Influence of the elbow shape on the unsteady pressure field in decelerated swirling flows

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Abstract. The induced flow instabilities are developed in the draft tube cone of the hydraulic turbines leading to the pressure fluctuations with negative impact on the mechanical components lifetime. Usually, two components (rotating and plunging) are discriminated in the unsteady pressure field induced by the swirling flow in the draft tube cone. The rotating component is associated with the precession motion of the flow instabilities (e.g. vortex rope) while the plunging part corresponds to the interaction of the swirling flow with the elbow. Extensive experimental investigations were carried out on Timisoara Swirl Generator test case in order to examine the influence of the elbow shape on the unsteady pressure field. Two elbow shapes (90° S shape elbow and 90° sharp heel) are selected to investigate their influence on the unsteady pressure field. Several geometrical configurations with pipe extensions placed between the cone and the elbow are considered for each elbow shape to determine the response of the hydraulic circuit. Two unsteady pressure signals located in opposite positions are measured on four levels placed along the cone. The Fourier spectra are determined for discriminated time series identifying both rotating and plunging components. Then, the ratio between the frequencies of the plunging and the rotating components is obtained for both elbow shapes in relation to the pipe length placed between the cone and the elbow. It is clear that the shape of the elbow and the distance between the cone and the elbow lead to a significant influence on the response of the hydraulic circuit.

1. Introduction

The large pressure fluctuations corresponding to the unsteady flow phenomena developed in the draft tube cone of the hydraulic turbines are extensively investigated during last decade [1-3]. These phenomena are known in literature as the draft tube surge [4]. The occurrence of the draft tube surge phenomena seriously limits the turbines’ operation range while the lifetime of the mechanical components is significantly diminished [5-8]. Therefore, several technical solutions were explored but only a few of them were implemented in the hydropower plants [9]. Finding solutions that meet both technical and economic constraints for each hydropower plant is an active area of research.

Both fundamental frequency and its amplitude associated with the draft tube surge phenomena are usually determined. However, several parameters are influencing the draft tube surge phenomena (e.g. operating point parameters, cavitating conditions and the geometrical configuration) [10-13]. As a result, our ongoing effort is focused on a systematic analysis of the draft tube surge phenomena induced by the geometrical shape of the draft tube elbow. In our case, two parts (the cone and the

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elbow) of the draft tube are considered neglecting the diffuser. Since, this last part of the draft tube known as diffuser is not significantly affecting the unsteady pressure field.

An extensive program study was started few years ago by our group to investigate the influence of the elbow geometry on the surge phenomena developed in swirling flows. Several geometrical configurations of the elbow are investigated in relation to the case without any elbow to indentify its contribution in the power spectra [14-16]. As a result, the synchronous component associated with the interaction of the swirling flow with the elbow is identified by Nishi et al. [17]. The in-depth flow analysis performed by Pasche et al. [18, 19] supports Nishi’s theory that the origin of the physical mechanism responsible for the generation of the synchronous pressure by the helical vortex rope at the part load conditions in Francis turbine draft tubes is a fluid–solid interaction problem.

The investigations included in this paper are focused on the comparison between two geometrical configurations of the elbows on the unsteady pressure field. Therefore, both frequency and amplitude changes of the synchronous/plunging component are correlated with the elbow geometry. The experimental investigations performed on the swirling test rig available at University Politehnica Timisoara are reported [20-22]. The experimental setup and two geometrical configurations of the elbow (90° S shape denoted SE90 and 90° sharp heel labelled HE90) are investigated. The HE90 corresponds to the old draft tubes (designed from 1910 to 1940) available in hydropower plants [23-25]. The S shape elbow corresponds to a particular case. Next, the unsteady pressure signals on the cone are acquired considering both elbows. Both rotating/asynchronous and plunging/synchronous components are discriminated indentifying the frequencies in the Fourier spectra for each case.

Next, several geometrical configurations with pipe extensions of 0, 100 mm, 200 mm and 300 mm placed between the cone and the elbow are considered for each elbow shape. This investigation is inspired by the hydropower plants equipped with two or more different power units. In these hydropower plants, all turbines are located at the same level while several technical solutions are adopted for the draft tubes in order to have the same suction head. In some cases, the angle of the draft tube cone is modified while in other situations, the cone angle is kept the same and a pipe extension is placed between the cone and the elbow [26]. Our investigation targets the cases corresponding to the second case. The parameters associated with the surge phenomena are quantified considering different geometrical configurations of the pipe extensions. The results obtained for all cases are comparatively presented.

