PERFORMANCE ANALYSIS AND EXPERIMENTAL VALIDATION OF A SINGLE PHASE CLAW POLE PERMANENT MAGNET MOTOR WITH COMPOSITE MAGNETIC CORE

Y.G. Guo, J.G. Zhu, and V.S. Ramsden
Faculty of Engineering, University of Technology, Sydney
P.O. Box 123 Broadway NSW 2007 Australia
Tel: +61 2 9514 2318 Fax: +61 2 9514 2435 E-mail: joe@eng.uts.edu.au

Abstract – This paper proposes a small single phase claw pole permanent magnet motor with composite magnetic core. Three dimensional finite element analysis has been conducted to predict the performance and improve the motor design. The method employed has been validated by the experimental measurements on a prototype.

1. Introduction

Small single phase AC motors are widely used in domestic electrical appliances. In general, these motors are of very low efficiency, typically 30%–50%. A lot has been done to improve the efficiency by using better motors and power electronic variable speed direct drives. When better technology is employed, however, the cost of the product increases accordingly. Therefore, it would be very beneficial to bring the cost down while keeping the improved performance. This can be achieved by using soft magnetic composite materials to reduce the manufacturing cost of high performance motors.

Soft magnetic composite materials produced by powder metallurgy techniques have undergone significant development in the past few years because of their unique properties and potential application fields [1-5]. This type of materials are made of iron powder of high purity and compressibility, or sometimes, alloy powders. The type of bonding between powder particles depends on the type of composite. In materials for injection molding, the bonding is effected by an additional substance, a dielectric, which also performs the function of insulating the particles of ferromagnetic powder.

Compared with electrical steels widely used in rotating machines and transformers, the major advantage of this material is the prospect of large volume manufacturing of low cost motors. Because the iron cores and parts are formed in a die, or iso-static press process, and can be combined to form complex net-shape components, the dimensional changes are minimized and hence the production costs are greatly reduced. In addition, the powdered nature of the material yields lower eddy current loss and isotropic magnetic properties, and therefore, it is suitable for specially structured, such as claw pole, motors with three dimensional fluxes. The permeability of this material, however, is lower than that of electrical steels. It is expected that this material would be appropriate for construction of permanent magnet motors, which are not sensitive to the permeability of the core.

To investigate the potential application of soft magnetic materials, several small machines with soft magnetic composite cores have been developed [6-9]. These designs were all based on the data supplied by the manufacturers, which were measured under alternating magnetic fluxes. In rotating machines, the magnetic fluxes rotate, and therefore, the magnetic properties of the core material with rotating fluxes need to be examined and employed in the performance simulation and design.

In order to make a good use of the material so as to produce motors of low cost and reasonably good performance, suitable topologies must be studied. For this purpose, a single phase claw pole permanent magnet motor with a composite magnetic core is being developed using SOMALOY™ 500, a magnetic soft composite recently developed by Höganäs AB, Sweden. This new soft magnetic composite material has a saturation flux density of 2.37 T at 340 kA/m, maximum relative permeability of 500, and reasonably low core loss at medium frequencies. For core loss prediction, rotational core losses of SOMALOY™ 500 with rotating magnetic fluxes were measured [10] and used in the design. The experimental results of our two dimensional magnetic property tests on thin square specimens cut in different orientations of the SOMALOY™ 500 preforms show that this soft magnetic composite material is in general isotropic in three dimensions. This makes the material very much suitable for construction of claw pole motors, in which the magnetic field is truly three dimensional. A commercial finite element package, ANSYS, was employed for the design and performance analysis.

Mechanically, however, this material is brittle. This makes the prototype manufacturing difficult by conventional means. In the design and construction of our first prototype, special attention was paid on the mechanical strength of claw poles whereas the overall performance of the motor was compromised. Based on the experience of the first prototype, a second prototype has been designed and is being constructed in the workshop. According to the three dimensional finite element magnetic field analysis, which has been validated by the experimental results of the first prototype, the performance of the second prototype would be better than that of the first one.

