On the sloshing free surface in the draft tube cone of a Francis turbine operating in synchronous condenser mode

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On the sloshing free surface in the draft tube cone of a Francis turbine operating in synchronous condenser mode.

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Abstract. Hydropower plants may be required to operate in synchronous condenser mode in order to supply reactive power to the grid for compensating the fluctuations introduced by the intermittent renewable energies such wind and solar. When operating in this mode, the tail water in the Francis turbine or pump-turbine is depressed below the runner by injecting pressurized air in order to spin in air to reduce the power consumption. Many air-water interaction phenomena occur in the machine causing air losses and a consequent power consumption to recover the air lost. In this paper, the experimental investigation of the sloshing motion in the cone of a dewatered Francis turbine performed by image visualization and pressure measurements is presented. The developed image post processing method for identifying the amplitude and frequency of the oscillation of the free surface is described and the results obtained are illustrated and discussed.

1. Introduction

Hydropower is the most exploited renewable energy source at a global scale. Thanks to its flexibility, it has the capability to compensate the variations of the energy production of the intermittent renewable energies such solar and wind. Moreover, since these fluctuations of energy production cause grid instability, a supply of reactive power is required for the grid stabilization. Hydropower plants can provide reactive power to the grid by operating in synchronous condenser mode. When operating in synchronous condenser mode, Francis turbine and pump-turbine are operated in dewatered conditions in order to minimize the power consumption [1][2]. The guide vanes are closed and the tail water level is depressed below the runner by injecting pressurized air in the cone of the draft tube.

Several problems occur to run the synchronous condenser mode operation in a hydropower plant since significant power losses are recorded due to the pressurized air lost in the machines. Previous study, such as Tanaka et al. [3] and Ceravola et al. [4], investigated the air-water interaction phenomena in a Francis turbine or pump turbine operating in synchronous condenser mode focusing on the sloshing motion of the free surface below the runner.

Tanaka et al. [3] studied the behavior of the water free surfaces and the related air losses changing the operation condition of the turbine by applying the densimetric Froude similitude to reach the similarity with the prototype. Air-water interaction phenomena such as sloshing motion of a free surface, turbulent waves causing the formation and entrainment of bubbles diffusing in the water volume and formation of droplets interfering with the runner were observed. The main influencing parameters identified were the densimetric Froude number defined in Eq.1, the air density and the water level in the cone of the draft tube.

$$Fr_d = \sqrt{\frac{\rho_a}{\rho_w}}\frac{N\sqrt{D_e}}{\sqrt{g}} \tag{1}$$

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ρ_a and ρ_w are respectively the air and water density, N is the rotational speed and D_e the low pressure diameter of the runner. Several studies were conducted to understand the behavior of an oscillating free surface such Royon-Lebeaud et al. [5] and Komori et al. [6]. These studies showed the dependence of the mass transfer of a gas into water on the wave frequencies and amplitude on the surface caused by a wind shear. The mass transfer plays an important role for understanding the air diffusion in water which is one of the causes of the air losses. As such, there has been a shortage of research into Francis turbine operating in condenser mode related to the determination of air losses and the description of the two-phase phenomena involved in the machine.

In the present paper a successful set-up and post-processing method for the experimental investigation of the sloshing motion of the air-water free surface below a Francis runner operating in synchronous condenser mode is presented. Image acquisition and pressure measurements are performed and analyzed in both time and frequency domain. The amplitude and frequency of the sloshing motion are illustrated and followed by a discussion of the results achieved.

2. Experimental set-up

The experiments are conducted in the reduced scaled physical model of a Francis turbine shown in Fig.1. The scaled model - composed by the upstream inlet pipe, the spiral case, the runner and the draft tube - is installed in a closed loop test-rig which is equipped with two axial double-volute pumps to generate the specific head. A generator connected to the model runner regulates the rotational speed. To operate in condenser mode, the guide vanes are closed and a blind plate was mounted at the end of the draft tube. A cooling discharge is injected through the runner and pressurized air is injected in the cone of the draft tube. A transparent draft tube cone with a flat water box window is installed to perform undistorted images acquisition. A camera is mounted as illustrated in Fig.1a) and a 90% uniform LED screen is employed to have uniform white light on the background to enhance the contrast between the liquid and gaseous phase in the cone of the draft tube. Image acquisition is performed at 30 frames per second for 60 s. Measurements of the wall static pressure are performed at $1.02D_e$ downstream the runner outlet with one pressure sensor installed at 35° from the investigated focus plane of the camera. Measurements are performed for 60 s at 3'000 Hz and synchronized with the image acquisition by an external trigger. The Froude similarity with the prototype is respected to choose the operational condition to investigate. Two gauge pressures and six densimetric Froude numbers are tested by varying the pressure in the cone and the rotational speed of the runner. The tested operational conditions of the machine are resumed in Fig.1b).