The paper is structured as follows: the test rig, the experimental setup and the geometrical configurations for two elbows are presented in section 2; the experimental data are given in section 3; the analysis of the experimental data is performed in section 4; the conclusions are drawn in the last section based on these investigations.

2. Test rig and experimental setup
A test rig available at University Politehnica Timisoara to investigate several swirling flow configurations is considered in our investigations. The test rig includes the following: (i) the main hydraulic circuit to generate the swirling flow in the test section is marked with blue colour in Fig. 1; (ii) a lower reservoir with a volume of 4 m³ is considered; (iii) a pump able to provide a maximum flow rate of 40 l/s is installed on main hydraulic circuit and (v) an upper reservoir equipped with a honeycomb section is employed to provide an uniform flow at the inlet of the test section.

The most important part of the rig is the test section given in Fig. 2. The test section includes the swirl apparatus with four leaned struts, two rows of blades (13 fixed guide vanes and 10 runner blades, respectively), a nozzle and the convergent-divergent section [20]. The purpose of the runner is to balance the total pressure by inducing an excess in the axial velocity near the shroud and a corresponding deficit near the hub, like a Francis turbine operating at partial discharge [21]. The runner thus acts as a turbine near the hub and as a pump near the shroud [22]. Figure 2 shows the swirl generator with the hub and shroud diameters of $D_{\text{hub}}=0.09$ m and $D_{\text{shroud}}=0.15$ m, respectively. The test section is manufactured from Plexiglas in order to allow flow visualization. The throat diameter is 100 mm while the conical diffuser has 8.5° half-angle and 200 mm in length. The unsteady pressure is measured on the cone wall at four levels using two pressure transducers installed on each level positioned at 180° each other. The first level corresponds to the throat (MG0) and the next levels are
displaced downstream at 50 mm (MG1), 100 mm (MG2) and 150 mm (MG3). The test rig is equipped with an acquisition system in order to record the discharge value and the runaway speed of the runner. The investigations included in this paper are performed considering a discharge value of 30 l/s. The flow configuration delivered by the swirl apparatus is directly correlated with the discharge value due to the runner spins freely at the runaway speed. One single vortex rope is developed in all cases. The experimental investigations are carried out with the test rig filled fully with water and the static pressure high enough to examine one single phase vortex rope [27].

A 90° S shape elbow (SE90) is installed downstream to the diffuser as in Fig. 3 in order to discriminate its contribution. Next, a 90° sharp heel elbow (HE90) is mounted instead of the 90° S shape elbow (SE90) to determine the influence of the elbow geometry on the unsteady pressure field. Several pipes with different lengths are installed between the diffuser and the elbows. In this way, the impedance of the hydraulic circuit is changed investigating its response to the flow self-excitation. In this paper, our experimental investigations are presented in order to identify the influence of the elbow geometry on the unsteady pressure field induced by the swirling flows encountered in the hydraulic turbines at the partial load conditions.
Figure 3. Photos of the test section with two geometrical configurations: 90° S shape elbow without any pipe extension (SE90E0) (left); 90° sharp heel elbow without any pipe extension (HE90E0) (center) and together with pipe length extension of 0.2 m (HE90E02) (right)

3. Experimental data processing

The unsteady pressure is measured using eight transducers mounted on four levels of the conical diffuser’s wall. Each set corresponds to an acquisition time interval of 32 seconds at a sampling rate of 256 samples/second. The unsteady pressure signals acquired on each level are processed discriminating both plunging and rotating components on the Fourier spectra using the methodology developed by Bosioc et al. [28]. The experimental data for 90° S shape elbow cases (SE90) are processed and discriminated in §3.1 while in §3.2 for 90° sharp heel elbow cases (HE90).

3.1. 90° S shape geometry of the elbow (SE90)

Figure 4. Fourier spectra with discriminated components (plunging and rotating) corresponding to the unsteady pressure levels from MG0 to MG3 levels associated with the geometrical configuration with 90° heel elbow (HE90E0)
The influence of the 90° S shape elbow on the response of the hydraulic circuit is determined. The Fourier spectra with discriminated signals for the geometrical configuration with 90° S shape elbow installed downstream to the conical diffuser (labelled SE90E0 in Fig. 2) are presented in Fig. 4. The fundamental frequency (fr) and its second harmonic (2xfr) associated with the rotating component are distinguished. This rotating component is not so dangerous due to it is trapped in the conical section [29]. However, the plunging component with low frequency around 6 Hz is identified in the geometrical configuration with 90° S shape elbow at all levels. As a result, this plunging frequency corresponds to the response of the hydraulic circuit with 90° S shape elbow.

