Hydrodynamic Performance and Vibration and Noise of Machine-pump Integration Device

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Abstract: As a new type of drainage equipment or underwater propeller, the machine pump integrated device composed of permanent magnet motor and pump blade of Halbach structure has many advantages and wide application prospects. Starting from the hydrodynamic analysis method of the machine pump integrated device, this paper reviews the research progress in this field at home and abroad in recent years. The results are summarized and analyzed. Finally, according to the current problem needs and the shortcomings of the research status, some ideas are put forward for the vibration and noise suppression method of the machine pump integrated device, which provides a reference for the follow-up related research.

1. Introduction

Liquid pumps are important equipment on ships. The existing liquid pumps all adopt traditional structures. The motor drives the pump blades to rotate through the drive shaft to transport the liquid out [1]. This traditional structure is large in size and high in noise, which is not conducive to the space optimization design of the ship and the stealth of the ship. The new integrated pump, the pump blades are directly connected with the inner surface of the rotor, eliminating the need for a drive shaft, and the liquid flows out directly through the inner diameter of the rotor during operation, which fundamentally solves the problem of large space occupied by the liquid pump.

Existing naval liquid pumps generally adopt a traditional structure, that is, the pump body is outside the rotating motor, and the two are coaxial. The pump blades are driven to rotate by the motor rotation during operation to deliver the liquid, as shown in Figure 1.

However, with the development of ship modernization and the continuous increase of tonnage and capacity, the supply areas of liquid such as seawater, fresh water, fuel oil and lubricating oil are increasing, and the supply situation is becoming increasingly complex [2]. In order to enhance the ship's advantages in stealth and cabin space utilization, the design and application of various oil and water pumps in the ship should be optimized.
Traditional pumps can cause many problems when applied to ships and submarines. Due to the design defects of traditional liquid pumps, traditional pumps are large in size, low in power density, and low in space utilization. Due to the special occasions of naval vessels, most traditional pumps need to be installed vertically when in use [3]. Even the most common ship needs at least dozens of pumps, and the internal space of the ship is inherently small and limited. This will inevitably cause installation difficulties and occupy too much space, and bring inconvenience to the crew’s daily life [4]. For example, the multiple water pumps of a certain type of destroyer are installed vertically in the aisles in the cabin, and the crew should pay attention to avoidance when getting on and off the cabin and walking back and forth. When encountering big winds and emergencies, the crew accidentally crashes into non-combat attrition, which has great hidden dangers. On the other hand, due to the large number of liquid pumps occupying a large space and difficult to install, it is difficult for large ships such as The space optimization design of aircraft carriers and nuclear submarines brings inconvenience [5].

By adopting a new integrated structure, the volume of the liquid pump can be reduced, and the space utilization rate in the naval cabin can be greatly improved. At the same time, the structure of the naval piping system is clearer, and the maintenance of equipment is more convenient, which will further enhance the vitality of the naval vessel. And combat effectiveness. Figure 2 is a schematic diagram of a mechanical pump integrated liquid pump without a mechanical drive shaft, and Figure 3 is a physical diagram of a mechanical pump integrated liquid pump.

2. Research status of The machine-pump integrated device

2.1. Development of pump and turbine integrated device at the present stage

The machine-pump integrated device can also be called the rim drive device. It can be seen from Figure 2 and Figure 3 that the rim drive device is driven by the prime mover directly through the impeller rim to drive the impeller, thus eliminating the transmission shaft link. The prime mover of the rim drive device is usually a motor, and a non-contact transmission is realized between the motor and
the rim of the impeller through electromagnetic force.

