric profile of the blade in a fluid flow with uniform velocity $\vec{V}_A$ (Fig. 3.). Points A and B correspond to the trailing and the leading edges, respectively. In the fixing point $\check{O}$ of the symmetric blade with the boom $OO^{\smile}$ we consider three coordinate systems, namely: the $O^{\smile}xy$ system with axis $O^{\smile}y$ oriented in the direction of

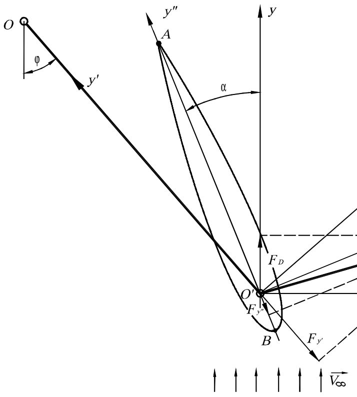


Fig. 3.

velocity vector $\vec{V}_A$, and axis $O^{\smile}x$ normal to this direction; the $O^{\smile}x^{\smile}y^{\smile}$ system with axis $O^{\smile}y^{\smile}$ oriented along the boom direction $OO^{\smile}$, and axis $O^{\smile}x^{\smile}$ normal to this direction, and finally the $O^{\smile}x^{\smile\smile}y^{\smile\smile}$ system with axis $O^{\smile}x^{\smile\smile}$ oriented along the profile's chord toward the trailing edge and axis $O^{\smile}y^{\smile\smile}$ normal to this direction. The angle of attack α is the angle between the profile chord AB and $\vec{V}_A$, and the positioning angle φ is the angle between the boom $O^{\smile}O$ and $\vec{V}_A$. The hydrodynamic force $\vec{F}$ has its components in directions $O^{\smile}x$ and $O^{\smile}y$, named lift and drag forces, respectively, given by

$$F_L = \frac{1}{2} C_L \rho_A V_A^2 S_p, \qquad F_D = \frac{1}{2} C_D \rho_A V_A^2 S_p, \tag{1}$$

while the pitching moment is given by

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

where ρ_A is the fluid density, V_A is the flow velocity, $S_p=ch$ (c is the chord length, h is the blade height) represents the lateral surface area of the blade, and C_L and C_D are the dimensionless hydrodynamic coefficients, named lift coefficient and drag coefficient. The hydrodynamic coefficients C_L, C_D and C_M are dependent on the angle of attack α, the Reynolds Re number and the aerodynamic shape of the blade's profile.

An inviscid – boundary layer method is used to perform an analysis of C_L, C_D and C_M. A high order panel method (linear distribution of sources and vortexes) is used to compute the velocity distribution along the surface of the blade's profile. Lift and moment coefficients are computed from it. In order to compute the drag coefficient for a given angle of attack the viscous boundary layer analysis is performed. Using velocity distribution provided by the panel method, an integral boundary layer method is implemented. For the laminar part we use a two equation formulation, for the turbulent part we use Head's model. The drag coefficient is then computed with the Squire-Young formula. The computations of the hydrodynamic coefficients were performed in Matlab using 120 panels for velocity distribution and 250 grid points for the boundary layer analysis. After computing the hydrodynamic coefficients for a rack profile standard, and, in particular, NACA profile with chord $c = 1.3m$. By applying the computation methods described above in order to calculate the coefficients corresponding to NACA 0016 profile with length chord $c_{ref} = 1m$: $C_{L,ref}, C_{M,ref}$ and $C_{D,ref}$. The coefficients that correspond to profile with length chord $1.3m$ are computed from the relations

$$C_L = C_{L,ref} \cdot 1.3, \tag{3}$$

$$C_M = C_{M,ref} \cdot (1.3)^2, \tag{4}$$

$$C_D = C_{D,ref} \cdot 1.3. \tag{5}$$

Fig. 4 contains the moment coefficient $C_{M,ref}$ with respect to the angle of attack α. Due to the fact that the hydrodynamic force does not have the application point in the origin of the blade axis system $O^{\smile}$, the pitching moment is produced. This moment is determined with respect to a certain reference point. As a reference point we will consider the point P situated at a distance ¼ of the chord from the leading edge B (Fig. 5).