Figure 5. Fourier spectra with discriminated signals associated with the unsteady pressure levels from MG0 to MG3 for geometrical configurations investigated with S shape elbow (SE90E0) and together with three pipe length extensions of 0.1 m (SE90E01), 0.2 m (SE90E02) and 0.3 m (SE90E03).

The response of the hydraulic circuit with the 90° S shape elbow (SE90) is investigated modifying its impedance. The impedance of the hydraulic circuit is changed installing pipe extensions of different lengths (0.1 m – SE90E01, 0.2 m - SE90E02 and 0.3 m - SE90E03) between the conical diffuser and 90° S shape elbow, Fig. 2. The Fourier spectra with discriminated components (plunging and rotating) on all levels for cases with 90° S shape elbow are plotted in Fig. 5. One can observe that all frequencies indentified in the spectra for SE90E0 case are recovered for all cases with pipe extension. The largest amplitude of the rotating component associated with the vortex rope precession is determined on MG1 level for all cases (from SE90E0 to SE90E03). The amplitude of the rotating component rises up with the increase of the length of the pipe extension between the cone and elbow. The exception is the last case SE90E03 in which the amplitude corresponding to the rotating...
The amplitude of the plunging component decreases slightly compared to the case SE90E02. The amplitude of the plunging component increases monotonically three times as the length of the pipe extension increases three times. The amplitude of the plunging component reaches 0.4 kPa at the pipe extension of 300 mm.

3.2. 90° sharp heel elbow geometry (HE90)

The hydraulic circuit response is examined mounting the 90° sharp heel elbow downstream to the conical diffuser (labelled HE90E0 in Fig. 2). The Fourier spectra with discriminated signals for the 90° sharp heel elbow geometry installed downstream to the conical diffuser (labelled HE90E0 in Fig. 2) are presented in Fig. 6. The rotating component frequency around 17 Hz associated with the self induced instability is distinguished. The plunging component with the frequency around 8.4 Hz is identified in the HE90E0 case at all levels. Conclusively, this plunging frequency corresponds to the response of the hydraulic circuit with 90° sharp heel elbow.

![Figure 6. Fourier spectra with discriminated components (plunging and rotating) corresponding to the unsteady pressure levels from MG0 to MG3 levels associated with the geometrical configuration with 90° heel elbow (HE90E0)](image)

The response of the hydraulic circuit with the 90° sharp heel elbow (HE90) is determined by changing its impedance by installing three pipe extensions of different lengths (0.1 m – HE90E01, 0.2 m - HE90E02 and 0.3 m - HE90E03) between the conical diffuser and 90° sharp heel elbow. The Fourier spectra with both plunging and rotating components corresponding to all four levels for all cases with 90° sharp heel elbow (HE90) are given in Fig. 7. The amplitudes corresponding to both rotating and plunging components grow monotonically up with the increase of the length of the pipe extension installed between the cone and the elbow. The largest amplitude of the rotating component associated with the vortex rope precession is determined on MG1 level for all cases with HE90. The largest amplitude around 2.5 kPa of the rotating component is measured on the cone wall at MG1 level for HE90E03 case. The amplitude of the plunging component rises up over four times for the HE90E03 case in relation to the HE90E0 case, respectively. The largest amplitude of 1 kPa corresponding to the
plunging component is determined for HE90E03 case. This observation suggests that a compact geometrical configuration should be selected for the hydraulic turbines in order to diminish the amplitude associated with the plunging component.

Figure 7. Fourier spectra with discriminated signals associated with the unsteady pressure levels from MG0 to MG3 for geometrical configurations investigated with 90° sharp heel elbow (HE90E0) and together with three pipe length extensions of 0.1 m (HE90E01), 0.2 m (HE90E02) and 0.3 m (HE90E03).