The machine-pump integrated device is a relatively novel power device [6]. The biggest difference from the conventional power device is that it does not have a traditional shafting structure and uses a wheel-driven hubless propeller. This new structure makes the pump-mechanical integrated device have the characteristics of simple and compact structure, small size, flexible installation and so on. Due to the absence of the influence of the structure of the hub and shafting, coupled with the rectification effect of the draft tube, this device is more effective than conventional propellers when used as a propeller under various working conditions including diagonal flow and ship rear. Uniform incoming flow, so its efficiency, and vibration and noise performance are also more excellent. Since the blades of the pump integrated device are fixed to the rim at the maximum radius, the blade section of the large radius part of the blade has a smaller radius part and the chord length and blade thickness are larger, and the large radius part of the blade can receive more The larger the torque, the larger the load can be distributed, so that the total thrust and torque of the device can be greatly improved, which means that the integrated pump and pump device can absorb more power and output more under the same scale. thrust. However, there are still relatively few research materials on the hydrodynamics of this new type of device, and its design and manufacturing process are relatively more complicated and difficult, which limits its application in engineering [7].

Literature [2] and [3] analyzed the vibration and noise performance of similar devices from the perspective of electromagnetic design and proposed design optimization. They did not analyze the hydrodynamic performance of their devices. Literature [8] used computational fluid dynamics methods to analyze A comparative study on the hydrodynamic performance of the shaftless rim turbine and the shafted turbine was carried out, and the superiority of the shaftless rim turbine was obtained; Reference [9] used CFD method to conduct a hydrodynamic analysis of a special propeller; Reference [10]Using the finite element simulation method to analyze the influence of the main parameters of the permanent magnet fault-tolerant rim propulsion motor on the performance of the motor. And this article will summarize and integrate the above literature methods from the perspective of hydrodynamics to study the performance of the integrated pump and pump unit.

2.2. Feasibility Analysis

This research group first conducted a preliminary design and performance analysis of the axial flow pump used in the integrated pump-mechanical device. Figure 4 shows the design results of the axial flow pump blades, and Figure 5 shows the corresponding performance curves. The results show that the use of axial flow pumps is feasible, but the design scheme is far from an optimal scheme.
Secondly, the no-load characteristics of the Halbach rotor permanent magnet motor, which meets the requirements of the integrated pump-mechanical device, are studied. Figure 6 shows the magnetic density distribution under no-load conditions, and Figure 7 shows the temperature distribution of the stator core and windings under no-load conditions (in the specific calculation, the stator core and winding losses obtained in the electromagnetic field are used as the heat source to introduce the temperature. In the field, the convective heat transfer coefficient of each surface of the motor is preliminarily set, and the influence of the fluid in the integrated machine-pump device has not been considered for the time being).

The above results show that the integrated pump-mechanical device is feasible in terms of hydrodynamic principles.

3. Research method analysis

3.1. Hydrodynamic research methods

Computational Fluid Dynamics (CFD), which is based on the theory of viscous flow to solve the Navier-Stokes equation (N-S equation) [11], has developed rapidly in recent years with the advancement of computer science. According to the different ways of controlling the discrete equations, the numerical solution of CFD can be basically divided into the following three methods: Finite Difference Method (FDM), Finite Element Method (FEM), Finite Volume Method (FVM). In the process of numerical calculation, the commonly used turbulence numerical simulation methods mainly include direct numerical simulation (DNS), large eddy simulation (LES) and Reynolds average simulation (RANS). Currently, computational fluid dynamics commercial software such as ANSYS Fluent, CFX, Star CCM+ has been widely used in fluid calculations. The current commercial software basically uses the finite volume method (FVM), because the discrete equation used in this method is conservative, the physical meaning of the coefficients in the discrete equation is clear, and the amount
of calculation required is also relatively large compared to the other two methods. [12] The CFD method does not simplify the model. Every detail in the flow field can be displayed in detail, such as hydrodynamic coefficients, velocity distribution, pressure distribution, vortex distribution, and streamline distribution. In view of the outstanding advantages of the CFD method, many scholars now directly use commercial CFD software as a means to perform various performance predictions and researches on marine propulsion [13]. Some scholars use CFD to directly calculate and analyze the overall ship-propeller-rudder model [14]. However, the further development and application of CFD also requires the support of more powerful computing capabilities of computers.

