Design Optimization of Magnetic Gears Using a PSO based Mesh Adjustable Finite Element Algorithm

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Abstract — Magnetic gears are a new class of magnetic devices which use the interaction of magnetic field produced by multipole magnetic sources to transmit torque with a high efficiency. Compared with conventional mechanical gears, due to no moving contact for the force transmission, no mechanical fatigue, mechanical loss and acoustic noise may be induced. Consequently, there is no need for lubrication and less need for maintenance. However, the excessive utilization of permanent magnet materials leads to the increasing of production cost. In this paper, a novel PSO based mesh adjustable finite element algorithm is proposed to optimize magnetic gear dimensions to reduce the PM utilization, as well as to improve the torque density of the machine. With the mesh adjustable finite element algorithm, the coordinates of mesh vertexes are moved according to dimension changes, while the mesh quality is still kept high. The advantage is that the mesh modification is minimal and the accuracy of optimized results is guaranteed. By combining the PSO algorithm, a reliable convergence to the global optimum is achieved. This method is newly applied to optimize the dimensions of two coaxial magnetic gear with surface mounted PMs and inset-type PMs. Optimal results confirm the validity and effectiveness of the proposed algorithm.

I. INTRODUCTION

Permanent magnet (PM) materials can be used to produce a constant magnetic field and exert magnetic force without any energy consumption. They are widely used in numerous industry applications. However, with the skyrocketed price of rare earth PM materials, how to efficiently use the PMs and reduce the cost of the PM associated products becomes a practical and urgent problem to be resolved.

Magnetic gears (MGs) are one class of magnetic devices to transmit torque between two rotating parts with different magnetic pole pairs through flux modulation poles [1, 2]. The reason why MGs gather more attention than ever before is that their contactless operation can effectively reduce mechanical loss and acoustic noise which is inevitable and harmful in mechanical gears. Unfortunately, excessively using PM materials in the MGs will to a large extent increase the cost of the products, especially within the time of price increasing of PMs under the worldwide shortage of rare earth PM supply. Hence, it is necessary and important for researches to find approaches to optimize the design of PM gears and improve the utilization rate of PM materials.

Finite element method (FEM) has been successfully used in the design of electric devices and serves as indispensable tools in the static and dynamic performance analysis of electromagnetic devices. Compared with analytical method, the advantages of FEM are its applicable to any complicated geometrical structures, its high accuracy and reliability. However, when dealing with optimization problems, the computation is time-consuming, because new many meshes need to be regenerated repeatedly according to the variations of geometrical parameters of designs.

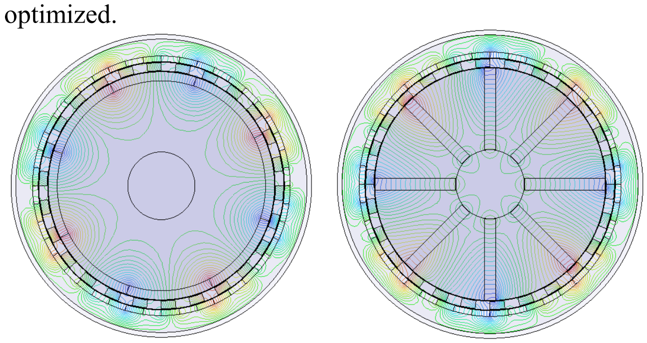
In this paper, a PSO based mesh adjusting optimization approach is applied in the MG design. The dimension displacements are determined by the PSO algorithm and the coordinates of the meshes are adjusted according to our proposed dimension modification method, which is based the solution of a Laplace's equation. Hence, the time-consuming geometry rebuilding and mesh regeneration process is avoided hence a global optimum is reached at a relatively fast speed of convergence.

The design optimizations of two kinds of MGs are presented, which realize the minimum utilizations of PMs to reach the required torque output. Optimal results confirm the proposed method. The optimized designs can effectively reduce the cost of the machines, as well as improve the torque density.

