INFLUENCE OF THE AIR ADMISSION ON THE UNSTEADY PRESSURE FIELD IN A DECELERATED SWIRLING FLOW

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Operating Francis turbine at part load is hindered by the flow instabilities developed downstream the runner, in the draft tube cone. The unsteady pressure field induced by the flow instabilities leads to vibrations. The paper presents the experimental investigations of the unsteady pressure field generated by the so-called vortex rope and its associated pressure fluctuations on the test rig available at Politehnica University Timisoara. The experimental measurements are performed without and with air admission in order to assess the control method. The unsteady pressure is recorded on four levels displaced along to the test section. As a result, the Fourier spectra without and with air admission are obtained in order to assess the air influence on the vortex rope parameters.

Keywords: unsteady pressure field, vortex rope, draft tube cone, air admission, Francis turbine.

1. Introduction

New requirements in the energy market impose hydraulic turbines to operate more and more frequently in transient and unsteady regimes in order to regulate the electrical grid. However, hydraulic turbines (i.e. Francis turbine), are designed to operate at, or in the neighborhood of, the best efficiency regime. Far from such optimal regime, hydraulic turbine operation is hindered by unwanted flow instabilities, with associated low-frequency phenomena developed in swirling flows [1]. The self-induced instability developed downstream the runner at partial discharge in a decelerated swirling flow has been termed *vortex breakdown* (or vortex rope), in the fluid mechanics literature.

The vortex breakdown phenomenon is associated with severe pressure fluctuations. It can excite other parts of the hydraulic or structural systems leading to severe problems [2, 3]. Problems associated with draft tube surging include pressure fluctuations, noise, vibrations, fatigue failures [4], power swings [5], and excessive axial movement and run out of the turbine runner and shaft [6]. Conventionally, the characteristic length for hydraulic turbines is the runner

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diameter (marked with *D* in Fig. 1) according to the IEC standards [7]. The Francis runner prototype diameters are typically in the range from 2 m to 10 m while the associated Reynolds number ranges from 10^7 to 10^8, Anton [8].

The vortex rope mitigation is an open problem. Numerous techniques have been examined for reducing these effects, with success varying widely. Typical devices include fins attached to the draft tube cone wall [9], or concentric cylinders mounted in the draft tube cone [10]. Other control methods use water injection with or without an external energy source [11]. The air admission/injection is a common method used in the hydropower plant to mitigate the pressure pulsations associated to vortex rope. The air admission is used when the pressure level in the turbine is lower than atmospheric pressure. In this case, the air is sucked without any additional energy. Contrary, an external energy source is required in order to inject air when the pressure level in the turbine is higher than atmospheric one. Therefore, it is required to be known the pressure distribution in the draft tube and the amount of air required in order to be selected in the control method. It was proved that a large volume of air (larger than 4%) leads to significant drop in overall turbine efficiency [12]. Therefore, it is recommended a limited volume of air for stabilizing the flow in the cone. Extensive in situ investigations have been performed for Francis turbines (with medium specific speed [5, 13] and low specific speed [14]) in order to assess the unsteady behavior with air control method over a wide operating range. A significant rise in the pressure pulsation was measured on the cone wall of the draft tube at deep part load operation [13] using control method with air admission. Consequently, it is recommended based on this investigation that dangerous operating regimes with air control method can be identified on each turbine. Papillon et al. [15] present the results on a model test using different locations to aerate a Francis turbine in order to increase the concentration of dissolved oxygen in water flow through the turbine. The performances of each solution are discussed in term of the air admission capacity, the efficiency alteration with and without air admission and the quality of air-water mixing.

The measurements performed without aeration are shown that the cone with baffles decreases the efficiency up to 0.5%. As a result, the baffles enhance air admission into the runner cone increasing the hydraulic losses. However, in the vicinity of the best efficiency point (when flow in the draft tube cone is almost axial) even smallest amounts of air cause efficiency deterioration. It is already shown that a large amount of air decreases turbine efficiency [16]. Therefore, the main goal of this paper is focused on the influence of air admission on the pressure fluctuations associated to swirling flow.