2. Motor Structure

Due to the nearly universal use in automobile alternators, electrical machines with claw pole rotors have been manufactured in mass production for many years. These machines have quite simple excitation coil and pole systems producing the excitation magnetic fields. They are capable of producing power densities up to three times greater than conventional machines because the topology allows the pole number to be increased without reducing the magnetomotive force per pole [11,12]. The excessive eddy current in the commonly used solid steel core, however, limits the motors to very small sizes and/or low speeds and results in low efficiency.

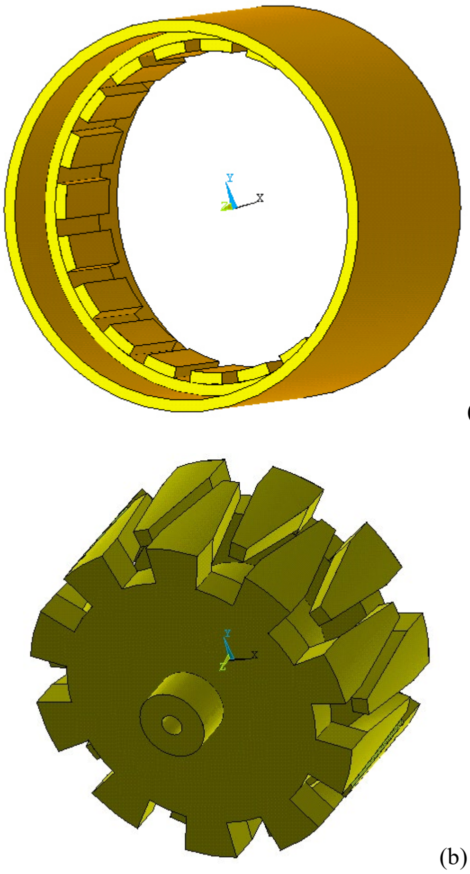
Because of the complex structure, it is very difficult to construct the claw poles using electrical steel laminations. Soft magnetic composite materials offer an opportunity to overcome these problems. Fig.1 illustrates the magnetically relevant parts of the rotor and the stator of the second prototype. The rotor consists of a mild steel cylinder, 20 surface mounted NdFeB magnets, and two aluminum end plates, which are not shown in the diagram. The stator has two identical soft magnetic composite claw pole pieces, a concentrated single phase winding housed between the two claw pole pieces, and a steel shaft. The stator size was to a large extent determined by the dimensions of the SOMALOY™ 500 preforms supplied by Höganäs AB, Sweden. Since a simple concentrated stator winding is used, a reasonably high fill factor can be achieved and the manufacturing cost can be very low. No originality is claimed for the machine layout, nor for that matter does the geometry exploit many of the special features of the material. It is best regarded as a simple prototype for practical testing of the material.

Because the output coefficient of a claw pole motor is not only proportional to the product of the air gap specific magnetic loading and the specific electric loading, but also directly proportional to the number of poles, the torque capability can be increased by simply increasing the number of poles. In practice, there is a limit to the torque capability of a motor due to the flux leakage and saturation. On the other hand, the rotor speed should also be considered in determine the number of poles. In our design, the first intended application is an electrical fan with a typical speed of 300 rev/min, and therefore, the number of poles was chosen as 20. Table 1 lists the dimensions and the major parameters of the second prototype, while the detailed field analysis and results will be described in the next section.

Table 1 Dimensions and major parameters of the second prototype claw pole permanent magnet motor

Dimensions and Parameters	Quantities
Frequency (Hz)	50
Number of phases	1
Rated voltage (V)	240
Rated power (W)	63
Rated current (A)	0.3
Rated speed (rev/min)	300
Rated torque (Nm)	1.7
Maximum torque (Nm)	2.5
Rated power factor	0.93
Rated efficiency (%)	79
Number of poles	20
Permanent magnet	NdFeB
Stator core material	SOMALOY™ 500
Number of turns of stator winding	2280
Wire diameter of stator winding (mm)	0.3
Rotor outer radius (mm)	50
Rotor inner radius (mm)	41
Rotor effective axial length (mm)	25
Stator outer radius (mm)	40
Stator axial length (mm)	40
Shaft radius (mm)	8
Major airgap length (mm)	1
Sub-airgap length* (mm)	4.2

* The sub-airgap is defined as the gap between the sides of the claw poles of the two separated pieces.



