Optimal Design of Impulse Turbine Prototype of Oscillating Water Column Type Wave Energy Power Generation Device

Zhiqian Wu¹, Zhenxi Li¹ and Xin Mi¹

¹ Leicester International Institute, Dalian University of Technology, Dagong Road, Panjin, China
E-mail: wuzhiqian2020@163.com

Abstract. The Oscillating Water Column Type is currently the most widely used wave energy generation device. The impulse turbine with fixed guide vanes has the advantages of high peak efficiency and excellent aerodynamic performance. Using three-dimensional numerical simulation methods to analyze the impulse turbine, construct and optimize the design of the turbine prototype, and provide suggestions for the subsequent innovation and improvement of the performance and structure of the impulse turbine with fixed guide vanes.

1. Introduction

With the continuous increase in the use and consumption of non-renewable energy in the world, countries are paying more and more attention to marine rights and marine resources. Wave energy is one of the most important clean energy in the ocean. Its development and utilization can effectively alleviate the energy crisis and reduce pollution. The survey results of the World Energy Commission show that there are nearly 2 billion kilowatts of wave energy resources available in the world, and the amount is considerable. At the same time, wave energy also guarantees its good developability due to its high quality, easy conversion, wide distribution, and large reserves.

As the main method of wave energy power generation system, the air turbine core machine and its supporting generator set are the key equipment of the oscillating water column technology (See: Figure 1). The core air turbines mainly include Wells turbines, impulse turbines, and Savonius turbines[1]. Among them, the impulse turbine has the advantages of high peak efficiency, excellent aerodynamic performance, and stable operation. Starting from the principle of impulse turbines, this
project hopes to design a new type of turbine core machine suitable for Asian seas, optimizing its blade shape and mechanical structure, etc., and finally use experimental methods to verify its feasibility.

2. Impulse turbine model with fixed guide vanes

In the Oscillating Water Column devices, reciprocating airflow will be generated due to the undulating waves, so it is necessary to adopt a turbine that can rotate in the same direction under the action of two-way airflow. There are two types of impulse turbines according to the classification of guide vanes, which are self-pitch-controlled guide vanes impulse turbines and fixed guide vane impulse turbines[2]. The efficiency of the impulse turbine with self-pitch-controlled guide vanes is slightly elevated because the inlet and outlet guide vanes move to fit the flow direction. However, the impulse turbine with fixed guide vanes is adopted in this study because the fixed guide vanes mitigate the maintenance and manufacture cost of rotor guide vanes which has a relatively complex structure and are more breakable than fixed ones.

![Design dimensions of impulse turbine equipped with guide vanes](image1)

**Figure 2.** Design dimensions of impulse turbine equipped with guide vanes

This article gives the design size which is shown in Figure 2, referring to the optimal size of the turbine blade of some oscillating water column devices[1, 3]. This article also gives a 3D model diagram of the overall device of the wave energy utilization device. It shows the appearance of an impulse turbine with fixed guide vanes in Figure 3, which mainly includes a hollow circular hub head at both ends, guide vanes, rotor blades, rotating blade hub and rotating shafts.

![Impulse turbine](image2)

**Figure 3.** Impulse turbine
3. Numerical Methods
In this project, the Navier-Stokes equation of the Reynolds average method is used in the three-dimensional numerical simulation of the model. Under a high Reynolds number, the turbulence model should consider the influence of turbulence viscosity. Therefore, the SST K-Omega model widely used in rotating machinery is used. This mathematical model has certain advantages in predicting the flow separation on the blade surface and the turbulent flow phenomenon in the turbine core rotor blade area, especially in the calculation of free shear flow and near-wall boundary. Consider using the Grid Sequencing method and the fast algorithm of the Convergence Accelerator (CCA).

The number of rotor blades calculated in this paper is 26, and the number of guide vanes is 30. [4] Since ideal calculation results can only be obtained when the grid size reaches one million and limited by computer configuration, in this project, the impeller part is split into a single flow channel when the three-dimensional fluid simulation analysis is carried out, that is, the method of creating periodic transformation boundaries is adopted.

A set of blades is divided into three parts, the left and right guide vane area and the middle rotor blade area (See: Figure 4). The area where the rotor blades are set is the rotation area, and the guide vane areas on both sides are the fixed areas. The upper bottom surface and the lower bottom surface are set as fixed wall surfaces, and the front and back surfaces are set as rotating wall surfaces.

The establishment of the mesh model adopts an automatic mesh to generate surface mesh and volume mesh for the obtained Boolean subtracted parts. The automatic mesh operation can manage all mesh generators so that the mesh parameters can be controlled. In particular, this operation can perform customized mesh refinement control for the blade surface. Finally, the model is divided into a million-level grid (more than 3 million) (See: Figure 4).

