

Article

Performance Analysis of Conical Permanent Magnet Couplings for Underwater Propulsion

Yukai Li ^{1,2,*} , Yuli Hu ^{1,2}, Baowei Song ^{1,2}, Zhaoyong Mao ¹ and Wenlong Tian ¹

¹ School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an 710072, China; zx670821@nwpu.edu.cn (Y.H.); songbaowei@nwpu.edu.cn (B.S.); maozhaoyong@nwpu.edu.cn (Z.M.); tianwenlong@mail.nwpu.edu.cn (W.T.)

² Key Laboratory for Unmanned Underwater Vehicle, Northwestern Polytechnical University, Xi'an 710072, China

* Correspondence: liyukaicst@mail.nwpu.edu.cn; Tel.: +86-187-9249-4121

Received: 27 May 2019; Accepted: 15 June 2019; Published: 18 June 2019



Abstract: Permanent magnet couplings (PMCs) are widely used in underwater propulsion because it can solve the deep-sea sealing problem effectively. In this paper, a new type of conical permanent magnet coupling (CPMC) is proposed, which is able to match the tail shape of the underwater vehicle and make full use of the tail space to increase pull-out torque capability. Based on the three-dimensional finite element method (3D-FEM), the electromagnetic characteristics of an initial model for CPMC are analyzed. In order to facilitate the design and optimization of CPMC, an equivalent three-dimensional (3D) analytical method for the pull-out torque calculation is presented, and its accuracy is verified by comparison with the 3D finite element results. Finally, the influence of design parameters such as half-cone angle, pole pair, pole arc coefficient and permanent magnet thickness on maximum pull-out torque and torque density of CPMC is analyzed, and a preliminary optimization model is obtained.

Keywords: underwater propulsion; conical permanent magnet coupling; equivalent three-dimensional analytical method; pull-out torque; influence of design parameters

1. Introduction

The deep sea is a huge treasure that still remains to be explored. With the rapid development of marine technology, the interest in deep sea exploration is increasing both in the scientific and business community [1]. There are various types of deep-sea exploration equipment, of which the most widely used are underwater vehicles with streamlined revolved body, such as UUV, AUV, ROV, etc. [2–5].

With the increasing working depth of underwater vehicle, the deep-sea sealing problem of the power output shaft has become one of the key technologies that need to be broken in the marine science and technology field. The deep sea environment is characterized by high corrosive, high hydrostatic pressure. Traditional mechanical seals have complex structures and serious mechanical losses. At the same time, it is easy to leak grease, which will damage the sea environment.

In recent years, more and more underwater vehicles have adopted a permanent magnet coupling (PMC) on the power output shaft to achieve non-contact torque transmission, which converts the dynamic seal into the static seal, and greatly improves the stability of the underwater propulsion unit [6,7]. The existing permanent magnet coupling is mainly divided into two forms: axial PMC and radial PMC, of which the radial PMC is generally chosen for underwater propulsion [8,9]. The maximum pull-out torque is one of the most important properties of PMC because it directly determines the power output capability of the propulsion unit. Therefore, how to improve the maximum pull-out torque has always been a research focus of PMC. In paper [10], the effect of pole pairs, inner and outer permanent magnets thickness and outer rotor yoke thickness on the maximum pull-out torque of radial

PMC is analyzed by three-dimensional finite element method (3D-FEM). In paper [11], the pull-out torque and magnet volume for three types of iron less cylindrical permanent magnet couplings are optimized using a nonlinear optimization method. Paper [12] optimizes the design of an axial-field magnetic coupling by using multi-objective genetic algorithms. In addition, new magnetic circuit structures are constantly being used, such as the use of single-sided or bilateral Halbach arrays to increase the maximum pull-out torque of PMC [13,14].

The existing PMC with traditional structure does not take into consideration the special needs of the underwater propulsion, and thus has many limitations in performance improvement. For the PMC used in underwater propulsion, its design should be coupled with the geometric structure of the vehicle, so as to maximize its performance. The traditional radial PMC is cylindrical and placed in the tail section, which does not match the shape of the tail and cannot make full use of the space. The line type of underwater vehicle is shown in Figure 1a, and there is a conical segment of the tail. In this paper, a new class of conical permanent magnet coupling (CPMC) for underwater vehicles is proposed, which is mounted in the tail, as shown in Figure 1b. The CPMC can make full use of the tail space to improve pull-out torque capability.

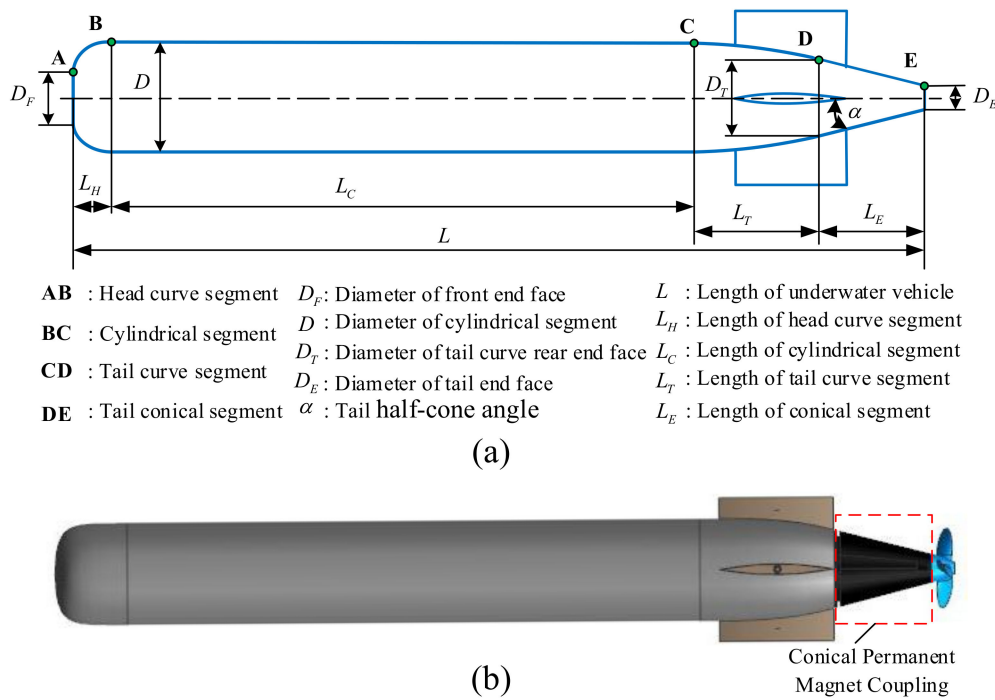


Figure 1. Underwater vehicle. (a) Parameters of line type. (b) Installation position of CPMC.

Considering the special structure of the CPMC, the pull-out torque can be calculated by 3D-FEM. However, the 3D-FEM is quite time consuming, not suitable for design and preliminary optimization of CPMC. The pull-out torque calculation methods for axial and radial PMCs have been extensively studied. Paper [15] proposes a three-dimensional analytical method for calculating the pull-out torque of radial PMC. In paper [16], simple analytical formulas are derived for computing the pull-out torque, and its accuracy is verified by 3D-FEM and measurements. Paper [17] presents torque analysis of radial PMC based on analytical magnetic field calculations and a Maxwell stress tensor method. In paper [18], the authors developed a 3D analytical method for calculating the pull-out torque of radial PMC based on the expression of one pair magnet.

In this paper, an equivalent three-dimensional analytical method is proposed, and the effects of design parameters such as half-cone angle, pole pair, pole arc coefficient and permanent magnet thickness on the maximum pull-out torque and pull-out torque density of CPMC are analyzed, which lays the foundation for the design and optimization of CPMC.

2. Configuration of the CPMC

The structure of the proposed CPMC is shown in Figure 2a. Like a traditional PMC, the CPMC is composed of an inner rotor and an outer rotor. The inner rotor is connected with motor output shaft, and the outer rotor drives the propeller. Non-contact torque transmission between the inner and outer rotors is achieved by the magnetic force. The dimensional parameters of CPMC include the front end diameter, axial length, half-cone angle, outer rotor yoke thickness, inner and outer permanent magnet thickness, air gap length and so on. Every parameter is illustrated in Figure 2b.

