Original Paper (Invited)

Flow-Feedback for Pressure Fluctuation Mitigation and Pressure Recovery Improvement in a Conical Diffuser with Swirl

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Abstract

Our previous experimental and numerical investigations of decelerated swirling flows in conical diffusers have demonstrated that water jet injection along the symmetry axis mitigates the pressure fluctuations associated with the precessing vortex rope. However, for swirling flows similar to Francis turbines operated at partial discharge, the jet becomes effective when the jet discharge is larger than 10% from the turbine discharge, leading to large volumetric losses when the jet is supplied from upstream the runner. As a result, we introduce the flow-feedback approach for supplying the jet by using a fraction of the discharge collected downstream the conical diffuser. Experimental investigations on mitigating the pressure fluctuations generated by the precessing vortex rope and investigations of pressure recovery coefficient on the cone wall with and without flow-feedback method are presented.

Keywords: Francis turbine, vortex rope, pressure fluctuations, pressure recovery coefficient, flow-feedback.

1. Introduction

When operating Francis hydraulic turbines at off-design regimes and in particular at partial discharge, the residual swirl downstream the runner leads to flow instability in the discharge cone, with the development of a precessing vortex rope and associated large pressure fluctuations [1]. This self-induced flow unsteadiness leads to cracks in runner blades, damage of machine bearings, and significantly increases the hydraulic losses in the draft tube [2].

Over the years many different types of stabilizer fins, cross-pipes, tripods, co-axial cylinder, and special aerators have been used by manufactures to control draft tube swirl and pressure fluctuations [3] but these methods reduce the effects not the causes. Kurokawa et al. [4] proposed a J-groove method to control and reduce the swirl in a conical diffuser of divergent angle 30º aiming to suppress a draft tube surge. Nishi et al. [5] examined the applicability of VGJs (vortex generator jets), to suppress the separation in a conical diffuser with 14º divergence angle. In their investigation, they mainly studied the effect of velocity ratio in the range VR=0 to 1.9. Two parameters were measured in order to evaluate the effects of VGJs: the static pressure recovery coefficient and total pressure loss coefficient. A widely used surge suppression solution is to inject air in the recirculation region surrounded by the vortex rope, thus producing an essentially axis-symmetric stable flow-a hollow (air) core surrounded by swirling water flow. Papillon et al. [6] present practical solutions for natural aeration of hydraulic turbines through the runner cone. This technique seems to have reached industrial maturity by developing reliable heavy-duty spring-free valves, and by performing extensive model tests to asses the influence of air admission on turbine efficiency. Ciocan et al. [7], investigate the swirling flow on a real turbine model in the FLINDT project. On that model they did measurements of velocity profiles with LDV, measurements of velocity field with PIV, and measurements of pressure pulsation on the draft tube cone wall, respectively. In parallel with experimental investigations they did numerical 3D simulation, and the comparison of results led to a good validation between them.

By examining the swirling flow which appears in the draft tube cone of Francis turbine, when is operating at part load, Susan-Resiga et al. [8], supports the introduction of a new system to control the swirling flow which involves the reduction or even the elimination of the effects of pressure pulsation and the stagnant zone, by injecting an axial water jet in the draft tube cone, along the runner crown (Fig.1).

The water jet injection has been proved to be successful in mitigating the vortex rope and the corresponding pressure fluctuation. But this method uses for supply of the jet, 10% from the flow discharge to eliminate the stagnant region, and this water is taken from upstream with an auxiliary energy source. Also this method brings volumetric losses in the system and leads to a decrease of the turbine efficiency.

Obviously it is not acceptable to bypass the runner with such a large fraction of turbine discharge. The answer at the question how we can supply the jet without any additional energy input, and without reducing the turbine efficiency, led to a first conclusion, namely, we can observe by examine the swirling flow in draft tube cone of Francis turbine, at part load an excess of static and total pressure on the cone wall. This conclusion led Susan-Resiga et al [9], [10], to introduce a new flow-feedback system, by taking a part of the flow from downstream of the cone wall, and redirecting to upstream, for eliminating the swirling flow, by injecting it through the crown. This system does not require any additional energy input, and the turbine efficiency is preserved by the fact that the jet produced is strong enough to remove the stagnant region.

