

## IN SITU UNSTEADY PRESSURE MEASUREMENTS ON THE DRAFT TUBE CONE OF THE FRANCIS TURBINE WITH AIR INJECTION OVER AN EXTENDED OPERATING RANGE

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*Operating Francis turbines over extended range is often hindered by the flow instabilities developed downstream the runner, in the draft tube cone. The unsteady pressure field induced by flow instabilities leads to pressure fluctuations. The paper presents the experimental investigations of the unsteady pressure field generated by flow instabilities into a draft tube of the Francis turbine over extended operating range. In situ measurements are performed without and with air injection in order to assess the control method. The unsteady pressure is recorded in five locations on the draft tube cone wall. As a result, the Fourier spectra are obtained without and with air injection in order to identify the fundamental frequency and associated amplitude. In this case, the air injection improves significantly the dynamic behavior at  $0.7Q_{BEP}$  while for operating points at lower discharge (around  $0.5Q_{BEP}$ ) the dynamic behavior is deteriorated.*

**Keywords:** Francis turbine, medium specific speed, experimental investigations, pressure fluctuations, air injection

### 1. Introduction

The hydraulic turbines with non-adjustable blades (e.g. Francis and propeller) lead to unwanted flow instabilities with associated low-frequency phenomena at part load conditions [1]. Unfortunately, these unsteady phenomena are associated with large pressure fluctuations just downstream to the runner into the conical diffuser of the draft tube [2]. Owing to operation of the hydraulic turbines at part load regimes with flow instabilities leads to various problems up to the failure of the runner [3].

Several methods were proposed and implemented into the hydraulic turbines in order to mitigate the consequences of the vortex rope [4]. Particularly, an innovative flow-feedback method is investigated by Tănasă et al. [5]. However, the wide spread method implemented in the hydropower plants in order to

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mitigate the unsteady phenomena associated to the part load operation is air admission or injection, respectively. Such techniques can be categorized as either active or passive, depending on the energy injected [6]. An early review of passive solutions that address flow instabilities in the draft tubes of hydraulic turbines including air admission was compiled by Thicke [7]. Active flow control methods generally use air injection, using an external energy source [8, 9].

The air admission is self-adjusting with the operating point. However, the large air pocket significantly changes the overall impedance of the hydraulic system, and it may trigger even larger problems than the original ones in case resonance occurs. Extensive experimental investigations are performed on the test rig in order to quantify the air effects by Papillon et al. [10].

The air effect is unclear even if several in situ results are reported [11]. Therefore, the paper presents our in situ experimental investigations into a Francis turbine in order to evaluate the air injection solution available in the power plant in order to improve the dynamic behavior.

## 2. Francis turbine test case

The test case corresponds to a medium specific speed Francis turbine with dimensionless specific speed  $\nu = 0.371$ . The distributor consists of 12 stay vanes and 16 guide vanes whilst the runner has 15 blades with the reference radius  $R_{2e} = 0.925$  m. Figure 1 shows the Francis turbine cross view with parameters from Table 1.

Table 1

Francis turbine parameters

Parameters	Eqs. according to IEC [12]	Value
discharge coefficient $\varphi$ [-]	$\varphi = Q(\pi\omega R_{2e}^2)^{-1}$	0.174
energy coefficient $\psi$ [-]	$\psi = 2E(\omega R_{2e})^{-2}$	1.171
hydraulic power coefficient $\lambda$ [-]	$\lambda = 2EQ(\pi\omega^3 R_{2e}^5)^{-1}$	0.22
dimensionless characteristic speed $\nu$ [-]	$\nu = \varphi^{0.5}\psi^{-0.75}$	0.371

First, the equipments are installed in hydropower plant in order to record the mechanical and electrical data: head water and tail water levels as well as the static pressure upstream and downstream to the turbine in order to compute the head (H); the pressure drop on the Winter-Kennedy taps in order to compute the discharge ( $Q$ ); pressures on the piston of the guide vane servomotors as well as guide vanes servomotor stroke ( $S_{AD}$ ) in order to compute the guide vane opening ( $a_0$ ); the generator power as well as the hydro unit power in order to compute turbine power; line voltages and phase currents at the generator and excitation

voltage and currents. The experimental procedure is performed according to IEC standard [12].

