# Design of New Type Universal Motor Using Soft Magnetic Composites

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**Abstract** - This paper presents a new structure for the universal motor using soft magnetic composite (SMC). The stator for this new type of motor is made by combination of the SMC pole and the silicon steel yoke. The shape of the 3D SMC pole is designed to minimize ohmic loss and amount of stator coil. To design the pole shape, the 3D analysis in the design procedure is replaced with an equivalent 2D analysis. Finally, the optimal shape is analyzed by 3D FEM and the performance is discussed.

**Keywords**: field winding, optimal design, soft magnetic composite, universal motor

## 1. Introduction

Recently, the development of powder metallurgy has resulted in improvements to the magnetic property and the competitive price of soft magnetic composite (SMC) materials. Therefore, the interest in this material has grown in the applications for electrical machines [1-4].

SMC has some advantages including precise material control, simple production, and 3D free shape design by the powder compaction process [5], which can be applicable to electrical machines. Especially, the coil length becomes shorter and the steel scrap loss can be drastically minimized by 3D free shape design. On the other hand, it has the drawbacks of low permeability and saturation flux density as compared with silicon steel. Consequently, the purely SMC applied structure hardly demonstrates superior performance over the conventional silicon core structure and its application has been limited to very special motors up to now [6-9].

To discuss the possibility of SMC application to general motors, it is adopted for a universal vacuum cleaner motor. A new stator structure is proposed to maximize the SMC material's merits and minimize its demerits. The stator consists of SMC pole and silicon steel yoke, where the former is adequate to make the length of the stator coil shorter. And the latter is proper to reduce the magnetic reluctance.

With a 3-dimensionally free shape in the SMC pole, the prediction of characteristics is very difficult with FEM unlikely in the 2D motor in general. Moreover, so many analyses are needed in the design procedure that it requires an intolerable amount of solving time.

In this paper, therefore, an equivalent 2D model replaces the 3D model to use 2D FEM. The 2D shape having the minimum length of stator coil is searched and its real shape is performed by 3D FEM to verify the results in the final stage.

## 2. Proposed Model

The specifications of a commercial universal motor for a vacuum cleaner and the full load operating point are given in Table 1. Fig. 1 shows the flux density distribution in the stator, when the motor is in the full load operation. According to the results in Fig. 1, the flux density in the yoke part is between 1.2~1.5T. However, the density in the pole part is much higher, at about 1.8T.

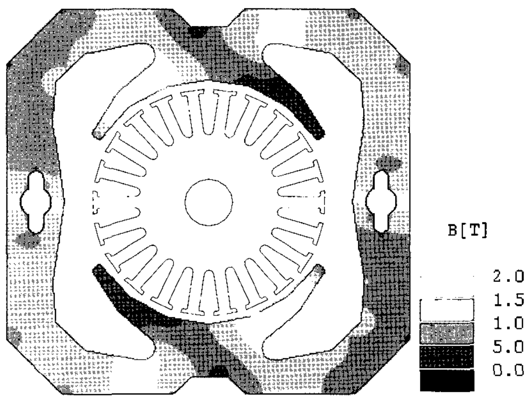


**Fig. 1** Flux density distribution of conventional motor at full load operation

**Table 1** Specifications of Conventional Motor

| Item | Value | Item | Value |
|---|---|---|---|
| Outer dia. | 82(mm) | Input voltage | 220(V) |
| Inner dia. | 41.5(mm) | Rated current | RMS 6(A) |
| Axial length | 28.5(mm) | Frequency | 60(Hz) |
| Stator coil | 125(turns) | Max. input | 1.8(kW) |
| Rotor coil | 30(turns/slot) | Max. rpm | 40,000(rpm) |

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Each flux density of pole and yoke is pointed on the BH characteristics of silicon steel and SMC in Fig. 2. It shows that over two times of material is needed for gathering the same amount of flux if the yoke part is made by SMC, so there is no benefit for adopting SMC material. But, in case of the pole part, only about a quarter is needed additionally. Moreover, there are advantages of shortening coil length in field winding according to 3D free design of the pole neck, because the coil is wound on the pole neck. This results in decrease of copper loss and material cost.