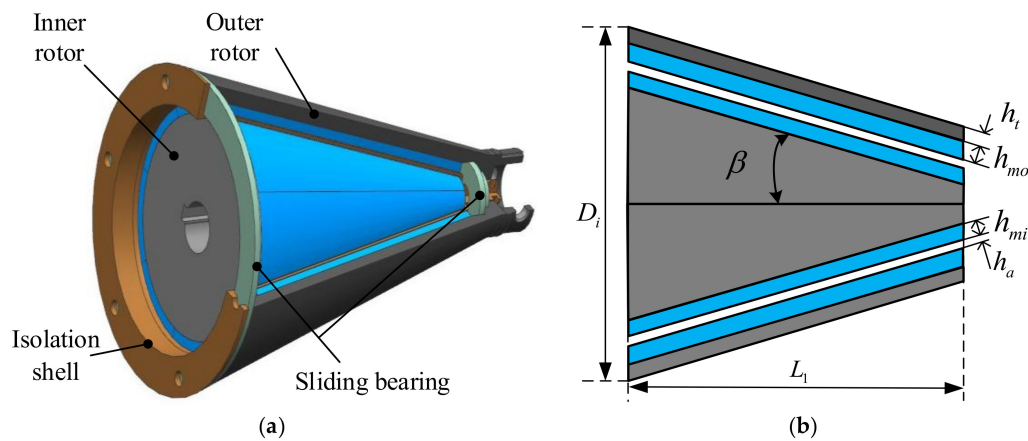


Figure 2. Structure of CPM (a) Components (b) Geometrical parameters.

The CPMC is tapered as a whole and the specific size is determined by the shape of the tail section of the underwater vehicle. The main parameters of an initially designed CPMC for an autonomous underwater vehicle (AUV) are shown in Table 1. Both the inner and outer rotors use high-performance permanent magnet Nd-Fe-B, the remnant flux density is 1.27 T and the relative permeability is 1.1045.

Table 1. Main parameters of the initially designed CPMC.

Design Parameters	Value
Front end diameter D_i	60 mm
Axial length L_1	55 mm
Half-cone angle β	12°
Outer rotor yoke thickness h_t	3 mm
Outer permanent magnet thickness h_{mo}	2 mm
Air gap length h_a	2 mm
Inner permanent magnet thickness h_{mi}	2 mm
Pole pairs p	6
Pole arc coefficient α	1

3. Performance Analysis of Proposed CPMC

Numerical simulation is a precise and high-efficient investigation approach of the PMC. Considering the special structure of the CPMC, the 3D-FEM is usually employed to compute its electromagnetic characteristics. All of the numerical simulations are carried out by using electromagnetic field analysis software Infolytica/MagNet. A cylindrical area of 200 mm in diameter and 150 mm in length is used as the computational domain for the CPMC. The CPMC is placed at the center of the computational domain. In order to ensure the calculation accuracy, mesh refinement is carried out on the air gap, permanent magnet and the yoke of CPMC. The adaptive mesh is generated using the meshing tool in Infolytica/MagNet, as shown in Figure 3. The maximum element size of the air gap, permanent magnets and yokes are 0.5 mm, 2 mm and 2 mm, respectively, and the total number of elements in the volume mesh is 337,100.

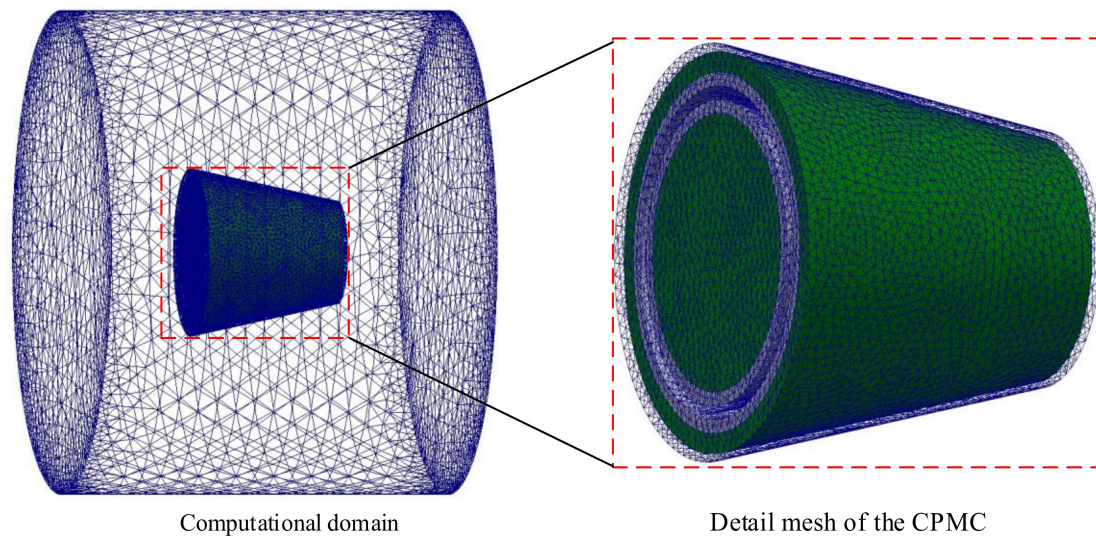


Figure 3. Mesh diagram of CPMC.

By establishing a suitable finite element analysis model, the magnetic field distribution and electromagnetic force of CPMC can be accurately calculated. However, the 3D-FEM is quite time consuming, it is suitable for analyzing a given prototype rather than for design and optimization. As a new type of permanent magnet coupling, it is very important to develop an analytical method to calculate its pull-out torque transmitted by the CPMC.

3.1. Electromagnetic Characteristics of CPMC

By utilizing electromagnetic field analysis software Infolytica/MagNet, the flux distribution of the whole CPMC at the aligned position and the maximum pull-out torque position, can be observed from Figure 4a,b, respectively. It can be seen that the magnetic field saturation mainly occurs at the rotor yoke and near the front end face of CPMC. The main reason is that when the pole arc coefficient is 1, there is a very serious magnetic leakage between poles.

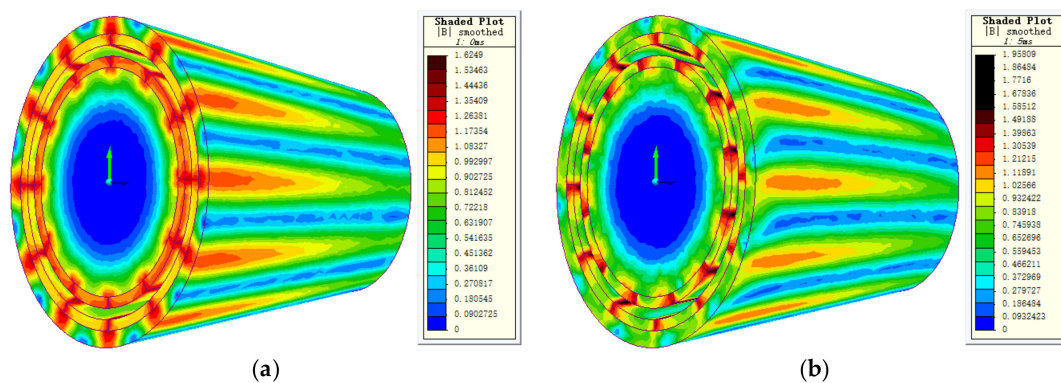


Figure 4. Flux distribution of the initially designed CPMC obtained by 3D-FEM. (a) At the aligned position. (b) At the maximum pull-out torque position.

Figure 5 displays the pull-out torque and axial force of the initially designed CPMC. Obviously, the CPMC generates axial force while transmitting torque, which is one of the characteristics of CPMC. When the inner and outer rotor permanent magnets with the same magnetization direction are aligned, the torque is zero, and there is a maximum axial repulsive force. When the inner and outer rotor deflection angle is at half pole angle, the pull-out torque is maximum, and there is still a repulsive force at the axial direction.

