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LDA MEASUREMENTS OF UNSTEADY VELOCITY FIELD FOR DECELERATED SWIRLING FLOWS WITH VORTEX ROPE IN A DISCHARGE CONE

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The discharge cone of hydraulic turbines remains the subject to numerous investigations since the flow unsteadiness developed at regimes far from the best efficiency point is responsible for large pressure pulsations or breakdowns of different components of the turbine. A special test rig was developed in laboratory in order to investigate the flow downstream the runner and to analyze different methods of control. The paper presents our experimental investigations of velocity field with LDA system. First is presented the setup in order to obtain this type of measurements and second is presented the mean and instantaneous flow field obtain from the measurements. The flow field obtain from measurements with phase average method will help us to understand the flow physics at the exit of the runner in the discharge cone. The main features obtained shown the flow non uniformity at the runner exit and the shape of the vortex rope in the discharge cone.

Keywords: vortex rope, discharge cone, experimental investigations, LDA measurements.

1. Introduction

The actual requirements from the energy market enforce that hydraulic turbine to operate far from the best efficiency point. When the hydraulic turbines operates at partial discharge or at overload discharge, downstream the runner (in the draft tube cone), the decelerated swirling flow becomes highly unstable. In these conditions is developed a spiral vortex breakdown, also known in engineering literature as the precessing vortex rope. The flow unsteadiness produced by the vortex rope results in severe pressure fluctuations that hinder the turbine operation or may cause accidents [1].

In order to mitigate the pressure fluctuations and control the flow instabilities in draft tube cones of Francis runners different methods are introduced such as: stabilizer fins, co-axial cylinders or special aerators [2]. All these methods produce other instabilities in draft tubes cones, not eliminate the effect and drop the efficiency. Our solution with water injection along the axis of

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the discharge cone was intensively tested in Bosioc et al. [3] and Tanasa et al. [4]. The experimental results showed clearly that water injection method diminish the pressure pulsations while the stagnant region is eliminated.

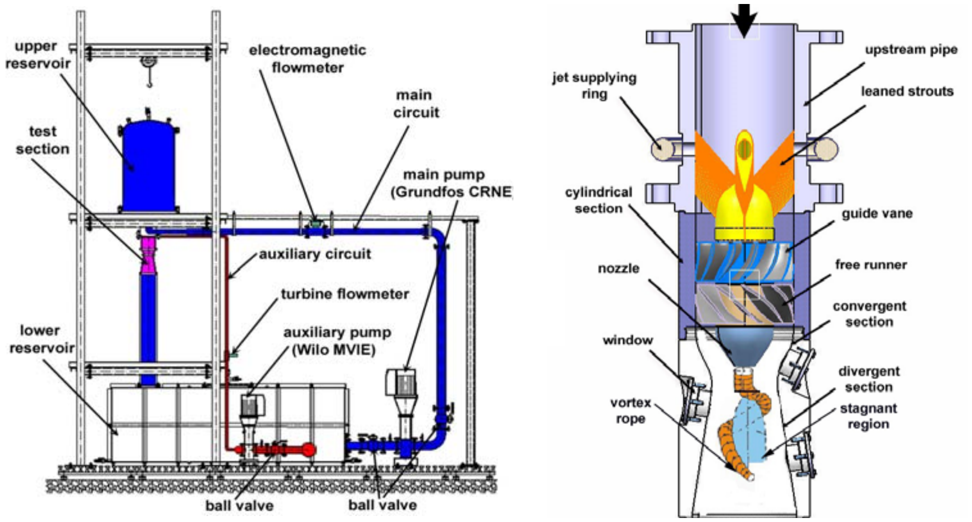

Fig. 1. Experimental test rig for investigation of the decelerated swirling flow (left) and sketch of the swirl apparatus with formation of stagnant region and vortex rope (right)

The paper presents our experimental investigations of mean and unsteady velocity fields in a discharge cone for decelerated swirling flow with vortex rope. The experimental test rig and the swirl apparatus in order to generate the swirling flow in the discharge cone are shown in section 2. Section 3 presents the LDA setup necessary for this type of experimental investigations. The mean and unsteady velocity fields for swirling flow with vortex are presented in the section 4. The conclusions are drawn in last section.

2. Experimental test rig for swirling flows

The experimental test rig developed in our laboratory serves to investigate the decelerated swirling flow with vortex rope from the draft tube cone and also helps to analyze different methods in order to eliminate the vortex rope instabilities [3], [4]. In order to generate a decelerated swirling flow different types of swirl generators are used [5], [6].

