

Effects of the vortex rope dynamic characteristics on the swirling flow in the draft tube cone

J Yang¹, Q J Hu², J H Ding¹, F B Kong³, W F Han¹, W Xiao¹ and Z W Wang⁴

¹ Technology Center, State Grid Xinyuan Company Ltd., Beijing, China.

² State Grid Xinyuan Company Ltd., Beijing, China

³ Rengcheng District Agricultural Comprehensive Development Office of Jining, Shandong, China

⁴ Department of Thermal Engineering, Tsinghua University, Beijing, China

yangjingshirley@163.com

Abstract. As the Francis turbine operated at the off-design conditions, the hydraulic instability may occur due to the vortex rope developed in the draft tube. The swirling flow produced at the blade trailing edge has been proved to have a direct effect on the vortex rope characteristics. Research on the swirling flow is meaningful for understanding the hydraulic instability mechanisms. In this paper, the different swirling flow characteristics at part load and overload conditions were studied by numerical method. The relations between the vortex rope dynamic characteristics and the swirling flows were deeply investigated. The results showed the swirl number, which was chosen to stand for the strength of the swirling flow, changed with the vortex rope evolution. The swirl number fluctuations and its frequency were closely related to the vortex rope precession and its diameter and length. The dominant frequencies of the swirling flow in spiral vortex rope flow field were consistent with the vortex rope. However, the swirl number frequency turned out to be the vortex rope harmonic frequencies in the columnar vortex rope condition. Besides, the propagation laws of the swirling flow in the draft tube cone were also different in the different vortex rope flow fields.

1. Introduction

Francis turbine is often required with wide operating region to meet the variation demands of the electrical grid. However, the vortex rope may develop as the hydraulic turbine operated far from the best efficiency point, which may cause strong pressure pulsations and vibrations due to the dynamic characteristics of the vortex rope. Extensively investigations have been conducted to study the mechanisms of the vortex rope. Till now, it has been widely accepted that the swirling flow plays a key role for the vortex rope formation ^[1].

The swirling flow produced at the trailing edge of the blades. The flow angles of the swirling flow entering in the draft tube would change with the flow rate. Under the centrifugal force effects induced by the swirling flow, the central zone pressure at the draft tube cone decreases with the swirling flow strength till to the saturation pressure, and then the cavitation vortex rope presents in the cone.

Göde et al ^[2] found the swirling flow had direct impact on the vortex rope characteristics and the draft tube hydraulic losses. Galv'an et al ^[3] analyzed the draft tube hydraulic losses in detail, and proved the losses can be decreased by optimizing the blade trailing edge and changed the swirling flow angle. Susan-Resiga et al ^[4] also suggested to study the relations of the swirling flow and draft



tube flow in the hydraulic design stage, it is necessary for improving the runner and draft tube design level. For specific swirling flow studies, Bosioc et al^{[5][6]} used the guide vane to produce the swirling flow, and a free runner was chosen to simulate the loads change. Their results proved the swirling flow change with the loads, and its propagation laws also changed with the loads. Chen et al^[7] simulated the swirling flow in a cone and a straight tube. They proved the swirling flow in a cone instable the flow in the columnar vortex rope condition and increase the flow instability in the spiral vortex rope condition. Dörfler et al^[8] also found the vortex structure is largely decided by the swirling flow and finally affected the flow stability. Nishi et al^[9] reviewed the recent research progress about the swirling flow. They systematically introduced the research conducted by swirl apparatus, for example the guide vane. They believed the draft tube surge is primarily related to the swirl flow at the draft tube cone. However, they also found the test apparatus cannot be applied to simulate the swirling flow at the overload conditions. But the instabilities aroused by overload vortex rope are even more serious.

Although many efforts have been paid on the swirling flow, the research on the dynamic vortex rope counteractions is still insufficient. Further study is needed to reveal more correlations between the swirling flow and vortex rope^[10]. Based on these conclusions, this paper focuses on the vortex rope dynamic characteristics effects on the swirling flow under part load and overload conditions according to the simulation results. The conclusions obtained in this paper are meaningful for discussing the instability flow mechanisms at the off-design conditions.

