Robust Design Optimization of PM-SMC Motors for Six Sigma Quality Manufacturing

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In our previous work, soft magnetic composite (SMC) material was employed to design cores for two kinds of permanent magnet (PM) synchronous motors, namely transverse flux motor and claw pole motor. This paper presents robust design optimization method for the quality control of these PM-SMC motors to improve their industrial applications. Besides traditional theoretical design and analysis, manufacturing condition, tolerance, noise factors and manufacturing costs are investigated in the robust design and optimization models in order to achieve six sigma quality manufacturing for these motors. Thereafter, a PM-SMC transverse flux motor is investigated to illustrate the performance of the proposed method. From the discussion, it can be found that the proposed method can significantly improve the manufacturing quality and reliability of the motor, and reduce the manufacturing cost as well.

***Index Terms*— PM transverse flux motor, robust optimization, six sigma quality manufacturing, soft magnetic composite.**

I. INTRODUCTION

RECENTLY, interest in soft magnetic composite (SMC) and its application in permanent magnet (PM) electrical machines have increased significantly [1]-[4]. SMC is a new type of soft magnetic material made of iron powder particles which are separated with electrically insulated layers. SMC has been employed to design cores for several kinds of motors, such as PM transverse flux motor (TFM) [4], [5] and claw pole motor [6].

Compared with traditional silicon steel sheets, SMC cores have the following advantages. Firstly, SMC cores are isotropic both mechanically and magnetically, so they are suitable for the design of 3-D flux path. Secondly, unlike the lamination structure of traditional silicon steel sheets, SMC cores can be manufactured by modules, so they are suitable for the motors with complex structures. Thirdly, SMC cores have low eddy current loss as SMC powders are separated with electrically insulated layers. Fourthly, SMC is a cheap material. And by using SMC cores, the material costs will be reduced significantly as leftover bits and pieces can be saved by modules. Finally, SMC is easy to recycle. Therefore, SMC is a promising material for the design of PM motors with complex structure and 3-D flux path, such as PM TFM and claw pole motor [4]-[6].

In our previous work, two kinds of PM-SMC motors, TFM and claw pole motor have been designed, fabricated and tested [4]-[7]. From the discussion, it was found that these motors can take advantage of the unique magnetic characteristics of SMC and provide good performances. However, two issues with respect to the manufacturing quality and cost are needed to investigate for the industrial applications of these motors. Firstly, there are many noise factors in the manufacturing process of these motors. Besides the structure parameters, the material parameters and manufacturing conditions should also be investigated to improve the manufacturing quality of these motors. Secondly, besides the material costs, manufacturing costs should also be considered for the industrial applications of these motors. Therefore, robust design optimization method is presented in this work to achieve good performances and high manufacturing quality for these PM-SMC motors.

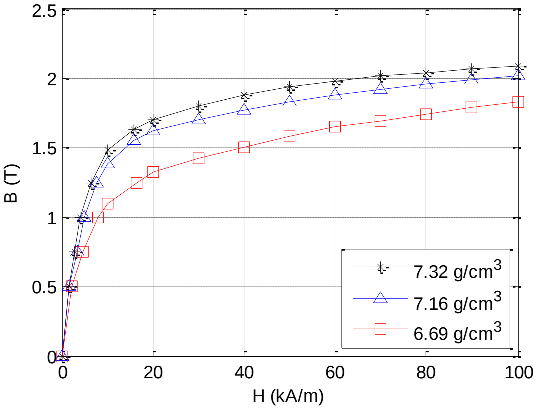

Fig. 1. B-H curves with respect to different SMC density values

II. MANUFACTURING OF PM-SMC MOTORS

Considering the manufacturing of PM-SMC motors, two issues are needed to investigate, namely manufacturing quality and cost. Manufacturing quality is defined as a motor's quality with respect to the design parameters and noise factors in the manufacturing process. There are many noise factors in the manufacturing process of PM-SMC motors. Besides the structure parameters, the material parameters, namely the type of SMC material and the mass density of SMC core are also important issues for the motor's performance and quality.

Fig. 1 illustrates three magnetization curves for different mass density values of a kind of SMC core [1]. From this figure, it can be found that there are significant differences of B-H data due to different mass densities. Actually, the density of SMC core depends on the manufacturing condition, such as the tons of the compacting press and its operation tolerance. Therefore, all these parameters and issues should be taken as design optimization factors as well as noise factors for the industrial applications of these motors to improve their manufacturing quality. For the manufacturing cost, except the SMC cores, other parts of SMC motors are manufactured by traditional techniques and do not have significant differences. Therefore, we only need to consider the manufacturing cost of SMC cores for the cost model in the latter discussion.

