NUMERICAL INVESTIGATION OF THE JET CONTROL METHOD FOR SWIRLING FLOW WITH PRECESSING VORTEX ROPE

Sebastian MUNTEAN*

Centre for Advanced Research in Engineering Sciences, Romanian Academy – Timisoara Branch, Romania

Romeo F. SUSAN-RESIGA

Hydraulic Machinery Department, Politehnica University of Timisoara, Romania

Alin Ilie BOSIOC

Hydraulic Machinery Department, Politehnica University of Timisoara, Romania

ABSTRACT

The paper presents our numerical investigations of the axial jet control technique for swirling flows in a discharge cone in order to mitigate the precessing vortex rope and its associated pressure fluctuations. The 3D unsteady and full turbulent numerical simulations are performed in order to compute the flow field without and with axial jet control. First, the vortex rope at different values of jet control discharge is visualized. Consequently, the quasi-stagnant central region which is the support of the vortex rope is moved downstream into the cone. Second, based on the unsteady pressure recorded on the cone wall the Fourier spectra are obtained. It is shown that, the vortex rope frequency decreases while the jet discharge increases. Next, the potential C_{PR} and kinetic C_{KR} energy recovery coefficients as well as the energy loss coefficient ζ and the kinetic-to-potential energy conversion ratio χ in the cone in terms of the control jet discharge are evaluated. The energy loss coefficient ζ decreases monotonically while the kinetic-to-potential energy conversion ratio χ increases monotonically when the jet control discharge is increased.

KEYWORDS

axial water jet control, precessing vortex rope, unsteady pressure fluctuations, hydraulic losses, pressure recovery

1. INTRODUCTION

The paper presents our numerical investigations of the axial jet control technique for swirling flows in a discharge cone in order to mitigate the precessing vortex rope and its associated pressure fluctuations. This novel technique was introduced by Susan-Resiga et al. [1] to control the draft tube flow instability at partial discharge. Consequently, the main goal

* *Corresponding author:* Center for Advanced Research in Engineering Sciences, Romanian Academy – Timisoara Branch, Bv. Mihai Viteazu 24, Timisoara, Romania, phone: +40256403692, fax: +40256403692, email: seby@acad-tim.tm.edu.ro

of this paper is to investigate numerically the flow in a straight draft tube, for a better understanding of the 3D swirling flow physics as well as how the pressure fluctuations associated to the precessing vortex rope are mitigated when the axial water jet is switched-on.

The variable demand on the energy market, as well as the limited energy storage capabilities, requires a great flexibility in operating hydraulic turbines. As a result, turbines tend to be operated over an extended range of regimes quite far from the best efficiency point. In particular, Francis turbines operated at partial discharge have a high level of residual swirl at the draft tube inlet as a result of the mismatch between the swirl generated by the wicket gates and the angular momentum extracted by the turbine runner [2]. Further downstream, the decelerated swirling flow in the draft tube cone often results in vortex breakdown, which is recognized now as the main cause of severe flow instabilities and pressure fluctuations experienced by hydraulic turbines operated at part load. More than three decades ago Palde [3] concluded that the draft tube surge is a hydrodynamic instability, known as vortex breakdown, occurring in the draft tube as a result of rotation remaining in the fluid as it leaves the turbine runner and enters the draft tube throat.

The main goal of a hydraulic turbine draft tube is to decelerate the flow exiting the runner, thereby converting the excess of kinetic energy into static pressure. Modern hydraulic turbines have compact elbow draft tubes, with rather short discharge cone. As a result, the draft tube hydrodynamics is very complex due to the combination of swirling flow deceleration with flow direction and cross-section shape/area changes. Most of the pressure recovery occurs in the draft tube cone, also called *discharge cone*. For economical reasons, this conical diffuser is short and it has a rather large angle. To minimize hydraulic losses associated with kinetic to potential energy conversion in the discharge cone, a certain level of residual swirl is provided at runner outlet.

It is known that a moderate level of residual swirl downstream the runner delays boundary layer separation at cone wall and so aids the pressure recovery. McDonald et al. [4] investigated the effect of inlet swirl flow on performance and outlet flow of conical diffusers. They found that the swirling inlet flow did not affect the performance of diffusers with only slightly separated flow. However, for diffusers which were moderately or badly separated for axial inlet flow, adding swirl at inlet caused large performance increases. Clausen et al. [5] found that generally there is a small range of swirl number (defined in their paper as the ratio of maximum circumferential to average axial velocity) that avoids both recirculation and separation. Their results highlight the interaction between the tendency toward boundary layer separation and the advent of recirculation in the core flow. The former is a viscous-dominated effect, whereas the latter is essentially inviscid and occurs only in swirling flow. Since both separation and recirculation must be avoided for good performance, the design of runner-diffuser tandem needs to account for these competing phenomena.