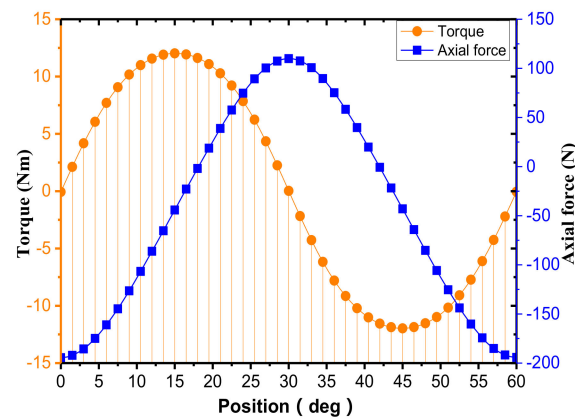


Figure 5. Pull-out torque and the axial force of the initially designed CPMC obtained by 3D-FEM.

3.2. Equivalent Three-Dimensional Analytical Method

3.2.1. Model Assumptions

To obtain an equivalent three-dimensional analytical solution of the torque transmitted by CPMC, the following assumptions have to be made:

1. The permanent magnet is uniformly magnetized.
2. The yoke material (steel 10) is infinite permeable ($\mu_r \approx \infty$), and no magnetization saturation occurred.
3. End-effect and magnetic flux leakage are neglected.
4. Ignoring the influence of isolation shell.
5. The permeability of all materials is assumed to be isotropic and homogenous.

3.2.2. Equivalent Model

The CPMC can't directly use a two-dimensional model to simplify the calculation as a traditional cylindrical permanent magnet coupling. However, the three-dimensional analytical model is very complicated because the permanent magnets of the CPMC are irregular in shape. In the calculation of some performances of permanent magnet motors, a multi-section two-dimensional model is used to approximate the three-dimensional model [19–21]. Similarly, we establish an equivalent 3D analysis model here by axial segmentation, as shown in Figure 6. The CPMC is divided into N modules along the axial direction, and each module is a common cylindrical permanent magnet coupling. The pull-out torque of the CPMC is approximately equal to the sum of the torque generated by the N modules.

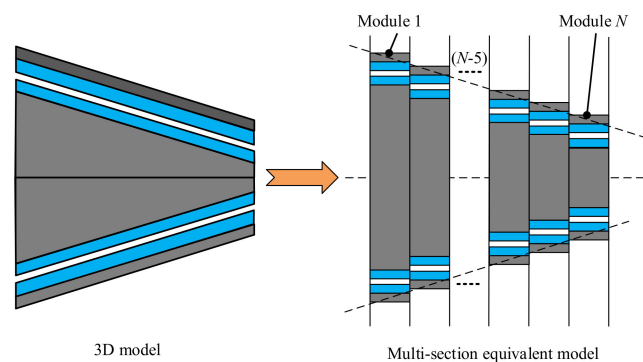


Figure 6. Equivalent 3D analysis model of CPMC.

3.2.3. Torque Calculation

The analytical solution of the torque of permanent magnet couplings has been extensively studied. For a common cylindrical permanent magnet coupling, the torque can be calculated by Maxwell equation [8,14]:

$$T_n = \frac{L_n}{\mu_0} \oint r_n^2 B_{rn} B_{\theta n} d\theta \quad (n = 1, 2, 3 \dots, N) \quad (1)$$

where, n means the n th module, θ is the deflection angle of internal and external rotors, μ_0 is the permeability of vacuum, r_m is the air gap radius, L_n is the axial length, B_{rn} and $B_{\theta n}$ are the radial and tangential components of the air gap flux density of the n th module, respectively.

When N is large enough, the torque of CPMC can be expressed as follows:

$$T_{all} \approx \sum_{n=1}^N T_n \quad (2)$$

The dimension parameters of cylindrical permanent magnet coupling are shown in Figure 7. The air gap flux density is jointly excited by the inner and outer rotor permanent magnets, so it can be expressed as:

$$B_{rn}(r, \theta) = B_{ri}(r, \theta) + B_{ro}(r, \theta) \quad (3)$$

$$B_{\theta n}(r, \theta) = B_{\theta i}(r, \theta) + B_{\theta o}(r, \theta) \quad (4)$$

where, $B_{ri}(r, \theta)$, $B_{ro}(r, \theta)$, $B_{\theta i}(r, \theta)$, $B_{\theta o}(r, \theta)$ are the radial and tangential components of flux density of the air gap flux density when the inner and outer rotors are separately excited. Each flux density component can be calculated through an analytical method [22]. When the magnetization mode of the permanent magnets is different, the analytical expression of the magnetization components M_r and M_θ are different, the waveform is shown in Figure 8.

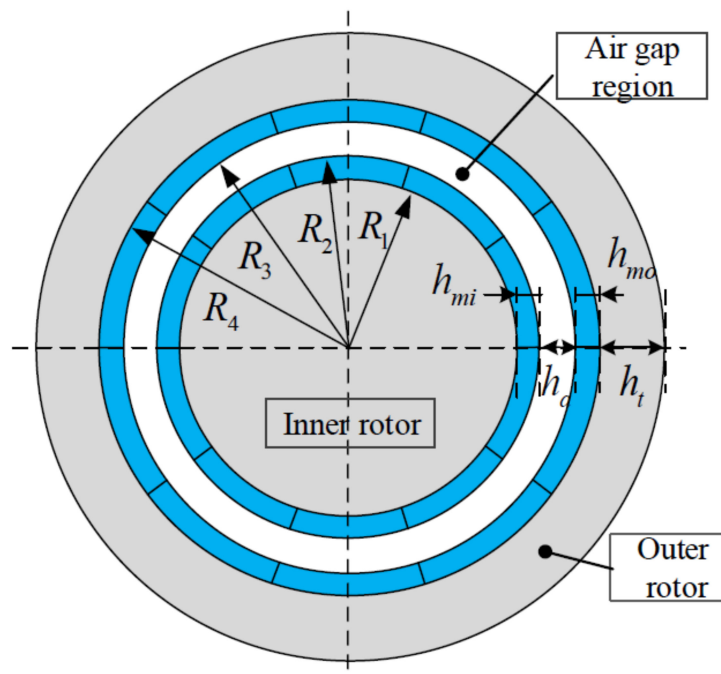


Figure 7. Two-dimensional model of cylindrical permanent magnet coupling.

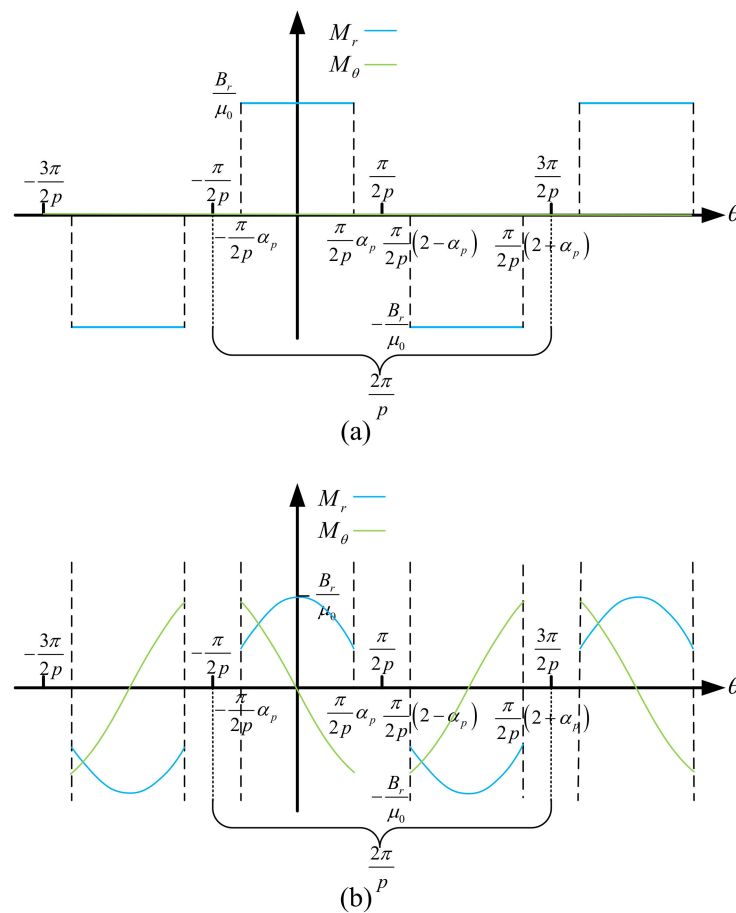


Figure 8. Waveforms of magnetization components M_r and M_θ . (a) Radial magnetization. (b) Parallel magnetization.

