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Research Article

Time-Stepping Finite Element Method for Integrated Motor Propulsor with Solid-Rotor

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Abstract: In this study, we design a novel Integrated Motor Propulsor (IMP) which worked underwater for propelling. The motor in this IMP was PM motor employing Halbach array and solid rotor; and a field-circuit-motion coupled time-stepping Finite Element Analysis (FEA) model is presented for analyzing this kind of solid-rotor motor and the problem that the parameters of rotor are hard to calculate is solved. The rotor resistance variation with speed difference is considered and the finite element analysis involving external circuit and electromagnetic field was provided. A moving air-gap boundary method combining motor motion equation was adopted to simulate the transient process of motor. The performance of the prototype of IMP is analyzed using the proposed model and the calculation results of back EMF and starting torque are tally well with those from tests, which indicates that the proposed method in this study is effective and exact and that it can be used to analyze other kind of solid-rotor motor.

Keywords: Field-circuit coupled, IMP, moving air-gap boundary, solid rotor, time-stepping finite element

INTRODUCTION

The Integrated Motor Propulsor (IMP) Technology is a novel propelling form which embeds propeller vanes into inner wall of motor rotor. This IMP integrates motor and propeller into the same shell and it has been paid attention to by people because it can overcome the problems such as high noise, bad stability and low power density which exist in traditional propelling form. The peculiar structure of IMP compels it to employ solid rotor in its PM motor.

So many advantages of solid rotor PM motor make it own lots of applications (Chen *et al*., 2008). However, as magnetic and electric circuit combine together in solid rotor, parameters of rotor are difficult to calculate (Liu and Yao, 2003) considering eddy current and skin effect in rotor during starting-up process. And all these above will influence the accurate calculation of starting-up torque and make it difficult to decide power grade of motor in the occasions needing start up with heavy load. In addition, air gap in this kind of motor is usually uniform and its back EMF is trapezoidal wave, so back EMF and starting-up torque cannot be calculated through traditional circuit method (Kulig *et al*., 2010). Qiao *et al*. (2004) and Ho *et al*. (2000) use penetrating depth method to analyze solid rotor, but they do not consider the influence from speed difference to rotor resistance. In view of its special structure, the calculating method suitable for ordinary PM motor cannot be applied to IMP and a new method is needed. The field-circuit coupled method can make it.

In recent years field-circuit coupled method is often used to analyze general induction and PM motor (Liu, 2003) and the related method is not suitable for motors in IMP. Hu and Huang (2003), Hu (2009) and Zhao (2006) discuss field-circuit coupled method used in PM motor, but they did not involve solid rotor; reference (Liu *et al*., 2007) studied starting-up performance of solid rotor PM motors, but it did not give out system formulation of field-circuit coupled method.

A novel Integrated Motor Propulsor (IMP) is designed in this study, employing Halbach array on its solid rotor. This IMP possesses a variety of merits such as thin rotor, low noise, large air gap and high power density; a time stepping Finite Element Analysis (FEA) model coupled circuit field and movement is used in analyzing the electromagnetic field of IMP, a moving air-gap boundary method is adapted to deal with rotation problem and parameters of solid motor in electromagnetic field is calculated. The novel IMP is analyzed through methods proposed in this study and conclusions are obtained.

In this study, we design a novel Integrated Motor Propulsor (IMP) which worked underwater for propelling. The motor in this IMP was PM motor employing Halbach array and solid rotor; and a field-circuit-motion coupled time-stepping Finite Element Analysis (FEA) model is presented for analyzing this kind of solid-rotor motor. And the problem that the parameters of rotor are hard to calculate is solved. The rotor resistance variation with speed difference is considered and the finite element analysis involving

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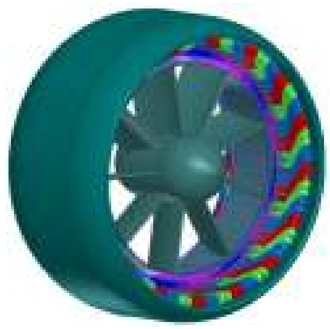


