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Parametric optimization to reduce erosion in a Francis turbine runner

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Abstract. More than a half of the overall power capacity in Ecuador uniquely depends on hydroelectric power, thanks to its geographical position and large water resources. Most of them use Francis turbines, which present detriment in their lifetime due to the presence of high hardness sediments in the water reservoirs located close to the Andean mountains. In order to mitigate such effect, a structured methodology, which identifies design space variables and defines parameters that governs the phenomenon is developed. The optimization is carried out through genetic algorithms formulated to determine optimal geometrical features and hydraulic parameters based on Euler meanline turbomachinery equation. The objective function for the optimization study at this preliminary stage was erosion factor, whilst the decision variables used were: outlet diameter, acceleration flow, degree of reaction and percentage of curvature deviation from a linear of the blade angle distribution. The results obtained showed that the erosion factor can be reduced by 49 % and that the relative flow velocity at the exit was a key optimization parameter to decrease the runner erosion. This great improvement at preliminary design has been compared with other similar studies, showing a good enough prediction of erosion and the capturing of the phenomena. Furthermore, the important contribution of the present methodology is the development of a simple and versatile tool to define the design space for erosion phenomena and in this way improve the lifetime of the blade turbine runner and hence decreasing maintenance costs.

1. Introduction

Due to the energy problems we are currently experiencing, where non-renewable resources are being depleted and considering the high danger associated with the use of nuclear energy, countries of Eurasia, Asia Pacific and America have focused their efforts on the development of renewable energies [1]. Among all types of sustainable energy, the use of hydropower has increased globally by being safe and environmentally friendly. More than 60% of hydropower plants in world production use Francis turbine [1] due to their low energy losses in operation, lower maintenance costs and wide range of operating conditions with different heads within a wide range of flows [2].



Water sources used for hydroelectrical plants are susceptible to sediments from volcanic eruptions and other types of natural phenomena, which cause erosion problems, cavitation and fatigue in the turbine blades. These aspects cause premature damage, vibration, excessive noise, frequent corrective maintenance, increased machine stops and increased investment in maintenance. Francis turbine components are completely immersed in water, causing them to be more exposed to erosion. Hydroelectric projects in the Andean region, whose tributaries are near active volcanoes use Francis type turbines that have not been properly selected to work in water conditions with erosion sedimentation, causing severe damage to Turbine components [3]. In Ecuador, a good example of the aforementioned is the Agoyan Hydroelectrical plant, which invests approximately 7 million USD per year in the overhaul of one of its units, the expenses of major maintenance works arise up to 2 million USD, the replacement of elements arise up to 6 million USD and the costs for mechanical repairs and anti-erosion coating become 2 million USD. From this cost analysis has been determined that if unscheduled repairs and major maintenance works are reduced, 4 million USD can be saved [2].

Assessing erosion is a cumbersome task, which depends on several parameters, such as: sediment type, sediment characteristics (shape, size, hardness, concentration), hydraulic design, operating conditions (flow rate, head, rotation speed, velocity, acceleration, turbulence, impingement angle, etc), and material used for the turbine components [3,6]. Nevertheless, the parameter that most influences erosion is the relative velocity of the particle at the time of the collision with the surface [7].

Experimental studies are important tools for the designer, which can be considered as one of the most accurate methods for predicting turbine performance. However, they cannot be used during preliminary design, as the model optimization will demand high costs and time. Each turbine runner is unique because each hydroelectric project has its own design criteria, in the hydrodynamic part, evaluation tools are used, ranging from low fidelity solutions to high fidelity analysis and simulations [4]. Recent developments in computational design tools have narrowed the gap between construction modelling and analysis or simulation with engineering software, opening the possibility of performing parametric design and optimization with low computational resources. In this work, the parametric tools will be explored as a way to define a methodology good enough for preliminary design stage, which enables the optimization of Francis runners with low computing resources.

