CAV2021
11th International Symposium on Cavitation
May 10-13, 2021, Daejon, Korea

Transition of a cavitation vortex rope from cylindrical to elliptical mode in Francis turbine draft tube

Arthur Favrel [1]*, ZhiHao Liu [2], Mohammad Hossein Khozaei [2], Tatsuya Irie [2] and Kazuyoshi Miyagawa [2]

[1] Waseda Research Institute for Science and Engineering, Waseda University, Japan
[2] Department of Applied Mechanics and Aerospace Engineering, Waseda University, Japan

Abstract: This paper focuses on the phenomenon of Upper Part-Load instability occurring around 80% of load in Francis turbines draft tube. Pressure measurements synchronized with two high-speed cameras are performed on a Francis turbine model. At a given operating point, intermittent noise and vibrations are observed. It is shown that high-frequency synchronous pressure pulsations spontaneously occur in the complete system and then vanish periodically. The pressure pulsations along the draft tube feature the shape of one high order eigenmode, with a pressure node located along the cavitation vortex. Video post-processing reveals that a transition of the cavitation vortex rope from cylindrical to elliptical mode occurs exactly when the high-frequency pressure pulsations appear and start propagating in the draft tube.

Keywords: elliptical cavitation vortex, high-speed visualization, upper-part load instability, Francis turbine

1. Introduction

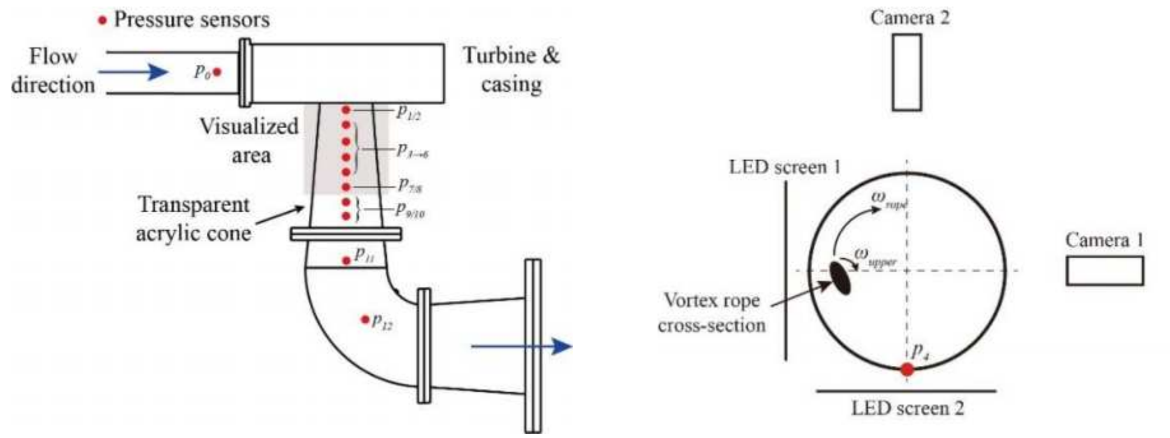
Upper part-load (UPL) instability is a fascinating phenomenon occurring in the draft tube of certain Francis turbines when operating within 70%-80% of the flowrate at their design conditions. This phenomenon is characterized by high-amplitude synchronous pressure pulsations occurring at a high frequency, in addition to the pressure fluctuations at the vortex rope precession frequency [1]. According to the literature, this instability goes along with an elliptical deformation of the vortex rope cross-section, as described in [2, 3] among others. However, the link between the UPL instability onset and this elliptical shape is not clearly established. Its self-rotation around the vortex axis might play a decisive role in the oscillation mechanisms according to certain authors [4] but this assumption is not in agreement with the synchronous nature of the pressure pulsations as pointed out by Dörfler [5]. In this paper, the UPL phenomenon is investigated on a Francis turbine model by means of pressure measurements synchronized with two high-speed cameras. The analysis of the pressure data shows that the system is self-excited during UPL instability at one of its high order eigenmodes featuring a pressure node along the cavitation vortex at the runner outlet. Visualizations reveal that a transition of the cavitation vortex from cylindrical to elliptical modes occurs exactly when the high frequency pressure pulsations start propagating in the draft tube.

