Three-dimensional coupled design for runner blades and guide vanes of tubular turbine based on bidirectional flow control

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Abstract. Tidal energy is one of the renewable energy resources in the ocean. The tide-power station can supply more continuous electricity if it produces electricity in rising tide and receding tide, which is conducive to the stable operation of power grids. So it is important that the tubular turbine can operate in both directions with higher efficiency in tide-power stations. A full three-dimensional coupled design model for tubular runner blades and guide vanes is established to take full account of the mutual influence of flow between the distributor and runner. Since the simultaneous governing equations are solved in the flow domain including both blades, the coupled performance matches further. The weighted design method for reversible runner blade is presented based on the bidirectional flow information. The designed blade is fit to operate in both directions, which combined characteristics of the two blades working nicely in the positive and negative direction respectively. The reasonable control on the comprehensive performance of reversible blades is realized by selecting the weighted coefficient flexibly.

Keywords: Tidal energy, Reversible runner blade, Three-dimensional coupled design, Bidirectional flow control, Turbulence simulation

1. Introduction

Tidal energy is one of the renewable energy resources in the ocean. In the operation mode of tidal power station, the bidirectional operation mode of power generation in both the rising tide and the ebbing tide can provide more continuous power, which has strong adaptability to the power grid, and can be used for peak regulation. It is required that the tubular turbine unit should be operated in the bidirectional power generation condition when applied in the tidal power station, and in the bidirectional power generation condition it has high operation efficiency.

The unit runner is the core component of the power plant, and its flow performance directly affects the operation of the power plant, which has always been the focus and difficulty of design and research. Based on the assumption that the fluid is inviscid, Hawthorne et al. [1-2] proposed the concept of bound vortex, and considered that the blade is a vortex layer without thickness, and the strength of the vortex layer is the velocity moment of the fluid. According to the conditions of the relative velocity of the fluid and the tangential direction of the vortex, the first order partial differential equation of the vortex surface is established, and then the shape of the vortex surface, namely the blade bone surface, is integrated. The three-dimensional solid blade is obtained by thickening according to the predetermined thickness. Borges et al. [3-5] extended the theory of vortex surface design, and divided the effect of bound vortex on the flow field into two parts by using the Clebsch transform, i.e. average flow and periodic flow. The solution method of average flow is the same as that of Hawthorne; the potential function of periodic flow is complex potential function, which needs to solve nonlinear Poisson equation with multiple complex coefficients after expanding into Fourier series. After the average flow and periodic flow are calculated, they are superposed to get the real flow field. Ye Shenghai et al. [6] used this method to design the thin blades of Francis turbine. On this basis, Luo Xingqi et al. [7] further considered the effect of blade thickness on the flow field. Peng Guoyi et
al. [8] designed axial flow runner blades under the condition of inflow and rotation. Zangeneh et al. [9] designed the impeller of mixed-flow pump, and the test results show that its hydraulic performance is good. Based on this method, Yang Lin [10] realized the design of high head reversible pump turbine blade.

Reversible unit has the characteristics of bidirectional operation. Because the optimal operating points in the two flow directions are usually not coincident, it is difficult to ensure the flow performance in the opposite direction by only designing the blade shape in one direction. To sum up, the design theory of runner blade that can effectively control the bidirectional flow performance of reversible hydraulic unit is not perfect, and the design method of spatial guide vane that can meet the dual requirements of flow and structure needs further study.

Based on this research background, the paper deeply studies the bidirectional flow performance control of low head bulb tubular reversible unit, establishes the coupled design model of guide vane and blade, and proposes the bidirectional flow reversible blade based on the two blade types with better one-way operation performance designed from the forward power generation and reverse power generation respectively, taking into account their bidirectional flow information. Method of weighted design of bone surface. The blade shape designed by this method has obvious S-shape characteristics and is more suitable for bidirectional power generation operation. By choosing the angle coordinate weighting coefficient flexibly, the comprehensive performance of the blade can be controlled reasonably.

2. Coupled design method of guide vane and blade

In this paper, the coupled design method of the blade and the guide vane is established under the condition of forward and reverse power generation. The three-dimensional vortex surface model [3-4] is adopted. The model assumes that the fluid is inviscid and incompressible, and the relative flow in the runner is steady. The blade and the guide vane are placed in the same calculation domain, and the coupled flow control equation is established and solved. At the same time, the blade and the guide vane with more matching performance are designed. If the bubble body and the water guide mechanism are located at the upstream of the runner, it is called forward power generation; if the bubble body and the water guide mechanism are located at the downstream of the runner, it is called reverse power generation.