The main part of our test rig is the swirl apparatus with two components: the swirl generator and the test section, Fig. 1 (right). The swirl generator is mounted in cylindrical part of the test section, with an interior diameter of 150 mm having three components: the ogive, the guide vane and the free runner. The ogive with four leaned struts helps to sustain the swirl generator and supply with water the jet nozzle. The stationary and rotating components of the swirl generator (guide vane and free runner) generates at inlet in the conical diffuser a configuration of the flow quite similar with the corresponding flow downstream the Francis runner operated at partial discharge [7], [8]. Note that during the experimental investigations the speed of the free runner was 925 rpm. The swirl generator ends with a nozzle with 30 mm located close to the throat section with a diameter of 100 mm [3]. The test section has a cylindrical part where is mounted the swirl generator and a convergent-divergent part. The divergent part of the test section is similar with a straight discharge cone of a Francis turbine, having a similar angle (8.6°). The swirl apparatus generates a vortex rope with Strouhal number equal to 0.39 quite close to the number determined on the Francis turbine model (Sh =0.408), [8]. Reynolds number equal to 3.7×10^5 corresponds to the flow in our test rig. This value is computed with throat diameter and nominal discharge of 30 l/s. The cavitating vortex rope developed in the test section is presented in Fig. 2 (left).

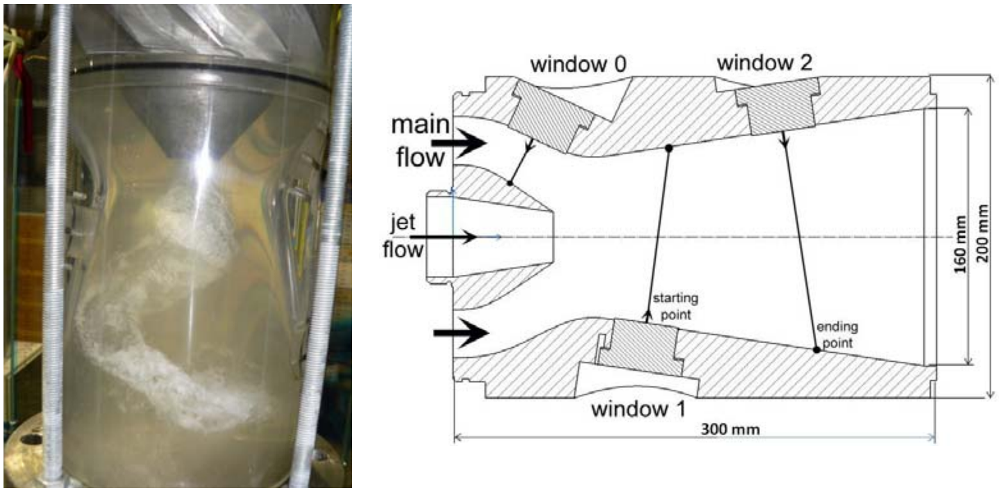

Fig. 2. Visualisation of the cavitating vortex rope developed in discharge cone of the test section (left) and sketch of the test section with windows and survey axis (right)

3. LDA experimental setup

In order to perform velocity measurements, was design a convergent – divergent test section. The design of the test section for LDA investigations takes into account that the flow inside should not be influenced by the measuring windows. To check the velocity profile at the entrance of the test section, one of the surveys axis was installed in the convergent area, where we have the flow given by the free runner only and is not influenced by the swirling flow with vortex rope or water injection. We called the survey axis from convergent part survey axis W0. Similar with survey axis W0 we called next: survey axis W1 and survey axis W2. Survey axis W1 and W2 was mounted at 113 and 168 mm respectively from the inlet of the test section in divergent part. On these axes is possible to check the flow which is influenced by the vortex rope. On each survey axis was mounted an optical window. A sketch of the test section with the measurement windows is presented in Fig. 2 (right).

All laser measurements have the starting measuring point on the wall of the measuring windows and continues on survey axis until is reaching on the wall of the test section. For the measurements was set an acquisition time by 30 seconds with maximum 50000 acquired particles. According with our phenomenon we have a main frequency around 15 Hz, while the frequency of acquisition is at least 100 times larger, which will provide a good accuracy of measurements.