Fig. 1: Structure of the IMP

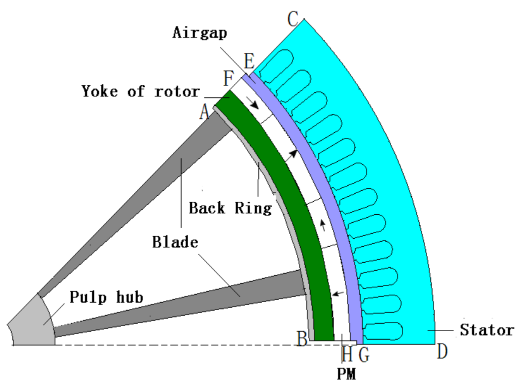


Fig. 2: The profile map of the solid rotor propellor

external circuit and electromagnetic field was provided. A moving air-gap boundary method combining motor motion equation was adopted to simulate the transient process of motor. The performance of the prototype of IMP is analyzed using the proposed model and the calculation results of back EMF and starting torque are tally well with those from tests, which indicates that the proposed method in this study is effective and exact and that it can be used to analyze other kind of solid-rotor motor.

DESIGN OF IMP

The design idea of IMP is that outer brim of propeller connects with inner brim of rotor, outer brim of stator connects with inner brim of the frame and the whole device can be installed at the bottom of ships as an independent propelling unit.

The structure schematic diagram of IMP designed in this study is shown in Fig. 1. Its main parts include frame, pipeline mechanism and motor-propeller device. Propeller is integrated into rotor; there is no centre bearing in it and the location and support of rotor is achieved by special bearings. The air gap between stator and rotor is large enough to enable water flow through it, bringing about excellent cooling condition.

The PM rotor of this IMP employs Halbach array on its solid rotor, strengthening flux density of air gap and weakening it of rotor. The profile map of IMP is shown in Fig. 2.

FIELD-CIRCUIT COUPLED TIME-STEPPING FINITE ELEMENT MODELING OF IMP

Field-circuit coupled model of solid rotor PM motor: In the model presented in this study, standard sine wave voltage is the input and transient circuit formulations of stator and rotor are combined and solved together with electromagnetic field equations. Within one pairs of poles shown in Fig. 2, steady electromagnetic field equations can be expressed as boundary value problem:

$$\begin{cases} \Omega: \frac{\partial}{\partial x}\left(\nu\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial A_z}{\partial y}\right)=-J \\ A_z|_{AB}=A_z|_{CD}=0 \\ S_2: \nu\frac{\partial A_z}{\partial n}=-H_t \\ L: \nu_a\frac{\partial A_z}{\partial n}=\nu_b\frac{\partial A_z}{\partial n} \\ A_z|_{EF}=A_z|_{GH} \\ A_z|_{AF}=A_z|_{BH} \\ A_z|_{CE}=A_z|_{DG} \end{cases} \tag{1}$$

where,

- Ω = The area to be solved
- S_2 = The second boundary condition
- L = Boundary line between different medium in motor

As to current density we can get following equations:

$$J=\begin{cases} 0 & \text{region of stator and airgap} \\ J_S & \text{region of stator winding} \\ J_e & \text{region of solid rotor} \end{cases} \tag{2}$$

In the FEM analysis crooked quadrangle is adopted as subdivision unit to obtain a higher precision. Through solving Eq. (1) we can get magnetic vector potential on every point in motor and back EMF of one phase can be obtained.

The average electric potential of one coil in motor can be expressed as:

$$e_{av}=-\frac{1}{A_b}\int_{A_b}\frac{\partial A}{\partial t}ds=-\frac{1}{A_b}\frac{\partial}{\partial t}\int_{A_b}A\,ds \tag{3}$$

where, Ab is the area of a slot. If a coil is divided into ne elements, the average electric potential of one coil is:

$$e = N_1 l_{ef} e_{av} = -N_1 l_{ef} \frac{\partial}{\partial t}\left(\frac{1}{A_b}\sum_{e=1}^{n_e} s^e (N_i A_i^e + N_j A_j^e + N_m A_m^e + N_n A_n^e)\right) \tag{4}$$