(a)

(b)

Fig.1 Magnetically relevant parts of (a) rotor and (b) stator

3. Three Dimensional Magnetic Field Analysis

Because of the symmetrical motor structure, it is only required to analyze the magnetic field in one pole pitch as shown in Fig.2. To determine the three dimensional magnetic field distribution, the scalar magnetic potential was employed with half-periodic boundary conditions. The whole solution region was divided into 13350 tetrahedral elements and 2642 nodes.

3.1 Magnetic Field Distribution at No Load

Fig.3 illustrates the flux density vectors with the line lengths proportional to the magnitudes when the motor is under no load. It can be found that the major path for the magnetic flux produced by the permanent magnets is along one of the permanent magnets – the main air gap – one of the composite claw pole stator core pieces – the rotor yoke and shaft – another composite claw pole stator core piece – main air gap – another permanent magnet and then – the mild steel rotor yoke to form a

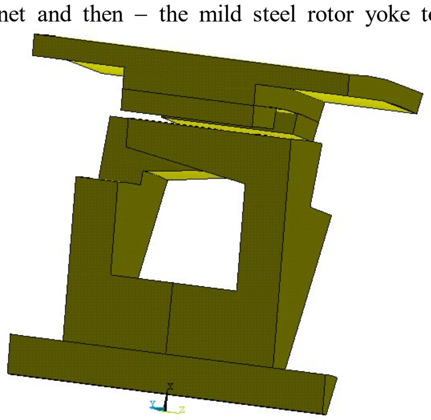


Fig.2 Solution region for one pole pitch

closed loop.

Fig.4 plots the radial component of flux density B_r along the periphery θr_g in the middle of the main air gap where r_g is the radius. The peak to peak value of the radial component of the flux density in the main air gap is 0.90 T (from −0.45 T to 0.45 T). It is shown that the spatial distribution is reasonably sinusoidal.

3.2 Magnetic Flux Linking the Stator Winding at No Load

As the rotor rotates, the flux linking the stator winding varies and an electromotive force (*emf*) is induced. The *emf* frequency depends on the rotor speed, while the *emf* waveform is determined by the waveform of the flux. At no load, the flux waveform was calculated by rotating the rotor magnets for one pole pitch in 20 steps. As plotted in Fig.5, this flux waveform is almost perfectly sinusoidal versus the rotor position.

