

3-D Multi-Material Topology Optimization of a Surface Permanent Magnet Motor with High Torque Density for Urban Air Mobility

Haruki Kinoshita¹, Yoshitsugu Otomo¹, and Takashi Abe¹

¹Graduate School of Integrated Science and Technology, Nagasaki University, Nagasaki 852-8521, Japan
yotomo@nagasaki-u.ac.jp

In this paper, we present a 3-D multi-material topology optimization (MMTO) method to improve the torque density of a surface permanent magnet (SPM) motor. In the proposed MMTO method, a 3-D optimization model is divided into several layers along the axis of rotation. Subsequently, the material distributions and magnetization directions of permanent magnets for each layer are simultaneously optimized. The 3-D optimized SPM motor demonstrates better torque density when compared with the reference and 2-D optimized counterparts since we directly consider the 3-D magnetic properties including the end effect.

Index Terms—Aircraft propulsion, design optimization, magnetization, permanent magnet motors.

I. INTRODUCTION

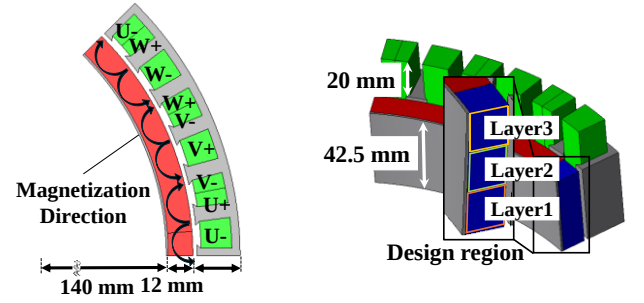
SURFACE permanent magnet (SPM) motors with high torque density are crucial for urban air mobility because they improve the maximum take-off weight and cruising distance by reducing weight and electric energy consumption [1]. To enhance the torque density of SPM motors, the average torque must be improved, while reducing the usage of permanent magnets (PMs) and magnetic core to ensure a lightweight design. The parameter optimization method has been recently developed for designing these motors, wherein a set of parameters are employed to determine the motor shape [2]. Although this approach can improve motor performance, obtaining new rotor and stator shapes using this method can be challenging.

The multi-material topology optimization (MMTO) method was recently proposed for designing SPM motors without relying on predefined shape parameters [3]. This method enables independent determination of various material distributions (magnetic core, air, and PMs) within a design region and also allows the independent determination of different magnetizations of PMs. This aids in realizing a novel rotor structure, which presents superior torque density for parameter-optimized rotors. However, the conventional MMTO method is limited by its optimization of only the 2-D cross-sectional shape, neglecting the end effects, such as leakage flux. Consequently, it does not fully account for the 3-D magnetic properties and motor structure, which are crucial to realize high-performance SPM motors for urban air mobility.

In this study, we propose a 3-D MMTO method for optimizing the 3-D structure of SPM motors. In the proposed MMTO method, the 3-D motor model is divided into cylindrical layers along the axis of rotation. Subsequently, the material distributions and magnetization directions of each layer are determined independently to improve the 3-D magnetic properties of the SPM motor. The superiority of the proposed method is demonstrated by comparing the torque density of the 3-D optimized SPM motor with those of the conventional and 2-D optimized SPM motors.

II. 3-D OPTIMIZATION METHOD

Fig. 1 depicts the 2-D reference and 3-D optimization models of the SPM motor, and Table I lists their specifications.



(a) 2-D reference model [3]. (b) 3-D optimization model.
Fig. 1. 2-D reference and 3-D optimization models of the SPM motor.
(2-D: 1/8 model, 3-D: 1/16 model)

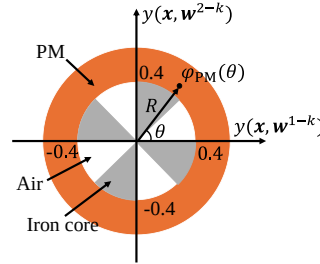


Fig. 2. State space for the MMTO.

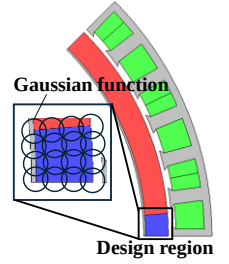


Fig. 3. Gaussian distributions for the design region.

