NUMERICAL ANALYSIS OF THE FLOW IN THE OLD FRANCIS RUNNER IN ORDER TO DEFINE THE REFURBISMENT STRATEGY

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S-au realizat investigații numerice asupra unui rotor vechi de turbină Francis normală (cu rapiditate medie), pe întreg domeniul de exploatare al turbinei. Câmpurile de viteze şi presiuni au fost determinate cu ajutorul CFD pentru func□ionarea în afara punctului de randament maxim. Au rezultat câmpuri hidrodinamice perturbate, ce au produs vibrații şi probleme mecanice, datorită geometriei palei. Pe baza analizei numerice, s-a propus strategia de retehno-logizare. Un nou rotor, cu performanțe hidrodinamice îmbunătățite, poate fi proiectat utilizând o abordare inovatoare şi noi instrumente, ce țin seama de datele disponibile privind condițiile de exploatare.

Numerical investigations into an old Francis turbine runner with medium specific speed at off-design conditions are performed. The velocity and pressure fields are computed at off-design conditions using CFD. As a result, the hydrodynamic filed is disturbed inducing vibrations and mechanical problems due to the geometry of the blade. Conclusively, the refurbishment strategy is proposed based on the numerical analysis. A new runner with improved hydrodynamic performances can be designed using novel philosophies and new tools in conjunction with data available about operating conditions.

Keywords: Francis runner, 3D flow analysis, CFD, refurbishment strategy

1. Introduction

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.

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The weight of the hydro component represents 20% of the world energy, i.e. 16% from the European budget and Romania 26% [8] hydro component, and it is a key component in management of the energy. Although important steps have been taken worldwide, the hydro energetic potential has 18% degree of use, and thus a huge reserve of hydraulic energy waiting to be exploit (in Romania this potential is exploited in limits of 44% [8]). It is important to mention that the majority of the hydropower plants were designed many years ago, among which 38% are more than 25 years old, 48% were built 15 to 25 years ago and the remaining 14% were put into operation in the last decade [8], and consequently a national strategy of rehabilitation and refurbishing of the hydropower potential comes as a must. Consequently, the Romanian national company S.C. Hidroelectrica S.A., which operate all large hydropower plants in Romania, is currently developing an important refurbishing program. The rehabilitation and refurbishment of the hydropower potential is the utmost economic importance for the national and European energy market.

The objectives of the refurbishment are to achieve: extended plant operation life to give an expectation of 30 years service without further major refurbishment or significant capital expenditure; maximize efficiency and output; improve environmental performance; reduce maintenance and operation and site safety improvements [3].

Nowadays, the replacement of experimental investigations by CFD in the process of design/ optimization/ rehabilitation/ refurbishment of hydraulic turbine is presented in the world trend, to mitigate the high costs necessary for the experimental investigations through the extensive use of the numerical analysis. For instance, an increase in efficiency and net output power can be obtained by redesigning the rotor, which leads to an excellent cost/investment [2, 9].

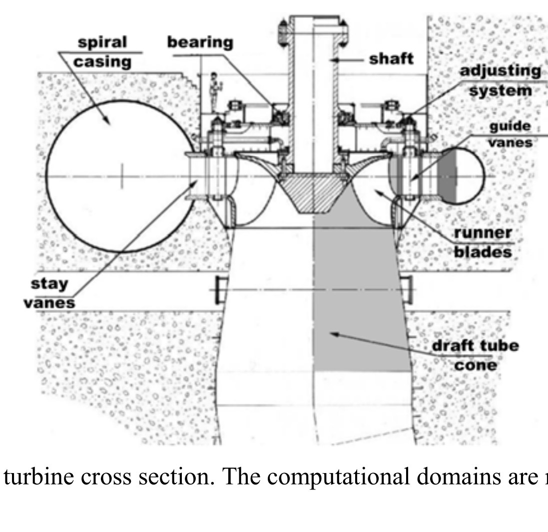

Fig. 1. Francis turbine cross section. The computational domains are marked with grey

These issues involve a careful analysis of the entire actual hydraulic passage and according to the technical conditions and economic possibilities one may involve the reshaping of the upstream components (stay vanes or guide vanes).

The paper presents our ongoing efforts in order to analyze the hydrodynamics of old Francis runner installed in Romania. The numerical results were computed on the Francis turbine prototype with the methodology developed and validated with experimental data on Francis turbine model, [4-6]. First, the Francis turbine test case is presented. Second, 3D computational domains are reconstructed and its meshes are generated. Third, the numerical investigations are performed in order to compute the coupled distributor-runner hydrodynamic field at best efficiency point (BEP) and off-design conditions. Consequently, the hydrodynamic field is investigated in order to improve the performances. The conclusions and perspectives are summarized in last section.