From the velocity measurements were calculated for the first time the mean velocity profiles. The mean velocity $\overline{u_i}$ was computed for each point with the equation:

$$\overline{u_i} = \sum_{i=0}^{N-1} \frac{1}{N} \cdot u_i \tag{1}$$

The measured and the analyzed data will be presented in dimensionless terms using the following reference values:

- the minimum radius from the convergent-divergent test section, in our case 0.05 m.
- the mean velocity from the throat is computed with equation, in our case 3.81 m/sec

For analysis of unsteady velocity field from the convergent-divergent test section with phase average method we start from the measured components of the velocity [9]:

$$u_i = \overline{u} + \hat{u} + u'_i \tag{2}$$

Where u_i represent the instantaneous velocity measured with LDA which can be divided in three components $\overline{u}$ (mean velocity of the signal), $\hat{u}$ (time varying periodic part) and u'_i (turbulent fluctuation). From equation (2) the phase average velocity is defines as:

$$\overset{\frown}{u} = \overline{u} + \hat{u} \tag{3}$$

The measurements where performed in phase with a reference signal, in our case the signal generated by the free runner blades (for W0) or by the pressure signal (for W1 and W2) collected from the wall inlet in the discharge cone. Having the velocity signal and a reference signal, were constructed the bins or phase intervals of velocity signal. The LDA program allows indicating the number of bins and width of each bin [10]. In order to have an analysis of phase average velocity depending by width of the bins, we initially tested 1°, 2° and 3° bin width with 360, 180 and 120 bins respectively for whole circumference. We have reach at conclusion that decreasing the bin width and increasing the bins, the variation of phase average velocity is large having also higher fluctuations of RMS. In our case we used 180 angle bins with a width of 2°.

4. Experimental results

A first step consisted by measurements of the averaged velocity profiles. We will focus on analysis of velocity profiles in convergent, Fig. 3 and divergent part of the test section, Fig. 4. With black we have represented the meridian velocity and with red the circumferential velocity, while the variation of root mean square value is added as a bar.

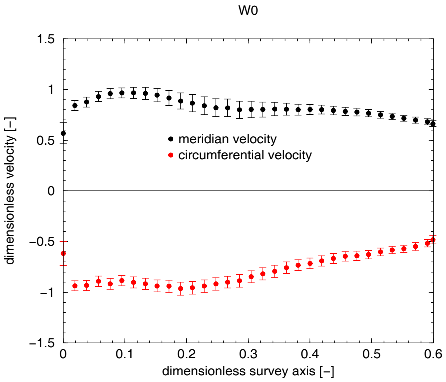

Fig. 3. Meridian and circumferential averaged velocity profiles for W0

From the first analysis of meridian velocity profile in convergent part, Fig. 3 is observed that close to the wall of the test section (for dimensionless representation of survey axis represents the abscissa equal with 0) is an excess of velocity and close to the wall of the nozzle is a velocity deficit. The velocity configuration corresponds for a hydraulic turbine operated at partial discharge. The next graphs presented in Fig. 4 will describe the evolution of averaged velocities for swirling flow with vortex rope on survey axis W1 and W2 from the divergent part of the test section. The meridian velocity component has a velocity deficit in the middle of both survey axes.

The spiral vortex rope is formed between the main flow area which is close to the draft tube cone walls and the staled area which is formed in the middle of draft tube cone according to Nishi et al. [11]. From this theory results that from mean velocity profiles we have a helical vortex rope which is developed in all length of the conical diffuser. Next the paper will present the analysis of unsteady velocity field with phase average method in order to observe more clearly the velocity field from the discharge cone.

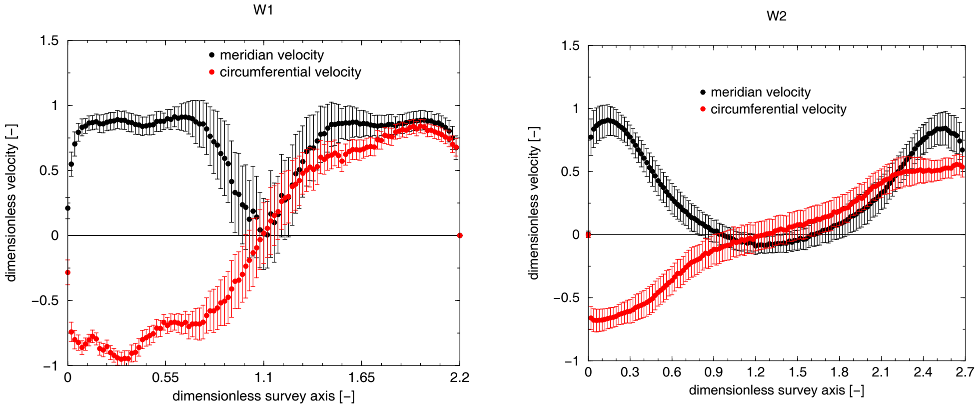

Fig. 4. Meridian and circumferential averaged velocity profiles for W1 and W2 in the case of swirling flow with vortex rope.

First results of instantaneous velocity field correspond to survey axis W0. In this case the flow is influenced only by the swirl generator (speed of the runner). In Fig. 5, is observed clearly the influence of the free runner in both velocity fields (meridian and circumferential velocity field). In the case of meridian velocity, is observed the weak from the blades of the runner. For circumferential velocity the influence of the blades of the free runner is smaller, but nevertheless the excess of velocity is observed close to periphery while close to the hub the velocity has a uniform variation.

