THE INFLUENCE OF RUNNER CONE PERFORATION ON THE DRAFT TUBE VORTEX IN FRANCIS HYDRO-TURBINE

by

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In Francis hydro-turbine, the pressure oscillation in the draft tube is the main source of flow-induced vibration and noise. The structural design of runner cone exerts significant influence on the tangential flow velocity within the draft tube and the pressure fluctuations downstream. In this work, we propose a simple and effective method by perforating through-holes on the runner cone to weaken or eliminate pressure fluctuations induced by the vortex ropes in draft tube. An 2 and 4 holes are perforated on the lower half of runner cone, and numerical simulations and experiments are conducted to understand the changing of phenomenology and features with regard to vortex ropes and pressure levels, comparing with the original unperforated case. The analyses are done for two different guide vane openings, α, and the results were validated by experiments with high-speed photography. It is found that at the two openings, the runner cone with perforations can reduce the volume of vortex ropes, and decrease the pressure fluctuation level. The motion of vortex ropes tends to be less violent with more perforated holes. Therefore, the runner cone perforation has the potential of reducing the vortex rope strength.

Key words: *francis hydro-turbine, runner cone perforation, draft tube, pressure fluctuation, high-speed photography*

Introduction

With the increasing demand on the stability and flexibility of power supply system, hydro-turbines (especially large-scale turbine) are frequently operated under off-design conditions, and need more efficient strategy for design [1]. At partial flow load, pressure fluctuations along with unstable flow are usually encountered. They serve as inherent source of the flow instabilities and the induced pressure oscillations. Consequently, some detrimental phenomena (such as structural vibrations, components breakage, noise, and power generation capacity degradation) arise. In Francis turbine, the pressure pulsations induced by the vortex rope in draft tube contribute the most to these problems [2, 3]. The vortex rope development is more associated with the vortex breakdown, which itself is an abrupt change in flow structure, eventually

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getting highly unsteady with recirculating flows at certain critical swirl levels [4]. For the case of draft tube, the flow comes from the downstream of runner. It is mainly driven by the tangential velocity component, which shifts the main flow towards the wall, leaving stagnated water at the center of draft tube.

On the mechanism of vortex rope development in draft tube, so far, there are some studies conducted to understand the pressure fluctuations and vibration. Through the velocity field measurement using particle image velocimetry (PIV), Kirschner *et al*. [2, 5] studied the relationship between vortex rope and the pressure fluctuation frequency near the wall area in draft tube. Favrel *et al*. [6] experimentally revealed that the rise in the pressure excitation source intensity was induced by an enlargement of the vortex trajectory and a simultaneous increase in the precession frequency, as well as the vortex circulation. Many more investigations have also been done to analyze the profiles of pressure fluctuation and vortex rope movements [7-9]. Thus, a great deal of effort by proposing new methods and designs was devoted to the target of decreasing the pressure pulsations amplitudes induced by vortex ropes. Examples include water injection, air admission, wall surface modification, *etc*., which tried to alleviate the cavitation by increasing the local pressure level. Kirschner *et al*. [5] investigated the efficacy of draft tube water injection method under two different partial load conditions, and they showed it was effective in terms of pressure fluctuation attenuation. This water injection method was initially presented by Susan-Resiga *et al*. [10]. The water is axially injected into the center of the draft tube, and the profile of the axial velocity at the inlet of the draft tube changes, so that the development of the vortex rope can be avoided. Later, Tanasa *et al*. [11] extended this method to an axial hydro-turbine. The draft tube air admission method has also been implemented in many cases, for instance, Papillon and Sabourin [12] and Chirkov *et al*. [13], among others. It has been well recognized that air admission technique is efficient to decrease the pressure fluctuations, especially at low loads for Francis turbine. Both the water injection method and the air admission method are active methods for pressure fluctuation alleviation. However, these methods suffer from the drawbacks including the design cost, complexity of extra devices and the limitation of the operating parameters. There are also various passive methods developed to deal with the unstable flow and pressure pulsations. Two examples are the J-grooves [14, 15] and draft tube fins [16]. Although these two methods are capable of reducing the pressure pulsations in the draft tube, their practical applications are limited due to their cost, technics and efficiency.

