Experimental Study on Hydraulic Torque of Guide Vane of Pump Turbine under Turbine Working Condition

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Abstract: In order to analyze the magnitude and variation of water torque of the guide vane of the pump turbine under turbine conditions, a pump turbine model of a pumped storage power station in China was used to process the movable guide vane shaft based on electrical stress analysis method, and the water torque tests of synchronous guide vane and asynchronous guide vane were conducted respectively. Analysis of the test results shows that: when the asynchronous guide vane is not used, the change of the guide vane water moment factor of all the guide vanes tested keeps consistent with the increase of the guide vane opening, and the direction of the water moment gradually turns from the guide vane closing direction to the guide vane opening direction; After setting 10 # guide vane as asynchronous guide vane, when the difference between the opening of asynchronous guide vane and the opening of synchronous guide vane is less than 16.4%, the water torque factor of the measured guide vane tends to be evenly distributed. when the difference is greater than 16.4%, the water torque increases sharply with the increase of the opening value, and the water torque factor of different guide vanes differs greatly.

Keywords: pump turbine; Guide vane; Water moment; Opening

Research background

Pumped turbine is the core component of pumped storage power station for energy conversion. The main function of its water guide mechanism is to form and change the flow velocity circulation entering the runner. As there are many operating conditions of the pump turbine, the pump turbine often needs to change its operating conditions, and its vibration is generally large in the pump operating conditions and transitional operating conditions, which sometimes causes resonance of the whole water guide mechanism and is prone to fatigue damage of the water guide mechanism. Therefore, it is of great significance to study the water moment of the guide vane [[1-2]].

At present, the research on the movable guide vane of pump turbine is not detailed. Cao Shuliang and Li Qifei and others [[4]] carried out numerical analysis of solid-liquid two-phase flow in the movable guide vane area to obtain wear prediction and hydraulic loss of the guide vane components. Luo Xing Kun and established a multi-objective optimization design system for hydraulic turbine movable guide vanes based on NSGA-II algorithm. Li Rennian and others [[6]] analyzed the influence of the flow pattern behind the guide vane on the internal flow of the runner when studying the S characteristics of the pump turbine. Guo Tao et al. [[7]], Huang Jianfeng et al. [8-9] , Wang Wenquan et al. [[10]] vane from different the turbulence characteristics in the movable guide vane. Ji xingying et al. [[11]] based on the model test of Zhuzhou tubular turbine, numerically calculated the turbine guide vane intake and analyzed the guide vane water moment at different blade angles. Li Rennian et al. [[12-13]] analyzed the pressure pulsation in the bladeless region and the runner region during the full flow channel numerical simulation. F.Botero and others [[14]] conducted non-invasive detection tests on the bladeless area of the pump turbine to analyze the rotating stall and backflow phenomena in the rotating wheel. Liu Jintao et al [[15]] proposed a new vortex-viscosity model to study turbulent kinetic energy in bladeless region of pump turbine. Vlad Hasmatuchi and others [[16]] studied the evolution and development of rotating stall in the runner by introducing high-pressure airflow into the guide vane region to observe the flow pattern. Christophe Devals and others [[17]] used the method of two-dimensional and three-dimensional relative ratio to carry out numerical simulation research on the torque of the movable guide vane and mutually verify with the test values.

Based on the above research situation, the research on the guide vane region by domestic and foreign scholars is mainly based on numerical simulation, with less experimental research. In this paper, the water torque test of the guide vane is carried out on the pump turbine model, and the water torque of the pump turbine under the conditions of synchronous guide vane and asynchronous guide vane are measured and compared. The research results can provide reference for the design of water guide mechanism, governor and operation of water pump turbine.

Test Contents

The model used in the test model test of 2.1 is a pump turbine model of a pumped storage power station in China. the parameters are shown in table 1 . the model test

The inspection device is shown in figure 1 . The measured guide vanes are numbered according to a certain rule as shown in fig. 2 . the measured guide vanes are 4#, 9#, 10#, 11#, 14#,

For 18#, set 10# guide vane as asynchronous when testing the water torque of guide vane with asynchronous guide vane. The measured opening starts from 18.4% to 100% to ensure the comprehensiveness of data analysis. In addition, in order to analyze the moment characteristics of water flow to guide vanes with different openings, several movable guide vane positions with different openings are selected as shown in figure 3.