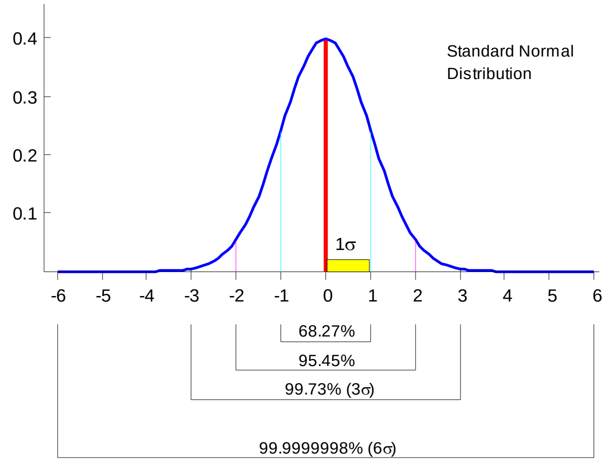

Fig. 2. Sigma level and its equivalent probability for normal distribution

Considering the manufacturing quality, cost and material characteristic of SMC cores, the design optimization model of PM-SMC motors can be defined as

$$
\begin{aligned}
\min: \quad & f(\mathbf{x}_s, \mathbf{x}_{mt}, \mathbf{x}_{mf}) \\
\text{s.t.} \quad & g_i(\mathbf{x}_s, \mathbf{x}_{mt}, \mathbf{x}_{mf}) \le 0, \ i = 1, \ldots, N \ , \\
& \mathbf{x}_l \le \mathbf{x} = [\mathbf{x}_s, \mathbf{x}_{mt}, \mathbf{x}_{mf}]' \le \mathbf{x}_u
\end{aligned}
\tag{1}
$$

where $\mathbf{x}_s$, $\mathbf{x}_{mt}$, and $\mathbf{x}_{mf}$ are the structure, material and manufacturing parameters respectively; $\mathbf{x}_l$ and $\mathbf{x}_u$ are the lower boundary and upper boundary of $\mathbf{x}$ respectively; and N is the number of constraints. For the six sigma quality manufacturing, the design model can be obtained as (2) within the framework of design for six sigma technology [8], [9].

$$
\begin{aligned}
\min: \ & F[\mu_f(\mathbf{x}), \ \sigma_f(\mathbf{x})] \\
\text{s.t.:} \ & \mu_{g_i}(\mathbf{x}) + n\sigma_{g_i}(\mathbf{x}) \le 0, \ i = 1, \ldots, N \\
& \mathbf{x}_l + n\sigma_{\mathbf{x}} \le \mu_{\mathbf{x}} \le \mathbf{x}_u - n\sigma_{\mathbf{x}} \\
& \mu_f - n\sigma_f \ge \text{LSL} \\
& \mu_f + n\sigma_f \le \text{USL}
\end{aligned}
\tag{2}
$$

where μ and σ are the mean and standard deviation of the corresponding terms; LSL and USL are the lower and supper specification limits; n is the sigma level which is generally with respect to a probability value of a standard normal distribution as shown in Fig. 2. In this work, the designed SMC motors are expected to achieve six sigma manufacturing quality, so n will be defined as 6. For industrial manufacturing and management, six sigma level manufacturing quality means 0.002 defects per million for the “short term sigma quality”, and 3.4 defects per million for the “long term sigma quality”, where there is about 1.5 sigma shift from the mean [9], [10].

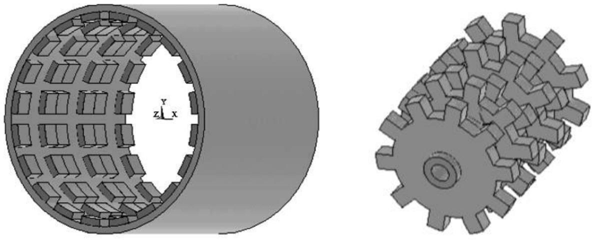
(a) (b)

Fig. 3. Magnetically relevant parts of TFM with SMC core (a) rotor, (b) stator

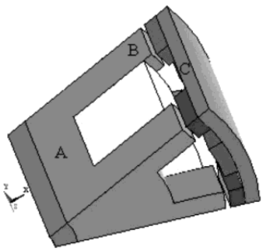

Fig. 4. Region for the three-dimensional magnetic field analysis

TABLE I
MAIN DESIGN MATERIAL AND PARAMETERS

Parameter	**Value**
Number of phases	3
Number of poles	20
Number of stator teeth	60
Number of magnets	120
Stator core material (SMC)	SOMALOY™ 500
PM	NdFeB, N30M