Nishi et al. [6] 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 (quasi-stagnant) water region surrounded by the swirling main flow. This model is also supported by the measured averaged pressure, which remains practically constant within the quasi-stagnation region. This model is also supported by the measured averaged pressure, which remains practically constant within the quasi-stagnation region [7], [8]. This result is also supported by the PIV investigation of the velocity field in the straight draft tube [9]. 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 instability [10].

The main goal of this paper is to investigate the axial jet control technique for decelerated swirling flow with precessing vortex rope introduced by Susan-Resiga et al. [1].

First, the 3D computational domain and numerical setup corresponding to experimental test rig is summary depicted. Second, the visualization of the precessing vortex rope and unsteady pressure results on the wall of straight draft tube without and with jet control are presented. Third, the numerical investigations for different values of axial jet discharge are analyzed. Using the unsteady pressure results the Fourier spectra are obtained. Next, the performances of the energetic conversion into a cone are investigated. Final considerations about axial jet control method and further perspectives are outlined in last section.

2. 3D COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

The 3D computational domain corresponds to the convergent-divergent section of the test rig, see Fig. 1. The inlet boundary of the computational domain is the annular section just downstream the free runner while the outlet section belongs to a cylindrical extension of the divergent part. Details about computational domain, boundary conditions and numerical set-up are presented in Muntean et al. [11], [12].

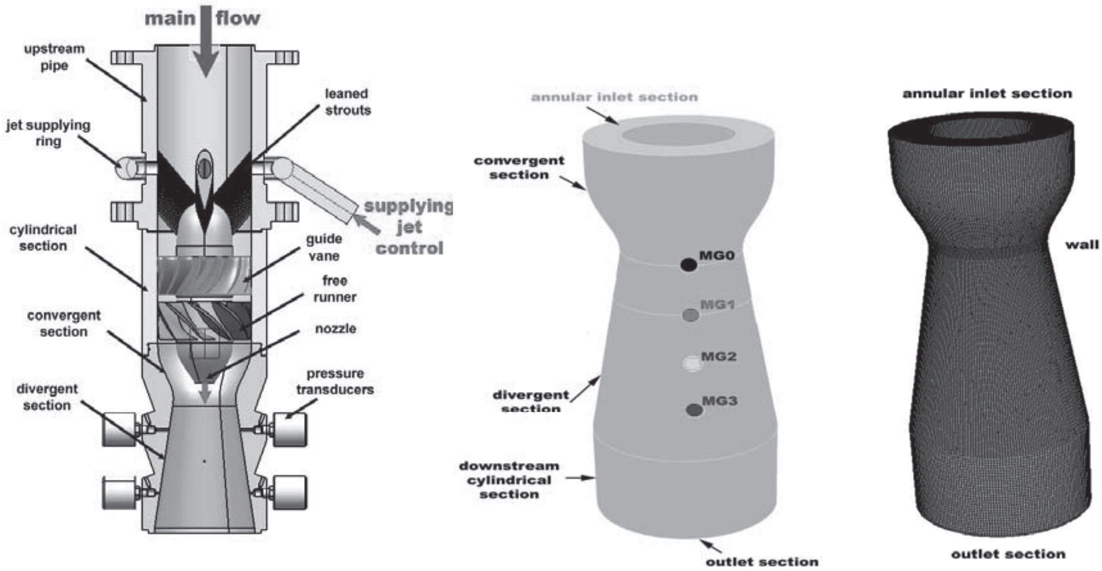

Fig. 1 Meridian cross-section of the swirling flow apparatus (left), 3D computational domain with pressure tap markers (middle) and grid with 2 million cells (right).

The water jet is supplied from auxiliary circuit and it is injected axially through the nozzle in central region, see Fig. 1 (left). In order to investigate the axial jet control technique for decelerated swirling flows with precessing vortex rope introduced by Susan-Resiga et al. [1] six discharge values of axial water jet control are considered, see Tab 1.

V_{jet} [m/s]	V_{jet}/V[%]	Q_{jet} [l/s]	Q_{jet}/Q[%]
1.0	0.262	0.707	2.356
2.0	0.524	1.414	4.712
3.0	0.785	2.121	7.068
4.0	1.047	2.827	9.425
4.5	1.178	3.181	10.603
5.0	1.309	3.534	11.781

Tab.1 Axial jet velocities investigated and associated discharges.

