

Numerical Investigation of Guide Vane Hydraulic Torque Characteristics of a Pump Turbine in Pump Mode

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Abstract. This study performs numerical simulations to investigate the hydraulic torque characteristics of a pump turbine at different guide vane openings in pump mode. The SST k- ω turbulence model is utilized to simulate the flow field at guide vane angles from 1° to 21°. The simulation results reveal that the overall hydraulic torque shows a decreasing trend as guide vane opening increases. However, significant asymmetry of hydraulic torque exists among different guide vanes at certain openings. This asymmetry highly correlates with the large vibration observed during pump start-up in the field test. By analysing pressure contours and velocity streamlines at openings of 3°, 9° and 17°, the causes for torque asymmetry are explored in depth. The primary factors are identified as circumferential flow non-uniformity, distinct flow discharge tendencies between boundary guide vanes, and reverse flow towards upstream stay vanes. The research findings provide important insights into the hydraulic torque characteristics of pump turbines at off-design conditions, and offer valuable guidance for the optimal design and stable operation of pump turbines in pump mode.

Keywords: SST k- ω turbulence model, Water pump turbine, Hydraulic torque.

1. Introduction

In the pump operation of pump turbine, the flow phenomena exhibit complex and diverse characteristics. As the water is introduced into the pump, high-speed vortices are formed between the impeller and the guide vanes. These vortices are rapidly accelerated and compressed under the action of the blades. Guided by the guide vanes, the water flows smoothly, effectively utilizing the kinetic energy of the impeller, thereby enhancing the pump's efficiency. However, the flow phenomena vary significantly at different guide vane openings. With smaller guide vane openings, the water flow is restricted, forming compact and high-speed streamlines, increasing the pump's pressure but potentially leading to flow instability. Conversely, with larger guide vane openings, the water flow has lower velocity and broader streamlines, reducing the pump's pressure, but it might affect the efficiency. Therefore, at pump mode, the flow phenomena at different openings have a significant impact on the performance of water pumps and turbines, necessitating in-depth research and optimized designs.

A large number of studies have focused on the hydraulic performance and mechanical characteristics of pump turbines under different guide vane openings. Mao et al. [1] delved into the impact of axial hydraulic forces during the startup of a pump-turbine on support brackets, main shafts, and rotors, distinguishing between unstable and steady regions during the startup process. Wang et al. [2] considered the clearance flow and balancing pipes, and simulated the internal flow characteristics and pressure pulsation of a pump turbine under no-load condition. They examined the blade passage vortex evolved from the high-speed water ring in the vaneless region. Tao et al. [3] conducted a comparative numerical study, exploring the flow energy dissipation characteristics of a pump-turbine in pump and turbine modes. They employed numerical simulation methods to compare the energy dissipation features in pump and turbine modes, providing insights for optimizing

performance under different operating conditions. Li et al. [4] analysed the influence of different numbers of runner blades on pressure fluctuation distribution in turbine mode, providing valuable insights for enhancing the performance of pump turbines. Lin et al. [5], utilized entropy generation theory and the Q-criterion to investigate the impact of different offset angles of inlet guide vanes on internal flow and energy dissipation of a centrifugal pump. Their research demonstrated that excessive offset angles of inlet guide vanes could lead to increased energy loss in the inlet pipe, thereby reducing the head and efficiency of the centrifugal pump.