Section 2 of this paper presents the technical solution for implementing the flow-feedback system using a twin spiral case installed at the conical diffuser outlet. Section 3 is dedicated to the experimental investigations of the unsteady pressure fluctuations without and with the flow-feedback system. The paper conclusions are summarized in section 4.
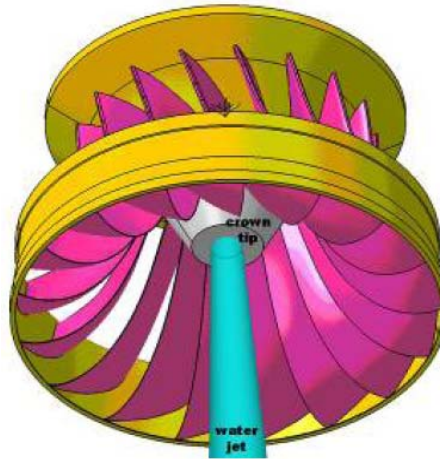

Fig. 1 Water jet injection along the runner crown. [8]

2. Flow-feedback system

Susan-Resiga et al. [8] developed a new swirling flow control method which mitigates the precessing vortex rope and his pressure fluctuation by injecting an axial water jet along to the draft tube cone axis. For this method, 10% from the discharge is necessary, to remove the central stagnant region associated to the vortex rope. This 10% from the main discharge is taken from upstream with an auxiliary energy source. Because of that, volumetric losses are present into the system. However Susan-Resiga et al. [9] have indentified a flow-feedback approach to supply the jet with water from downstream of draft tube cone, without any additional energy source, and without any additional losses into the system.

The flow-feedback approach supposed to take the water to supply the jet, from downstream of draft tube cone (approximately 10%), by implementing of a twin spiral case on the outlet of the cone, with the help of a by-pass system, which take this flow and inject it through the crown (Fig.2). The name of entire system is flow-feedback [11]. A cross section of the swirling flow apparatus with test section assembled with twin spiral case is shown in Fig.3. The swirl generator presented by Resiga et al. in [12], [10] has an upstream ogive with four leaned struts, followed by a set of guide vanes and a free runner, and ending with a nozzle. The test section presented by Bosioc et al. [13] have a convergent-divergent shape, with 8 pressure transducers installed two by two at four levels (L0…L3), which allow the pressure to be measured. The Cole-Parmer pressure transducers have ± 1bar range, 0.13% precision, and the upper limit of frequency is around 50 Hz. The first level (L0) is in the convergent-divergent part, and the next levels (L1, L2, L3), are displaced at 50, 100 and 150 mm relative to the first one.

Figure 2 show the practical implementation of flow-feedback system on test rig developed at the "Politehnica" University of Timisoara – National Centre for Engineering of Systems with Complex Fluids [9]. Downstream of the test section is positioned a twin spiral case which collects the water from the cone wall. The water passes through the two cooper pipes with two valves for opening and closing the jet supply, reaching to the ogive struts and to the nozzle (Fig. 2 and Fig. 3).

The main component of the flow-feedback system is the twin spiral case. The spiral case is one of the main components of hydraulic turbines, which makes the connection between pressure-gallery and guide vane. From hydraulic point of view, the losses along the spiral case have to be minimum for the maximum of flow rate. The design of the twin spiral case supposed to reduce the hydraulic losses while increasing the pressure recovery. The manufacturing of the final spiral case (Fig.4) was made by rapid-prototyping machine (Fig.5) [11]. Finally the twin spiral case was assembled with the convergent-divergent test section presented by Bosioc et al. [13]. Figure 6 shows a longitudinal cross-section of the twin spiral case assembled with test section where the water is injected in the convergent part, and goes out to downstream (outlet).