where, l_{ef} is length of core, s is area of one element, i, j, m, n are numbers of quadrangle nodes. As phase back EMF is made up by that of coils, then it can be expressed as:

$$e_w = -\frac{\partial}{\partial t}\left(\frac{2PN_1 l_{ef}}{a \cdot A_b}\sum_{1}^{q}\sum_{e=1}^{n_e} s^e (N_i A_i^e + N_j A_j^e + N_m A_m^e + N_n A_n^e)\right) = -\frac{\partial}{\partial t}\left(2Pl_{ef}\sum_{1}^{q}\sum_{e=1}^{n_e}\left[\mathbf{D}^e\right]^T \begin{bmatrix} A_i^e \\ A_j^e \\ A_m^e \\ A_n^e \end{bmatrix}\right) \tag{5}$$

In (5) we know that phase back EMF is dependent on core length, turns and motor magnetic field.

In the starting-up progress skin effect is obvious in the solid rotor made up by compound materials. To deal with this problem intensive subdivision should be made during a certain depth of the rotor and the size of subdivision element is decided by the permeation depth (Liu *et al*., 2007):

$$\zeta = \sqrt{\frac{2\rho}{\omega \mu_r \mu_0}} \tag{6}$$

In field equations winding current is unknown and difference is done instead of derivation from magnetic vector potential and current to time to obtain the equations of stator winding and through the same method equations of rotor also can be acquired. By combining all these we can gain the field-circuit couple expressions (Hu and Huang, 2003):

$$\boldsymbol{D_1} \cdot \begin{bmatrix} \boldsymbol{A}^t \\ \boldsymbol{i}_s^t \\ \boldsymbol{u}_r^t \\ \boldsymbol{i}_r^t \end{bmatrix} = \begin{bmatrix} \boldsymbol{P}_1^t \\ \boldsymbol{P}_2^t \\ 0 \\ 0 \end{bmatrix} + \frac{1}{\Delta t}\boldsymbol{D_2} \cdot \begin{bmatrix} \boldsymbol{A}^{t-\Delta t} \\ \boldsymbol{i}_s^{t-\Delta t} \\ \boldsymbol{u}^{t-\Delta t} \\ \boldsymbol{i}_r^{t-\Delta t} \end{bmatrix} \tag{7}$$

where,

$$\mathbf{D}_1 = \begin{bmatrix} \mathbf{G}_{11}^t + \frac{\mathbf{D}_{11}^t}{\Delta t} & \mathbf{G}_{12} & \mathbf{G}_{13} & \mathbf{0} \\ \frac{\mathbf{D}_{21}^t}{\Delta t} & \mathbf{G}_{22}^t + \frac{\mathbf{D}_{22}^t}{\Delta t} & \mathbf{0} & \mathbf{0} \\ \frac{\mathbf{D}_{31}^t}{\Delta t} & \mathbf{0} & \mathbf{G}_{33}^t & \mathbf{G}_{34}^t \\ \mathbf{0} & \mathbf{0} & \mathbf{G}_{43}^t & \mathbf{G}_{44}^t + \frac{\mathbf{D}_{44}^t}{\Delta t} \end{bmatrix}$$

$$\mathbf{D}_1 = \begin{bmatrix} \mathbf{D}_{11}^t & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{D}_{21}^t & \mathbf{D}_{22}^t & \mathbf{0} & \mathbf{0} \\ \mathbf{D}_{31}^t & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{D}_{44}^t \end{bmatrix}$$

where,

A^t = The line vector of unknown magnetic potential
i_s^t = Line vector of stator current
u_r^t = Line vector of rotor voltage
i_r^t = Line vector of equivalent rotor current

In (10), the first row is electromagnetic field equation, the second row is stator winding equation, the third row is equations about circuit of rotor current and the fourth row is equations about rotor voltage.

As the motor of IMP is different from general PM motor, it is difficult to establish its current and voltage equations. Expression (7) proposed in this study improved the equations of ordinary PM motor and current density of rotor is given initial value and rotor resistance as well as other rotor parameters are calculated in electromagnetic field.