For the working value of the angle of attack $\alpha = 18^o$, we have $C_{M,ref} = -0.026$. Thus the pitching moment with respect to point P is:

$$M = \frac{1}{2} C_M \rho V_A^2 c S_p = -39.92\ N \cdot m, \tag{6}$$

where $V_A = 1m/s$, $c = 1.3m$ and $h = 1.4m$. The components of the hydrodynamic force in the

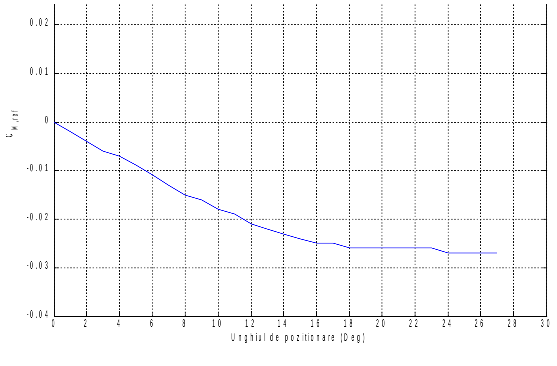


Fig. 4.

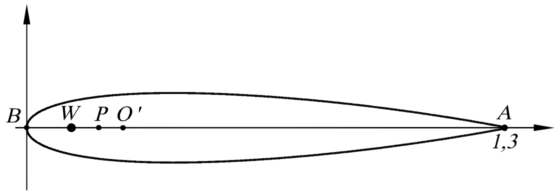


Fig. 5.

coordinate system $O'x''y''$ are given by

$$\begin{aligned} F_{x''} &= F_L\cos\alpha + F_D\sin\alpha\,, \\ F_{y''} &= -F_L\sin\alpha + F_D\cos\alpha\,. \end{aligned} \tag{7}$$

By using the values of F_L and F_D obtained from previous computations, we get $F_{x''} = 1601.2\,N$ and $F_{y''} = -413.8\,N$. Therefore

$$|O'P| = |M|/|F_{x''}| = 0.0249m \approx 25mm\,. \tag{8}$$

In order to assure the stability of the blade’s movement, the fixing point W should be chosen such that $25mm \le |O'W| \le H$, where $H_{\min} \le H \le H_{\max}$. The values of $H_{\min}$ and $H_{\max}$ shall be derived in the future work such that the friction force in the kinetic coupling of the orientation mechanism is minimal.

4. Shape optimization of the blade’s profile

In order to maximize the torsion moment developed by the micro-hydro power plant the shape optimization of the blade’s profile was carried. The blade’s profiles are chosen from the NACA 4 and 5 digits library with the shape expressed as a function of three parameters: maximum thickness, maximum camber and maximum camber location. As a shape parameter we consider only maximum thickness. Due to the use of symmetric profiles maximum camber shape parameter is taken to be zero, while the maximum camber location is arbitrary. The angle of attack is considered to be the second parameter. The goal of the shape optimization is to maximize the lift force, while keeping the pitching moment and drag coefficient not too large.

The following design optimization problem is considered:

$$\text{Maximize } C_L = C_L(\theta,\alpha) \tag{9}$$

subject to bounds on C_D and C_M,

where θ is the maximum thickness and α is the angle of attack. The values of the bounds are derived as follows: the maximum negative value for the pitching coefficient is chosen to correspond to the solution at zero angle of attack. The maximum value for the drag coefficient is chosen to correspond to the solution at angle of attack $\alpha = 18^o$. We also add bounds on the parameters themselves, so that the optimization is performed in the space of reasonable profiles: $10\% \le \theta \le 20\%$ and $0^o \le \alpha \le 20^o$. In order to find the optimal values of a given function $f = f(x_1,\ldots,x_n)$ the variable metric iterative methods can be used:

```
While given precision is not attained do
    Solve $B_i s_i = -\nabla f(x_i)$
    $x_{i+1} = x_i + \alpha_i s_i$
End do
```

where α_i are step multipliers and B_i are positive definite approximations to the Hessian of f. The derivative of f with respect to the i^{th} component can be approximated by the central difference formula

$$\frac{\partial f}{\partial x_i}(x) = \frac{f(x+he_i) - f(x-he_i)}{2h}\,, \tag{10}$$

where e_i is the i^{th} basis vector.