Taking forward power generation as an example, the calculation domain includes the leading section in front of the guide vane, the guide vane section, the transition section between the guide vane and the blade, the blade section and the draft section behind the blade. Fig. 1 shows the schematic diagram of the meridian flow channel.

![Fig. 1 Meridian Passage](image)

Since the distance between the guide vane and the runner is far, it is assumed that the fluid flows through the guide vane and enters the runner after fully mixing. The effect of blade attachment vortex and source sink instead of guide vane and blade with thickness on the flow field. According to the periodicity of the flow, the flow is divided into two parts: the circumferential average flow $\bar{V}$ and the periodic pulsating flow $\tilde{V}$. 
The flow equation is solved by nine node Galerkin finite element method, and the blade equation is solved by integral method and iterative calculation, which can realize the full three-dimensional coupled design of blade and guide vane.

3. Weighted design method of blade bone surface

The tubular reversible turbine can generate electricity in both the forward and reverse directions. The speed triangles of forward and reverse design blades at the optimal operating point are shown in Fig. 2 (a) and (b).

![Fig.2 Speed triangles of blades at the optimal operating point](image)

At the optimal operating point in the forward direction of power generation, assuming that there is no impact at the blade inlet, the average setting angle of the inlet is:

$$\alpha_1 = \arctan \left( \frac{V_n}{\omega r - |V'|_1} \right)$$  \hspace{1cm} (1)

Where, $V_n$ is the meridian velocity, $\omega r$ is velocity moment, $\omega$ is the rotating angular velocity of the runner, which is obtained from the rotating speed of the runner, and it is 0 in other areas.

Assuming that the blade outlet circulation is close to 0, the average setting angle of outlet is:

$$\alpha_2 \approx \arctan \left( \frac{V_n}{\omega r} \right)$$  \hspace{1cm} (2)

At the optimal operating point in the reverse direction of power generation, assuming that the blade inlet circulation is 0, the average inlet setting angle is:

$$\beta_1 = \arctan \left( \frac{V_n}{\omega r} \right)$$  \hspace{1cm} (3)

Assuming that there is no slippage at the blade outlet, the average setting angle of the outlet is:

$$\beta_2 = \arctan \left( \frac{V_n}{\omega r + |V'|_2} \right)$$  \hspace{1cm} (4)

Among them, the angular velocity $\omega$ of the runner for forward and reverse generation is equal; the meridian velocity $V_m$ is directly proportional to the flow $Q$. If $\alpha_1 = \beta_2$, $Q < Q$, then $\alpha_2 < \beta_1$; if $\alpha_2 = \beta_1$, $Q = Q$, then $\alpha_1 > \beta_2$. Therefore, it is impossible to meet $\alpha_1 = \beta_2$ and $\alpha_2 = \beta_1$ simultaneously under the optimal operating point of bi-directional generation is not coincident. Therefore, it is difficult to guarantee the performance of power generation in the opposite direction only by designing the reversible blade type under the condition of one-way power generation. In order to improve the controllability of the bi-directional flow performance in the design, this paper proposes a bone weighted design method for reversible blades which is suitable for the operation of bi-directional power generation.

The bone surface weighted design of reversible blade is based on the forward and reverse design. The shape of blade bone surface designed under forward and reverse power generation conditions shown in Fig. 3. In the figure, the water inlet side of the forward design blade and the water outlet side
of the reverse design blade are both located at the guide vane side, so they are drawn at corresponding positions; the water outlet side of the forward design blade and the water inlet side of the reverse design blade are drawn at corresponding positions.

Fig. 3 Schematic diagram of bone surface weighting method

\[ f'(i, j) = a \cdot f_1(i, j) + (1-a) \cdot f_2(i, j) \]  \hspace{1cm} (5)

Where: \( f_1 \) is the angular coordinate of the node on the bone surface of the forward design blade, \( f_2 \) is the angular coordinate of the node on the bone surface of the reverse design blade, and \( f' \) is the angular coordinate of the node on the weighted average back bone surface; the value range of the weighted coefficient \( a \) is \([0, 1]\), when \( a = 1.0 \), it means the bone surface of the forward design blade, when \( a = 0.0 \), it means the bone surface of the reverse design blade.

