Design Comparison of Outer- and Inner-Rotor Permanent Magnet Motors for Hydrofoil Boat

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***Abstract*—This paper presents the design criteria of a permanent magnet motor for hydrofoil boat applications. Based on the dynamic analysis of hydrofoil boat, the constraints of propulsion motor are derived and therefore the surface-mounted permanent magnet motor is chosen as the competitive candidate. In order to have large power density in the permanent magnet motor, the outer- and inner-rotor motors are investigated and compared to demonstrate their advantages at different design constraints, which will provide the theoretical basis to improve the propulsion system in the hydrofoil boat from the perspective of motor design.**

***Index Terms*—Permanent magnet motor, optimal design, hydrofoil boat**

NOMENCLATURE

rho	The water density
α	Pole-arc to pitch-arc ratio
η_0	the efficiency of the propeller
η_e	the efficiency of the motor
η_h	The efficiency of the hull
η_r	The relative rotative efficiency due to the mixed wake field for the behind-hull propeller
b_{si}	The radius of the slot bottom
b_{so}	Slot-opening length
D	The diameter of the propeller
D_m	The motor outer diameter
g	Air-gap length
h_m	PM height
J_a	Advance coefficient
k_p	The parameter coefficient for uniformizing the different scales of the motor parameters
K_Q	Torque coefficient
k_s	Split ratio
K_T	Thrust coefficient
l_m	The motor effective length
n	The rotational speed of the motor
n_{motor}	The motor maximum speed
p_0	The parameter value
P_e	The effective power of driving the boat
P_m	The motor power of driving the propeller
P_n	The motor nominal power
p_{max}	The maximum value of the parameter
p_{min}	The minimum value of the parameter
R_a	The motor inner radius
R_m	The inner or outer radius of PM for the outer-rotor or inner-rotor motor
R_t	The total resistance of the boat
R_{sb}	Stator yoke height
T_m	The torque of the motor
V_a	The water speed passing through the propeller
V_b	The speed of the boat

I. INTRODUCTION

Hydrofoils have existed for decades but the demand for fossil-free propulsion, innovations in composite materials and hydrodynamic design methods have started a new trend for marine transportation where hydrofoils enable electric propulsion with competitive range and performance. As a hydrofoil boat's hull is lifted out of the water, the friction resistance can be significantly reduced, making the travel much more efficient [1]. Furthermore, the direct-drive electrical motor integrated into a propeller is used to provide the thrust making a simple and efficient propulsion system.

In [2], an overview of the state-of-the-art electric propulsion systems for electric boats was presented. The flux switching motor [3], multi-phase permanent magnet (PM) motor [4], and interior permanent magnet motor [5] were investigated for the traditional electric boat. The comparative study of four PM motor topologies was given to show the volume-versus-loss trade-offs for marine propulsion applications [6]. However, there are very few works of literature about electric motors for hydrofoil boats, and there is lack of understanding about the design constraints when the submerged motor needs to overcome the water friction at high cruising speed. In this circumstance, it is a wise choice to design a thin and long motor to produce enough propulsion with small resistance, according to the theory of hydrofoil boats [7].

This paper investigates the design criteria of a permanent magnet motor for hydrofoil boat application. Two types of PM motors with either outer-rotor or inner-rotor are proposed and optimized to show their advantage and disadvantage in the hydrofoil application case. The parameter sensitivity is used to reduce the calculation time in the motor design. Based on the finite-element analysis of PM motors at different air-gap lengths and motor inner radius, the outer-rotor PM motor shows better performance than the inner-rotor PM motor.

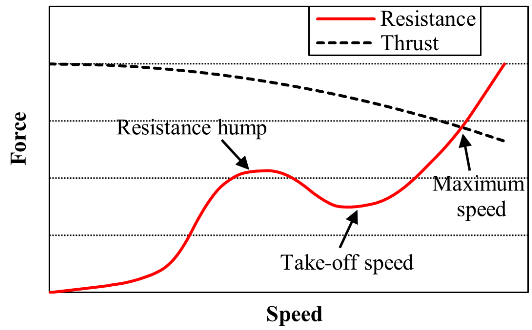


Fig. 1. The variation of thrust and resistance to speed in the hydrofoil.

