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Experimental Investigation of the Unsteady Pressure Field in Decelerated Swirling Flow with 74º Sharp Heel Elbow

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Abstract. The unsteady pressure at the wall of the conical diffuser without and with a 74° heel elbow is examined. The self-induced instability is experimentally investigated on the swirl generator test rig. As a result, the asynchronous (rotating) pressure pulsation associated with the vortex rope and it second harmonic are discriminated. The discriminated Fourier spectra with plunging and rotating components of the unsteady pressure signals are analyzed for several geometrical configurations in order to identify the frequency associated to the heel elbow. It is shown that a plunging component of 8 Hz corresponds to a 74° heel elbow in the Fourier spectra.

1. Introduction

The Francis turbines operated at part load conditions develop hydrodynamic instabilities in the draft tube cone due to the residual swirl delivered by the runner. These phenomena are recognized as the main cause of severe pressure fluctuations called draft tube surge by Rheingans [1]. Extensively investigations were conducted during last decades in order to elucidate it mechanism [2-4]. A synopsis outlook about these investigations is presented by Nishi and Liu [5].

The group coordinated by Prof. Nishi has shown that the pressure pulsation consists of a synchronous part (plunging) and an asynchronous part (rotating), respectively. He has conducted experimental investigations to demonstrate that a synchronous component resides in the draft tube elbow [2]. Recently, a low-frequency synchronous component corresponding to the self-induced instability of the swirling flows is measured [6]. In this case, this self-induced low frequency component is one distinct than the frequency of the synchronous component associated to the elbow.

An extensive research program is developed by our group to elucidate the swirling flow interaction with different geometries of the draft tube elbow in order to explain the physical mechanism that produces the plunging pressure pulsations with low-frequencies. The 90° sharp hell elbow geometry corresponds to the old draft tubes available in hydropower plants [7-10]. A low-frequency synchronous component of 7 Hz is measured on our test rig for a 90º sharp heel elbow configuration being associated to swirling flow interaction with elbow. This low-frequency plunging component of 7 Hz is around 40% from the frequency of the asynchronous one [11].

In this paper, our experimental investigations are presented in order to examine the cause of low frequency oscillation in a 74º sharp heel elbow. The 74º heel elbow corresponds to underground draft

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tube geometry available in a hydropower plant. The experimental setup is described in Section 2 while the Fourier spectra obtained on the wall of the test section is presented in Section 3. The conclusions are drawn in the last section.

2. Experimental setup

The test rig is designed to investigate several swirling flow configurations. Several swirling flow configurations are generated using different guide vane geometries together with a free runner [12-14]. These swirling flow configurations correspond to hydrodynamic conditions associated to Francis turbine operation [14]. The test rig is equipped with an acquisition system in order to record the discharge and runner speed [13]. The most important part of the rig is the test section, Fig. 1. The test section includes the swirl apparatus with two rows of blades (13 guide vanes and 10 runner blades) [13] and the convergent-divergent section [15]. The test section is manufactured from plexiglass in order to allow flow visualization. The throat diameter is 100 mm while the conical diffuser has an 8.5° half-angle and a length of 200 mm. A sharp heel elbow with 74º is added downstream to diffuser providing the geometrical configuration labeled HE74E0 in Fig. 1. Also, several pipe extensions of 100 mm, 200 mm and 300 mm are added between the diffuser and 74º sharp heel elbow leading to the geometrical configuration named HE74E01, HE74E02 and HE74E03, respectively.

