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FLOW-FEEDBACK CONTROL TECHNIQUE FOR VORTEX ROPE MITIGATION FROM CONICAL DIFFUSER OF HYDRAULIC TURBINES DRAFT TUBE

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It is known that 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. It is shown by Resiga et al. [6] that a water jet introduced axially through the runner crown mitigates the vortex rope and associated phenomena. However, numerical simulation and experimental measurements shown the control jet discharge is higher than 10% from main discharge, Bosioc et al [8]. This fraction of water which bypasses the runner is taken into account like volumetric losses. Sometimes, this water fraction used to supply the jet is not valid. Consequently, this paper investigates a new flow control technique proposed by Resiga et al. [10] which supplies the axial jet from downstream of the conical diffuser of hydraulic turbines. The water to supply the jet is driven by the pressure drop between cone wall and crown tip. This control technique is called "flow-feedback".

Key words: Flow-feedback control technique; Vortex rope; Conical diffuser; Hydraulic turbines.

1. INTRODUCTION

One of the major dynamic problems in hydraulic machinery is the vortex rope in the draft tube, especially for Francis turbines at part load. The vortex rope produces severe pressure fluctuations and damage of the runner blades. The vortex rope occurs when the turbine operates far from the best efficiency point. Consequently, this unsteady phenomenon limits the operation of the hydraulic turbines.

Nishi *et al.* [2] supposed that vortex rope evolves from the instability of a vortex sheet which rolls-up a helical vortex (spiral vortex core), around a central stalled region. An experimental investigation of pressure fluctuations in correlation with the shape of vortex rope shows that for different operating regimes, the shape of the vortex rope and rotation frequency changes with the cavitations number [3]. Ciocan *et al.* [4] investigated the vortex rope on a real turbine model in the FLINDT project. The velocity profiles and pressure fluctuations in the draft tube was measured. The pressure pulsation amplitude and the vortex frequency obtained with three-dimensional numerical simulation agree well with experimental data.

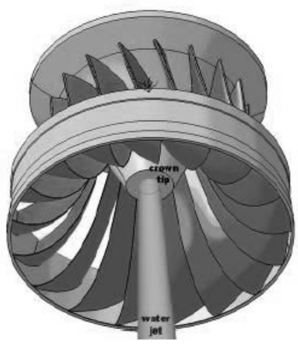

Fig. 1 – The axial injection of water at the runner crown tip.

Over the years many types of solutions have been used by manufactures to mitigate the pressure pulsations generated by the vortex rope [5]. But the method targets the pressure fluctuation in the framework of hydro-acoustic system, rather than addressing the main excitation source. Resiga *et al.* [6] propose a new solution to mitigate the vortex rope. The new solution implies to inject axially a water jet at the end of the runner crown (Fig. 1). This technique was investigated experimentally on a test rig developed at "Politehnica" University of Timisoara [7], with a swirl apparatus (Fig. 2) that mimics the swirling flow in a real Francis turbine [8]. First, the water jet discharge is taken from upstream de turbine and from the last results of Bosioc *et al.* [9] the jet discharge has to be more than 10% from the main discharge. This method has been proved to be successfully in mitigating the vortex rope and the associated pressure fluctuation.

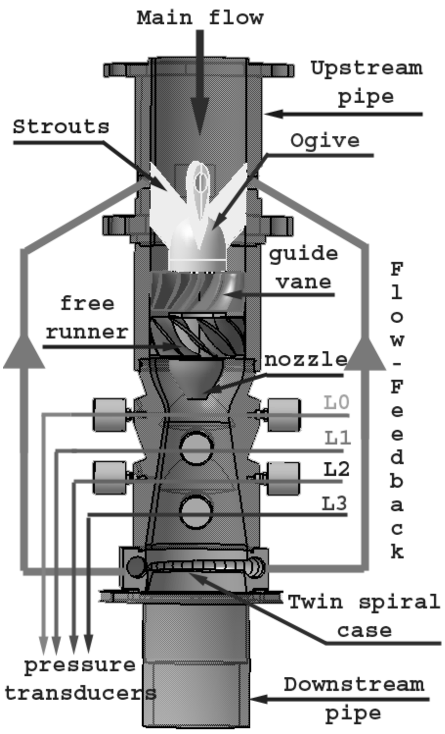

Fig. 2 – The swirl generator with the test section and flow-feedback system.