Transient progress can be calculated by combing field-circuit coupled and motion equations. The torque can be calculated as follow:

$$T_e = \frac{2pL_{ef}}{g\mu_0}\int_S rB_n B_t \mathrm{d}S \tag{8}$$

where,

T_e = Electromagnetic torque
g = Air gap length
S = Integration area of region
r = Arbitrarily radius in air gap
B_n, B_t = Normal and horizontal components of flux density

Methods for motion between stator and rotor: Moving air-gap boundary method is adopted to deal with motion between rotor and stator (Qiao *et al*., 2006) namely immobile and mobile coordinate are given to stator and rotor respectively and the air gap is divided into 2 layers along axis direction and divided averagely along circle direction (for example, 360 divisions). During motions the layer belong to stator keep still and the layer belong to rotor keep moving. The equations of rotor and stator can be listed and solved.

EXPERIMENT AND SIMULATION

Magnetic field distribution of this solid rotor motor in IMP can be obtained using the field-circuit-motion coupled time-stepping finite element method. The flux distribution is shown in Fig. 3. The calculated and measured no-load back EMF of motor at 1000 rmp is shown in Fig. 4 and 5. From these two figures we find that the calculated result is very close to measured one.

Prototype designed in this study and its experiment spot are shown in Fig. 6. When conducting experiment the motor is powered by inverters. In Fig. 6b, the motor on the right is designed by this study and in the middle of the picture it is a torque measuring instrument and on

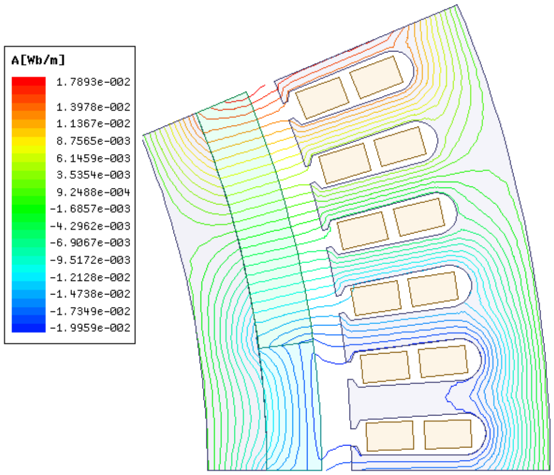


Fig. 3: Distribution of flux lines

Table 1: Peak value of phase emf

Speed (rmp)	Measured phase voltage (V)	Calculated phase voltage (V)	Error (%)
1200	282.8	287.2	1.55
1000	243.4	246.3	1.19
800	187.86	189.1	0.66
700	168.65	171.2	1.5

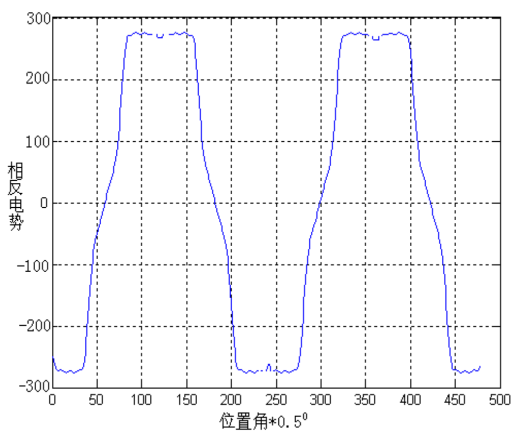


Fig. 4: The calculation waveform of the back electromotive force

the left it is a turbine machine to measure power. The motor is drawn to different speed such as 700, 800, 1000 and 1200 rpm, respectively to get its no-load back EMF and the results are shown in Table 1.

From Fig. 4 and 5 we find that the calculated result is very close to measured one and the max error in Table 1 is no more than 2%. In order to verify the effectiveness of method proposed in this study, the parameters of solid rotor are also calculated. As these parameters are hard to test through experiments, the torque which is dependent on the rotor parameters deeply is measured and calculated to further prove the validity of proposed method.