Some studies have also paid attention to the flow non-uniformity among multiple guide vane passages and the variation patterns of guide vane hydraulic torque. Fan et al. [6] studied the relationship between noise frequency and head of a pump turbine at slight guide vane opening. By introducing the torque variation rate of a single guide vane and CFD flow simulation, they found that the repeating reversal of fluid in the guide vane region is the cause of vibration during load rejection. Ji et al. [7] investigated abnormal sounds and vibrations occurring in the distributor of a reversible pump-turbine when guide vanes were slightly opened (maximum opening of about 6%) during the pump mode. They applied a three-dimensional numerical CFD method to study the unsteady flow behaviour in the guide vane region of a pump-turbine operating in pump mode. Dynamic meshing techniques were introduced to accurately capture flow pattern variations. The study revealed significant flow deflection between the GVs during startup and shutdown processes, leading to vibrations and abnormal sounds due to abrupt changes in hydraulic torque (HT) on the GVs. Jin et al. [8] studied the flow characteristics around guide vanes during rapid guide vane closing, and found the variation of hydraulic loss caused by guide vanes reached 362.5%. Besides, at a guide vane angle of 2-3°, significant pressure pulsation was generated in the vaneless region. Li et al. [9] investigated the differences in guide vane hydraulic torque between using synchronous and asynchronous guide vanes. They found that when the guide vane opening was lower than 16.4%, the discrepancy between the two schemes was not noticeable. However, when the opening exceeded 16.4%, the discrepancy increased markedly. Wang et al. [10] conducted a numerical investigation on the effect of the closure law of wicket gates on the transient characteristics of a pump turbine in pump mode. Their study explored the impact of the closure law on transient characteristics and provided essential information for the design and operation of pump-turbines.

This study places significant emphasis on utilizing advanced numerical simulation techniques to analyse the behaviour of pumps and turbines at different guide vane openings. Through rigorous simulations, we observed a remarkable phenomenon: substantial instability occurs at moderate to low vane angles. This instability is characterized by significant torque fluctuations, highlighting a crucial aspect in pump operation that requires further investigation.

Our research delves deeply into understanding the behaviour of a pump turbine, focusing specifically on the hydraulic torque experienced by guide vanes under pump mode conditions. By combining experimental observations, theoretical insights, and cutting-edge numerical simulations, we aim to unravel the complexity of hydraulic machinery. Through these efforts, we have contributed valuable knowledge to the field, enhancing the design, efficiency, and stability of pumps and turbines across various applications.

2. Research Method

The research object of this study is a prototype pump turbine. The number of runner blades, denoted as Z , is 7. The number of stay vanes and guide vanes, denoted as Z_{sv} and Z_{gv} , are 20 and 20 respectively. The diameter at the runner inlet D_1 is 2.72 m, and the diameter at the outlet D_2 is 2.066 m. The rated speed of the runner is 200 rpm. The guide vanes of the unit are numbered as shown in Figure 1.

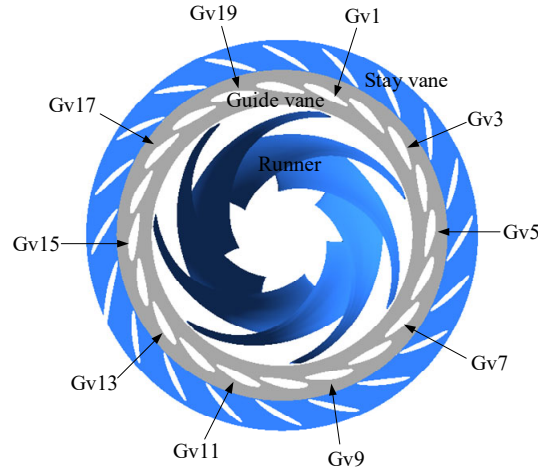


Figure 1. Movable guide vane number

According to existing research and engineering experience, the guide vane hydraulic torque is small at large opening and tends to become unstable at small opening. Therefore, this study selected multiple openings below the rated opening for flow calculation, ranging from 1° to 21° with an interval of 2° . The hydraulic torque is the integral of the moment on the entire vane surface with respect to the center of rotation. Following the International Electrotechnical Commission standard (IEC60193) [11], the guide vane hydraulic torque is converted into the guide vane hydraulic torque coefficient using Equation (1):

$$T_{G,ED} = \frac{T_G}{\rho g H D_1^3} \quad (1)$$

Where $T_{G,ED}$ is the guide vane hydraulic torque coefficient; T_G is the guide vane hydraulic torque, N·m; ρ is water density, kg/m³; g is gravitational acceleration, m/s²; H is water head, m; D_1 is runner inlet diameter, m.