Table 1 Geometric Parameters of Model Pump Turbine

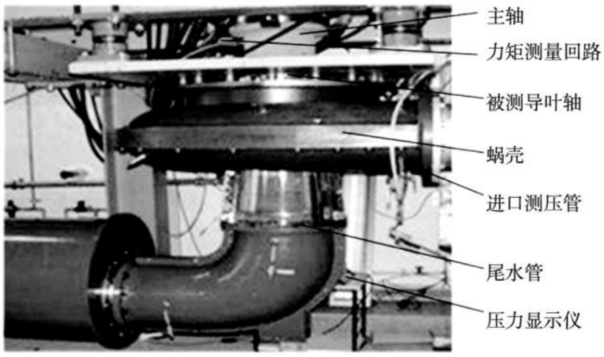
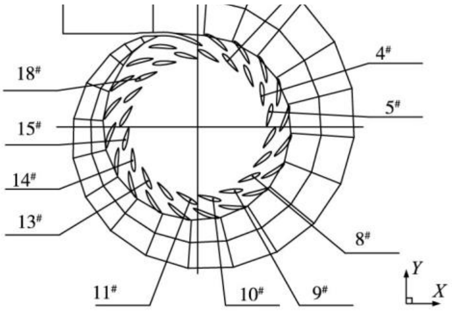


Figure 1 Model Test Facility



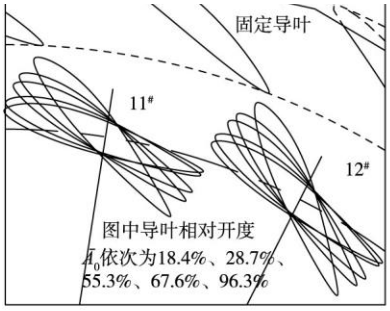


Fig. 2 guide vane arrangement under test fig. 3 guide vane movement diagram

The test plan of 2.2 is to measure the water torque of the guide vane of the model pump turbine. Based on the electrical stress analysis method, two groups of wire resistance strain gauges are pasted on the processed guide vane shaft in two directions forming 45° and 135° with the axis, and are connected in parallel to form a full bridge type measuring bridge circuit. When the torque of the movable guide vane shaft changes, the resistance value of the strain gauge pasted on the guide vane shaft changes, finally the sensitivity coefficient changes, the corresponding current value is measured through current amplification, and the corresponding torque value is obtained through weight calibration. The calibration of the force measuring movable guide vane uses the method described in document [[18]]. In order to ensure the sensitivity of measurement, the guide vane shaft shall be specially processed. The diameter of one section of guide vane shaft with strain gauge affixed is 30% smaller than that of the section without strain gauge affixed. The shaft section fitted with the shaft hole shall be polished to make the friction torque between the shaft and the small as possible [[19]]. After all working conditions are tested, the opening values of all guide vanes are converted into dimensionless relative opening [[20]], and the of guide vanes is used to express the magnitude of water moment. According to the requirements of International Electrotechnical Commission (IEC) Standard Specification [[21]], the following formula is used to calculate the guide vane water moment factor:

Where: ρ is the density of water, kg/m^3 ; ; D is the diameter of the low pressure side of the runner, M; H is the test head, M; g is the acceleration of gravity, m/s^2;

T and G are guide vane water moments, nm; For the directions of T and G, take the guide vane closing direction as + and the guide vane opening direction as -. The test head is set at 30 m during the water moment test of synchronous guide vane. In order to make the measured value as close as possible to the prototype operation

(Prototype machine rated speed 250 r/min, limit low head 175 m, rated head 190 m and maximum head 220 m), when converting the model measurement operating point into prototype machine, the speed should reach the rated speed, and the head should reach the lowest head, rated head and maximum head respectively. According to equation (2), the unit rotational speed can be obtained, only the rotational speed of the model machine needs to be adjusted, and the main valve at the inlet end can meet the requirements.

Analysis of Test Results

Synchronous Vane Hydraulic Torque Change The test results of synchronous vane hydraulic torque are shown in Table 2. Turn the measured value of guide vane water torque through equation (1)
Replace with the guide vane water moment factor and draw it as the point line graph shown in figure 4, and figure 4 is the one corresponding to the limit low head, rated head and highest head.

