EXPERIMENTAL AND NUMERICAL ASSESSMENT OF THE VELOCITY PROFILES USING A PASSIVE METHOD FOR SWIRLING FLOW CONTROL

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ABSTRACT
The hydraulic turbines operated at partial discharge (especially hydraulic turbines with fixed blades, i.e. Francis turbine), developing a central stagnant region in the conical diffuser of draft tube. As a result, the helical vortex breakdown, also known in the literature like “precessing vortex rope” is developed. This paper introduces a novel approach for mitigating the swirling flow instabilities using a diaphragm into the cone. Consequently, the severe flow deceleration and corresponding central stagnant region are diminished, with an efficient mitigation of the precessing helical vortex. Four cases (one without and three with diaphragm) are numerically and experimentally investigated. The velocity profiles measurements will show that the diaphragm can mitigate the stagnant region associated to the vortex rope.

KEYWORDS
conical diffuser, swirling flow, velocity profiles, passive method, stagnant region

1. INTRODUCTION
The conical diffuser (discharge cone) is an essential component of the hydraulic turbines, which converts the excess of the kinetic energy at runner outlet into static one. When the turbine operates far from the best efficiency point, the swirling flow in the discharge cone becomes unstable leading to large pressure fluctuations and significant hydraulic losses. The flow downstream the runner of a Francis turbine evolves at partial discharge values in a precessing helical vortex (or vortex rope) producing a high level of the pressure pulsation. Consequently, several hydraulic, mechanical and even electrical problems are identified in service. Nishi et al. [1] put forward a qualitative model for the precessing vortex rope, based on their experimental investigations. They suggest that the circumferentially averaged velocity profiles in the cone could be represented satisfactorily by a model comprising a dead (stagnant) water region surrounded by the swirling main flow. This model is also supported

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by the measured averaged pressure, which remains practically constant within the stagnant region. All these considerations led to the conclusion that the spiral vortex core observed in the draft tube of a Francis turbine at part load is a rolled-up vortex sheet which originates between the central stalled region and the swirling main flow. A successful numerical analysis of unsteady swirling flow in draft tube cone was made by Ruprecht et al. [2]. The numerical results are compared and validated with the experimental ones. An important step in order to elucidate the flow phenomena developed at partial operation in draft tube cone was performed within the project FLINDT, Ciocan et al. [3].

Different techniques have been proposed in order to eliminate or to mitigate the instabilities developed in the draft tube cone at partial load operation. Given by the energy injected in the draft tube cone these methods can be divided into active [4] or passive [5]. These methods lead to some improvements in reducing the pressure pulsations for a narrow regime but they are not effective or even increase the unwanted effects. Resiga et al. [6] have proposed a novel and robust method to mitigate the vortex rope: a water jet is injected along the discharge cone axis. This technique was investigated on a test rig developed at the “Politehnica” University of Timisoara. Also, Susan-Resiga et al. [7] demonstrated that a 2D axisymmetric simulation is able to capture the formation and development of swirling flow phenomena at levels similar to a 3D numerical simulation. The only observation is that for a 2D axisymmetric simulation the pressure pulsations cannot be investigated, consequently the maximum amplitude peaks cannot be identified.

A passive method to mitigate stagnant region associated to the vortex rope in the draft tube cone of hydraulic turbine is presented in this paper. The method involves the development of a progressive and controlled throttling (shutter), of the flow cross section at the bottom of the conical diffuser (Fig. 1-down). The adjustable cross section is made on the basis of the shutter-opening of circular diaphragms (Fig. 1), while maintaining in all positions the circular cross-sectional shape, centered on the axis of the turbine. The vortex rope occurs when the turbine is operated at part load. The stagnant region and the pressure pulsations associated to the vortex rope are mitigated when it is controled the diaphragm [8, 9]. The opening of the diaphragm can be automatically correlated with the turbine operating regime.

The present paper focuses on 2D axisymmetric turbulent swirling flow simulation in order to evaluate the new control method. A stagnant region model (SRM) [10] is used essentially enforcing a unidirectional circumferentially averaged meridian flow as suggested by the experimental data. Numerical results obtained with both models (with and without SRM), are compared against measured meridian and circumferential velocity profiles, as well as for the vortex rope location. The second and the third sections of the paper present the experimental and numerical setup. Section four presents the numerical results and validation against experimental data. The conclusions are summarized in last section.