From Fig.7, it result that the twin spiral case has an inlet diameter with a value of D_i=160mm, a tongue diameter D_t = 152mm, and an outlet diameter D_e = 160mm. The tongue of the twin spiral case takes a fraction of the discharge near the cone wall and redirects it toward the crown, like axial jet injection. The maximum radius has a value of R_{max} = 16.5mm, and minimum radius is R_{min} = 4mm.
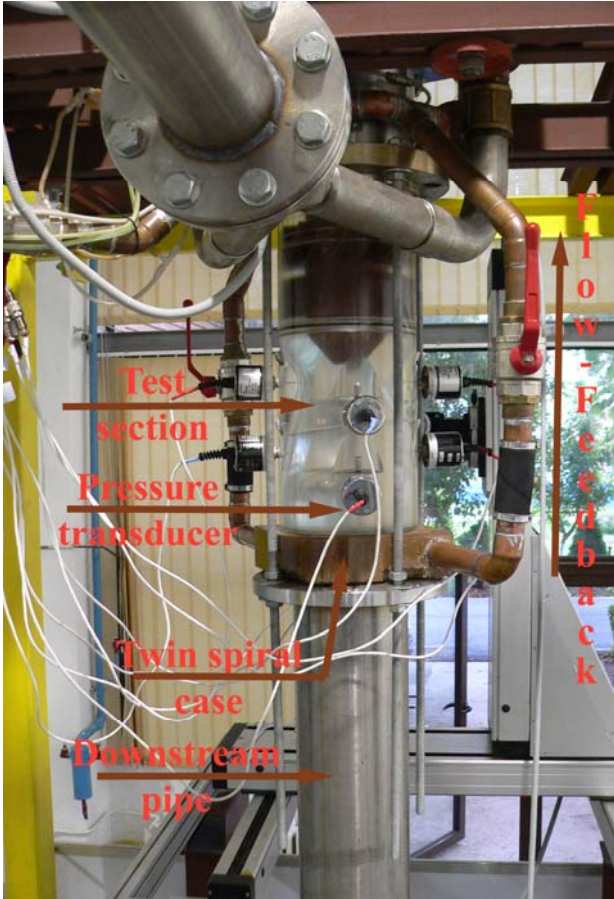
Fig. 2 Photography of the flow-feedback system installed on test rig.
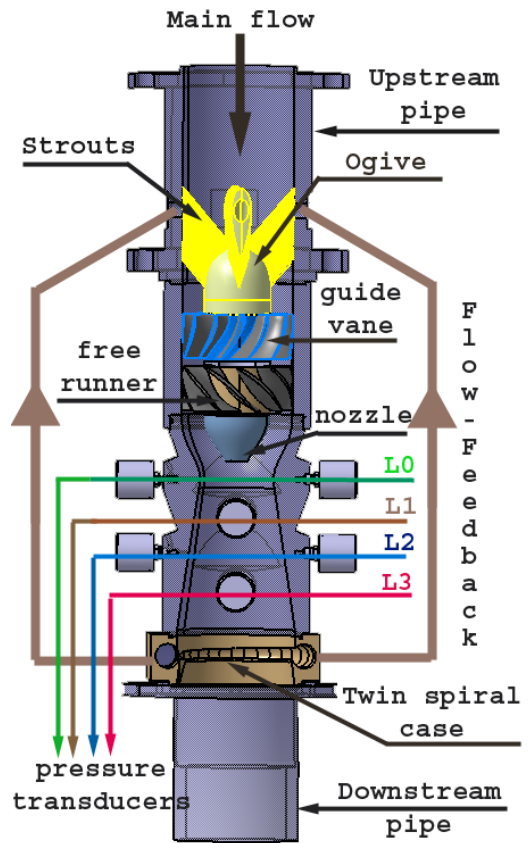

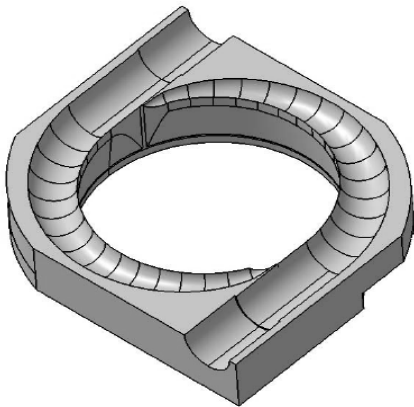**Fig. 3** Cross-section of the assembled test section with twin spiral case.

Fig. 4 Twin spiral case section.

Fig. 5 Twin spiral case manufactured by rapid-prototyping machine.
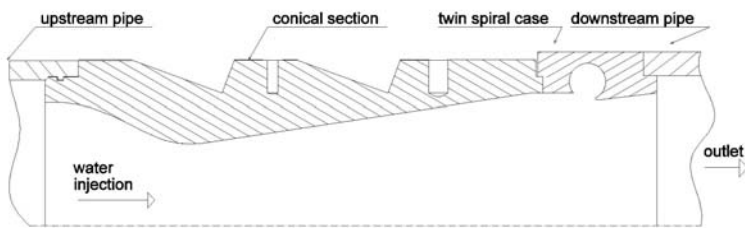

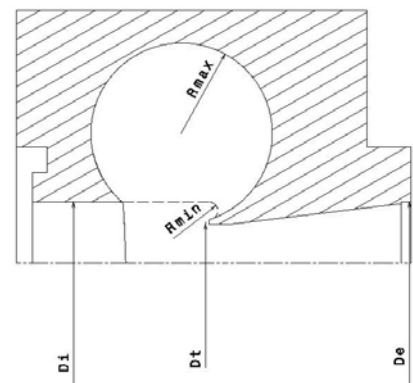**Fig. 6** Cross-section of twin spiral case assembled with conical section.

Fig. 7 Detail of the twin spiral case section.

