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HYDRODYNAMIC DESIGN AND NUMERICAL ANALYSIS OF A NEW FRANCIS TURBINE WITH HIGH SPECIFIC SPEED

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ABSTRACT

The paper presents our ongoing efforts in order to develop a new Francis turbine with high specific speed. First, the Francis turbine is designed based on classical method. Second, numerical investigation is used in order to improve the hydrodynamic performances. The computational domains correspond to meridional cross view for Francis turbine distributor, runner and draft tube cone, respectively. As a result, the band contour is modified in order to improve the cavitational behaviour.

KEYWORDS

Francis turbine, high specific speed, hydrodynamic design, numerical analysis

NOMENCLATURE

V	[m/s]	absolute velocity
Vm/Vm_{in}	[-]	relative meridional velocity
c	[m]	curvature
n_s		specific speed

Subscripts and Superscripts

1e	reference section (runner inlet section)
m	meridional direction
r	radial direction
u	tangential direction
z	axial direction
max	maximum
min	minimum

ABBREVIATIONS

LE, TE	leading edge and trailing edge of the blade
in, out	inlet section, outlet section
sf	dimensionless streamfunction
BEP	best efficiency point
HPP	hydropower plant

INTRODUCTION

Renewable energy is energy generated from natural resources - such as sunlight, wind, rain, tides and geothermal heat - which are renewable (naturally replenished). Renewable energy technologies include solar power, wind power, hydropower, biomass and biofuels.

Hydropower is the largest source of renewable energy and it is the most efficient way to generate electricity. Hydropower is still the only means of storing large quantities of electrical energy for almost instant use. This is done by holding water in a large tank behind a dam with a hydroelectric power plant below. In addition to producing electricity, dams provide for flood control, water supply, irrigation, transportation, recreation, or wildlife habitat and refuges.

The hydropower energy is generated in hydroelectrical power plants. The hydraulic structures of the power plant include a dam, tunnel, surge tank, penstock and hydraulic turbine. The hydraulic turbine selection is based mostly on the available water head and the discharge. The Francis turbines are the most common water turbine in use today. They operate in a head range of thirty meters to several hundred meters and are primarily used for electrical power production. The Kaplan turbine with adjustable blade pitch are well-adapted to wide ranges of flow at low head conditions, especially under forty meters. That means, the Francis turbine cover the range of specific speed from fifty to five hundred while the Kaplan turbine beyond to four hundred. Consequently, the Francis and Kaplan turbines overlap on a norrow domain. This domain requires an innovative design. This new turbine is suitable for sites with characteristics that allow the installation a high specific speed Francis turbine or a low specific speed Kaplan turbine. The runner is 50 % radial flow and 50 % axial flow and so can be regarded as a design that is between a Kaplan and Francis turbine.

Classical turbine design methods were developed more then one hundred year ago. However, the classical design is improved based on statistical data yielded from experimental investigations, [2] [5], [10]. Accordingly, refined classical design methodologies are developed in order to improve Francis turbines performances, [1] [8] [13]. Nevertheless, a new design philosophy of Francis turbine runners is proposed by Prof. Brekke and applied to obtain the X-blades [3], [4].

The paper presents our ongoing efforts in order to design and analysis the hydrodynamic of a new Francis turbine with high specific speed. First, the Francis turbine hydrodynamic design concepts are presented. Second, the numerical investigations are performed in order to compute the hydrodynamic field. Consequently, different band contours are investigated in order to improve the hydrodynamic performances. The conclusions and perspectives are summarized in last section.

HYDRODYNAMIC DESIGN OF THE FRANCIS TURBINE WITH HIGH SPECIFIC SPEED

Up to now, the team from S.C. HydroEngineering S.A. Resita have designed more than one hundred Francis turbines with specific speed from ninety to three hundred and thirty. According to the energy market requirements a new Francis turbine with high specific speed is needed. Consequently, an innovative Francis turbine is developed. The parameters correspond to Cindere HPP from Turkey.