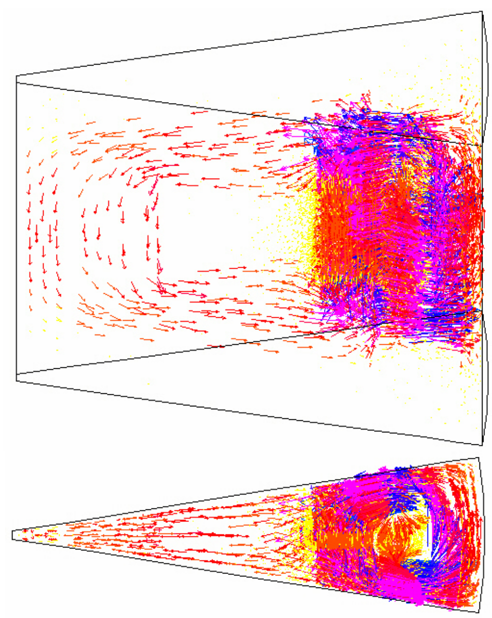


Fig.3 Magnetic flux density vectors at no-load

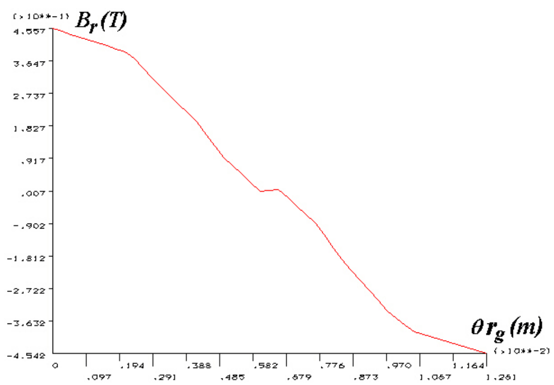


Fig.4 Radial component of flux density in main air gap

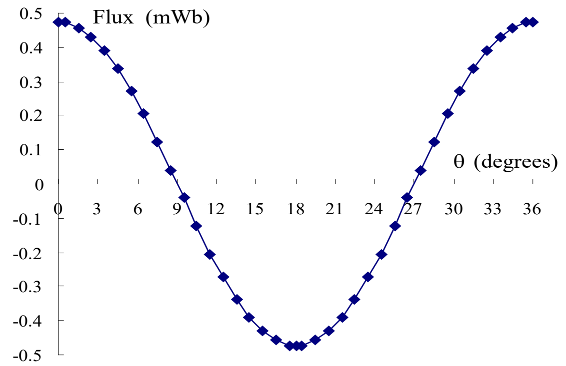


Fig.5 No-load flux linking the stator winding

3.3 Cogging Torque

Cogging torque is caused by the tendency of the rotor magnets to line up with the stator poles in a particular direction where the magnetic circuit has the highest permeance when the motor is under no load. It can be calculated by the partial derivative of magnetic coenergy with respect to the angular displacement as

$$T_{cog} = \frac{\partial W_f'}{\partial \theta} \tag{1}$$

where W_f' is the total coenergy of the field and θ the rotor position. Numerically, this partial derivative can be calculated approximately as the variation of coenergy against the rotor angular displacement:

$$T_{cog} \approx \frac{\Delta W_f'}{\Delta \theta} = \frac{W_{f2}' - W_{f1}'}{\theta_2 - \theta_1} \tag{2}$$

Fig.6 plots the variation of cogging torque versus the rotor position. This curve was calculated by rotating the rotor for one pole pitch in 18 steps with 1° (mechanical) per step.

4. Performance

The steady state performance can be predicted by an equivalent circuit including the induced *emf* in the stator winding due to the permanent magnets, the stator winding resistance and reactance, which can be determined from the results of three dimensional magnetic field analysis. Fig.7 presents the input power, output power, electromagnetic torque, output torque, stator current, efficiency, and power factor of the second prototype against the load angle.

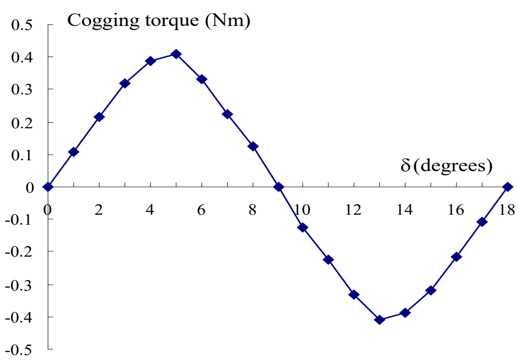


Fig.6 Cogging torque versus rotor position

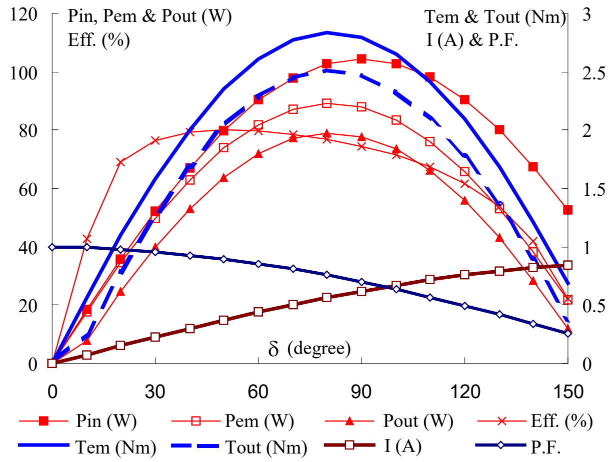


Fig.7 Steady state performance of the second prototype

5. Experimental Validation

The above method of three dimensional field analysis, equivalent circuit parameter calculation, and performance prediction was validated by the experimental results of the first prototype. Figs.8 and 9 plot together the measured and predicted cogging torque and induced *emf* in the state winding respectively. The theoretical and experimental results are in substantial agreement.

