

Multi-material Topology Optimization Method for PMSM based on NGnet Mesh Sequence Cleaning Algorithm

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To address the spatial structural un-continuity of topology optimization, this paper proposes a multi-material topology optimization approach for permanent magnet synchronous motor (PMSM) under consideration of manufacturing constraints. This method integrates normalized Gaussian network (NGnet) with differential evolution, embedding the K-means clustering algorithm to achieve effective multi-material topology optimization. The proposed mesh sequence cleaning algorithm is utilized to optimize structure topology by systematically eliminating micro-regions within the design domain. The obtained rotor structure with varying cleaning level parameters is subjected to analysis. Numerical examples illustrate that the proposed method not only ensures manufacturability of optimized design but also enhances average torque of PMSM rotor while reducing the volume of permanent magnet.

Index Terms—Topology optimization, permanent magnet synchronous motor, manufacturing, mesh sequence cleaning algorithm.

I. INTRODUCTION

The continuous emergence of new technologies and materials has rendered traditional dimensional optimization [1] and shape optimization [2] design methods insufficient for addressing the evolving demands of practical engineering applications in the realm of electric motors. The multi-material topology optimization method facilitates the realization of innovative motor structures in alignment with specified objective functions and constraints, thereby providing designers with increased degrees of freedom. The present study focuses on the multi-material topology optimization of motors, specifically addressing the utilization of permanent magnets (PMs), magnetic flux barriers, and iron cores, which is to optimize the utilization of PM materials, leading to improved structural design and operational performance [3]. The application of topology optimization method is not without its challenges. For example, there are numerous design variables, and a lack of manufacturability of optimized structures [4] [5].

To address the above issues, this paper proposes a multi-material topology optimization for PMSM based on the mesh sequence cleaning algorithm NGnet. In accordance with the NGnet theory, a mesh sequence cleaning algorithm is proposed to optimize topological structure. To achieve an even distribution of NGnet within the designated design region, the K-means clustering algorithm is employed in conjunction with topology optimization. To ensure that the responses of adjacent Gaussian functions overlap appropriately, the nearest neighbor radius is applied to determine the Gaussian radius.

II. THE PROPOSED TOPOLOGY OPTIMIZATION METHOD

A. Mesh Sequence Cleaning Algorithm

The mesh sequence cleaning algorithm modifies material clusters by transferring mesh elements with fewer continuous members than a specified cleaning level parameter M to adjacent materials. Fig. 1 illustrates the cleaning process and the resulting material distribution after applying this algorithm

to a 1/8 motor model. As depicted in Fig. 1(a) where $M=1$, it represents no cleaning. When $M=2$, any material cluster containing fewer than two continuous elements adopts the properties of its surrounding material. Air1 performs the cleaning to be removed and changed to iron, a similar approach is applied in the subsequent cleaning stages (b) to (d). The analysis reveals that, for a given number of cells, increasing M leads to a more pronounced cleaning effect. Consequently, the integration of the mesh sequence cleaning algorithm with topology optimization enables the elimination of micro-regions within the design area, thereby optimizing the topological structure and enhancing spatial continuity.

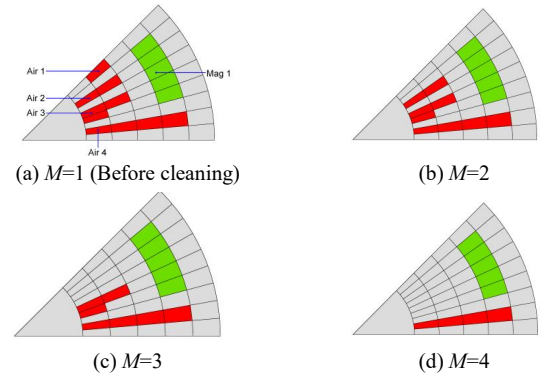


Fig. 1. Cleaning process.

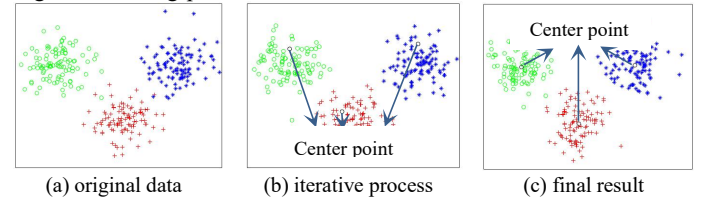


Fig. 2. Iterative process of the K-means clustering algorithm.

B. K-means Clustering Algorithm

To ensure design consistency, NGnet must uniformly occupy the entire design space, reflecting the influence of each mesh on the objective function. In this paper, the K-means clustering algorithm is integrated into the topology optimization to determine the center position of NGnet within the design domain. The process is shown in Fig. 2.

C. Topology Optimization Method

The NGnet is to introduce a continuous function in space and approximate it using a normalized Gaussian kernel function $f(\mathbf{x})$ defined in (1). This approach maps the topology of the elements and the material properties in the vicinity of each node into a continuous, high-dimensional function space.

$$f(\mathbf{x}) = \sum_{i=1}^N w_i \left[G_i(\mathbf{x}) / \sum_{i=1}^N G_i(\mathbf{x}) \right] \quad (1a)$$

$$G_i(\mathbf{x}) = 1/(2\pi\sigma) \cdot \exp[-(\|\mathbf{x} - \mathbf{x}_i\|^2)/(2\sigma^2)] \quad (1b)$$

where $\mathbf{x}$ is position coordinate in design area, N is number of Gaussian functions $G_i(\mathbf{x})$, $f(\mathbf{x})$ is normalized by coefficient w_i . The flowchart is shown in Fig. 3.