3. VISUALIZATION OF THE INSTANTANEOUS FIELD

First, the instantaneous axial velocity field together with associated vortex rope is visualized, see Fig. 2. The vortex rope is visualised in Fig. 2 using a snap-shot of an iso-surface of constant static pressure and the meridian cross-section is colored by axial component of the velocity.

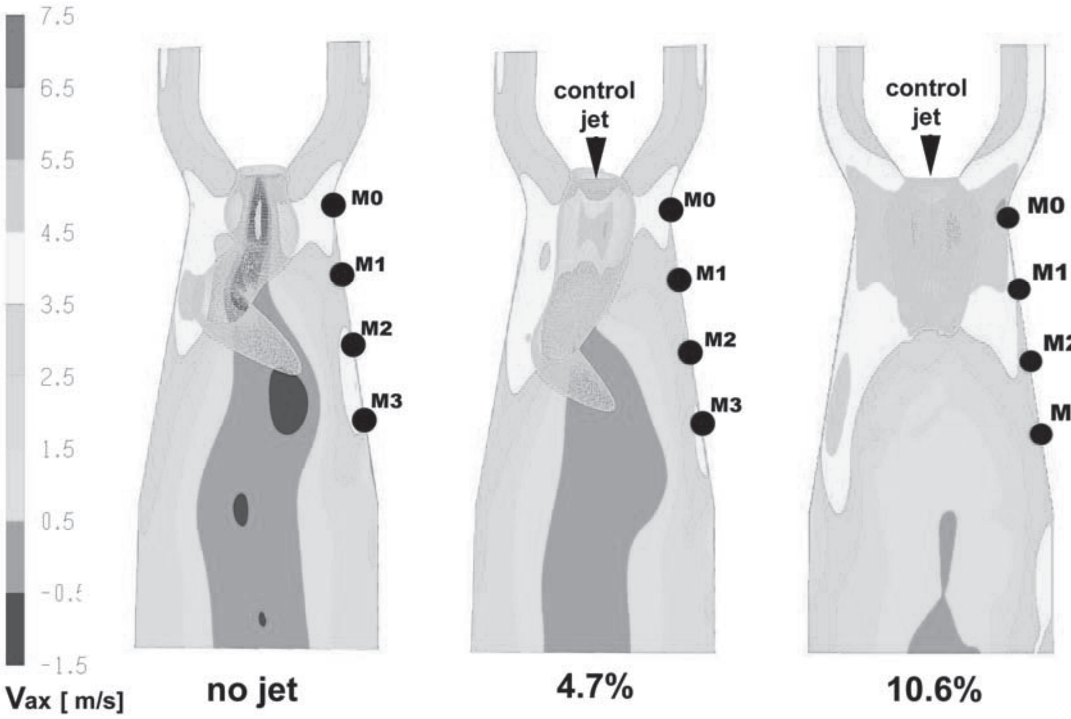

Fig. 2 The precessing vortex rope and quasi-stagnant region visualized in the test section. Three snap-shots from numerical simulations without (left) and with control jet discharge: 4.7% (middle) and 10.6% (right).