Gjøsæter [8] using a generator of 6 pairs of poles and uses a quadratic blade angle distribution informs a with similar, it reduces the erosion factor by 50%. The disadvantages of the design are the increase in the cost for the generator and the complexity in the blade manufacture. Another combination is to use directly as a parameter design the tangential rotor velocity of 45 m/s by experience and the same quadratic distribution, the erosion factor is reduced by 39%, CFD results show that a swirl is present in the blade channel. Khanal [9] uses 91 models with different quadratic equations for the blade angle distribution, with the optimal distribution equation, the erosion rate is about 31,5% less than baseline design. Thapa and others [10] optimized designs are developed by varying hydraulic design parameters in reference design to get the same power output. The hydraulic design parameters are varied within a defined range and its effects on erosion factor is evaluated in computational fluid dynamic.

2. Methodology

Figure 1 shows a flow diagram of the proposed methodology using an erosion model that assumes erosion proportional to the relative velocity cubed [3, 5, 6, 8-11]. In the proposed methodology, the Francis turbine runner will be conceptually designed, knowing the flow rate Q , the net height H_n and the number of poles pairs of electric generator as hydraulic parameters. Firstly, for the conceptual turbine analysis using Euler meanline design, six parameters are chosen: inlet diameter, outlet diameter, degree of reaction, inlet reduced peripheral velocity, flow acceleration and the blade angle distribution. The velocity triangles at inlet and outlet of the runner in the best efficiency point (BEP) are determined, then

the design space of the runner is defined and the variables, which affect erosion are analyzed. These results allow obtaining the objective functions for the optimization process. The data obtained in the optimization process are: the inlet and outlet velocity, the flow acceleration, degree of reaction, submergence height, outlet diameter and equation of the blade angle distribution. Mathematical adjustment is compared with results available in the open domain literature. Once the hydraulic design parameters are known, the geometry of the blade is built in three dimensions for subsequent numerical assessment.

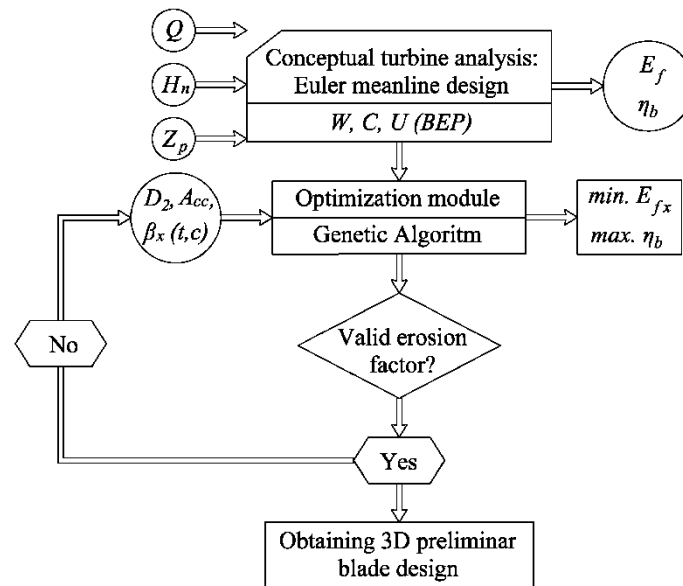


Figure 1. Flow diagram of the proposed conceptual design process [5].

2.1 Optimization process

The optimization process is performed in Matlab using genetic algorithms (GA), which are a heuristic search and optimization technique inspired by natural evolution, which allow to find the optimum values of the hydraulic design parameters for the runner, as well as the blade angle distribution to decrease the erosion factor and increase blade efficiency. The design space variables are: outlet diameter, flow acceleration, degree of reaction, coordinate of the position of curvature and the percentage of deviation from a linear of the blade angle distribution. The limits for the optimization process are defined based on information in the open domain and characteristic values for preliminary design of Francis turbines. These values were taken from [5, 9, 10] and these ones are shown in Table 1.

Table 1. Optimization range of hydraulic parameters design.

Parameter	Nomenclature	Unit	Reference value*	Optimization range
Outlet diameter	D_2	[m]	0.54	0.4 – 1
Flow acceleration through the blade	A_{cc}	[%]	10	10 – 50
Degree of reaction	σ	[%]	54	50 – 75
Blade angle distribution	β	[o]	Linear equation	Quadratic equation
				$0 \leq x \leq 1$
				$0.1 \leq z \leq 0.9$
				$0\% \leq c \leq 50\%$

* The reference value is taken from Gjøsaeter [8].