As for the runner cone, its configuration and geometry also significantly influence the pressure oscillations as it changes the distribution pattern of the vortex rope in the draft tube [1, 13]. Qian *et al*. [17] confirmed by numerical results that the extended runner cone, runner cone with grooves and the round-top runner cone are able to suppress the low-frequency pressure oscillations. Sano *et al*. [18] also investigated the influence of spiral grooved runner cone on the draft pressure pulsations, and they found that the amplitude of pressure oscillation was reduced. In a very recent study, Gogstad [19] has experimentally investigated the effects of air injection and cone extension on the pressure pulsations. It was shown that although cone extension decreased the peak-to-peak values in some flow conditions, it also increased these values at other operation points.

In this study, we propose a new passive method by perforating holes on the runner cone. The effects of these holes on the vortex ropes and pressure pulsations will be investigated. This kind of perforation method has been used for blades of compressors or fans to improve the compressor surge margin [20]. Recently, we have successfully applied this method to the runner blades in a Francis hydro-turbine. It is found that the cavitation zone was greatly decreased, and the amplitude of pressure fluctuations and the related flow-induced noise reduced [21]. In this work, the influence of runner cone perforation on the draft tube pressure field characteristics is studied for the first time. Three runner cone model designs, viz. unperforated, 2-hole and 4-hole perforated, were experimentally investigated through high-speed photography to capture the vortex rope shapes in the draft tube. Meanwhile, numerical simulations based on ANSYS CFX were conducted for validation.

Experimental and numerical method

Geometrical model

This study investigates the influence of runner cone perforation on the flow characteristics within a Francis hydro-turbine, and the mechanism by which the draft tube-based vortex rope and associated pressure fluctuation amplitudes are altered. The studied turbine model has a hydraulic head of $H = 57$ m at rated condition. The runner diameter D_2 is 366.58 mm, and the numbers of runner blades, guide vanes and stay vanes are $z = 15$, $z_g = 24$, and $z_s = 24$, respectively.

For the Francis turbine, different runner cones with perforations were designed. As shown in fig. 1, the first two holes were drilled symmetrically on the bottom half of the runner cone, then another two holes were punched on the further bottom. The diameters of all holes are 7 mm, and their locations are decided based on the lowest pressure locations for the unperforated case (the details can be found in [21]). Except the perforation feature, all other geometrical characteristics are the same for the three used runner cone models. The vortex characteristics and the corresponding pressure pulsations in the draft tube will be investigated.

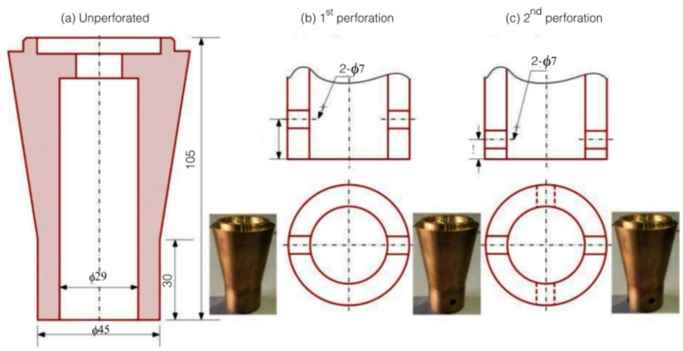


Figure 1. Three types of runner cones; (a) without perforation, (b) with 2 holes, (c) with 4 holes

Experimental set-up

The experimental tests were carried out on a test rig based at Harbin Electric Machines Company Ltd. (HELM) in China, where the test set-up was designed according to the IEC60193-1999 standard [22]. In order to obtain adequate data in terms of pressure field characteristics and its evolution within the draft tube, the high-speed photography method was adopted, and pressure sensors (Type 112A22, PCB, USA) were equipped at the wall of draft tube to measure the pressure fluctuations. For high-speed imaging, an endoscope with optical fiber (10 mm × 300 mm × DOV 50/80/90°, WOLF Inc., Germany) and a high-speed camera (i-SPEED 2, Olympus, Japan) were used. To decrease the distortion of images, a rectangular shell was designed as the outer wall of the draft tube.