However, sometimes it is not acceptable to by-pass the runner with such large fraction of turbine discharge because of the turbine efficiency is decreased.

How can be supplied the jet without reducing the turbine efficiency? The answer is given by Resiga et al. [1] which observe an excess of static and total pressure near to the cone wall. This conclusion led Resiga et al. [10] to introduce a new flow control technique which uses a fraction of the discharge from downstream of the draft tube cone wall in order to supply the water jet through the runner crown. This new control technique is called "flow feedback", see Fig. 2. This technique does not require any additional energy to mitigate the vortex rope and associated effects. Consequently, the overall turbine efficiency is preserved.

This paper present the results obtained with new flow feedback technique. In section 2 the numerical results computed using a 2D axi-symmetric swirling flow model is shown. The practical implementation of the flow feedback is presented in section 3 together with experimental data measured on the test rig. The main conclusions are outlined in last section.

2. JET CONTROL WITH FLOW-FEEDBACK

In our previous work is shown that an effective control of the swirling flow with vortex rope can be achieved by injecting a water jet along the axis [8]. However, the pressure pulsations generated by a strong vortex rope are mitigated only if the jet discharge is higher than 10% from the incoming discharge. Consequently, the flow feedback technique is investigated in order to avoid any additional volumetric losses used to supply the jet and keep as large as the overall turbine efficiency.

2.1. Two-dimensional axi-symmetric numerical simulation

In order to understand the complex physics of the decelerated swirling flow with flow feedback a numerical simulation was performed. The 2D axi-symmetric computational domain with flow-feedback is presented in Fig. 3. The annular inlet section is considered just downstream the runner blades, see Fig. 2. The convergent-divergent part corresponds to the test section while the conical diffuser ends with a discharge cylindrical pipe. The flow feedback system is implemented at the end of the divergent part (to the cone).

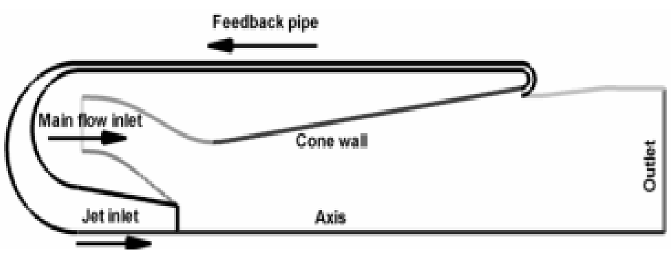

Fig.3 – Computational domain in a meridian half-plane for the test section with flow-feedback control system.

The following boundary conditions are imposed in order to perform the numerical simulation: 1) the velocity profiles and turbulent quantities like inflow conditions [10]. 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 the 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,

$$\frac{\partial p}{\partial r} = \frac{\rho V_\theta^2}{r} . \quad (1)$$

The 2D numerical simulation is performed using FLUENT code. Figure 4 shows the streamlines for axi-symmetric swirling flow without (upper half-plane) and with (lower half-plane) flow feedback control.

One can observe the stagnant region is washed away by the jet if the flow feedback system is switched on. That means the vortex rope is removed. Consequently, the associated pressure pulsations are eliminated.

The total pressure distribution shown in Fig. 5 emphasizes the excess of total pressure near the cone wall with respect to the central region near to the crown tip. This pressure difference supports the flow-feedback mechanism. Consequently, the flow feedback discharge is adjusted in terms of the swirling flow level.