2. Experimental test-case

The tests are conducted on a Francis turbine model of specific speed Ns = 161.7 m-kW featuring an unshrouded runner with 18 blades. The model is installed on Waseda University open-loop test rig that allows to simulate a net head of maximum 20m approximately. 12 wall flush-mounted pressure sensors are installed along the draft tube cone (Figure 1a, from p_1 to p_{12}). In two cross-sections, two sensors (p_1/p_2 and p_7/p_8) spaced by 180 degrees are installed to identify the nature of the pressure fluctuations by cross-spectral analysis. Moreover, one pressure sensor p_0 is placed upstream of the spiral casing. High-speed

* Corresponding Author: Arthur Favrel, arthur.favrel@aoni.waseda.jp

visualizations of the draft tube flow are performed by using two Lavision camera spaced by 90°, as illustrated in Figure 1b.



(a) Scheme of the reduced scale model **(b)** High-speed visualizations set-up

Figure 1. Francis turbine model and experimental set-up.

3. Results

Pressure measurements (acquisition time of 40s with f_s = 2'000Hz) are first performed at one operating point with $Q_{11} = 0.8 \times Q_{11}^*$ *and* $n_{11} = n_{11}^*$ (the star indicates the values at the Best Efficiency Point), for which intermittent noise and vibrations are observed.

3.1. Pressure fluctuations during UPL onset

Figure 2 shows the time history of pressure fluctuations measured by the sensors p_1 and p_2 (runner outlet). From $t = 0$ to $t = 130 \times n$ (n is the runner frequency), only pressure fluctuations at the precession frequency of the vortex rope are observed. At $t = 130 \times n$, high-amplitude pressure fluctuations at a frequency f_{UPL} starts developping (part 2), which is confirmed by a cross-spectral density analysis between the two signals, see Figure 3.

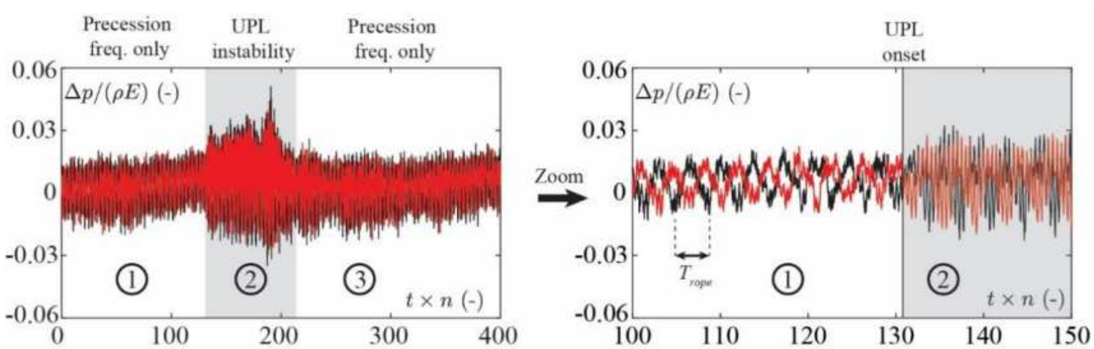
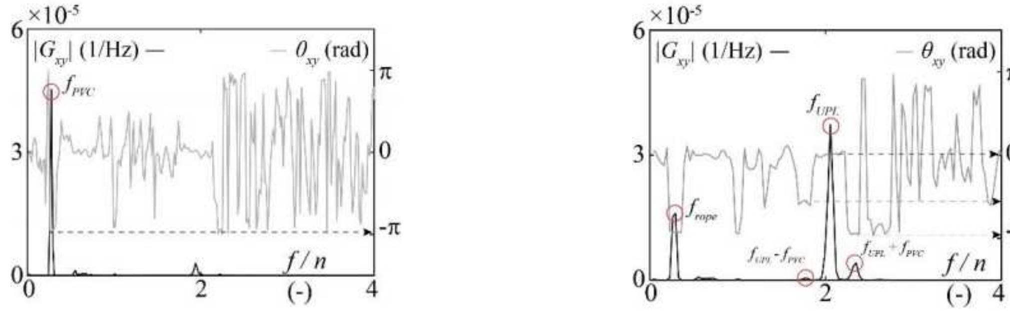


Figure 2. Pressure fluctuations signals in the draft tube cone during UPL instability onset.