2. Physical model and Numerical methods

A model Francis turbine with a diameter of 0.42m was used in the simulation. The entire computational domain is consisted of spiral casing, stay vane (20), guide vane (20), runner (17 blades) and draft tube. The numerical methods have been detailed introduced in paper "The numerical simulation of draft tube cavitation in Francis turbine at off-design conditions" published in Engineering Computations. The total mesh is 1666000 nodes and 7140000 elements. The time step of 0.000167s was set, which is 1/360 of one revolution of runner. The boundary conditions were set to be total pressure inlet and static pressure outlet.

The swirl number, which stands for the strength of the swirling flow, was used in this paper to quantitative analysis the swirling flow intensity. This parameter is defined as the ratio of angular momentum flux to axial momentum flux, see equation (2.1). Here v_z is the axial velocity, v_θ is the circumferential velocity, R_w is the maximum diameter of the draft tube inlet.

$$S = \frac{\int_0^{R_w} v_\theta v_z R^2 \cdot dR}{R_w \cdot \int_0^{R_w} v_z^2 R \cdot dR} \quad (2.1)$$

The swirling flow originates at the trailing edge of the blade, and then spreads in the draft tube. Under the effects of vortex rope, the strength of the swirling flow will no doubt change in the draft tube cone. Study the evolution characteristics of the swirling flow is helpful for understanding its interaction with vortex rope. Since the vortex rope mainly develops in the draft tube cone, four sections in the cone, which respectively named as dtin, dt1, dt2, dt3, dt4 (see figure 1), were set to emphasis analyze the swirling flow in it.

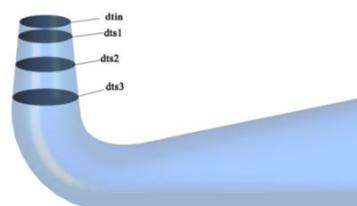


Figure 1. Defined sections in draft tube cone

3. Results and discussions

Based on Chen et al [7]'s conclusion, the swirling flow have different effect on the cavitating flow according to the vortex rope type. The swirling flow at the spiral vortex rope condition (cond1: $n_{11}=n_{opt}$, $0.744Q_{opt}$) and columnar vortex rope condition (cond2: $n_{11}=0.876n_{opt}$, $1.162Q_{opt}$) were simulated in this paper to analyze the differences between them. The detailed cavitation structures and pressure pulsation results can refer to "The numerical simulation of draft tube cavitation in Francis turbine at off-design conditions" published in Engineering Computations. This paper only focuses on the cavitation dynamic characteristics effects on the swirling flow. The frequency, length and diameter were chosen to stand for the dynamic characteristics of the vortex rope.

Firstly, the results of spiral vortex rope flow fields are presented. Figure 2 shows the hydraulic turbine efficiency and swirl number changes with the cavitation evolution at this condition. It is known to all that the efficiency begins to decrease after the inception cavitation occurs, and then it drops rapidly if the local pressure keeps decreasing. It is worth noting that the swirl number also changed with the cavitation, and it showed a similar change trend to efficiency with the cavitation development. The vortex rope encouraged the swirling flow strength at the inception cavitation stage, and then the stronger vortex rope suppressed the intensity of the swirling flow as the cavitation fully developed.

For further investigation, the cavitation condition of Thoma number $\sigma=0.005$ under cond1 was selected to obtain the detail swirling flow characteristics. The swirl numbers fluctuations in the four defined sections are shown in figure 3(a). It can be observed the periodic evolutions of the swirl numbers in the four sections with different amplitudes. The fluctuations in dts1 and dts2 are higher, which may relate to the stronger disturbance aroused by thicker vortex rope diameter near there. Besides, the obviously phase shift of the swirl number can be seen because of the eccentric precession effects of the spiral vortex rope.

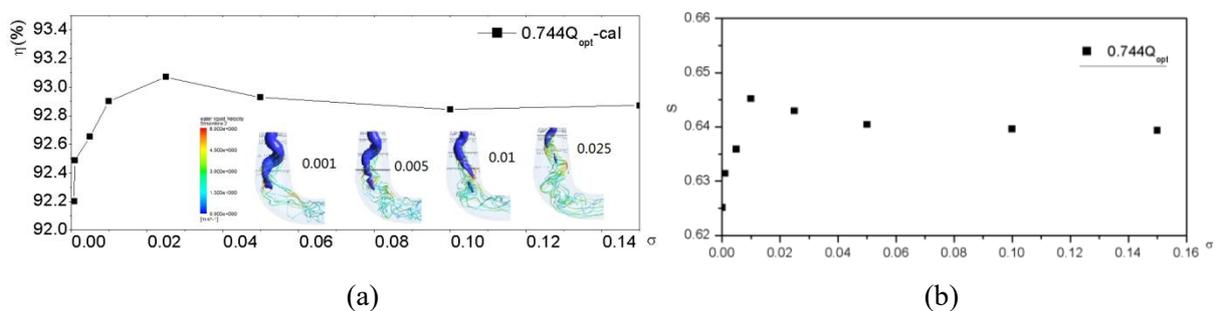


Figure 2. (a) Efficiency and (b) swirl number changes with cavitation evolution under spiral vortex rope conditions ($n_{11}=n_{opt}$, $0.744Q_{opt}$).