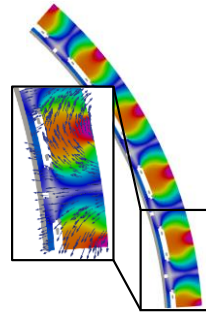


Fig. 4. 2-D optimized rotor shape.

TABLE I SPECIFICATIONS OF THE SPM MOTOR.	
Number of poles	40
Number of slots	48
Magnetization	1.4 T
Number of coil turns	5
Coil current	250 A _{rms}
Motor thickness	85 mm
Magnetic core grade	YEP-2V 0.1mm

The black arrows in the red region in Fig. 1(a) represent the magnetization direction of the PM. In the proposed MMTO method, the 3-D optimization model is divided into three layers along the axis of rotation, as shown in Fig. 1(b); however, the number of layers remains arbitrary [4]. The material attribute, M_e , of the finite element, e , in the design region for the k -th

layer is determined from angle θ , with $\theta = \tan^{-1}\{y(\mathbf{x}, \mathbf{w}^{2-k})/y(\mathbf{x}, \mathbf{w}^{1-k})\}$, and radius R , which are defined in the state space presented in Fig. 2 as follows:

$$M_e = \begin{cases} \text{Air}, & 90n \leq \theta < 90n + 45, R < 0.4, \\ \text{Iron}, & 90n + 45 \leq \theta < 90(n + 1), R < 0.4, \\ \text{Magnet}, & R \geq 0.4, \end{cases} \quad (1)$$

where n denotes the integer and $y(\mathbf{x}, \mathbf{w}^{j-k})$ represents the shape function defined by

$$y(\mathbf{x}, \mathbf{w}^{j-k}) = \sum_{i=1}^N w_i^{j-k} b_i(\mathbf{x}), \quad (j = 1, 2), \quad (2)$$

where $\mathbf{x}, w_i^{j-k} \in [-1, 1]$, $b_i(\mathbf{x})$, and N denote the position vector, j -th weighting coefficient for k -th layer, normalized Gaussian function, and number of Gaussian bases, respectively. In this study, we uniformly deployed 16 Gaussian basis functions in the blue design region for each layer, assuming the mirror symmetry of the rotor, as shown in Fig. 3. When a magnet is assigned as an element material from (1), the magnetization direction, $\varphi_{PM}(\theta)$, is simultaneously determined based on the following equation [3]:

$$\varphi_{PM}(\theta) = \left| \tan^{-1} \left(\frac{y(\mathbf{x}, \mathbf{w}^{2-k})}{y(\mathbf{x}, \mathbf{w}^{1-k})} \right) \right|. \quad (3)$$

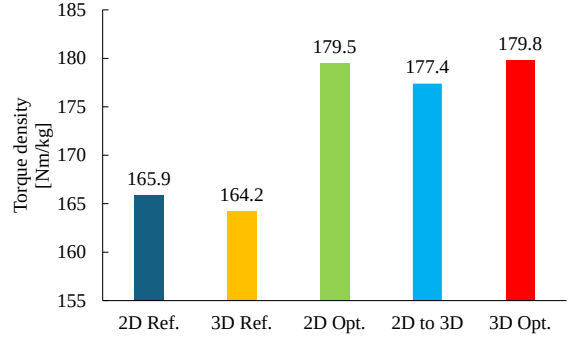
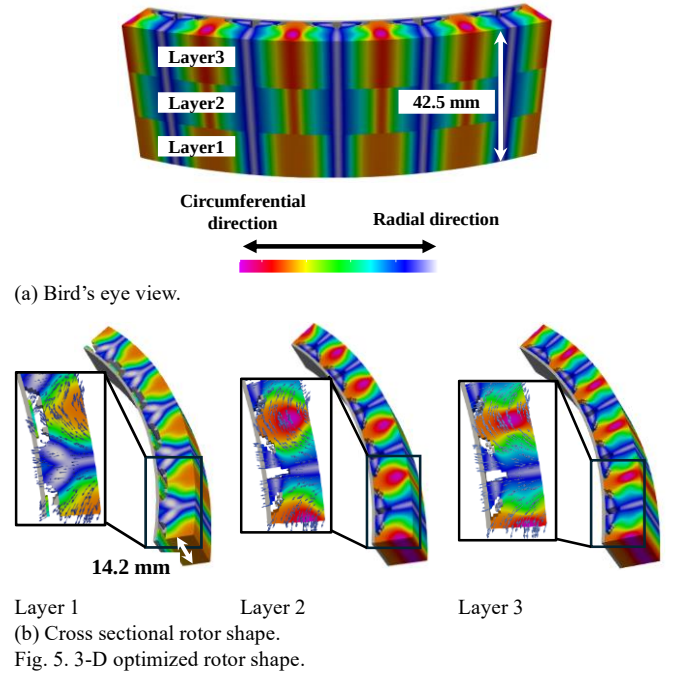
In the proposed 3-D optimization method, the weighting coefficients, $\mathbf{w}^{1-k}$ and $\mathbf{w}^{2-k}$ ($k = 1, 2, \dots$), are determined based on the covariance matrix adaptation evolution strategy (CMA-ES) to improve the objective function.