2. Francis turbine test case

The test case corresponds to a medium specific speed Francis turbine with dimensionless specific speed $\nu = 0.444$. The distributor consists of 16 stay vanes and 16 guide vanes whilst the runner has 14 blades with the reference radius $R_{2e} = 1.1375$ m. Figure 1 shows the Francis turbine cross view with parameters from Table 1, while the three-dimensional geometry of the Francis runner is presented in Figure 2.

Table 1

Parameters of the Francis turbine with medium specific speed.

Parameters	Value	Eqs. according to IEC 60193/1999
characteristic speed n_s	207	$n_s = nP^{0.5}H^{-1.25}$
discharge coefficient φ	0.28	$\varphi = Q\left(\pi\omega R_{2e}^3\right)^{-1}$
Energy coefficient ψ	1.264	$\psi = 2E\left(\omega R_{2e}\right)^{-2}$
hydraulic power coefficient λ	0.354	$\lambda = 2EQ\left(\pi\omega^3 R_{2e}^5\right)^{-1}$
dimensionless characteristic speed ν	0.444	$\nu = \varphi^{0.5}\psi^{-0.75}$

The hydrodynamic field was computed in six operating points displaced at constant head. The investigated operating points correspond to: best efficiency point (BEP), four points at partial load (marked with PL) and one overload point (denoted with OL), see Table 2, where relative discharge is computed with (1):

$$Q_r[\%] = \frac{(Q)_x}{(Q)_{BEP}}100\,. \tag{1}$$

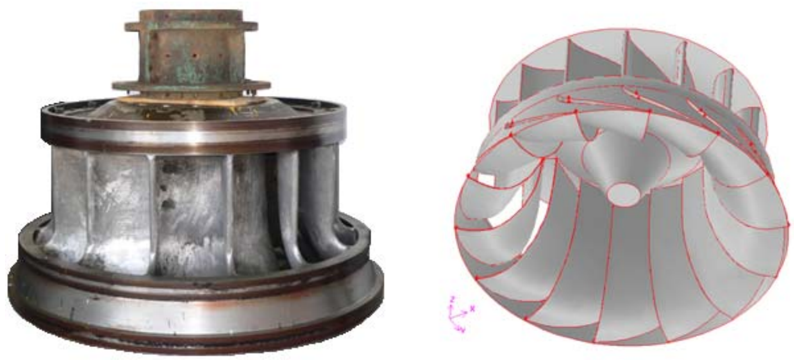

Fig. 2. The old Francis runner geometry: photo (left) and 3D reconstruction (right)

Table 2

Investigated operating points

Label	Relative discharge Q_r (%)	Operating points
PL4	68.23	part load operating points
PL3	75.83	
PL2	85.41	
PL1	92.81	
BEP	100.00	best efficiency point
OL1	106.66	overload operating point

3. Numerical results

Developments in computer software and hardware made possible the computation of three-dimensional flows in turbomachines. However, computing the real flow (turbulent and unsteady) through the whole hydraulic turbine requires large computer memory and CPU time even for the present day computers. As a result, a simplified simulation technique must be employed to obtain useful results for turbine analysis, using currently available computing resources. The *mixing interface technique* is used for coupling the distributor and runner velocity and pressure fields as well as the turbulence quantities. This approach performs a circumferential averaging of the velocity components and pressure field while the turbulence quantities on the distributor outlet. Since this approach performs a circumferential averaging, it is equivalent to the full mixing of the wakes (or any other circumferential non-uniformities) [4]. The method is designed to solve only for steady flows (absolute or relative), and therefore the partial time derivatives vanish. The absolute flow equations are the natural choice for the distributor, and for the runner it is convenient to use absolute velocity conditions at the runner inlet section. The iterative process employed for achieving continuity for both absolute velocity and pressure across the distributor-runner interface was presented in [4]. Moreover, the numerical results computed with this technique were validated against experimental data measured on the Francis turbine model [4-6]. In order to compute the velocity and pressure fields a segregated solver is used within the FLUENT code.