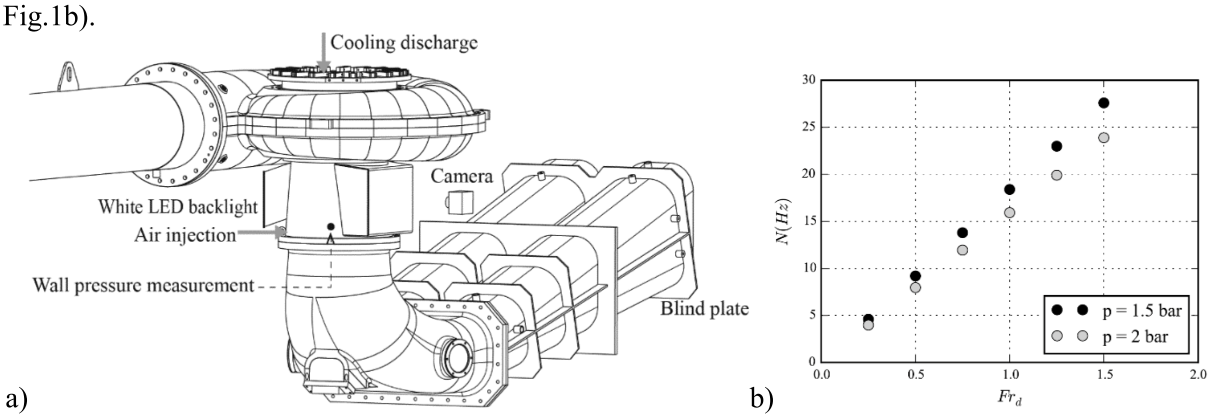

Figure 1. a) Reduced scale model of the Francis turbine on the test rig together with the experimental instrumentation. b) Investigated operation condition of the Francis turbine operating in condenser mode.

3. Methodology

A method for the images post-processing is developed to measure the amplitude and frequency of the sloshing motion of the air-water free surface below the runner. A calibration of the camera is performed with a 200×200 dotted target mounted in the nose of the runner for guaranteeing the alignment of the camera on the horizontal and vertical slit. The focus plane is centered on the central plane of the draft tube cone and a conversion ratio of 2 pixel mm^{-1} is computed. As illustrated in Fig.2, two fixed matrices of pixels of 15 mm width are extracted from each frame and an adaptive threshold filter [7] is applied to identify the illuminated liquid phase in contrast with the dark background. The pixel discretization and the presence of bubbles and droplets induce errors in the identification of the sloshing amplitude since they can locally change the position of the free surface. To limit this problem, the method is based on the identification of the linear equations describing the segments AB and CD in order to identify the position of the points B and C. As a first step, the position of the free surface on the *y* axis, introduced in the reference system in Fig.2, is identified for each column *i* of the matrices of pixels by solving Eq.2:

$$y_{\mathrm{AB},i} = \sum_j \left(\mathrm{E}(j,i) = 255\right) \quad \text{and} \quad y_{\mathrm{CD},i} = \sum_j \left(\mathrm{F}(j,i) = 255\right) \tag{2}$$

As second step, the linear regression to best fit a linear equation to the data set of the computed positions of the free surface is performed by using the least squares method. This leads to identify the linear equation describing the segments AB and CD and the positions of the points B and C by solving Eq.3.

$$y_\mathrm{B} = \mathrm{a}x_\mathrm{B} + \mathrm{b} \quad \text{and} \quad y_\mathrm{C} = \mathrm{c}x_\mathrm{C} + \mathrm{d} \tag{3}$$