On the basis of the above discussion, we propose a new type of motor that has the combined stator structure of SMC and silicon steel, as indicated in Fig. 3. The yoke is still made of silicon steel, but the pole is replaced with SMC material.

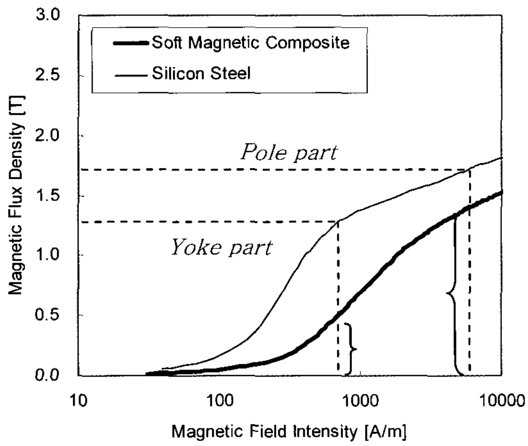
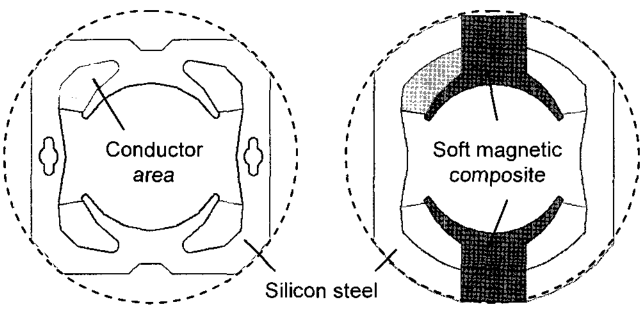



**Fig. 2** B-H characteristics of magnetic material used for motor core




(a) Conventional (b) Proposed

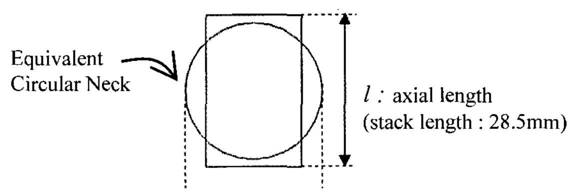
**Fig. 3** Comparison of conventional and new type motor

## 3. SMC Pole Shape Design for Minimal Coil Length

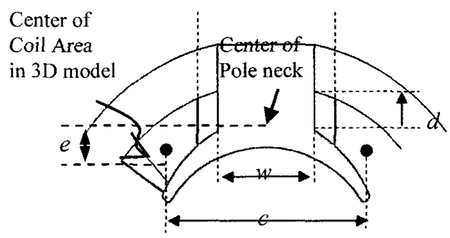
Because the coil should be wound on the pole neck, the best pole neck shape is circular thereby making the coil length minimal. As such, the problem approaches to determining the diameter of the pole neck. To obtain the characteristics of the motor with circular pole neck, the high cost 3D analysis is required. In this paper, the 3D model is substituted with an equivalent 2D one.

### 3.1 Equivalent 2D Simulation

The equivalent 2D rectangular pole neck is assumed, which has the same area with circular neck, and is depicted in Fig. 4. At first, we predict the performance of the motor with the 2D rectangular pole neck and redesign it iteratively using 2D FEA, and then the best shape is transformed to a 3D circular shape. The target of design is to minimize the coil length on the condition of the same torque-field current performance, because the coil length is proportional to the copper loss and the material cost.




