Multi-field Coupling Analysis of Integrated Motor Propulsor

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Abstract
A kind of integrated motor propulsor (IMP) which can be used in underwater propulsion is designed in this paper, and the rotor of its propelling motor employs the Halbach structure. This paper considers the characteristics of IMP, and coupling model of the motor is established. Time-stepping finite element method is used to analyze the field-circuit coupling problem, and research in the aspect of electromagnetism-thermal coupling is developed. The back emf and temperature are measured through experiments, and the comparison between calculation and tests results suggests that the method to solve multi-field coupling problem proposed in this paper is exact and effective.

Keywords: Integrated Motor Propulsor; multi-field coupling; electromagnetism-thermal coupling; Halbach

1. Introduction
Integrated Motor Propulsor (IMP) develops with the podded thrusters, and has been a novel propulsion form in the field of electric power propulsion of ships. As IMP involves in the cross of multiple physics, traditional analysis method can not meet with the needs in the design and calculation of this device. But multi-field coupling method can give a comprehensive design for IMP simultaneously in the electromagnetic, thermal and fluid field, and can be the theory foundation of advanced IMP design.

Although there are so many articles about analysis of coupled system in the field of machinery and electromagnetism [1-7], references related to study of multi-field coupling in PM motor are still seldom seen. As IMP differs from ordinary PM motor in structure, heat dissipation and working condition, existing calculation methods are not suitable to analyze IMP.

This paper studies a 22.5kW IMP designed by ourselves, and the field-circuit coupled model as well as electromagnetism-thermal coupled model are established, and time-stepping finite element method is employed to analyze the field-circuit coupled problem, meanwhile, approaches to solve electromagnetism-thermal coupling are also given, and interactions between each fields are considered. At the end of this paper, performances of the IMP designed by ourselves are analyzed through the method given in this paper, and experiments are conducted to verify the calculation results.

2. Structure design of IMP
Structure of the designed IMP is shown in Figure 1. It consists of three parts: the shell of this device, the absorbing duct, and propeller. There is rubber damping isolation layer between shell and ducts. PM motor with inner rotor is selected as prototype machine, and its power is 22.5kw. Propeller is embedded in rotor and there is no central shaft in the pump. Axially and radial bearing in the air-gap support and locate the rotor. Water pass through the air-gap between stator and rotor, bringing excellent cooling condition for motor but high requirement for insulating material. The basic structure parameters of the motor is shown in Table 1. And the simplified model for calculation is shown in Figure 2.
3. Research Method

3.1 Field-circuit couple and time-stepping finite element method

The analysis model in this paper considers the input voltage as sine wave, and combines the external control circuit and electromagnetic field equations together to solve this coupling problem. Taking one pair of poles of motor shown in Fig 2 as an example, the steady electromagnetic field problem can be presented in the form of boundary equations as follows:

\[
\begin{align*}
\Omega \frac{\partial}{\partial x} \left( \frac{\partial A_x}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\partial A_y}{\partial y} \right) &= -J \\
A_{ix} &= A_{iy} = 0 \\
S_2 : \frac{\partial A_x}{\partial n} &= -H \\
L : \frac{\partial A_x}{\partial n} &= \nu_0 \frac{\partial A_y}{\partial n} \\
A_{ix} &= A_{iy} \\
A_{ix} &= A_{iy} \\
A_{ix} &= A_{iy}
\end{align*}
\]

(1)

In the equations above, Ω represents the region to be solved; \( S_2 \) means the second boundary condition; \( L \) is line of demarcation between different materials in motor. And we can get the vector magnet potential \( A_t \) of every point in motor, then, back emf of each winding can be obtained [8-9] in (2).