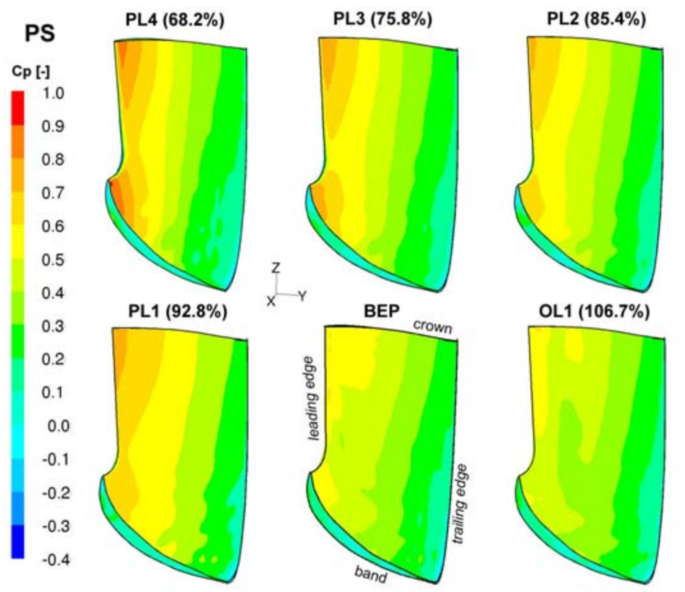

Fig. 3. Distribution of pressure coefficient (c_p) on the pressure side for investigated operating points. The red or orange stripes on the color maps show the regions with maximum pressure coefficient that means the flow impact on the blade

Figure 3 and Figure 4 present the pressure coefficient (c_p) distribution for the investigated operating points on the pressure side (PS) and suction side (SS), respectively, where

$$c_p = \frac{p - p_{ref}}{\rho g H} \tag{2}$$

The red and orange stripes show the maxima values for pressure coefficient that means flow impact on the blade. When the Francis runner operates at larger relative discharge than 90% the flow impact appears on the suction side near to the crown on the blade. Consequently, the minimum values of pressure coefficient are obtained on the suction side near to band at the trailing edge. This observation is supported by cavitation erosion on the runner blade.

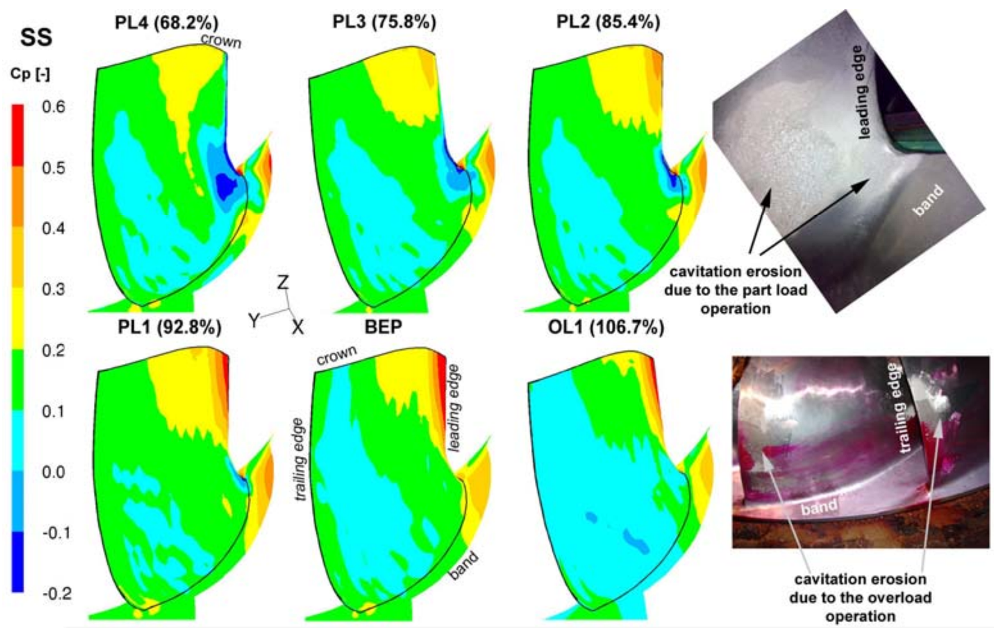

Fig. 4. Distribution of pressure coefficient (c_p) on the suction side for investigated operating points. The blue spots on the color maps show the regions minimum pressure coefficient that means maximum cavitation risk

Pressure coefficient distribution along to the three streamlines (near to the crown, middle and near to the band) at BEP is plotted in Figure 5. One can observe the minimum pressure is obtained on the suction side near to the band. However, an unwanted pressure distribution near to crown as well as near to the band at leading edge is obtained. The distribution near to the crown is acquired due to flow impact on the suction side. The flow impact is moved on the pressure side when the Francis runner operates under 90% relative discharge. As a result, the minimum pressure coefficient arises on suction side near to leading edge at the junction with the band, Figure 4. This statement is promoted by pressure coefficient distribution along to the streamline near to the band at part load operating point PL3, see Figure 6. The numerical results at part load operation are validated by cavitation erosion on the runner blades, see Figure 4.