For the optimization process the figures of merit which set the best design are: blade efficiency, outlet erosion tendency and the erosion factor along the blade. These ones are calculated through equations (1) to (6). Because it is desirable to reduce the sediment erosion of the runner turbines, a preliminary estimate of erosion is calculated based on the runner relative velocity at inlet and outlet [3, 6, 8-13] as shown in equation (5). The latter equation determines the erosion factor, which is valid to assess the erosion trend, and to set the improvement in the design based on a reference baseline case. For the case of study the reference values given by Gjøsæter [8] were used to generate the baseline design. The erosion factor is defined in equation (6), which includes in the analysis the variation of flow velocities through the blade passage and hence implementing the distribution of the blade angle as a parameter of analysis. This is the main contribution of this work, where the latter factor enables the calculation of erosion at different chordwise stations starting with the shroud streamline. To determine the spanwise calculation a parametric streamline generation is carried out based on the method of Gjøsæter. The variation of the meridional velocity is assumed as a linear relation by the principle of conservation of energy in the fluid, as shown in equation (7). From the sensitivity analysis performed [5, 12], it was determined that the optimal distribution of the beta angle is a quadratic concave equation. The distribution of the blade angle β_x is set by equation (8). The meridional velocity and the angle distribution depend on the position x that the fluid takes within the streamline where zero represents the inlet of the blade and one the outlet of the blade. The constants of the quadratic equation (8) are found by equations (9) to (11) and the position of curvature deviation from a linear of the blade angle distribution is defined by equation (12).

The following equations shown the objectives functions used for the optimization process:

$$\min W_1 = \sqrt{\left(U_1 - \frac{\eta_h g H}{U_1}\right)^2 + \left(\frac{4Q}{\pi D_2^2} / \left(1 + \frac{A_{cc}}{100}\right)\right)^2} \quad (1)$$

$$\min W_2 = \sqrt{\left(\frac{4Q}{\pi D_2^2}\right)^2 + \left(\frac{\pi D_2 N}{60}\right)^2} \quad (2)$$

$$U_1 = \frac{n_h g H}{\left(1 - \frac{\sigma}{100}\right) 2gH + \left(\frac{4Q}{\pi D_2^2}\right)^2 \left(1 - \left(1 + \frac{A_{cc}}{100}\right)^{-2}\right)} \quad (3)$$

$$\max \eta_b = \frac{\eta_h g H}{n_h g H + \frac{1}{2} \left(\frac{4Q}{\pi D_2^2}\right)^2} \quad (4)$$

$$\min E_f = \frac{W_1^3 \left(1 + \frac{A_{cc}}{100}\right) + W_2^3}{2 + \frac{A_{cc}}{100}} \quad (5)$$

$$\min E_{f_x} = \frac{\sum_{x=0}^1 \left(C_{m_x}^2 \left(\frac{1 + \tan^2(\beta_x)}{\tan^2(\beta_x)} \right)^{3/2} \right)}{\sum_{x=0}^1 \left(\frac{1}{C_{m_x}} \right) E_{ref}} \quad (6)$$

$$C_{m_x} = (C_{m2} - C_{m1})x + C_{m1} \quad (7)$$

$$\beta_x = Ax^2 + Bx + C \quad (8)$$

$$A = (\beta_2 - \beta_1) - \left(\frac{\beta_2 z^2 - t + \beta_1(1 - z)}{z^2 - z} \right) \quad (9)$$

$$B = \frac{\beta_2 z^2 - t + \beta_1(1 - z)}{z^2 - z} \quad (10)$$

$$C = \beta_1 \quad (11)$$

$$t = (\beta_2 - \beta_1)z + \left(1 + \frac{c}{100}\right)\beta_1 \quad (12)$$

3. Results and discussion

In this section, the results and discussion of the optimization methodology is presented. To validate the method, the work of Thapa [10] was utilized because it shows graphs of the flow velocities distribution along the runner blade surface.