The complete solution for the flux density components in the air gap can be deduced from the general solution of Laplacian/quasi-Poissonian equations with specified boundary conditions.

$$B_{ri}(r, \theta) = \sum_{k=1,3,5,\dots}^{\infty} K_{Bi}(k) f_{Bri}(r) \cos(kp\theta) \quad (5)$$

$$B_{ro}(r, \theta) = \sum_{k=1,3,5,\dots}^{\infty} K_{Bo}(k) f_{Bro}(r) \cos[kp(\theta + \phi)] \quad (6)$$

$$B_{\theta i}(r, \theta) = \sum_{k=1,3,5,\dots}^{\infty} K_{Bi}(k) f_{B\theta i}(r) \cos(kp\theta) \quad (7)$$

$$B_{\theta o}(r, \theta) = \sum_{k=1,3,5,\dots}^{\infty} K_{Bo}(k) f_{B\theta o}(r) \cos[kp(\theta + \phi)] \quad (8)$$

where,

$$K_{Bi}(k) = \frac{\mu_0 M_{ki}}{\mu_{ri}} \frac{kp}{(kp)^2 - 1} \times \left\{ \frac{\{A_{3ki} - 1\} + 2\left\{\frac{R_{ri}}{R_{mi}}\right\}^{kp+1} - \{A_{3ki} + 1\}\left\{\frac{R_{ri}}{R_{mi}}\right\}^{2kp}}{\frac{\mu_{ri}+1}{\mu_{ri}} \left[1 - \left[\frac{R_{ri}}{R_{si}}\right]^{2kp}\right] - \frac{\mu_{ri}-1}{\mu_{ri}} \left[\left[\frac{R_{mi}}{R_{si}}\right]^{2kp} - \left[\frac{R_{ri}}{R_{mi}}\right]^{2kp}\right]} \right\} \quad (9)$$

$$K_{Bo}(k) = \frac{\mu_0 M_{ko}}{\mu_{ro}} \frac{kp}{(kp)^2 - 1} \times \left\{ \frac{\{A_{3ko} - 1\} + 2\left\{\frac{R_{ro}}{R_{mo}}\right\}^{kp+1} - \{A_{3ko} + 1\}\left\{\frac{R_{ro}}{R_{mo}}\right\}^{2kp}}{\frac{\mu_{ro}+1}{\mu_{ro}}\left[1 - \left[\frac{R_{ro}}{R_{so}}\right]^{2kp}\right] - \frac{\mu_{ro}-1}{\mu_{ro}}\left[\left[\frac{R_{mo}}{R_{so}}\right]^{2kp} - \left[\frac{R_{ro}}{R_{mo}}\right]^{2kp}\right]} \right\} \quad (10)$$

$$f_{Bri}(r) = \left(\frac{r}{R_{si}}\right)^{kp-1} \left(\frac{R_{mi}}{R_{si}}\right)^{kp+1} + \left(\frac{R_{mi}}{r}\right)^{kp+1} \quad (11)$$

$$f_{B\theta i}(r) = -\left(\frac{r}{R_{si}}\right)^{kp-1} \left(\frac{R_{mi}}{R_{si}}\right)^{kp+1} + \left(\frac{R_{mi}}{r}\right)^{kp+1} \quad (12)$$

$$f_{Bro}(r) = \left(\frac{r}{R_{so}}\right)^{kp-1} \left(\frac{R_{mo}}{R_{so}}\right)^{kp+1} + \left(\frac{R_{mo}}{r}\right)^{kp+1} \quad (13)$$

$$f_{B\theta o}(r) = -\left(\frac{r}{R_{so}}\right)^{kp-1} \left(\frac{R_{mo}}{R_{so}}\right)^{kp+1} + \left(\frac{R_{mo}}{r}\right)^{kp+1} \quad (14)$$

For radial magnetized,

$$\begin{cases} M_{rn} = 2 \frac{B_r}{\mu_0} \alpha_p \left\{ \sin \left\{ \frac{k\pi\alpha_p}{2} \right\} / \frac{k\pi\alpha_p}{2} \right. \\ M_{\theta n} = 0 \\ M_{ni} = M_{no} = M_{rn} + npM_{\theta} \\ A_{3ni} = A_{3no} = np \end{cases} \quad (15)$$

The size parameters are as follows:

$$\begin{cases} R_{ri} = R_1, R_{mi} = R_2, R_{si} = R_4 & \text{inner rotor} \\ R_{ro} = R_4, R_{mo} = R_3, R_{so} = R_1 & \text{outer rotor} \end{cases} \quad (16)$$

3.2.4. Comparison with 3D-FEM

The CPMC is divided into N modules and the number of N affects the analytical calculation results. When N changes from 5 to 600, the maximum pull-out torque of the initially designed CPMC calculated by analytical method is shown in Figure 9. As can be seen from the figure that N of 200 and 600 gave substantially the same results. Considering the accuracy and time economy, set N equal to 200 for the following calculations.

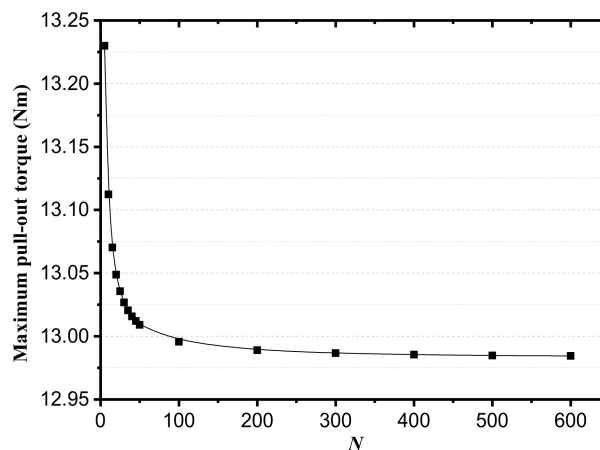


Figure 9. Influence of N on the analytical calculation results.

The proposed analytical method and 3D-FEM are used to calculate the pull-out torque of CPMC at different deflection angles, and the pull-out torque curve of half cycle is obtained, as shown in Figure 10. It can be seen that the torque curve obtained by the two methods have the same trend, and the results calculated by the equivalent three-dimensional analytical method are slightly larger than

the 3D-FEM results. When the inner and outer rotor deflection angle is 15° , the maximum pull-out torque is obtained. The relative error between the calculation results of the two methods is 7.4%, which proves the validity and accuracy of the analytical method. The main reason for the error is that the equivalent multi-section method ignores the effects of yoke magnetic field saturation, end effect and magnetic flux leakage.