The calculation adopts ANSYS CFX with the SST k- ω turbulence model. The SST k- ω model adds two equations on the basis of the typical k- ω model, incorporating the advantages of both the k- ω and k- ϵ models. Through a blending function, the model behaves like the k- ϵ model in the free-stream region and the k- ω model near the wall. In the near-wall region, compared with the typical k- ω model, the SST model further considers the transport of shear stress and limits the eddy-viscosity [12]. This enables good capture of near-wall flow characteristics even with relatively low grid number.

3. Result and Discussion

3.1 Global simulation results

Figure 2 shows the guide vane (GV for short) hydraulic torque coefficients at different guide vane openings (GVOs for short). Overall, smaller GVO leads to larger average torque coefficient. TG, ED is around 0.42 when the GV is almost fully closed, and decreases to around 0.08 when the guide vane angle (GVA for short) reaches 21° . At the same GVO, hydraulic torques also differ among GVs. As shown in Figure 3, at a GVA of 1° , the torque difference among GVs is small. However, as the GVA increases to 3° , 5° , 7° and 9° , significant differences emerge among GVs. The maximum range of TG, ED reaches 0.1 at GVA of 3° and 0.08 at GVA of 9° . The difference then decreases rapidly, and rises again at GVA of 17° and 19° , with maximum range of 0.09 at GVA of 17° . The standard deviation of TG, ED for all GVs exhibits a similar pattern, with three peak values at GVA of 3° , 9° and 17° .

The initial cause for this phenomenon can be identified from Figure 4. At GVA of 3° , 9° and 17° , GV16 or GV17 has the minimum torque. These two GVs are located between the second flow passage from the volute tongue in the clockwise direction. This implies excessive flow rate through the first

or third passage as water enters the volute tongue, potentially resulting in insufficient flow and decreased torque in the second passage.

In addition, at GVA of 3° , GV13 and GV14 have noticeable influence, at GVA of 7° , GV8 and GV9 have noticeable influence, while at GVA of 17° , GV1 to GV4 have relatively large torque. This indicates different inducing factors for torque differences at the three GV angles, requiring further detailed analysis.

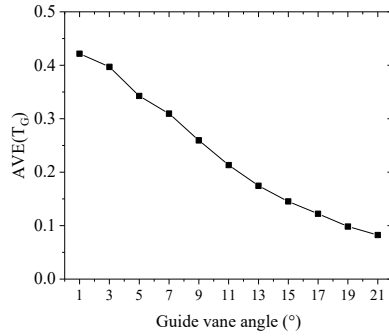


Figure 2. The $T_{G,ED}$ varies with the angle of guide vanes.

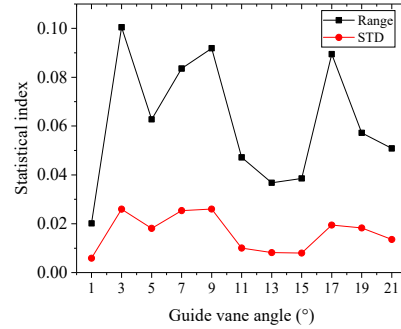


Figure 3. Range and standard deviation of $T_{G,ED}$ among guide vanes.