Numerical simulation method

In simulations, the configuration and geometry is the same as that in experiments, and the grids for computations were generated. Five sets of meshes were done for grid-independency check [23], as shown in fig. 2, and finally the grid number of 7 million was used.

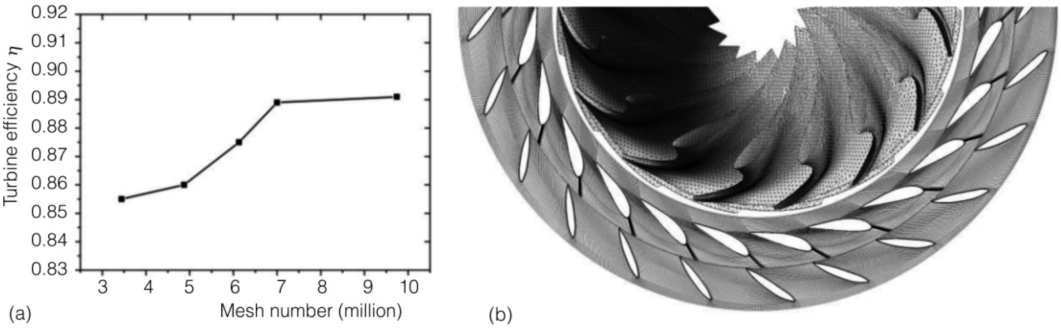


Figure 2. (a) Grid-independency check for partial load flow condition and (b) meshes for vanes and runner

Table 1. Operating conditions for the study

	α [mm]	n_{11} [rmin^{-1}]	Q_{11} [m^{3}s^{-1}]	σ
Partial load condition	16	80.4	0.486	0.258
Full load condition	28	83.2	0.768	0.277

To investigate in details the pressure fluctuation characteristics and their evolution, two cases viz. partial and full load conditions are tested, as presented in tab. 1. Therein, α, n_{11}, Q_{11}, and σ are the opening of guide vanes, the unit speed, the unit flow rate, and the cavitation number of device, respectively. The used SST k- turbulence model, being a combination of k-ω and k-ε turbulence models, has the advantage of adequately capturing flow field characteristics at targeted flow area. As for the discretization method, high-resolution scheme was used. The convergence criterion was set to 10^{-5}. The frozen rotor interface types were adopted to connect the rotating and stationary parts. In addition, the mass-flow rate condition, pressure outlet condition and no-slip wall condition were, respectively, set for the inlet of spiral casing, the outlet of draft tube and all the walls.

Results and discussion

Partial load condition

To investigate the effect of runner cone perforation on vortex rope development and associated pressure fluctuations, simulation results are first presented and analyzed. Figure 3 shows the vortex rope structure within the draft tube with different runner cone designs at partial load condition. The vortex ropes are presented in the form of iso-surfaces of pressure values. It can be seen that under the same flow condition, the volume of vortex rope in the draft tube becomes smaller as the thorough holes perforated. Meanwhile, if looking into the inter-blade flow vortices (not shown here), they also gradually reduced in volume.

To carefully check up on the formation of vortex ropes, the details of vortex ropes in the vicinity of runner cones are also presented in fig. 3. The vortex rope generates at the bottom half of runner cone, and grows along with the flow field in the draft tube. For the unperforated case, several starting points for vortex rope generation and growth were found. For perforation cases, the number of start location. In particular, there is only one vortex rope generates for the 4-holes runner cone. Meanwhile, with perforations the diameter of vortex rope also gets smaller. The decrease of the vortex rope volume would considerably contribute to the reduction of vortex ropes' vibrations and the associated pressure fluctuation amplitudes (will be discussed later).