2. EXPERIMENTAL SETUP

In order to investigate experimentally the diaphragm passive method, we are using the test rig with a closed loop hydraulic circuit (Fig. 3a) described in [11]. Instead of testing the diaphragm on a model hydraulic turbine, we have designed and built a special swirl apparatus, Fig. 3b. The swirling flow apparatus, included in the main hydraulic circuit, contains two main parts: the swirl generator and the convergent-divergent test section. The swirl generator has an upstream annular section with stationary and rotating blades for generating a swirling flow. It has three components: the ogive, the guide vanes and the free runner, see the detail in Fig 3b. The ogive with four leaned struts sustains the swirl generator and supplies the jet nozzle. The guide vanes and the free runner are installed in a cylindrical section with $D_r = 150 \text{ mm}$. The nozzle outlet with $D_n = 30 \text{ mm}$ is located close to the throat section with $D_t = 100 \text{ mm}$. 
This swirl generator provides a swirling flow configuration at the inlet of the conical diffuser quite similar to the corresponding flow downstream a Francis runner operated at partial discharge. As a result, the decelerated swirling flow in the cone develops a precessing vortex rope with the same Strouhal number as the one corresponding to the Francis turbine model investigated in [3]. The cone half-angle is 8.6 degrees, similar to the compact discharge cones used in the modern draft tubes for hydraulic turbines. However, in our case the ratio between the cone length ($L = 200 \text{ mm}$) and the throat diameter ($D_t = 100 \text{ mm}$) is quite large ($L/D_t = 2$) in order to capture the entire vortex rope in the conical diffuser. The results have been obtained for a test rig discharge of $Q = 0.03 \text{ m}^3/\text{sec}$. Also, all experimental investigations have been done under overpressure conditions. Moreover, the hydraulic circuit is fully filled with water. As a result, only non-cavitating vortex ropes were considered in our investigations, meaning no air volume trapped inside.

<table>
<thead>
<tr>
<th>Diaphragm interior diameter $d$ [m]</th>
<th>Diaphragm interior area $A_d$ [m$^2$]</th>
<th>Test section outlet area $A_o$ [m$^2$]</th>
<th>Shutter area $A_s$ [m$^2$]</th>
<th>Areas ratio $A_d/%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.113</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>50</td>
</tr>
<tr>
<td>0.1</td>
<td>0.0078</td>
<td>0.02</td>
<td>0.012</td>
<td>60</td>
</tr>
<tr>
<td>0.088</td>
<td>0.006</td>
<td>0.02</td>
<td>0.014</td>
<td>70</td>
</tr>
</tbody>
</table>

Tab. 1 The parameters corresponding to three cases with different interior diameters.

The diaphragm control method implemented on our swirl apparatus is sketched in Fig. 2. The main component of this new method for mitigating the vortex rope is the diaphragm (Fig. 1 - up). Three values of the diaphragm interior diameter of $d = 0.113, 0.1, 0.88$ m are considered in the experimental and numerical investigations. The diaphragm is located at the cone outlet (Fig. 2). Table 1, shows the ratio between diaphragm interior area and the outlet test section area with $D = 0.16$ m. The experimental data were measured using a Dantec Dynamics 2D LDV system with two components (meridian and circumferential velocity). The main characteristics of the optical system are: focal length of the probe 159.6 mm, beam diameter 2.2 mm and the beam spacing 39.2 mm. Two pairs of beams with wavelength of 488 nm and 514.5 nm are generated. A 3D traversing system is installed for probe positioning within 0.01 mm accuracy on each axis. The measurements were performed considering a step of 1 mm and 15000 samples or 20 seconds acquisition.
time, respectively. On the test section, three optical windows were installed in order to measure the velocity profiles with LDV, Fig. 3b. The first window W0 is located in the convergent part of the test section. The second window W1 is displaced on the divergent part near to the throat whiles the third one W2 near to the cone outlet, respectively.

The time averaged velocity was calculated with equation:

\[
\bar{v} = \frac{1}{N} \sum_{i=0}^{N-1} v_i
\]

where \(N\) is number of samples, and \(v_i\) the velocity for each sample. The data are presented in dimensionless form, using the following reference values: the minimum diameter of the test section \(D_{\text{throat}} = 0.1\) m and the mean velocity at the throat corresponding to the discharge \(Q\):

\[
v_{\text{throat}} = \frac{Q}{\pi \cdot \frac{D_{\text{throat}}^2}{4}}
\]

where \(Q\) is the main flow discharge and \(D_{\text{throat}}\) is the throat diameter of the test section. The plotted velocity profiles for meridian and circumferential velocity have points obtained from experimental investigation with and without diaphragm, at overall discharge values \(Q = 0.03\) m\(^3\)/sec in dimensionless values and the variation of Random Mean Square Velocity (\(v_{\text{RMS}}\)) for each point also in dimensionless values. The variation of RMS was calculated with formula:

\[
v_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{i=0}^{N-1} (v_i - \bar{v})^2}
\]

3. NUMERICAL SETUP

The above experimental investigations offer only a limited amount of data. As a result, in order to understand the complex physics of the decelerated swirling flow we perform numerical simulations as well. As mentioned before, in the present paper we focus on the time-averaged flow field. Therefore, a simplified flow model corresponding to the axial-symmetric turbulent swirling flow downstream the free runner of the swirl generator is considered. The 2D axial-symmetric domains for numerical simulation are presented in Fig. 4 (without diaphragm – upper half-plane and with diaphragm – lower half-plane). The annular inlet section is considered just downstream the runner blades. Then we have a convergent section up to the throat, and a conical diffuser ending with a discharge cylindrical pipe. In the numerical domain we have the survey axis where meridian and circumferential velocity
profiles are validated against LDV measured ones. First, the swirl generator was analyzed numerically using a three-dimensional turbulent flow computation.