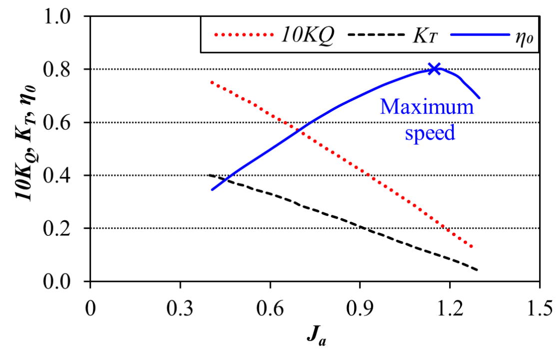


Fig. 2. The variation of K_Q, K_T, and η_0 to J_a for the hydrofoil boat.

II. Electric Motor For Hydrofoil Boat

A. Maintaining the Integrity of the Specifications

Compared with conventional boats, the hydrofoil boat hull travels out of the water at high speed except for the submerged piercing foils and supporting system. These foils produce the lift force to support the boat's hull based on the hydrodynamic mechanism and can significantly reduce the total resistance.

Fig. 1 illustrates the resistance variation when the hydrofoil boat speeds up from the stationary condition. The resistance hump in the red curve shows that the boat's hull is about to "take off" from the water, and the resistance consists of the hull, the foil, and the supporting system. As the speed increases, there is a significant drop in the resistance because the hull starts to leave the water. After that, the resistance of the hydrofoil boat rises again due to the increasing speed in the foil and supporting system still in the water. Finally, it reaches the maximum speed when the thrust from the propulsion system is equal to the resistance. The work duty of hydrofoil boat is quite different from that of electric vehicles and conventional boats, making the motor design of hydrofoil boat challenging. The power rating of the propulsion motor is extracted from the boat's working condition at maximum speed. The propulsive coefficients of a hydrofoil boat connect P_m with P_e. Therefore, the quasi-propulsive coefficient is defined as [7]

$$QPC = \frac{P_e}{P_m} = \frac{R_t V_s}{2\pi n T_m} = \eta_h \eta_0 \eta_r \tag{1}$$

To find the constraints and goals for the motor design, the characteristic of the propeller is the most critical information in the analysis. The torque for driving the propeller T_m and the corresponding thrust for propelling the boat F_t in the open water is the crucial formula for extracting the torque and speed curves of the electric motor [7].

$$T_m = K_Q \rho n^2 D^5 \tag{2}$$

$$F_t = K_T \rho n^2 D^4 \tag{3}$$

$$J_a = \frac{V_a}{nD} \tag{4}$$

According to (2)-(4), the propeller efficiency η_0 can be expressed as [7]

$$\eta_0 = \frac{V_a F_t}{2\pi n T_m} = \frac{J_a K_T}{2\pi K_Q} \tag{5}$$

Fig. 2 gives the curves of a single propeller characteristic working in open water, which is applicable to any other propeller with the same geometric form but a different diameter or scale ratio. Usually, the propeller is designed to work at the highest efficiency point where the hydrofoil boat travels at the maximum speed in Fig. 1. Accordingly, the torque and speed of the propulsion motor can be determined for the hydrofoil boat.

III. Outer- And Inner-Rotor PM Motors

After analyzing the hydrofoil boat, the requirement of a typical propulsion motor is given in Table I. The surface-mounted permanent magnet motor is employed and optimized to fulfill such requirements. Still, there is a lack of comparison of outer- and inner-rotor PM motors to give a better choice for such an application. Even though the outer-rotor PM motor can produce large torque due to the greater split ratio, its pole number is larger to reduce the height of rotor yoke, resulting in a higher electric frequency and electromagnetic loss at the same rotational speed. Therefore, the total loss of both motors should be kept the same for fair comparison. The general view of both motors is given in Fig. 3. The pole number of outer-rotor motor is larger than that of inner-rotor motor to keep the similar height of rotor yoke for both motors.