Factor value of guide vane water moment. From the curve in the figure, it can be seen that under 3 water head, the change trend of moment factor tends to be consistent with the increase of opening degree of all guide vanes under test.
At very low water head, as shown in fig. 4 (a), the moment value of the tested guide vane increases at a fixed rate of change in general and does not appear.

Table 2 Test Results of Vane Water Moment under Cavitation Coefficient of Device

	$\bar{A}_0$/%	$4_{\#}$ T_G（/	$9_{\#}$ T_G（/	10 T_G（/	11 T_G（/	14 T_G（/	18 T_G（/
	34.8	-0.2048	-0.0871	0.0158	0.1099	0.7829	-0.0918
	38.9	-0.1144	-0.4963	0.1424	0.0205	0.0691	0.0316
	43.0	-0.1282	-0.4091	-0.0316	-0.0461	-0.3528	-0.0664
	51.2	-0.3009	-0.4672	-0.3797	-0.1720	-0.9635	-0.5854
H_{min}=172.07m，	55.3	-0.6692	-0.4963	-0.7752	-0.3178	-0.5625	-0.8670
	59.4	-0.8827	-0.7577	-1.0600	-0.7621	-1.8396	-1.2657
	67.6	-1.9805	-1.5687	-1.9143	-1.5458	-1.9611	-2.1469
	75.8	-2.5526	-2.2998	-1.8036	-2.4264	-2.8064	-2.7671
	84.0	-3.0701	-3.1688	-3.3857	-3.2978	-3.6967	-3.4949
	92.2	-3.4542	-3.3504	-3.8129	-3.6265	-4.0395	-4.0565
	100	-3.7633	-3.5997	-4.0818	-3.6635	-3.7450	-4.1514
	38.9	-0.1129	0.1235	0.3797	0.5912	-0.1498	-0.0443
	43.0	-0.2524	-0.1186	0.2215	0.4255	-0.5067	-0.0965
	51.2	-0.5256	-0.3607	-0.1266	-0.0974	-0.9477	-0.5569
	55.3	-0.6615	-0.5423	-0.3797	-0.2586	-0.5325	-0.6977
H_r=190m，	59.4	-0.7310	-0.7287	-0.5854	-0.5166	-1.5517	-0.9951
n_{11}=59.67r/min	67.6	-1.6250	-1.3097	-1.4872	-1.0805	-1.8538	-2.0156
	75.8	-2.1097	-1.8689	-2.1042	-2.0100	-2.5577	-2.3953
	84.0	-2.4361	-2.6193	-2.7845	-2.6758	-3.4180	-3.0060
	92.2	-2.7646	-2.7331	-3.3066	-3.2950	-3.5836	-3.5154
	100	-3.0170	-2.9025	-3.4964	-3.3889	-4.2309	-3.6815
	18.4	-0.4613	-1.0918	-0.3006	-0.1845	0.7214	-0.2642
	26.6	-0.3571	-0.5108	-0.0791	-0.0433	0.9585	-0.0506
	34.8	-0.2753	-0.0920	-0.1740	0.3241	0.9735	-0.1424
	38.9	-0.2360	-0.5108	-0.2531	0.1242	0.4119	-0.0174
	43.0	-0.1997	-0.4115	-0.5221	-0.0803	-0.2371	-0.1313
H_{max}=219.25m，	51.2	-0.3285	-0.4769	-1.4081	-0.1686	-0.8811	-0.5284
n_{11}=55.55r/min	59.4	-0.8214	-0.7335	-1.5979	-0.6784	-1.6799	-1.1676
	67.6	-1.9738	-1.3097	-2.1042	-1.5282	-1.6682	-2.0172
	75.8	-2.4780	-2.3506	-2.6579	-2.4417	-2.7307	-2.4776
	84.0	-3.0037	-2.8735	-3.4964	-3.2716	-3.2840	-3.2259
	92.2	-3.3153	-3.0478	-3.7496	-3.5843	-3.4829	-3.6056
	100	-3.5962	-3.3310	-3.9236	-3.6162	-4.3091	-3.7432

Mutation. According to the guide vane movement diagram of figure 3, when the opening is small, the front stagnation point of the flow around the airfoil is located in the negative angle of attack area of the measuring surface on the airfoil

The lift generated by the flow approaches zero. At the same time, according to the variation trend of water torque of all guide vanes under 3 water head, it can be inferred that the opening is small.