The shape optimization is performed within the Matlab optimization toolbox: a Sequential Quadratic Programming algorithm with a linesearch and a BFGS Hessian update. The quadratic subproblems are solved with a modified projection method. The gradients of $C_L = C_L(\theta,\alpha)$ are computed with central difference formulas with a constant stepsize h=1e^{-04}. As initial point for the optimization the symmetric NACA 0016 profile is used considered at angle of attack $\alpha = 18^o$. The initial and optimal profile shapes are shown in Fig. 6. About 30 iterations were needed in optimization subprogram to achieve the suitable convergence.

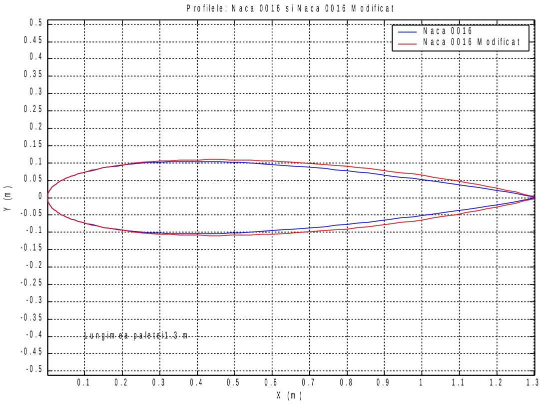


Fig. 6.

5. Determination of the optimal position of the blades in order to minimize the energy losses

In order to establish the optimal position of the blades we compare the torsion moment developed by one blade and the total torsion moment developed by all blades for different angle of attacks. The results are presented in Fig.7 and 8. It can be seen that the

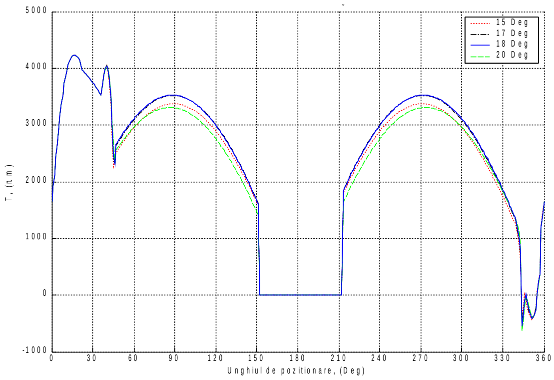


Fig. 7.

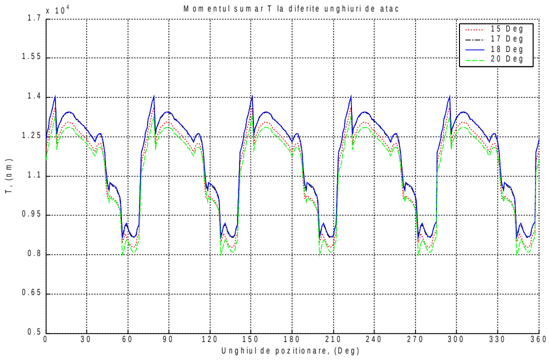


Fig. 8.

optimal angle of attack is $17^o \le \alpha \le 18^o$, therefore the torsion moment is stable with respect to angle of attack. All computations were performed for the optimized profile NACA 0016M for the flow velocity 1m/s. Also we have analyzed the performance of the rotor with 3, 4 and 5 blades in order to choose the suitable rotor configuration. The total torsion moments developed by all blades for these configurations are presented in Fig.9.

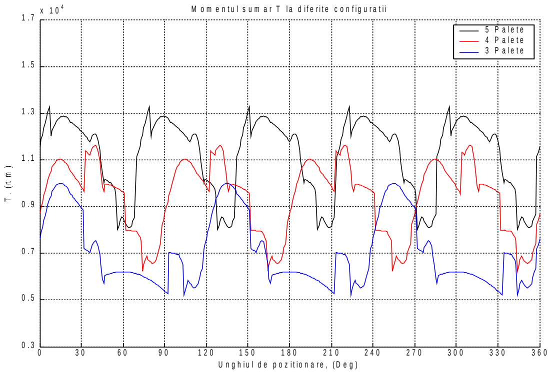


Fig. 9.

As future work we need to study the turbulence in the rotor area by carrying out a number of computer simulations in CFX5.7 software. Thus the spatial interaction between the rotor and fluid will be investigated for various functional parameters in order to increase the efficiency of the turbine and decrease the energy loss.

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