The constants a and c are the slopes and b and d the intercepts on the *y* axis of the linear equations computed by the linear regression. Finally, the sloshing amplitude *h* is computed as follows in Eq. 4:

$$h = y_\mathrm{B} - y_\mathrm{C} \tag{4}$$

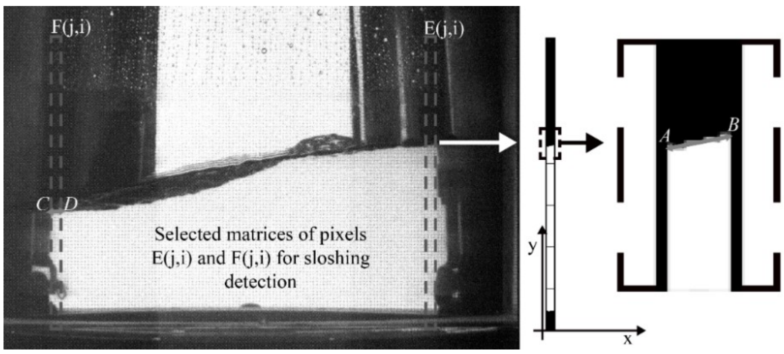

Figure 2. Extracted matrices of pixels and filtering for sloshing detection.

4. Result and discussion

4.1. Amplitude and frequency of the sloshing motion

The image post-processing is applied to the visualization of the sloshing motion, enabling a quantitative description of the oscillation of the free surface for all the investigated values of the densimetric Froude number. A sequence of images of the oscillation of the air-water free surface below the runner at $p = 2$ bar and $Fr_d = 0.75$ is presented in Fig.3a). The extracted sloshing amplitude by the method presented in Sec.3 is illustrated in Fig.3b).

A discrete Fourier transform analysis is applied on the sloshing amplitude and pressure measurements to compute the spectrum of the signals and to identify the frequency of the oscillation of the free surface for the investigated operation condition of the Francis turbine. The magnitude of the spectrum computed by the Fourier analysis is presented in Fig.3c).

4.2. Influence of the densimetric Froude number

The behavior of the air-water free surface below the runner in dependency on the Fr_d is illustrated in Fig.4. For $Fr_d < 0.5$ no sloshing motion is observed while for $Fr_d > 0.5$ the oscillation of the free surface is recorded. At $Fr_d = 0.5$ the behavior of the free surface has a transient condition. Starting from a steady flat condition, the free-surface develops an oscillation until the maximum amplitude as shown in Fig.5

at a gauge pressure of 1.5 bar. The pressure data are normalized by defining a pressure coefficient as follows in Eq.5.

$$C_p = \frac{p - \overline{p}}{0.5\rho_{\mathrm{w}} U_{\mathrm{tip}}^2} \tag{5}$$

U_{tip} is the peripheral velocity of the blade tip.

Both amplitude and pressure fluctuations measurements confirm the transient condition of the sloshing motion of the free surface at this operation condition of the Francis turbine. A peak on the sloshing amplitude coincides with a peak in pressure. The phase shift is due to the physical angular shift of the pressure sensor with respect to the focus plane of the camera. Moreover, for $Fr_d > 0.5$ the amplitude of the sloshing motion decreases by increasing the densimetric Froude number as it is noticed by observing the images of the sloshing motion for the investigated Fr_d in Fig.4. The sloshing amplitude in function of the Fr_d is illustrated in Fig.6 (left) in dimensionless term by dividing the measured amplitude by the exit diameter of the Francis runner. On the other hand, the frequency of the oscillation slightly increases with the Fr_d, as shown in Fig.6 (right) where the frequency is represented in dimensionless term by dividing by the exit diameter and the gravity.

4.3. Influence of the gauge pressure

The amplitude of the oscillation of the free surface depends also on the gauge pressure as illustrated in Fig.6. By increasing the gauge pressure a higher amplitude is recorded while the frequency is not affected. The maximum difference in frequency which is measured at the two investigated gauge pressures counts the 0.8% of the computed frequency at 2 bars at $Fr_d = 0.75$.