(a) Conversion of rectangular to circular neck

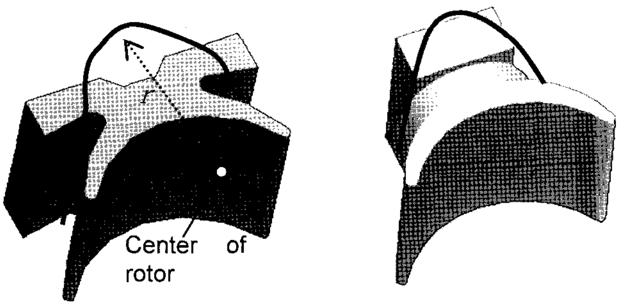



(b) Design variables

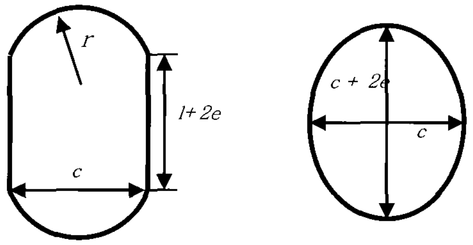
**Fig. 4** Design scheme and variables

In the equivalent 2D design process, the corresponding real coil length of the 3D shape should be evaluated. In practice, the real coil shape is somewhat complex because the coils are only wound over the pole neck; therefore, the coil length is the function of the variable $e$ and $c$ related to the position of the coil center in Fig. 4, where $c$ is the direct length between the centers of coil areas. We could suppose by experiences that the coil shapes are represented in Fig. 5 according to rectangular and circular pole neck respectively. By the above coil modeling, the coil length of the conventional motor is calculated to 194.4mm.

To find the optimum pole shape, two design variables, pole neck width $w$ and neck length $d$ are chosen and shown in Fig. 4. The core loss should be included for an accurate simulation. However the majority of losses are ohmic because the power density of a general universal motor for a vacuum cleaner is very high. Moreover the core loss is concentrated in the armature, and then the core loss may be out of this discussion. So the magneto-static analysis is reliable and it is performed with 6A and 750AT (amper-turn) of stator current, which is the motor's full load operating condition. Torque characteristics are obtained by 2D FEA according to the variance of variables and represented in Fig. 6. The wider the neck width and the shorter the length, the greater the torque is, which is very natural because the reluctance is getting smaller.




(a) Approximated coil shape




(b) Coil length calculation

**Fig. 5** Coil modeling

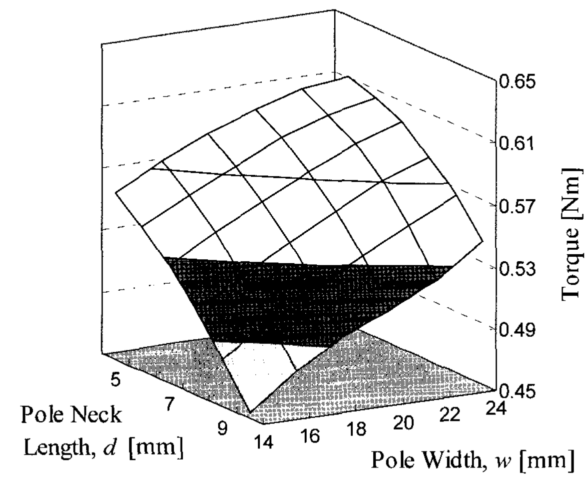



**Fig. 6** Torque according to design variables

Among the results in Fig. 6, the combinations of variables giving the same torque with the conventional motor are searched and shown by contour line in Fig. 7. The variables on the contour line in Fig. 7 are transformed to the 3D circular pole neck, and then the center point of the coil area is calculated. The coil length can be calculated by the coil shape assumption in Fig. 5. To make the calculations simple, 6 points on the contour are selected and the coil lengths are represented in Fig. 8. It shows that the minimum coil length and copper loss can be obtained when the pole neck diameter is 13mm and the pole neck length, d is 7.5mm. The optimum combination gives 166.3mm of coil length and it is about 15% less than the conventional one's 194.4mm.

