Quantitative analysis of backflow of reversible pump-turbine in generating mode

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Abstract. Significant vibration and pressure fluctuations are usually observed when pump-turbine is operated during the off-design conditions, especially turbine brake and runaway. The root cause of these instability phenomena is the abnormal unsteady flow (especially the backflow) inside the pump-turbine. In the present paper, numerical simulation method is adopted to investigate the characteristics of the flow inside the whole passage of pump-turbine with two guide vane openings (6° and 21° respectively) and three kinds of operating conditions (turbine, runaway and turbine braking respectively). A quantitative analysis of backflow is performed in both the axial and radial directions and the generation and development of backflow in the pump turbine are revealed with great details.

1. Introduction

The instability problem of pump-turbine caused by abnormal unsteady flow is a big barrier to the development of the pumped storage power plant [1-12]. The safety and efficiency of the units decrease with the increase of pressure fluctuation, vibration, swing of the shaft and so on. For example, rotating stall of pump-turbine could cause significant flow separation and backflow. For further improvement of pump-turbine design, a quantitative description of backflow (e.g. in terms of amplitude, distribution and development stage) is badly needed.

The flow inside the pump-turbine during the off-design conditions (especially turbine brake and runaway modes) is very complex, e.g. generation of significant backflow. The backflow has been investigated by many researchers. Hasmatuchi et al. [7] and Widmer et al. [8] found the backflow phenomenon in the vaneless space during turbine brake. Sun et al. [9] studied the backflow in pump-turbine with misaligned guide vanes. Zhang et al. [10] employed a one-dimensional and three-dimensional coupling approach to analyse backflow in the transient process of pump-turbine. A more detailed study of backflow in pump turbine was performed by Giovanna et al. [11] and Sun et al. [12]. Previous work mainly focused on the backflow in the vaneless space. In fact, the backflow can also be observed in many other domains (e.g. stay vanes or guide vanes) and shows strong non-uniformity in different channels of runner. Those characteristics of backflow in the full domain of pump-turbines have not been revealed yet. Hence, a thorough quantitative analysis of the backflow (e.g. in terms of the distribution and stage of development) is indeed necessary.
In the present paper, a quantitative analysis of backflow in the pump-turbine is performed in the whole passage of the pump-turbine. Distributions of backflow along the axial, radial and circumferential directions in the whole passage of pump-turbines (e.g. stay and guide vanes, vaneless space and runner) are revealed together with their magnitudes. Two typical guide vane openings and three kinds of operating conditions are employed for comparison.

2. Description of method

In the present paper, the inner flow of pump-turbine is numerically studied in generating mode during off-design conditions. Six operating conditions with two different guide vane openings of pump-turbine were quantitatively analysed with a focus on the flow state of the pump-turbine. The simulated domain covers the whole fluid passages of pump-turbine with geometrical parameters shown in table 1.

| Parameters                        | Values |
|-----------------------------------|--------|
| Number of blades                  | 9      |
| Number of guide vanes             | 20     |
| Number of stay vanes              | 20     |
| Diameter of runner outlet         | 0.5 m  |

Two typical guide vane openings (6° and 21° respectively) were selected for the analysis with 6° representing the maximum opening of prototype pump-turbine and 21° demonstrating strong S-shaped characteristics. Three kinds of operating conditions (i.e. turbine, runaway and turbine brake modes) were selected for each guide vane opening. For the simplicity of demonstration, the velocity field was adopted to recognize the backflow. As the runner is a rotating part of the machinery, the relative velocity (or streamline) with the runner blade as the reference frame was adopted for the analysis. In the following analysis, the streamline was colored by the turbulence kinetic energy.

In generating mode, the fluid passes through the spiral case, guide vanes, vaneless space, impeller, and draft tube in sequence. In order to quantify the comparison, velocity in the rotating coordinate can be decomposed into three components (referring to Fig.1): circumferential velocity, axial velocity and radial velocity respectively. Through such kind of decomposition, the radial velocity can be employed to represent the existence and developing stage of backflow in the pump-turbine.

![Figure 1. Decomposition of the velocity in rotating coordinates [13]](image-url)
Backflow could lead to the decrease of total flow entering into the runner, and also cause the generation of vortex. A large amount of backflow occur at off-design conditions of pump-turbine, especially during runaway and turbine brake modes.

In the present paper, a cross-section surface (named as “surface A” in the following analysis) in the vaneless space between the runner and guide vanes was employed for the analysis. The surface was colored by the magnitude of radial velocity. The vector perpendicular to the surface A represents the radial direction with inside being the positive direction and outside being the negative direction. The magnitude of radial velocity is described by the different color and sizes of vectors.

To quantify the distributions of backflow, backflow discharge was calculated in several specific surfaces for all kinds of operating condition and guide vane openings based on the numerical simulations. The total flow rate can be calculated as

$$ q = \int_{s} v ds, \quad (1) $$

where $q$ is the total flow rate; $\vec{v}$ is the vector of radial velocity. $q_{in}$ and $q_{out}$ are defined as,

$$ q_{in} = \int_{s} v_{in} ds, \quad (2) $$

$$ q_{out} = \int_{s} v_{out} ds, \quad (3) $$

where $v_{in}$ stands for the radial velocity in the direction from the guide vane to the runner and $v_{out}$ represents the radial velocity in the opposite direction. Then, the total flow rate can be represented as

$$ q = q_{in} - q_{out}. \quad (4) $$

The backflow distribution varies with the fluid passing passages significantly along the flow direction. To obtain the variations of backflow along the flow direction or axial direction, the whole passage of pump-turbine was divided to three domains (i.e. guide vane, vanless space and runner).