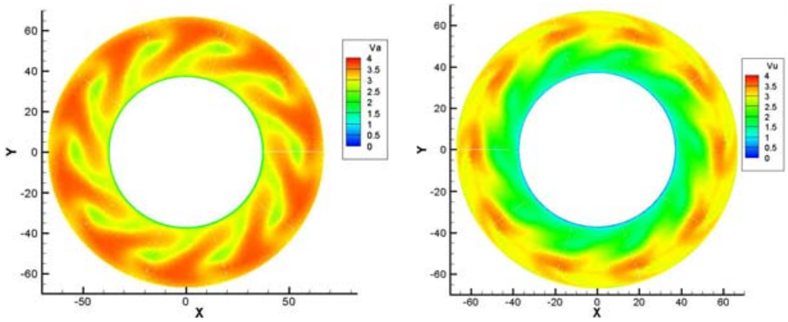

Fig. 5. Phase-resolved meridian (left) and circumferential (right) velocity for survey axis W0.

The next analysis consists in evaluation of velocity field with phase average method for survey axis W1 and W2. For these two survey axes the reconstruction field starts to the wall of the measuring window and continues until the survey axis meets the symmetry axis of the test section.

For swirling flow with vortex rope as is presented in Fig. 6, in instantaneous meridian velocity field on survey axis W1 is observed the deficit of velocity close to the axis and an eccentrically stagnant region. Anyway at the inlet in discharge cone (survey axis W1), the flow has no uniformities.

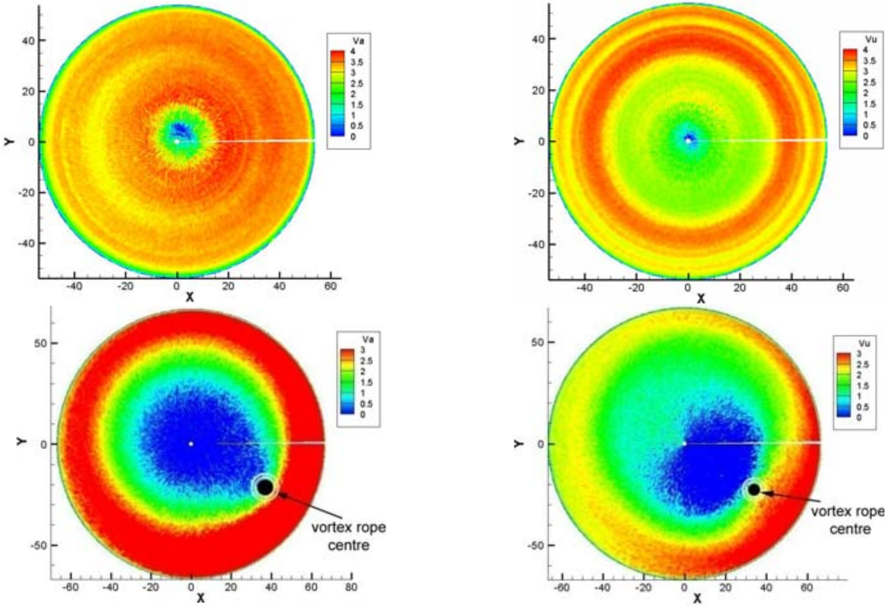

Fig. 6. Phase-resolved meridian (left) and circumferential (right) velocity for survey axis W1 (up) and W2 (down) for swirling flow with vortex rope case.

At the exit from the conical diffuser, corresponding to survey axis W2, the influence of the vortex rope in the flow is observed very well. In the case of meridian velocity is observed clearly the stagnant region which is formed in the middle of the cone and the shape of the vortex rope which rotates around the stagnant region. The influence of the vortex rope is observed also in circumferential velocity profile, where the stagnant region is displaced from the centre. According with Johnson et al. [12] the centre of the vortex rope is found by analysing the high and low velocity regions. In our case the centre of the vortex rope in both velocity components (meridian and circumferential velocities) was found.

5. Conclusions

The aim of the paper was to investigate experimentally the velocity field in a discharge cone for swirling flow with vortex rope. The velocity measurements were performed with a LDA system with two velocity components. Firstly, it was analyzed the mean velocity profiles. The mean velocity profiles help us to observe the main velocity distribution in the discharge cone. Secondly, the instantaneous velocity field using phase average method is obtained. The unsteady velocity field obtained with phase average method helps us to be yielded the velocity distribution with the development of flow unsteadiness. The mean and unsteady velocity results allow us to be characterized the flow field leading to the identification the vortex rope location and extension of the stagnant region. The results will be used to validate mathematical models used in early design stage.

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