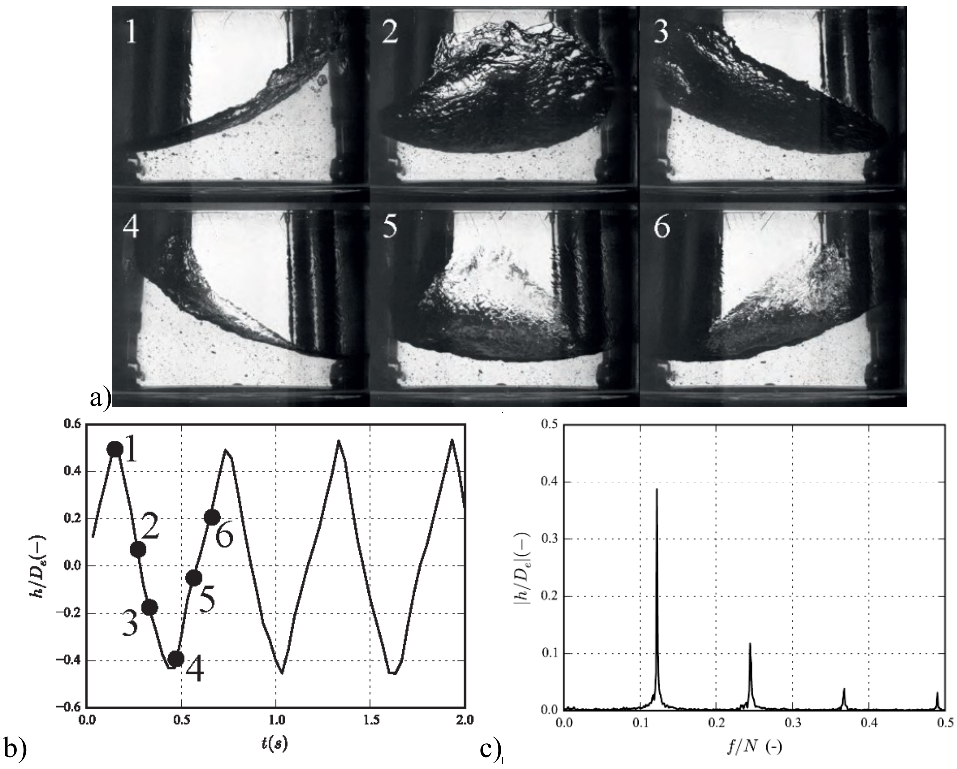

Figure 3. a) Sequence of images of the air-water free surface oscillating during the condenser mode operation of the Francis runner at p = 2 bar and $Fr_d = 0.75$. b) Time resolved signal of the sloshing amplitude measured with the image post-processing method. c) Corresponding spectrum magnitude of the signal in b).

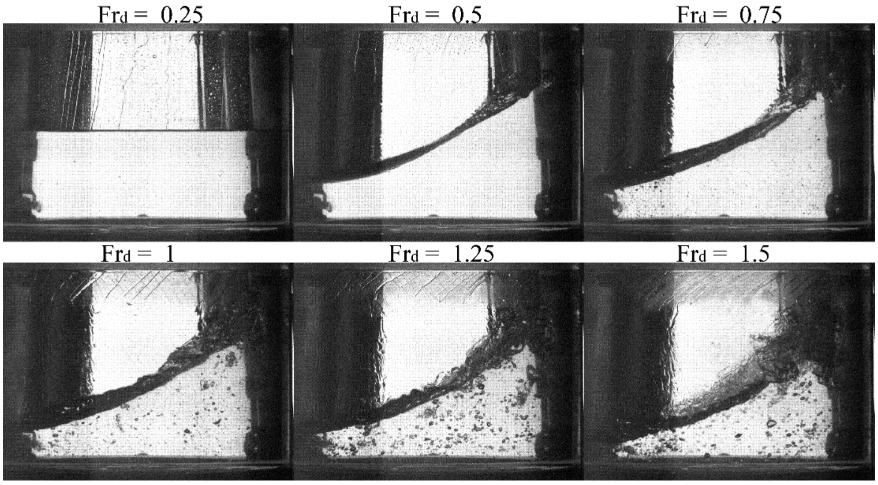

Figure 4. Example images of the sloshing motion of the free surface in the draft tube cone of a Francis turbine operating in condenser mode at p = 1.5 bar for six different densimetric Froude numbers.