Combining the equations of stator and rotor we can obtain the field-circuit coupling equation of the whole PM motor [10] as formula (3).
\[
e_e = -\frac{\partial}{\partial t}\left(\frac{2PN_l}{a \cdot A_b} \sum_{i=1}^{N_s} \sum_{i=1}^{N_p} \varepsilon^e (N_i A_i^e + N_j A_j^e + N_m A_m^e)\right)
\]
\[
= -\frac{\partial}{\partial t}\left(2PL_e \sum_{i=1}^{N_s} [D]^T \begin{bmatrix} A_i^e \\ A_j^e \\ A_m^e \end{bmatrix}\right)
\]
\[
D_t \begin{bmatrix} A^e_i \\ \hat{\epsilon}^e_i \\ u_i^e \\ \hat{g}^e_i \end{bmatrix} = \begin{bmatrix} P_1^e \\ P_2^e \end{bmatrix} + \frac{1}{\Delta t} D \begin{bmatrix} A^{e-a} \\ \hat{\epsilon}^{e-a} \\ u^{e-a} \\ \hat{g}^{e-a} \end{bmatrix}
\]

and:
\[
D_1 = \begin{bmatrix} G_{11} + \frac{D_{11}^t}{\Delta t} & G_{12} & G_{13} & 0 \\
\frac{D_{12}^t}{\Delta t} & G_{22} + \frac{D_{12}^t}{\Delta t} & 0 & 0 \\
\frac{D_{13}^t}{\Delta t} & 0 & G_{33} & G_{34} \\
0 & 0 & G_{33}^t & G_{34}^t + \frac{D_{14}^t}{\Delta t} \\
\end{bmatrix}
\]
\[
D_2 = \begin{bmatrix} D_{11}^t & 0 & 0 & 0 \\
D_{21}^t & D_{22}^t & 0 & 0 \\
D_{31}^t & 0 & 0 & 0 \\
0 & 0 & 0 & D_{44}^t \\
\end{bmatrix}
\]

As to the meanings of every part in the equations above, readers can refer to [8] and [9].

3.2 Method of electromagnetism-thermal coupling analysis

The equations about thermal-electricity couple and thermal-magnet couple in IMP are as follows:
\[
\begin{bmatrix} C^e \\ 0 \end{bmatrix} \begin{bmatrix} \{T\} \\
\{V\} \end{bmatrix} + \begin{bmatrix} K^e \\ K^e \end{bmatrix} \begin{bmatrix} \{T\} \\
\{V\} \end{bmatrix} = \begin{bmatrix} \{Q\} \\
\{I\} \end{bmatrix}
\]
\[
\begin{bmatrix} C^{eA} \\ 0 \end{bmatrix} \begin{bmatrix} \{A\} \\
\{T\} \end{bmatrix} + \begin{bmatrix} K^{eA} \\ K^{eA} \end{bmatrix} \begin{bmatrix} \{A\} \\
\{T\} \end{bmatrix} = \begin{bmatrix} \{\psi\} \\
\{Q\} \end{bmatrix}
\]
In the above two equations, $\{T\}, \{V\}$ and $\{A\}$ are respectively the main freedoms of each field, namely temperature array, electric potential array and vector magnet potential array; $\{Q\}, \{I\}$ and $\{\psi\}$ are respectively the definite load of each field, namely heat source, current and magnetic field load. Meanings of each element in the coefficient array are as follows: $\{K^T\}$ is array of conduct and convection coefficient; $\{K^V\}$ is array of conductivity coefficient; $\{K^{AA}\}$ is array of permeability coefficient, and its material property can be influenced by temperature; $\{K^{Vt}\}$ is array of thermal-electricity coefficient; $\{C^t\}$ is array of thermal capacitance coefficient; $\{C^{AA}\}$ is array of magnet damping coefficient.

4. Simulation and Experiment

Through the methods proposed in this paper, 3-D electromagnetism-thermal coupled calculation of a 22.5kW IMP designed by ourselves is carried out on the basis of considering field-circuit couple.