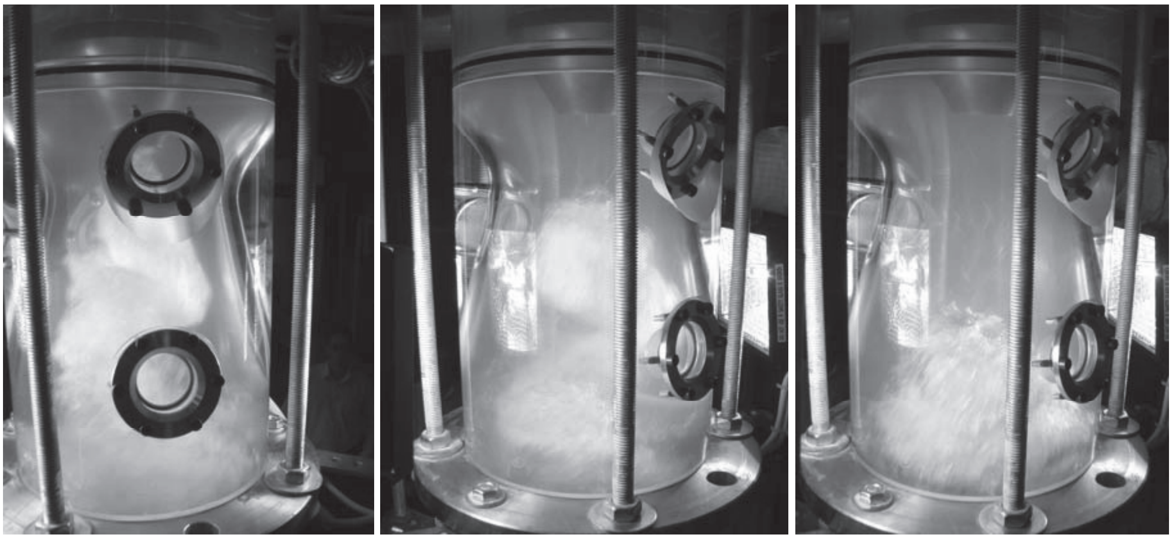

Fig. 3 Air visualization of the vortex rope and quasi-stagnant region in the test section. Three snap-shots from experimental investigations without (left) and with control jet discharge: around 4% (middle) and around 10% (right).

Fig 2 includes the case without control jet, when the 3D flow has a well developed precessing helical vortex, and the case with a control jet injection with 4.7% and 10.6% discharge with respect to the discharge through the inlet section. A qualitative assessment of the 3D numerical results versus experimental visualization in Figs. 2 and 3 indicates a strong similarity in both cases without and with control jet. One can observe an axial extension in the first part of the vortex rope (called the vortex rope body) if the control jet discharge is 4.7%. In this case, the quasi-stagnant region is moved down in cone. However, when the swirling flow is stabilized with the control jet discharge 10.6% and becomes practically axi-symmetric after mitigating the helical vortex, the quasi-stagnant region is moved away in the pipe, as expected.

4. PRESSURE FIELD ANALYSIS WITH AXIAL WATER JET CONTROL

The Fourier spectra for pressure fluctuations in the monitors MG0 - MG3 with different control jet discharge are plotted in Fig. 4. The fundamental harmonic amplitude seems to reach largest values in the first part of the cone, where the vortex rope is well developed without jet control. The largest amplitude of the fundamental harmonic is moved down into the cone if the jet control discharge is increased gradually.