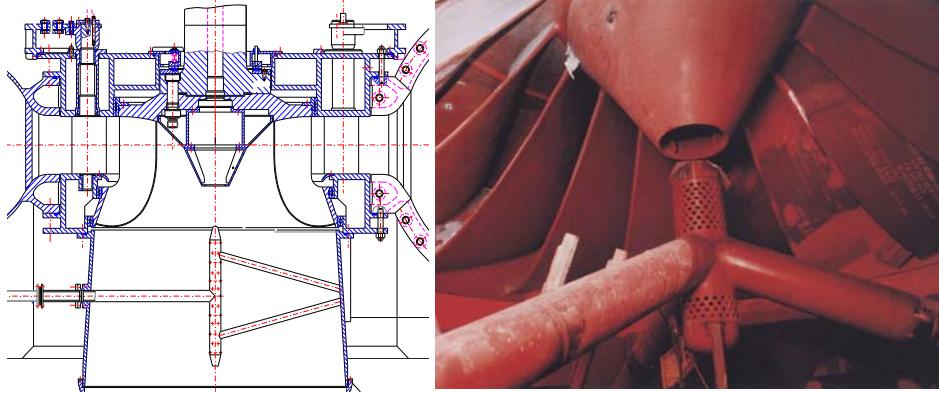


Fig. 1. Francis turbine cross section with air injection system (left) and a photograph of the air injection system displaced under the Francis runner (right).

### 3. Experimental investigations into the hydropower plant

The experimental investigations were performed in seven operating points displaced at constant nominal head. The investigated operating points correspond to: six points at partial load (marked with PL) and one overload point (denoted with OL), see Table 2,

Table 2

Operating points investigated

Label	relative discharge $Q_r$ (%)	relative unit power $P_{max,r}$ [%]	turbine efficiency $\eta_T$ [%]	operating points
PL6	28.8	16.7	67.72	part load
PL5	41.8	28.3	76.48	
PL4	53.1	39.3	79.20	
PL3	69.1	55.3	85.52	
PL2	80.7	69.0	89.49	
PL1	91.6	78.7	92.37	
OL1	109.1	95.0	92.49	overload

where the relative discharge  $Q_r$ , the relative unit power  $P_{max,r}$  and the turbine efficiency  $\eta_T$  are defined as following:

$$Q_r [\%] = \frac{(Q)_x}{(Q)_{BEP}} 100, \quad P_{max,r} [\%] = \frac{(P)_x}{(P)_{max}} 100 \quad \text{and} \quad \eta_T [\%] = \frac{M\omega}{\rho g Q H} 100. \quad (1)$$

The draft tube cone includes three parts with total height of  $h=3.5R_{2e}$  with respect to the reference radius at runner outlet and the semi angle of cone  $4^\circ$ . Six pressure taps were flush mounted on the wall of the draft tube cone in order to record the unsteady pressure for all operating range, see Figure 2. Three pressure

taps were mounted along to the element of the cone with the tap number 2 (denoted  $Pt2$ ) situated at 1.55 m ( $1.65R_{2e}$ ) downstream from runner outlet and the pressure tap number 6 ( $Pt6$ ) at 0.8 m ( $0.85R_{2e}$ ) with respect to  $Pt2$ , Figure 2. The pressure tap 4 ( $Pt4$ ) is located at the middle distance between  $Pt2$  and  $Pt6$ . The pressure taps  $Pt1$ ,  $Pt2$ ,  $Pt3$  and  $Pt5$  are located at the same level but shifted with  $90^\circ$ . Unfortunately,  $Pt1$  was failed during the preliminary experimental investigations. As a result, the unsteady pressure in five pressure taps was recorded for each operating regime. The mean value ( $P$ ) and fluctuant component ( $p'$ ) are yielded from unsteady pressure signal  $p$  recorded in situ:

$$p = P + p' \quad (2)$$



Fig. 2. The Francis turbine draft tube cone with air injection system (left) and the pressure taps installed on the cone (right).

The experimental investigations were performed without and with air injection (AI) in order to evaluate the dynamic behavior of the hydraulic turbine. Therefore, the pressure fluctuations ( $p'$ ) are analyzed based on Fourier spectra in order to identify the fundamental frequency and the associated amplitude.