3.1. Operating conditions and optimization constrains

Based on the work of Gjøsæter [8], the operating data was obtained. The number of pole pairs was used as input based on typical specific speeds for Francis turbine [3, 5]. The turbine operates with a head of 201.5 meter and a volume flow rate of 2.35 m³/s at BEP and based on reduce sediment erosion low rotation speed are used, this is achieved by increasing the number of pole pairs of electric generator. In this case, 4 pole pairs are selected with a synchronous speed rotor of 750 rpm to obtain a frequency of 50 Hertz and 13 blades [5, 12].

3.2. Runner Blade optimization

From the genetic algorithm optimization, a Pareto diagram has been used to select the solution family that suits the best for the case of study. Figure 2 (a) shows the Pareto front of the results obtained, relating the erosion factor to the submersion height. This latter is an important factor related to the performance of the turbine to reduce the appearance of cavitation. If water pressure in the runner is lower than the vapor pressure, cavitation may occur. In order to avoid the water pressure to drop below the vapor pressure, Francis turbine used to be submerged. The submergence height depends on the turbine geometry, flow rate, speed runner, atmospheric pressure and positive net suction height. It is observed that there are combinations of results that allow to obtain a factor of erosion lower than the baseline design (erosion factor equal to 1). Therefore, the likelihood of cavitation for reaction turbines, can be reduced when installing the turbine at heights below the submersion height. Run-of-river scheme power plants seldom have a turbine submergence of more than ten meters [8]. Three to eight meters below tail water level is relatively common, but the deeper the submergence, the higher is the development costs for the power plant. It is however important to remember that cavitation is more prone to occur on turbines operating in silty water. Thus, it may be necessary to submerge the turbine a 0.5 meters than what is calculated as required, as this value is valid for clean water operation only. For the parametric design, the results of the submersion height of -2.59 meters is considered based on the afore mentioned and since it allows a reduction of 49% for the erosion factor.

In Figure 2 (b) are shown the optimal blade angle distribution obtaining in this work, the quadratic distribution obtained in the work of Thapa [10] and the energy distribution along the streamline surface from inlet (0) to outlet (1). Choosing the blade angle distribution gives the designer full control of the design outcome, and avoids any strange designs. The shape of blade angle distribution of optimum blade is similar to shape obtained by Thapa et al. The energy distribution describes the transformation from pressure energy to rotational energy along the blade, in this case, the form of energy distribution is uniform. The data of the optimized variables is shown in Table 2.

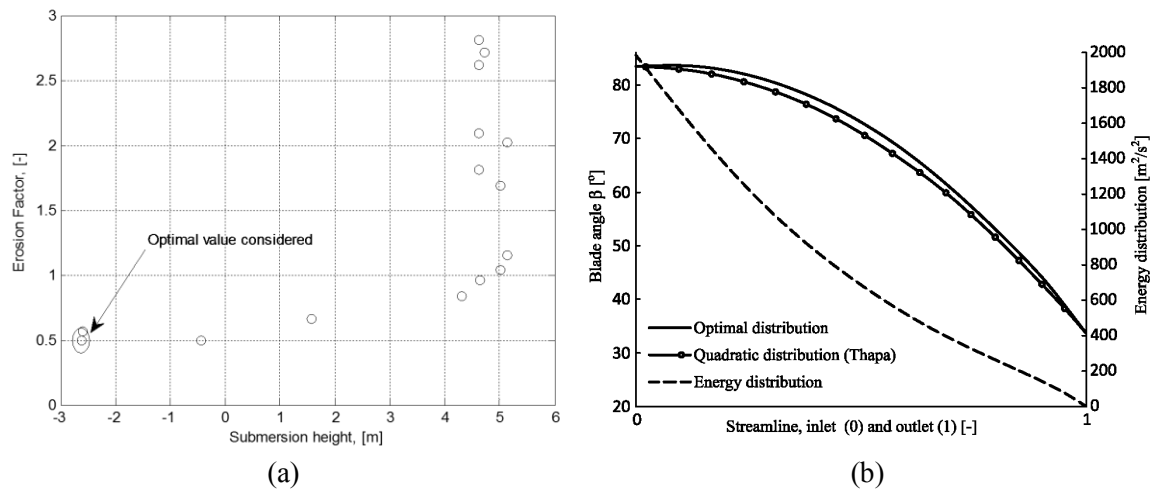


Figure 2. Pareto front per intent 1 (a) and blade angle distribution (b).