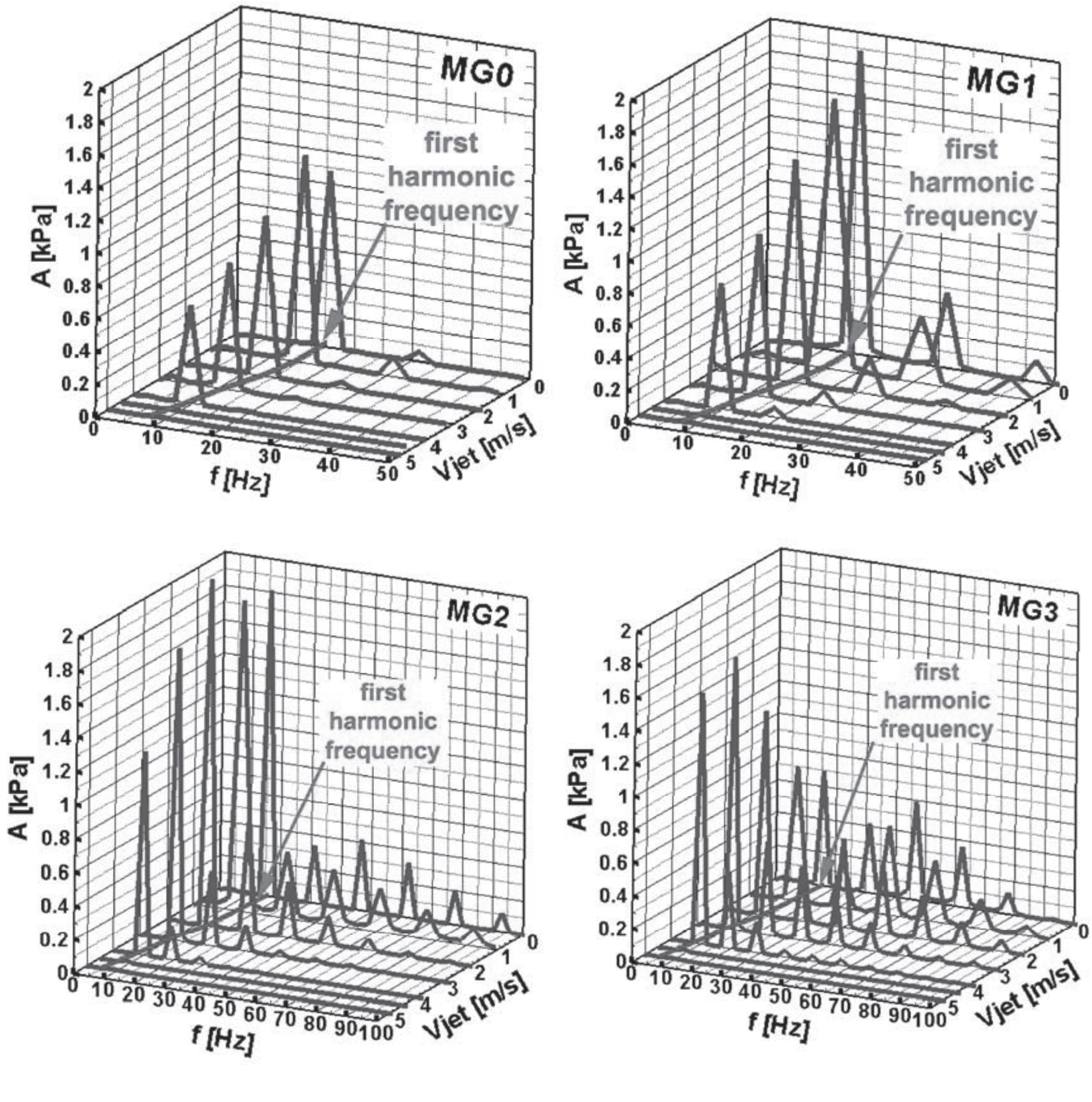

Fig. 4 Fourier spectra computed at MG0, MG1, MG2 and MG3 for different values of the water jet control discharge.

Also, the higher harmonics are reduced step by step if the water jet discharge is monotonically increased. The pressure fluctuations die out if the jet velocity is larger than 4 m/s (that means an associated discharge larger than 10%). More detailed analysis is presented in Muntean et al. [11].

The vortex rope frequency is reduces from 15.5 Hz to 8.3 Hz when the jet velocity increases. However, the pressure fluctuations are mitigated even if the frequency is not vanished due to the central region is axi-symmetric.

5. NUMERICAL RESULTS

The main purpose of the cone, is to convert as much as possible the kinetic energy into pressure potential energy with minimum hydraulic losses. In order to analyze the kinetic-to-potential energy transformation process, we introduce the following integral quantities on a generic cross section $S(z)$ at the axial distance z from the inlet section:

Flux of potential energy $$\Pi(z) \equiv \int_{S(z)} p(z,r)\, \mathbf{V}\cdot\mathbf{n}\,\mathrm{d}S \;\; [W] \quad (1)$$

Flux of kinetic energy $$\mathrm{K}(z) \equiv \int_{S(z)} \frac{\rho V^2(z,r)}{2}\, \mathbf{V}\cdot\mathbf{n}\,\mathrm{d}S \;\; [W] \quad (2)$$

Flux of mechanical energy $$\mathrm{E}(z) \equiv \Pi(z) + \mathrm{K}(z) \quad (3)$$

For a loss-free flow the flux of total mechanical energy E is constant. However, when hydraulic losses are present E decreases monotonically as the cross section $S(z)$ is moved downstream, i.e. for increasing z in our case. If we denote $\Pi_0 = \Pi(z=0)$ and $\mathrm{K}_0 = \mathrm{K}(z=0)$, where $z=0$ corresponds to the inlet section (the throatP), the total hydraulic power dissipated up to a section $S(z)$ is $\mathrm{E}_0 - \mathrm{E}(z) > 0$, where obviously $\mathrm{E}_0 = \Pi_0 + \mathrm{K}_0$.

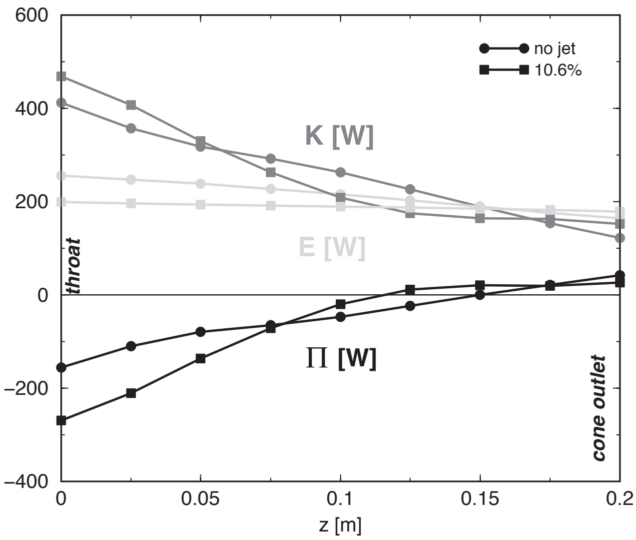

Fig. 5 The fluxes of potential energy Π, kinetic energy K and mechanical energy E along to the axial coordinates of cone without and with jet control (is plotted only the jet control with velocity 4.5 m/s associated with 10.6%).

