Visualization of the elliptical form of a cavitation vortex rope and its collapse by two cameras

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Abstract. This article presents preliminary results of an experimental study of the upper-part load instability and the associated elliptical form of the cavitation vortex rope in a Francis turbine draft tube. The influence of the operating parameters on the onset and the development of the instability is first briefly studied by pressure measurements in the draft tube. Visualizations of the cavitation vortex rope and its associated elliptical form are performed by using two synchronized high-speed cameras spaced by an angle of 90°. This allows to reconstruct the instantaneous position of the vortex center along the draft tube. It is confirmed that using a single camera leads to biased estimations of the cavitation volume fluctuations. The breathing behaviour of the vortex rope, responsible for the pressure pulsations according to several authors, cannot be definitely demonstrated without a proper reconstruction of the vortex shape based on high-speed videos from several positions. Finally, unique intermittent collapses of cavitation in the vortex center, giving rise to two distinct cavities connecting on both sides the vortex rope, are highlighted.

1. Introduction

Within the range 70% – 80% of their design conditions, Francis turbine may experience high-amplitude synchronous pressure pulsations at a high frequency $f_{upper}$, ranging from 2 to 4 times the runner frequency, in addition to the pressure fluctuations induced by the precession of the cavitation vortex rope. These pressure pulsations are not observed only in the draft tube but also in the upstream pipes of the machine. An elliptical deformation of the vortex rope cross-section can be also observed, as shown for instance by Nicolet et al. [1]. Its self-rotation around the vortex axis might play a decisive role in the oscillation mechanisms according to certain authors [2] but this assumption is not in agreement with the synchronous nature of the pressure pulsations as pointed out by Dörfler [3]. Some authors assumed a self-excited behaviour of one higher eigenmode of the hydraulic circuit [4, 3] and the breathing behaviour of the cavitation vortex rope was highlighted by Nicolet et al. [1] using high-speed visualizations with a single camera.

This article presents preliminary results of an experimental study of the upper-part load instability and the associated elliptical form of the cavitation vortex rope in the draft tube of a Francis turbine reduced scale model. Dynamics pressure measurements are first performed to determine the influence of the operating conditions on the pressure pulsations. High-speed
visualizations of the cavitation vortex rope by two synchronized cameras are finally presented. Based on a proper post-processing, the vortex rope position along the draft tube can be reconstructed. However, no final conclusion can be made on the occurrence of a breathing nature of the vortex cavity but it is shown that using a single camera leads to a biased estimation of the cavitation volume fluctuations. Finally, intermittent disappearances of the cavitation within the vortex core giving rise to two distinct cavities connecting on both sides the cavitation vortex are highlighted.

2. Test case
The test case is a reduced scale model of a Francis turbine of specific speed $N_s = 161.7$ m$^{-}$kW featuring an unshrouded runner and 18 runner blades [5]. The reduced scale model is installed on the open-loop test rig of Waseda University. An overview of the test rig components, together with the position of the pressure sensors, is given in Figure 1.

![Figure 1: Waseda University open-loop test rig with the reduced scale model of a Francis turbine.](image)

The operating conditions of the reduced scale model are defined by the speed coefficient and discharge coefficient, defined by IEC International Standard as $n_{11} = ND/\sqrt{H}$ and $Q_{11} = Q/D^2\sqrt{H}$ respectively. The pressure level in the draft tube, characterized by the Thoma number $\sigma$, can be changed by using a suction pump placed downstream the vacuum tank.

![Figure 2: Tested operating conditions, together with the influence of the swirl number on the Strouhal number of the precession frequency and upper-part load pulsations frequency.](image)
3. Upper-part load pressure pulsations and associated elliptical vortex rope

The influence of the discharge coefficient on the pressure fluctuations for three different values of speed coefficient at constant Thoma number is first investigated with a refinement in the zone where upper-part load pulsations occur, see Figure 2a. The operating conditions of the machine are characterized by a single parameter, the swirl number, which can be expressed as a function of the speed and discharge coefficients [6]. The influence of the swirl number on the precession frequency $f_{\text{rope}}$ and the upper-part load pulsations frequency $f_{\text{upper}}$ is provided in Figure 2b. High-frequency pulsations occur typically in the range $S = 0.3 - 0.5$ whatever the value of the speed coefficient. When the flow discharge is decreased, typically in the range 70% - 80% of the value in no-swirl conditions, $f_{\text{upper}}$ rapidly decreases from about $4 \times n$ to $2 \times n$.