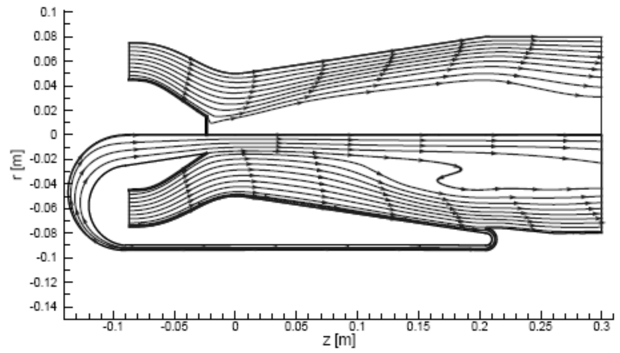

Fig. 4 – Streamlines for the axisymmetric swirling flow without flow control (upper half-plane) and with flow-feedback control (lower half-plane).

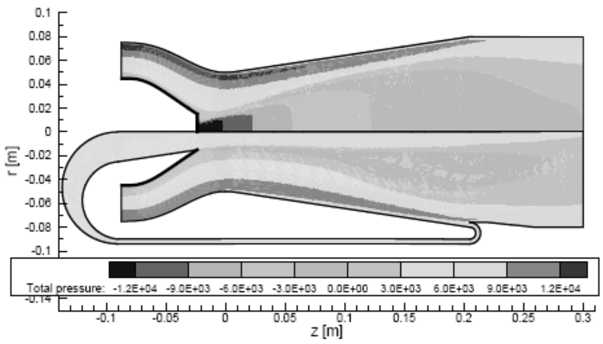

Fig. 5 – Total pressure for the axisymmetric swirling flow without flow control (upper half-plane) and with flow-feedback control (lower half-plane).

A quantitative assessment of the static, kinetic and total head distribution along to the cone is presented in Fig. 6 using the following quantities:

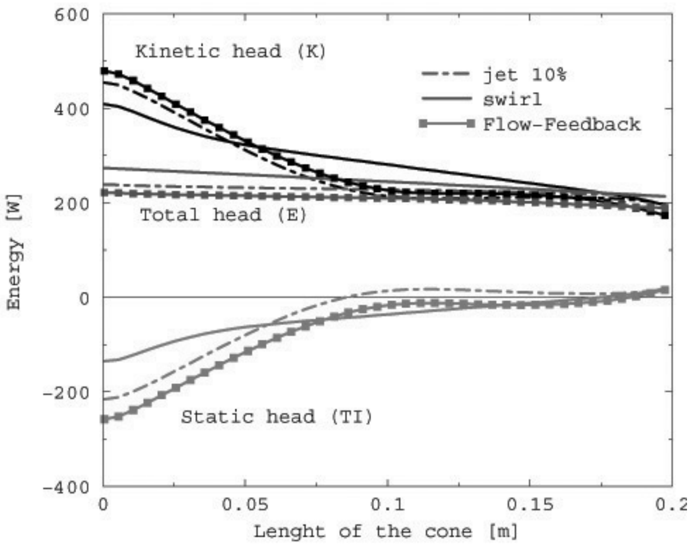

Fig. 6 The fluxes comparison of kinetic head (K), total head (E) and static head (Π), without and with jet control from upstream, and flow-feedback.

$$K(x) = \int_{S(x)} \frac{\rho V^2(x,r)}{2} V \cdot n\mathrm{d}S \quad [\mathrm{W}], \tag{2}$$

$$\Pi(x) = \int_{S(x)} p(x,r) V \cdot n\mathrm{d}S \quad [\mathrm{W}], \tag{3}$$

$$E(x) = \Pi(x) + K(x) \quad [\mathrm{W}]. \tag{4}$$

As is expected, the static head increases along to the cone while the kinetic head decreases. The total head monotonically decreases due to the hydraulic losses. From Fig. 6 it can be seen the conversion of kinetic to static head is significantly improved by the flow-feedback jet injection, within the upstream part of the conical diffuser. Moreover, one can be observed a slightly improvement between flow-feedback and jet injection with 10% discharge. This result is important for modern hydraulic turbines, where short and compact discharge cone is used in order to reduce the building cost of hydropower plant.