The cross-spectral analysis is applied to all pressure signals measured during UPL instability, i.e. from $t = 130 \times n$ to $t = 240 \times n$. The signal measured in p_1 is used as a reference. The amplitude and phase at the high frequency f_{UPL} are identified for each sensor and plotted against their position along the draft tube in Figure 4. The system seems to be self-excited at one of its high order eigenmodes during UPL instability, as already reported in the literature [5, 6]. A sudden drop of amplitude is observed in p_3 at the half of the length of the cavitation vortex rope (see Figure 4c), which is accompanied by a phase change of π: the

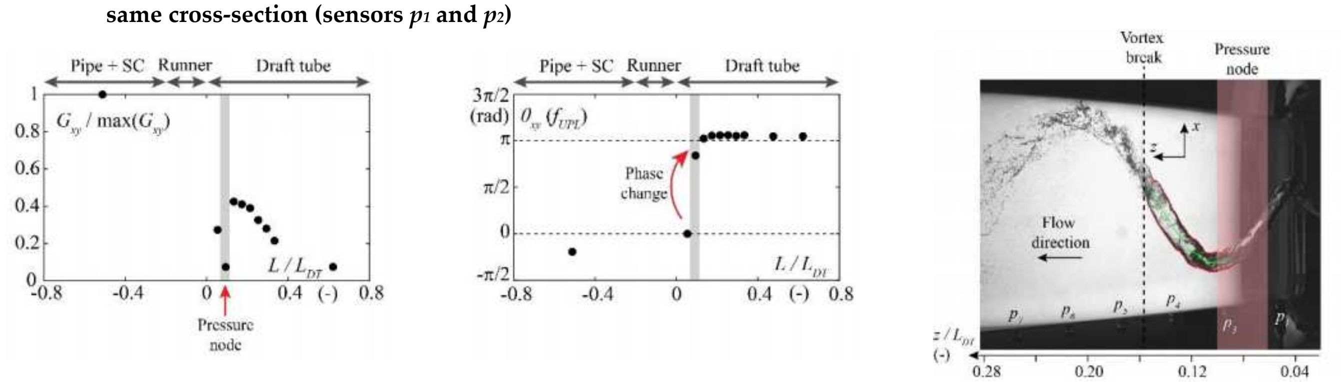
* Corresponding Author: Arthur Favrel, arthur.favrel@aoni.waseda.jp

pressure in the downstream part of the draft tube pulsates in opposite phase with the pressure at the runner outlet.



(a) Part 1 ($t = 0 - 130 \times n$) **(b)** Part 2 ($t = 130 - 210 \times n$)

Figure 3. Cross-spectral density function amplitude and phase of two pressure sensors located in the same cross-section (sensors p_1 and p_2)



(a) Mode amplitude **(b)** Mode phase **(c)** Position of the pressure node

Figure 4. Amplitude and phase mode in the draft tube excited at f_{UPL}

3.2. Transition in the vortex shape

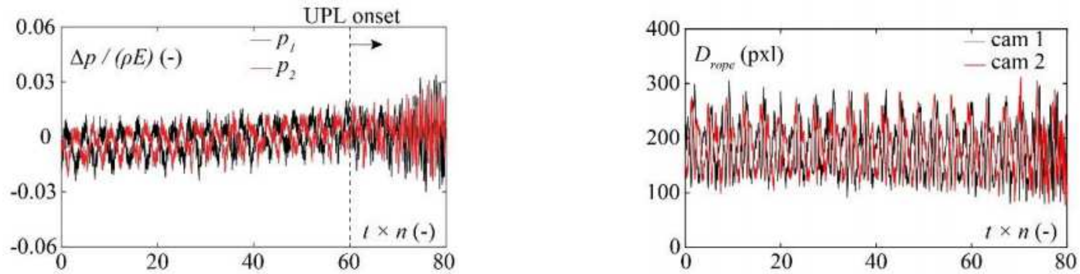
High-speed visualizations synchronized with pressure measurements are performed at the same operating point (acquisition time of 3.2s with f_s = 1'000 Hz). Images are post-processed [3] to estimate the evolution of the cavitation vortex shape along the draft tube. The time history of the vortex section diameter at $z = 0.12 \times L_{DT}$ captured by both cameras is given in Figure 5, together with the corresponding pressure signals. A clear onset of UPL pulsations is observed beyond $t = 60 \times n$ in the pressure signals but the point of transition does not appear clearly in the vortex diameter results. The FFT of the pressure signals and vortex section diameter (camera 2) is estimated on 0.5s-windows (overlap of 80%) and plotted as a function of time in Figure 6. Fluctuations at high frequency appears at the same time in both pressure and vortex diameter FFT from $t = 60 \times n$ and then continuously increase. A cross-spectral analysis between the data obtained with both cameras (not shown here) shows that the fluctuations around $f = 2 \times n$ are associated to real pulsations of the cavitation volume while the fluctuations at $f = 2.5 \times n$ correspond to "artificial" fluctuations induced by the self-rotation of the vortex elliptical cross-section around its axis. Therefore, the elliptical deformation of the cavitation vortex rope cross-section occurs exactly when the UPL pressure pulsations start propagating in the draft tube. The latter also induce fluctuations of the cavitation volume at the same frequency f_{UPL}.