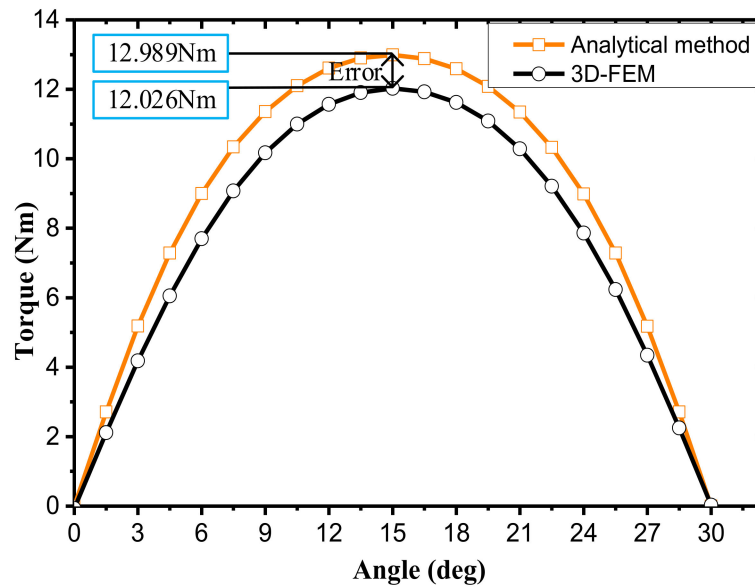


Figure 10. Comparison of 3D-FEM and analytical method.

4. Design Consideration and Optimization

In engineering applications, we most concerned about the maximum transmission torque ($T_{\max}$), because it directly determines the power output capability of the propulsion unit. Since permanent magnets are relatively expensive, it is also necessary to increase the $T_{\max}$ generated by per unit volume of permanent magnets and define the torque density S_T , as follows:

$$S_T = T_{\max} / V_p \quad (17)$$

where, V_p is the volume of the permanent magnets of CPMC. Considering that the S_T is very meaningful for making full use of permanent magnets and reducing the cost of CPMC. In the next study, the influence of design parameters on $T_{\max}$ and S_T of the initially designed CPMC will be analyzed by equivalent three-dimensional analytical method.

4.1. Influence of Half-Cone Angle

Keeping the diameter of the front end face and axial length unchanged, the variation of the $T_{\max}$ and S_T of the CPMC with the half-cone angle is studied by analytical method, as shown in Figure 11. It can be seen that as the half-cone angle increases, the $T_{\max}$ and S_T are continuously reduced. In practical applications, the size of the half-cone angle is often determined by the shape of the tail section of the underwater vehicle.

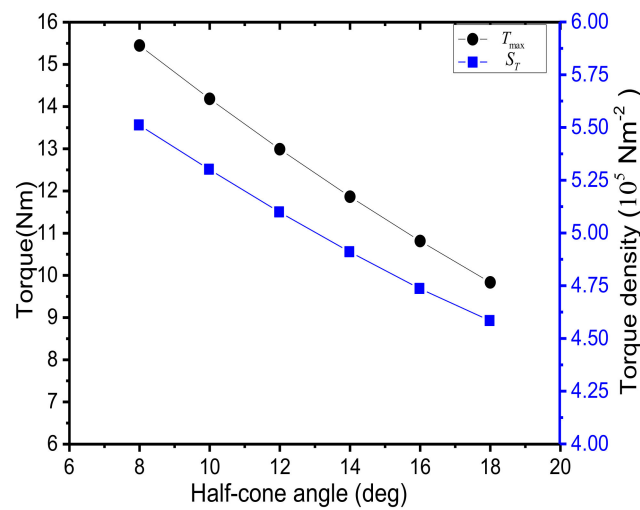


Figure 11. $T_{\max}$ and S_T versus half-cone angle.

4.2. Influence of Pole Pairs

Keeping the size parameters constant, the $T_{\max}$ and S_T of the CPMC versus different pole pairs are calculated with the pole pair increasing from 5 to 10. As shown in Figure 12, both the $T_{\max}$ and S_T increase first and then decrease as the number of pole pairs increases, and have a maximum value when the pole pair is 8.

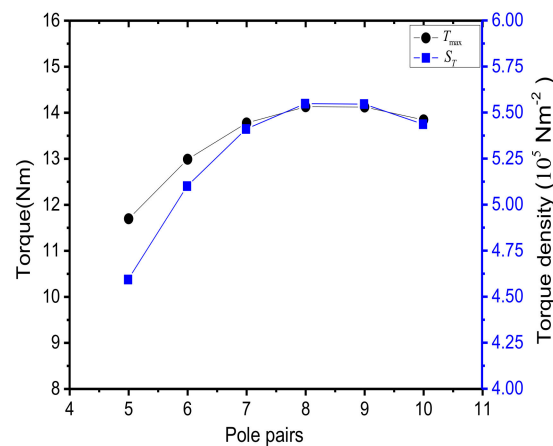


Figure 12. $T_{\max}$ and S_T versus pole pairs.

4.3. Influence of Pole Arc Coefficient

The change of pole arc coefficient means a change of the volume of the permanent magnet, and a larger volume of permanent magnets often means a bigger pull-out torque. Figure 13 shows the variation of $T_{\max}$ and S_T versus the pole arc coefficient. The $T_{\max}$ increases with the increase of the pole arc coefficient, and the S_T increases first and then decreases as the pole arc coefficient increases, and have a maximum value when the pole arc coefficient is 0.7.

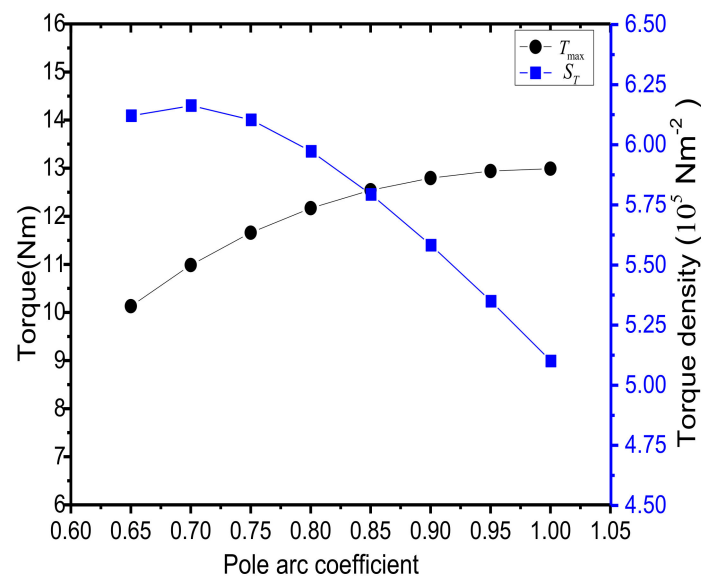


Figure 13. $T_{\max}$ and S_T versus pole arc coefficient.

4.4. Influence of Permanent Magnet Thickness

Assuming that the thickness of internal and external permanent magnets is the same, the thickness of rotor yoke is at least 1.5 times that of permanent magnets. Keeping other parameters unchanged, and only changing the thickness of permanent magnet, the variation of $T_{\max}$ and S_T are shown in Figure 14. The maximum value of $T_{\max}$ and S_T are obtained with different thicknesses.

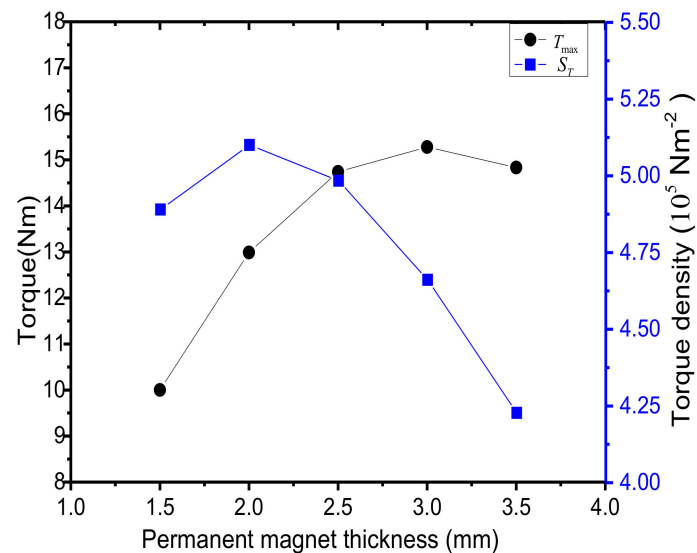


Figure 14. $T_{\max}$ and S_T versus permanent magnet thickness.