Select the appropriate weighting coefficient \( a \), according to formula (5), the new blade bone surface can be obtained, as shown in Fig. 3. After thickening, the actual blade shape is obtained. The shape of the blade combines the characteristics of the two blade types, especially the setting angle of the inlet and the outlet. After weighted average, the blades have obvious S-shape characteristics, which may be more suitable for bi-directional power generation operation.

4. Results and analysis

4.1. Results of the forward design

According to the above design method, the blade and guide vane of a low head tubular turbine are designed. Design parameters are shown in Table 1.

Meridian flow channel and calculation grid are shown in Fig. 4. Fig. 5 shows the distribution of velocity moment given on the inner and outer streamline.

As shown in Fig. 6 and Fig. 7, the meridian section and vertical section of the coupled design blade are shown.

| Parameters                        | Value | Parameters         | Value |
|-----------------------------------|-------|--------------------|-------|
| Head (m)                          | 2.6   | Blade number       | 4     |
| Discharge (m³/s)                  | 23.0  | Hub ratio          | 0.38  |
| Speed (r/min)                     | 125   | Guide vane height (m) | 1.0    |
| Blade diameter (m)                | 2.5   | Guide vane number  | 16    |
| Distance between guide vane and blade (m) | 1.88  | Dip angle (degree) | 65.0  |
4.2. Results of the reverse design

Under the condition of reverse power generation, the blade and guide vane of a low head tubular turbine are designed coupled. The design parameters are the same as the forward power generation conditions (see table 1). The meridian flow passage and calculation grid are shown in Fig. 9, and the velocity moment distribution given on the inner and outer streamline is shown in Fig. 10. Fig. 11 and Fig. 12 are the meridian section and vertical section of the design blade.

Under the design condition, the three-dimensional turbulent simulation of the coupled design blade and the guide vane is carried out. The calculation results show that the unit efficiency is 87.4%.

The flow field simulation results of the coupled design blade and the guide vane show that the unit efficiency is 91.1%, which is 1.1% higher than the results of the independent design blade. This is mainly due to the increase of the inlet angle near the outer edge, which reduces the inlet incidence angle and the impact loss. Therefore, the unit performance is improved. The static pressure distribution on the blade surface shows in Fig. 8.

In order to design the two blade models at the same time, the control equations are solved in the same calculation domain. Because of the careful consideration of the flow state between the distributor and the runner, the inlet angle of the blade is more matched with the flow conditions formed after the fluid passes through the guide vane, the inlet impact of the blade is reduced, and the efficiency is improved. It is verified that the method can design the blade and the guide vane with better coupled flow performance.
The static pressure distribution on the blade surface is shown in Fig. 13.

![Diagram of meridian section and calculation grid](image1)

![Diagram of velocity moment distribution](image2)

![Diagram of meridian section](image3)

![Diagram of vertical section](image4)

**4.3. Results of bone surface weighted design**

The forward design and the reverse design are carried out by the coupled design method, and they have the same design head \((H=2.6\text{m})\), flow \((Q=23.0\text{m}^3/\text{s})\) and rotation speed \((n=125\text{r/min})\). Fig. 14 shows the shape of bone surface when different weighting systems are selected. In this paper, the design of the same bi-directional tubular reversible blades which at the same head is carried out by using the above design results.

For the blade of forward design \((a = 1.0)\) and reverse design \((a = 0.0)\), according to the analysis of blade inlet and outlet velocity triangle, it can be seen that because the design discharge is equal, thus the average placement angle of the two blades on the side away from the guide vane is equal, and the difference of blade is not significant; while on the guide vane side, the placement angle of forward design is greater than that of reverse design, and the difference of blade is relatively obvious. When choosing different angle coordinate weighting coefficients, the larger the weighting coefficient is, the closer the blade shape is to the forward design; the smaller the weighting coefficient is, the closer the blade shape is to the reverse design.

With different weighting coefficients, different blade shapes are obtained, and the flow performance will be different. The full channel turbulent simulation of the designed blade profile is
carried out under the condition of forward and reverse power generation respectively. The calculation conditions are as follows: the design water head is 2.6 m, and the rated speed is 125 r/min, the design opening of the forward power generation is 70 degrees, and the opening of the reverse power generation is 95 degrees, which can reach the maximum flow; the blade is obtained by weighted average and appropriate thickening according to formula (5), and the opening (design opening) remains unchanged after weighting. Fig. 15 shows the calculation results of the relationship between the bi-directional operation efficiency and the weighting coefficient of the unit. It can be seen that, with the decrease of the weighting coefficient, the efficiency of the unit under the forward generating condition decreases gradually, while the efficiency of the unit under the reverse generating condition increases gradually. This shows that the bi-directional flow performance of the blade can be controlled by flexibly selecting the value of the weighting coefficient.