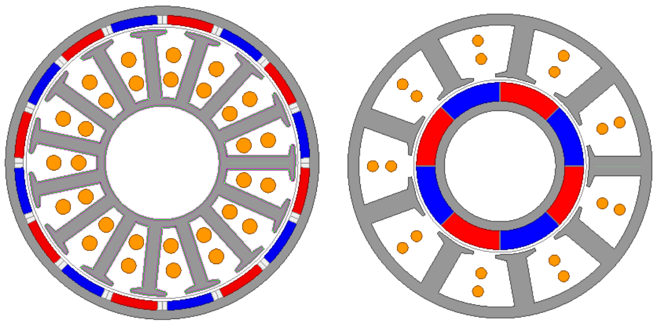
Other constraints for the propulsion motor are given as follows:

1) As the entire motor is operated under the water, the sizeable air-gap length is required to reduce the water friction loss. Therefore, the air-gap g of 1 mm, 1.5 mm, and 2 mm is chosen for comparison.

2) To reduce the friction resistance of the hydrofoil boat due to water flow, the cross-sectional area of the motor should

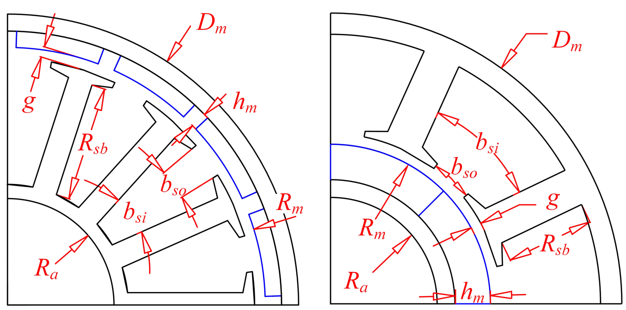
TABLE I
Requirement of the Propulsion Motor For Hydrofoil Boat

Parameter	*Value*
Motor diameter D_m	≤90 mm
Motor length l_m	≤120 mm
Nominal power P_n	≤10 kW
Maximum speed n_{motor}	≤3500 rpm



(a) Outer-rotor (b) Inner-rotor

Fig. 3. The general view of both PM motors.



(a) Outer-rotor (b) Inner-rotor

Fig. 4. The general view of both PM motors.

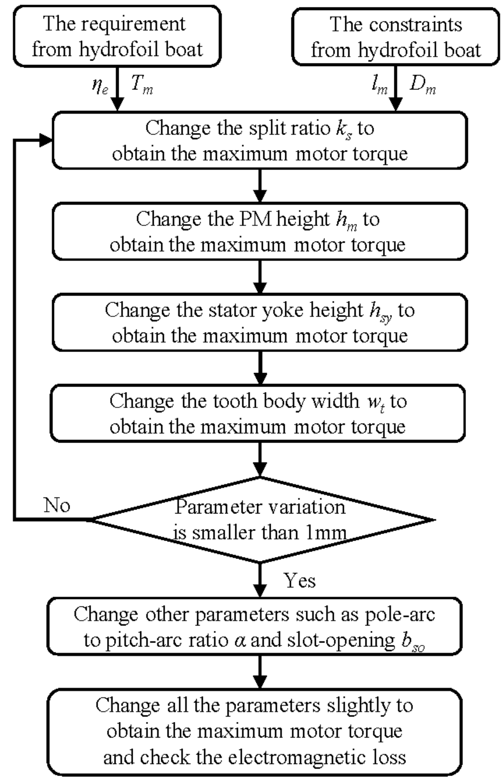


Fig. 5. The optimization process of PM motors for the hydrofoil boat.

be minimized [7]. To simplify the fluid analysis, the outer diameters of both outer-rotor and inner-rotor motors are the same, but their inner diameters are variable. Therefore, the inner radius of the motor R_a can be set as large as 15 mm and 20 mm for comparative purposes.

3) The total electromagnetic loss, including iron loss, magnet loss and copper loss cannot exceed 500 W to guarantee the motor reliability when the hydrofoil boat travels at cruise speed.