III. 3-D OPTIMIZATION RESULT

We solved the following optimization problem to maximize the torque density, T_{den} , of the SPM motor under the average torque constraint:

$$\begin{aligned} \min_{\mathbf{p}} F(\mathbf{p}), \quad F(\mathbf{p}) &= -T_{den}(\mathbf{p}), \\ \text{sub. to } T_{avg}(\mathbf{p}) &\geq T_{avg}^{Ref}, \end{aligned} \quad (4)$$

where $\mathbf{p}$, $T_{avg}(\mathbf{p})$, and T_{avg}^{Ref} denote the design variable and average torque of the optimized and reference SPM motors, respectively. We demonstrated the superiority of the proposed 3-D MMTO by further solving (4) using the 2-D MMTO [3]. Figs. 4 and 5 depict the 2-D and 3-D optimized rotors of the SPM motor obtained using the MMTO methods, respectively. The colored contours and blue arrows in the magnetic region represent the magnetization directions of the PMs. The 3-D optimized rotor depicted in Fig. 5 exhibits different material distributions and magnetization directions along the axis of rotation. Specifically, the magnetization directions of layers 2 and 3 can be approximated to the Halbach-array PMs, which concentrate the magnetic flux at the stator core. These PMs effectively increase the torque density of the SPM motor. Fig. 6 depicts the torque densities of the reference and optimized SPM motors, where “3D Ref.” and “2D to 3D” represent the 3-D magnetic



properties of the reference and 2-D optimized SPM motors. It can be observed that the 3-D optimized SPM motor has 15.6 and 2.4 Nm/kg higher torque density when compared with the reference and 2-D optimized counterparts, respectively, when the magnetic properties were evaluated using the 3-D model. This superior performance of the 3-D optimized SPM motor is attributed to the fact that the proposed MMTO method directly considers the 3-D magnetic properties including the end effect. In future works, we aim to simultaneously optimize the thickness of each layer of the design region to further improve the torque density of the SPM motor.

REFERENCES

- [1] N. Polaczyk, *et al.*, “A review of current technology and research in urban on-demand air mobility applications”, in *Proc. 8th Biennial Auton. VTOL Tech. Meeting 6th Annu. Electr. VTOL Symp.*, pp. 333–343, 2019.
- [2] Y. Ni, Z. Liu, B. Xiao, and Q. Wang, “Optimum Split Ratio in Surface-Mounted Permanent Magnet Machines With Pieced Halbach Magnet Array”, *IEEE Trans. Energy Convers.*, vol. 35, no. 4, pp. 1877–1885, 2020.
- [3] S. Hayashi, *et al.*, “Topology Optimization of a Surface Permanent Magnet Motor With High Torque Density”, *IEEE Trans. Magn.*, vol. 60, no. 3, Art. no. 8201005, 2024.
- [4] Y. Otomo, *et al.*, “2.5-D Multi-Phase Topology Optimization of Permanent Magnet Motor Using Gaussian Basis Function”, *IEEE Trans. Magn.*, vol. 58, no. 9, Art. no. 8205404, 2022.