4. Concluding remarks

This paper demonstrates that UPL instability and elliptical deformation of the cavitation vortex rope in Francis turbines draft tube are defnitely connected and occur at the same time, even if the reasons for this

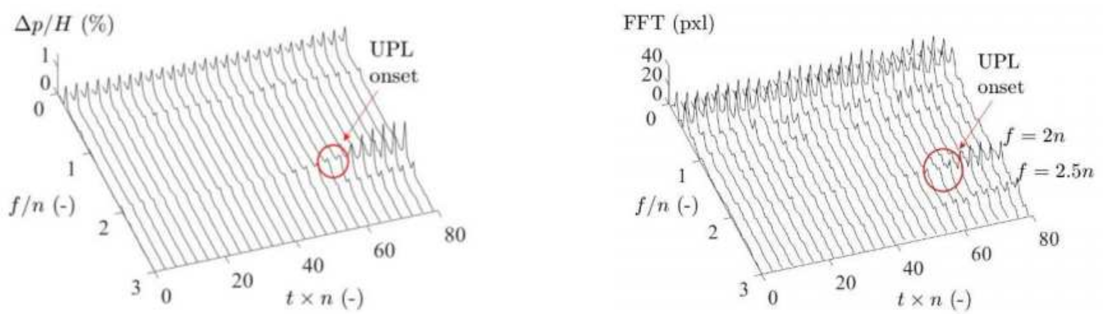
* Corresponding Author: Arthur Favrel, arthur.favrel@aoni.waseda.jp

elliptical shape are not yet elucidated. It may be induced by the radial gradient of UPL pressure flcutuations, as suggested by Dörfler [5]. Further analysis will focus on the reconstruction of the pulsations and ellipticity of the cavitation volume along the draft tube and their correlation with the vortex radial position.



(a) Pressure **(b)** Vortex section diameter

Figure 5. Time history of pressure (p_1 and p_2) and vortex section diameter (z = 0.12×L_{DT})



(a) Pressure **(b)** Vortex section diameter (cam 2)

Figure 6. Waterfall diagram of FFT of pressure signal (p_1) and vortex section diameter (z = 0.12×L_{DT}) over time

Acknowledgments: The authors would like to thank the Waseda Research Institute for Science and Engineering (WISE) for providing support to the presented research, in the framework of the project: 'High performance and high reliability research for hydraulic turbomachinery systems'

References

1. Arpe, J.; Nicolet, C.; Avellan, F. Experimental evidence of hydroacoustic pressure waves in a Francis turbine elbow draft tube for low discharge conditions. *Journal of Fluids Engineering, Transactions of the ASME,* **2009**, *131*.
2. Nicolet, C.; Zobeiri, A.; Maruzewski, P.; Avellan, F. On the upper part load vortex rope in Francis turbine: Experimental investigation. *IOP Conference Series: Earth and Environmental Science,* **2010,** *12, 012053*
3. Favrel, A.; Liu, Z.H.; Takahashi, W.; Irie, T.; Kubo, M.; Miyagawa, K. Visualization of the elliptical form of a cavitation vortex rope and its collapse by two cameras. *IOP Conference Series: Earth and Environmental Science,* **2019,** *405, 012035*
4. Koutnik, J.; Krüger, K.; Pochyly, F.; Rudolf, P.; Haban, V. On Cavitating vortex rope form stability during Francis turbine part load operation, Proceedings of the IAHR Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, Barcelona, Spain, 2006
5. Dörfler, P. On the High-partial-load Pulsation in Francis Turbines, *International Journal of Fluid Machinery and Systems*, **2019**, *12(3), 200-216*
6. Alligné, S.; Nicolet, C.; Avellan, F. Identification by CFD Simulation of the Mechanism Inducing Upper Part Load Resonance Phenomenon, Proceedings of the 4th International Meeting on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, Belgrade, Serbia, 2011

* Corresponding Author: Arthur Favrel, arthur.favrel@aoni.waseda.jp