2.2. Practical implementation of flow-feedback system on test rig

The practical implementation of the flow-feedback system on the test rig is presented in Fig. 7. The main components of the flow-feedback system are twin spiral case and hydraulic circuit with two branches, Fig. 8. Each branch of hydraulic circuit includes pipes with one valve in order to switch on the jet [12]. The twin spiral case is displaced downstream the test section in order to collect the water from the cone wall. The twin spiral case was manufactured using rapid-prototyping machine [13]. The water collected by flow feedback system passes to the nozzle through the ogive struts [14].

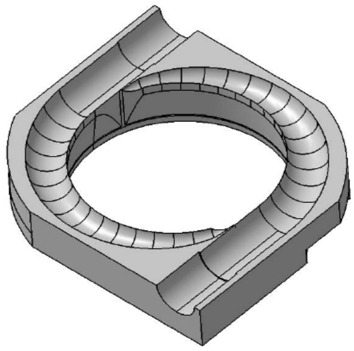

Fig. 7 – The twin spiral case.

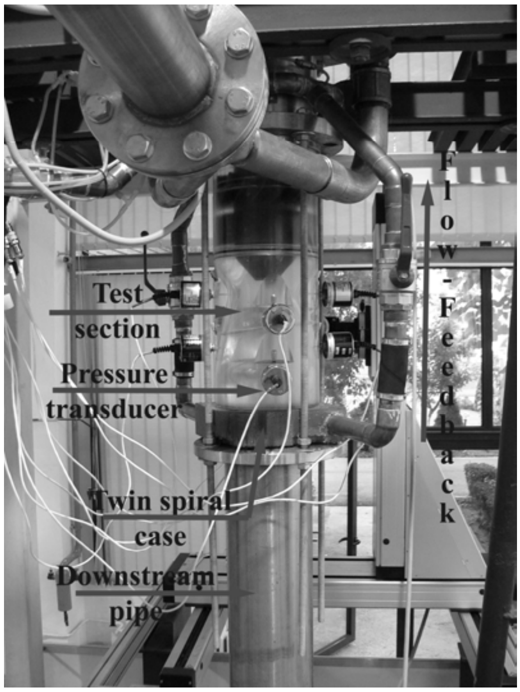

Fig. 8 – The flow-feedback system available on test rig.

3. RESULTS AND DISCUSIONS

3.1. Experimental investigations

The unsteady pressure is measured with eight unsteady pressure transducers flush mounted on the conical diffuser wall (Fig.8). The pressure transducers were mounted in pairs (two transducers at each level with 180° one of each other) on four levels along to the cone. First level corresponds to the throat, the second one at 50 mm downstream, and the next two levels with 50 mm spacing further downstream in the conical diffuser. The labels of each pressure transducer level are L0 for the throat level, and L1, L2 and L3 for the next three levels (Fig. 2). It was measured 10 sets of data acquisitions in order to obtain reliable data. Each set is acquired using Lab View program and corresponds to 32 seconds with 256 samples/second. The capacitive pressure transducers have an accuracy of 0.13% within a range of ±1 bar relative pressure. The pressure measurement was performed in order to asses the pressure recovery coefficient, amplitude and frequency with and without flow-feedback control. The results are presented and discussed in the next chapter.