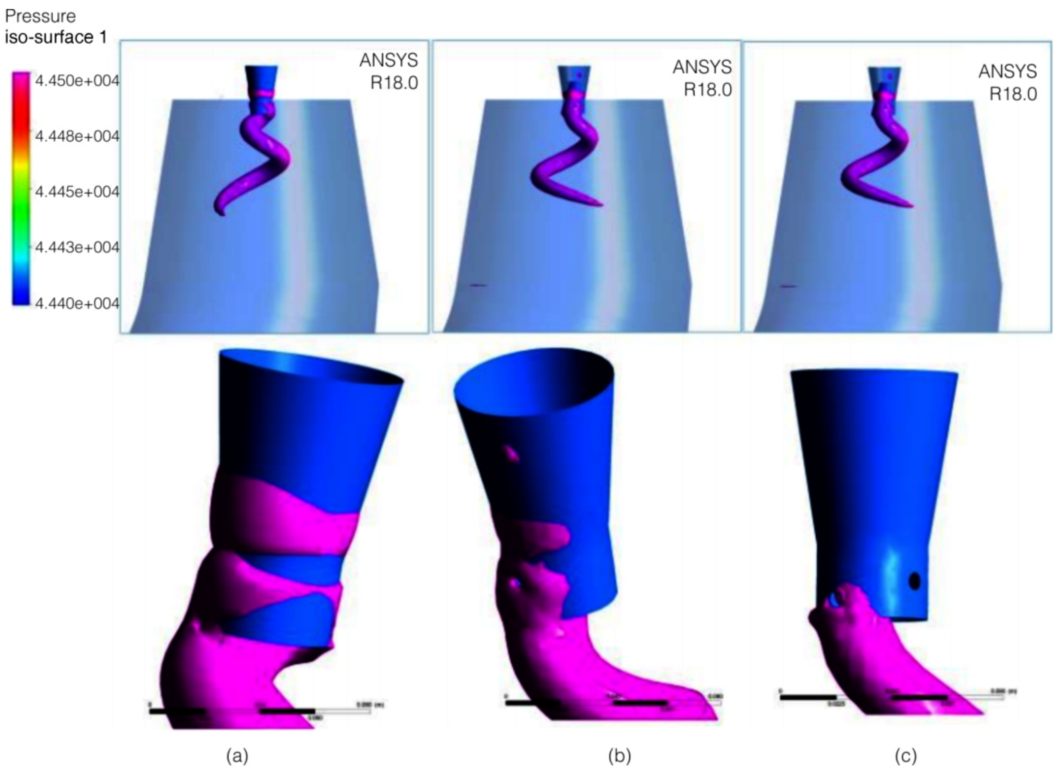


Figure 3. First row: Vortex ropes with different perforation strategies, in the shape of iso-surfaces of pressure value 44.500 Pa (α = 16 mm, σ = 0.258, n_{11} = 80.4 rpm); (a) without perforation, (b) with 2 holes, (c) with 4 holes; second raw: zoom-in of the shapes of vortex ropes in the vicinity of runner cones

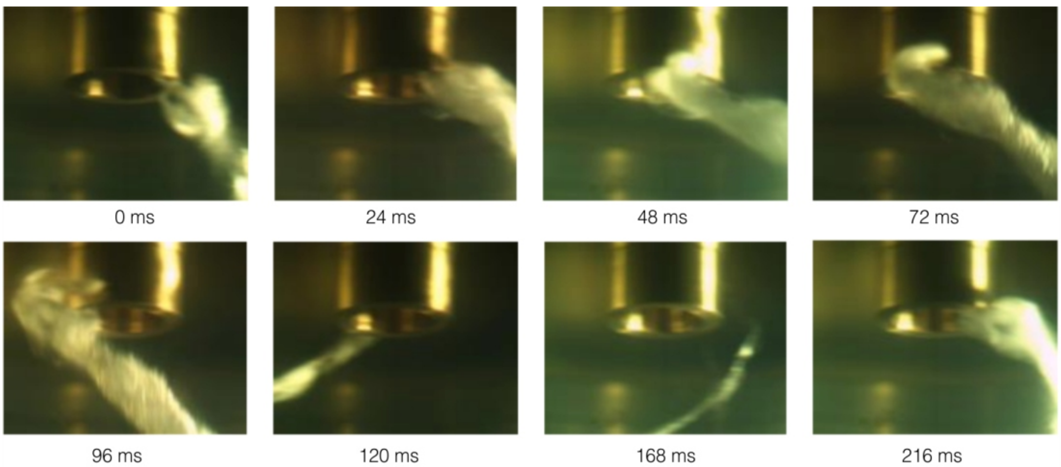


Figure 4. Development of vortex rope in draft tube without runner cone perforation