The moment at 34.8% is positive, and the direction refers to the direction in which the guide vane is closed.

Under the rated water head, as shown in figure 4 (b), the change trend of the measured guide vane water moment factor value is generally close to the same as the opening degree increases, but changes at a smaller rate before the opening degree of 55.3%, and the moment factor value is relatively small, because it is smaller than

Under the opening of 55.3%, the front stagnation point of fluid flow around the movable guide vane airfoil is in the range of zero lift angle of attack (0 degree to -5 degree), and when the opening

When it is less than 18.4%, the negative angle of attack is larger, causing the airfoil to have poor flow around. This kind of airfoil flow also brings about flow resistance of different sizes, which is composed of viscous friction resistance in boundary layer and pressure drag formed by boundary separation [[22]].

At the maximum water head, as shown in figure 4 (c), the moment factor value is messy when the opening is less than 34.8% compared with extremely low water head and rated water head. After the 43.0% opening value, the torque value changes tend to be consistent. In general, the torque under 3 head conditions is relatively small under small opening, and the torque value gradually increases with the opening degree increasing, and the direction of torque is turned from the guide vane closing direction to the guide vane opening direction with the opening degree increasing. In the range where the opening is greater than 34.8%, the torque direction refers to the opening direction of the guide vane. This is because the higher the water head, the greater the pressure energy and kinetic energy that the pump turbine can utilize, and when the opening is small, the unit operates in the off-design region, so the distribution of the water torque factor is more affected by the distribution position of guide vanes with different numbers when the opening is small than when the opening is large. The pump turbine rapidly increases or decreases the load during operation, and the hydraulic vibration is large. The impact of water flow on the guide vane in pump operation is larger than that in turbine operation. The water moment factor extreme value in pump operation is also verified to be larger than that in turbine operation. The pump turbine is designed according to the pump operating condition and checked according to the turbine operating condition, so the pump turbine's guide vane self-closing performance under the turbine operating condition is worse than that under the pump operating condition.

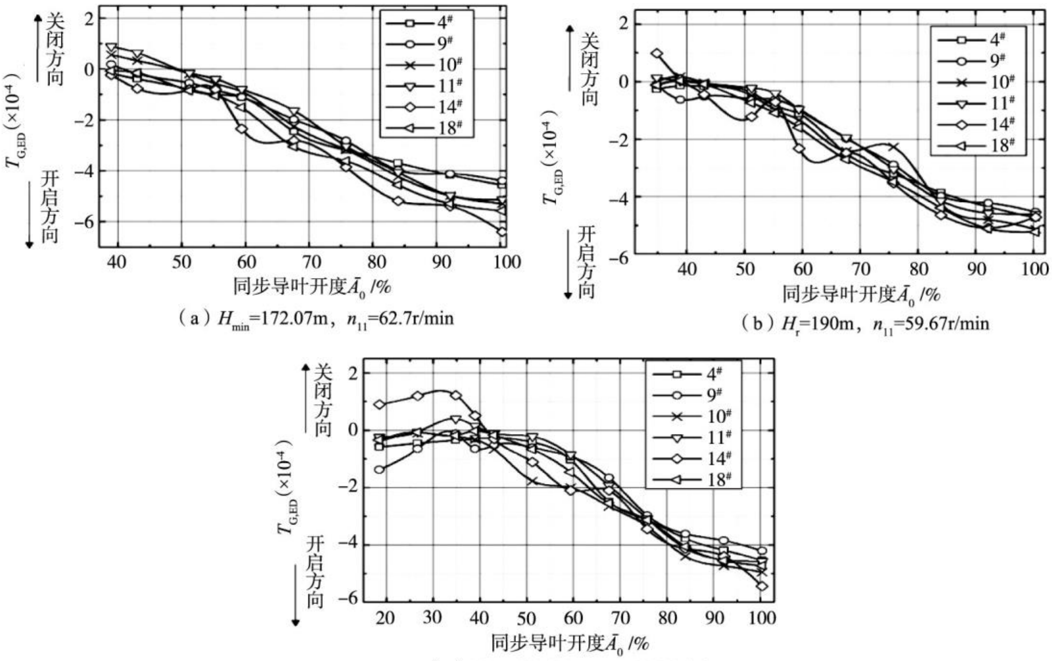
The optimal opening of pump turbine model guide vane used in the test is 51.2%. The water moment values under the minimum head and rated head are optimal.