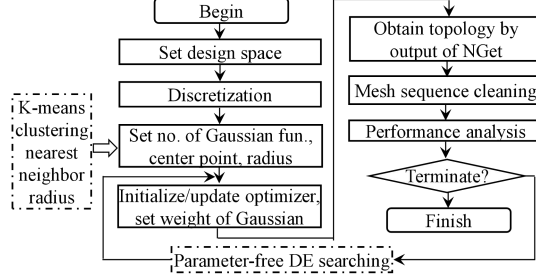


Fig. 3. Flowchart of NGnet topology optimization algorithm.

III. NUMERICAL RESULTS

The PMSM as shown in Fig. 4 is applied to demonstrate the proposed methodology. The design area focuses on rotor domain from 0° to 45° . The weight w_i is the design variable, where $w = \{w_i | i=1, 2, \dots, N\}$, the value range of w is $-1 \sim 1$.

The object is to enhance output torque T_{ave} while reducing volume V_{pm} of the PM. The mathematical model is as follows:

$$\text{Min } F = -K * (T_{ave}/T_{ave0}) + (1-K) * (V_{pm}/V_{pm0}) \quad (2)$$

where K is set to 0.2. The optimized material consists of four distinct types: PMs with two different magnetization directions: $(0, 1)$ and $(1/\sqrt{2}, 1/\sqrt{2})$, corresponding to the magnetization vectors of PM materials 1 and 2, respectively; silicon steel sheet and air. The material distribution I_e for element e within the design region is determined by outputs $f_1(\mathbf{x}_e)$ and $f_2(\mathbf{x}_e)$ of two Gaussian networks. The center of gravity of element e is denoted by $\mathbf{x}_e$, the material distribution is illustrated as follows:

$$I_e \begin{cases} \text{permanent magnet material 1} & f_1(\mathbf{x}_e) \geq 0 \quad f_2(\mathbf{x}_e) \geq 0 \\ \text{permanent magnet material 2} & f_1(\mathbf{x}_e) < 0 \quad f_2(\mathbf{x}_e) \geq 0 \\ \text{silicon} & f_1(\mathbf{x}_e) \geq 0 \quad f_2(\mathbf{x}_e) < 0 \\ \text{air} & f_1(\mathbf{x}_e) < 0 \quad f_2(\mathbf{x}_e) < 0 \end{cases} \quad (3)$$

Fig. 4(a)~(d) illustrate the impact of M on rotor topology and performance of PMSM, where red is permanent magnet material 1 and brown is permanent magnet material 2. The number of design domain partitioned mesh densities are 90, inserting 10 Laplace functions. When $M=2$ and $M=3$, the rotor has obvious shape characteristics of interior PMSM. When $M=4$, the material distribution becomes significantly constrained resulting in a shape resembling that of a surface-mounted PMSM, proportion of PM materials is reduced by 2.20%, leading to enhanced optimization and a greater concentration of topological materials, which is conducive to

later production and manufacturing. The average torque is shown in Fig. 5. Comparing the average torque at $M=2$ and $M=3$ shows that the highest average torque occurs at $M=4$, with increases of 2.50% and 1.10%, respectively. For clarity, Table I provides a comparison of the optimal results.

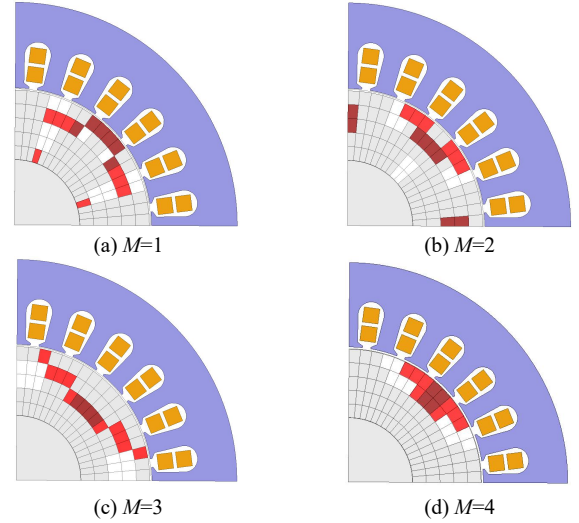


Fig. 4. Influence of cleaning level parameters on rotor design domain of 90 mesh densities.

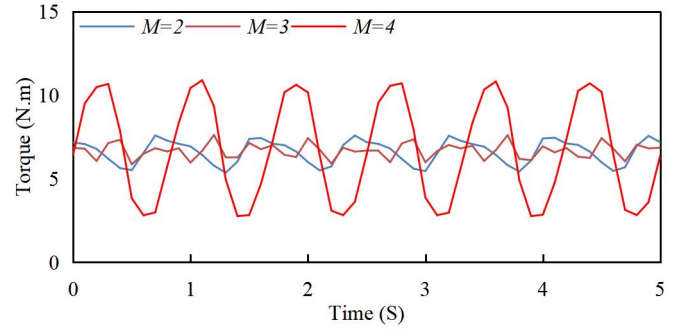


Fig. 5. Average torque comparison with 90 mesh densities.

TABLE I COMPARISON OF OPTIMAL RESULTS

Parameter	$M=2$	$M=3$	$M=4$
Average torque (N.m)	6.59	6.68	6.75
Proportion of permanent magnet volume (%)	15.50	15.50	13.30

IV. REFERENCES

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