Evaluation of guide vanes effect over runner Francis turbine sediment erosion using a quasi-two dimensional approach

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Abstract. Francis turbines are widely used in hydroelectric power plants all over the world, Ecuador is not an exception to this trend. Hence, Francis turbine design and assessment have taken importance in order to provide in-house design methods to enhance their performance in the region. The volcanic nature of the region facilitates sediment formation, which produces drastic erosion problems in many Francis turbines. Since guide vanes set the inlet flow velocity of the runner and erosion is related with the velocity distribution through this latter, this work evaluates guide vane profiles using a quasi-two dimensional approach to assess the impact of guide vane design on erosion rate. For this aim, parametric analysis and a mean line analysis are employed for the conceptual geometrical design, which then is coupled with a panel vortex model to assess the two dimensional hydro profiles for the guide vanes. Thus, the velocity triangles at entry and exit of the guide vane-runner setup can be related to the erosion rate within the runner. At this stage the calculations were carried out at the BEP and for the validation experimental data from the San Francisco hydroelectric power plant was used. The results show how the model developed captures main performance trends and enables the correlation of erosion with the geometrical features of the guide vanes. The method used is accurate enough for preliminary design and its low computational resources with versatility make it suitable for optimization routines for erosion proof designs.

1. Introduction
Ecuador privilege geography due to the Andes Mountain chain make this region perfect for hydroelectric energy generation. Since, the region is full of rivers with big affluence it is possible to use the potential energy of the flow to generate renewable energy [5]. Despite this, Ecuador’s hydroelectric plants, located in the highland, coast and Amazon region only use the 23.05% of the potential hydroelectric resources, leaving the rest untapped [6]. This untouched potential energy sources presents a great opportunity for hydroelectric projects. However, the due to volcanic and geological activity, the rivers of the region have suspended sediments, which are the principal factor that caused phenomena such as erosion and cavitation in the principal mechanic elements of a turbo machine.

In the case of a Francis turbine, the elements that suffer accelerated erosion are mainly runner blades [8]. The guide vanes are in charge of directing the flow towards the runner to keep the turbine speed constant when the load varies, in order to preserve the level of efficiency [9].
As they are in charge of regulating the inflow to runner, they are considered very important components which study require special interest.

Due to the importance of the erosion phenomena and how it affects the different components of a generation turbine, several studies have been made to predict the damage in those components and how to mitigate this affection. Koirala [2] presented a selection of the profile for Francis turbine guide vanes. A computational and experimental study of 4-digit NACA profiles such as: NACA 0012, 1412, 2412 and 4412, was done. The study showed that the NACA profile 4412 presents the lowest erosion compared to the rest of the profiles and a low pressure difference between the suction and the pressure side. It also shows a better performance in waters loaded with sediments. Lama [3] carried out a numerical research of performance and erosion with different guide vane profiles for a Francis turbine using computational tools. The research studied the turbine performance predictions at different angles around the BEP. NACA 4412 showed high performance with minimal sediment erosion on the runner blades for all operating conditions. The same year, Chitrakar [1] studied the effect of the leakage flow through the free spaces induced by erosion of the guide vanes. The leakage flow is quantified by calculating the perpendicular component of the velocity to the guide vane chord and the factor flow rate [1]. The results showed that there is a reduction of the perpendicular component of velocity along the chord up to 40% in NACA 4412 in BEP compared to the others profiles. The Runner’s efficiency is increased by up to 3% using NACA 4412 guide vane. Pressure pulsation amplitude was reduced between 49% and 63% at runner inlet using NACA 4412 profile compared to NACA 0012. Profiles Asymmetric plants showed improved erosion and efficiency yields.

Nora [4] studied the erosion in the guide vanes through a numerical and experimental analysis. Based the study on the NACA 4412 and NACA 0012 profiles to determine which is the best profile to reduce erosion. Consider that it was developed more investigations to verify what was proposed to validate the results, and thus established an improved design of the vanes guide.

Aponte [8], in his research work, proposed a multi-objective optimization methodology to minimize erosive wear in a Francis turbine. The applied methodology generates a database starting from generally used geometries that feeds an artificial neural network (ANN). After several iteration processes an asymmetric profile is obtained for the vane guide which shows a qualitative decrease in erosion. A wide variety of options are considered for profile optimization, such as climate, energy costs, and geographic conditions.