Table 1. The Cindere HPP tehnical data.

nominal net head (H_n)	43.2 [m]
maximum net head (H_{max})	50.1 [m]
minimum net head (H_{min})	28.1 [m]
nominal discharge (Q_n)	23.4 [mc/s]
speed (n)	375 [rpm]
turbine diameter (D_{1e})	1.5 [m]

Based on Francis turbine database from S.C. Hydro Engineering S.A. Resita and using the clasical design a new turbine with high specific speed (n_s=360 rpm) is designed. The hydraulic passage includes: spiral case, stay vanes, guide vanes, runner and draft tube, see Figure 1.

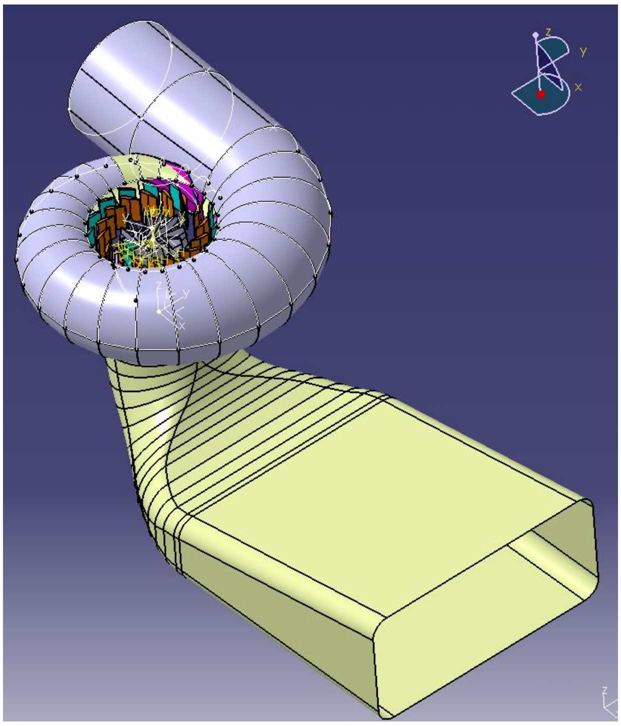

Figure 1. 3D view of Francis turbine with high specific speed.

Table 2. Main parameters of new Francis turbine with high specific speed.

Spiral casing parameters	
penstock diameter (D_c)	1.533*D_{1e}
diameter of the spiral case inlet section (D_{iSC}), see Figure 2	1.427*D_{1e}
distance between axis (L_{AC}), see Figure 2	1.4*D_{1e}
spiral angle (α_{sp})	31^0
Stay vanes parameters	
profile type	asymmetric
high of stay vanes (b_0)	0.352*D_{1e}
number of stay vanes (Z_s)	16
Guide vanes parameters	
profile type	asymmetric
high of stay vanes (b_0)	0.352*D_{1e}
number of stay vanes (Z_0)	16

The parameters of the Francis turbine are computed according to the equations:

$$n_{11} = \frac{nD_{1e}}{\sqrt{H}} \tag{1}$$

$$Q_{11} = \frac{Q}{D_{1e}^2 \sqrt{H}} \tag{2}$$

Consequently, the following values are obtained at best efficiency point: unit speed n_{11}BEP=87.68 and unit discharge Q_{11}BEP=1.5032.

Using the formula available in literature [1] and the Francis turbine database from S.C. Hydro Engineering S.A., the following dimensions are considered for spiral casing, stay vanes and guide vanes with respect of the reference diameter D_{1e}, see Table 2.