3.2. Analysis of the pressure pulsations

The pressure pulsations and the associated Fourier transform of the measurements, for levels L1 and L2 with flow-feedback (long-dashed line) and without flow-feedback control (black solid line) at discharge $Q = 30$ l/s, are plotted in Fig. 9. From the Fourier transform it can be observe that for that levels it is an decrease of frequency, from ≈ 15 Hz in the case without flow-feedback (vortex rope), to ≈ 10 Hz in the case with flow-feedback (the decrease is ≈ 33%). For that levels (L1, L2), the vortex is well developed, and the amplitude has a decrease from ≈ 1.1 kPa for the case without flow-feedback to ≈ 0.8 kPa for the case with flow-feedback, that means ≈ 28% decrease. From the paper presented by Muntean et al. [15] it can be observed exactly the development of the vortex rope in the test section, and the influence of the jet injection method. The results presented above are plotted from the initial experimental measurements. So, next step was to find equivalent amplitude and frequency (the real value of them), for all levels. For that we used the Parseval's theorem which is described very well in [12] and [14]. The Parseval's theorem analyse a single harmonic of the amplitude corresponding to sum of the harmonics amplitude from all signals. According with the definition of

Parseval's theorem it is possible to determine a single value of amplitude for a sinusoidal signal and the reconstructed signal will have the same average similar with the initial signal and also the same frequency [16]. In order to validate the results obtained by flow-feedback, we choose to compare them with the method of jet supply with water from upstream. The comparison of both axial water jet injection (JET 10%, and flow-feedback), is necessary because, from experimentally point of view we can not determine the discharge in the flow-feedback system. Figure 10 presents the dimensionless amplitude *vs*. Strouhal number (Sh), recorded to all levels (L0-L3), without water jet control (vortex rope), with axial jet control from upstream (JET 10%), and with flow-feedback control.

In order to obtain the dimensionless amplitude is used the formula:

$$\overline{A}_{eq} = \frac{\sqrt{2}\,p_{RMS}}{\rho \cdot \dfrac{v_{throat}^2}{2}} \quad . \tag{5}$$