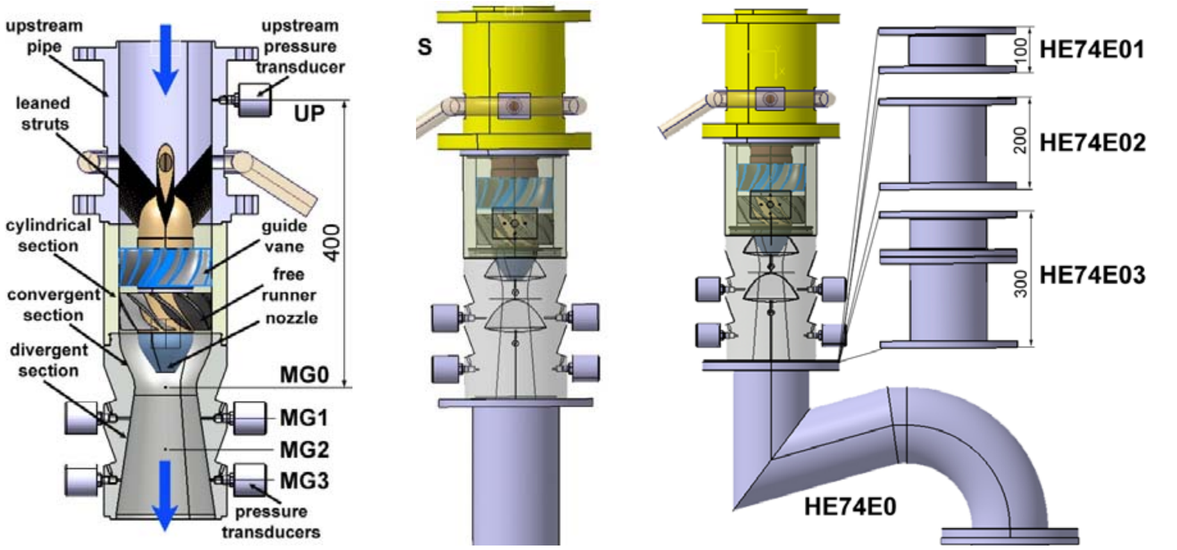

Fig. 1 Sketch of the test section and geometrical configurations: straight (S) and 74° sharp heel elbow (HE74E0) together with three pipe extensions of 0.1 m (HE74E01), 0.2 m (HE74E02) and 0.3 m (HE74E03)

The test section allows us to measure the unsteady pressure on the cone wall at four levels using eight transducers, see Fig. 1. As a result, two pressure transducers are installed on each level being located at 180° each other. This experimental setup allows us to examine the flow structure with one single vortex as it is visualized on our test rig. Moreover, this experimental setup is able to discriminate the type of first harmonic. Several numerical investigations were performed in order to indentify the type of higher harmonics in the Fourier spectra [6, 16].

The first level corresponds to the throat (MG0) and the next levels are displaced at 50 mm (MG1), 100 mm (MG2) and 150 mm (MG3) with respect to the first one. The transducers measurement range was ±1 bar with a precision of ±0.13%. However, the upper limit of frequency for unsteady pressure transducers is beyond to 50 Hz. In our investigations a nominal discharge of 30 l/s is selected. In this case, the swirling flow configuration provided by the stay vanes leads to a free runner speed around 1020 rpm. In this paper only the swirling flows under non-cavitating conditions are examined.

Fig. 2 Photo of the swirling flow test section considering three geometrical configurations: straight (S) and 74° sharp heel elbow together with pipe extensions of 0.1 m (HE74E01) and 0.3 m (HE74E03), respectively

3. Experimental data

Firstly, two unsteady pressure signals acquired on each four level of the cone are used to discriminate the plunging and rotating components. The experimental setup allows us to The Fourier spectra of the decomposed signals recorded from MG0 to MG3 levels on the test section (see Fig. 1) are plotted in Fig. 3 for a straight diffuser (denoted with S) and a straight diffuser with 74° sharp heel elbow (denoted HE74E0), respectively.

The plunging component around 19 Hz can be clearly identified in all power spectra. This frequency was identified in our experimental investigations performed on test rig without any row blades. In this particular case, the flow is axial without any swirling component. This plunging component around 19 Hz is associated to the honeycomb structure installed upstream to the test section in order to uniform the flow at the test section inlet [6].

One can observe that the rotating component frequency associated to the vortex rope is around 18 Hz in power spectra for straight diffuser (denoted with S). The largest amplitude of the rotating component is measured on MG0 level. The frequency around 36 Hz is distinguished on the Fourier spectrum of the rotating component on MG0 and MG1 levels, respectively. This frequency corresponds to second harmonic of the vortex rope (36 Hz = 2 x 18 Hz). The largest amplitude of this frequency is assessed on MG0 level being the same level with rotating component. It is obvious that these two frequencies are connected with the vortex rope. The rotating component is generated by the vortex rope and it remains trapped in the cone [3].

Two frequencies at 8 Hz associated the plunging component (blue) and around 17 Hz and it second harmonic around 34 Hz correspond to rotating one (red) can be clearly identified in power spectra with 74° heel elbow (HE74E0). The difference between both rotating components is coming from a slight deviation of free runner speed. As a result, the synchronous component of 8 Hz is associated to swirling flow interaction with 74° sharp heel elbow. This low-frequency synchronous (plunging) component of 8 Hz is around 47% from the frequency of the asynchronous (rotating) component.

Next, the interaction between decelerated swirling flow developed in the conical diffuser and 74° sharp heel elbow is investigated. This study is performed installing three pipe extensions with different lengths (0.1 m – HE90E01, 0.2 m - HE90E02 and 0.3 m - HE90E03) between the conical diffuser and 74° sharp heel elbow (see Figs. 1 and 2). Consequently, the Fourier spectra with discriminated components (plunging and rotating) on all levels for cases with 74° sharp heel elbow are plotted in Fig. 4.