A. Optimization Process

According to the analytical model in [8] and [9], PM motors' magnetic and electric loading can be represented by the dimension of the PM area and slot area. The PM height, the stator tooth width, the stator yoke height, and the diameter of the air gap are the critical parameters for improving the motor torque. When considering the iron saturation, the stator and rotor iron should be adequately designed to maximize the torque while keeping the electromagnetic loss at a reasonable level. Hence, these parameters should be optimized in the initial design. It is noted that the air-gap diameter is equivalent to the split ratio of the motor. In this paper, the split ratio k_s is defined as $k_s = \frac{2R_m}{D_m}$. The design parameters are also shown in Fig. 4 to giva a clear view about the geometry of the inner-rotor and outer-rotor.

Then, other parameters such as pole-arc to pitch-arc ratio α and slot-opening b_{so} are optimized to improve the motor performance further. At this stage, all the motor parameters will be slightly modified to obtain the best performance according to the requirement from the hydrofoil boat. The optimization process of the PM motor with either outer-rotor or inner-rotor is given in Fig. 5. The whole parameters of the motor are divided into two categories, the first one will change the performance of the motor significantly while the latter has smaller influence on it. Therefore, the optimization process of the motor can speed up to give the comprehensive study of the motor with either outer-rotor or inner-rotor for the hydrofoil boat. As the air-gap length and the inner diameter of the motor is mainly affected by the friction resistance in the hydrofoil boat, they will be obtained from the dynamic analysis rather than the electromagnetic calculation, which can simplify the optimization process.

B. Outer- and Inner-Rotor Motor

The 16-pole/15-slot outer-rotor PM motor and 8-pole/9-slot inner-rotor PM motor are proposed for the hydrofoil boat. They are designed based on the proposed optimization process. The parameter sensitivity is carried out to show the feasibility of the optimization and the importance of different parameters on the motor performance. The parameter coefficient k_p is defined as

$$k_p = \frac{p_0 - p_{\min}}{p_{\max} - p_{\min}} \tag{6}$$

Figs.6-7 show that the slot area has a significant influence on the torque for the outer-rotor PM motor at R_a = 20 mm and g = 1.5 mm. However, the stator yoke height R_{sb} can

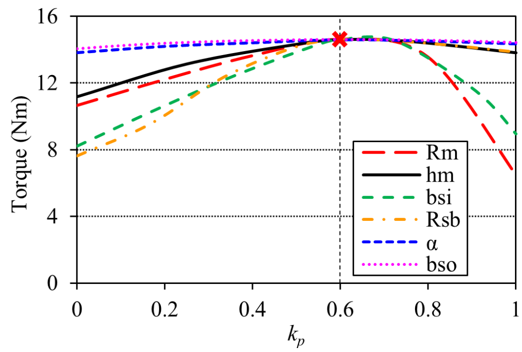


Fig. 6. The variation of torque to k_p for outer-rotor PM motor.

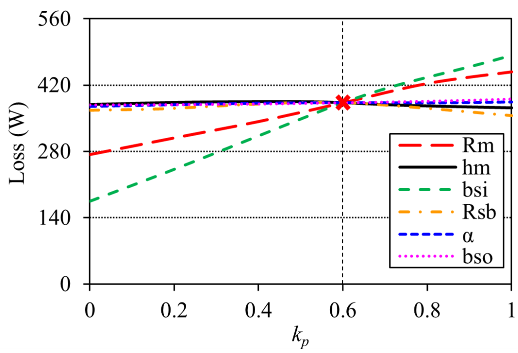


Fig. 7. The variation of total loss to k_p for outer-rotor PM motor.

hardly influence the total loss due to the trade-off between the copper loss in the slot area and the iron loss in the stator yoke. Figs. 8-9 show that the slot area has a significant influence on both torque and total loss for the inner-rotor PM motor. The split ratio is always an essential factor for the performance of both motors.