At the 43.0% to 57.4% opening near the opening, the water moment factor values of each guide vane tested are the closest, and the difference is less than 1.262(×

10^{-4}) ; At the maximum water head, the measured guide vane torque value is the closest at the 43.0% opening. Under most of the degrees of separation less than 34.8% and greater than 57.4%, the measured vane water moments at different positions differ by more than 1.262(×10^{-4}).

Water Torque Changes of Asynchronous Guide Vanes In this paper, the torque characteristics of asynchronous guide vanes are experimentally studied. Set 10# guide vane as asynchronous guide vane, and select the model test operating point corresponding to the maximum water head of the prototype machine for testing. The synchronous guide vanes are opened to 18.4%, 34.8%, 51.2%, 67.6%, 84.0%, 100% ",respectively, and the asynchronous guide vanes 10# are opened to each synchronous opening

18.4%, 34.8%, 51.2%, 67.6%, 84.0%, 100% "were tested respectively, and the asynchronous vane water torque test was carried out in total.



(a) H_{min}=172.07m, n_{11}=62.7r/min

(b) H_r=190m, n_{11}=59.67r/min

(c) H_{max}=219.25m, n_{11}=55.55r/min

Fig. 4 synchronous guide vane water torque

36 group. The distribution of the water moment factor obtained from the test results is shown in figure 5 (a)—(f). As can be seen from the figure, the coverage of the maximum and minimum values of the water torque of the guide vane is obviously increased after the asynchronous guide vane is used, especially the torque value of the $10_{\#}$ guide vane which is asynchronous changes greatly under different asynchronous opening degrees. However, when the asynchronous opening and the synchronous opening coincide, the torque values of the asynchronous guide vane and the synchronous guide vane are close, i.e. the points with similar torque values move backward as the opening of the asynchronous guide vane increases.

As shown in fig. 5 (a), when $10_{\#}$ guide vane is opened as 18.4% asynchronously, the torque factor values of synchronous guide vanes $9_{\#}$ and $11_{\#}$ are close to the torque factor values of $10_{\#}$ guide vane near the synchronous opening of 18.4%; However, when the opening difference is large, the moment factor values are also different, even the direction of the moment is different. When the opening of the non-synchronous guide vane is small and the opening of the synchronous guide vane is large, the blocking effect of the non-synchronous guide vane on the fluid in the guide vane flow passage increases the flow resistance loss of itself and the front and rear guide vanes, and causes a large pressure difference. at this moment, the force on the guide vane increases sharply, thus forming a larger water moment factor of the $10_{\#}$ guide vane in the rear half section of fig. 5 (a) and fig. 5 (b). When the opening of the asynchronous guide vane is large and the opening of the synchronous guide vane is small, as shown in fig. 5 (f), the water torque of $10_{\#}$ asynchronous guide vane gradually decreases with the increase of the synchronous opening. At this time, the force applied to the movable guide vane is just opposite to that in figs. 5 (a) and 5 (b). when the synchronous guide vane is opened to a small opening, due to the large opening of the $10_{\#}$ guide vane, the fluid impacts the lower side of the airfoil at the leading edge of the $10_{\#}$ guide vane with a large positive angle of attack, while the fluid at the trailing edge of the guide vane impacts the area near the trailing edge measured on the guide vane airfoil, thus forming a clockwise moment about the guide vane axis, i.e., the guide vane opening direction, and the moment factor is large.