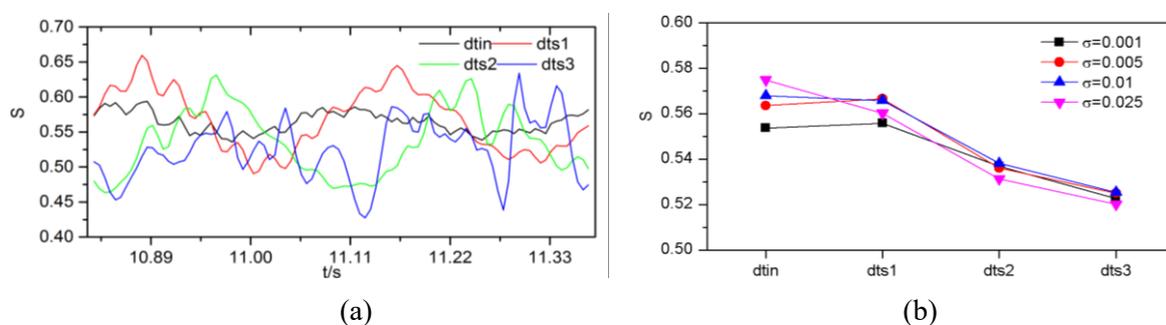


Figure 3. (a) Swirl numbers at the defined sections in two vortex rope precession periods; (b) Spread of the average swirl numbers at the draft tube cone ($n_{11}=n_{opt}$, $0.744Q_{opt}$, $\sigma=0.005$).

The fluctuation characteristics of the four swirl number in the defined sections showed the swirling flow changes in the draft tube cone. Thus, its propagation laws under different cavitation stages were also analyzed according to the average swirl numbers, as displayed in figure 3(b). The swirl number basically decreases with the strength dissipating in the draft tube cone. For the condition $\sigma=0.025$, the vortex rope length didn't reach to the section dts2 as shown in figure 2(a), the swirl number close to a linear descent law in the draft tube cone. With the Thoma number decreasing, the swirl numbers at dts1 section displayed a little rise. That may relate to the vortex rope length and diameter fluctuations with the cavitation development. But overall, the changes are not significant except at the draft tube cone inlet section. In section dtin, the swirl number keeps decreasing with the cavitation development.

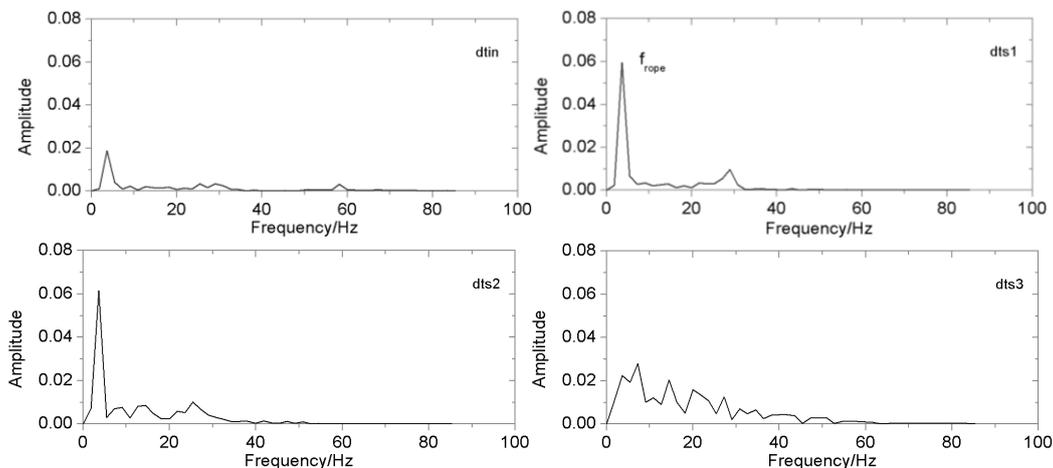


Figure 4. Frequencies of the swirl numbers at the draft tube cone sections ($n_{11}=n_{opt}$, $0.744Q_{opt}$, $\sigma=0.005$).