III. DESCRIPTION OF A PM TFM WITH SMC CORE

In this work, a PM TFM with SMC core is investigated to illustrate the manufacturing quality by using the proposed method. Fig. 3 shows the magnetically relevant parts of this machine. It was designed to deliver a power of 640 W at 1800 r/min. Fig. 4 shows the finite element analysis model for this machine [5]. We can see that 3D flux path design is needed for this machine. Table I lists several parameters and materials for this machine. From our design experience, eight structure parameters are significant to the quality of this machine. They are x_1 and x_2: circumferential angle and axial width of PM; x_3 to x_5: circumferential width, axial width and radial height of SMC tooth; x_6 and x_7: number of turns and diameter of copper wire winding; and x_8: air gap.

Now we consider the material parameter and machnufacturing condition. As the SMC core is compressed by module, SMC’s density is calculated from the compacting pressure applied on the core’s surface and the pressure is related to ton’s value of the used stamping press. Furthermore, the manufacturing cost of SMC cores directly depend on the selected type of stamping press. Fig. 5 shows the manufacturing cost and productivity of this SMC core by using different stamping presses. Therefore, ton value is also selected as a design factor as well as a noise factor for the robust manufacturing quality design.

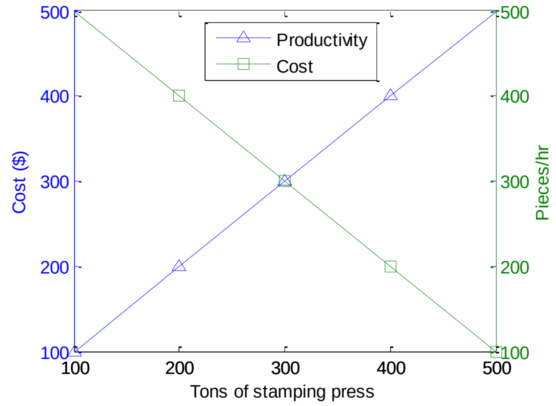

Fig. 5. Manufacturing cost and productivity for SMC cores

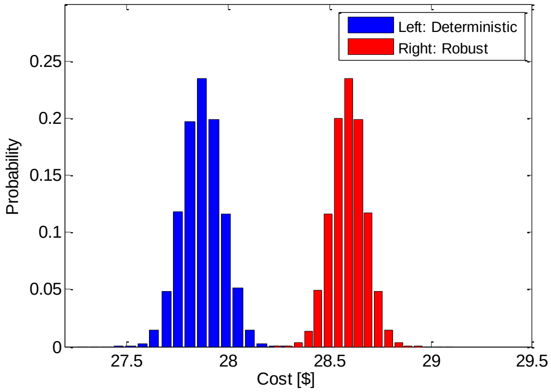

Fig. 6. Cost distributions of deterministic and robust optimization solutions

Firstly, the deterministic optimization model for this TFM can be defined as

$$\begin{aligned} &\min:\ f(\mathbf{x}) = Cost/C_0 + P_0/P_{out} \\ &\text{s.t.}\ \begin{cases} g_1(\mathbf{x}) = 0.795-\eta \le 0, \\ g_2(\mathbf{x}) = 640 - P_{\text{out}} \le 0, \\ g_3(\mathbf{x}) = sf - 0.8 \le 0, \\ g_4(\mathbf{x}) = J_c - 6 \le 0. \end{cases} \end{aligned} \tag{3}$$

where **x** is a vector of design parameters which include eight structure parameters and one manufacturing parameter; while material parameters are fixed (shown in Table I) in this work. Cost in the objective includes material costs of PM, SMC core, wire winding, steel and manufacturing cost; C_0 and P_0 are the cost and output power of the initial design scheme [5]; η and P_{out} (unit: W) expressed as g_1 and g_2 are the motor's efficiency and output power respectively; sf and J_c (unit: A/mm^2) as g_3 and g_4 are the fill factor and current density of the winding respectively.

