High-Efficiency Ship Propeller Based on Electric Direct Drive Without Shaft Rim

Yefan Yang*
School of Transportation, Wuhan University of Technology, Wuhan, China

*Corresponding author: yefan_yang@whut.edu.cn

Abstract. The ship propeller is a key component of a ship, a device for energy conversion, and a device for converting the energy emitted by the main engine into ship power. The most popular types of shaft-driven propellers derived from propeller propellers are currently on the market, including ducted propellers, pod propellers, and flat-rotating propellers. This type of propeller has many disadvantages of the shaft-driven propeller (system). These shortcomings have caused most of the existing small and medium-sized ships to have problems such as low transportation efficiency, high operation and maintenance costs, noise pollution, and lubricant leakage pollution. Therefore, the shaftless rim electric direct drive has gradually become an important development direction in the field of high-end marine propulsion equipment.

Keywords: Ship propeller, Shaftless rim, Water lubrication.

1. Introduction
The traditional ship "primary mover-transmission system-propeller" propulsion device has problems such as large space occupation, large vibration and noise, and oil leakage from the seal. Shaftless rim electric direct drive has become an important development direction in the field of high-end energy and power equipment. Among them, the ship’s shaftless rim thruster integrates permanent magnet motors, propellers, water-lubricated bearings and rudders, and has a compact structure, high efficiency, low noise, flexible layout, green and environmental protection. This project has overcome several key technical difficulties in the manufacture of shaftless rim thrusters, and developed a shaftless rim thruster product.

Figure 1 Internal structure diagram of a certain type of submarine using shafting propulsion mode
2. Design background
The appearance of internal combustion engines and propellers brought the development of the shipbuilding industry to a new era. However, with the development of the shipbuilding industry, the disadvantages and disadvantages of propellers have gradually become prominent. Emerging ship propulsion technologies such as pod propulsion devices and water jet propulsion devices have emerged. Although they meet the special needs of some special ships, the shortcomings of traditional shaft drive propellers have not been solved, and they have been infinitely amplified during use, such as many parts, complex structures, large cabin space occupation, large energy loss, vibration and Noise control is difficult, construction and maintenance costs are high. Even if the electric propulsion system is used, the traditional electric propulsion device transfers power through the main shaft just like the traditional main engine directly driving the propeller. Since the motor is separated from the propeller, there are still problems such as sealing and shafting vibration, and once the main shaft fails, the propulsion function will be lost.

In view of this, a new type of propulsion device, namely Shaftless Rim-driven Thruster (RDT) was born. The shaftless rim thruster breaks the conventional way of thinking and propulsion mode, and highly integrates the high-efficiency permanent magnet DC motor, shafting, rudder and tail thruster into one. The propulsion device except the controller is installed outside the hull. It occupies the space in the cabin and has significant advantages such as compact structure, small size, low vibration and noise, high propulsion efficiency and good control performance. [1]

![Image of Shaftless rim thruster](image)

Figure 2 Shaftless rim thruster manufactured by Schottel, Germany

3. Project Overview
Based on the accumulation of rich experience in the research and development of shaftless propellers, the project designed a new type of propulsion device—an autonomous integrated water jet propulsion device based on the Coanda effect, which is more targeted than traditional water jet propulsion devices. It has improved many pain points and improved the overall performance of the water jet propulsion device.

At present, the power range of the shaftless rim thruster series of this project is 200w~1000kw, mainly including: permanent magnet motors and controllers, propellers, water lubricated bearings and ducts, etc., if equipped with a full rotation device, it can also achieve 360° turn around. The propeller designed in this project has the advantages of high-power density, low vibration and low noise; the bearings are lubricated with water, and there is no risk of lubricating oil leakage; and the overall control is flexible.
4. Core Technology
The core technology and advantage of this project is to overcome the domestic leading key technologies such as propeller hydrodynamic design and efficiency enhancement technology, large load bearing water lubrication bearing technology and propeller system collaborative optimization technology. On the basis of this core technology, it has developed the shaftless rim propulsion products of the company can be used as a reference for other shaftless rim propulsion technologies.

4.1. Propeller hydrodynamic design and efficiency enhancement technology
Overcoming the hydrodynamic design and efficiency enhancement technology of the propeller is the basis for designing high-performance, high-power, stable, and highly integrated high-performance shaftless rim propellers. The project team established a hydrodynamic simulation model considering the gap, and explored the impact of hydrodynamic design on the propeller by studying the gap flow power consumption and heat dissipation of the shaftless rim thruster, the hydrodynamic performance analysis method of the propeller, and the blade strength verification method. The performance impacts.

The project team took a four-blade shaftless rim thruster as the research object, and based on numerical simulation methods, calculated the torque values of the inner and outer surfaces, front and rear ends of the rim, and compared them with the empirical formula values in each area. The thrust and torque calculated by JD75+Ka4-70 ducted propeller are compared with the experimental values. The strength of the blade is checked based on the one-way fluid-solid coupling method, and the thickness distribution is changed to analyze the influence of the thickness change on the hydrodynamic performance and blade strength of the shaftless rim propeller. Through this research, the project team has grasped the law of the equivalent stress distribution of the blade surface and the back of the blade of the shaftless rim propeller, and the influence of the change of the thickness of the blade on the friction torque of the front and rear surfaces of the rim and the inner and outer surfaces. Method to design a reasonable blade thickness distribution plan. [2]

![Figure. 3 Performance comparison of optimized design of shaftless propeller](image)

