

Design of an Integrated Propulsor for the Autonomous Underwater Vehicle Based on the Shaftless Propulsion Motor

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The shaftless pump-jet propulsor achieves superior speed and efficiency in autonomous underwater vehicles (AUV) due to its compact, low-noise, high-performance integrated motor and blade design. This study optimizes the collaboration between the blades and the motor, employing Computational Fluid Dynamics (CFD) for fluid and thermal analysis and Finite Element Method (FEM) for electromagnetic modeling. Through multi-field coupling and parametric design, the research systematically verifies the propulsion's performance, with experimental results demonstrating that it can attain speeds up to 26 knots. This work represents a substantial contribution to the advancement of underwater propulsion technology.

Index Terms—Shaftless propulsion motor, autonomous underwater vehicles (AUV), integrated design, multi-physics coupling

I. INTRODUCTION

Autonomous underwater vehicles (AUV) with mechanical drive systems under conventional power cannot meet the requirements of ultra-wide speed modulation from low speed to high speed, because their drive modes, energy configurations and external structures vary at different speeds. In order to enable the vehicles to achieve wide speed modulation at low, medium and high speeds, a hybrid integrated shaftless propulsion motor underwater vehicle is proposed, which can realize the low-speed gliding mode driven by buoyancy and the medium-high speed navigation mode driven by the propeller.

Some scholars used using computational fluid dynamics to evaluate the traditional water jet propulsion system[1]. They revealed that the conventional propeller generates non-uniform inlet flow, leading to uneven flow distribution and consequently reducing overall efficiency. The lumped parameter thermal network method was employed to analyze electromagnetic-thermal coupling issues[2]. In the traditional propulsion device design, the motor and propeller can be designed separately. In the shaftless propeller, the motor and blade are integrated, the structure is more compact, the design requirements are higher, and there is a complex multi-physical field coupling mechanism inside. To satisfy the design requirements for the integration of motor and propeller, a design methodology incorporating multi-physics coupling and parametric design is proposed. The design solution is achieved through iterative optimization of the interface between the motor and blade, along with parametric design within the motor. To validate this approach, a prototype was fabricated and evaluated.

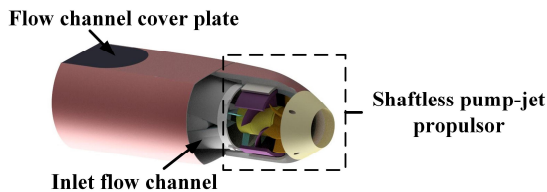


Fig. 1. Vehicle propulsion device

II. INTEGRATED DESIGN OF PROPULSION SYSTEM

The design process of multi-physics coupling is shown in Fig. 2. Firstly, an initial outer diameter for the propeller is established, with the AUV's (Autonomous Underwater Vehicle) drag and cruising speed serving as inputs for the flow field analysis. Employing Computational Fluid Dynamics (CFD) methods, target values for the rotation speed and load torque are calculated. Next, under the constraint of the specified propeller outer diameter, a multi-objective optimization model for motor design is developed, taking into account the bidirectional coupling between the electromagnetic field and temperature field. This model aims to obtain optimal motor design parameters that efficiency, temperature, and power density. Finally, the calculated rotation speed and load torque from these parameters are compared against the target values. If they meet the targets, the corresponding motor parameters are outputted. Conversely, if the targets are not met, the initial propeller outer diameter is reset, and the aforementioned steps are repeated until the desired performance metrics are achieved.

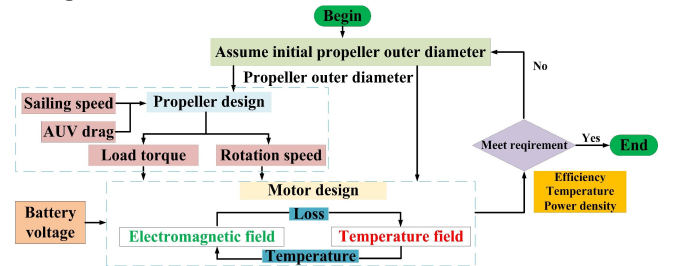


Fig. 2. Flow chart of multi-physics coupling design

A. Propeller device

In the integrated design of the motor and propeller, the ratio of rotor diameter to blade edge was optimized through coupled fluid dynamics and electromagnetic field calculations. The flow path of the propulsor is shown in Fig. 3. The hydrodynamic performance of the AUV was numerically simulated using Computational Fluid Dynamics (CFD), establishing a relationship between sailing speed, rotational speed and flow

rate, which is used as the input of the propeller fluid field model to simulate the output index of the motor. The obtained results are shown in TABLE I.