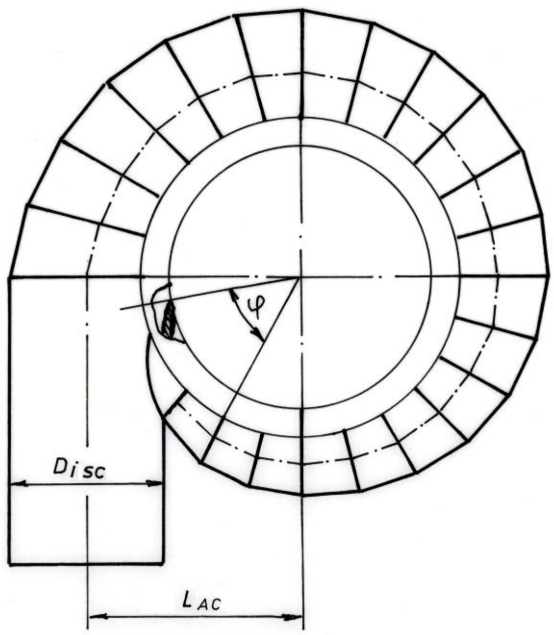

Figure 2. 2D view of Francis turbine spiral casing with high specific speed.

The main element of the Francis turbine is the runner. It can be seen from equations (1) and (2) that the n_{11} and Q_{11} depend on reference diameter D_{1e} which define the size of the flow channel, Figure 3. Based on the values of diameter ratio ($D_{1e}/D_{2e}=r_{1e}$ $D_{1i}/D_{2e}=r_{1i}$ and $D_{2i}/D_{2e}=r_{2i}$) the critical points of meridional cross section are computed. However, the values of diameter ratio ($D_{1e}/D_{2e}=r_{1e}$ and $D_{1i}/D_{2e}=r_{1i}$) can be selected in a large range according to the literature recommendations, [1] [2] [5] [10] [13]. In our case, the following value is selected: D_{1e}/D_{2e}=0.90744. The rest of values ($D_{1i}/D_{2e}=r_{1i}$ and $D_{2i}/D_{2e}=r_{2i}$) are selected based on our experience.

The meridional cross section is defined by four contours, describing the crown, band and the projected leading edge and trailing edge of the blade. Using the Bovet curves family [2] the crown and band contours of flow channel are obtained. In this case, the projected leading edge and trailing edge of the blade are generated using Chebyshev polynomial distribution. Based on our preliminary design of the runner, eleven blades are considered.

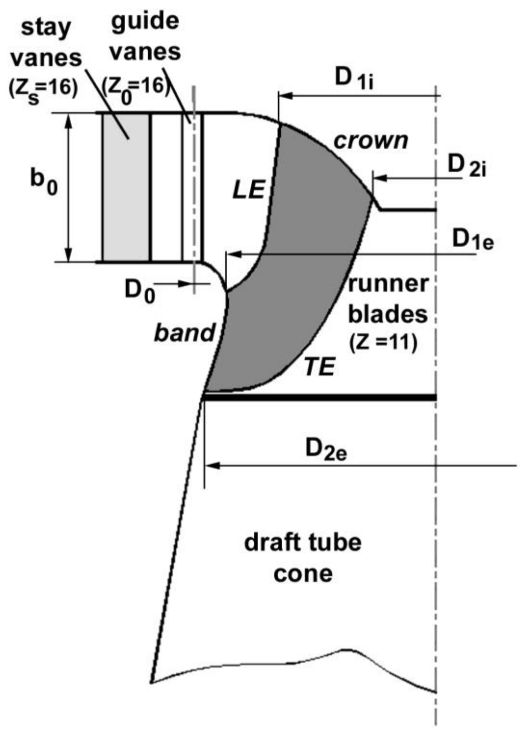

Figure 3. Meridional cross view of Francis turbine with high specific speed.

NUMERICAL INVESTIGATIONS

Numerical simulation introduces a step-forward in developing new methodologies and aided design tools to improved turbomachinery design procedures [6], [11]. In this paper are presented our numerical investigation in order to analysis and improve the design procedure of the band contour.

Assuming axial symmetry is an important simplification for the flow numerical simulation. As a result, the problem can be studied in a 2D domain within a meridional half-plane [12], [15], instead of considering a full 3D computational domain, [11]. This is generally the case for hydraulic turbines, where the characteristic Reynolds number usually reaches $10^6 \ldots 10^7$. Consequently, inviscid model based on Euler equations is suitable in order to compute the flow at best efficiency point, [14].