Fig. 5 presents the fluxes of potential energy Π, kinetic energy K and mechanical energy E along to the axial coordinates of cone without and with jet control. Moreover, the flux of mechanical energy E with jet control is nearly to a horizontal line associated to loss-free flow. That means the cone is working better with control jet than without this control technique.

A dimensionless *loss coefficient* ζ is usually defined as:

$$\zeta(z) \equiv \frac{\mathrm{E}_0 - \mathrm{E}(z)}{\mathrm{K}_0} = \left(1 - \frac{\mathrm{K}(z)}{\mathrm{K}_0}\right) - \frac{\Pi(z) - \Pi_0}{\mathrm{K}_0} \quad (4)$$

The first term in Eq. (4) corresponds to what we call *kinetic energy recovery coefficient*,

$$C_{KR}(z) \equiv 1 - \frac{\mathrm{K}(z)}{\mathrm{K}_0} \quad (5)$$

while the second term in Eq. (4) corresponds to the so-called *potential energy recovery coefficient*,

$$C_{PR}(z) \equiv \frac{\Pi(z) - \Pi_0}{\mathrm{K}_0} \quad (6)$$

Since $\zeta > 0$ for viscous flows, we always have $C_{KR} > C_{PR}$. Moreover, for diffusers we have $\mathrm{K}(z) < \mathrm{K}_0$ because the flow is generally decelerated, therefore $C_{KR} < 1$. In addition, because of the pressure rise in diffusers we have $\Pi(z) > \Pi_0$, thus $C_{PR} > 0$. As a result, the kinetic and potential energy recovery coefficients satisfy the following inequalities for diffuser flow:

$$0 < C_{PR} < C_{KR} < 1 \quad (7)$$

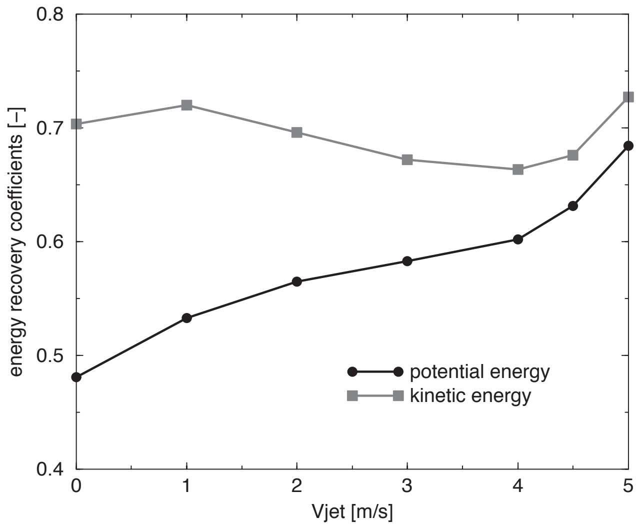

Fig. 6 Potential, C_{PR}, and kinetic, C_{KR}, energy recovery coefficients versus control jet velocity.

The potential, C_{PR}, and kinetic, C_{KR}, energy recovery coefficients versus control jet velocity are plotted in Fig. 6. The potential energy recovery coefficient C_{PR} increases monotonically from 0.48 to 0.68 with the jet control velocity while the kinetic energy recovery coefficient C_{KR} reaches a minim value 0.67 at jet control velocity 4 m/s (associated to jet control discharge around 10%). This value corresponds to the threshold where the pressure fluctuations are mitigated.

The *kinetic-to-potential energy conversion ratio* can be quantified as

$$\chi(z) \equiv \frac{\Pi(z) - \Pi_0}{\mathrm{K}_0 - \mathrm{K}(z)} < 1 \quad (8)$$

Accurate evaluation of χ requires the evaluation of integrals from Eq. (1) and Eq. (2). This is possible only if both velocity and pressure profiles are known.

The above considerations show that the flow in the diffuser can be quantified with two dimensionless coefficients, either ζ and χ, or C_{PR} and C_{KR}. Once a pair of coefficients is evaluated, the other pair follows immediately:

$$\zeta = C_{KR} - C_{PR}\,,\ \chi = \frac{C_{PR}}{C_{KR}} \text{ and } C_{PR} = \frac{\zeta\chi}{1-\chi}\,,\ C_{KR} = \frac{\zeta}{1-\chi} \qquad (9)$$

For diffusers with large outlet/inlet area ratio it is common practice to neglect the outlet kinetic energy, thus C_{KR} 1. As a result, there is only one coefficient to be used in evaluating the diffuser performance, either the pressure recovery coefficient C_{PR} or the losses coefficient $\zeta = 1 - C_{PR}$.