3. Experimental results
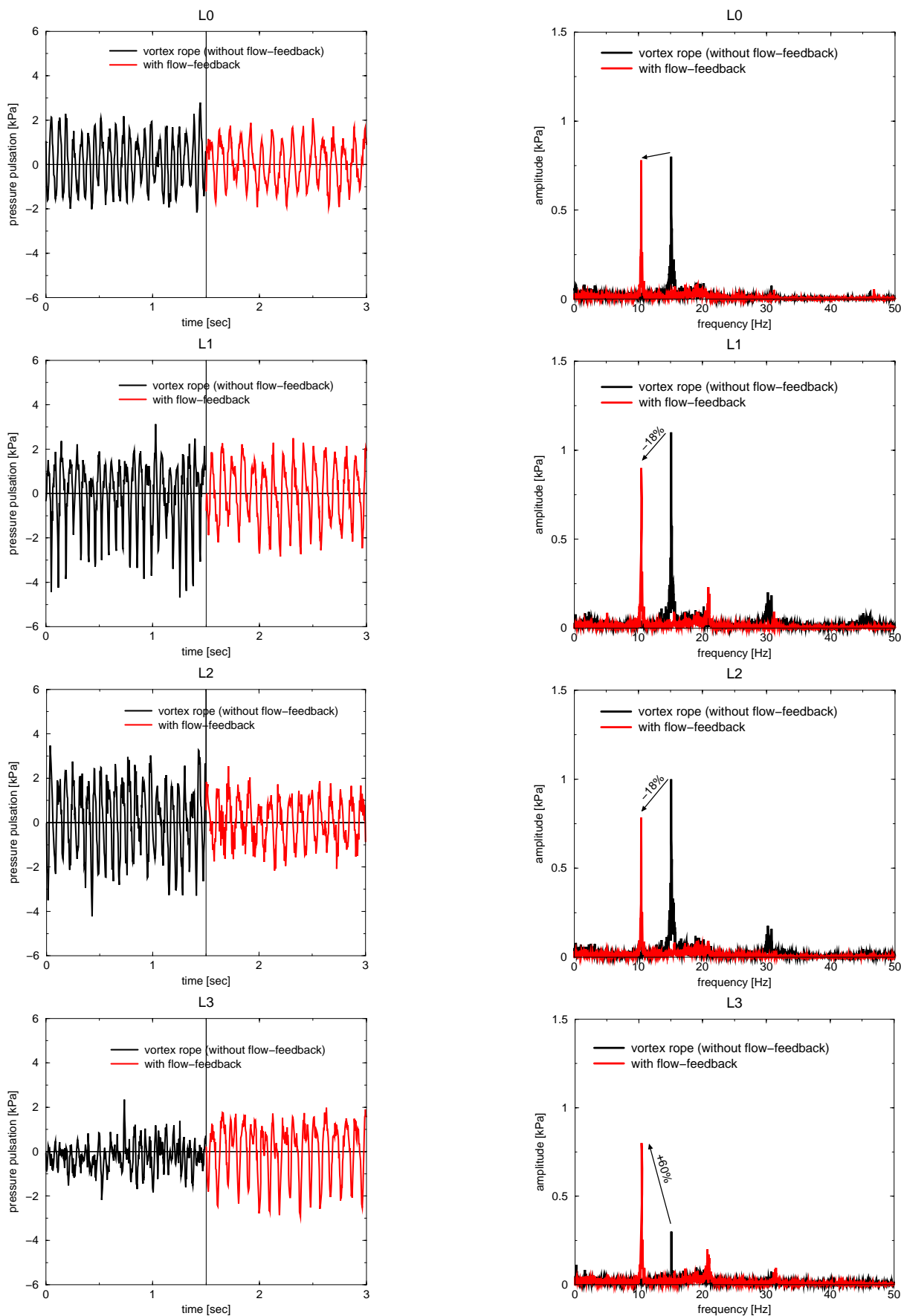
3.1 Pressure pulsation fluctuations

Fig. 8 The pressure pulsations and the appropriate Fourier transform of the initial measurements, for all levels, with vortex rope (without flow-feedback), and with flow-feedback jet injection method, at discharge Q = 30 l/s.

The experimental measurements were performed using a Lab View program with the acquisition time of 32 seconds to a sampling rate of 256 samples/second. The pressure pulsations and the appropriate Fourier transform of the initial measurements, for all levels (Fig. 3) with flow-feedback (red solid line) and without flow-feedback jet injection method (black solid line) at discharge Q=30 l/s, are plotted in Fig. 8.

From the Fourier transform it can be observe that for all 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%). The amplitude for the first level from the throat (L0), in the both cases is approximately the same, but at this level the vortex rope it is at the beginning, and it is not very developed. For the second and third level (L1, L2), where the vortex is well developed, 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. At the last level (L3), it is an increase of the amplitude with approximately 60% since with the flow-feedback jet injection method. At this level the vortex rope still has an eccentricity region 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).