As mentioned above, both the model and the flow field structure are periodic. Therefore, the inlet of the guide vane on the left side of the calculation domain is selected as the pressure inlet condition, and the outlet of the guide vane on the right side of the calculation domain is the pressure outlet condition. The calculation domain is extended to a certain extent along the watershed to ensure sufficient flow, and the motion reference frame model (Reference Frame) is used to deal with the rotation of the rotor blades.[5]

Thus, the following solution results are obtained. (See: Figure 5, Figure 6)
4. Optimized Design of Physical Model

4.1 Blade shape optimization
For the initial blade design, the pressure gradient distribution map was obtained by numerical analysis using calculation software (See: Figure 7). It was found that the efficiency was not high, and the next improvement was made to thin the rotor blade edge and increase the number of rotor blades (See: Figure 8).
4.2 Rotating Blade Hub

4.2.1 The Optimized Concept of the Rotating Blade Hub. The rotating blade hub is the core active part of the impulse turbine wave energy utilization device, and its structure will directly affect the aerodynamic performance and operational stability of the overall device. The key to the design is to enable the turbine to resist sudden speed fluctuations while accelerating rapidly and obtain the best acceleration under the smallest possible mass moment of inertia. Since the blades have been optimized through numerical simulation to produce a larger power output, the focus of the project team’s research has been on the hub structure and the assembly structure of the hub and blades. The shape of the hub that the project team wanted to find is to minimize the mass moment of inertia of the hub and still withstand high loads.

For the turbine hub, its structure is the main support of the rotor blades. It has the functions of connecting the rotor blades, bearing the rigid moment of inertia between the blades and the hub, transmitting the circumferential rotational kinetic energy brought by the blades to the rotating shaft, and bearing the torque and torsional stress of the rotating shaft. When the turbine runs at a high speed in the actual device, the centrifugal force is also the limiting factor to determine the maximum speed of the turbine, and the weight of the hub also contributes to its centrifugal load. Therefore, for the design of the hub, while ensuring sufficient strength, it is also necessary to reduce the weight as much as possible and make the mass distribution uniform. Only in this way can it be ensured that it can provide a higher speed to the rotating shaft so that the device can output higher power.[6]

4.2.2 Hub centre structure design. In the initial design, the project team designed the hub as a simple cylindrical stepped shape with a spline groove in the centre for kinetic energy transmission (See Figure 9).

![Figure 9](image1.png) Spline groove in the center

![Figure 10](image2.png) Five-pillar porous bolt structure

At the same time, the hub and the rotating blades are manufactured in an integrated manner (in one piece), and the physical prototype of the first version of the hub is obtained through 3D printing. Although this design method has a simple structure and relatively good mechanical properties, the use of metal materials in actual manufacturing will greatly increase the weight of the device. This will reduce the rotation speed and output power. In addition, the integration of the hub and the blade is difficult for traditional machining, which will increase the manufacturing cost. And it is not conducive to the replacement of damaged blades at a later stage. Therefore, after adjustments, referring to the hub shapes of automobile and aviation turbines, the project team designed a series of hubs with a "five-pillar porous bolt structure" (See Figure 10).

Compared with the first version of the hub, this structure uses a hollowed-out idea, and only retains five supporting columns to fix the structure, which greatly reduces the weight of the metal hub while ensuring its strength. At the same time, the separate manufacturing of the hub and the blade also reduces the manufacturing cost. However, this solution has high requirements for the size and feed position of the turning tool during mechanical manufacturing, and the processing time is long, and the tool loss is large. Under such circumstances, large-scale industrial manufacturing at a low cost cannot be achieved.
After the series evolution of the hub, the project team finally proposed the design of the block-type combined hub.

The hub is split into three parts (See: Figure 11), and the parts are first connected simply by buckling during assembly. The hub blocks 2 and 1 are fixed by 6 pins inserted diagonally through the curved surface of the 2 to 1; the hub blocks 3 and 2 are fixed by 6 pins in the axial direction. At the same time, hub segment 1 is hollowed out to reduce weight. The spline groove on it is changed to a single key groove. Through such a design, the mass distribution of the overall device is still relatively symmetrical, which can reduce the weight while ensuring the strength of the hub and meet the requirements of low-cost and low-difficulty manufacturing.

4.3 Optimization of the assembly structure of the hub and blades.

The design of the rotating blade wheel is also closely related to the connection between the blades and the hub. From the design perspective, if the blades and the hub are connected by bolts, the hub should be an integrated structure; and if the combined structure of independent blades and the hub is adopted, the hub should have the function of symmetrically buckling and fixing the blades in the middle. In the initial stage of the design, the project team adopted the integrated design of the blade and the hub, and the corresponding turbine prototype was directly integrated by 3D printing; in actual manufacturing, the integrated structure was formed by metal die-casting or welding the blade on the hub (See: Figure 12). Such a design has proven to be infeasible because of the following reasons: (1). Non-metallic polymer materials will be used for the rotor blades to reduce weight, while die-casting can only form metal in one piece. (2). It is difficult to locate the rotor blade during welding, and due to the influence of welding heat, mechanical problems such as deformation at the root of the rotor blade and stress concentration during operation will affect the stability of the structure. (3). The damaged single blade cannot be replaced. When the blade is damaged, the rotating blades hub can only be re-made, resulting in high manufacturing cost.