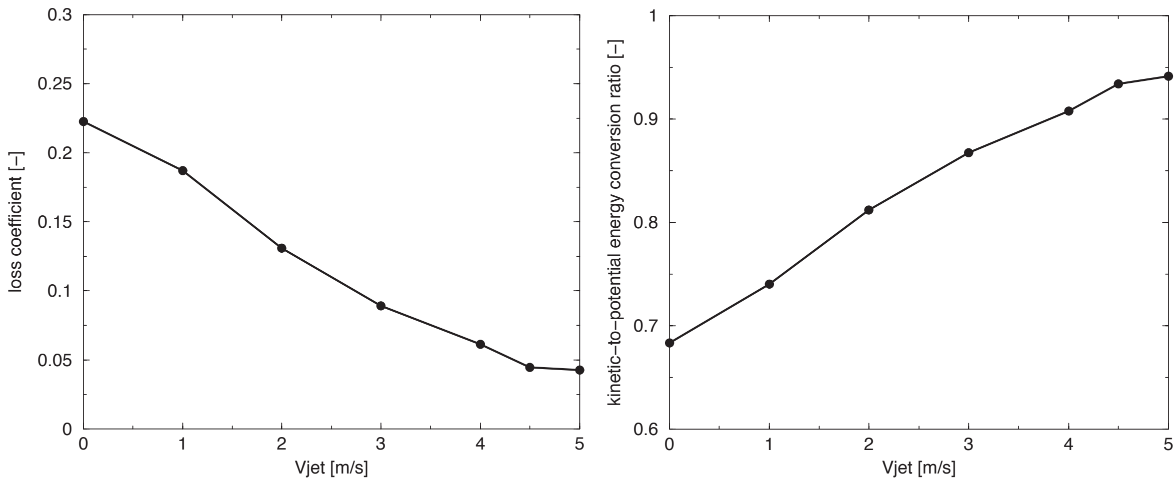

Fig. 7 Energy loss coefficient, ζ, and kinetic-to-potential energy conversion ratio, χ, in the cone, versus control jet velocity.

In our case, we compute the dimensionless coefficients between S_0 the inlet section of the cone (throat) and the downstream section (the cone outlet section), and we examine their variation with respect to the jet control velocity, see Fig. 7. The evolution of the loss coefficient ζ emphasizes the rapid decreases monotonically from 0.222 to 0.048 if the jet control velocity increases from 0 to 5 m/s. One can observe in Fig. 7 (right), the kinetic-to-potential energy conversion ratio χ increases monotonically from 0.68 to 0.95 in the same range of the jet control velocity.

Consequently, it was proved the axial jet control technique mitigates the pressure pulsations associated to the vortex rope in conjunction with improving the energetic performances of the cone. For example, after observing that for practical applications a 10% jet discharge is too large and inacceptable from the energy point of view, we have developed a flow feedback method, [13].

6. CONCLUSION

An axial water jet flow control technique for decelerated swirling flows with non-cavitating precessing vortex rope is investigated numerically. The 3D computational domain corresponds to the convergent-divergent section from the test rig. The swirling flow in a convergent-divergent, using a 3D unsteady and full turbulent flow is investigated. The inlet boundary conditions correspond to numerical data for velocity and turbulent quantities downstream a free runner from the test rig.

First, the vortex rope at different values of jet control discharge is visualized. A qualitative assessment of the 3D numerical results versus experimental visualization indicates a strong similarity in both cases without and with control jet. Those results present the displacement of quasi-stagnant central region when the jet discharge is increased. The quasi-stagnant central region is moved away from cone when the jet discharge is large enough.

Second, the unsteady pressure is recorded in four positions along to the element of the cone on the wall of the test section. The Fourier spectra of the unsteady pressure are obtained without and with axial jet control. Fourier spectra analysis present the maximum amplitude of the fundamental harmonic is moved down along to the cone while the discharge jet is increased. The vortex rope frequency moves down from 15.5 Hz without axial jet control to 8.3 Hz with axial jet control discharge larger than 3 l/s (associated to jet velocity V_{jet}=4 m/s). However, all pressure fluctuations are cut out only if the jet discharge is larger than 3.0 l/s (jet discharge corresponds to 10% from operating point discharge). That means the control jet is strong enough in order to generate an axi-symmetric vortex rope. The pressure fluctuations are mitigated even if the frequency is non zero.