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 [14] which analyse a single harmonic of the amplitude corresponding to sum of the harmonics amplitude from all the signals [15]. In order to obtained reliable data, 10 sets of measurements were performed for three different cases: without any jet injection (vortex rope), with jet injection from upstream with 10% from the main discharge (JET 10%), and with flow-feedback.

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. From previous work of Resiga et al [8] we know that is necessary 10% from main flow to supply the jet. All pressure transducers are aligned with respect to the static head. Harmonics higher than 50Hz are not captured due to the upper limit of unsteady pressure transducers. The FFTRF subroutine from International Math and Statistics Libraries (IMSL) [16] is used to compute the discrete Fourier transform.

According with the definition of Parseval's theorem [14] 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. The equation of Fourier transform for a continuous signal p (t) is defined according with Eq. 1 [15]:

$$p(t) = \frac{a_0}{2} + \sum_{m=1}^{\infty} \left[a_m \cos\left(\frac{2\pi mt}{T}\right) + b_m \sin\left(\frac{2\pi mt}{T}\right) \right] \tag{1}$$

where T is the time period, $a_0/2$ the mean value of the unsteady pressure signal p (t), m the mode and t the time, a_m and b_m are the coefficients of cosine and sine of the Fourier transform. This coefficients are defined as fallows:

$$a_m = \frac{2}{T} \int_{t_0}^{t_0+T} p(t) \cos\left(\frac{2\pi mt}{T}\right) dt; b_m = \frac{2}{T} \int_{t_0}^{t_0+T} p(t) \sin\left(\frac{2\pi mt}{T}\right) dt$$

where t_0 is the initial time, and a_0 defined as:

$$a_0 = \frac{2}{T} \int_{t_0}^{t_0+T} p(t) dt = 2\bar{p}$$

Then will result that $a_0/2$ is the mean value of the p (t) and the amplitude and the angular frequency can be written as:

$$A_m = \sqrt{a_m^2 + b_m^2}; \qquad \omega_m = m\frac{2\pi}{T}$$

The Parseval's theorem applied to the Fourier transform is defined as fallows:

$$\frac{1}{T} \int_{t_0}^{t_0+T} |p(t)|^2 dt = \sum_{m=0}^{\infty} |c_m|^2 = \bar{p}^2 + \frac{1}{2} \sum_{m=1}^{\infty} \left(a_m^2 + b_m^2\right) \tag{2}$$

The definition of root mean square (RMS) for a continuous signal is defined as:

$$p_{RMS} = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} \left[p(t) - \bar{p}\right]^2 dt} \tag{3}$$

Based on the Parseval's theorem the root mean square of the pressure pulsation can be written as:

$$p_{RMS}^2 = \frac{1}{2}\sum_{m=1}^{\infty}\left(a_m^2 + b_m^2\right) = \frac{1}{T}\int_{t_0}^{t_0+T} p^2(t)dt - \overline{p}^2 \tag{4}$$

The root mean square is defined for a continuous signal. This formula transformed into a discrete signal is:

$$p_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(p_i - \overline{p}\right)^2} \tag{5}$$

Which it means that the amplitude for a discrete signal could be defined:

$$A_{eq} = \sqrt{2}p_{RMS} \tag{6}$$

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

$$\overline{A}_{eq} = \frac{\sqrt{2}p_{RMS}}{\rho \cdot \dfrac{v_{throat}^2}{2}}\ , \tag{7}$$

$$\text{where } v_{throat} = \frac{4Q}{\pi \cdot D_{throat}^2}$$

The resulted amplitude from a discrete signal is the correct amplitude and is possible to reconstruct a signal in order to have the same range similar with the initial signal. It means that all contributions of power spectrum from other frequencies are collected to the fundamental frequency yielding the equivalent amplitude. The processed data are presented in dimensionless values. The dimensionless frequency uses as the Strouhal number (Sh) as a reference, defined by Eq. 8:

$$Sh = \frac{f \cdot D_{throat}}{V_{throat}} \tag{8}$$

where $D_{throat} = 0.1$ m is the throat diameter, $Q = 30$ l/s nominal discharge, V_{throat} is the throat velocity, and f is the fundamental frequency.