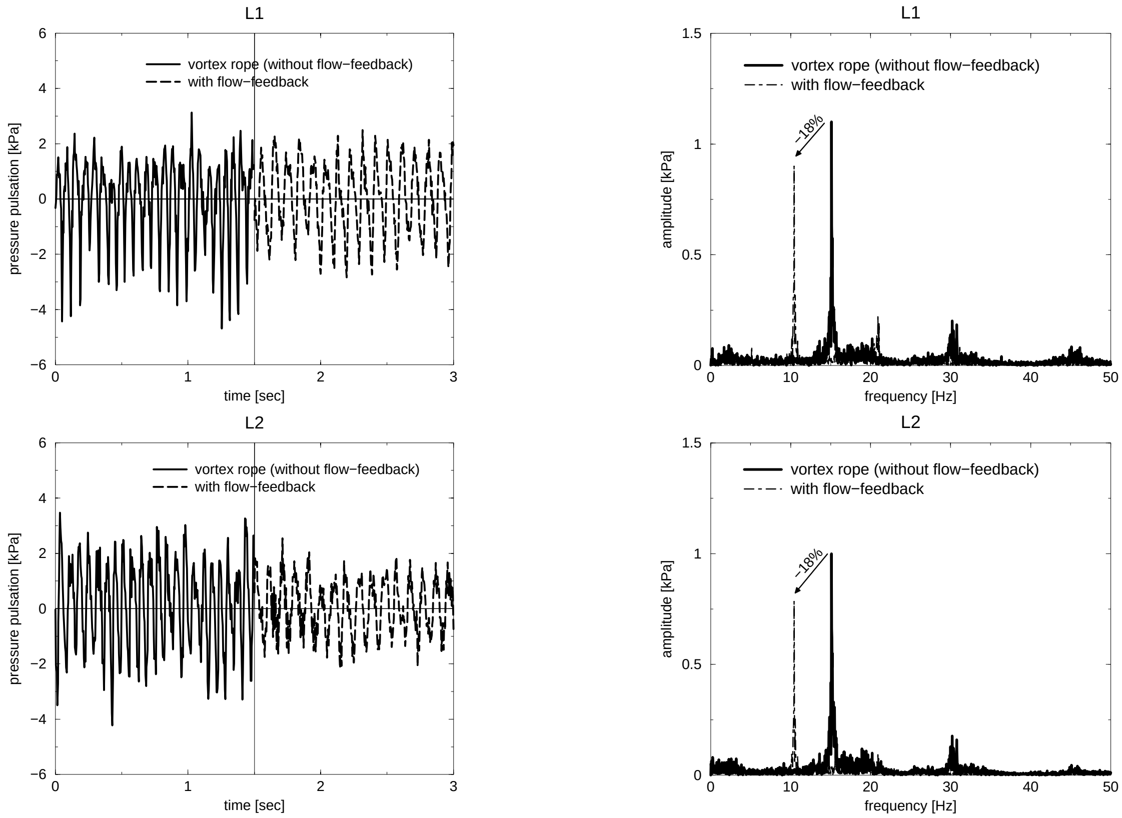

Fig. 9 – The pressure pulsations and the appropriate Fourier transform of the initial measurements, for all levels, with vortex rope (without flow-feedback control), and with flow-feedback control, at discharge $Q = 30$ l/s.

The dimensionless frequency uses as the Strouhal number (Sh) as a reference, defined by Eq. 6:

$$\mathrm{Sh} = \frac{f \cdot D_{throat}}{v_{throat}}, \tag{6}$$

where v_{throat} is the throat velocity (eq. 7), p_{RMS} is the root mean square of pressure pulsation (eq.8), $D_{\mathrm{throat}} = 0.1$ m is the throat diameter, $Q = 30$ l/s nominal discharge, and f is the fundamental frequency.

$$v_{throat} = \frac{4 \cdot Q}{\pi \cdot D_{throat}^2}, \tag{7}$$

$$p_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(p_i - \overline{p}\right)^2}\ , \tag{8}$$

First of all, we see the results of flow-feedback method have approximately the same values for the dimensionless amplitude and Strouhal number, like the results obtained with JET 10%, for all levels. It is obvious that Strouhal number for both methods decrease in comparison with the situation without any jet injection methods. In fact for the initial situation we have a frequency of 15 [Hz] corresponding to a Sh = 0.392, for the second situation (flow-feedback) the frequency is 10.5 [Hz] with Sh = 0.261, and for the third situation (JET 10%) the frequency is 10.7 [Hz] corresponding to a Sh = 0.28. Anyway, the frequencies of both axial water injection methods decrease than the situation without any jet injection methods with approximately 32%. If the decrease of amplitude in the throat (L0 level) is smaller with approximately 16.6% than the case without any jet injection method (we know the vortex in that region is not very strong), in the L1 and L2 locations where the vortex is well developed, the decrease of amplitude is significant, when the jet injection is starting. The decrease of amplitude for L1 it is with approximately 25% and for L2 with 21%, respectively. At L3 the amplitude increases when the jet is injected with approximately 60% but, the vortex has a large dissipation region with eccentricity and a lot of noise because the test section was designed to be twice bigger in the divergent part, to see exactly the influence of the jet injection method. So we are interest just for the first three levels (L0, L1, and L2).

