Analysis of the part load helical vortex rope of a Francis turbine using on-board sensors

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Abstract. The cavitation helical vortex rope arising at Francis turbine partial load induces pressure fluctuations at the rope precession frequency, which can be decomposed into two components; the convective one and the synchronous one. The latter acts as an excitation source for the hydraulic system and is amplified in case of resonance. The present paper aims to highlight the impact of both components on the mechanical behaviour of the runner by performing on-board measurements. It is shown that the use of on-board pressure sensors enables to naturally separate the components of the pressure fluctuations. In addition, the synchronous component has little impact on the mechanical behaviour of the runner, even for the case in which hydro-acoustic resonance occurs.

1. Introduction
In the case of Francis turbine part load condition, a cavitation vortex rope is formed in the draft tube cone (figure 1), with a frequency of precession of about \(0.3 \times f_0\), where \(f_0\) is the rotational frequency of the runner. It induces pressure fluctuations in the draft tube cone at the same frequency, which can be decomposed into two different components [1]. The convective or asynchronous one corresponds to the rotation of the pressure pattern with the vortex core. The second one, called synchronous component, is known to propagate into the hydraulic system, acting consequently as an excitation source for the hydraulic system [2].

Figure 1. Visualization of the cavitation precessing vortex rope in the draft tube cone.
In case of resonance, the latter is amplified, leading to a dynamic pressure and power surge which may jeopardize the system stability [3]. The pressure fluctuations observed at part load condition are expected to impact the mechanical behaviour of the runner and therefore its lifetime. However, the exact impact of both synchronous and convective components is sparsely documented, notably in case of hydro-acoustic resonance between the hydraulic system and the excitation source. For this purpose, an experimental investigation with an instrumented runner is carried out, including on-board pressure sensors and strain gauges. The impact of resonance on both dynamics pressure and strain measured on the runner blade is then analysed.

2. Experimental setup
The test case is a reduced scale physical model of a 16 blades Francis turbine with a specific speed \( \nu = 0.27 \). The model is installed on EPFL test rig PF3 operating in a close-looped configuration. Dynamic pressure is measured in the draft tube cone by 4 flush-mounted piezo-resistive sensors installed in one cross-section of the cone. On-board sensors are installed on the runner blades, including pressure sensors and strain gauges (figure 2). The investigation is focused on a particular operating point at partial load. The speed factor \( n_{\text{ED}} \) is equal to 0.288 (nominal value) while the discharge factor is fixed at \( Q_{\text{ED}} = 0.128 \), corresponding to 64\% of the value at the best efficiency point.

3. Pressure sensors in the draft tube cone
Pressure sensors in the draft tube cone are traditionally used during model tests to analyse the pressure fluctuations generated by the helical vortex rope. Fourier analysis of the recorded time signal evidences that the dominant frequency is equal to \( f_s = 0.31 \times f_0 \) (figure 3). This corresponds to the classic hallmark of the helical vortex rope seen in the non-rotating frame. The second harmonic is also observed, but at a significantly lower level.

| Frequency  | Level (norm. pressure) |
|------------|------------------------|
| \( f_s \)  | 1.00                   |
| 2 \( \times f_s \) | 0.30                   |

Figure 3. Frequency spectrum of a draft tube cone pressure sensor (\( \sigma = 0.11 \)).

The synchronous and the convective components of the helical vortex rope are then observed at the same frequency. It is possible to separate them by using a set of sensors distributed around the draft tube cone at the same elevation and to apply the relevant mathematical method called Spatial Harmonic Decomposition [4]. It should be noted that the eigen frequency identified in [5] is observed in figure 3 at 0.17 \( \times f_0 \).
4. **Pressure sensors on the runner**

By definition, the frequency of the synchronous part of the helical vortex does not depend on the reference frame of the sensor, whereas the frequency of the asynchronous component depends whether or not the sensor rotates. Consequently, the frequency spectra of the on-board pressure sensors show two distinctive peaks: a first one at \( f_s = 0.31 \times f_0 \) and a second one at \( f_a = f_0 - f_s = 0.69 \times f_0 \) (figure 4). The latter corresponds to the rotating component of the vortex rope seen from the rotating frame (figure 5). Using on-board pressure sensors rotating with the runner enables to separate naturally the components of the part load helical vortex rope and to analyse them individually. Moreover, the peak at \( 0.17 \times f_0 \) is observed at the same frequency in the rotating frame, confirming the synchronous nature of this pressure fluctuation.

![Figure 4. Frequency spectrum of a runner pressure sensor (\( \sigma = 0.11 \)).](image)

![Figure 5. Relative position of the runner rotating frame (Oxy) and the part load vortex rope (V). At t = 0 (a), the runner frame and the vortex rope are aligned. At t = 1 / \( f_0 \) (b), the rotating frame has made one revolution while the vortex has made \( f_s / f_0 \) revolution. At t = 1 / (\( f_0 - f_s \)) (c), the runner frame and the vortex are aligned again.](image)

5. **Strain gauges on the runner**

Strain gauges are sensitive to the mechanical behaviour of the material on which they are located. By placing them at the surface of the runner, they give the opportunity to observe how the pressure fluctuations generated by the part load vortex rope impact the structure. As these sensors are in the rotating frame, the frequency spectra shows two peaks similar to those observed with the on-board pressure sensors. However, it appears clearly that the synchronous component of the vortex rope, at \( f_s \), has a low impact on the runner compared to the asynchronous one (figure 6). This means that it is the convective component of the vortex rope that is the most likely to generate fluctuating stresses and potential fatigue damage to the runner.

![Figure 6. Frequency spectrum of a runner strain gauge (\( \sigma = 0.11 \)).](image)
6. Impact of resonance

The cavitation number, $\sigma$, is modified step by step from $\sigma = 0.11$ (prototype condition) to $\sigma = 0.37$ (cavitation-free condition) by changing the pressure over the free surface of the downstream reservoir. By increasing the Thoma number, the cavitation volume in the draft tube cone decreases, inducing a rise of the hydraulic system’s eigen frequencies [6]. The resonance conditions are met when the first eigen frequency of the system matches with the precession frequency [5], which occurs for this test case at $\sigma = 0.17$.

![Figure 7](image)

**Figure 7.** Evolution of the dynamic pressures and strain plotted against $\sigma$ (left) and evolution of the amplitude of the peaks $f_s$ and $f_a$ of the runner pressure sensor plotted against $\sigma$ (right).

Pressures in the draft tube cone and in the runner show a similar evolution, with a significant increase in resonance conditions (figure 7). On the contrary, the dynamic strain is almost not affected by the hydro-acoustic resonance. By separating the synchronous component from the asynchronous one using a pressure sensor on the runner, it can be observed that only the former is sensitive to the resonance. Moreover, the asynchronous component, $f_a$, has the same evolution as the dynamic strain.

7. Conclusion

On-board strain gauges located at the surface of the runner reveal that the asynchronous component of the part load helical vortex rope is a predominant source of mechanical excitation. On the contrary, the synchronous component of the vortex has a lower impact on the mechanical excitation. In the case of hydro-acoustic resonance, it is principally the synchronous component which is affected. As a consequence, the dynamic pressure significantly increases, while the dynamic strain is almost not affected. These observations show that the usual peak-to-peak pressure fluctuations measured by the draft tube cone pressure sensors are not sufficient to estimate the impact of the cavitation part load vortex rope on the mechanical stress of the runner. A more physical approach based on the decomposition of the components of the part load vortex rope should be preferred.

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