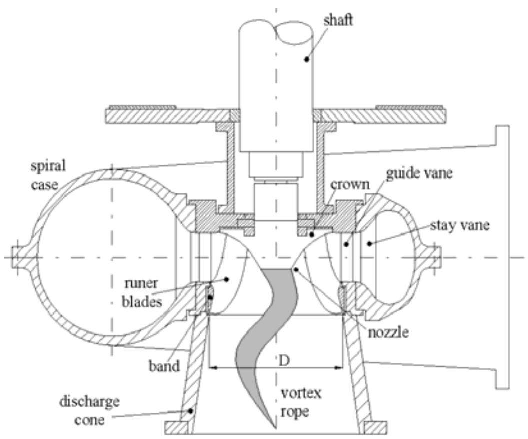

Fig. 1. Cross-section through a Francis hydraulic turbine.

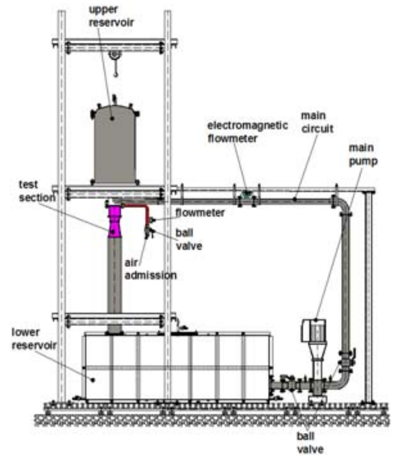

Fig. 2. Experimental test rig available at Politehnica University of Timisoara. Sketch of the test rig with the main elements.

The paper presents experimentally investigations on swirling flow with and without air admission in a draft tube in order to assess the dynamic performances. The second section presents the experimental test rig used in these investigations. The swirl generator provides a flow similar to the one encountered in hydraulic turbines operated at partial discharge. A well developed vortex rope is observed in the cone. The experimental setup for pressure measurements is also detailed in Section 2. An extensive analysis of unsteady pressure signals acquired on the conical diffuser wall is presented in Section 3. The paper conclusions are summarized in Section 4.

2. Experimental setup

2.1. Swirling flow apparatus and pressure measuring setup

The test rig with a closed loop circuit is used [17] (Fig. 2) to investigate the swirling flow with and without air admission. The decelerated swirling flow with a vortex rope is generated in the conical diffuser. The test rig developed includes the following main elements: (i) the main hydraulic circuit used to generate the decelerated swirling flow in the conical diffuser; (ii) the circuit for air admission. The main hydraulic circuit is employed to generate a flow similar to the one encountered at partial discharge operated Francis runner [18]. The air circuit is used for air admission in the conical diffuser's inlet through nozzle.

The swirling flow apparatus, Fig. 2, include two main parts: the swirl generator and the convergent-divergent test section. The swirl generator has an upstream annular section with stationary and rotating blades for generating a swirling flow. It has three components: the ogive, the guide vanes and the free runner, see the detail in Fig 3. The ogive with four leaned struts sustains the swirl generator and supplies the jet nozzle. The guide vanes and the free runner are installed in a cylindrical section with $D_s = 150 mm$. The nozzle outlet with $D_n = 30 mm$ is located close to the throat section with $D_t = 100\ mm$. The cone half-angle is 8.6 degrees, similar to the compact discharge cones used in the modern draft tubes for hydraulic turbines. However, in our case the ratio between the cone length ($L = 200 mm$) and the throat diameter ($D_t = 100 mm$) is quite large ($L/D_t = 2$) in order to capture the entire vortex rope in the conical diffuser. The Reynolds number of 3.8 x 10^5 corresponds to our investigation on the test rig, taking into account the main discharge of Q=30 l/s in the throat section with $D_t = 100\ mm$. The decelerated swirling flow in the cone develops a precessing vortex rope with the same Strouhal number as the one corresponding to the Francis turbine model [3].

The present paper is focused on the wall pressure measurements on the conical diffuser, using eight fast responding transducers located at four levels labeled L0, L1, L2 and L3, Fig. 2. The L0 level corresponds to the throat of the convergent-divergent test section. The next three levels are located downstream at 50, 100 and 150 mm with respect to the throat section. The pressure transducers with accuracy of ±0.13% within a full range of ±100 kPa are flush-mounted on the cone wall. At least 10 data sets have been acquired for each investigated flow regime in order to insure data reliability. Each set corresponds to an acquisition time interval of 16 seconds at a sampling rate of 256 samples per second. More than 20 samples per period were acquired to ensure a good resolution for the fundamental frequency of f ≈ 19 Hz associated to the vortex rope.

The results have been obtained at the discharge of Q=30 l/s. A flow meter with accuracy of ±0.15% on the full range of 50 l/s is installed on the test rig. The experimental investigations with air admission have been done. The measurements for cavitating vortex rope are compared against data without air admission in order to assess its influence.