![Figure 2. Selected surfaces and line in runner and guide vane for the analysis](image)

The surfaces or lines employed for quantitative study in the present paper are shown in Figure 2. A line between the hub and shroud in the runner channels was selected for analysis. The backflow of each blade channel was shown using the inlet surfaces of channels (as shown in Figure 2) with “channel 1” representing the inlet surface of the first channel and the other channels numbered counter-clockwise along the circumference direction of the runner. “Surface 1-4” divide “surface A”
equally into four parts from top to bottom. Surfaces representing inlet and outlet of guide vanes respectively fit the boundary of the guide vanes.

3. Results and discussions
Firstly, the backflows for different guide vane openings and operating conditions are shown. Figures 3 and 4 display the vector of radial velocity on surface A and relative streamline in the runner. The structure and distribution of vortex can also be observed through the distribution of streamline near the surface A. The color of streamline represents the magnitude of turbulent kinetic energy. The distributions of streamline and turbulent kinetic energy are symmetrical in turbine mode, whereas they are uneven in turbine brake and runaway modes. Due to a lot of vortex structure blocking the passage during off-design conditions, the internal flow field is distorted significantly and turbulent kinetic energy at runner inlet is higher than one at the other area.

The generation of vortex structure is closely connected with the backflow described by the radial velocity hence the vector distribution on surface A will be emphatically analysed. During off-design conditions (e.g. turbine brake and runaway modes), backflow mainly appears at the runner inlet with strong non-uniformity. The mechanism of the generation of backflow can be explained from two viewpoints. On the one hand, the coming flow collides with the blades when it enters into the runner, leading to the increase of flow resistance and decrease of kinetic energy. On the other hand, the centrifugal force in the flow passage is large for the runner with long channels (e.g. those in the pump turbines) and when the centrifugal force is greater than the flow inertia force, the backflow generates. The backflow disappears when pump-turbine operated at the turbine mode as shown in Figure 3c and also previous work [14]. Therefore, special attention will be paid to the characteristics of backflow during turbine brake and runaway modes.

![Figure 3](image)

**Figure 3.** The backflow at surface A and relative streamlines in the runner during different conditions of pump-turbine with guide vane openings 21°. Surface A was colored with radial velocity and the streamline was colored with turbulence kinetic energy. (a) braking operation; (b) runaway; (c) turbine operation.

![Figure 4](image)

**Figure 4.** The backflow at surface A and relative streamlines in the runner during different conditions of pump-turbine with guide vane openings 6°. Surface A was colored with radial velocity and the streamline was colored with turbulence kinetic energy. (a) braking operation; (b) runaway; (c) turbine operation.
Comparing Figures 3 and 4 (with guide vane opening respectively at 21° and 6°), it is obvious that the flow condition gets worse for large guide vane opening in terms of the maximum radial velocity and vortex structures in channel.

The flow state also varies with fluid passing zones. One typical line along the axial direction in the runner and several cross-sectional surfaces in three domains were selected to analyse the distributions of backflow along axial direction and radial direction.

Figure 5 shows the variation of radial velocity from shroud to hub in the runner. Backflow can hardly be observed near the shroud and it occurs at 40% of the total height between the shroud and the hub at the shroud side. After 40% point, the magnitude and direction of radial velocity ($V_r$) fluctuate with the increase of the height. These phenomena demonstrate that backflow shows strong spatial distribution in the axial direction with significant occurrence near the hub.

As a periodical distribution of backflow in circumferential direction of the runner was observed in Figures 3 and 4, Figure 6 further shows the backflow discharge at each inlet of blade channel. The channels were numbered in Sec. 2. When the guide vane opening is 6°, the backflows in different channels show no observable difference. Whereas, when the guide vane opening is 21°, a remarkable difference among the backflows in different channels can be observed with the biggest difference of discharge even up to 0.16m$^3$/s. To be emphasized, operational modes and guide vane openings are also paramount parameters determining the characteristics of backflow.

To further demonstrate the distribution of backflow along the axial direction, surface A was divided into four parts with surface 1 representing the top layer near the hub and surface 4 representing the bottom layer near the shroud. The variations of backflow discharge along the axial direction of the surface A is quite different between 21° and 6°. When the guide vane opening is 6°, the backflow discharge is high in the middle part of the surface A but it is small at the hub and shroud. At 21°, the backflow discharge slightly increases with the variations of height from the hub to the shroud.
Figure 7. The variation of backflow discharge versus the height of surface A during different operational conditions. 1 represents the top subsurface of surface A, and so on.

Figure 8. The backflow discharge at the outlet and the inlet of guide vanes during different operational conditions.

Figure 8 represents the backflow discharge at the inlet and outlet of guide vane. The backflow at the outlet is obviously higher than one at the inlet, especially when the guide vane opening is 6°. Figure 8 also demonstrates that backflow is also affected by the operational conditions.

4. Conclusion

The backflow of pump-turbine is strongly influenced by the guide vane opening and operational conditions. Through quantitative analysis of backflow in different zones and directions, the main findings of the present paper can be summarized as following:

1. The backflow occurs during turbine brake and runaway modes of pump-turbine while no significant backflow can be observed for turbine mode.
2. The distribution of backflow shows strong spatial characteristics. For example, at 21°, strong backflow shows near the hub in the runner channel while the backflow is significant near the shroud in the vaneless space in turbine brake mode. In the runner, backflow also distributes non-uniformly in different channels.
3.Guide vane opening is a critical parameter determining the characteristics of backflows.

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