The referenced studies show that the application of asymmetric profiles has a better performance with high operating yields and less erosion. The topic addressed so far is directed to the selection of profiles through a dimensionless analysis. The present work uses a methodology that allows selecting a profile based on an analysis with a quasi-two dimensional approach, taking the drag forces generated by the profile and calculating the velocity triangle for the different NACA profiles to obtain factors related to erosion which are indicators of the wear that could occur in the guide vane. Validation is carried out by comparing the calculations made with experimental data obtained from previous works by other authors for the same case study.

2. Methodology

Figure 1 shows the diagram of the proposed methodology to select the appropriate profile for guide vane to reduce the sediment erosion in the runner blades. The methodology considers a direct relation between erosion over runner and relative velocity. First, the Flow Rate \( Q_d \) and Net Head \( H_d \) are considered as input to a parametric modelling. Based on 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, for the parametric modelling. The design for the best point efficiency (BEP) was carried out, where the following...
parameters are calculated: relative flow velocity ($W$), Peripheral velocity ($U$), absolute velocity ($C$) and the exit angle ($\alpha_0$). Based on these results, a non-dimensional analysis was done for Naca profiles. The drag coefficient was analysed for different attack angles using the software JavaFoil. The profiles which generates the minimum drag was selected. Then, the velocity triangles at inlet and outlet of the runner in the best efficiency point (BEP) are determined. After completing the described steps, the velocity triangle was analyzed. It was checked which are changes in the direction of the fluid speed at the exit of the guide vane (runner relative velocity inlet). Afterwards, the Erosion Tendency ($E_t$) and the Erosion Factor($E_f$) (shown in equations 2 and 3) were calculated using the models proposed by Biraj Thapa [10]. These factors are used to analyze the reduction in the runner erosion. The erosion factors are compared and the profile that presented the minimal is selected.

![Figure 1. Selection methodology](image)

2.1. Parametric modelling
The Francis turbine and guide vanes parametric design used by Okyay [15] are applied to the present work, where all the calculations are carried out for the Best Point Efficiency (BEP) to minimize losses. The equations of the different variables used are shown in table 1. It is assumed that the flow at the outlet is parallel to the guide vane. The methodology omits irreversibilities presented in the turbo-machine operation, however it is a suitable approach. NACA profiles are used in various applications. Francis turbines are not the exception, finding in several guide vanes profiles [1, 2, 3, 4]. Their nomenclature is easy to understand and there are several tools for its analysis. The present study uses a JavaFoil computational tool which allows to obtain the different types of profiles.
Table 1. Parametric design

| Variable              | Equation                                      |
|-----------------------|-----------------------------------------------|
| Discharge             | $Q_d \text{ [m}^3\text{/s]}$                 |
| Head                  | $H_d = \left( P_{\text{inlet}} - P_{\text{Outlet}} \right) / \text{Dmaxg} \text{ [m]}$ |
| Power                 | $P_d = \rho g Q_d H_d \text{ [MW]}$           |
| Rotational Speed      | $n = n_q \frac{H_2}{P_d} \text{ [rpm]}$       |
| Specific Speed        | $n_s = n_{\text{sync}} \frac{P_d}{H_1} \text{ [rpm]}$ |
| Angular rotational speed | $\omega = 2\pi \frac{n_q}{60} \text{ [rad/s]}$ |
| Turbine Working Principle | $\Gamma = \frac{1}{4} c V \cos(\alpha_0) dl$ |

2.2. Non-dimensional Analysis

The Non-dimensional analysis was focused on the variation of the drag coefficient ($C_D$). It is important that the different elements of the turbine generate low drag forces because it is relative to energy losses. The profiles of the guide vanes can be analyzed in their two-dimensional form.

In addition to the analysis performed for the BEP condition, the variation of the $C_D$ with different angles of attack is analyzed taking as a reference the angle of zero degrees.