C. Comparison and discussion

The performance of the optimized motors with different air-gap g and inner radius of motor R_a is given in Figs. 10-11. The outer-rotor PM motor shows better performance for the hydrofoil boat than the inner-rotor PM motor with the same constraints. For example, when both motors reach the maximum loss of 500 W with R_a = 20 mm and g = 1.5 mm, the outer-rotor PM motor can deliver the torque of 19.7 N·m while the inner-rotor PM motor reaches 17.9 N·m. Besides, the motor's inner radius has a larger influence on the outer-rotor PM motors than the inner-rotor PM motor. When R_a is reduced from 20 mm to 15 mm, the maximum torque of the outer-rotor motor rises significantly due to the increased slot area. However, for the inner-rotor PM motor, both R_a and g have a similar influence on the torque, as shown in Fig. 8. The advantage of the outer-rotor motor owes to its large split ratio, because even though the electric frequency of the outer-rotor motor is twice as large as that of inner-rotor motor, the core loss and magnet loss of the outer-rotor motor only increases about 30%-80%, making the split ratio become the

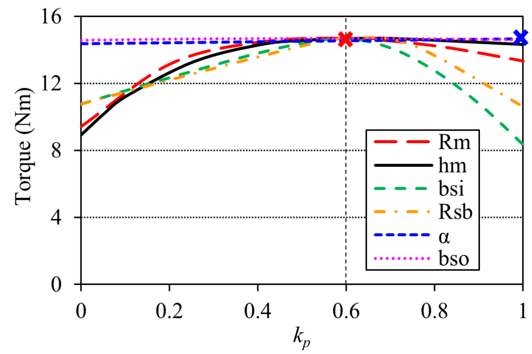


Fig. 8. The variation of torque to k_p for inner-rotor PM motor..

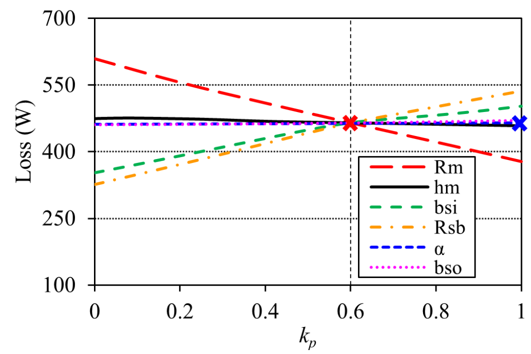


Fig. 9. The variation of total loss to k_p for of inner-rotor PM motor.

most important factor for the motor torque. With a smaller pole number for the outer-rotor PM motor, its electromagnetic performance will be further improved. Besides, the inner-rotor PM motor will suffer from the over-heat of magnet due to poor cooling condition compared with the outer-rotor PM motor, which can benefit from the presence of surrounding water on the rotor surface.

IV. Conclusion

This paper compared the outer- and inner-rotor PM motors for a hydrofoil boat considering its special work duty. The different air-gap length and the motor inner radius are compared for both motors. The finite-element analysis shows

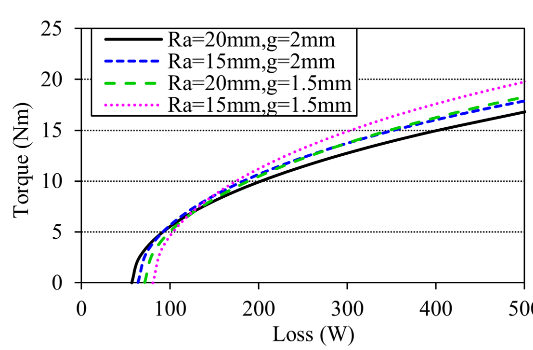


Fig. 10. The variation of torque to the total loss for outer-rotor PM motor.

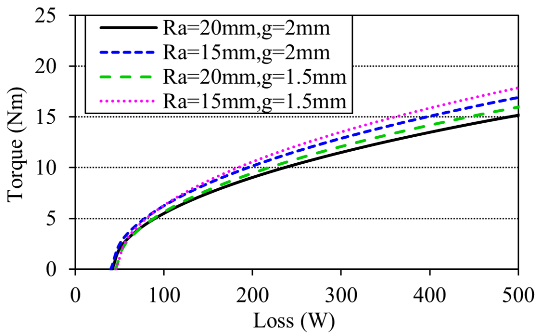


Fig. 11. The variation of torque to to the total loss for inner-rotor PM motor.

that the outer-rotor PM motor exhibits better performance in the application of hydrofoil boat due to large torque density. More work related to the fluid analysis and thermal analysis in the motor will be carried out to show the effectiveness of the motor comparison for the hydrofoil boat.

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