3.2. Vibration and noise research methods
Military ships have higher requirements for their own concealment, and the integrated pump and engine device is the main source of vibration and noise on board when used as a propeller, and its vibration and noise level has been paid more attention. Compared with the traditional drive device, the machine-pump integrated device eliminates the transmission mechanism such as the shaft system and eliminates the vibration and noise caused by the rotation of the shaft system; it has fewer connections with the hull, which greatly reduces the interaction between the device and the hull. Vibration noise generated. The machine-pump integrated device drives the motor stator to work and at the same time can be used as a propeller shroud, which can delay the generation of propeller blade cavitation and shield the fluid noise generated by the rotation of the rotor. Therefore, from the perspective of its working principle, the machine-pump integrated device itself is a quiet driving device in the true sense, but the difference between its structure and the traditional driving device causes its vibration mechanism to be completely different from the existing theory. How to pass Methods such as optimizing the mechanical structure, improving the manufacturing process, and improving the work efficiency to give play to its advantages of low vibration and noise, and to reduce vibration and noise reasonably, have also become research hotspots.

The noise sources of the machine-pump integrated system mainly include electromagnetic noise and liquid dynamic noise. For liquid dynamic noise, the relevant theories of computational fluid dynamics can be applied to optimize the design of the blade to reduce the vibration and noise of the system [15]. The electromagnetic noise of the permanent magnet synchronous motor and the fluid dynamic noise are obviously different in the vibration noise spectrum, so the two kinds of vibration noise can be optimized separately.

Reasonably designing the parameters of the motor is the key to reducing the electromagnetic vibration and noise of the motor. Theories and relevant practical experience show that the vibration and noise of the motor can be effectively reduced by selecting the appropriate slot-pole fit, rotor air gap size, and optimizing the rotor magnetic pole structure [16]. On the other hand, while reducing the vibration and noise of the motor, other performance indicators of the motor cannot be sacrificed. For example, in order to reduce the vibration and noise of the motor, the motor loss and the motor torque pulsation are too high. This approach is not advisable. Therefore, in the design of low-noise motors, it is necessary to consider motor loss, torque ripple and other issues, so that all aspects of the motor can meet the requirements of use [17].

4. Research methods in this article

4.1. Use FLUENT to build a model
The NS equation that needs to be used in ANSYS FLUENT software is a discontinuous equation, and it is also a momentum conservation equation. It is a basic law that any flow system must satisfy. It can be expressed as: the rate of change of the momentum of the fluid in the micro-element body with respect to time is equal to the outside world The sum of various forces acting on the micro-element body. This law is actually Newton's second law. According to this law, the momentum conservation equations in the x, y, and z directions can be written:
\[ \frac{\partial (\rho u)}{\partial t} + \text{div}(\rho uu) = \frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + F_x \]

\[ \frac{\partial (\rho v)}{\partial t} + \text{div}(\rho vu) = \frac{\partial p}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + F_y \]

\[ \frac{\partial (\rho w)}{\partial t} + \text{div}(\rho wu) = \frac{\partial p}{\partial z} + \frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + F_z \]

In the formula, \( u, v, \omega \) represent the displacement, velocity and acceleration of the fluid movement respectively; \( P \) is the pressure on the fluid micro-element body; \( \tau_{xx}, \tau_{yy}, \tau_{zz} \) are the component of viscous stress caused by the effect of molecular viscosity on the surface of the micro-element body; \( F_x, F_y, F_z \) represent the physical force on the micro-element body, if the physical force is only gravity, and the z-axis is upright. Then \( F_x=0, F_y=0, F_z=-\rho g. \)