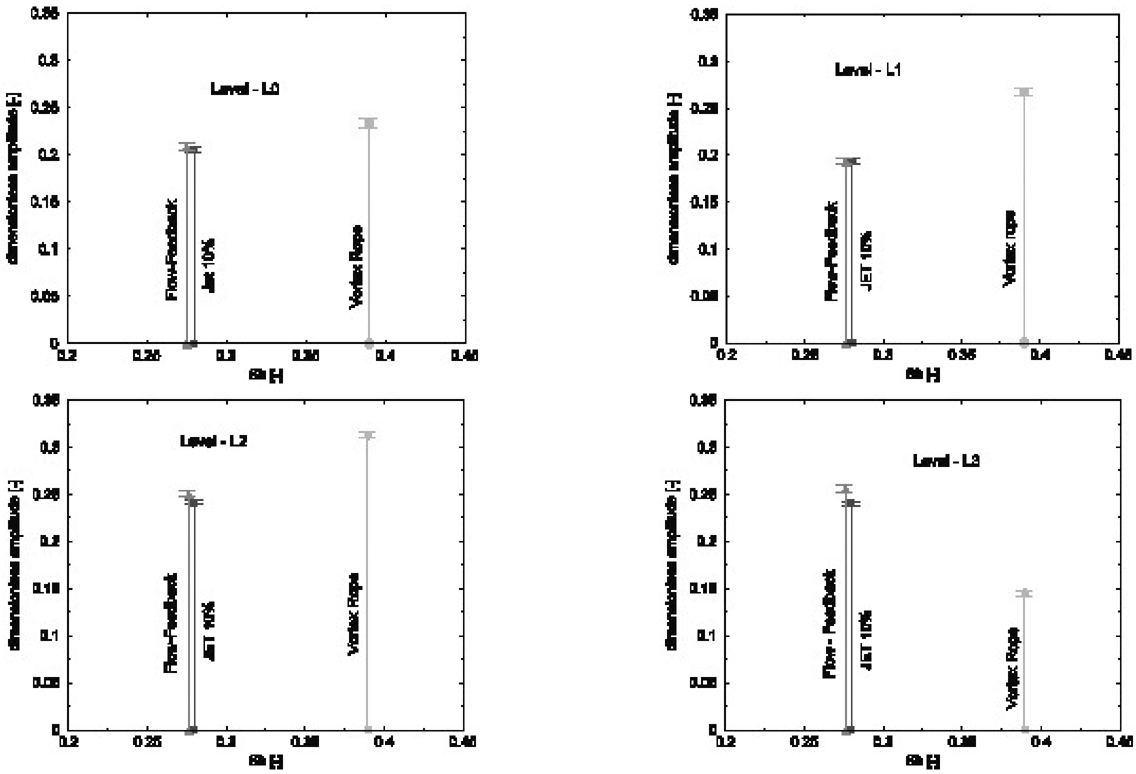

Fig. 10 – Dimensionless equivalent amplitude of pressure pulsation *versus* Strouhal number for all locations L0-L3, Fig. 2.

3.3. Pressure recovery coefficient

Another part of the investigations, was to find the pressure recovery coefficient on the cone wall when is injected the jet with flow-feedback method. So we are interested in the time-averaged pressure values, in order to assess the wall pressure recovery for the conical diffuser without and with flow-feedback. The dimensionless wall pressure recovery coefficient, c_p, is defined as:

$$c_p = \frac{\overline{p} - \overline{p}_{throat}}{\left(\rho \cdot v_{throat}^2\right)/2}, \tag{9}$$

where $\overline{p}$ is the time averaged value of the wall pressure, with the corresponding value at the throat. All graphs of pressure recovery coefficient contain the variation of the random mean square RMS (eq. 8). Experimental investigations were performed at discharge values of 30 l/s and 35 l/s.

The analyzed data are presented in dimensionless form with respect the kinetic term for pressure recovery coefficient (eq. 9), and the axial coordinate was made dimensionless with respect the throat radius R_{throat}. Fig. 11 shows the pressure recovery coefficient on the cone wall in dimensionless values, (with dashed line is represented the nominal flow at 35 l/s, and with solid line is represented the nominal flow at 30 l/s), for each level of the test section. First of all we can observe that is a well agree between the wall pressure recovery coefficient with the main discharge of 30 l/s and 35 l/s, for both cases (with and without flow-feedback). We see that the wall pressure recovery reaches to a value of approximately 0.55 in the first part of the test section, when the decelerated swirling flow has a precessing vortex rope (the case without flow-feedback). So the pressure recovery in that level (in the case with flow-feedback injection), is higher with approximately 35% than the case with vortex rope. In the second part of the test section, since with flow-feedback injection, the wall pressure recovery coefficient reaches to a value of approximately 0.84 that means a double value in recovery of pressure than the case with vortex rope. For the last level it can be observed a small increase in pressure recovery in the case without flow-feedback, and a small decrease of the pressure recovery in the case with flow-feedback. But it was shown that the vortex rope in this part of the test section is at the end, not very strong and still keeps an eccentricity zone. Anyway we are interest on the L1 and L2 levels, where the vortex rope is well developed.