Figure 3 presents the Fourier spectra at two part load operating points ( $PL2 = 0.81Q_{BEP}$  and  $PL3 = 0.69Q_{BEP}$ ). The Fourier spectra obtained for  $PL1$  ( $0.92Q_{BEP}$ ) are not included because are similar with  $PL2$ . One can observe a small influence of the air injection for  $Pt4$  and  $Pt5$  at  $PL2$ . Contrary, the air injection influence is significantly revealed at  $PL3$ . The fundamental harmonic (1<sup>st</sup> harmonic) corresponds to the vortex rope and associated frequency is around 20% from runner frequency. The maximum amplitude (0.8% from nominal head) is obtained at  $Pt4$  situated in the middle of the cone. The maximum amplitude decreases with more than three times if the air is injected. Moreover, one can clearly see that the spectrum is mitigated at this operating point if the air control method is applied. Particularly, the dynamic behavior is improved if this Francis turbine operates around  $PL3$  with air injection control method.

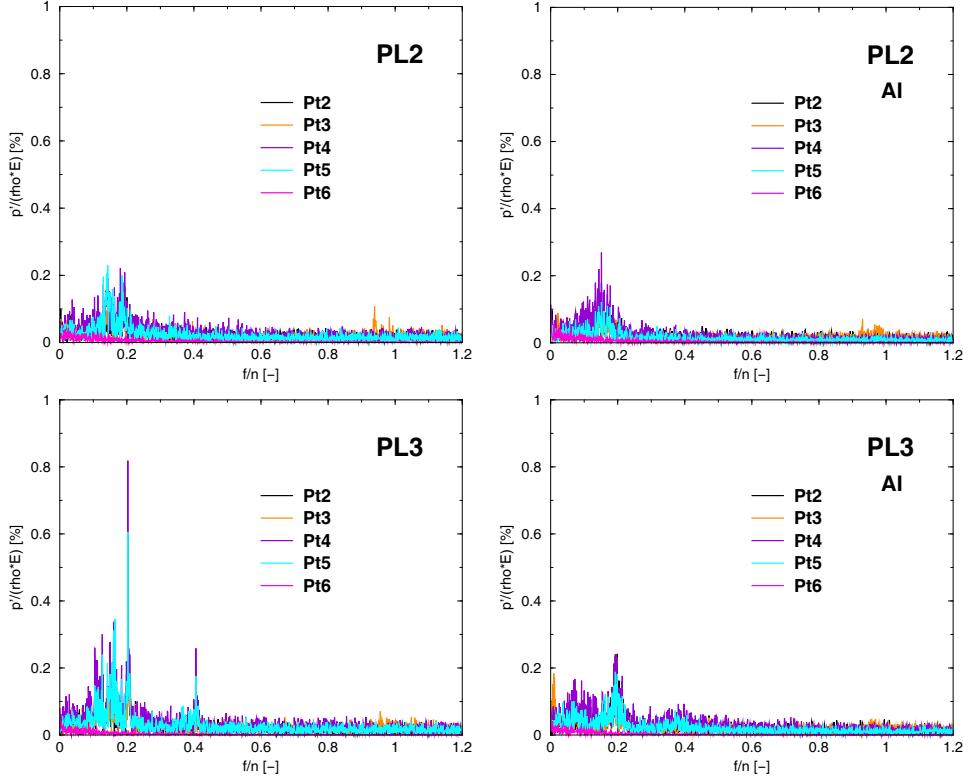
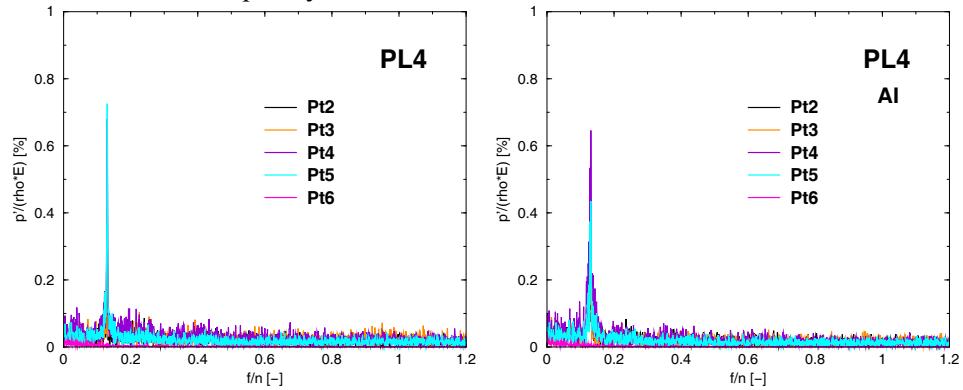