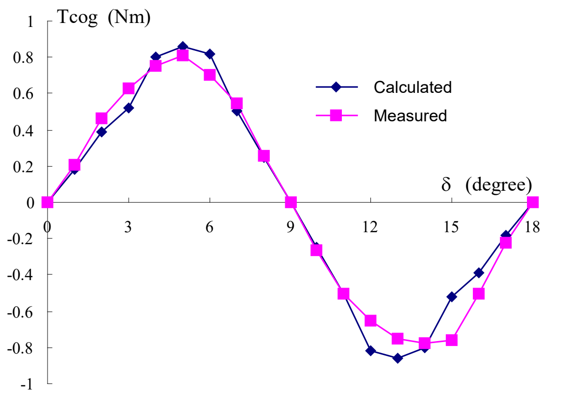


Fig.8 Comparison of calculated and measured cogging torque

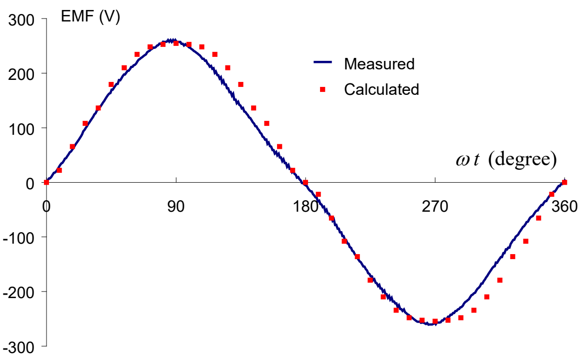


Fig.9 Measured and calculated *emf* waveforms in the stator winding when the rotor rotates at 300 rev/min

6. Conclusions

Soft magnetic composite materials can be suitable for construction of small motors of complex topologies, such as claw pole motors. In design of such motors, special consideration is required on the mechanical properties of the composite material. The numerical techniques used for three dimensional magnetic field analysis, equivalent circuit parameter calculation, and performance prediction of single phase permanent magnet claw pole motors has been validated by the experimental results of the first prototype. By using the validated method, a second prototype has been designed and is being constructed in workshop.

Acknowledgment

The authors would like to thank Höganäs AB, Sweden, for supplying preforms of SOMALOY™ 500.

References

[1] "The Latest Development in Soft magnetic Composite Technology, from Höganäs Metal Powders", Höganäs Manual

[2] "Soft Magnetic Composites from Höganäs Metal Powders - SOMALOY™ 500", Höganäs Manual

[3] A.J. Moses, "Development of Alternative Magnetic Core Materials and Incentives for Their Use", J. of Magnetism and Magnetic Materials, No. 112, 1992, pp. 150-155

[4] M. Persson, *et al*, "Soft Magnetic Composite Materials - Use for Electrical Machines", 7th Int. Conf. on Elect. Mach. and Dr., Durham, UK, Sept. 1995, pp. 242-246

[5] P. Jansson, *et al*, "Powdered Soft Magnetic Materials for Medium Frequency Applications", Soft Mag. Mat.'96, San Francisco, Feb. 1996

[6] C.P. Maddison, *et al*, "Claw Pole Geometries for High Performance Transverse Flux Machines", Proc. of Int. Conf. on Elect. Mach., Istanbul, 1998, pp. 340-345

[7] B.C. Mecrow, *et al*, "Permanent Magnet Machines with Soft Magnetic Composite Stators", Proc. of Int. Conf. on Elect. Mach., Istanbul, Turkey, 1998, pp. 346-351

[8] A.G. Jack, "Experience with the Use of Soft Magnetic Composites in Electrical Machines", Proc. of Int. Conf. on Elect. Mach., Istanbul, Turkey, 1998, pp. 1441-1448

[9] A.G. Jack, *et al*, "Claw Pole Armature Permanent Magnet Machines Exploiting Soft Iron Powder Metallurgy", 1997 IEEE, MA1-5.1~5.3

[10] J.G. Zhu, *et al*, "Power Losses of Composite Soft Magnetic Materials under Two Dimensional Excitations", Journal of Applied Physics, Vol.85, No.8, April 1999, pp. 4403-4405

[11] S. Huang, *et al*, "Evaluation of the transverse flux circumferential current machine by the use of size equations", Elect. Mach. and Dr. Conf., Milwaukee, 1997

[12] I. Ramesohl, *et al*, "Three Dimensional Calculation of Magnetic Forces and Displacements of a Claw-Pole Generator", IEEE MAG-32, No. 3, May 1996, pp. 1685 - 1688