The spectral analyses results about the swirl numbers are also presented in figure 4. And the diameters and lengths frequencies of the vortex rope in dts1 and dts2 are shown in figure 5. It can be seen the main frequencies of swirling flow at dtin, dts1 and dts2 were basically corresponding to the vortex rope frequency. The amplitudes in dts1 and dts2 were higher, and then it showed a rapidly drop in dts3. That may relate to the diameter and length fluctuations of the vortex rope. Because the rope diameter frequency in dts1 is the f_{rope} as shown in figure 5, which is the same with the swirl number in this section. The high frequency amplitude in dts2 may be the results of the combined effects of diameter and length. Besides, in figure 2(a), the vortex rope length kept changing with small ranges of vortex shedding at the rope tail and the section dts3 just close to the tail, so the fluctuation amplitude of the swirl number decreased in this section. These relations proved the impacts of the vortex rope dynamic behaviors on the swirling flow.

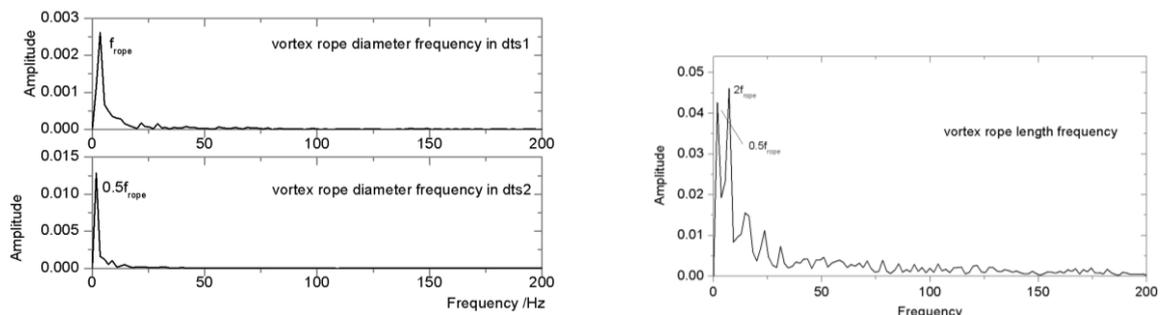


Figure 5. Frequencies of the Vortex rope diameter and length ($n_{11}=n_{opt}$, $0.744Q_{opt}$, $\sigma=0.005$).

Because of the different dynamic characteristics between the columnar vortex rope and spiral vortex rope, the swirling flow may show a new pattern in columnar vortex rope flow field. To verify this, the swirling flows at the overload condition were also discussed in this paper.

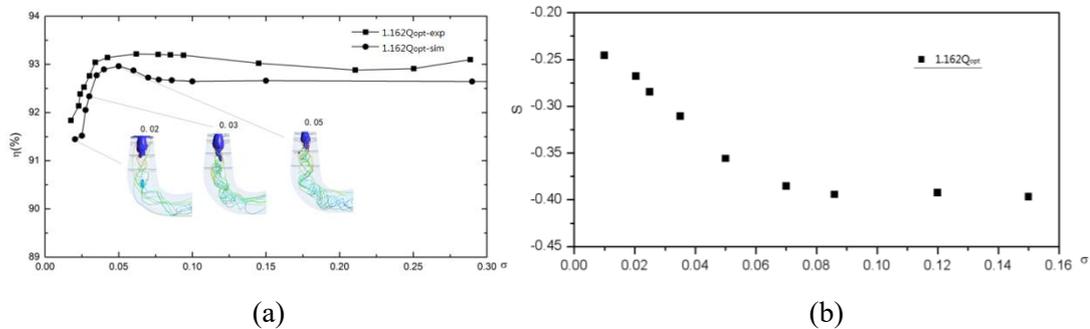


Figure 6. (a) Efficiency and (b) swirl number changes with the cavitation evolution under columnar vortex rope conditions ($n_{11}=0.876n_{opt}$, $1.162Q_{opt}$).