Third, the potential C_{PR} and kinetic C_{KR} energy recovery coefficients as well as the energy loss coefficient ζ and the kinetic-to-potential energy conversion ratio χ in the cone in terms of the control jet discharge. The energy loss coefficient ζ decreases monotonically from 0.222 up to 0.048 while the kinetic-to-potential energy conversion ratio χ increases monotonically from 0.68 to 0.95 if the jet control is increased. Consequently, the hydraulic loss coefficient of the cone is improved when the jet control is applied.

However, a 10% jet discharge is required in order to operate without pressure fluctuations. As a result, in order to efficiently apply the jet control technique to hydraulic turbines a flow-feedback approach introduced by Susan-Resiga and Muntean [13] must be taken into account.

7. ACKNOWLEDGEMENTS

Authors would like to thanks for support to Romanian National Authority for Scientific Research through the CNCSIS PCE 799 project.

8. REFERENCES

[1] Susan-Resiga, R., Vu, T.C., Muntean, S., Ciocan, G.D., and Nennemann, B.: "Jet Control of the Draft Tube Vortex Rope in Francis Turbines at Partial Discharge", Proc. *23rd IAHR Symposium on Hydraulic Machinery and Systems*, Yokohama, Japan, 2006, Paper F192.

[2] Escudier, M.: "Confined Vortices in Flow Machinery," Annual Review of Fluid Mechanics, **19**, 1987, pp. 27-52.

[3] Palde, U. J.: "Influence of the Draft Tube Shape on Surging Characteristics", preprint, *American Society of Civil Engineers National Water Resources Engineering Meeting, Atlanta*, U.S.A. 1972.

[4] McDonald, A. T., Fox, R. W., and Van Dewoestine, R. V.: "Effects of Swirling Inlet Flow on Pressure Recovery in Conical Diffusers", AIAA Journal, **9**(10), 1971, pp. 2014-2018.

[5] Clausen, P. D., Koh, S. G., and Wood, D. H.: "Measurements of a Swirling Turbulent Boundary Layer Developing in a Conical Diffuser," Experimental Thermal and Fluid Science, **6**, 1993, pp. 39-48.

[6] Nishi, M., Matsunaga, S., Okamoto, M., Uno, M., and Nishitani, K.: "Measurement of three-dimensional periodic flow on a conical draft tube at surging condition", in Rohatgi, U.S., et al., (eds.) *Flows in Non-Rotating Turbomachinery Components*, FED, Vol. 69, 1988, pp. 81-88.

[7] Susan-Resiga R., Muntean S., Stein P., and Avellan F.: "Axi-symmetric Swirling Flow Simulation on the Draft Tube Vortex in Francis Turbines at Partial Discharge" *Proc. 24th IAHR Symposium on Hydraulic Machinery and Systems*, Foz do Iguassu, Brazil, 2008, Paper 13.

[8] Susan-Resiga R., Muntean S., Tanasa C. and Bosioc A., "Three-dimensional versus Two-dimensional Axi-symmetric Analysis for Decelerated Swirling Flow" *Proc. 14th Int. Conference on Modelling Fluid Flow (CMFF'09)*, Budapest, Hungary, 2009.

[9] Ruprecht A., Grupp J., Al-Salaymeh A., and Kirschner O.: "Experimental and Numerical Investigation of Vortex Control in a Simplified Straight Draft Tube Model" Proc. *24th IAHR Symposium on Hydraulic Machinery and Systems*, Foz do Iguassu, Brazil, 2008, Paper 173.

[10] Susan-Resiga R., Ciocan G.D., Anton I., and Avellan F. : "Analysis of the Swirling Flow Downstream A Francis Turbine Runner" *J. of Fluids Eng.*, Vol. 128, 2006, pp. 177-189.

[11] Muntean S., Susan-Resiga R., and Bosioc A.I.: "3D Numerical Analysis of Unsteady Pressure Fluctuations in a Swirling Flow without and with Axial Water Jet Control" *Proc. 14th International Conference on Modelling Fluid Flow (CMFF'09)*, Budapest, Hungary, 2009.

[12] Muntean S., Nilsson H., and Susan-Resiga R.: "3D Numerical Analysis of the Unsteady Turbulent Swirling Flow in a Conical Diffuser using FLUNET and OpenFOAM", submitted at Proc. *3rd IAHR Int. Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems*, Brno, Czech Republic, 2009.

[13] Susan-Resiga, R., and Muntean, S., "Decelerated Swirling Flow Control in the Discharge Cone of Francis Turbines", Proc. *4th Int. Symposium on Fluid Machinery and Fluid Engineering*, Beijing, China, 2008, pp. 89-96.