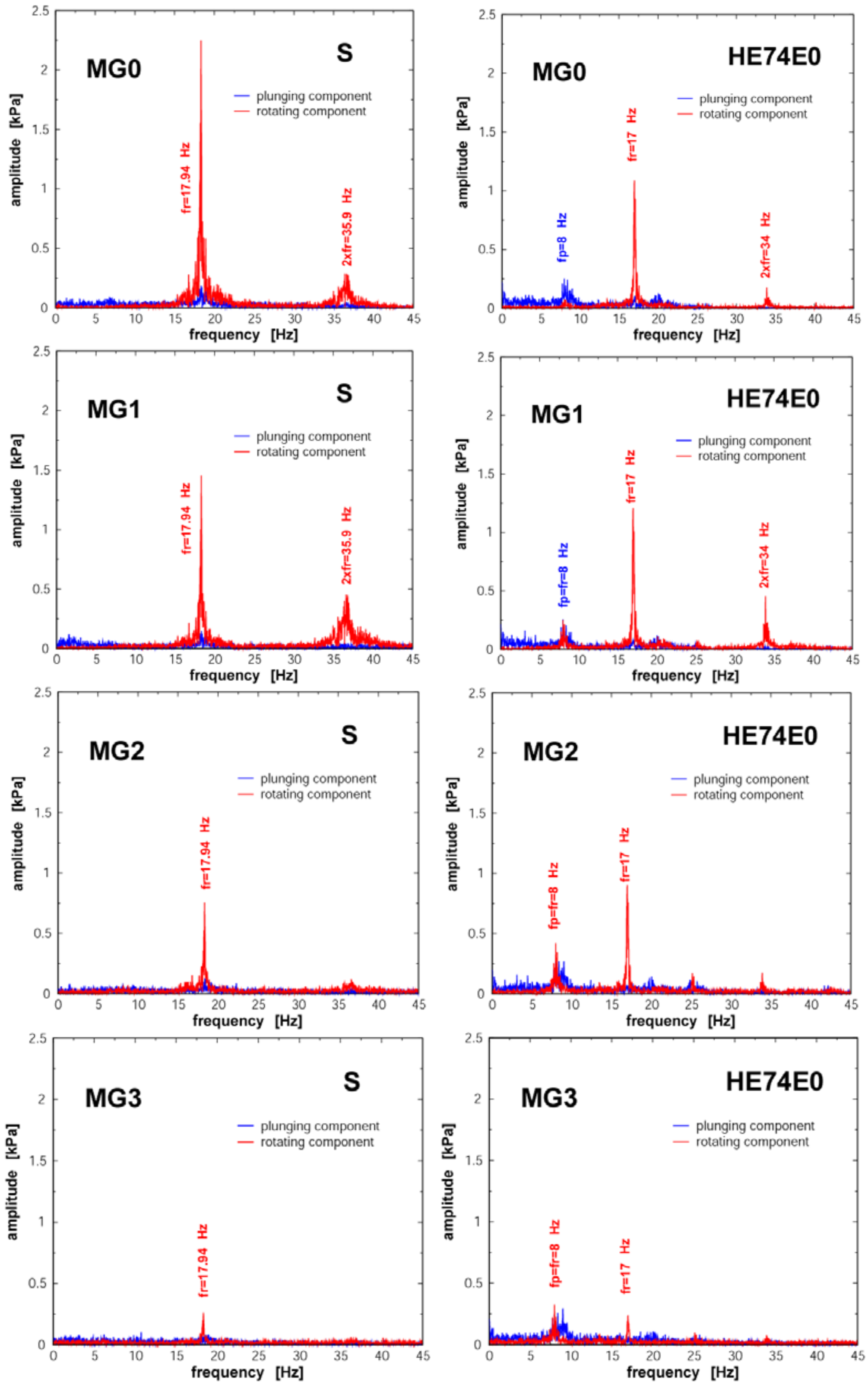

Fig. 3 Fourier spectra of the decomposed unsteady pressure signals on the first three levels at the cone wall (from MG0 to MG3, Fig. 1).