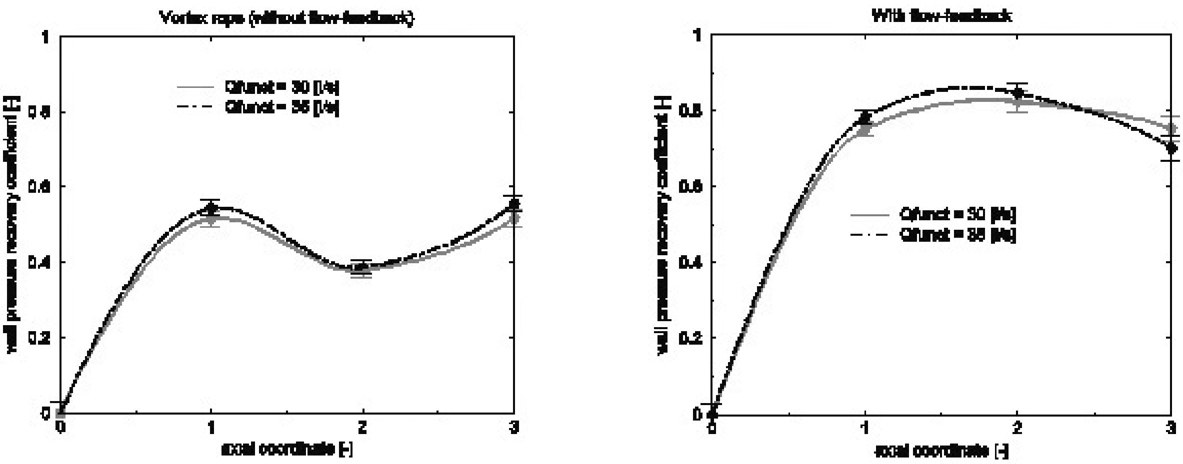

Fig. 11 – Pressure recovery coefficient on the cone wall for the case without flow-feedback (left), and the case with flow-feedback (right), at the main discharge Q = 30 [l/s] and Q = 35 [l/s].

4. CONCLUSIONS

The axial water injection technique introduced by Susan-Resiga *et al.* [6] was found to require a relatively large fraction (at least 10%) in order to effectively mitigate the strong vortex rope. If the control jet is supplied with a fraction of the turbine discharge that by-pass the runner, the equivalent volumetric losses might by unacceptably large. As a result, we examine in this paper the flow-feedback control technique to supply the jet, using a fraction of the discharge taken from the discharge cone outlet. It was installed a twin spiral chamber downstream to the cone in order to collect and drive the water toward the nozzle. As a result, the flow-feedback system does not require any additional energy in order to supply the jet. Firstly, the new technique with flow feedback is numerically investigated. Consequently, the complex physics of the decelerated swirling flow with flow feedback was deeply understood. Second, the flow-feedback technique was implemented on the test rig. It is shown that the flow-feedback significantly reduces the frequency of the pressure fluctuations with 32% as well as the amplitude with 20…25% with respect to the signal recorded for vortex rope. Moreover the pressure recovery coefficient on the cone wall is twice improved by the flow-feedback method to the levels L1 and L2. It is proved that the flow-feedback technique mitigates the pressure fluctuations generated by the precessing vortex rope without any additional energy consumption. Moreover, pressure recovery along to the cone is improved. One can conclude, the flow feedback control technique promotes the solutions with shorter and compact conical diffusers in hydraulic turbines. Consequently, the overall costs to build the hydropower plants are diminished with improved turbines performances along to the extended operating range.

ACKNOWLEDGMENTS

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