![Figure 3: Cross-spectral analysis of two pressure signals measured in section 1 (p₁ and p₂, spaced by 180°) at $n_{11} = 62$ and $Q_{11} = 0.61$.](image)

An example of cross-spectral analysis between two pressure signals measured in section 1 at a given operating point is provided in Figure 3. Similar to previous studies, spectral side-bands are observed at the frequencies $f_{\text{upper}} - f_{\text{upper}}$ and $f_{\text{upper}} + f_{\text{upper}}$. The phase shift at $f_{\text{upper}} + f_{\text{upper}}$ corresponds to the geometrical angle between both sensors, highlighting the convective nature of this frequency. However, contrary to the results obtained by Arpe et al. [7], a pure convective behaviour is not highlighted at the frequency $f_{\text{upper}} - f_{\text{upper}}$.

The deformation of the cavitation vortex rope and the self-rotation of its elliptical cross-section are also observed when high-frequency pressure pulsations occur, as illustrated in Figure 4. The next section focuses on the visualization of the cavitation vortex rope by two synchronized high-speed cameras.

4. High-speed visualization of the vortex rope

4.1. Experimental set-up

Several authors performed visualization of the cavitation vortex rope by using a single camera, as in [8] for the axisymmetric vortex at full load and in [1] for the cavitation vortex rope featuring an elliptical form at upper-part load conditions. However, using only one camera in the case of a cavitation vortex rope featuring a precessing motion together with an elliptical cross-section probably leads to a biased estimation of the cavitation volume and finally a misinterpretation of the phenomenon. In the following, two synchronized Lavision high-speed cameras ($f_{\text{sampling}} = 3000 \text{ Hz}$ and $T_{\text{record}} = 3s$) making an angle of 90° are used to visualize the cavitation vortex rope according to the set-up illustrated in Figure 5a.

The images from both cameras are first post-processed individually. After subtracting the background image, each image is transformed into a binary image and the cavitation vortex rope
Figure 4: Visualization of the cavitation vortex rope in a Francis turbine draft tube during upper-part load instability. Several instants over one period $T_{section}$ of the vortex cross-section rotation are given.

Figure 5: Set-up for the visualization and example of post-processed images. They correspond to the images viewed by both cameras at the same time.

limits (in red), center (in green) and cross-section (blue arrow) can be identified, as illustrated in Figure 5b.

4.2. Estimation of the vortex center position
The time history of the vortex center position at a given $z$-position viewed by both cameras is shown in Figure 6a. The coordinates of the vortex center in the corresponding $z$-plane can be derived, leading to an estimation of the radius and angle between the vortex center and the section center. By using the same procedure for all the $z$-planes within the zone of interest (see Figure 5b), the vortex filament can be reconstructed, as shown in Figure 6b. In this figure, the vortex filament is extrapolated along the complete draft tube by fitting the vortex radius and angle as a function of the $z$-coordinate.

4.3. Estimation of the cavitation volume fluctuations
The area of the cavitation vortex rope in the zone of interest is estimated at each time for both cameras by integration of the vortex section along the $z$-axis. The time history of the cavitation vortex rope area, made dimensionless by the cone area, is given in Figure 7a. The
amplitude and phase of the cross-spectra between both sets of data are also provided in Figures 7b-c. The precession period $T_{\text{rope}}$ can be identified: it is however caused by the periodical optical distortions induced by the rotation of the vortex around the focal plane of the cameras. In addition, the period $T_{\text{section}}$ of the self-rotation of the vortex elliptical cross-section is also observed. However, the occurrence of a breathing behaviour of the cavitation vortex cannot be confirmed, or refuted, since these fluctuations are only due to the rotation of the elliptical section, as illustrated by the opposite phase between both cameras. To determine the time history of the cavitation volume, a proper reconstruction of the vortex elliptical form must be performed. This will be in the scope of further investigations.

4.4. Vortex core collapse

Despite the fact that a potential breathing behaviour of the vortex rope cannot be highlighted (or refuted) without advanced post-processing, collapses of the cavitation in the vortex core are intermittently observed, as illustrated in Figure 8. Only the center of the vortex rope disappears, giving rise to two distinct cavities connecting on both sides the cavitation vortex rope. This unique phenomenon could be explained by the propagation of waves with a non-uniform pressure.
distribution, as it is observed for high-frequency waves propagating in ducts featuring low wave speed (as is the case in draft tube cavitation flow).

Figure 8: Visualization of the precessing vortex rope during cavitation collapse of the vortex core.

5. Conclusion

Experimental investigation of the upper-part load instability and the associated elliptical form of the cavitation vortex rope is presented. It is first shown that the instability occurs for a narrow range of swirl number values, for which the precession frequency of the vortex decreases when the swirl number increases. On the contrary, the frequency of the pressure pulsations induced by the upper-part load instability rapidly decreases. Novel visualizations of the cavitation vortex rope and its elliptical form are performed by using two synchronized high-speed cameras. It is confirmed that using a single camera is not suitable to determine the cavity volume pulsations and its potential breathing behaviour cannot be verified or refuted without advanced post-processing, which will be in the scope of further investigations. In addition, an unique phenomenon of collapse of the cavitation within the vortex core giving rise to two distinct cavities is highlighted.

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