In experiments, the flow features in the draft tube have been recorded with high-speed photography. Figure 4 shows the evolution of vortex rope shape within a complete rotational cycle for the unperforated case. At partial load, the rotational period and the frequency of vortex rope were found to be around 216 ms and 4.5 Hz, respectively. Without perforation, the vortex rope shows a helical shape, consisting of 2 or 3 smaller ropes, twisted downstream. Also, the start points of these vortex ropes are not fixed during rotation, but continuously varying along the runner cone. The existence of several ropes was found to be closely related to the large low-pressure area around the runner cone, possibly giving rise to several cavitation inception points if the low-pressure area on the runner outlet gets larger.

Similarly, figs. 5 and 6 show the development of vortex ropes in the draft tube with 2 and 4 holes in the runner cone in one rotational cycle, respectively. After the perforation, the vortex rope volume was found to be noticeably reduced. With the number of perforation holes increased, the vibration of vortex ropes diminished. Especially for runner cone with 4 holes, the volume of vortex rope dramatically decreased around the runner cone, where there were only some tiny vortices instead of a single strong vortex rope. Nevertheless, small ropes still existed, though the volume was much smaller, which indicates that the cavitation energy may still exist. In other words, the amplitude of pressure fluctuation becomes lower but still remarkable.

To better understand such differences in vortex ropes, the velocity fields around the runner cone with 2 and 4 holes were also presented in figs. 5 and 6. It can be seen that the thor-

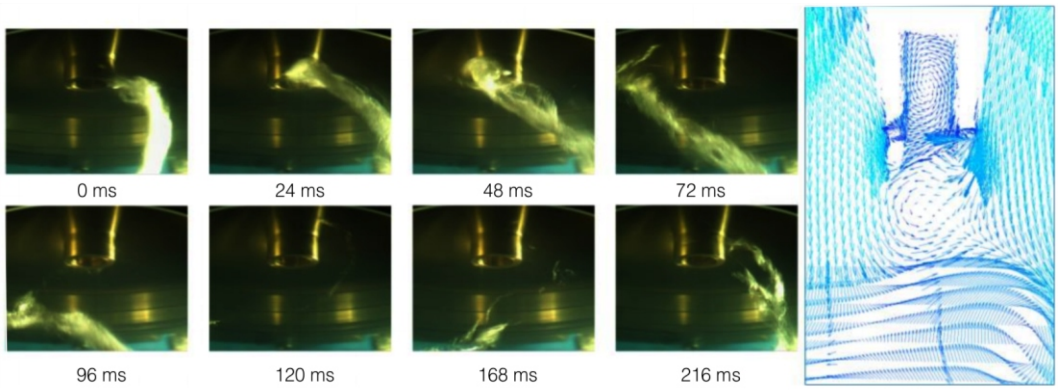


Figure 5. Development of vortex rope in draft tube with 2 holes in runner cone (partial load: α = 16 mm, σ = 0.258, n_{11} = 80.4 r/min), and a snapshot of velocity field (magnitude) around the runner cone (right)