It should be noted that although the energy conservation equation is the basic governing equation for fluid flow and heat transfer problems, for incompressible flow, if the heat exchange is very small, it can be ignored, so it will not be explained here. At this stage, when using the NS equation to analyze and calculate the fluid, the most used methods are the large eddy current simulation method (LES) and the Reynolds average simulation method (RANS). The models available for calculation in the FLUENT software are: Spalart-Allmaras Model, standard k-\( \varepsilon \) model, RNG k-\( \varepsilon \) model, k-\( \varepsilon \) model with swirl correction, k-\( \omega \) model, pressure correction k-\( \omega \) model, Reynolds pressure model, large vortex simulation model, etc. This study uses the standard k-\( \varepsilon \) turbulence model.

4.2 Hydrodynamic performance analysis

To calculate the open water performance of the propeller in the device, it is necessary to introduce the advance speed coefficient \( J \). The concept of advance speed coefficient refers to the ratio of the propeller process to the diameter of the propeller. The conversion formula is:

\[ J = \frac{V_A}{nD} \]  

In the formula, \( n \) is the speed of the propeller, \( D \) is the diameter of the propeller, \( V_A \) is the speed of the propeller.

According to the above-mentioned advance speed coefficient formula, the incoming flow speed is obtained by taking different advance speed coefficients \( J \); through this method, the steady hydrodynamic performance of the propeller under different advance speed coefficients is calculated separately, that is, the thrust coefficient \( K_T \), torque coefficient \( K_Q \), and open water efficiency \( \eta \) of the propeller. The relationship between them is described in the following formula:

\[ K_T = \frac{T}{\rho n^2 D^4} \]  

\[ K_Q = \frac{Q}{\rho n^2 D^5} \]  

\[ \eta = \frac{K_T J}{2\pi K_Q} \]
4.3. Vibration analysis of integrated pump-mechanical device

Using electromagnetic force calculation, the electromagnetic force is obtained by establishing a finite element model of the electromagnetic field of the motor. Then, according to the results of the hydrodynamic performance of the device previously obtained, the electromagnetic force is applied as an excitation to the finite element model of the stator duct structure to solve the vibration response, and the influence of different propeller conditions on the vibration of the device is analyzed. At the same time, the vibration response of the stator duct under various working conditions is measured through experiments to verify the accuracy of the finite element calculation and perform error analysis. Finally, combined with the finite element model of the device, the vibration frequency spectrum of the stator duct under various working conditions is analyzed to determine the main reason for the vibration of the device.

4.4. Noise analysis of integrated pump-mechanical device

The noise of a general motor usually includes electromagnetic noise, mechanical noise and air noise. According to different causes, mechanical noise can be divided into noise caused by rotor mechanical imbalance, bearing noise and brush noise. Because the integrated propulsion motor uses sliding bearings and is a brushless motor, bearing noise and brushes are not considered. Noise, and the noise caused by the mechanical imbalance of the rotor can be basically eliminated through the dynamic balance experiment. The integrated pump-mechanical propulsion motor runs in water, so there is no problem of air noise. Compared with the onshore independent electric motor and the motor with separate propellers in the cabin, the electromagnetic noise and propeller noise of the integrated pump and propulsion motor always exist at the same time and are coupled with each other. In order to facilitate the comparison with the measurement results, the propeller noise should also be considered when the computer-pump integrated propulsion motor underwater noise.

5. Conclusion

This article summarizes the development history and research status of the integrated pump-mechanical device, focusing on how to suppress the vibration and noise of the integrated pump-mechanical device through hydrodynamic performance. The specific description is as follows:

1) Use ANSYS FLUENT software to model and analyze its hydrodynamic performance.
2) Combining the finite element model of the device, analyze the vibration frequency spectrum of the stator duct under various working conditions, determine the main reason for the device vibration, and design the motor parameters reasonably according to the research.
3) In the design of low-noise motors, it is necessary to consider the noise of the motor's underwater propeller, so that all aspects of the motor can meet the requirements of use.

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