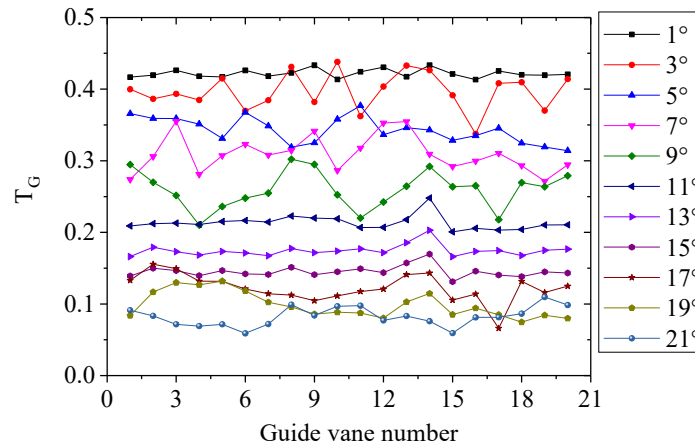


Figure 4. $T_{G,ED}$ differences between different guide vanes

3.2 Field test result

In previous work, some field test data was obtained. Figure 5 shows the low-frequency vibration data in the Y direction of the lower bracket (LBY) and the Z direction of the head cover (HCZ) from field testing. It can be seen that during the guide vane opening stage, there is a short period of intense vibration. The maximum vibration occurs when the GVO is 10.2%. According to the design data, the corresponding GVA is 3.6° at this time. Since each moment during start-up is affected by the inertia force of the previous moment, the actual GVA that results in the maximum unit vibration should be slightly less than 3.6° . This is in good agreement with our previous computational results.

Figure 6 shows the analysis results of the high-frequency vibration signal from the acceleration sensor on the head cover using short-time Fourier transform (STFT). It can be observed that when the GVO is 28% and 49%, the 95% confidence peak-to-peak value of the head cover vibration has maximums. The corresponding GVAs are 10.1° and 17.7° , which is also in good consistency with the computational results.

The most significant frequency component in the field test signal is 70Hz, corresponding to 21 times the rated speed or 21fn, which belongs to the rotor-stator interaction frequency. Since the measurement point is above the head cover, the main vibration energy comes from the rotor-stator

interaction phenomenon generated by all guide vanes together. But undoubtedly, the hydraulic torque asymmetry caused by different GVOs intensifies the head cover vibration at three specific GVAs.

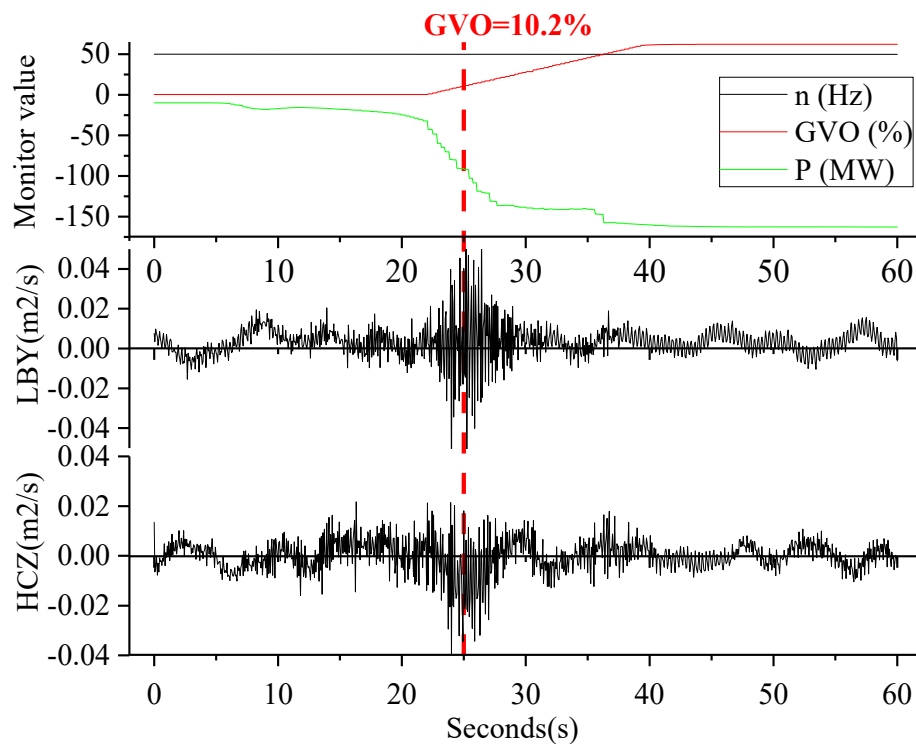


Figure 5. Vibration in Y direction of the low bracket (LBY) and Z direction of the head cover (HCZ) during pumping startup (field test data).