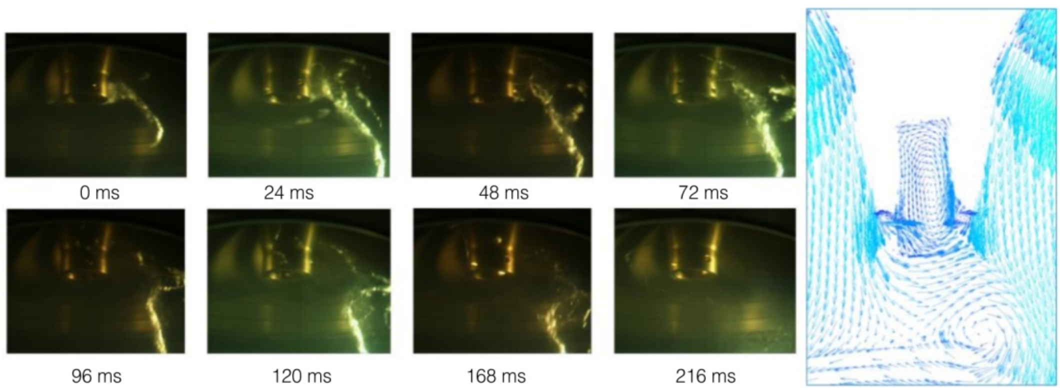


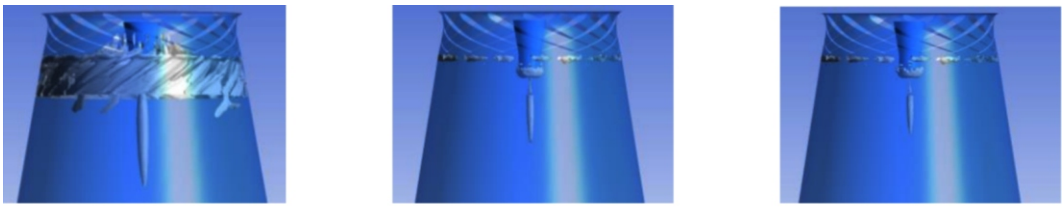
Figure 6. Development of vortex rope in draft tube with 4 holes in runner cone (partial load: α = 16 mm, σ = 0.258, n_{11} = 80.4 r/min), and a snapshot of velocity field (magnitude) around the runner cone (right)

ough holes connected the flows of high-pressure and low-pressure zone. Consequently, the lowest pressure zone, *i. e.*, the most probable starting points of vortex ropes, is shifted. In these two cases, they are shifted downstream, and at the same time the vortex zone decreases.

Full load condition

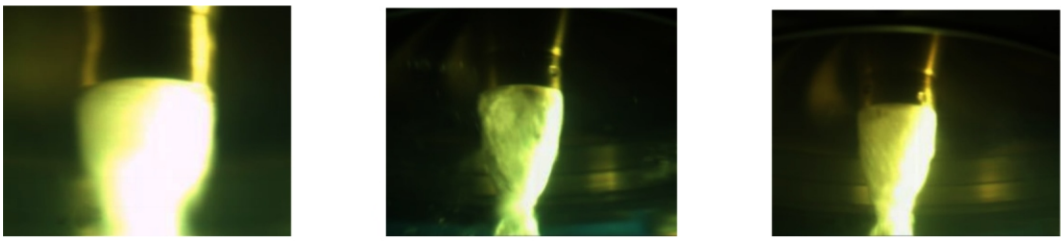
The full load condition is close to the limitation line of 95% power output, and the hydro-turbine only occasionally runs under this condition. For this condition, the vortex ropes are presented in fig. 7. They show a cylindrical shape for both perforated case and unperforated case. As expected, the volume of vortex rope decreases with the increasing of holes' number. Experimental observations are shown in fig. 8, and they confirm that vortex volume at the outlet of runner is obviously reduced after the perforations.

For a vortex with cylindrical structure, the evolution of its shape in time is not noticeable. Since the vortices for those three cases are similar, the changes of the associated pressure



(a) Without perforation (b) With 2 holes (c) With 4 holes

Figure 7. Numerical results of vortex ropes under full load condition with different runner cone designs



(a) Without perforation (b) With 2 holes (c) With 4 holes

Figure 8. Vortex ropes under large discharge condition with the three runner cone designs

pulsations should stem from the intact area below the runner. Actually, by checking the numerical and experimental results, the main difference lies in the vortex shapes below the runner. Under the full load condition, lumps of (cavitated) vortices shed from the outlet of the runner, which accounts for large portion for unperforated runner cone. As for the perforated cases, the number of shed vortices gradually decreases, and finally vanishes for 4 holes case. This feature would lead to complex changing in the pressure pulsations downstream.