Because the optimal operating points are not coincident, it is necessary to take into account the bi-directional flow characteristics to comprehensively evaluate the performance of the designed blade. At present, the evaluation system of tidal power station benefit is not clear, and there is no simple and unified evaluation standard. In this paper, several simple evaluation indexes are used to evaluate the comprehensive performance of the blade design. In the performance acceptance test of conventional turbine, the weighted average efficiency is usually taken as the guarantee value \[1\] , that is:

\[
\eta_W = \frac{W_1 \cdot \eta_1 + W_2 \cdot \eta_2 + W_3 \cdot \eta_3 + \cdots}{W_1 + W_2 + W_3 + \cdots} \tag{6}
\]

Where: \(\eta_W\) is the weighted average efficiency, \(\eta\) is the unit efficiency under each control condition, and \(W\) is the weight factor. For the tubular reversible turbine, a power generation condition in the forward and reverse direction is selected as the control condition, and the weight factors are equal, then the average value of power generation efficiency under the two conditions can be taken:

\[
\eta = \frac{1}{2} (\eta_1 + \eta_2) \tag{7}
\]

Approximate as the evaluation index. If the calculated condition in Fig. 15 is taken as the control condition, the comprehensive performance of the unit is the best when the weighting coefficient is about 0.60. The maximum efficiency of reverse power generation is generally lower than that of forward power generation. If it is not desired that there is too much difference in bi-directional flow performance, then if the efficiency of reverse power generation under control condition is 5% lower than that of forward power generation as the standard, when the weighting coefficient is about 0.53, the requirements are met. Therefore, compared with unidirectional design \((a=1.0 \text{ or } a=0.0)\), the blade designed by bone surface weighting method proposed in this paper is more suitable for bidirectional power generation operation. Moreover, according to different evaluation criteria, selecting appropriate weighting coefficient can design reversible blades that meet different comprehensive performance requirements.

Based on the above two evaluation methods, when the weighting coefficient is between 0.53 and 0.60, the comprehensive power generation performance of the designed blade is better. Therefore, the
paper takes the blade design with a weighting coefficient of 0.60 as an example to calculate the performance under non-design conditions, in order to obtain the optimal performance of its bi-directional power generation. In the case of forward power generation, a calculation condition point is selected from the blade opening interval of 5 degrees, the average interval of water head is 0.3m, and the range of water head is 1.2-5.5m; in the case of reverse power generation, a calculation condition point is selected from the blade opening interval of 5 degrees, the guide vane opening of 95 degrees to the maximum flow, and the average interval of water head 0.3m, and the range of water head is 1.2-5.5m. See Table 2 for the calculated maximum efficiency parameters of two-way power generation. Among them, the highest efficiency of forward generation is 87.6%, and that of reverse generation is 77.6%. Under the optimal condition, the static pressure distribution on the blade and guide vane surface is shown in Fig. 16.

Table 2: Optimal operating condition of bi-directional power generation

| Working condition | Guide vane opening | Blade opening | Head (m) | Discharge (m³/s) | Efficiency (%) | Power (Kw) |
|-------------------|--------------------|---------------|----------|-----------------|----------------|------------|
| Forward generation| 65                 | 15            | 2.03     | 18.1            | 87.6           | 315        |
| Reverse generation| 95                 | 15            | 2.14     | 21.1            | 77.6           | 343        |

In order to extend the generating time and increase the generating capacity, according to the reversibility principle of the flow of hydraulic machinery, the unit can be put into the forward and reverse pumping mode to work in the way of pumped storage in the flat tide time, when the drop between the reservoir and the ocean is close to 0. In this paper, the flow performance of the blade designed with a weighting coefficient of 0.6 under pumping condition is studied.