4.5. Interaction Between the Pole Pair, Pole Arc Coefficient and Permanent Magnet Thickness

The half-cone angle of the CPMC designed for underwater propulsion is 12° , which is determined by the vehicle's profile. The analytical method can be used to analyze the interaction between the pole pairs, pole arc coefficient and permanent magnet thickness (as shown in Figures 15–20), which is the basis for the optimal design of CPMC. The pole pair number is a discrete value within a limited range and determining the pole pair in advance can simplify the optimization process.

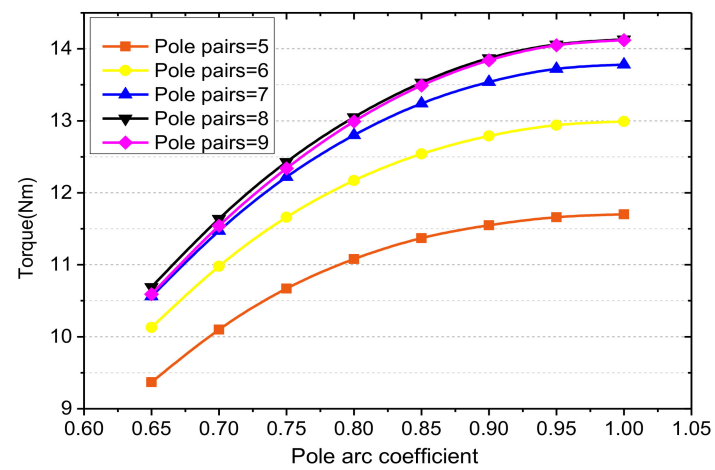


Figure 15. $T_{\max}$ versus pole arc coefficient for several pole pairs.

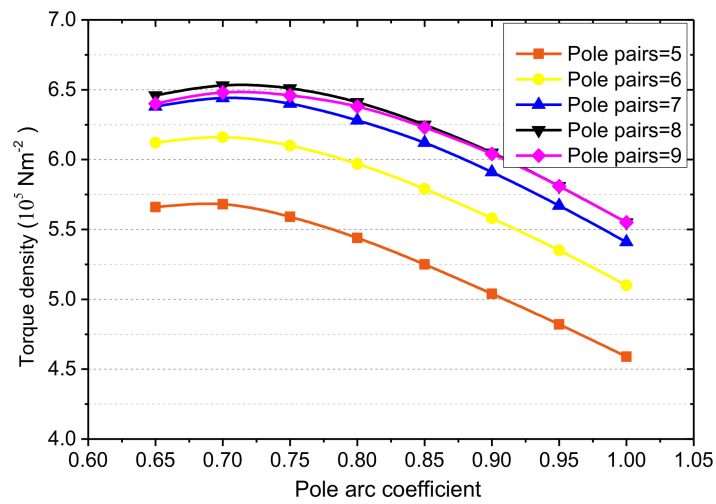


Figure 16. S_T versus pole arc coefficient for several pole pairs.

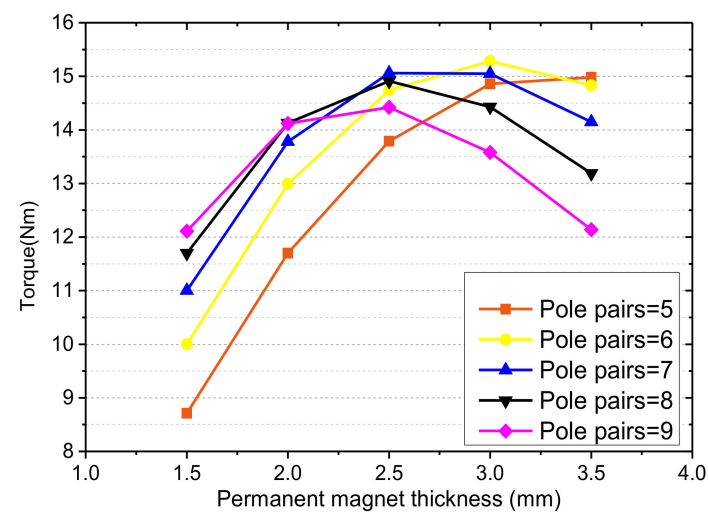


Figure 17. $T_{\max}$ versus permanent magnet thickness for several pole pairs.

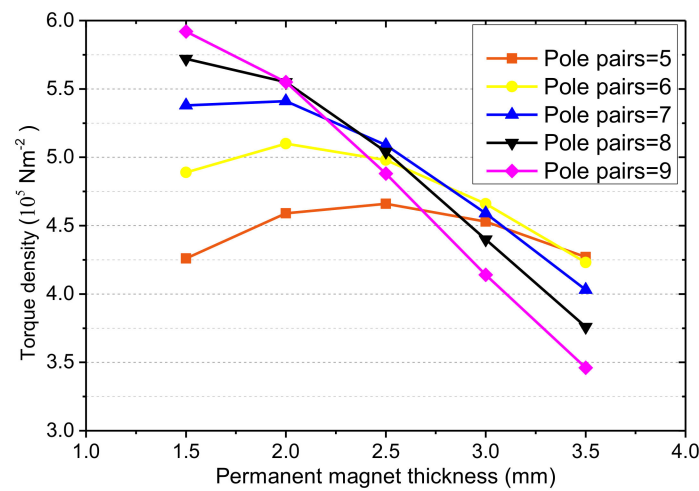


Figure 18. S_T versus permanent magnet thickness for several pole pairs.

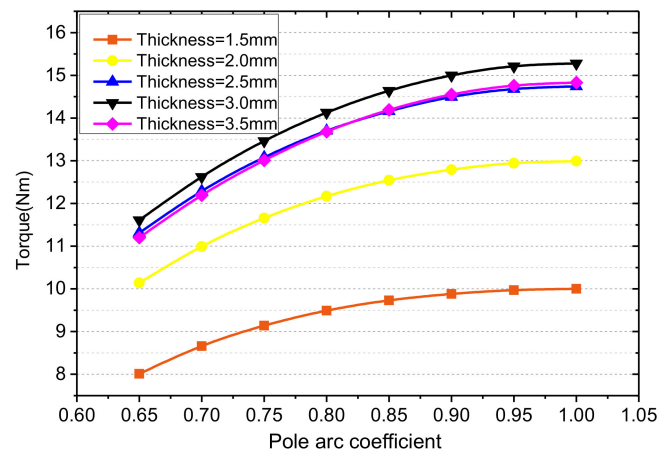


Figure 19. $T_{\max}$ versus pole arc coefficient for several permanent magnet thickness.

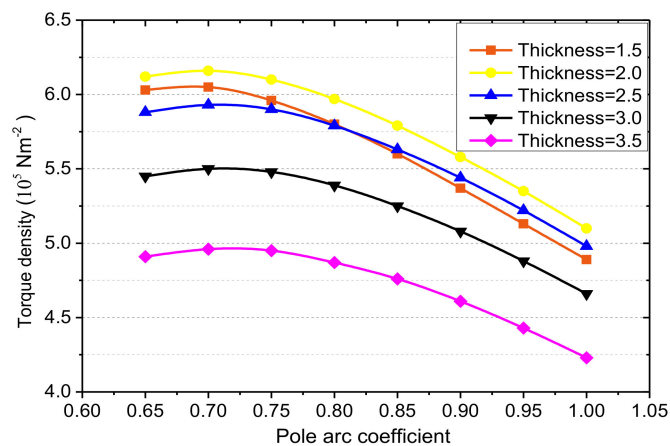


Figure 20. S_T versus pole arc coefficient for several permanent magnet thickness.

It can be seen from the figures below that under different pole arc coefficients, the CPMC with a pole pair of 8 always has the maximum $T_{\max}$ and S_T . The CPMC with a pole pair of 8 also has good performance at different permanent magnet thickness. Hence, for the CPMC studied in this paper, the pole pairs be 8 is more suitable for further study. Then, the CPMC optimization design problem can be

simplified to an optimization problem of two independent variables the permanent magnet thickness h_m and the pole arc coefficient α .