The hydrodynamic analysis of the old Francis runner with medium specific speed at best efficiency point as well as off-design conditions leads to define the refurbishment strategy. These unwanted aspects will be avoided if the leading edge is leaned according to the flow from guide vane outlet.

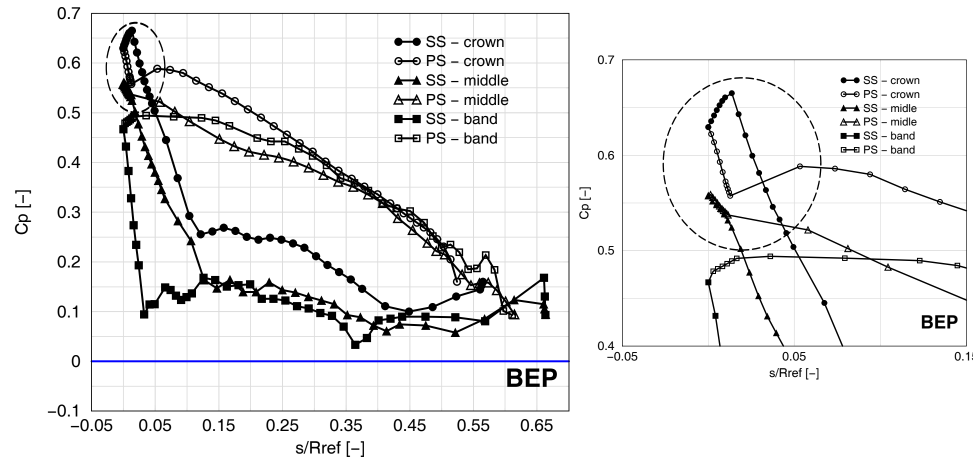

Fig. 5. Distribution of c_p at best efficiency point (BEP) along to the three streamlines displaced: near to the crown (● SS, ○ PS), middle (▲ SS, Δ PS) and near to the band (■ SS, □ PS)

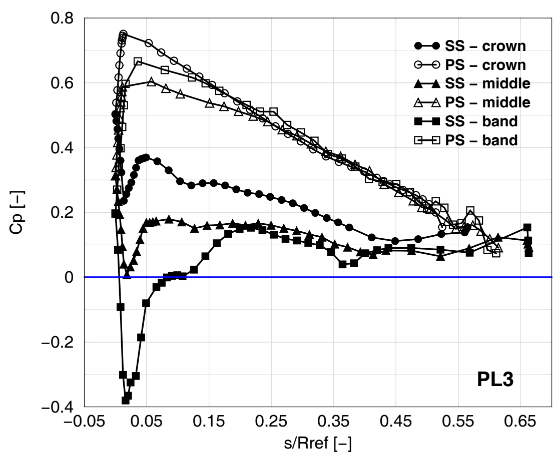

Fig. 6. Distribution of c_p at part load operation point PL3 along to the three streamlines displaced: near to the crown (● SS, ○ PS), middle (▲ SS, Δ PS) and near to the band (■ SS, □ PS)

Moreover, the hydraulic efficiency can be increased up to 2% as well as the cavitational behavior will be improved. Also, the Francis runner can be sensitive to off-design conditions due to the geometry of the blade [7].

6. Conclusions

The paper presents the numerical results computed on old Francis turbine with medium specific speed installed in Romania. The 3D geometry of the Francis runner was reconstructed based on the drawings. Next, the distributor and runner computational domains are generated together with its structured mesh. The hydrodynamic field was computed at best efficiency point (BEP) and off-design conditions using mixing interface algorithm. As a result, the pressure coefficient distribution on the runner blade is obtained. The area with maximum cavitation risk is indentified for each operating regime investigated. Consequently, at partial load the maximum risk arises on the suction side at leading edge near to the band while for overload conditions appears on the suction side at the trailing edge near to the band, respectively. The runner was designed four decades ago using the classical philosophy [1]. A new runner with improved hydrodynamic performances can be designed using novel philosophies and new tools in conjunction with the data available about operating conditions during the years. Consequently, the energetic and cavitational behaviors of the Francis runner can be improved.

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