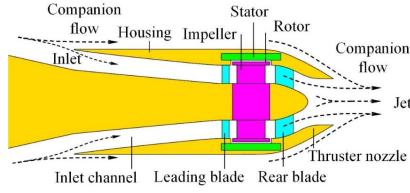


Fig. 3. Schematic diagram of flow channel

TABLE I
PREDICTED HYDRODYNAMIC RESULTS OF PROPULSOR

Sailing speed/kn	Rotation speed/rpm	Propeller torque/Nm	Output power/kW
16	1500	33.2	5.262
21	2000	59.9	12.65
30	2900	127	38.73

The simulation of the fluid velocity field of the propeller is shown in Fig. 4. The rear guide vane can transform the radial eddy current at the front into axial eddy current, thus increasing the axial overflow volume, realizing energy recovery.



Fig. 4. Simulation of fluid velocity field

B. Shaftless motor

The rotor adopts halbach magnetic array in order to obtain more sinusoidal air gap magnetic density and reduce the radial space. Moreover, owing to the relatively stable temperature in the underwater environment, NdFeB was chosen as the permanent magnet material. Compared to SmCo, NdFeB can provide a stronger magnetic field within a smaller volume, thereby enhancing the utilization of radial space. A core structure is added at the rim to provide magnetic shielding and prevent magnetic leakage issues. The design optimizes key geometric parameters—such as crack ratio, slot opening ratio, tooth width ratio, and slot depth ratio—to enhance efficiency and reduce torque ripple, achieving optimal performance. The basic parameters of the motor are summarized in TABLE II. The flux-line distribution under load condition is shown in Fig. 5. The temperature field of the motor is calculated by using the Computational Fluid Dynamics (CFD) method. The primary modes of heat transfer are conduction and convection, as depicted in Fig. 6.

TABLE II
BASIC PARAMETERS OF PROTOTYPE

Parameters	Value
Stator outer diameter	235mm
Rotor core thickness	2.5mm
PM thickness	4.25mm
Sleeve thickness	0.5mm
Coil pitch	5
Slot number	96
Pole number	16
Phase number	12
PM material	NdFeB
Stator sleeve material	TA16

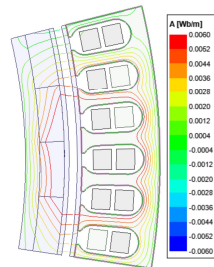


Fig. 5. Magnetic flux-line distribution under load condition

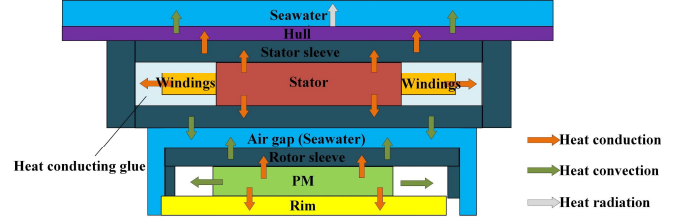


Fig. 6. Heat flow of motor

III. PHYSICAL TESTS OF THE MOTOR

The prototype machine and its working state are shown in Fig. 7. The experimental data and design values are compared as shown in TABLE III. The speed error is caused by the voltage in the power supply system.



Fig. 7. Test platform and main parts of shaftless propulsion motor

TABLE III
COMPARISON OF EXPERIMENTAL VALUES AND DESIGN VALUES

Performance parameter	Design value	Measured value	Error
Rated power / kW	38.73	37.5	3.2%
Speed /rpm	2900	2829	2.4%
RMS of no-load line voltage / V	148.0	148.4	0.2%
RMS of load phase current / A	39.74	43.67	10.1%
Winding temperature rise/K	113.43	116	2.3%

IV. CONCLUSION

In this paper, an innovative design methodology for an integrated shaftless propeller is introduced. The multi-physics coupling method based on the flow field, electromagnetic field and temperature field is used to parameterize the propulsion device, including blade and motor. After several iterations, the design results, hydrodynamic performance and motor performance of the propeller under this scheme are obtained. The experiment shows that the error of the designed speed is less than 5%, and the sailing speed can reach 26kn. This design method can be applied to other integrated shaftless thrusters.

References

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