Then with the robust optimization framework of (3), we can get the robust optimization model of (4).

$$\begin{aligned} \min:\ & \mu_f(\mathbf{x})+\sigma_f(\mathbf{x}) \\ \text{s.t.:}\ & \mu_{g_i}(\mathbf{x})+6\sigma_{g_i}(\mathbf{x})\le 0,\ i=1,\dots,4 \\ & \mathbf{x}_l+6\sigma_{\mathbf{x}} \le \mu_{\mathbf{x}} \le \mathbf{x}_u-6\sigma_{\mathbf{x}} \\ & \mu_f-6\sigma_f \ge \text{LSL} \\ & \mu_f+6\sigma_f \le \text{USL} \end{aligned} \tag{4}$$

TABLE II
OPTIMIZATION RESULTS FOR TFM

Par.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9
Unit	deg	mm	mm	mm	mm	turn	mm	mm	ton
Step size	0.05	0.05	0.05	0.05	0.05	1	0.01	0.01	100
Det.	11.20	7.20	8.00	7.00	9.25	114	1.30	0.90	200
Rob.	10.85	7.60	8.20	7.30	10.0	118	1.29	0.92	100

TABLE III
PERFORMANCE PARAMETERS FOR TFM

Par.	*cost*	η	P_{out}	*sf*	J_{c}	ρ
Unit	$	---	W	---	A/mm^2	g/cm^3
Det.	27.4	0.82	731.0	0.59	5.99	7.26
Rob.	28.4	0.83	701.6	0.58	5.73	6.60

TABLE IV
SIGMA LEVELS FOR CONSTRAINTS AND POF FOR TFM

Par.	g_1	g_2	g_3	g_4	*POF*
Det.	6	6	6	0.6275	0.5303
Rob.	6	6	6	6	≈ 0

Monte Carlo analysis is used to estimate the mean and standard deviation terms in (4), and the sample size is 10^4. It should be noted that the optimization parameters in (3) and (4) are discrete values, and their step sizes are shown in Table II.

IV. DISCUSSION AND RESULTS

In the implementation, each parameter is defined to follow a normal distribution with standard deviation as 1/3 of its manufacturing tolerance. The tolerance values of the sixth and ninth motor parameters are defined as 1% of their mean values. Other parameters' tolerance values are the same as their step sizes. Tco illustrate the performance of different methods, probability of failure (POF) is taken as a criterion, which is defined as

$$\text{POF} = 1 - \prod_{i=1}^{4} P(g_i \le 0)\,. \tag{5}$$

Tables II and III show the optimization results and the corresponding performance and quality parameters obtained from two methods for this TFM, namely deterministic (Det. row) design optimization and robust (Rob. row) design optimization. Table IV shows the robust levels for all constraints, and the POF values for the motor. From these results, we can draw the following conclusions.

1) For the deterministic design optimization, in the obtained performance parameters of the TFM, the cost is $27.4 and output power is 731 W. For the robust design optimization, the cost is $28.4 and output power is 701.6 W. The robust design scheme has higher cost and lower output power. However, these values are still better than those of the initial design scheme, which are $34.1 and 640 W respectively.

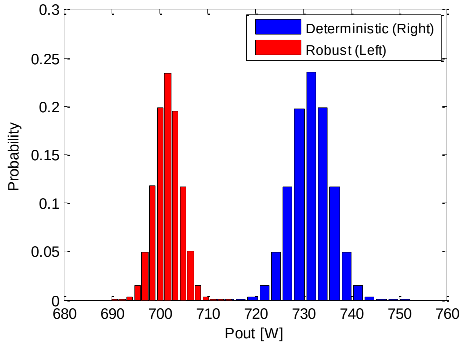

Fig. 7. Output power distributions of deterministic and robust solutions

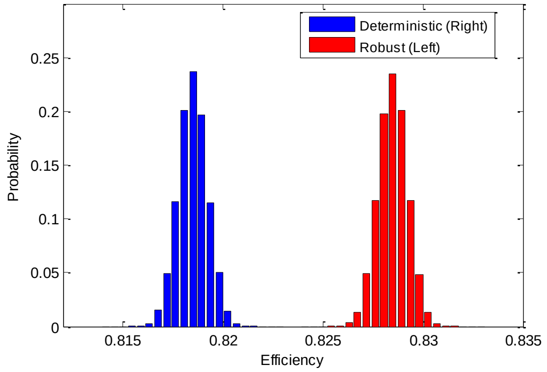

Fig. 8. Efficiency distributions of deterministic and robust solutions

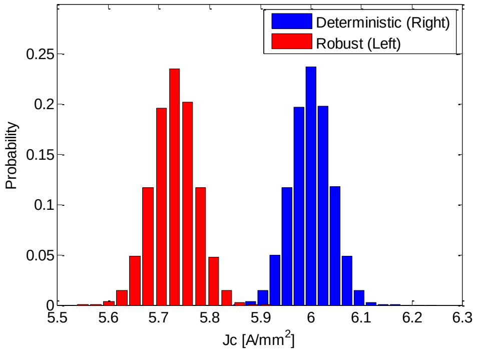

Fig. 9. Current density distributions of deterministic and robust solutions

2) Considering the manufacturing cost, 200-ton stamping press is suggested by the deterministic method. The corresponding manufacturing cost is $0.5 for each SMC core, and its mass density is 7.26 g/cm^3. 100-ton stamping press is suggested by the robust method, manufacturing cost is $0.2 for each SMC core, and mass density is 6.60 g/cm^3. Therefore, lower manufacturing condition and cost are requested for the robust method.