4.6. Preliminary Optimization Design

In this paper, the non-dominated sorting genetic algorithm-II (NSGA-II) was utilized to solve the multi-objective optimization of CPMC. NSGA-II is one of the most widely used multi-objective optimization algorithms, which has the characteristics of high efficiency, minimum user interaction, solutions uniformly distributed and so on [23,24].

Generally, NSGA-II is a method of searching for the Pareto optimal solutions according to several certain known models (surrogate models). In this paper, these surrogate models are established by using Kriging method, such as maximal pull-out torque ($T_{\max}$) and torque density (S_T). The constraint conditions were given based on the actual size of the CPMC. The multi-objective function could be defined as:

$$\begin{cases} V : F(X) = \text{MAX}\{T_{\max}(X), S_T(X) \\ \text{s.t. } 1.5 \leq h_m \leq 3 \\ 0.65 \leq \alpha \leq 1.0 \\ X = [h_m, \alpha]^T \end{cases} \quad (18)$$

NSGA-II could find a set of Pareto optimal solution and corresponding design parameters of the CPMC.

The h_m changes from 1.5 mm to 3 mm with a 0.5 mm interval and the pole arc coefficient α changes from 0.65 to 1.0 with a 0.05 interval. 40 samples were analyzed by using the equivalent three-dimensional analytical method. The objective $T_{\max}$ and S_T is shown in Tables 2 and 3. The response surfaces of two sub objective function are built as shown respectively in Figures 21 and 22.

Table 2. $T_{\max}$ of 40 samples.

$T_{\max}$ (Unit: Nm)		Permanent Magnet Thickness h_m (mm)				
		1.5	2.0	2.5	3.0	3.5
α	0.65	8.992	10.692	11.189	10.784	9.832
	0.70	9.775	11.640	12.190	11.753	10.718
	0.75	10.405	12.426	13.032	12.576	11.474
	0.80	10.894	13.054	13.715	13.247	12.093
	0.85	11.256	13.531	14.241	13.768	12.579
	0.90	11.504	13.865	14.613	14.139	12.919
	0.95	11.649	14.063	14.835	14.361	13.125
	1.0	11.696	14.129	14.909	14.434	13.193

Table 3. S_T of 40 samples.

S_T (Unit: $10^5 \text{N} \cdot \text{m}^{-2}$)		Permanent Magnet Thickness h_m (mm)				
		1.5	2.0	2.5	3.0	3.5
α	0.65	6.764	6.459	5.821	5.251	4.907
	0.70	6.827	6.529	5.888	5.312	4.963
	0.75	6.784	6.506	5.875	5.301	4.953
	0.80	6.658	6.407	5.797	5.230	4.886
	0.85	6.474	6.251	5.665	5.111	4.775
	0.90	6.249	6.050	5.490	4.953	4.628
	0.95	5.995	5.813	5.280	4.764	4.451
	1.0	5.718	5.548	5.041	4.548	4.250

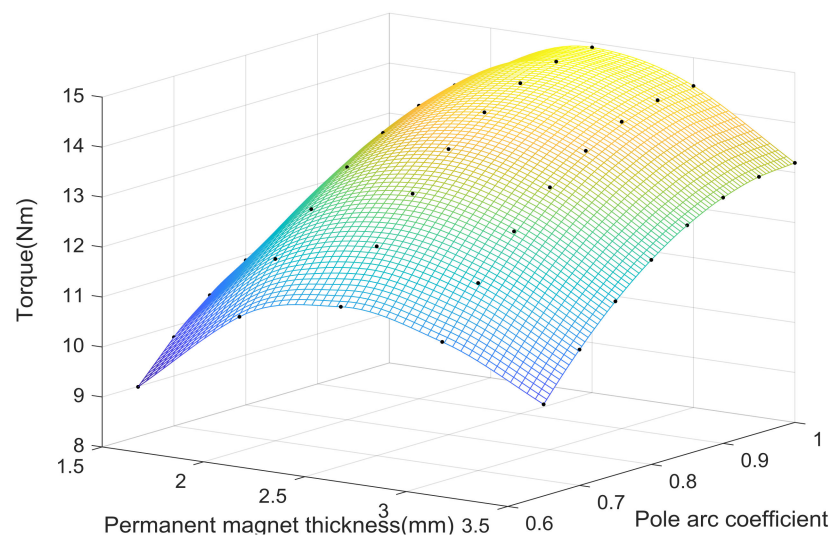


Figure 21. Response surface of sub objective $T_{\max}$.

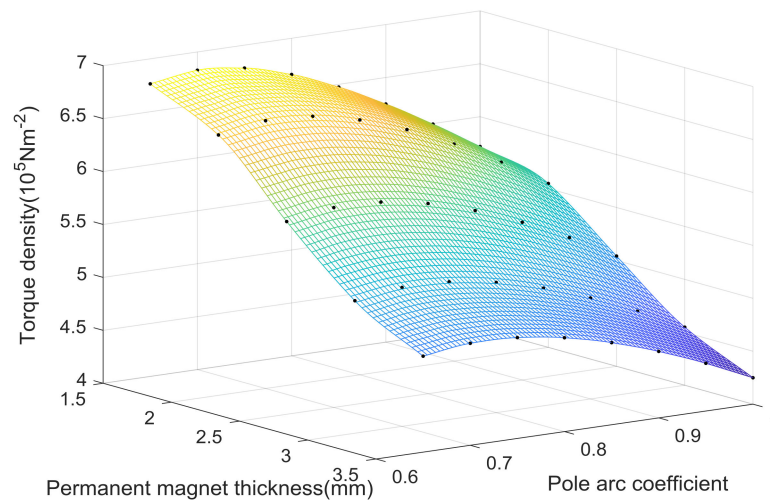


Figure 22. Response surface of sub objective function S_T .

The optimization procedure uses 100 individuals evolving during 50 generations, the mutation probability is 0.05, and the recombination probability is 0.5. Figure 23 shows the Pareto front of the maximum pull-out torque and torque density of CPMC. The points A and C are the optimum design points which can be obtained by single-objective optimization. For the CPMC, it is necessary to achieve a given pull-out torque, while making the torque density as large as possible. Setting the pull-out torque to 14 Nm, the optimum design points is marked with the red five-pointed star B. The optimum design parameters and objective values obtained by NSGA-II are shown in Table 4. The pull-out torque of the preliminary optimized model is improved by 17.545% and the torque density increased from $5.101 \times 10^5 \text{ N} \cdot \text{m}^{-2}$ to $5.997 \times 10^5 \text{ N} \cdot \text{m}^{-2}$ when compared with that of the initially designed CPMC.

Table 4. Optimum design parameters and objective functions.

Variable	Value
Permanent magnet thickness (mm)	2.168
Pole arc coefficient α	0.869
$T_{\max}$ (Nm)	14.136
S_T ($10^5 \text{ N} \cdot \text{m}^{-2}$)	5.997

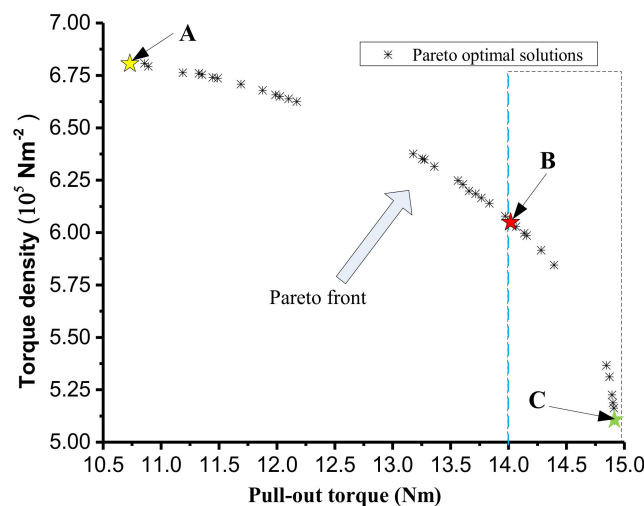


Figure 23. Pareto front of two optimization objectives.

