Experimental and numerical analysis of decelerated swirling flow from the discharge cone of hydraulic turbines using pulsating jet technique

C Tanasa¹, R Szakal², D Mos², T Ciocan² and S Muntean³
¹ Politehnica University of Timisoara, Research Institute for Renewable Energy – RIRE, Victoriei Square, No.2, Timisoara, Romania
² Politehnica University of Timisoara, Department of Hydraulic Machinery, Bv. Mihai Viteazu, No.1, Timisoara, Romania
³ Romanian Academy, Center of Advanced Research in Engineering Sciences, Timisoara Branch, Bv. Mihai Viteazu, No.24, Timisoara, Romania

E-mail: constantin.tanasa@upt.ro

Abstract: It is well known that the spiral vortex (or vortex rope) is developed in the conical diffuser of hydraulic turbines with fixed pitch blades (e.g. Francis and propeller) when operating conditions are far away from best efficiency point. The paper will present a new technique in order to mitigate, even eliminate the bad behavior associated to this phenomenon. By injecting a pulsating water jet, along the cone axis, the unsteady pressure fluctuations given by the vortex rope are mitigated. Our investigations are performed on the test rig from Politehnica University. In order to assess the velocity profiles given by the swirling flow with and without pulsating water jet, an extensive 3D numerical simulations were performed. Second, the experimental data of pressure fluctuations was analysed. This technique, shows that the pressure recovery is improved and the hydraulic losses decreases along the conical diffuser. Also, it is shown that the stagnant region associated to the spiral vortex is mitigated since the pulsating jet is introduced. Also, the pressure fluctuations are mitigated.

1. State of the art
To be competitive the industry is always looking for better products with reduced design cycles and lower costs. The new requirements of the energy market makes it attractive by imposing the operation of hydraulic turbines over their optimal operating conditions. In addition, many of hydropower plants have old turbines and they need refurbishment. When the turbine operating far from the best efficiency point, the swirling flow in the discharge cone occur. 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 fluctuations. In addition, different technical problems occurs in the turbine [1]. In order to eliminate the consequences given by vortex rope, some techniques have been proposed and implemented in situ [2-4]. These solutions bring improvements at some operating points but they have negative consequences at best efficiency point. The qualitative model showed by Nishi et al. [5] supposed that the vortex rope has a precessing motion with a quasi-stagnant zone, surrounded by the swirling flow.
Blommaert and Boyer [6] developed an active control method for mitigating the low frequency fluctuations. The goal is to eliminate this component because of high amplitudes peaks. These fluctuations appear when turbine operates far away than maximum efficiency point. The method was implemented on a Francis turbine. To avoid the turbine natural frequency, they have generated an external excitation using a rotating valve. The results have shown that pressure fluctuations can be significantly reduced. However, their method addressed to the results and not their main cause. Our group has proposed water injection through the runner crown along to the turbine axis to control the decelerated swirling flow in the draft tube cone of the hydraulic turbines operating at part load conditions [7, 8]. Extensive experimental investigations were carried out by Bosioc et al. [9] showing that a jet discharge larger than 10 - 12% of the volumetric flow rate associated to the operating point is required to remove the vortex rope and its effects. However, the pressure fluctuations with low-frequencies are still exist even if the maximum discharge jet is applied.

In order to mitigate the pressure fluctuations with low-frequencies and also the vortex sheet corresponding to vortex rope, we introduced a novel technique. This new technique supposed to introduce a pulsating water jet along the cone axis, respectively. A 3D numerical simulations with and without pulsating jet was done in order to evaluate the meridian and circumferential velocity profiles, also the energetic and dynamic evaluation of the technique. The, the experimental pressure fluctuations associated to the swirling flow, in both cases, is presented. At the end the conclusions will be summarized.