Pressure pulsations

The purpose of runner cone perforation is to reduce the pressure fluctuation levels in the draft tube. In this section, the pressure pulsations for each case are presented and discussed. Four pressure monitoring points are set at the wall of the draft tube, *i. e.*, two points with a dis-

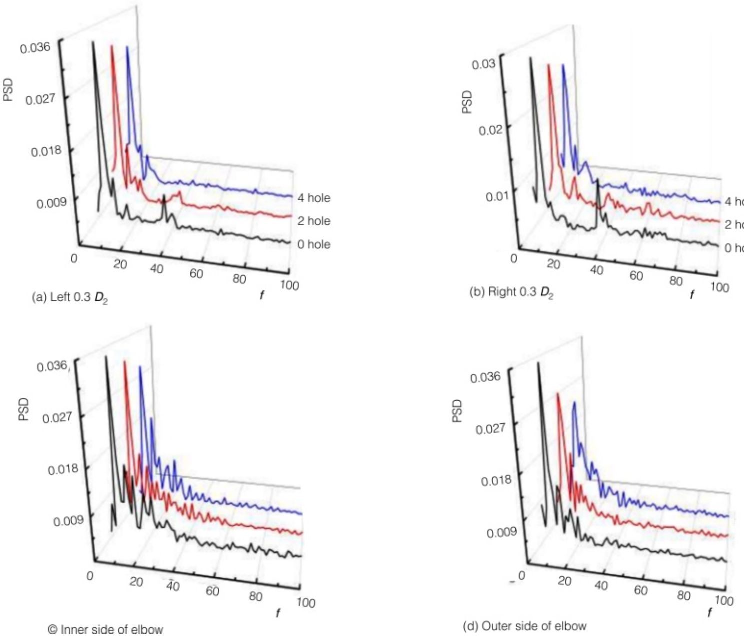


Figure 9. Energy distribution of pressure pulsations at partial load condition (α = 16 mm, σ = 0.258, n_{11} = 80.4 r/min)

Table 2. Pressure fluctuations for various runner cones and flow conditions

Conditions	Cone design	n_{11} [r/min]	$\Delta H/H$ [%]	Main frequency [Hz]
	0 hole		6.13	4.52
α = 16 mm	2 holes	80.4	7.14	4.52
	4 holes		6.17	4.52
	0 hole		1.67	3.05
α = 28 mm	2 holes	83.2	1.36	2.93
	4 holes		1.47	8.06

tance 0.3 D_2 below the runner outlet (left 0.3 D_2 and right 0.3 D_2), one point at the inner side of the draft tube elbow, and last point at the outer side of the draft tube elbow. The locations of these monitoring points are decided according to the standard of IEC-60193 [22].

The energy distributions of pressure pulsations under the partial load are shown in fig. 9. Without perforations, the pressure pulsation at the outer side of elbow is the largest, and it also decreases the most after perforations. Other points show the same trend of pressure pulsation mitigation. However, for the full load condition, the trend of pressure pulsation for various runner cones is not consistent. As increasing the holes number, the magnitude of pressure pulsations decreases at the points of left 0.3 D_2, right 0.3 D_2, and the outer side of elbow at full load. At the same time, the main frequency also decreases. Whilst for the point at the inner side of elbow, the energy of pressure fluctuations decreases not too much, but the main frequency obviously increases, tab. 2. This should be due to the complex changing in the flow field, and it requires a further investigation.

Conclusion

This work proposed a new method of runner cone perforation to mitigate the pressure pulsation in the draft tube in a Francis hydro-turbine. Numerical and experimental studies with two designs (2 hole perforations and 4 hole perforations in the runner cone) are performed to investigate the their influence on the evolution of vortex ropes and the associated pressure pulsation magnitudes. It is found that the runner cone perforation positively impacts the flow characteristics in the draft tube by reducing the vortex rope volume. At partial load, after perforations, the vortex rope patterns changes from several twisted ropes to a single thin rope, and therefore the pressure pulsation magnitude greatly decreases for all the four monitoring points. However, for the full load, although the volume of cylindrical vortex rope decreases after perforation, its effect on the pressure fluctuations is not the same for different monitoring points. Therefore, the runner cone perforation method could serve as an efficient way to deal with the pressure pulsation induced problems in the turbine. However, more research are still required to deepen the understanding about the hydrodynamics behind the presented method and to explore its applications.

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