5. Conclusions

A special CPMC for underwater propulsion is proposed and analyzed in this paper. The electromagnetic characteristics are analyzed by 3D-FEM at first. Then, an equivalent three-dimensional analytical method used to compute the pull-out torque of CPMC has been derived based on a multi-section two-dimensional model. The accuracy of proposed analytical method is verified by comparing with the 3D finite element results. Based on the analytical method, the influence of design parameters such as half-cone angle, pole pair, pole arc coefficient and permanent magnet thickness on maximum torque and torque density of CPMC are analyzed, and a preliminary optimization model is obtained. Further work will focus on the experimental research of the CPMC, as well as the multi-level and multi-disciplinary optimization of the overall performance of CPMC. Furthermore, since the flux density of the CPMC yoke is unevenly distributed in the axial direction, the thickness of the yoke could be unequal in the axial direction or a Halbach array could be used to reduce the volume of the yoke.

Author Contributions: Conceptualization, Y.L., and Y.H.; methodology, Y.H. and Y.L.; software, Y.L. and Z.M.; validation, Y.H., B.S. and Z.M.; formal analysis, Y.L. and W.T.; writing—original draft preparation, Y.L. and Z.M.; writing—review and editing, B.S.; supervision, Z.M. and W.T.; project administration, Z.M. and W.T.; funding acquisition, Y.H., Z.M. and B.S.

Funding: This research was funded by the National Science Foundation of China (Grant Nos. 51179159, 61572404) and the Shaanxi Province Youth Science and Technology New Star Project (Grant No. 2016KJXX-57).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zhang, Z.H.; Nie, S.L.; Zhang, L.M.; Yuan, S.H. Development of seawater hydraulic pump tester in deep-sea simulated environment. In Proceedings of the 2015 International Conference on Fluid Power and Mechatronics, Harbin, China, 5–7 August 2015; pp. 667–671.
2. Byron, J.; Tyce, R. Designing a vertical/horizontal AUV for deep ocean sampling. In Proceedings of the OCEANS 2007, Vancouver, BC, Canada, 29 September–4 October 2007; pp. 1–10.
3. Fletcher, B. UUV master plan: A vision for navy UUV development. In Proceedings of the OCEANS 2000 MTS/IEEE Conference and Exhibition, Providence, RI, USA, 11–14 September 2000; pp. 65–71.
4. Zhang, B.S.; Song, B.W.; Mao, Z.Y.; Jiang, J.; Sun, C.Y. Hydrodynamic characteristics and stability simulation of four-rotor dish-shaped UUV landing on the seabed. In Proceedings of the OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, USA, 19–23 September 2016; pp. 1–5.
5. Provencher, L.; Sarraillon, S. The MASKI+ underwater inspection robot: A new generation ahead. In Proceedings of the 2016 4th International Conference on Applied Robotics for the Power Industry (CARPI), Jinan, China, 11–13 October 2016; pp. 1–6.

6. Charpentier, J.F.; Fadli, N.; Jennane, J. Study of ironless permanent magnet devices being both a coupling and an axial bearing for naval propulsion. *IEEE Trans. Magn.* **2003**, *39*, 3235–3237. [\[CrossRef\]](#)
7. Qi, C.P.; Zhao, J.X.; Zheng, Y.Y. Design of Halbach array magnetic coupling for underwater propeller. *Micromotors* **2017**, *50*, 80–83.
8. Cheng, B.; Pan, G. Analysis and structure optimization of radial Halbach permanent magnet couplings for deep sea robots. *Math. Probl. Eng.* **2018**, *2018*, 7627326. [\[CrossRef\]](#)
9. Yu, Y.L.; Zhao, B. Study on eddy current loss and system transmission efficiency in insulation shell of the under-water permanent magnet shaft coupling. *Trans. China Electr. Tech. Soc.* **2014**, *29*, 15–22.
10. Högberg, S.; Mijatovic, N.; Holbøll, J.; Jensen, B.B.; Bendixen, F.B. Parametric design optimization of a novel permanent magnet coupling using finite element analysis. In Proceedings of the 2014 IEEE Energy Conversion Congress and Exposition, Pittsburgh, PA, USA, 14–18 September 2014; pp. 1465–1471.
11. Charpentier, J.F.; Lemarquand, G. Optimal design of cylindrical air-gap synchronous permanent magnet couplings. *IEEE Trans. Magn.* **1999**, *35*, 1037–1046. [\[CrossRef\]](#)
12. Dolisy, B.; Mezani, S.; Lubin, T.; Lévêque, J. A new analytical torque formula for axial field permanent magnets coupling. *IEEE Trans. Magn.* **2015**, *30*, 1–8. [\[CrossRef\]](#)
13. Yuan, D.Q.; Li, J.P.; He, Y.Q.; Zhang, H. Characteristic analysis of transmission torque of magnetic coupling with Halbach array. *J. Magn. Mater. Devices* **2011**, *42*, 36–40.
14. Seo, S.W.; Kim, Y.H.; Lee, J.H.; Choi, J.Y. Analytical torque calculation and experimental verification of synchronous permanent magnet couplings with Halbach arrays. *AIP Adv.* **2018**, *8*, 0566091–0566096. [\[CrossRef\]](#)
15. Ravaut, R.; Remarquand, V.; Remarquand, G. Analytical design of permanent magnet radial couplings. *IEEE Trans. Magn.* **2010**, *46*, 3860–3865. [\[CrossRef\]](#)
16. Lubin, T.; Mezani, S.; Rezzoug, A. Experimental and theoretical analyses of axial magnetic coupling under steady-state and transient operations. *IEEE Trans. Ind. Electron.* **2014**, *61*, 4356–4365. [\[CrossRef\]](#)
17. Choi, J.Y.; Shin, H.J.; Jang, S.M.; Lee, S.H. Torque analysis and measurements of cylindrical air-gap synchronous permanent magnet couplings based on analytical magnetic field calculations. *IEEE Trans. Magn.* **2013**, *49*, 3921–3924. [\[CrossRef\]](#)
18. Zhu, Z.N.; Meng, Z. 3D torque calculation of magnetic coupling and its characteristic parameters analysis. *Electr. Mach. Control* **2017**, *21*, 94–101.
19. Gyselinck, J.J.C.; Vandevelde, L.; Melkebeek, J.A.A. Multi-slice FE modeling of electrical machines with skewed slots—the skew discretization error. *IEEE Trans. Magn.* **2001**, *37*, 3233–3237. [\[CrossRef\]](#)
20. Urresty, J.C.; Riba, J.R.; Romeral, L.; Garcia, A. A simple 2-D finite-element geometry for analyzing surface-mounted synchronous machines with skewed rotor magnets. *IEEE Trans. Magn.* **2010**, *46*, 3948–3954. [\[CrossRef\]](#)
21. Hong, C.; Huang, W.; Hu, Z. Performance calculation of a dual stator solid rotor axial flux induction motor using the multi-slice and multi-layer method. *IEEE Trans. Magn.* **2019**, *55*, 1–9. [\[CrossRef\]](#)
22. Zhu, Z.Q.; Howe, D.; Chan, C.C. Improved analytical model for predicting the magnetic field distribution in brushless permanent-magnet machines. *IEEE Trans. Magn.* **2002**, *38*, 229–238. [\[CrossRef\]](#)
23. Vo-Duy, T.; Duong-Gia, D.; Ho-Huu, V.; Vu-Do, H.C.; Nguyen-Thoi, T. Multi-objective optimization of laminated composite beam structures using NSGA-II algorithm. *Compos. Struct.* **2017**, *168*, 498–509. [\[CrossRef\]](#)
24. Deb, K.; Pratap, A.; Agarwal, S.; Meyarivan, T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **2002**, *6*, 182–197. [\[CrossRef\]](#)