For a better understanding on how Parseval's theorem can give a good result on pressure fluctuations reconstruction, in Fig. 9 it is presented an example of Fourier transform of pressure fluctuation and associated reconstructed signal (the example is given for level L1 without water jet control).
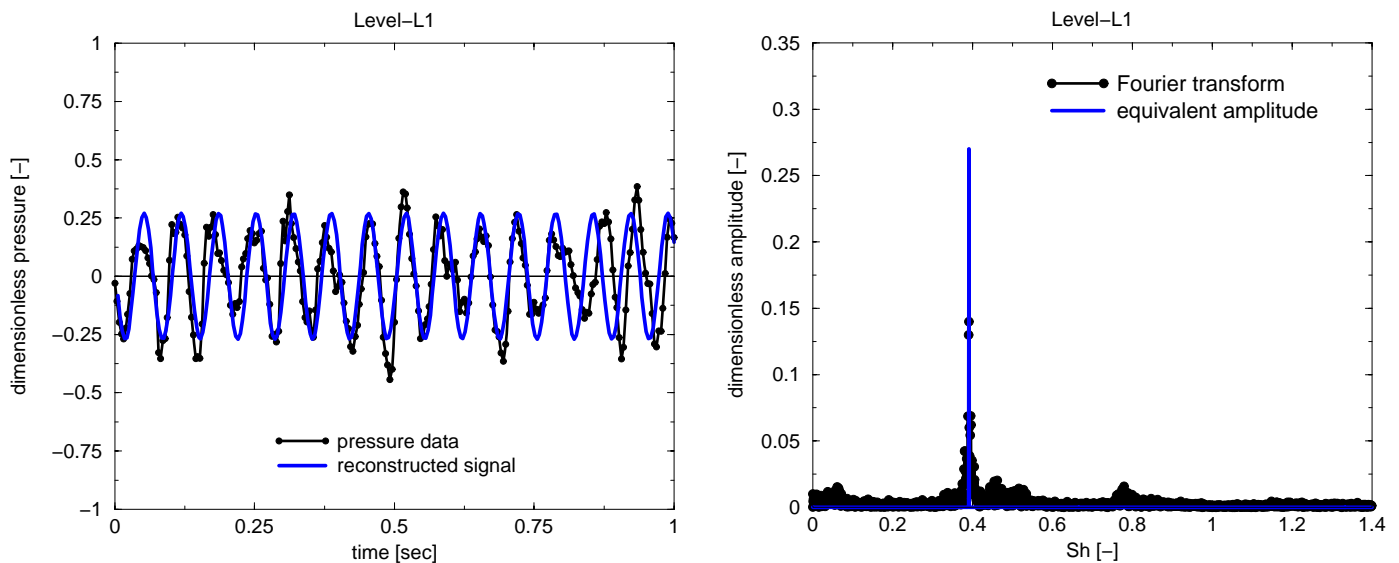

Fig. 9 Unsteady pressure recorded for level L1, from experimental investigation (with black solid line) and Fourier reconstruction signal with Parseval's theorem (with blue solid line) without water jet control (vortex rope).

Figure 9 presents the dimensionless pressure signal (with black solid line), measured at L1 level and the reconstructed signal with fundamental harmonic and equivalent amplitude based on Parseval's theorem (with blue solid line). One can observe a quite well reconstruction of the original signal with this theory based on Parseval's theorem. The dimensionless pressure signal was obtained with respect to the throat velocity (Eq. 9):