At the same time, the project team took the 5.5kw shaftless rim thruster as the research object. Aiming at the additional frictional power consumption caused by the relative motion in the gap, the friction torque of each surface of the gap was calculated by numerical methods, and then the results were verified by empirical formula the effectiveness of the, found the relationship between the gap flow field friction power consumption and gap size, motor speed and water flow speed and other factors and the gap inflow velocity on the motor heat dissipation.
4.2. Heavy-duty water-lubricated bearing technology

Large-load water-lubricated bearing technology is the key technology for the manufacture and high-power of shaftless rim thrusters. The project team broke through the bottleneck of water lubrication technology and developed a variety of wear-resistant water-lubricated polymer composite materials, such as modified rubber, Bionic self-lubricating polymer composite materials, etc., established a water-lubricated bearing thermo-fluid-solid coupling simulation model, designed a variety of new water-lubricated bearing structures, suitable for a variety of scenarios such as shaftless rim thrusters, such as rubber bullet-supported tilting tiles Thrust bearings: Water lubricated thrust-diameter combined bearings, variable step damping thrust bearings. During this process, the project team independently developed a number of shaftless thruster bearing test benches and test systems.

(1) New water-lubricated bearing structure

In view of the defects in the existing bearing structure, the team designed a variety of water-lubricated bearings with different structures based on the preparation of water-lubricated materials. Take the water-lubricated thrust-diameter combined bearing as an example. The unique structural design enables the bearing to withstand a certain amount of radial force while bearing the axial force, which overcomes the traditional radial and thrust combined bearing’s large volume and complex structure. The water-lubricated radial bearing based on the distributed material design adopts the design of different elastic modulus materials distributed in the axial direction of the surface layer, which can effectively solve the existing water-lubricated bearings that have large local deformation, stress concentration and wear under eccentric load Serious problems.

(2) Fluid-solid-heat coupling simulation technology for water-lubricated bearings
In order to optimize the structural design of water-lubricated bearings and study the influencing factors of the performance of water-lubricated bearings, a bearing thermo-hydrodynamic pressure lubrication performance calculation model, namely fluid-solid-thermal coupling model, was proposed, which was solved by finite element method and studied the load, speed, and tile the influence of block size and aspect ratio on bearing performance.

![Figure 6 Bearing water film pressure distribution](image)

(3) Water-lubricated bearing performance testing technology

Most of the current oil film thickness measurement methods have the defects of damage to the bearing working surface, inability to measure the minimum oil film thickness, difficulty in revealing the lubrication status and warning of wear. The team proposed two non-invasive ultrasonic measurement methods for bearing oil film thickness distribution, namely, full-circumferential measurement and measurement based on limited measurement points.

Within the calibration range, the relative error of most identification values is less than ±5%, and some are less than 3%. In most working conditions, the relative deviation between the experimental value and the simulated value is less than 8%. It shows that the measurement method has high accuracy.

4.3. Cooperative optimization technology of thruster system

According to the connection between the motor and hydraulic components through torque and the diameter of the propeller, a coupling model of the motor and hydraulic components is established. First, the overall efficiency of the design target is determined, and the coupling model is determined according to the relationship between the parameters Design parameters. Secondly, the initial values of these design parameters should be given. Finally, the multi-parameter nonlinear optimization method should be selected, and the set inequality constraints (considering the gap friction torque; the conductor temperature constraint of the thermal model; the tooth profile of the winding, the permanent magnet Demagnetization, electromagnetic converter electrical frequency; propeller hydrodynamic performance parameters) and equality constraints (motor size, copper loss, iron loss, efficiency; inequality constraints on cavitation; other constraints) are optimized, after continuous iteration The optimal solution is calculated. Taking the 5.5kw shaftless rim thruster as an example, the overall efficiency of the thruster can be increased by 5.79% after collaborative optimization.

5. Innovative advantages

Compared with traditional propellers, the shaftless rim drive propeller designed by the team has five core advantages: compact structure, high system efficiency, low noise, environmental protection, and a wider range of applications. [3]
Table. 1 Comparison and analysis table of two kinds of thruster’s performance

|                          | Traditional mechanical propeller                                      | Shaftless rim thruster                                      |
|--------------------------|------------------------------------------------------------------------|-------------------------------------------------------------|
| Effectiveness            | Many transmission links, low efficiency                                | Direct drive, efficiency increased by 8%~15%                 |
| Vibration                | Gears, uneven flow of propellers, large vibration                      | No gears, uniform flow of propellers, low vibration          |
| Noise                    | Gears, noisy                                                           | Without gears, the noise is reduced by 10~15dB               |
| Tightness                | Dynamic seal is easy to wear, causing oil leakage and water ingress   | Static sealing, no leakage                                  |
| Weight                   | Complex machinery, heavy weight                                       | Simple structure, weight reduction 60%                       |
| Volume                   | Large                                                                  | Smaller                                                     |
| Reliability              | Low                                                                    | Higher                                                      |
| Use Depth                | Sealing problem, cannot be used in deep water                          | Can be used in deep water                                   |
| Maintainability          | Too many parts, difficult to repair                                    | Simple structure and simple maintenance                      |

6. Application scenarios
The propellers designed by the team can be widely used in various small and medium-sized ships, such as underwater vehicles, yachts, sightseeing boats, fishing boats, patrol boats and smart ships. At the same time, the team and partners are actively carrying out technical exchanges, intending to solve the design and manufacturing problems of higher-power shaftless rim thrusters, and to overcome the design and manufacturing problems of higher-power shaftless rim thrusters, making shaftless rim propulsion the device will be applied to large ships such as luxury cruise ships, bulk carriers, and base cruise ships.

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