3) After Monte Carlo analysis, we can get the sigma levels for all constraints and POF values for both methods. For the deterministic scheme, the reliability of constraint g_4 is 0.4697, and the corresponding sigma level is only 0.6275. Actually, the current density is 5.99 A/mm^2, which is almost the same as the limit of this constraint (6 A/mm^2). As a result, the POF of motor is only 53.03%, namely about 53 defects per hundred. For the robust scheme, the sigma levels for all constraints are larger than 6 and the POF is almost 0. This means there are less than 0.002 defects per million for the "short term sigma quality", and less than 3.4 defects per million for the "long term sigma quality". Therefore, this scheme is much better than the deterministic design scheme. In conclusion, robust method can produce high reliability products and this is very important for industrial manufacturing and applications.

4) Figs 6 to 9 show the distributions of cost, output power, efficiency and current density respectively for both methods. From Figs. 6 and 7, we can see that the standard deviations of cost and output power of robust design scheme are smaller than those of deterministic scheme. From Fig. 8, it can be seen that the robust design scheme can produce larger mean and smaller standard deviation for the efficiency of this TFM than those of deterministic scheme. From Fig. 9, it can be found that all J_c distribution points of robust design scheme are satisfied with the condition of "no larger than 6.0 A/mm^2"; while the points of deterministic design scheme are not obviously satisfied with the condition. Therefore, the reliability and sigma level of this constraint of deterministic method are very low, and the POF of motor is high, which means the quality is low. Actually, the lower cost of deterministic optimization scheme is obtained at the cost of low quality, namely low reliability and robustness.

V. CONCLUSION

Robust design optimization is presented as a quality control method for PM-SMC motors to achieve a given (namely six sigma level) manufacturing quality in this work. From the investigation of a PM TFM, it can be found that the proposed method can significantly improve the reliability and manufacturing quality of the motor with less manufacturing condition and cost. Though the cost of robust design scheme is higher, the motor's efficiency, the standard deviations of output power and current density are smaller than those of deterministic scheme. Therefore, robust design optimization can provide high manufacturing quality PM-SMC motors.

REFERENCES

[1] Höganös AB, SOMALOY Technology for Electric Motors [Online]. Available: www.hogonas.com.

[2] G. Gvetkovski and L. Petkovska, "Performance improvement of PM synchronous motor by using soft magnetic composite material," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 3812-3815, 2008.

[3] D. H. Kim, J. K. Sykulski, and D. A. Lowther, "The implications of the use of composite materials in electromagnetic device topology and shape optimization," *IEEE Trans. Magn.*, vol. 45, no. 3, pp. 1154-1157, 2008.

[4] J. G. Zhu, Y. G. Guo, Z. W. Lin, *et al*, "Development of PM transverse flux motors with soft magnetic composite cores," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 4376-4383, 2011.

[5] Y. G. Guo, J. G. Zhu, P. A. Watterson, and Wei Wu, "Development of a PM transverse flux motor with soft magnetic composite core," *IEEE Trans. Energy Conver.*, vol. 21, no. 2, pp. 426-434, 2006.

[6] Y. G. Guo, J. G. Zhu and D. Dorrell, “Design and analysis of a claw pole PM motor with molded SMC core,” *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4582-4585, 2009.

[7] Y. K. Huang, J. G. Zhu, Y. G. Guo, *et al*, “Design and analysis of a high speed claw pole motor with soft magnetic composite core,” *IEEE Trans. Magn.*, vol. 43, no. 6, pp. 2492-2494, 2007.

[8] P. N. Koch, R. J. Yang, and L. Gu. “Design for six sigma through robust optimization,” *Struct. Multidiscip. Optim.*, vol. 26, no. 3-4, pp. 235-248, 2004.

[9] X. J. Meng, S. H. Wang, J. Qiu, Q. H. Zhang, J. G. Zhu, Y. G. Guo, and D. K. Liu, “Robust multilevel optimization of PMSM using design for six sigma,” *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 3248-3251, 2011.