$$p_{dimensionless} = \frac{p_i}{\rho \dfrac{v_{throat}^2}{2}} \qquad (9)$$

The unsteady pressure recorded to all levels (L0-L3), without water jet control (vortex rope - solid green line), with axial jet control from upstream (JET 10% - solid blue line), and with flow-feedback system control (flow- feedback – solid red line), are plotted in Fig.10.
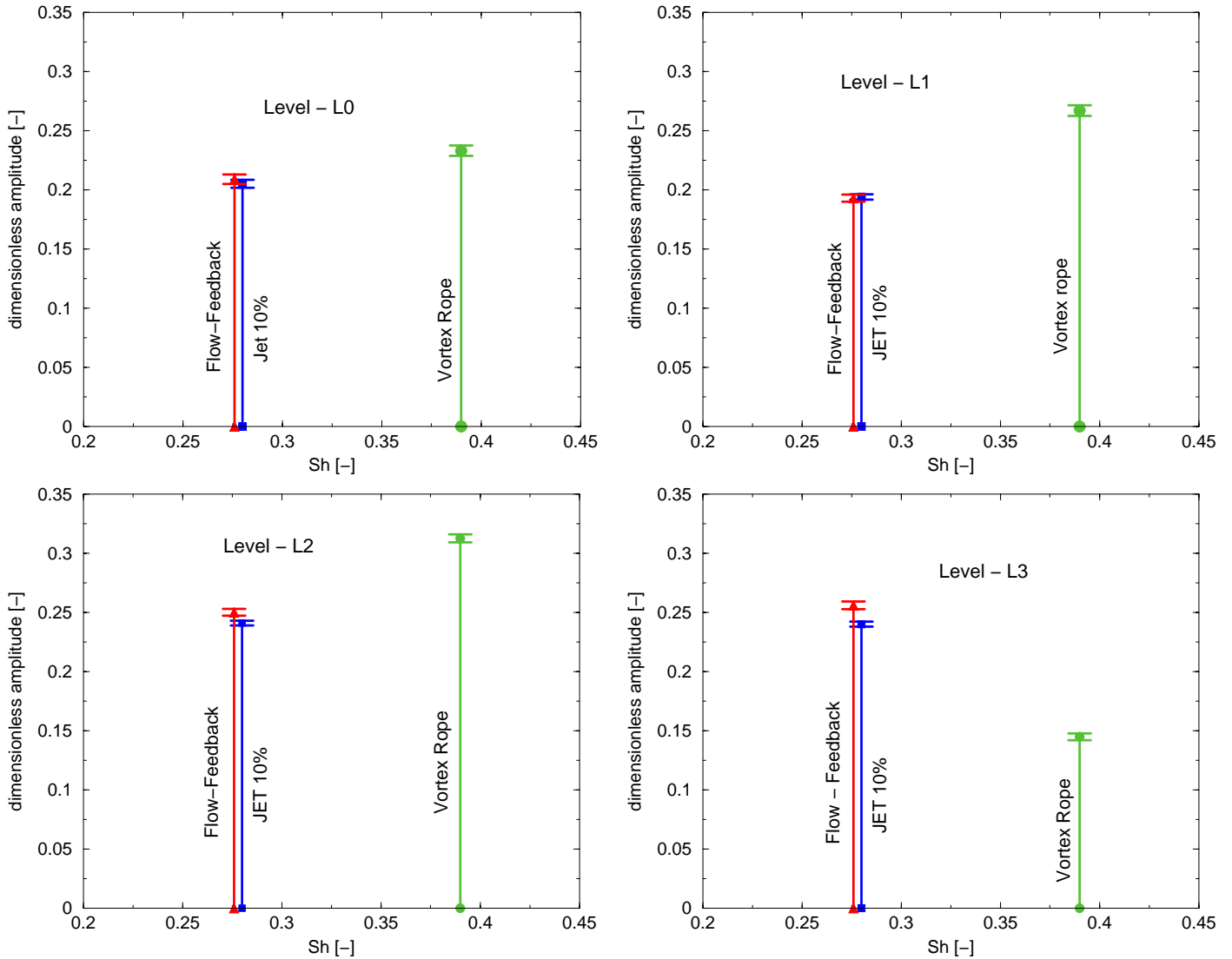

Fig. 10 Dimensionless amplitude vs. Strouhal number from experimental data at locations L0-L3.

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% (Table1).

For L0 throat level, the dimensionless amplitude is approximately the same for all three cases, because the vortex begins to appear (that means the vortex rope is compact in the throat). For L1 and L2 levels we can observe that the dimensionless amplitude for the case without any jets has the highest value (that means the vortex rope is well developed), and when we have a jet injection the stagnant region is pushed down and the pressure fluctuations has a major decrease. For L3 level, by injecting the jet, the stagnant region is pushed down, but still exist an eccentricity region, with a large dissipation and noise of the vortex rope.

Table 1 The maximum values of dimensionless pressure fluctuation amplitude and frequency for L0-L3 levels.

Level	Vortex rope	Frequency [Hz]	Strouhal number Sh [-]	JET 10%	Frequency [Hz]	Strouhal number Sh [-]	Flow-Feedback	Frequency [Hz]	Strouhal number Sh [-]
L0	0.233			0.205			0.209		
L1	0.267	15	0.392	0.194	10.7	0.28	0.193	10.5	0.261
L2	0.312			0.241			0.25		
L3	0.145			0.24			0.256		

Table 1 presents the maximum values of dimensionless pressure fluctuations amplitude, for all three investigated cases in the locations L0-L3. 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.

3.2 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:

$$c_p = \frac{\bar{p} - \bar{p}_{throat}}{\left(\rho \cdot v_{throat}^2\right)/2} \qquad (10)$$

where $\bar{p}$ 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. 5)

