

Vibration Reduction for Switched Reluctance Motor with Amorphous Alloy Core Based on Multi-material Topology Optimization

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To reduce the vibration of switched reluctance motor with amorphous alloy core (SRMA), a multi-material topology optimization method based on adding negative magnetostrictive material is proposed in this paper. Firstly, the properties of negative magnetostrictive material are used to the stator core of SRMA to offset the vibration caused by magnetostrictive force and radial electromagnetic force. The Young's modulus and relative permeability of the core materials in the optimized area are expressed as continuous functions of double design variables. Then, the hybrid-design variables interpolation function is coupled to the vibration reduction topology optimization to determine the distribution and boundary structure of multiple materials. Considering the computational complexity of multi-dimensional constraints in the optimization framework, the augmented Lagrangian method is used to accelerate the calculation speed. The vibration displacement amplitude of stator core after optimization is reduced by 36%. The calculation time of multi-material topology optimization is reduced by 30%.

Index Terms—Vibration reduction, Switched reluctance motor, Topology optimization, Magnetostrictive effect.

I. INTRODUCTION

Amorphous alloy used to manufacture switched reluctance motor core can significantly reduce core losses as for its high relative permeability and weak eddy effect. However, its high stress sensitivity and giant magnetostrictive coefficient will intensify magnetostrictive effect and interfere with magnetization state, leading to the core vibration [1].

At present, topology optimization, parameter optimization and shape optimization are usually used to suppress the vibration of SRMA [2]. Topology optimization can find the optimal layout of the structure by distributing materials in the design, which has obvious advantages compared with other optimizations. The level set equation is utilized to define the boundaries of materials for motor topology optimization, but the update of the level set equation may slow down the convergence speed and even cause the result to diverge. The ON/OFF method is used for motor topology optimization, but it is difficult to directly obtain the distribution of multiple materials, and the optimized structure boundary is not smooth.

To design the multiple materials structure and improve the computation efficiency, a hybrid-design variables interpolation function is proposed, which can determine the distribution of multiple materials in the optimization area. The augmented Lagrangian method is used to transform the high-dimensional constraints in the optimization framework into unconstrained problems, which shortens the calculation time.

II. MULTI-MATERIAL TOPOLOGY OPTIMIZATION FOR STATOR CORE VIBRATION REDUCTION

As the vibration which is caused by magnetostrictive force and radial electromagnetic force is more severe in stator core of SRMA, the stator is set as the optimized area, as shown in Fig. 1. The samarium-iron alloy with negative magnetostrictive properties, which can offset the vibration caused by

magnetostrictive force and radial electromagnetic force, is added to the optimized area.

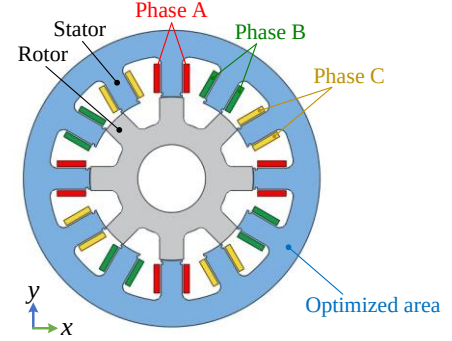


Fig. 1. Overall structure of the 12/8 pole SRMA.

A. The hybrid-design variables interpolation function

To determine the position and shape of different materials in the optimized area, the hybrid-design variables interpolation function is proposed. Two design variables ρ_1 and ρ_2 are introduced in the interpolation function and their values can change continuously from 0 to 1.

Then, the penalty factor p is set to punish intermediate value of the hybrid-design variables for obtaining the clear material boundary. The Young's modulus and relative permeability of the core materials in the optimized area are expressed as

$$\begin{cases} \mu_{r-op}(\rho_1, \rho_2) = \rho_1^p \left[\rho_2^p \mu_{Am} + (1 - \rho_2^p) \mu_{Sm} - 1 \right] + 1 \\ E_{r-op}(\rho_1, \rho_2) = \rho_1^p \left[\rho_2^p E_{Am} + (1 - \rho_2^p) E_{Sm} - E_A \right] + E_A \end{cases} \quad (1)$$

where μ_{Sm} and μ_{Am} are the relative permeability of samarium-iron and amorphous alloy, respectively. E_A is the Young's modulus of air. E_{Sm} and E_{Am} are the Young's modulus of two materials, respectively. The range of ρ_1 and ρ_2 are $0 \leq \rho_1, \rho_2 \leq 1$.

The combination rules for determining the distribution density of different materials in the optimized area are defined by the output results of ρ_1 and ρ_2 , as shown in Fig. 2.

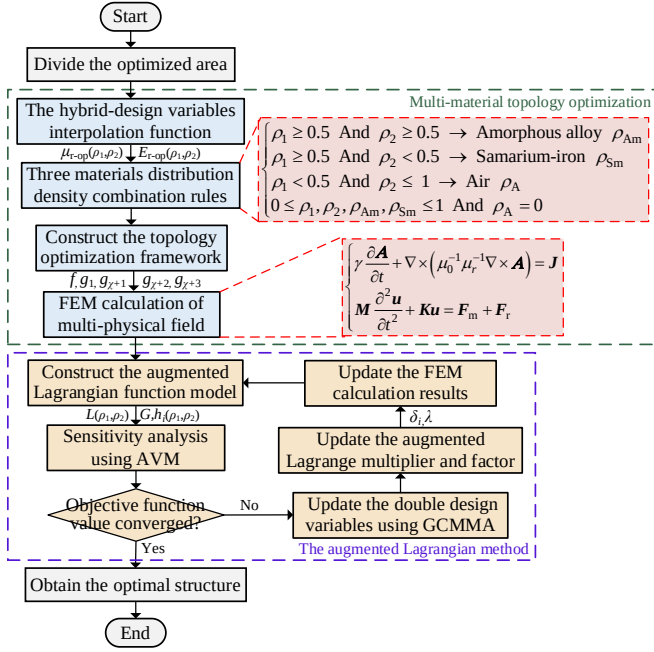


Fig. 2. Overall flow chart of the proposed method.