2. Numerical simulation

The 3D numerical simulations was done on the domain corresponding to the swirl apparatus from Politehnica University Timisoara - UPT, figure 1 and it was presented previously in our papers [9, 10]. The test section cone has the same angle (8.5°) like the one from Francis turbine of FLINTDT project [11]. The mesh is structured with 2.1M cells. The boundary conditions supposed to have at the inlet a velocity profile for both cases obtained from computation of the flow upstream the test section. In that way was obtained a velocity profile for 925 rpm speed of the runner. Corresponding to this speed we have the main discharge Q = 30 l/s and jet flow Qj et which represent 12% from main flow. The Fluent code was used in order to accomplish the 3D unsteady numerical simulations for both cases. The RSM turbulence model was used in order to have all the final quantities. The time step of 0.1 ms for both cases (with and without pulsating jet) was used and the residuals was below 10^-3. It was input the survey axis W0, W1, W2, on the domain, which correspond to the real measuring axis from the rig. The survey axis will give us the velocity profiles of meridian and circumferential components.

![Figure 1. Numerical domain and the test section dedicated to pressure measurements.](image1)

![Figure 2. Time period used as boundary condition for pulsating jet on the nozzle outlet.](image2)
3. Experimental setup

The experimental investigations are performed on the test rig from UPT. The hydraulic circuit presented in figure 2 contains two main components as the swirl generator and the test section with convergent/divergent shape. The swirling flow given by the swirl generator has the same configuration as the one determined in a Francis turbine operated at part load [11]. Several details about swirl generator are available in two test cases: (i) Timisoara Swirl Generator test case available at Turbomachinery Special Interest Group (TSIG) [12]; and (ii) AC6-14 test case included in the ERCOFTAC database [13]. The cone angle of $17^\circ$ corresponds to the real diffusers. The ratio of the cone length is $L = 200\, \text{mm}$ and the corresponding diameter from the throat $D_t = 100\, \text{mm}$ is enough large $L/D_t = 2$ to catch the spiral vortex inside of it.

To evaluate the pressure oscillations with low frequencies, an elbow was introduced on the rig [14]. The adjustable valve from the secondary circuit, allows to obstruct the flow or redirecting on the pulsating water jet system, figure 3. In addition, flowmeter 3 allows to find the discharge on the pulsating water jet system, or by making the difference between flowmeter 2 and 3, respectively. The rotating valve is driven by the electric motor with variable speed, and represent the main element of the pulsating system. The purpose of the rotating valve is to drive the water pulse to the nozzle of the swirl generator. The rotating speed of the motor is controlled by the voltage from an amplifier. Also, a buffer tank is mounted upstream the rotating valve, in order to diminish the pressure pulsations give it by the secondary hydraulic circuit.

4. Results

First results give us the time-averaged velocity components represented on the survey axis located along the test section domain. From survey axis W0 can be observed that the meridian flow given by the swirl generator is dominant, being prove that our swirl apparatus has the same configuration like a real turbine, figure 4 [11]. It is clear that the swirl in our apparatus has similar characteristics to the one in a Francis model operated at part load. From meridian velocity component in, figure 5, the vortex rope and the corresponding quasi-stagnant zone is well developed in the case without pulsating jet. Since, with pulsating jet injection, the meridian velocity profile evolves to an axial jet profile. The velocity components from W2 axis, figure 6, in the case without pulsating jet, show that the quasi-stagnant zone is larger than the one from W1. Also, in this case, the meridian velocity profile evolves to an axial jet profile when the pulsating jet in injected. Consequently, the quasi-stagnant zone and the corresponding spiral vortex is eliminated. The circumferential velocity profiles shows that the flow evolution downstream in the cone is correctly represented for velocity field.

**Figure 3.** Experimental test rig and detail of pulsating water jet system.
The iso-surface pressure filed in the both cases is presented in figure 7 and it show how the spiral vortex and the corresponding quasi-stagnant zone is mitigated when the pulsating jet is introduced. The energetically part of the kinetic-to-potential conversion ratio or pressure recovery ($\chi$) and the loss coefficient ($\zeta$) vs axial coordinate is presented in figure 8 [15].

The loss coefficient in dimensionless form is:

$$\zeta(x) = \frac{E_0 - E(x)}{K_0}$$  \hspace{1cm} (1)
and the conversion of the pressure recovery coefficient is:

\[
\chi(x) = \frac{\Pi(x) - \Pi_0}{K_0 - k(x)} < 1
\]  

(2)

In is observed that the hydraulic losses decreases up to 10% and the pressure recovery increases up to 12% when the pulsating jet is introduced. In the case of a real turbine, this pressure recovery is translate as the increase of the efficiency.