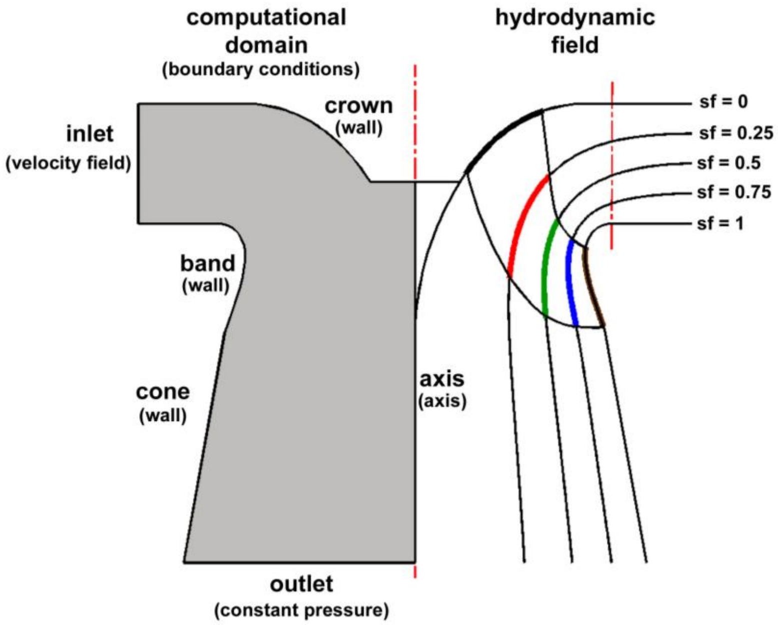

Figure 4. Francis turbine model with high specific speed: 2D computational domain and boundary conditions (left) and streamlines of the hydrodynamic field (right).

The governing equations for the incompressible, unsteady, inviscid and axi-symmetric flow in cylindrical coordinates are:

$$\frac{\partial V_z}{\partial z}+\frac{\partial V_r}{\partial r}+\frac{V_r}{r}=0 \qquad (3)$$

$$\frac{\partial \mathrm{V_z}}{\partial \mathrm{t}}+\frac{1}{\mathrm{r}}\frac{\partial}{\partial \mathrm{z}}\left(\mathrm{rV_zV_z}\right)+\frac{1}{\mathrm{r}}\frac{\partial}{\partial \mathrm{r}}\left(\mathrm{rV_rV_z}\right)=-\frac{1}{\rho}\frac{\partial \mathrm{p}}{\partial \mathrm{z}} \qquad (4a)$$

$$\frac{\partial \mathrm{V_r}}{\partial \mathrm{t}}+\frac{1}{\mathrm{r}}\frac{\partial}{\partial \mathrm{z}}\left(\mathrm{rV_zV_r}\right)+\frac{1}{\mathrm{r}}\frac{\partial}{\partial \mathrm{r}}\left(\mathrm{rV_rV_r}\right)=-\frac{1}{\rho}\frac{\partial \mathrm{p}}{\partial \mathrm{r}} \qquad (4b)$$

The following boundary conditions are considered:

inlet	velocity component are imposed: radial component is computed based on discharge at best operating point while the circumferential and axial components are zero.
outlet	constant pressure is imposed.
wall	an impenetrable condition is imposed. That means the normal velocity component is zero.
axis	a symmetric boundary condition is considered.

The streamlines are obtained based on the hydrodynamic field computed using the axisymmetric flow model, [7]. Plotting the relative meridional velocity distribution along to the streamlines reveals a maximum value on the band. The relative meridional velocity distribution associated with the runner blade region is marked with thick lines in Figure 5. Consequently, the cavitational maximum risk appears on the runner band.