The variation of $C_D$ was analyzed in accordance with equation 1, which describes the variation of this parameter with respect to the previous value for a deflection angle. The analysis started considering the the angle of attack of zero degrees, as reference.

$$\Delta C_D = \frac{C_{Di} - C_{Di-1}}{C_{Di-1}}$$

(1)

$\Delta C_D$ is multiplied by 100 to obtain the percentage variation, where $C_{Di}$ is the drag coefficient for an angle of attack $\alpha_i$. The coefficient at the current position is subtracted from the value of the previous position. The difference obtained is divided for the the previous value.

2.3. Erosion estimation

Erosion Tendency and the Erosion Factor by Thapa [10] and Bone [13] were calculated, based on the variations of the relative velocity in the runner. For that, the velocity triangles were analyzed at the BEP condition. The following equations were used to the estimation:

$$E_t = \frac{\sum W_i^3 A_i}{\sum A_i}$$

(2)

$W_i$ is the relative velocity in each segment area $A_i$ on the runner blade.

$$E_f = \frac{(E_t)_{\text{new design}}}{(E_t)_{\text{referenced design}}}$$

(3)

$$E_t = \frac{W_1^3 C_m2 + W_2^3 C_m1}{C_m1 + C_m2}$$

(4)

The sub-indices indicate the speeds to the runner’s inlet and outlet.
3. Results & discussions

3.1. Case of study: San Francisco-Ecuador

San Francisco Hydroelectric power plant, which is part of the Hidroagoyan business unit of CELEC E.P., was selected as case study of the present work. It has been generating electric energy for Ecuador since 2007 and is located in Baños de Agua Santa, Tungurahua province, in the Pastaza River basin. The installed power is 230 [MW], operating with a Francis type turbine [9]. The Rio Pastaza has volcanic material, clays, suspended [11]. Causing serious inconveniences in the operation, generating damage to the elements of the turbo-machines. Currently, the guide vanes were manufactured from the NACA 0012 profile [12], and going to be the reference for the analysis. The guide vanes suffer serious erosion and abrasion damage by the sediments, for which it is necessary to present solutions to these different problems.

3.2. Validation

The validation was carried out by comparing the estimates of the parametric modeling and the operation data of the case study Mora [16]. The discharge and height conditions were considered as input data. Power, torque, efficiency were estimated. Table 2 shows the corresponding values for a flow rate of 58 [m³ / s] (BEP condition). An error of 19.35 % is determined, based on the calculated power. The high error is explain due to the calculation method is purely theoretical with a two-dimensional approach. Irreversibilities were not considered in the method. Therefore, there is major gap of error. However, the result obtained is acceptable to continue with the work.

| Variables | \(Q_{exp}[m^3/s]\) | \(Power_{exp}[MW]\) | \(Power_{cal}[MW]\) | \(Efficiency_{cal}\) | \%Error |
|-----------|---------------------|----------------------|----------------------|----------------------|---------|
| 58        | 103.18              | 83.21                | 75.85                | 19.35                |

3.3. Francis turbine and guide vane parametric design

Table 3 lists the calculated parametric design values for the opening guide vanes angle of 23.03 °, corresponding to the BEP condition. Hence, it is consider that the flow is parallel to this element. Four NACA profiles are selected based in the literature and design methodology. Profiles with 0% and 60% of chamber and a camber of 0% 4% 5% and 6% are used for selecting the best profile. The tool JavaFoil was used for plotting the hydrofoils.

3.4. Non-dimensional number analysis

3.4.1. Drag analysis: The analysis is focus on the BEP condition, however it is considered important to verify the behavior of the profiles for different angles of attack. This information allow to determinate how effective is the profile. Figure 2 shows the percentage variation of the drag coefficient versus the angle of attack for the profiles NACA 0012, 4412, 5412 and 6412. Based on that, the following observations can be determinate:

- In the range from -30 to 0 degrees, the lowest variation in \(C_D\) is found in the NACA 0012 profile compared to the other three profiles, which is desirable for its selection;
- In the range from -30 to -20 degrees, the drag variation is minimal for all profiles but asymmetric profiles have a lower value compared to NACA 0012. It is due to asymmetric profiles manage to the flow to generating less turbulence for high Reynolds numbers.
- In the range from 0 to 30 degrees, it has an undesirable behavior because the variation of the coefficient is much higher than that of the other three profiles under analysis, which is not
Table 3. Parametric design BEP

| Variable | Value       |
|----------|-------------|
| $Q_d$    | 58 [m³/s]  |
| $H_d$    | 146.76 [m] |
| $P_d$    | 83.21 [MW] |
| $n$      | 279.84 [rpm]|
| $n_s$    | 215.49 [rpm]|
| $\omega$| 34.271 [rad/s]|
| $\alpha_0$| 23.0299° |

suitable for our turbine.
- The profiles NACA 4412, 5412 and 6412 have soft variations of the $C_D$. For that, they would be suitable for guide vane profiles. However, It is necessary additional non-dimensional analysis for consider the erosion.