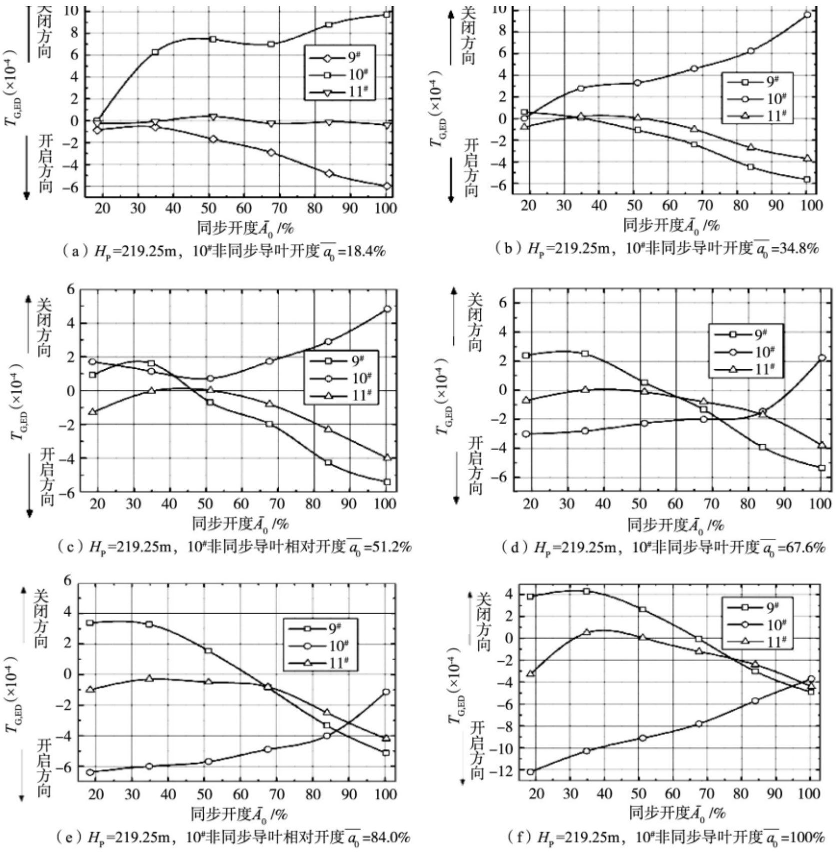


Fig. 5 water moment of asynchronous guide vane

When the difference of the opening between the asynchronous guide vane and the synchronous guide vane is greater than 32.8%, with the increase of the opening of the $10_{\#}$ asynchronous guide vane, the torque factor of the synchronous guide vane is greatly affected, especially the torque factor of the $9_{\#}$ and $11_{\#}$ guide vanes. In contrast to the guide vane water moment factors of $9_{\#}$ and $11_{\#}$ guide vanes in figure 4 (c), the difference between the maximum values of the guide vane water moment factor values using asynchronous guide vanes is not more than 1.35($\times 10_{-4}$), which is not the same in use.

After the guide vane was stepped, the difference between the maximum values of the water torque factor reached 7.19($\times 10_{-4}$). Figure 5 (F) shows that the original flow symmetry and stress uniformity were seriously damaged after the asynchronous guide vane was used, which is not conducive to the stable operation of the unit.

When the opening difference between the asynchronous guide vane and the synchronous guide vane is 16.4%, as shown in fig. 6 (a) (c). The moment values of $9_{\#}$ guide vane and $11_{\#}$ guide vane are greatly reduced, especially in the range of 43.0% to 92.2%. However, when the synchronous opening is 67.6%, the torque factor value of $10_{\#}$ guide vane, which is non-synchronized, increases by 29.75% at the maximum. under other synchronous openings, the water torque factor value of $10_{\#}$ guide vane also increases slightly, as shown in fig. 6 (c).

Fig. 6 (b) (d) shows the comparison of the guide vane water moment factor when the difference between the opening of the asynchronous guide vane and the opening of the synchronous guide vane is 32.8%. In Figure

6 (B), when the synchronous opening is 34.8%, the difference in water torque factor between 9# guide vane and 11# guide vane is the largest, reaching 2.49 (× 10^{-4}); In Figure 6 (D), the water torque factor of 10# guide vane with synchronous opening of 67.6% as asynchronous guide vane is increased by 5.16(×10^{-4}) compared with that of synchronous guide vane. As a result, very serious local stress unevenness and flow circumferential asymmetry are formed around asynchronous guide vane.