Fig. 3. Fourier spectra of the unsteady pressure signals recorded at part load conditions (PL1 – up, PL2 – middle, PL3 - down) on the Francis turbine cone: without (left) and with air injection (right)

Fig. 4 includes the Fourier spectra at three part load operating points (PL4 –  $0.53Q_{BEP}$ , PL5 –  $0.42Q_{BEP}$  and PL6 –  $0.29Q_{BEP}$ ). The maximum amplitude measured for these operating points corresponds to fundamental frequency of 13–15% from runner frequency at Pt5 located downstream to the runner.



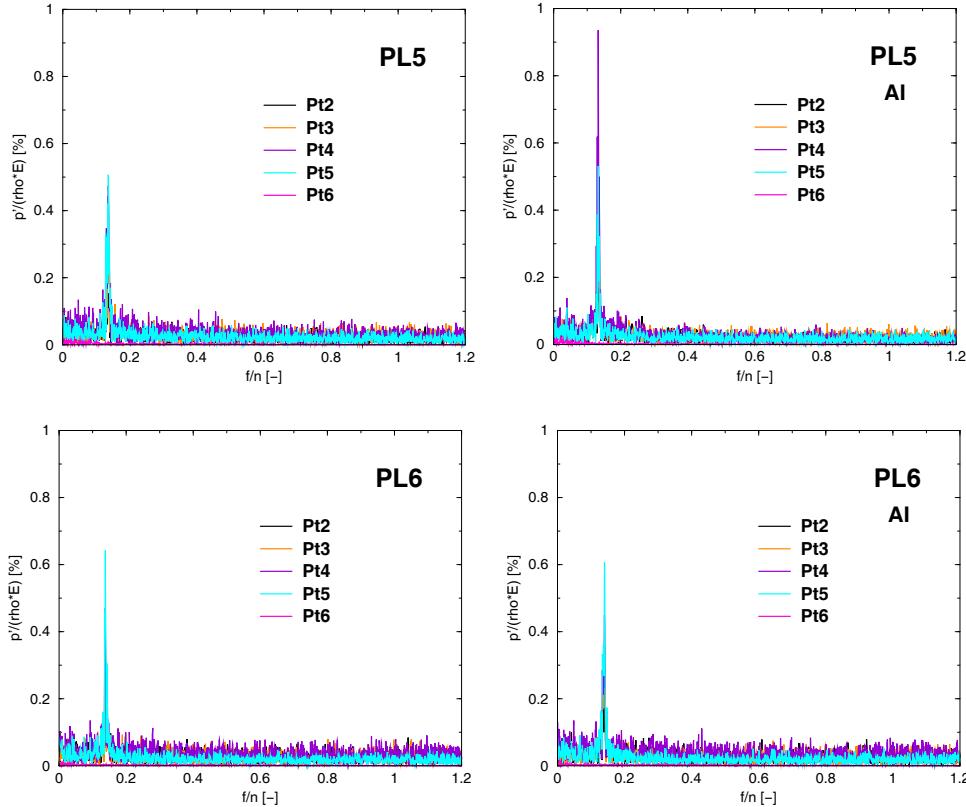


Fig. 4. Fourier spectra of the unsteady pressure signals measured at part load operating point (PL4 – up, PL5 – middle, PL6 – down) on the cone: without (left) and with air injection (right).

Notably, the maximum amplitude increases up to twice at PL5 if the air is injected while the fundamental frequency seems to be unchanged. The maximum amplitude with air injection is measured at *Pt4* situated in the middle of the cone, see Figure 2. The maximum amplitude at this operating point with air injection is even larger than the maximum value obtained at PL3 with no control method. This result can be associated with the shape modification of the air-water mixture region which it is developed in the cone center [10, Fig. 3]. The observation from PL5 is indistinguishably at PL6. Particularly, one can conclude that the dynamic behavior is seriously deteriorated if this Francis turbine operates around PL5 with air injection control method.