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. 1), and the axial coordinate was made dimensionless with respect the throat radius R_{throat}:
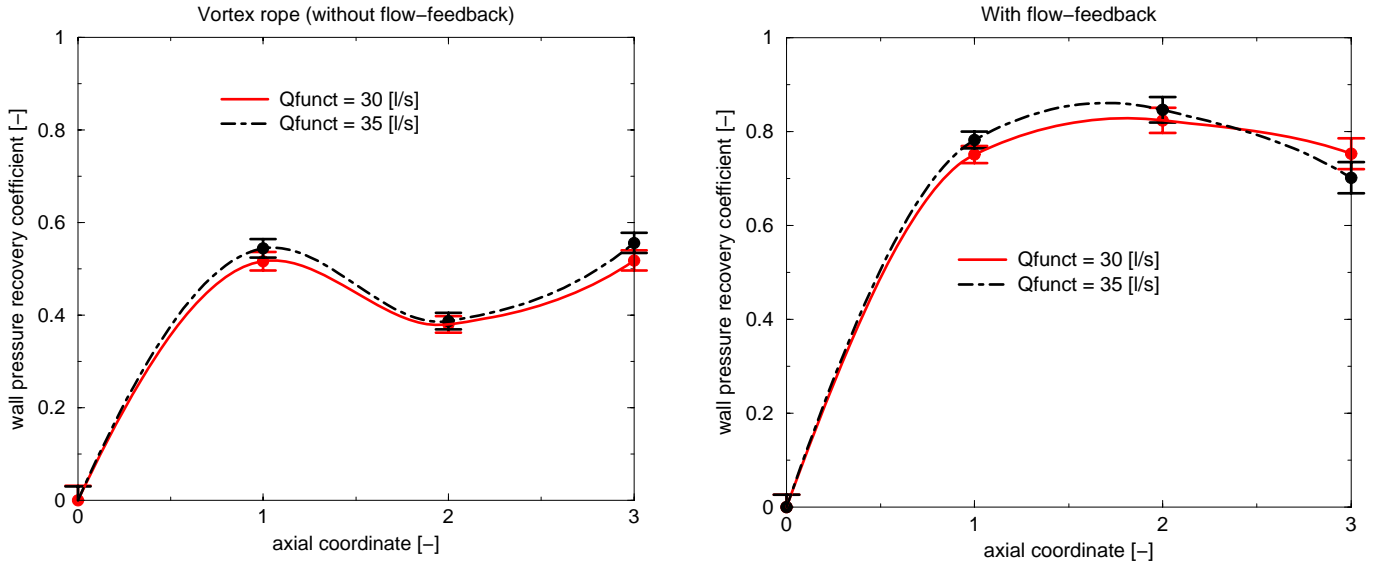

Fig. 11 Pressure recovery coefficient on the cone wall for the case without flow-feedback (left), and the case with flow-feedback (right), at the main discharge Q = 30 [l/s] and Q = 35 [l/s].

Fig.11 shows the pressure recovery coefficient on the cone wall in dimensionless values, (with black dashed line is represented the vortex rope, and with red solid line is represented the flow-feedback), for each level of the test section (the levels of the test section are described in Section 2, Fig. 3).

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.

This is an important improvement in the diffuser performance, which for real turbines will lead to a corresponding increase of the overall performance. We conclude that the flow-feedback has the potential of improving the pressure recovery in the discharge cones of real turbines over a wide operating range.

4. Conclusions

The new flow control technique introduced by Susan-Resiga et al. [8] was found to require a relatively large fraction of the discharge for the jet injected from the runner crown (at least 10%) in order to effectively mitigate the 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 a new approach to supply the control jet, by using a fraction of the discharge taken from the discharge cone outlet. In order to implement this new technique, we install a twin spiral chamber downstream the cone, and guide the water flow toward the nozzle. The resulting flow-feedback system does not require additional energy and it does not affect the runner flow. We investigate experimentally this flow-feedback approach in a test rig that mimics the decelerated swirling flow in a Francis turbine discharge cone when operated at partial discharge. It is shown that the flow-feedback significantly reduces the frequency of the pressure fluctuations by 32%, and the amplitude by 20…25% with respect to the original vortex rope.

In conclusion, we demonstrated that the flow-feedback technique to supply the control jet in a discharge cone with swirling flow, has the potential to mitigate the pressure fluctuations generated by the precessing vortex rope, without any additional energy consumption. Moreover the pressure recovery coefficient on the cone wall is significantly improved by the flow-feedback jet injection method with approximately a double value in the area where de vortex rope it is well developed (level L1 and L2).

Nomenclature

Q	Volume flow rate [m^3/s]		f	Frequency [Hz]
D_{throat}	Throat diameter [m]		$L0,L1,L2,L3$	Labels for levels from the test section
V_{throat}	Throat velocity [m/s]		ρ	Fluid Density [kg/m^3]
p_{RMS}	Root mean square [-]		m	Mode [-]
A_{eq}	Equivalent amplitude [Pa]		A	Amplitude [Pa]
Sh	Strouhal number [-]		A_m	Amplitude mode [Pa]
a_m	Cosine coefficient of Fourier transform [-]		p_i	Instantaneous pressure signal [Pa]
b_m	Sine coefficient of Fourier transform [-]		p_t	Continuous signal [Pa]
c_m	Fourier coefficients given by sum of sine and cosine coefficient [-]		T	Period [s]
$\overline{p}$	Average pressure signal [Pa]		t	Time [s]
N	Number of data sets		t_0	Initial time [s]

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