The normal velocity boundary is given at the inlet and the reference value of static pressure is given at the outlet. The blade opening interval is 5 degrees, the guide vane opening interval is 5 degrees, and the head is 0.2-1.2 m with an average interval of 0.2m. See Table 3 for the calculated maximum efficiency parameters of bi-directional pumping. Among them, the highest efficiency of forward pumping is 81.1%, and the highest efficiency of reverse pumping is 74.3%, which shows that the designed blade profile can be used for bi-directional pumping operation. Under the optimal condition, the static pressure distribution on the blade and guide vane surface is shown in Fig. 17.

Table 3: The optimum condition of bi-directional pumping

| Working condition | Guide vane opening | Blade opening | Head (m) | Discharge (m³/s) | Efficiency (%) | Power (Kw) |
|-------------------|--------------------|---------------|----------|-----------------|----------------|------------|
| Forward generation| 70                 | 15            | 0.90     | 15.9            | 81.1           | 173        |
| Reverse generation| 95                 | 10            | 1.03     | 11.6            | 74.3           | 157        |
5. Conclusion

Considering the interaction of flow field between runner and guide vane, the coupled design method of blade and guide vane is established. The blade and guide vane are placed in the same calculation domain, and the flow control equations in the transition region between the two blade profiles are solved in detail, which makes the designed blade and guide vane more matching, and thus more effectively controls the coupled flow performance of the two.

Considering the flow information of two-way power generation, a weighted design method of the blade's bone surface is proposed. The angle coordinates on the blade's bone surface designed under the condition of forward and reverse power generation are weighted and averaged respectively, and the actual blade shape is obtained by thickening. Compared with the blade designed under the condition of one-way power generation, the blade is more suitable for two-way power generation. And by choosing the value of different angle coordinate weighting coefficient flexibly, it can realize the reasonable control of the comprehensive power generation performance of the blade. The results of turbulence simulation show that the designed blade is also suitable for two-way pumping operation.

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Nomenclature

\[ V = \text{absolute velocity} \]
\[ r = \text{radial coordinate} \]
\[ \theta = \text{tangential coordinate} \]
\[ t = \text{time} \]
\[ Q = \text{discharge} \]
\[ p = \text{static pressure} \]
\[ \rho = \text{density} \]
\[ \nu = \text{viscosity coefficient} \]
\[ g = \text{gravity acceleration} \]
\[ A_i = \text{area} \]

References

[1] Hawthorne W R, Wang C, Tan C S, et al. Theory of blade design for large deflections: part I – two dimensional cascades. Journal of Engineering for Gas Turbines and Power, 1984, 106(4): 346-353.
[2] Tan C S, Hawthorne W R, McCune J E, et al. Theory of blade design for large deflections: part II – Annular cascades. Journal of Engineering for Gas Turbines and Power, 1984, 106(4): 354-365.
[3] Borges J E. A three-dimensional inverse method for turbomachinery: part I – theory. Journal of Turbomachinery, 1990, 112(7): 346-354.
[4] Borges J E. A three-dimensional inverse method for turbomachinery: part II—experimental verification. Journal of Turbomachinery, 1990, 112(7): 355-361.

[5] Zangeneh M. A compressible three-dimensional design method for radial and mixed flow turbomachinery blades. International Journal for Numerical Methods in Fluids, 1991, 13: 599-624.

[6] Naixiang C, Shenghai Y, Ruchang L. A Three-dimensional Inverse Calculation of Mixed Flow Rotor Thin Blade[J]. JOURNAL OF HYDROELECTRIC ENGINEERING, 1995(1): 59-65

[7] Xingqi L, Wuke L, Naixiang C, et al. A 3-D rational flow inverse design of Francis runners[J]. Journal of Hydraulic Engineering, 1996(10): 27-31, 38.

[8] Guoyi P, Xingqi L, Qisheng G, et al. A fully three-dimensional inverse method for axial hydraulic turbine runners in rotational flow[J]. JOURNAL OF HYDRAULIC ENGINEERING, 1996(10): 61-67.

[9] Zangeneh M, Ejiri E, Kubo M. On 3D inverse design of an automotive torque converter pump impeller in shear flow//Proceedings of the International Conference on Fluids Engineering. Tokyo, Japan: 1997: 201-206.

[10] Lin Y, Naixiang C, Honggang F. Three-dimensional reverse design method for pump-turbine runners. [J] Journal of Tsinghua University (Science and Technology), 2005, 48(8): 1118-1121.

[11] Zhengzong M. Weighted mean efficiency of hydraulic turbines and method of calculation. Power Engineering, 1989(1):53-58.