Fig. 4 2D computational domain in a meridian half-plane without diaphragm (upper) and with diaphragm (lower), respectively.

The following boundary conditions are imposed in order to perform the numerical simulation: 1) the velocity profiles and turbulent quantities like inflow conditions. These values are obtained from 3D turbulent computation performed for free runner; 2) the no-slip condition on the walls; 3) the negligible evolution of all variables in the radial direction is considered like condition along to the axis; 4) the outlet section corresponds to the cylindrical downstream pipe and the radial equilibrium condition is considered on it,

\[
\frac{\partial p}{\partial r} = \rho v_\theta^2 \frac{1}{r}
\]  

4. RESULTS

Once the numerical solution for the axial-symmetric turbulent swirling flow is obtained, we first check the accuracy of the velocity profiles. In doing so, we compare the computed meridian and circumferential velocity profiles with the LDV measurements on the survey axis located in the three windows of the test section. The results of the velocity profiles with and without SRM for all cases (with and without diaphragm), are presented in the dimensionless form with respect the throat diameter and the velocity from the throat test section (see eq. 2). Fig. 5 presents the velocity profiles for window W0 (for the case without and with diaphragm d=0.088 m), where a very good agreement between computations and measurements is observed.

The RMS for W0 is 20% for each measured point. Fig. 6 – window W1, shows that the stagnant region for the cases without and with diaphragm d=0.113 m are quite similarly, and the model without SRM has a better correlation with experimental data. For the other cases of diaphragm d=0.1 m and d=0.088 m, the stagnant region is decreasing below zero, this means recirculation region occurs when the flow is throttled increasingly. Also, for these cases the
SRM model has a better capture on experiment. For window W2 (Fig. 7), in the case without diaphragm the stagnant region is larger than others from W1. The meridian velocity profile evolves from a weak profile to an axial jet profile while the diaphragm diameter becomes smaller. As a result, the stagnant region associated to vortex rope is mitigated, even eliminated. For all cases is a good agreement between experiment and 2D axisymmetrical numerical simulation (with and without SRM).

![Fig. 6 Velocity profiles measured along to survey axis W1.](image6)

![Fig. 7 Velocity profiles measured along to survey axis W2.](image7)
The 2D axi-symmetric turbulent swirling flow with SRM model produces a central stagnant region and the main flow occupying an annular section up to the wall. The stagnant region is identified on axial velocity component map for all investigated cases, Fig. 8. According to Nishi et al. [1] the vortex rope is wrapped on a quasi-stagnant region developed in the axis neighbourhood. As a result, the vortex sheet generated between the stagnant region and the main stream is an indicator about self-induced instability. Therefore, the vorticity magnitude map is plotted in Fig. 9 selecting the maximum values in the computational domain in order to be visualized the vortex sheet. Clearly, the vortex sheet angle is constant for all cases (Fig. 9). However, the self-induced instability type cannot be identified based on 2D axi-symmetric numerical analysis.

5. CONCLUSION

A passive method to mitigate the stagnant region associated to the vortex rope in the draft tube cone of hydraulic turbine is presented in this paper. The method involves the development of a progressive and controlled throttling (shutter), of the flow cross section at the bottom of the conical diffuser. The adjustable cross section is made on the basis of the shutter-opening of circular diaphragms, while maintaining in all positions the circular cross-sectional shape, centered on the axis of the turbine. When the turbine is operated at part load the vortex rope occur, by closing the diaphragm, the quasi-stagnant region is mitigated and also the vortex rope. In order to evaluate the new method, the present paper was focused on 2D axisymmetric turbulent swirling flow simulation, by introducing a stagnant region model (SRM). Numerical results obtained with both models (with and without SRM), are compared against measured meridian and circumferential velocity profiles, as well as for the vortex rope location. Numerical and experimental results for four cases (without and with diaphragm) are analyzed for a particular swirling flow configuration. The evolution of the quasi-stagnant region is quantified plotting the velocity map. The vortex sheet angle is constant for all cases. Consequently, the results reported in this paper, it clearly shows that the stagnant region associated to vortex rope is mitigated when the new method with diaphragm is implemented downstream the conical diffuser.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