Table 2. Results of the optimization process.

β_2 [°]	A_{cc} [%]	σ [%]	H_s [m]	E_f [-]	D_2 [m]	z [-]	c [%]	A [-]	B [-]	C [-]
33.61	40.78	56	-2.59	0.51	0.53	0.90	6.23	-59.65	9.78	83.49

3.3. Comparison of the method

To contrast the methodology presented information available in the open domain regarding parametric design of Francis turbines is utilized. Figure 3 shown a comparison between the energy and velocities distribution along the streamline with the energy and the velocities distribution found in work of Thapa [10]. The tendency of distribution of each velocity comes to be like those found by Thapa methodology.

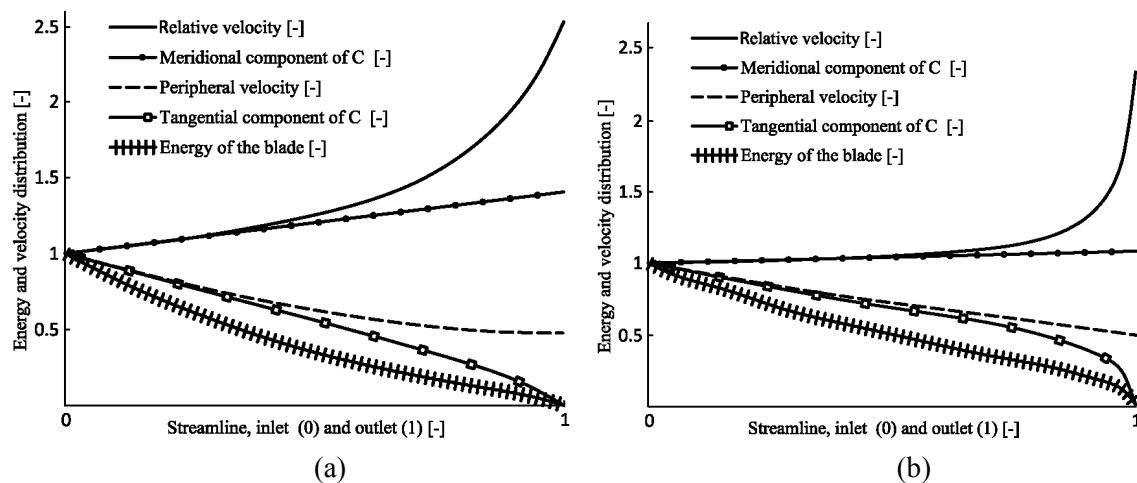


Figure 3. Energy and velocity distribution: optimization by genetic algorithms (a) and optimized design by Thapa's methodology [10] (b).

3.4. Parametric geometrical generation

With the design inputs established in Table 2 a graphic user interface program developed in Matlab create 3D runner which can be exported as CAD document for further analysis in ANSYS. The 3D geometrical generation is based on the design of the streamlines of the flow, which goes through the runner, considering the ideal path of the working fluid, that is to say, from the calculation of the flow path it is possible to calculate the points of the geometry that comprise the blade. Figure 4 shows the views obtained from the generation module [13], the design starts by obtaining the main views (axial and radial) then join them forming the figure of the blade in three dimensions. However, this geometry is thickless, so by means of criteria of form at the inlet (leading edge) and the outlet (trailing edge), the final form of the blade is obtained. The main inputs required to calculate the parameters of the working flow are the flow rate and the head, in the other hand, to calculate the kinematics variables, is necessary to know the inlet and outlet desired diameter, the number of pole pairs of the turbine generator to calculate its synchronous speed, and the acceleration of the flow through the blade.