3.4.2. Velocity analysis: The deflection in the camber line, produced in asymmetric profiles, helps to have a better performance in the Francis turbine [1, 2, 3, 4, 5]. This bent of the profile encourages the flow to be deflected by changing the direction of the exit velocity. It is analyzed along this entire line trying to capture the behavior of the flow in the SS and PS, as shown in figure 3. It was observed that a marked deflection were presented on the profiles NACA 4412, 5412 and 6412 in comparison with the NACA 0012, where deflection is not noted. The deflection taken into account in the camber line for NACA profiles, is shown in figure 4.
Based on the different profiles deflection, the exit direction of the velocity changes and also its magnitude along the profile, as shown in figure 5. This change in magnitude and direction along the camber line is analyzed. For NACA 0012 profile, there are no variations since the flow comes out parallel to profile. The most notable change produce in the flow is noted with NACA 6412 profile, followed by the other two profiles.

### 3.5. Erosion assessment

The asymmetric profiles deflect the flow until it reaches the runner. Hence, the erosion produced by the solid particles impact is modified. Figure 6 shows the erosion factor estimation. The NACA 0012 profile is the reference design. The other profiles present a lower erosion factor because their asymmetry achieves a change in the relative velocity. The profile NACA 6414 shows less erosion than other profiles.
3.6. Costs

The cost analysis is carried out based on the feasibility study for the design of an industrial machining plant for the reconstruction of Francis turbines of company CELEC E.P. [7]. Table 4 shows a cost maintenance estimation of the case of study, for all profiles analyzed. The reference cost considered is for NACA 0012 profile, which is currently installed in the Francis Turbine. The maintenance and repair costs for the guide vanes (GV) and the runner (RN), are more than three million dollars, representing 47.95% of the budget, Sagñay & Pilamunga [7]. For an initial estimation of the cost reduction due to implementation of the other profiles, a proportional relation between the erosion factor ($E_f$) a maintenance cost is considered. It is noted that new profiles provide a resounding savings that exceeds one hundred thousand dollars. The profile with maximum savings achieved is the NACA 6412, ensuring a greater useful time for the runner and other elements.

4. Conclusions and future work

An evaluation of guide vanes effect over runner Francis turbine erosion using a quasi-two dimensional approach was developed. Considering a parametric modelling, non-dimensional analysis and erosion assessment. Four NACA profiles were used in the analysis: 0012, 4412, 5412, 6412. The profile NACA 0012 was considered as point of reference due to it is widely
Table 4. Total costs comparison

| Concept           | Total cost GV | Total cost RN | Profiles | $E_f$ | Saving       |
|-------------------|---------------|---------------|----------|-------|--------------|
| New parts         | $812,568.96   | $2,336,987    | NACA 0012| 1     | $0           |
| Mechanical repair | $216,200      | $524,200      | NACA 4412| 0.9979| $189,200.49  |
| Surface coating   | $180,800      | $110,275      | NACA 5412| 0.9974| $191,200.60  |
|                   |               |               | NACA 6412| 0.9970| $192,800.69  |

used in the guide vane of the turbines in the case of study. In this context, the profile NACA 6412 showed a better performance to reduce the erosion in the Francis Turbine. However, design studies with higher fidelity are necessary to confirm this preliminary result. Furthermore, the following observations can be highlighted:
- The variations of the $C_D$ are similar for the four profiles analyzed.
- The savings in maintenance and repair costs could be approximately $192,800.69, which is a significant value. A more precise study is required to determine the precise economic benefits of replacing the blades in the turbine with the new asymmetric profiles.
- The results obtained are accurate enough considering the methodology used. However, a high-fidelity analysis is required to verify the predictions model. The present work serves as a starting point in the development of a high-fidelity design methodology.

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