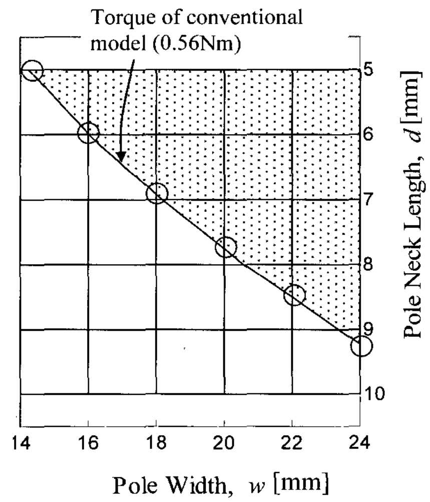



**Fig. 7** Contour line of the same torque with conventional motor and selection of variable combinations

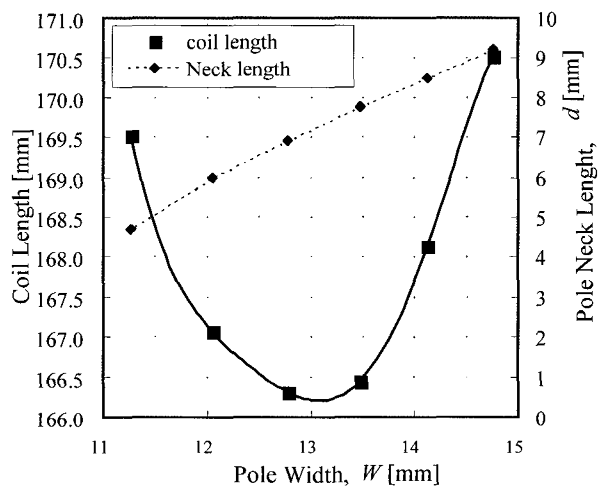
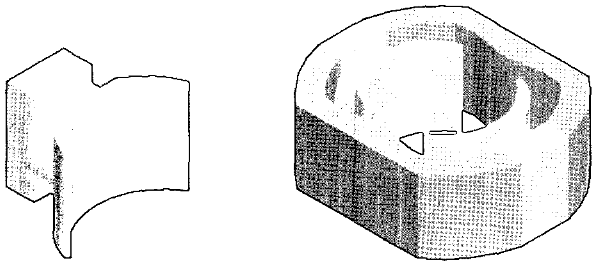



**Fig. 8** Coil length of the selected combinations

### 3.2 Verification with 3D Simulation

A 3D-SMC pole having the same cross sectional area with a 2D rectangle is determined and Fig. 9 presents its shape and combined stator structure. The 3D FEA is performed with commercial software, Ansoft's Maxwell 3D, where the simulation condition is identical with that in the 2D FEA, that is, magneto-static analysis at 6A of coil current, 750AT of MMF. To compare with the results of 2D analysis, the conventional and the SMC combined models are both simulated. The total elements for the analysis are about 250,000 and the target error is 2%.

The calculated torque characteristics are arranged in Table II. According to the results, in the case of the conventional motor, torque of 3D analysis is 0.58Nm, which is a little bit larger than 0.56Nm of 2D analysis due to both coil-ends of the stator and rotor. On the contrary, in the case of the SMC combined model, the torque is 0.55Nm, which is 5% less than that of the conventional one in 3D analysis.



(a) Pole neck shape (b) Combined stator structure

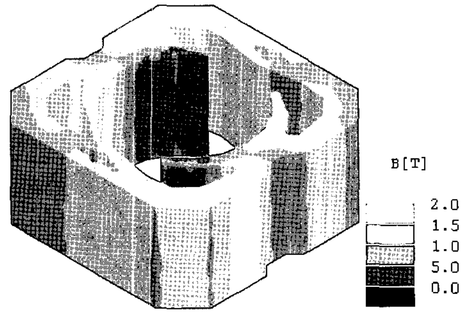
**Fig. 9** 3D shape model for analysis

**Table 2** Calculated torque with 750AT of stator MMF

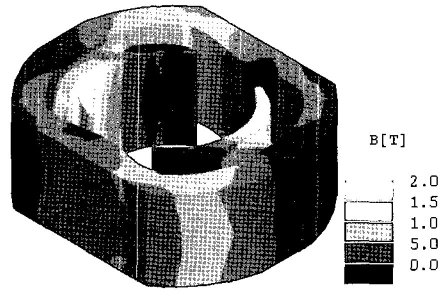
| Model | 2D-FEA(Nm) | 3D-FEA (Nm) |
|---|---|---|
| Conventional | 0.56 | 0.58 |
| SMC combined | 0.56 | 0.55 |