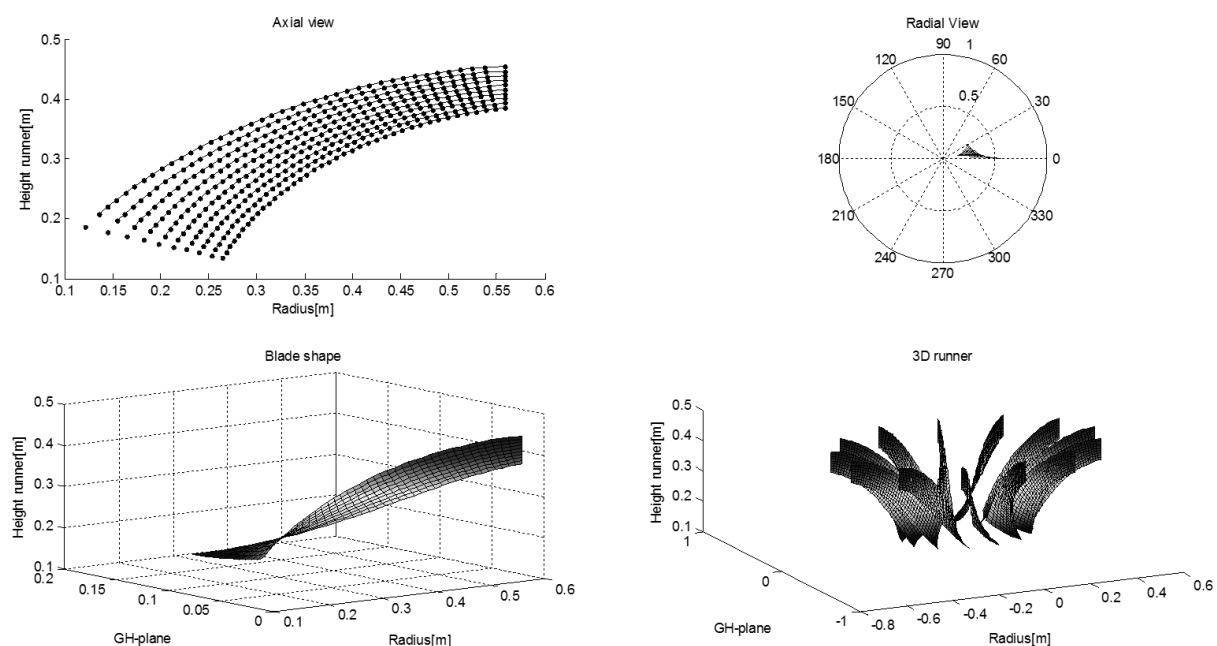


Figure 4. Geometry obtained from the model.

4. Conclusions

This work has evaluated a method of multi objective optimization by genetic algorithms with five objective functions based on geometry and performance to reduce erosion. For this aim was found a family of parameters for the inlet and outlet of the blade. The result was chosen according to comparison with proved designs in the literature. Furthermore, this work found an optimal of the blade angle distribution to decrease the erosion rate.

With the intention of reflecting the local conditions, its necessary to carry out a study of the type, relative number, shapes and sizes of particles to improve the erosion model. The model on which part of this work is based, considers ideal working conditions, which may give results a little different from reality, however, it is a light and powerful tool for the geometrical modeling of the blade.

Nomenclature

W	Relative flow velocity to the blade [m/s]	Z_p	Number of pairs of generator poles [-]
U	Peripheral or tangential rotor velocity [m/s]	f_g	Frequency of electric current
C	Absolute velocity of fluid [m/s]	g	Gravity acceleration [m/s ²]
C_m	Absolute velocity meridional component [m/s]	z	Curvature position [-]
C_u	Absolute velocity tangential component [m/s]	c	Curvature deviation percentage [%]
E_f	Erosion factor [-]	t	Curvature position route [-]
E_{ref}	Erosion factor of the reference model [-]	A, B, C	Blade angle distribution equation constants [-]
N	Synchronous velocity [rpm]	η_h	Hydraulic efficiency [%]
Q	Flow rate [m ³ /s]	η_b	Blade efficiency [%]
H_n	Net head [m]	b	Blade inlet height [m]
H_s	Minimum submersion height [m]		

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