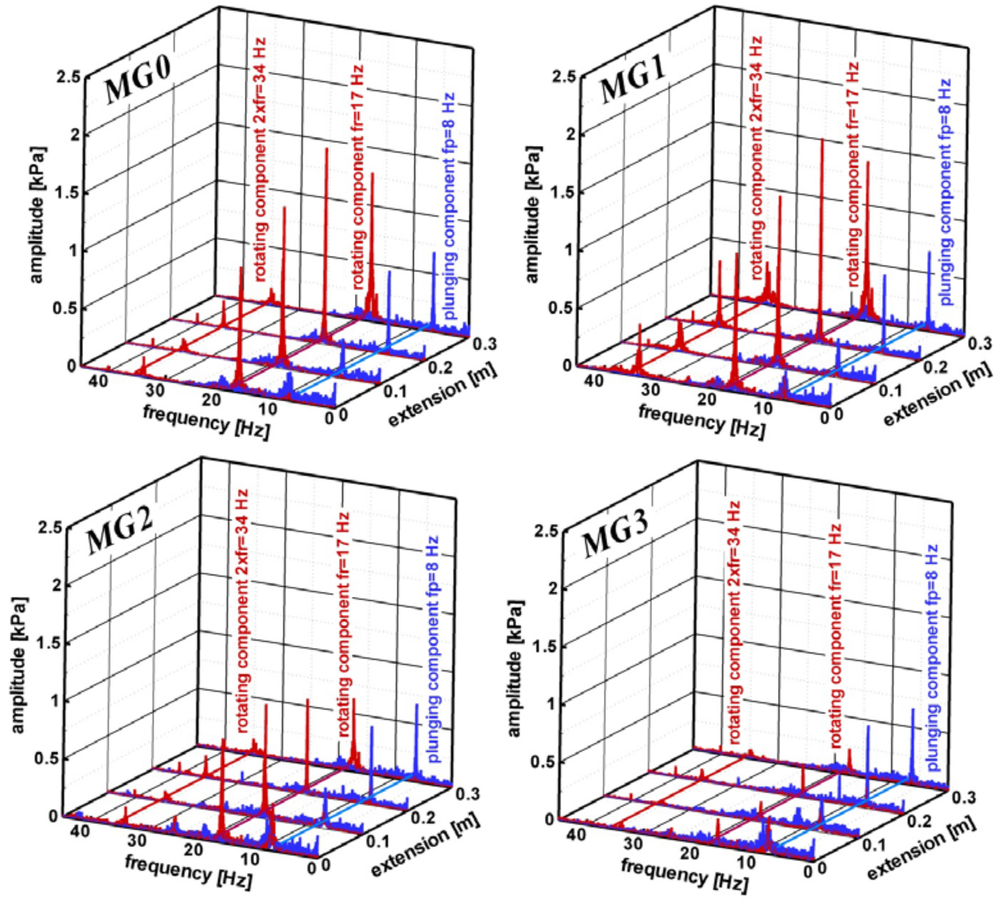

Fig. 4 Fourier spectra with discriminated signals associated to the unsteady pressure levels from MG0 to MG3 for geometrical configurations investigated: straight (S) and 74° heel elbow (HE70E0) together with three pipe length extensions of 0.1 m (HE74E01), 0.2 m (HE74E02) and 0.3 m (HE74E03)

One can observe that all frequencies indentified in the spectra associated to 74° sharp heel elbow case (HE74E0) are recovered for the cases with pipe extensions. However, the amplitude value associated to the plunging component of 8 Hz increases with the pipe length extension. This amplitude grows up over three times for the configuration with the largest pipe extension of 0.3 m (HE74E03 case) considered in our investigation with respect to the configuration without any extension (HE74E0 case), respectively. This observation suggests that a compact geometrical configuration should be selected for the hydraulic turbines to diminish the amplitudes associated to the plunging component.

4. Conclusions

The paper investigates the decelerated swirling flow in a straight draft tube, using a swirl generator that mimics the flow in the discharge cone of hydraulic turbines operated at partial discharge. The unsteady pressure measurements were performed on the cone wall of the test section. Eight points located on four levels were investigated for each geometrical configuration (straight diffuser without and with a 74° sharp heel elbow). The unsteady pressure signal is decomposed in two parts: rotational and plunging components, respectively. The rotational (asynchronous) component of pressure pulsation associated with the self induced instability is identified. The plunging component around 8 Hz is identified for geometrical configuration with 74° sharp heel elbow. This low-frequency synchronous (plunging) component of 8 Hz is around 47% from the frequency of the asynchronous (rotating) one. It amplitude grows up when the distance between conical diffuser and sharp heel elbow is increased. The main conclusion emerging from the analysis of the swirling flow interaction with the sharp hell elbow is responsible for the plunging (synchronous) pressure fluctuations. It is well known that the plunging pulsation propagates into the whole hydraulic system. Therefore, a compact geometrical configuration should be selected for the hydraulic turbines to diminish the plunging component.

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