2.2 Air admission system

The air admission system implemented on our test rig is sketched in Fig. 4. The air is sucked in decelerated swirling flow through the nozzle when the level of static pressure falls below atmospheric value. The air admission circuit includes a pipe and the inside passage of the swirl generator up to the nozzle. The pipe with the length of 600 mm and the diameter of 30 mm is considered for air circuit. A valve and a flow meter are installed on the air circuit. Figures 5 and 6 show the shape of vortex rope with and without air admission.

3. Pressure data analysis

3.1 Data analysis of pressure fluctuations

A qualitative model of the vortex rope flow field was given by Nishi et al. [19] who observed a quasi-stagnant (stalled) region with the spiral vortex core wrapped around it. This statement was validated with experimental data using the FLINDT turbine model operating at part load by Resiga et al. [20]. Dynamically, the unsteady pressure signal's Fourier spectrum has to be analyzed in order to understand the swirling flow configuration and to assess the air admission system. Figure 7 shows pressure fluctuations and Fourier transform in the case without air admission for all levels of test section. The fundamental frequency associated to the vortex rope is around 19 Hz. One can see in Fig. 4 that the amplitude associated to fundamental frequency decreases with more than 2 kPa from 2.7 kPa on 1st level to 0.4 kPa on 4th level. These differences in amplitude on each level (Fig. 8), corresponding to Qair/Q=0 are due to the vortex rope shape. Since the unsteady part of the pressure signal is periodic, we characterize it using the vortex rope precessing frequency and the equivalent amplitude computed using Parseval's theorem.

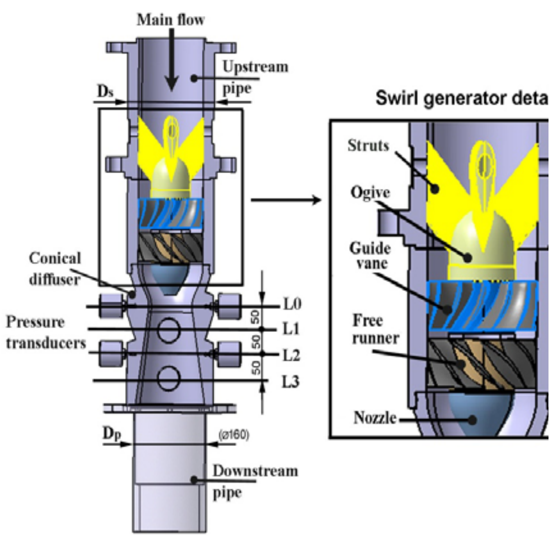

Fig. 3. Cross-section through the swirling flow apparatus and detail of the swirl generator.

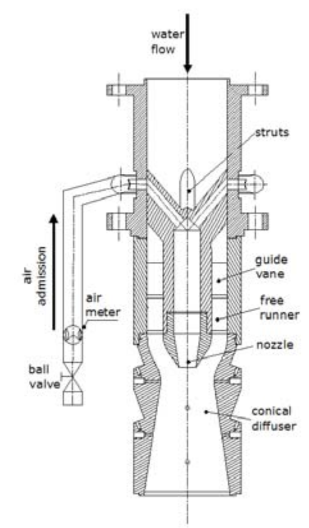

Fig. 4. Schematic representation of air admission system (AAS) on the test rig.

The dimensionless form of the vortex rope precessing frequency is expressed using the Strouhal number,

$$Sh = f\frac{D_t}{V_t}, \quad V_t = \frac{4(Q+Q_{air})}{\pi D_t^2} \tag{1}$$

and the pressure pulsation amplitude is defined as follow

$$A \equiv \frac{\sqrt{2}\, p_{\mathrm{RMS}}}{\rho V_t^2 / 2} \quad (2)$$

The equivalent pressure fluctuation amplitude is $\sqrt{2}\, p_{\mathrm{RMS}}$ according to Parseval's theorem, where it is the random mean square of the fluctuating part of the pressure signal.

Fig. 5. Photos of non-cavitating (left) and cavitating (right) vortex ropes, respectively on test rig.

Fig. 6. Photo of the cavitating vortex rope on test rig with air admission at tank pressures of 0.2 bar (left) and its schematic representation (right).