Fig. 10 indicates the flux density distributions of both the conventional and SMC combined motors, where the flux density on the pole-face of the conventional motor is uniform along the axial direction. Meanwhile the newly designed motor's flux density is distorted near the mid-area of the face and its whole values are a little lower. The phenomena of decrease of torque and flux density can be explained by the following reason. Clearly the circular pole neck has the same cross section area with that of the rectangular neck in 2D analysis. And the circular neck is connected mechanically with the following rectangular pole face. There are, however, magnetic discontinuities at the joint. Fig. 11 shows the detail flux density distribution on the surface of a pole. The abrupt change of flux pattern occurs at the connecting area between neck and face. The cut plane of the pole neck and the more detail flux density on the plane are shown in Fig. 12. It shows that the flux is concentrated on the right outer surface and the density is very high, because the flux path at the region is shorter and smoother than that of other places. Generally, when total magneto-motive force is fixed, the more the flux concentrates at a specific area, the higher the magnetic resistance becomes and the lower the total flux becomes.

Because of the magnetic disturbance, the same torque as the conventional model can be obtained by increasing the MMF of field winding or armature winding. We focus on the SMC's usage; therefore the simulations are performed according to increasing the MMF of the stator winding




(a) Conventional motor




(b) SMC combined motors

**Fig. 10** 3D Flux density distributions on the stator

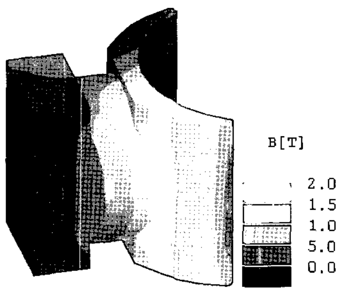
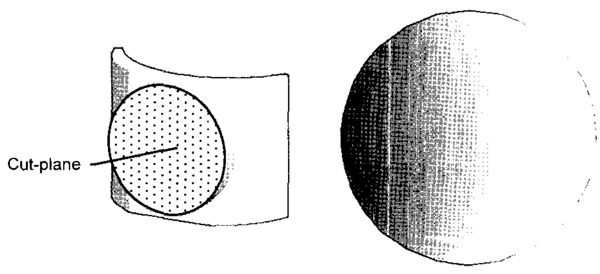



**Fig. 11** Flux density on the SMC pole surface




(a) (b)

**Fig. 12** (a) Cut-plane of pole and (b) Flux density on the plane

only and the results are given in Table III. From the results, it is known that 795AT of the stator's MMF makes the same torque, which means that 6% of field winding turns are needed additionally. Consequently, the total advantages expected by using the SMC pole is about 15% from the optimal design minus 6%, that is, 9% saving of coil length and stator copper loss.

**Table 3** Calculated torque according to stator MMF

| Model | 3D-FEA (Nm) | Stator MMF(AT) |
|---|---|---|
| SMC combined | 0.57 | 780 |
| | 0.58 | 795 |
| | 0.59 | 810 |
| Conventional | 0.58 | 750 |

## 4. Conclusions and Discussion

The potential of SMC (soft magnetic composite) powder in application to the general electric machine was discussed and, as an example, a new combined-structure for a universal motor considering SMC's mechanical merit and electromagnetic demerit was proposed. The stator is composed of the silicon-steel yoke and the circular SMC pole. The 3D shape design of the SMC pole is performed to have the same torque with the conventional motor and the minimum coil length. In the design process, the 2D and the 3D analyses are performed effectively. There is some deviation between the 2D and the 3D analyses, which is produced by the transition region between the circular neck and the rectangular face. Despite the above deviation, the proposed motor is expected to have an advantage of 9% coil saving by using the SMC pole. When, therefore the SMC material is applied properly in general electric machines, it has considerable beneficial potential.

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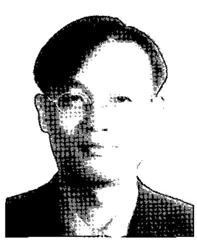

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