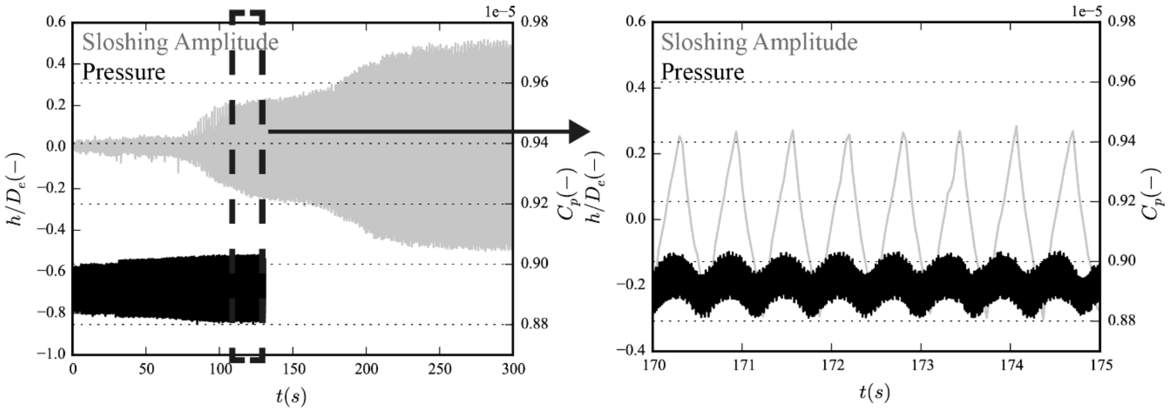

Figure 5. Simultaneous time history of the sloshing motion relative amplitude extracted by the images post-processing and pressure coefficients derived from pressure measurements in the lower section of the draft tube cone at p = 1.5 bar and $Fr_d = 0.5$.

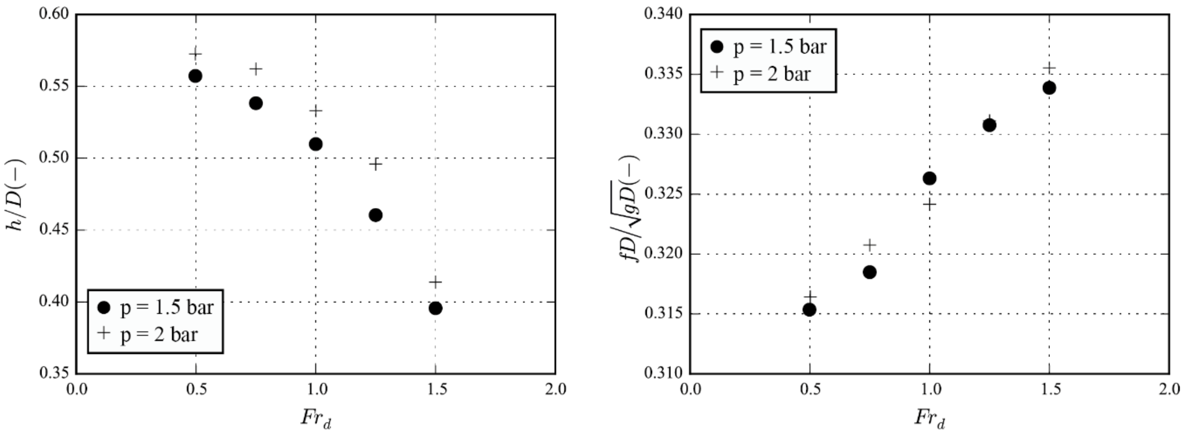

Figure 6. Relative amplitude computed as peak to peak height of the sloshing wave divided by the exit diameter of the Francis runner (left). Frequency of the sloshing motion divided by the gravity *g* times the exit diameter of the Francis runner (right).

5. Conclusion

Images acquisition of the sloshing motion of the air-water free surface below the runner in the draft tube cone of a reduced scale physical model of a Francis turbine operating in condenser mode was performed. A method for the image post-processing was developed for measuring the amplitude of the sloshing motion. Pressure measurements were also performed in the lower section of the draft tube cone. The pressure signals and the sloshing amplitude data were analyzed and compared in both time and frequency domain and the results are elucidated in the present paper.

Twelve operating conditions were investigated by varying the densimetric Froude number between 0.25 and 1.5 and the gauge pressure at 1.5 and 2 bar in order to evaluate their influence on the amplitude and frequency of the sloshing motion, respectively. Higher pressure value could not be reached because of the pressure limitation of the reduced scale physical test.

The results highlight the dependency of the sloshing motion dynamic behaviour on the Fr_d. The free surface has a steady flat condition for $Fr_d < 0.5$. The transition between the steady flat condition and the oscillation is recorded at $Fr_d = 0.5$ and for $Fr_d > 0.5$ the oscillation is observed. The amplitude of the sloshing motion decreases by increasing the Fr_d, while the frequency slightly increases.

The gauge pressure influences also the amplitude of the sloshing motion: the higher the gauge pressure, the higher is the amplitude. No influence has been recorded on the frequency of the sloshing motion.

In light of the presented results, the key parameters which influence the dynamic behaviour of the air-water free surface below the runner are identified and a quantitative description of the phenomenon is provided.

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