Figures 8 and 9 show both equivalent amplitude and Strouhal number of the pressure fluctuation measured on all levels of the conical diffuser using the air admission method. The results are presented in dimensionless form. The following reference values are considered in the analysis: (i) the throat diameter of the test section D_t=0.1 m, (ii) the throat velocity V_t, (iii) the overall throat discharge, which includes the main circuit discharge Q=30 l/s and the air admission discharge Qair (associated with a different air admission regime). The stagnant region associated to the vortex rope is gradually pushed downstream of the cone when the air admission is switched on. Consequently, the amplitudes decrease with 75% for all levels at the largest amount of air, while the

Strouhal number decreases with 88%.

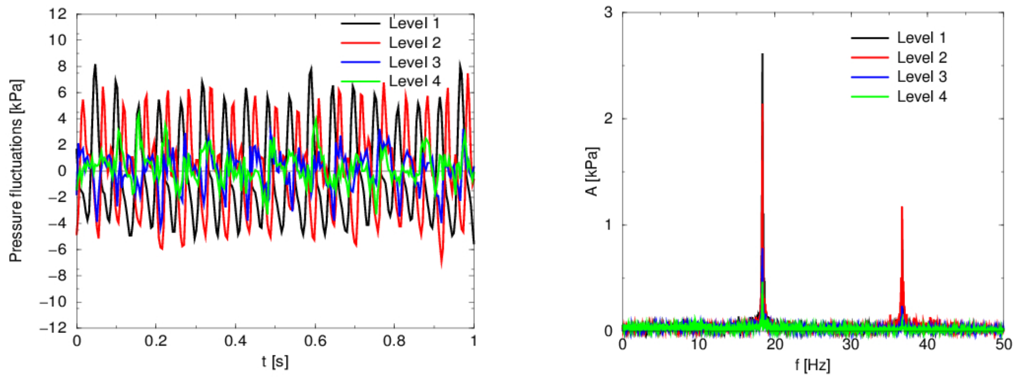

Fig. 7. Pressure fluctuations signals and Fourier spectra at all levels measured on the cone wall without air admission.

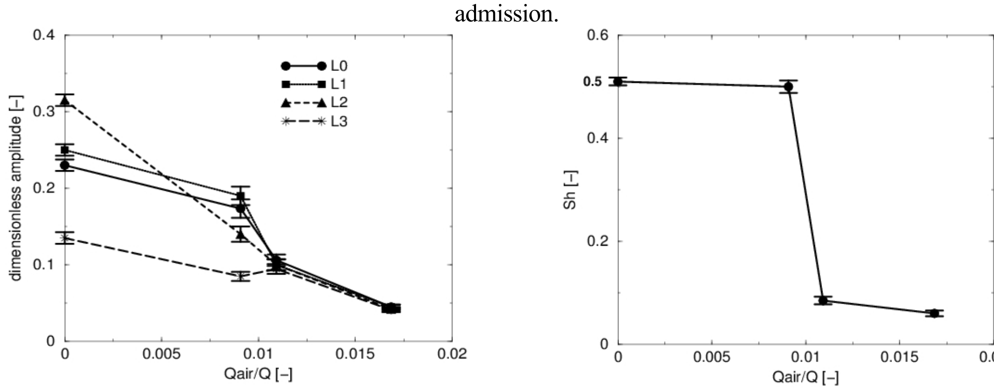

Fig. 8. Equivalent amplitudes (left) and Strouhal number (right) vs. Q_{air}/Q on all levels of the test section.

3.2 Signal decomposition

Two types of pressure fluctuations associated with the draft tube surge are identified in the literature Wahl [21]. The first one is the *asynchronous* (rotating labeled R) pressure fluctuation associated to the precession of the helical vortex. This component remains trapped in the cone [22]. The second type is a *synchronous* (plunging labeled P) pressure fluctuation which travels in all hydraulic system. This type of fluctuation is dangerous due to other parts of the hydraulic system can be excited by it. Several theories have been advanced to account for the presence of synchronous pressure fluctuations. Nishi et al. [19] have conducted experimental investigations which proved that the synchronous pulsation does not exist in a straight draft tube. As a result, he stated that the synchronous component resides in the elbow. The above idea is promoted by Fanelli [23] considering that the synchronous fluctuation corresponds to the interaction between the helical vortex and the draft tube elbow. The presence of a cavitated vortex core (i.e., a two-phase flow) has also been considered as a requirement for synchronous surging. Jacob and Prenat [24] use the phase analysis of two simultaneously acquired pressure signals from transducers mounted on the discharge cone of a Francis turbine to discriminate between rotating and plunging fluctuations, respectively. The equations (4) and (5) are used to yield the decomposed signals starting from two acquired signals provided by Eq. (3).