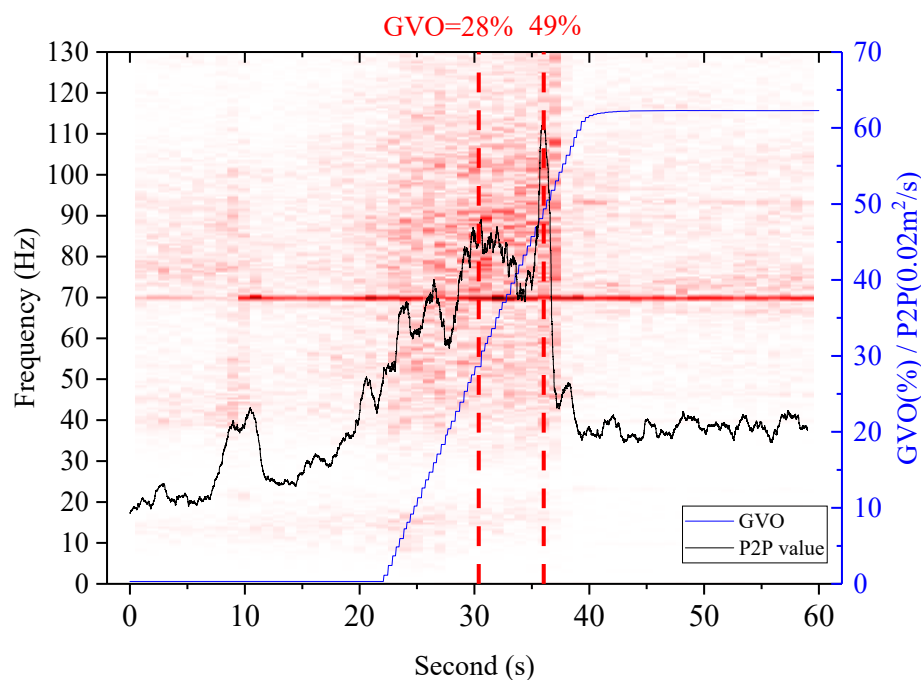


Figure 6. Signal spectrogram of HCZ. STFT results, 95% confidence peak-to-peak value and guide vane opening (field test data).

3.3 Discussion

It should be noted that the research object of this study is in the ring region. As can be seen from Figure 1, the distribution of stay vanes is not completely uniform. Near the volute tongue, the stay vanes are closer to the center of rotation, while on the opposite side of the volute tongue, they are further away from the center of rotation. This is for the consideration of flow uniformity at turbine mode, but it may also amplify the non-uniformity of flow from guide vanes to stay vanes at small openings of pump mode.

Figure 7 shows the pressure contours at different guide vane angles, and Figure 8 shows the corresponding velocity streamlines. By comparing the two, some interesting flow phenomena can be discovered.

3.3.1. GVA=3°

At a guide vane angle of 3°, jets are generated between the guide vanes towards the stay vane region. Ideally, the hydraulic torque of a guide vane is mainly affected by two factors: (1) the jet velocity at the inner side of the leading edge, and (2) the jet velocity at the outer side of the trailing edge. As the torque vector is positive when it aligns with the Z-axis, higher jet velocities at the inner leading edge and outer trailing edge correspond to lower guide vane torque. However, some variations exist in the actual numerical simulation.

From the statistical results, GV6, 11, and 16 have relatively small hydraulic torques, while GV5, 8, 10, 13 and 14 have relatively large hydraulic torques. As shown in Figure 7(b), the pressure distribution on the external side is very uniform for the former group of guide vanes, while for the latter group, most have a low-pressure region at the leading edge on the external side. This low-pressure region tends to open the guide vane and increase the hydraulic torque. Observing the streamlines in Figure 8(b), we can find these low-pressure regions originate from the high-speed flow areas on the external sides of the corresponding guide vanes, which arise from the non-uniformity of outflow. The jets from many guide vane passages, when entering the region between the stay vanes and guide vanes, do not flow out along the stay vane passages due to insufficient pressure. Instead, they flow circumferentially clockwise and accumulate continuously until generating adequate radial velocity to interact with the stay vanes. The stay vanes sometimes guide the fluid to flow out to the volute, such as SV13, while sometimes the trailing edges obstruct the outflow, such as SV11. The guided fluid flows out rapidly, forming a low pressure region, while the obstructed fluid generates an adverse pressure gradient flow, adhering to the external side of the next guide vane at high speed. Both scenarios ultimately lead to low pressure regions at the leading edge on the guide vane external side, resulting in higher hydraulic torque.