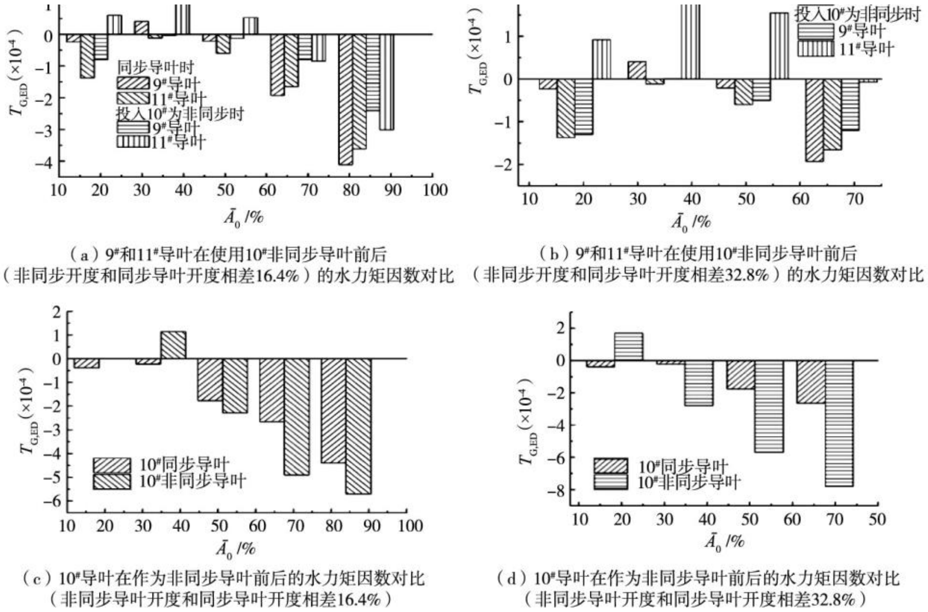


Fig. 6 effect of asynchronous guide vane on water torque of synchronous guide vane

From the above results, it can be seen that from the angle of guide vane water torque, if the difference between the opening value of the pre-guide vane and the opening value of the synchronous guide vane is within 16.4%, the water torque of the synchronous guide vane can be improved, and the water torque factor of each guide vane is also.

It tends to be evenly distributed and there is no obvious sudden change in torque factor. If the difference is greater than 16.4%, the use of asynchronous guide vanes follows the opening value

On the contrary, the increase of has a negative impact on the water torque of synchronous guide vanes, i.e. when the opening difference is greater than 16.4%, the use of asynchronous guide vanes increases sharply with the increase of the opening value, and the water torque factor of different guide vanes varies greatly.

Conclusion

In this study, the electric stress analysis method was successfully used to test the guide vane water torque of the model pump turbine. Through the comparative analysis of the measurement results, the following conclusions were drawn: (1) When the guide vane is opened synchronously, the change trend of the guide vane water torque factor is consistent with the increase of the guide vane opening at very low water head, rated water head and maximum water head. When the opening of the guide vane is less than 43.0%, the flow rate through the guide vane runner is small and the guide vane water moment is small. After the 43.0% opening degree, the water torque gradually increases at a gentle rate of change with the increase of overflow. (2) When the opening degree of the movable guide vane is less than 34.8%, the water moment factor of different guide vanes tested changes more sharply than when the opening degree is greater than 43.0%, and is most obvious under the maximum water head. When the water head is lower than the rated water head, each measured guide vane water moment factor is near the optimal guide vane opening (43.0% to 57.4%)

The values are relatively close, and the difference is less than 1.262 ($\times 10^{-4}$); When it is less than 34.8% and more than 57.4%, the measured vane water moment at different positions differs by more than 1.262($\times 10^{-4}$). (3) When an asynchronous guide vane is installed, the hydraulic moment of the guide vane is quite different under different pre-opening degrees. Through comparative analysis, the opening of asynchronous guide vane is 16.4% and 32.8% larger than that of synchronous guide vane.
It is concluded that the synchronization can be improved when the asynchronous guide vane is used, if the difference between the opening value of the asynchronous guide vane and the opening value of the synchronous opening is less than 16.4%

Water moment distribution of guide vanes: If the difference is greater than 16.4%, the use of asynchronous guide vanes will cause a sharp increase in the guide vane water torque, and there will be serious local uneven stress and flow circumference asymmetry, which will adversely affect the synchronous guide vane water torque.

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