$$
\begin{aligned}
ST_1(t) &= A_1\,sin(\omega t) + A_2\,cos(\omega t) \\
ST_2(t) &= A_1\,sin(\omega t) + A_2\,cos(\omega t + \varphi)
\end{aligned}
\tag{3}
$$

$$P(t) = \frac{ST_1 + ST_2}{2} \tag{4}$$

$$R(t) = ST_1 - P \tag{5}$$

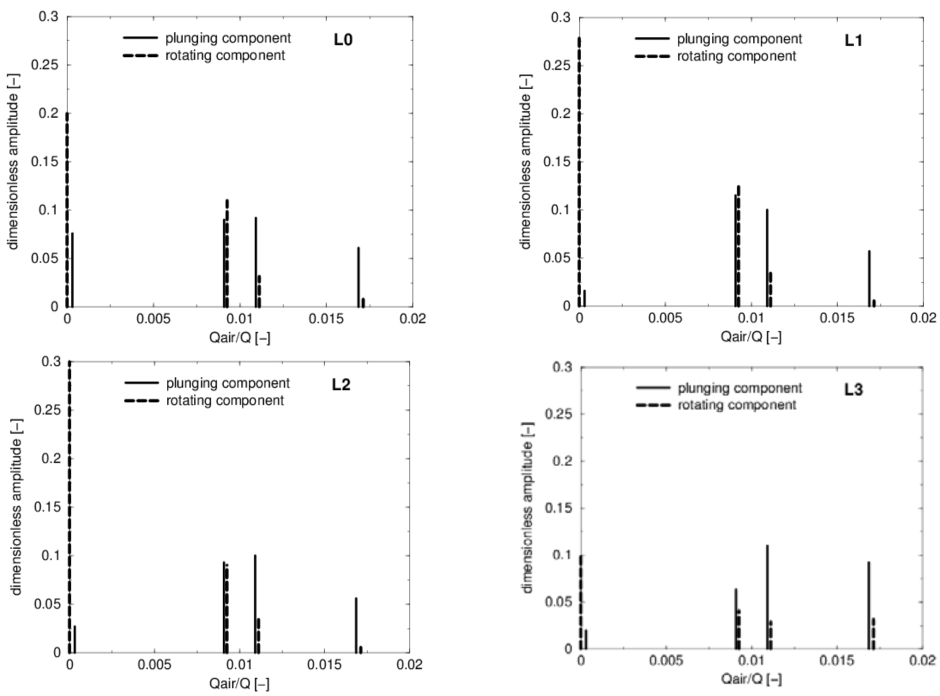

Fig. 10. Pressure pulsations types distributions versus air discharge.

It can be observed that the amplitude of the rotating component associated to the vortex rope is gradually diminished up to a ratio of Qair/Q=0.01. Further, a sudden drop on all levels is indentified around a threshold value of Qair/Q=0.01.

Practically, the rotating component associated to the vortex rope is diminished at the largest air amount of Qair/Q=0.017. As a result, the vortex rope effect is diminished due to the rotating component is negligible, Fig. 10. However, the unsteady pressure field reveals only plunging fluctuation with small amplitude. It is clear that the air admission practically changes the ability of the decelerated swirling flows to generate both rotating and plunging fluctuations. A similar behavior was obtained for axial water control method investigated by Bosioc et al. [17].

4. Conclusions

The paper presents experimental investigations with and without air admission on the unsteady pressure field in a decelerated swirling flow with vortex breakdown. The swirling flow corresponds to the flow configuration encountered in a Francis turbine operated at partial discharge. The unsteady pressure signals are acquired on four levels located along to the cone for three values of the air amount. Both rotating and plunging components are discriminated for each case.

The main conclusions can be summarized as follows: i) the air amount diminish the level of the pressure fluctuation quantified by the equivalent amplitude and Strouhal number; ii) the air amount mitigates the rotating component associated to the vortex rope but leaves a residual plunging (synchronous) fluctuation, with lower amplitude and frequency.

Acknowledgements

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS – UEFISCDI, PN-II-RU-TE-2014-4-0489 and partially supported by the strategic grant POSDRU/159/1.5/S/137070 (2014) of the Romanian Ministry of National Education, co-financed by the European Social Fund – Investing in People, within the Sectoral Operational Programme Human Resources Development 2007-2013.

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