4. Experimental data analysis
The unsteady pressure signal’s Fourier spectra have to be analyzed in order to assess the influence of the elbow geometry type on the response of the hydraulic circuit. The ratio between the plunging (fp) and rotating (fr) frequencies collected on each Fourier spectrum is considered in this section to compare the data for all investigated cases, Fig. 8. One can observe in Fig. 8, that a constant value of 0.355 is fitted on all SE90 cases. This means that the frequency ratio (fp/fr) remains unchanged when the hydraulic circuit impedance is modified. Definitively, the frequency response of the hydraulic circuit remains unchanged for SE90 elbow. However, the amplitude of the plunging component increases monotonically three times as the length of the pipe extension increases three times.

On the contrary, the frequency ratio (fp/fr) is significantly influenced by the modification of the hydraulic circuit impedance with the HE90 cases. The frequency ratio (fp/fr) changes from 0.48 to 0.4 if the dimensionless length (L/D) between the cone and the elbow varies from 0 to 1.3. The frequency of the plunging component is modified in these cases while the frequency of the rotating component remains practically unchanged. The frequency response of the hydraulic circuit changes with 20% if a
strong interaction between the decelerated swirling flow and the 90° sharp heel elbow geometry (denoted HE90E0) is selected. The frequency ratio value of 0.4 is unchanged if the dimensionless length (L/D) is selected beyond the value of 1.3. Another additional case called HE90E05 was taken into account to check the plateau value of 0.4. The equation of the frequency ratio \( fp/fr = 0.48 - 0.081 \cdot \text{erf}(1.3 \cdot L/D) \) fits quite well the experimental data. The Gauss error function \( \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_{-x}^{x} e^{-t^2} dt \) is used in the above equation.

Figure 8. Comparison between the responses of the hydraulic circuit obtained for all cases with two elbows: 90° sharp heel elbow (HE90) and 90° S shape elbow (SE90). The frequency ratio (fp/fr) versus the dimensionless length (L/D).

Conclusively, the response provided by the hydraulic circuit with 90° sharp heel elbow (HE90) is significantly different than the one delivered by the hydraulic circuit with 90° S shape elbow (SE90). Additionally, the amplitude of the plunging component is 2.5 times larger for the HE90 elbow than SE90 elbow.

5. Conclusions
The response of the hydraulic circuit to the swirling flow excitation is investigated when its impedance is modified. The hydraulic circuit impedance is changed using two elbows (90° S shape elbow (SE90) and 90° sharp heel elbow (HE90)). Also, the hydraulic circuit impedance is modified using several pipe extensions with different lengths (100 mm, 200 mm, 300 mm and 480 mm) installed between the cone and two types of elbows (SE90 and HE90). The eight unsteady pressure signals located on four levels denoted MG0, MG1, MG2 and MG3 were acquired on the cone wall of the test section for each geometrical configuration. Both rotating and plunging components are discriminated based on the unsteady pressure signals acquired on each level. The rotating component is directly linked with the swirling flow configuration delivered by the swirl apparatus. The largest amplitude of the rotating component associated with the vortex rope precession is determined on MG1 level for all cases. The previous observation supports the assertion that the swirling flow configuration delivered by the swirl apparatus is practically unchanged. The response of the hydraulic circuit is quantified by the plunging component. The ratio between the plunging (fp) and rotating (fr) frequencies is considered to compare the data for all cases. In this way, it is avoided any deviation of the plunging value provided by the slight variation of the swirling flow configuration.
Based on the data presented in this paper, it is summarized that the response of the hydraulic circuit with 90° sharp heel elbow (HE90) is significantly different than the one given by the hydraulic circuit with 90° S shape elbow (SE90). A constant frequency ratio value of 0.355 is obtained for all SE90 cases. This means that the frequency ratio (fp/fr) remains unchanged when the hydraulic circuit impedance is modified. As a result, the frequency response of the hydraulic circuit with SE90 elbow remains unchanged if the impedance is changed. On the contrary, the amplitude of the plunging component increases monotonically three times as the length of the pipe extension increases three times.

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One can conclude that the amplitude of the plunging component grows up when the distance between the cone and the elbow is increased. It is well known that the plunging pulsation propagates as standing waves into the whole hydraulic system. Therefore, a compact geometrical configuration should be selected for the hydraulic turbines in order to diminish the amplitudes associated with the plunging components.

Further investigations will explore if the outlet section position of the elbow geometry may play certain role on the reflection of the pressure/standing waves to alter the response of the hydraulic circuit.

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