The efficiency and swirl number changes with the cavitation are shown in figure 6. The efficiency curve is similar to the result of last condition, but the swirl number curve was different from that. The swirl number kept climbing after the inception cavitation. That is to say, the cavitation gradually suppressed the swirling flow strength. And it can be observed in figure 6(a) the rotation of the streamline was reduced in the draft tube. To prove this, the swirling flow spreading law in the draft tube cone was also discussed.

Figure 7(a) displays the swirl numbers at the defined four sections in two columnar vortex rope precession periods under $\sigma=0.05$. Comparing the swirl numbers fluctuations in the four sections, the frequency was obviously higher than that in the part load condition. The strongest fluctuations occurred in dts1 section, which is the same with the situation in spiral vortex rope flow field.

The swirl numbers propagations along the draft tube cone are shown in figure 7(b). The change trends were similar to the results in spiral vortex rope flow but with different meanings. In this condition, the strength of the swirling flow increased along the draft tube except near the dts1 section. Moreover, the swirl numbers were more affected by the cavitation, the average swirl numbers increased with the cavitation evolution, the strength of the swirling flow decreased with it.

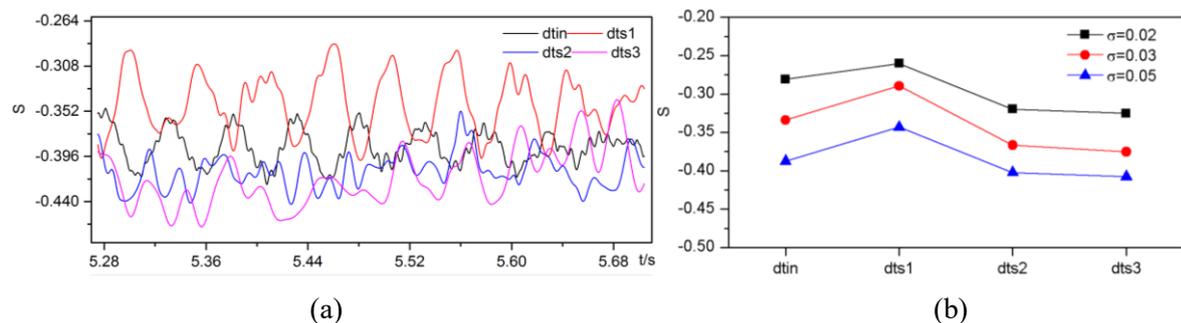


Figure 7. (a) Time history of the average swirl number at the draft tube cone sections in two vortex rope precession periods; (b) Spread of the average swirl number at the draft tube cone. ($n_{11}=0.876n_{opt}$, $1.162Q_{opt}$, $\sigma=0.05$).

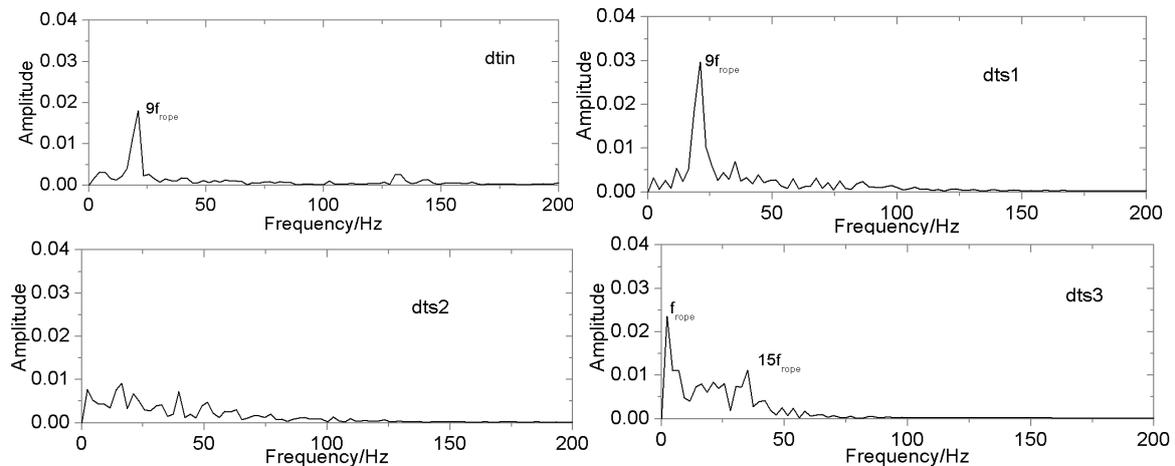


Figure 8. Frequencies of the swirl numbers at the four draft tube cone sections ($n_{11}=0.876n_{opt}$, $1.162Q_{opt}$, $\sigma=0.05$).