3.3.2. GVA=9°

From the statistical results, higher hydraulic torques occur at GV1, 8, and 14, while lower hydraulic torques occur at GV4, 11, and 17. As shown in Figure 7(e), the former group of guide vanes all have large low-pressure regions on the external side. Although the latter group does not have low pressure regions on the external side, the low pressure regions that should have been caused by jets at the trailing edge on the external side are also absent.

Observing the velocity streamlines in Figure 8(e), it can be seen that GV4, 11, and 17 are all located at periodic boundaries. They have high-speed outflow at the leading edge passages but significantly lowered velocity at the trailing edge passages. We tentatively term these three guide vanes as “boundary guide vanes”. The flow directions on either side of them differ noticeably. In the passages before the boundary guide vanes, the flow tends to discharge from the previous stay vane passage, such as the flow between GV10 and GV9 discharging along SV9 and SV8. In the passages after the boundary guide vanes, the flow discharges along the nearest stay vanes, such as the flow between GV13 and GV12 discharging along SV13 and SV12. This state is unique in the present study: at smaller guide vane angles, the outflow from all guide vane passages discharges from the previous stay vane passage, while at larger guide vane angles, the outflow all discharges along the nearest stay vane passage.

3.3.3. GVA=17°

From the statistical results, at a guide vane angle of 17°, GV2, 3, 13, 14 have larger hydraulic torques, while GV17 has a smaller hydraulic torque. From the pressure contours in Figure 7(i), the guide vanes with larger torques have a low-pressure region extending to the previous stay vane passage at the leading edge on the external side. This means both the distribution area and intensity of the low-pressure region at the leading edge on the external side increase, resulting in increased hydraulic torque. However, the low-pressure region of GV17 is still strictly distributed at the inner side of the leading edge and outer side of the trailing edge. The increased velocity will simply reduce the hydraulic torque.

From the velocity streamlines in Figure 8(i), it can be seen that the flow state at this time is opposite compared to the flow characteristics at GVA=9°: some of the outflow from guide vane passages flows counterclockwise into the next stay vane passage along the leading edge of the guide vane. For example, part of the outflow from GV1 and GV2 discharges between SV1 and SV2, while another part flows around the trailing edge of SV2 and discharges between SV2 and SV3. This flow state is also critical, because at smaller guide vane angles, the outflow angle decreases and the flow can hardly go upstream around; at larger guide vane angles, the gap between guide vanes and stay vanes narrows, and the fluid going upstream needs to overcome greater adverse pressure gradients.