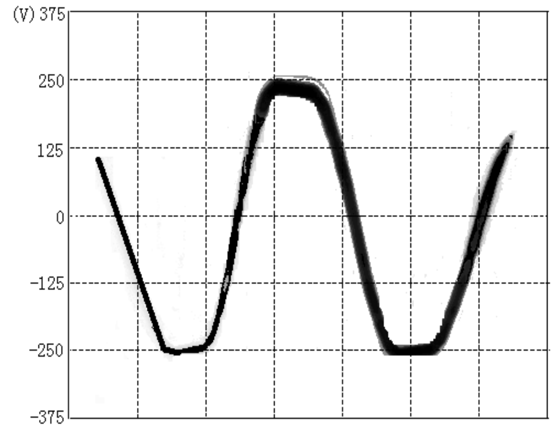
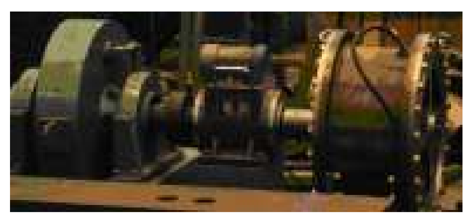


Fig. 5: The experiment waveform of the back electromotive force

(a)



(b)

Fig. 6: Prototype of IMP and its experiment spot

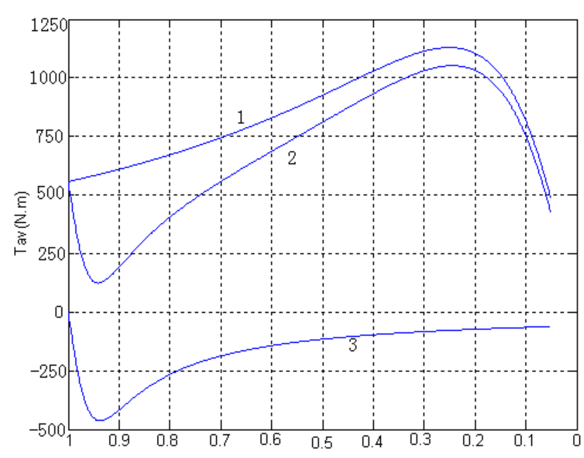


Fig. 7: The curve of starting torque

Table 2: Test value of locked-rotor current, power and torque

Locked-rotor voltage(V)	Locked-rotor current (A)	Locked-rotor power (W)	Locked-rotor torque(N. m)
378.7	253.07	88820	580
333.8	214.67	55750	433
285.8	176.2	46760	302
233	135.8	29100	187

The value of starting-up torque at various speed differences is obtained through field-circuit-motion coupled equations and shown in Fig. 7. The curve 1 represents the dragging torque T_c of PM motor, curve 3 represents braking torque T_g and curve 2 represents synthetic torque.

Locked rotor experiment is conducted to obtain the maximal torque of motor and locked-rotor current, power and torque as shown in Table 2.

From Fig. 7 we can see that in the starting-up progress the braking torque is large and the dragging torque is small. As speed increase, braking torque decreases and the dragging torque becomes larger. When slip ratio s = 0.25, dragging torque increases to its maximum.

We can find in Table 2 that the starting-up torque of solid rotor is so large that it is 2.78 times of rated value. Experiment results coincide with calculated ones.

CONCLUSION

A novel IMP prototype is designed and a field-circuit-motion coupled time-stepping finite element analysis (FEA) model is presented to analyze its solid rotor motor. Experiments are conducted and conclusions are as follows:

- The field-circuit-motion coupled time-stepping finite element method proposed in this study is suitable for analyzing solid rotor motor of this kind of IMP. A new method to precisely calculate parameters of solid rotor is presented and the method considered the influence from slip ratio to rotor resistance. Torque and back EMF are calculated and measured and the good agreement between theory calculation and experiment results verify the effectiveness of the proposed method.
- High eddy current will appear in solid rotor when the motor works in complex conditions, resulting in temperature rise in rotor and this will have a severe affect to rotor parameters. So it is the main part of our future work to establish the coupling model involving electromagnetic field, thermal field and fluid field to get more accurate results.

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