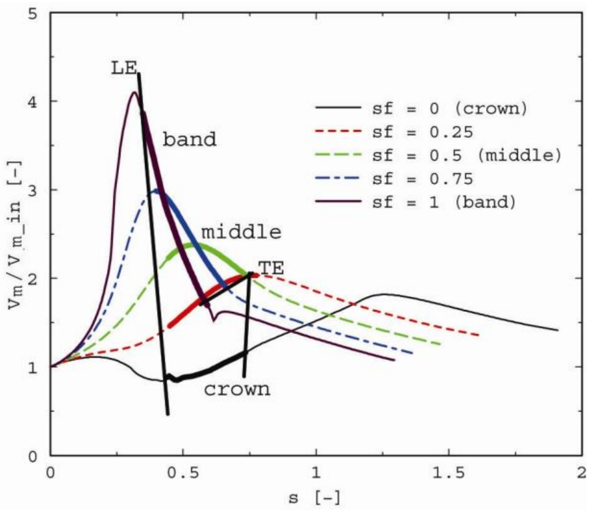

Figure 5. Relative meridional velocity distribution along to the streamlines.

The band contour will be modified in order to improve the cavitational behaviour of the runner. As a result, the curvature of band contour designed with Bovet functions is computed, see Figure 6. One can observe large values of curvature on the band, especially at the junction with the lower ring, while the curvature associated to the lower ring and cone wall is zero because straight lines are considered. Consequently, it is proposed a new criterion in order to reshape the band based on curvature distribution. The optimum curvature distribution of band is necessarily to be with minimum curvature that means maximum radius and smooth distribution.

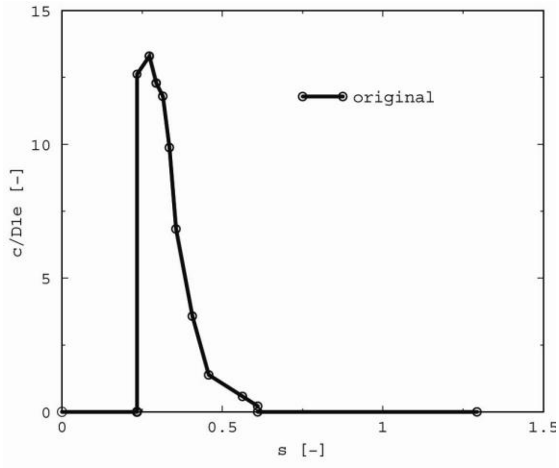

Figure 6. Dimensionaless curvature distribution along to the original band contour.

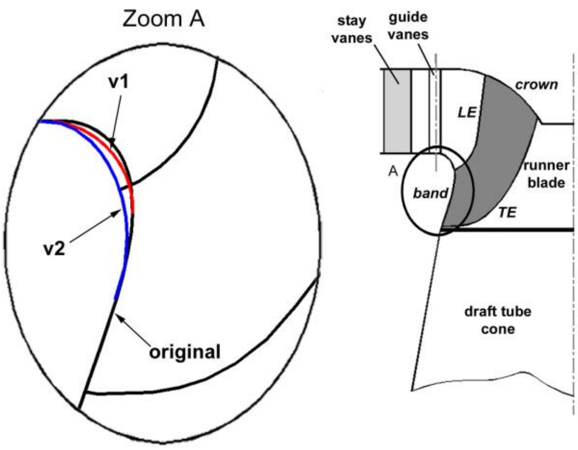

Figure 7. Generating different band contours using geometrical considerations.

The band contour can be reshaped using both geometrical and/or hydrodynamical considerations. As a result, geometrical modifications of runner band are used. First, the band is round using an arch with a larger radius (see case **v1** in Figure 7). The relative meridional velocity distribution along to the modified band decreases with 3% than the original distribution, see Figure 8.

However, the arch radius is limited by geometrical constrain. Consequently, an ellipse is considered to reshape the band in order to increase the flexibility, (see case v2 in Figure 7). In this case, the relative meridional velocity distribution along to the modified band goes down up to 15% with respect to the original one.