Figure 3(a) is 3-D model of our IMP, and considering the convenience of calculation, we give a simplified PM motor model in Figure 3(b), not considering propellers and the outer shell. In these two figs, the end part of motor winding is modeled exactly with practical condition, and the accuracy of calculation can be guaranteed.

![Figure 3. 3-D model of IMP](image)

In order to save calculation resource and time, 1/8 of the whole model is used in the analysis of electromagnetic field and thermal field.

Figure 4 is 3-D distribution of magnetic field on the condition that the motor operates on no load.

Figure 5 is temperature distribution of stator and windings. In specific calculation winding and core losses got from electromagnetic field are loaded into thermal field as heat source, and influence of fluid field in this paper is ignored. After thermal field calculation is completed, temperature results feed back to electromagnetic field, then the material properties that vary with temperature will be refreshed, and electromagnetic field will be calculated again. The processes above will be repeated until obtained field results meet with error requirement.

Figure 6 is the pressure results of propeller in fluid field. The influence from propeller and its fluid field will be considered in future research.

Figure 7 is the prototype of IMP and its experiment spot.
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Figure 4. 3-D distribution of magnetic field on no load

Figure 5. Temperature distribution of stator and windings

Figure 6. Pressure results of propeller in fluid field.

Figure 7. Prototype of IMP and its experiment spot.
The back emf and temperature are calculated through the methods proposed in this paper, and the comparison between calculation and tests results are shown in Table 2 and Table 3.

Table 2 is the value of phase back emf at different speed, and Table 3 is the value of temperature in motor, and it is clear that calculation results through methods in this paper is very close to experiment results. However, one point we should pay attention to is that as fluid effect is ignored, the calculated values of temperature at the inlet and outlet of motor do not coincide with experiment so well.

### Table 2 Test and calculation value of peak value of phase emf

<table>
<thead>
<tr>
<th>Speed (r/min)</th>
<th>Measured emf (V)</th>
<th>Calculated emf (V)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>282.8</td>
<td>287.2</td>
<td>1.55</td>
</tr>
<tr>
<td>1000</td>
<td>243.4</td>
<td>246.3</td>
<td>1.19</td>
</tr>
<tr>
<td>800</td>
<td>187.86</td>
<td>189.1</td>
<td>0.66</td>
</tr>
<tr>
<td>700</td>
<td>168.65</td>
<td>171.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Table 3 Test and calculation value of temperature in motor

<table>
<thead>
<tr>
<th>Time (hour:min)</th>
<th>Measured temperature of inlet of motor (°C)</th>
<th>Calculated temperature of inlet of motor (°C)</th>
<th>Measured temperature of outlet of motor (°C)</th>
<th>Calculated temperature of outlet of motor (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Am 11:25</td>
<td>20.6</td>
<td>20.1</td>
<td>25.1</td>
<td>24.7</td>
</tr>
<tr>
<td>Am 11:55</td>
<td>23.1</td>
<td>22.7</td>
<td>28.7</td>
<td>28.7</td>
</tr>
<tr>
<td>Pm 12:25</td>
<td>23.7</td>
<td>23</td>
<td>29.3</td>
<td>28.7</td>
</tr>
<tr>
<td>Pm 12:55</td>
<td>23.8</td>
<td>23.1</td>
<td>29.6</td>
<td>29.3</td>
</tr>
<tr>
<td>Pm 13:55</td>
<td>24.7</td>
<td>24.5</td>
<td>30.5</td>
<td>30.1</td>
</tr>
</tbody>
</table>

### 5. Conclusions

After analysis and experiment above, we can obtain some conclusions:

(1) This paper established the multi-field coupling model, took external circuit into account, and proposed corresponding calculation and analysis methods. Back emf and temperature experiments verify the effectiveness and veracity of the presented methods.

(2) When IMP works underwater, its thermal field distribution is influenced greatly by the temperature and speed of fluid (namely, seawater). So the fluid effect should be considered in future multi-field couple research in order to get exact temperature results.

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### References