So, after research, the project team began to design the hub and blade connection structure separately.
For the hub, it is designed as a porous bolt structure (See: Figure 13). Two countersunk head screws are driven into the blade from the inner ring of the hub, and a countersunk head screw is driven into the hub from the top of the blade. This design proved feasible, but the introduction of many screws increased the weight of the hub.

![Figure 13: Three screws fixed](image1)

![Figure 14: Two screws fixed](image2)

Therefore, a configuration was designed in which only two countersunk screws were driven into the blade from the inner ring of the hub (See: Figure 14). However, after testing, it was found that the relative motion between the blade and the hub may still occur under high-speed motion. As mentioned above, the segmented hub was finally innovatively designed to achieve the effect of easy processing and lightweight while ensuring strength.

For blades, the integrated blades are split into individual blades. When designing a single blade, we noticed that if simply imitating the dovetail groove design of an aviation turbine blade, it will cause interference between the root cones of the rotor blade. In order to have more contact areas between the blades, a blade root cone with a geometric shape similar to that of the rotor blade was designed[6]. Since a single blade is not easy to assemble, a combined design of two groups of blades is adopted (See: Figure 15).

![Rotor Blade](image3)

![Blade Root](image4)

![Figure 15: A combined design of two groups of blades](image5)

Finally, the block-type hub and the double-combination-parallel blades are fixed using a tenon

![Figure 16: Final design](image6)
structure (See: Figure 16) and horizontally driven pins. In this way, kinetic energy can be transferred well in the case of high-speed rotation. And there is no relative movement in all directions, and the overall rotating blade wheel weight is low, and the mass distribution is even. After testing, this method has a good practical effect.

5. Actual Manufacturing
After optimizing the design, the team manufactured the turbine prototype (See: Figure 19). Aluminium alloy is used for CNC 5-axis machining on the hub (See: Figure 17), shaft, and sleeve. GFRP lightweight materials are used for high-precision industrial-grade 3D printing in the rotor blades (See: Figure 18) and guide vanes, making the start-up of the device easier and more stable, to better capture energy.

6. Conclusions
Based on previous research, this article completed the design of the turbine, and gave the conceptual design drawing of the impulse turbine and planned the size design of the blades. This paper realizes the three-dimensional numerical simulation of the impulse turbine of the designed oscillating water column devices.

The design of the blade profile is improved in this paper according to the numerical simulation results. Based on the actual manufacturing process, the rotor blade hub and the blade connection mode are optimized. On this basis, it is possible to conduct more in-depth research on the working performance and structure of the impulse turbine with fixed guide vanes, to provide more ideas for the innovation and improvement of the turbine part of the Oscillating Water Column devices.
7. References:

[1] M. Takao and T. Setoguchi, "Air Turbines for Wave Energy Conversion," *International Journal of Rotating Machinery*, vol. 2012, pp. 2382–2396, 2012.

[2] T. Setoguchi, S. Santhakumar, H. Maeda, M. Takao, and K. Kaneko, "A review of impulse turbines for wave energy conversion," *Renewable Energy*, vol. 23, no. 2, pp. 261-292, 2001.

[3] T. Setoguchi and M. Takao, "Current status of self rectifying air turbines for wave energy conversion," *Energy Conversion and Management*, vol. 47, no. 15/16, pp. 2382-2396, 2006.

[4] R. Badhurshah and A. Samad, "Multiple surrogate based optimization of a bidirectional impulse turbine for wave energy conversion," *Renewable Energy*, vol. 74, no. feb., pp. 749-760, 2015.

[5] Z. Liu, H.-y. Zhao, and Y. Cui, "Effects of rotor solidity on the performance of impulse turbine for OWC wave energy converter," *China Ocean Engineering*, vol. 29, no. 5, 2015.

[6] A. Thakker, J. Jarvis, M. Buggy, and A. Sahed, "3DCAD conceptual design of the next-generation impulse turbine using the Pugh decision-matrix," *Materials and Design*, vol. 30, no. 7, pp. 2676-2684, 2009.

Acknowledgements

Firstly, we would like to extend our deep gratitude to the Dalian University of Technology for the platform provided.

Secondly, we are extremely grateful to our mentor, Professor Chen Bing, who is especially selfless, for guiding us all the time.

Thirdly, we owe our special thanks to every member of the team and the seniors who have given us strength.

Then our faithful appreciation also goes to all the teachers, experts and scholars who reviewed this paper.

Ultimately, we would like to express our thanks to the Dalian University of Technology for the support of the "College Student Innovation and Entrepreneurship Training Program".