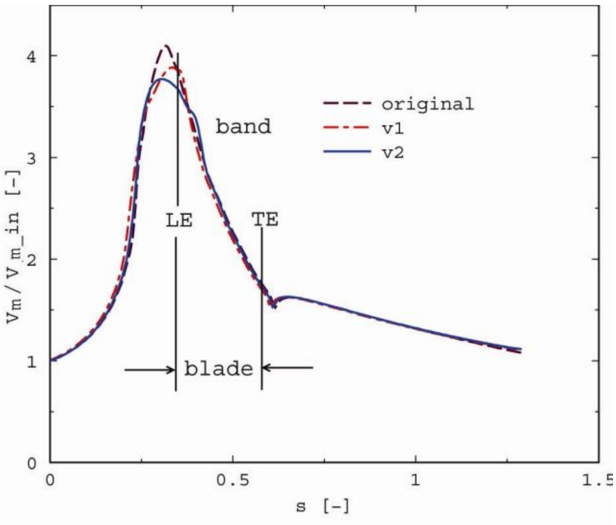

Figure 8. Comparison relative meridional velocity distribution along to band on the original geometry against modified cases (v1 and v2).

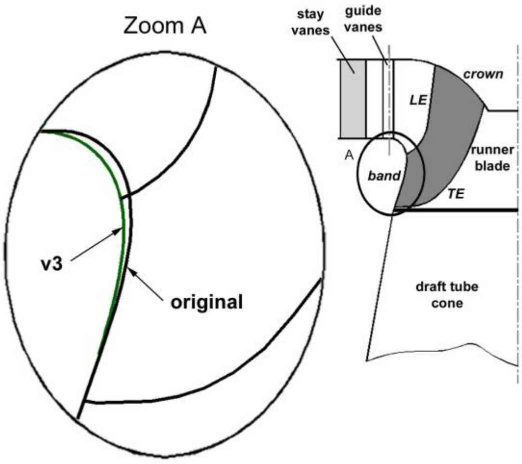

Figure 9. Generating a new band contour based on hydrodynamic considerations.

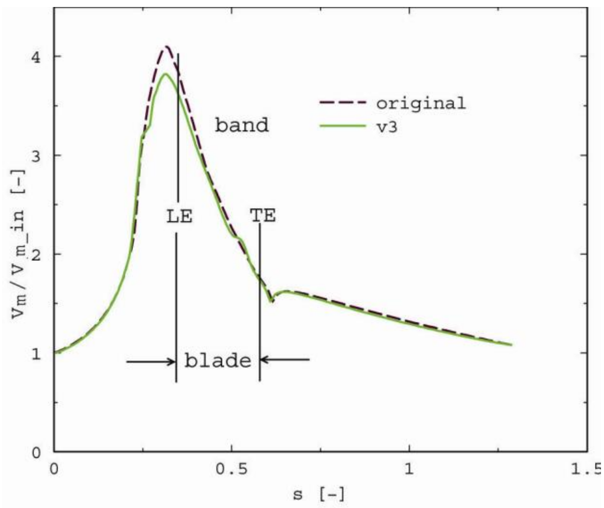

Figure 10. Comparison relative meridional velocity distribution along to band on the original geometry against modified case v3.

Nevertheless, it is impossible to select the optimum geometrical contour of runner band without any hydrodynamic field computation. Hence, it is necessary to compute the hydrodynamic field. Accordingly, the band contour can be modified using a streamline selected from hydrodynamic field already computed. In this case, we have selected the streamline associated to dimensionless value (*sf*=0.96), see case v3 in Figure 9. Consequently, the relative meridional velocity decreases along to the modified band with 10%.

CONCLUSIONS

The paper present both design considerations and technical data for a new Francis turbine with high specific speed using classical method. After that, the numerical investigation is used in order to analyse the hydrodynamic performances. The maximum relative meridional velocity is obtained on band contour. Consequently, the band is modified based on geometric and hydrodynamic considerations in order to decrease the maximum curvature value. As a result, the maximum relative meridional velocity on the band is decreased leading to improved cavitational behaviour. Using the improved band contour a new three dimensional runner will be designed.

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