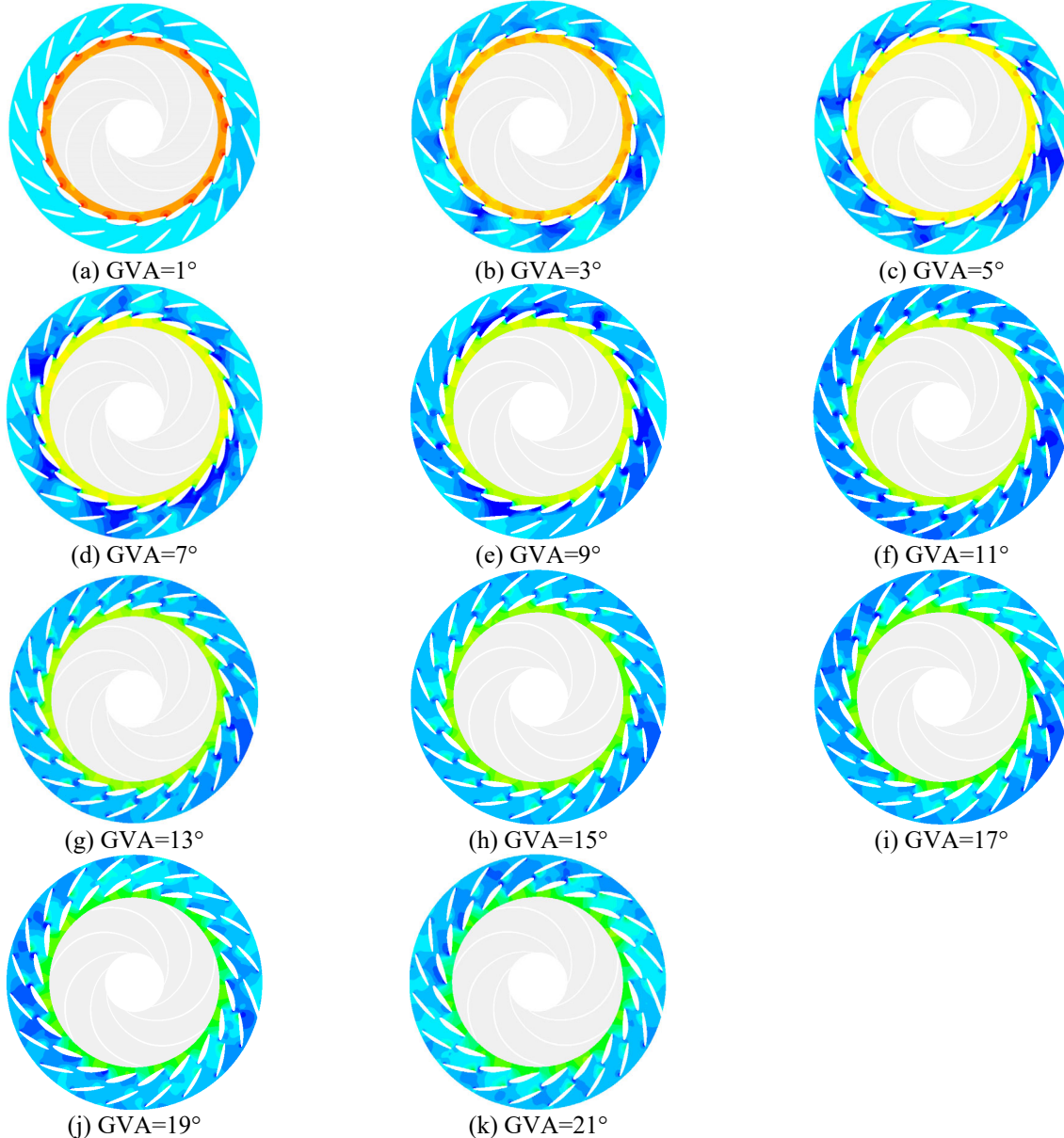


Figure 7. Pressure contour of different guide vane angles at ring sections.