B. The topology optimization framework

Based on the electromagnetic-mechanical coupling numerical model of SRMA considering magnetostrictive effect, as shown in Fig. 2, a multi-material topology optimization framework is constructed. The objective function and constraint conditions can be expressed as

$$\begin{cases} \text{minimize} & f = \int_{\Omega} \frac{\mathbf{u}^{(n)}}{\mathbf{u}^{(0)}} d\Omega \\ \text{s.t.} & g_1 = W_s^{(n)} \leq W_s^{(0)} \\ & g_{\chi+1} = \sigma^{(n)} \leq \sigma^{(0)} \\ & g_{\chi+2} = T_{av}^{(0)} \leq T_{av}^{(n)} \\ & g_{\chi+3} = T_{rip}^{(n)} \leq T_{rip}^{(0)} \end{cases} \quad (2)$$

where f is objective function, so that the vibration displacement of stator core is minimized at each iteration. $\mathbf{u}$ is the vibration displacement. n is the number of iterations. For the constraints $g_1, g_{\chi+1}, g_{\chi+2}, g_{\chi+3}$, χ is the number of finite element meshes. W_s is elastic strain energy. σ is the stress value. T_{av} is the average torque. T_{rip} is the torque ripple coefficient.

C. The augmented Lagrangian method

By introducing a normalization term, the high-dimensional constraint problem in the optimization framework is transformed into an unconstrained problem. The objective function in the optimization framework is rewritten as

$$L(\rho_1, \rho_2) = f(\rho_1, \rho_2) + \frac{1}{\chi_m} G(\rho_1, \rho_2) \quad (3)$$

where $\chi_m = \chi + 3$, the penalty term G can be expressed as

$$G = \sum_{i=1}^{\chi_m} \left[\delta_i h_i(\rho_1, \rho_2) + \frac{\lambda}{2} h_i^2(\rho_1, \rho_2) \right] \quad (4)$$

where h_i can be expressed as

$$h_i(\rho_1, \rho_2) = \max \left[g_{\chi+1}(\rho_1, \rho_2), -\frac{\delta_i}{\lambda} \right] \quad (5)$$

where λ and δ_i are the Lagrangian penalty factor and the Lagrange multiplier, respectively, which will be updated at each iteration. The overall flow chart of the proposed method for vibration reduction is shown in Fig. 2.

III. RESULTS AND DISCUSSION

Using the optimal stator structure obtained by the multi-material topology optimization, the vibration of SRMA is simulated. The combined distribution density of three materials in the quarter-optimized area after smoothing is shown in Fig. 3. The red and yellow areas represent amorphous and samarium-iron alloy, respectively. The blue area represents holes (air).

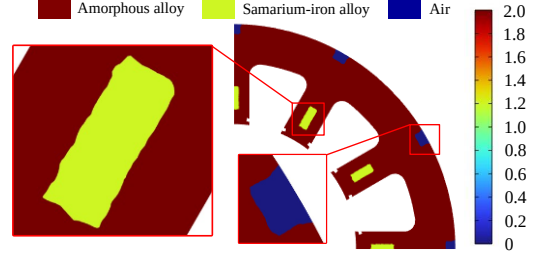


Fig. 3. The combined distribution density of three materials after smoothing.

The vibration displacement curve of the point with larger vibration displacement on the stator core and calculation speed curve are shown in Fig. 4. As shown, compared with the traditional structure, the vibration displacement amplitude is reduced by 36%. Compared with the traditional method without augmented Lagrange transform, the calculation time is shortened by 30%, and the optimization effect is unchanged.

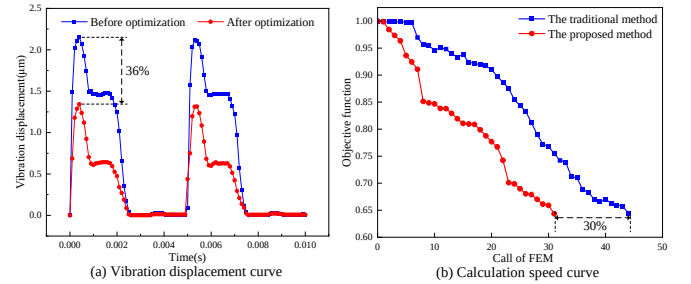


Fig. 4. Vibration displacement and calculation speed curves.

IV. CONCLUSION

In this paper, a multi-material topology optimization method for stator core vibration reduction is proposed. By this method, the clear distribution of three materials after optimization is obtained, the vibration displacement amplitude of stator core after optimization is reduced by 36%, and the calculation time is reduced by 30%. Subsequently, more discussions and experimental verifications will be presented in the entire paper.

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