The evolution of the Fourier spectrum from one operating point to another is plotted in Figure 5 on pressure taps *Pt5* and *Pt4*. These spectra support the conclusions underlined above. It is reminded that the pressure taps *Pt2*, *Pt3* and *Pt5* are situated at the same level on the cone and the Fourier spectra are quite

identical. The Fourier spectra without and with air injection reveal negligible changes at  $Pt6$ . Therefore, these spectra are not included in the paper.

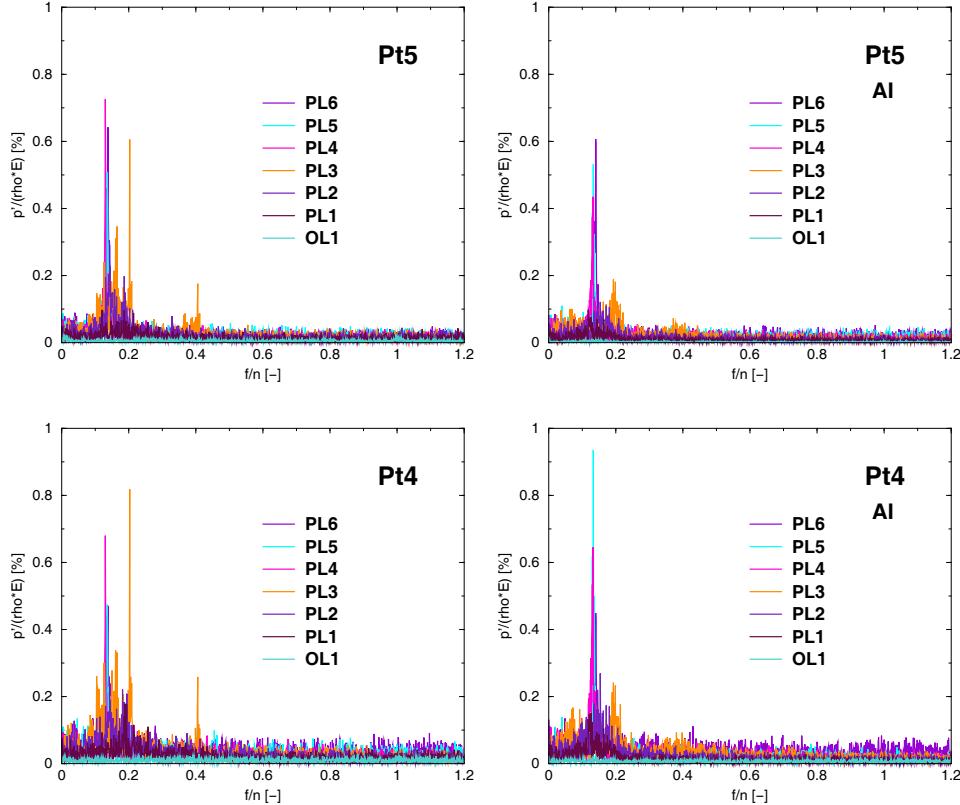


Fig. 5. Fourier spectra of the unsteady pressure recorded on the taps (Pt2 – up and Pt4 – down) located on the Francis turbine cone for all regimes: without (left) and with air injection (right).

#### 4. Conclusions

The paper presents our ongoing efforts in order to asses the control methods for flow instabilities at part load operation in Francis turbines. In situ experimental investigations are performed in order to evaluate the dynamic behaviour without and with air injection. The unsteady pressure was recorded in five taps mounted on the cone wall at seven operating point (from PL6 –  $0.29Q_{BEP}$  to OL1 –  $1.09Q_{BEP}$ ). Consequently, the fundamental harmonic corresponding to the flow instabilities (e.g. vortex rope) and associated frequency is around 15-20% from runner frequency. The following conclusion are underlined for this particular Francis turbine: (1) a small influence of the air injection is revealed for operating

with larger discharge than  $0.81Q_{BEP}$  (PL2); (2) the air injection significantly improves the dynamic behavior around operating point PL3 ( $0.69Q_{BEP}$ ); (3) the dynamic behavior is deteriorated if this turbine operates between  $0.53Q_{BEP}$  (PL4) and  $0.29Q_{BEP}$  (PL6) with air injection. Especially, the turbine operation around PL5 ( $0.42Q_{BEP}$ ) with air injection can lead to mechanical problems. Therefore, it is recommended to be investigated the air control method on each turbine in order to be identified dangerous operating regimes.

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