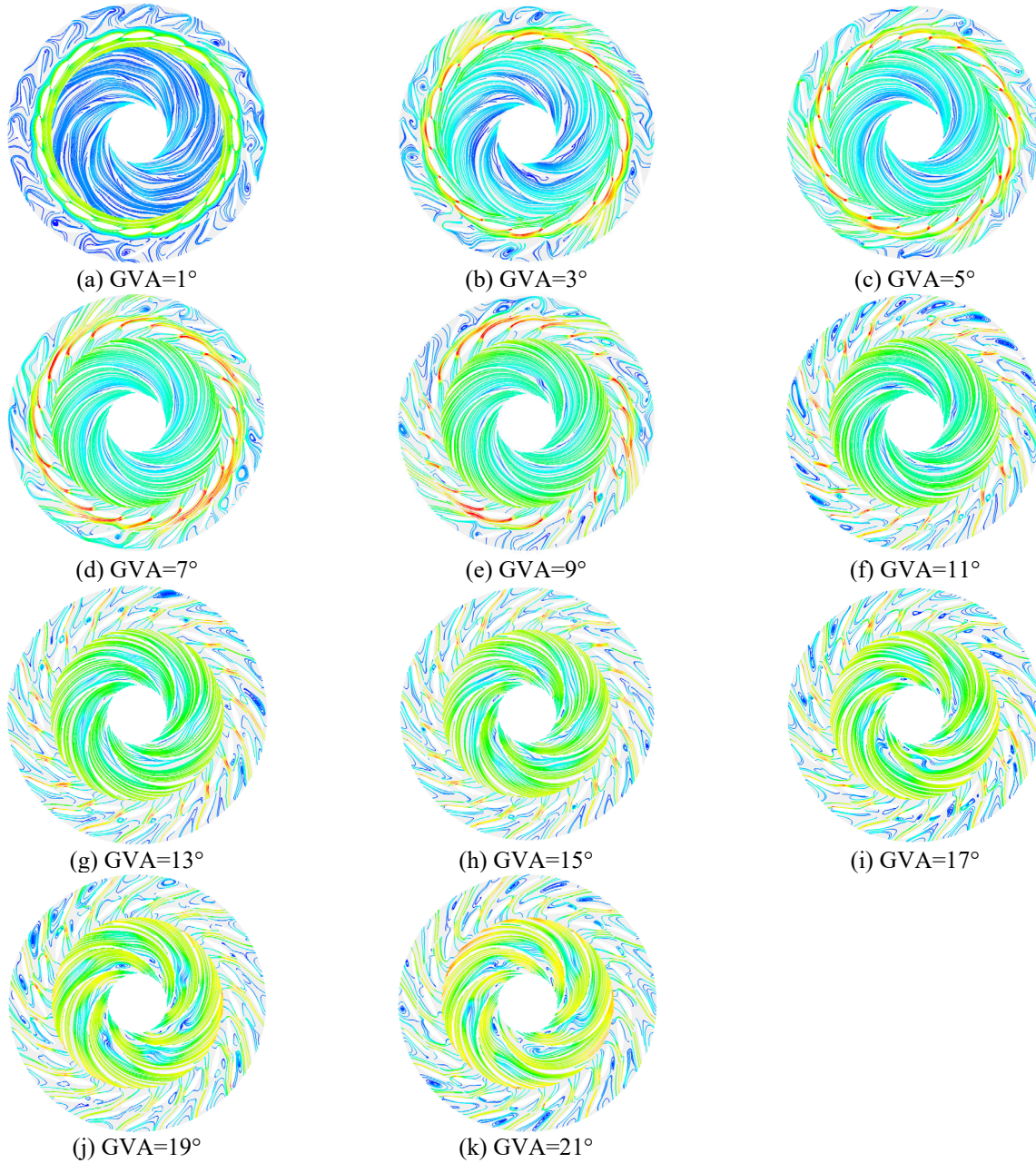


Figure 8. Streamline of different guide vane angles at ring sections.

4. Conclusion

This study performed CFD simulations of a pump turbine operating at different guide vane openings in pump mode, and summarized the variation pattern of hydraulic torque. By comparing with field test data, three operating conditions with asymmetric hydraulic torque were discovered, and the causes of torque asymmetry were explored. The main conclusions are as follows:

(1) As the guide vane opening increases, the hydraulic torque of the guide vanes shows an overall decreasing trend. At some openings, significant differences exist in the hydraulic torque of different guide vanes, which may be an important reason for the large vibration of the hydropower station at certain moments during start-up in pump mode.

(2) At a guide vane angle of 3° , due to the low flow rate, only a few stay vane passages undertake the outflow function, resulting in circumferential flow non-uniformity and differences in guide vane hydraulic torque.

(3) At a guide vane angle of 9° , the outflow direction of each guide vane passage points between the nearest stay vane passage and the previous stay vane passage, leading to different destinations of outflow from different guide vane passages and differences in hydraulic torque.

(4) At a guide vane angle of 17° , as the flow rate further increases, the outflow direction of each guide vane passage is closer to the next stay vane passage, resulting in some flow from certain guide vanes discharging from the next stay vane passage and bringing differences in hydraulic torque.

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