It is also worth noting that the swirl numbers frequencies in the four sections were different from each other as shown in figure 8. The main frequency at dtin and dts1 were the multiple frequency of the vortex rope, which is differ from the results in spiral vortex rope conditions, in which the main frequency was equal to the vortex rope as stated above. In dts2 section, the swirl number had the lowest amplitude and more complex frequencies. In figure 6(a), we can see the vortex rope diameters reached to the maximum near the section dts1, which explain the maximum fluctuation amplitude in this section. But the average swirl number was lowest in section dts1. What's more, the maximum length of the vortex rope had not reach to the section dts3 and the swirling flow was less affected by the vortex rope. However, its average swirl number value was the largest as shown in figure 7(b). These results indicated the vortex rope instable the swirling flow under the columnar vortex rope conditions, which is consistent with the conclusions proposed by Javadi et al [11] and Chen Changkun [7].

The reason for the multi-times frequency may also relate to the stronger dynamic characteristic of the columnar vortex rope. In figure 9, the frequencies of the vortex rope diameter and length are also shown. Because of the shorter length of the vortex rope at this condition (see figure 6(a)), only the diameter at dts1 section and vortex rope length is shown. We can see the vortex rope diameter and length exist multiple frequencies, reflecting the strong dynamic fluctuations of the columnar vortex rope. Under the superposition of the two factors, the multi-times frequencies of the swirl numbers were produced. In dts3 section, only the vortex rope precession effect was revealed, thus, the main frequency at dts3 transferred to the vortex rope frequency, again. It's no doubt that the swirling flows under these conditions are more complex than that in the spiral vortex rope conditions.

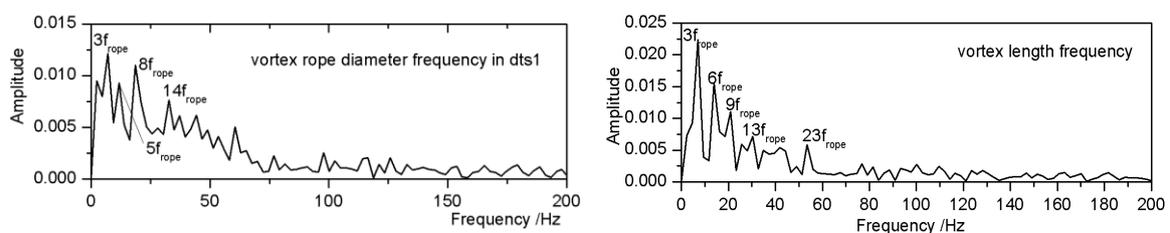


Figure 9. Diameter and length frequency of the vortex rope ($n_{11}=0.876n_{opt}$, $1.162Q_{opt}$, $\sigma=0.05$).

4. Conclusions

According to the analysis of the swirling flow in the part load and overload conditions, the swirling flow variations in the draft tube cone with the vortex rope evolutions were discussed in this paper.

The result showed the swirl number frequency in the defined draft tube cone sections was the same with the vortex rope under part load condition. And the swirl number amplitude largely depended on the diameter and length fluctuation of the vortex rope. The propagation laws of the swirl number basically displayed a gradually dissipation trends in the draft tube cone under spiral vortex rope conditions. However, the situations were different in the overload conditions. The swirl numbers presented multiple frequencies under the superposition effects of the vortex rope length, diameter and precession dynamic characteristics. And the swirling flow strength gradually decreased with the cavitation development. The lowest average swirl number means the strongest vortex rope diameter fluctuations. The swirling flow spreading law presented similar trends with that in spiral vortex rope conditions. But it revealed the opposite intensity change meaning in columnar vortex rope condition.

By synthesizing these results, it can be concluded that the swirling flow is obviously affected by the vortex rope type, especially in overload condition. The fluctuation frequency of the swirl number has direct relations with the vortex rope diameter, length and vortex rope precession. The dynamic behaviors of the columnar vortex ropes stable the swirling flow with the cavitation development. But in spiral vortex rope flow field, the swirl number shows a similar change trend to the efficiency. Considering the strong flow instability, the swirling flow in cavitating vortex rope flow field still need further studies to prove these results.

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