Figure 7. Iso-surface of pressure filed for the case without (right) and with (left) pulsating water jet.

Figure 8. Loss coefficient (\(\zeta\)) and pressure recovery coefficient (\(\chi\)) along the cone.

Experimental investigations performed, evaluate the performance of the new technique. The following, are the results of the measurements, their evaluation focusing on the dynamic part, namely the evaluation of the pressure signals and the rapid Fourier transform. Detailed investigations of elbow implementation and testing are presented by Moş et al. [14]. The results of unsteady pressure field are evaluated by Fast Fourier Transform (FFT) analysis on the 4 levels of the dedicated test section for this type of measurements, figure 2. The results and their interpretation are made for 3 cases: no jet (with vortex rope), axial jet and axial jet + pulsating jet.

The case without jet (with vortex rope):

For this case, the FFT shows firs of all, at least 3 harmonics on each level of the test section. The results are presented in dimensionless form as: the amplitude was dimensionless using the kinetic term \(\rho V_t^2/2\) where \(\rho\) is the water density and \(V_t\) is the reference velocity from the throat of the test section.

Strouhal number was used as reference for frequency. In dimensionless form the Strouhal number is defined as: \(Sh = f D/V_t\), where \(D\) is throat test section diameter and \(f\) is the frequency [Hz]. The main harmonic give it by the vortex rope (VR), is at a high value on the L0…L2 levels. On the last level L3, this harmonic is decreasing because of disintegration of the VR (vortex rope). The Strouhal number has a constant value for all levels. Also, can be observed the 2\(^{nd}\) harmonic for L1 and L2, and the low-frequencies of the VR and the elbow. The low-frequencies are the worsts because they can be propagated in the entire hydraulic system.
Figure 9. FFT in the case without jet.

The case with axial jet:

Figure 10. FFT in the case with axial jet.
Also, the results presented for this case, are in dimensionless form like in the case without jet, with the condition of using the both nominal and jet ($Q = Q_{nom} + Q_{jet}$). The results shows clearly, a decreasing of the amplitudes and frequencies for all levels comparing with the case without jet. Moreover, the low-frequencies harmonics, are eliminated. Anyway, on the last level the main harmonic associated to VR, is not completely eliminated because the discharge of the axial water is not strong enough in order to eliminate the pressure pulsations on this level. Bosioc et al. [8] shows that in order to completely eliminate the VR and the associated pressure pulsations, it is necessary ~ 12% in the jet, from the main discharge.

The case with axial jet + pulsating water jet

![Figure 11. FFT in the case with axial jet + pulsating water jet.](image)

The results shows an significant decreasing of the amplitudes and frequencies since the axial water + pulsating water jet is introduced, comparing with the cases of no water injection (vortex rope) and axial water injection, respectively. Indeed, the 2nd harmonic has an increasing, probably influenced by the pulsating water injection. Anyway, from dynamically point of view, the method has reach the goal, in order to eliminate the low-frequencies harmonics, on the other side to eliminate the vortex sheet.

5. Concluding remarks

The pulsating water jet technique for mitigating the vortex rope in the conical diffuser of hydraulic turbines was exposed. First results of three-dimensional numerical simulations for both cases shows the components of meridian and circumferential velocity. It is clearly that the quasi-stagnant zone is mitigated when the pulsating jet is introduced. Consequently the spiral vortex (or vortex rope) is eliminated. From energetically point of view the pressure recovery is up to 12% and the losses decreasing along the cone up to 10%. From dynamically point of view, this technique can be compared with the axial jet injection technique used by Bosioc et al. [7].
The pressure fluctuations obtained from experimental measurements show the sudden drop of the amplitudes when the pulsating water jet + axial water jet is introduced (the decreasing is up to 80% compared with the case without water jet). In addition, the Strouhal number has a constant decrease for all levels along the cone axis, with ~50% in the case of pulsating jet.

To conclude, this novel technique has the capacity to mitigate the low-frequency pressure fluctuations associated to vortex rope from the conical diffusers of hydraulic turbines, and also the vortex sheet. More of that, this technique improve the efficiency of the turbines which are operated at part load.

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