II. CONFIGURATION AND OPTIMIZATION PROBLEMS

A. Constructions

Fig. 1 shows the constructions of MGs used in this study and one is a MG with surface mounted PM (SPM) and the other is with inset-type PM (IPM). Both of the MGs have $p_h = 4$ pole pairs of NdFeB PMs in the high speed rotor and $p_l = 22$ pole pairs in the low speed rotor and the flux modulation pole number $p_{fer} = 26$. The gear ratio is $G_r = -p_l / p_h = -5.5$. For the purpose of comparison, the initial outside diameters of the outer low speed rotor and modulation ferrite poles are designed the same, namely $r_m = 130\text{mm}$. The static torque is calculated by FEM when the high rotor is rotated at 150 rpm while keeping the low rotor and the modulation poles static. The torque waveforms are shown in Fig. 2 and it is shown that the torque ratio is 5.5 at any position which is consistent with the principle of MG. After finding the maximum torque point, the MG is ready to be optimized.



(a) (b)

Fig. 1. Magnetic flux distribution in Magnetic gears. (a) SPM MG. (b) IPM MG.

B. Optimal Problem

The design constrains are that outer radius $r_m \leq 130\text{mm}$ and output peak torque $T \geq 200\text{Nm}$. The dimensions of SPM MG and IPM MG are optimized until reaching the maximum of torque per unit volume of PMs as shown in Equ. (1) and (2), respectively. Fig. 3 shows the design parameters of the two MGs.

$$\max f_{spm}(x) = T(r_m, h_{mo}, h_{mi}, h_{ro}, r_i) / V(h_{mo}, h_{mi}) \quad (1)$$

$$\max f_{ipm}(x) = T(r_m, h_{mo}, h_{mi}, h_{ro}, r_i, d_h, d_w) / V(h_{mo}, d_h, d_w) \quad (2)$$

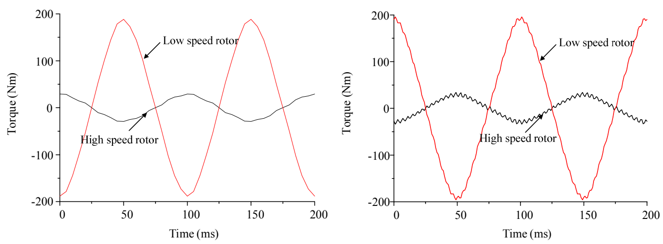


Fig. 2. Static torque waveforms. (a) SPM MG. (b) IPM MG.

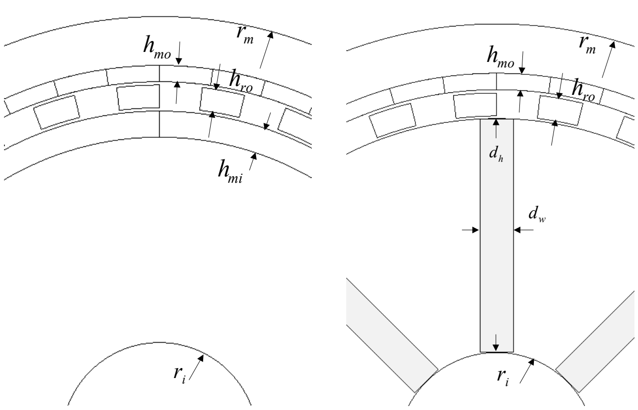


Fig. 3. Design parameters of MGs. (a) SPM. (b) IPM.

III. METHODS AND RESULTS

A. PSO Algorithm

The particle swarm optimization (PSO) method is a population based stochastic searching and optimization algorithm [3]. In PSO, a potential solution is named as a particle. The trajectory of each particle is gracefully adjusted towards its own best position and the global best position discovered by its neighbors, as well as the whole swarm. The algorithm is expressed as:

$$v_d^{k+1} = \omega_i v_i^k + c_1 r_1 \left(p_d^i - x_d^i(k)\right) + c_2 r_2 \left(g_d^i - x_d^i(k)\right) \quad (3)$$

$$x_d^i(k+1) = x_d^i(k) + v_d^i(k+1) \quad (4)$$

where, c_1 and c_2 represents the acceleration coefficients, r_1 and r_2 are two uniform random functions, v_d^{k+1} and x_d^k are the velocity and position, g_d^i represents the best particle position among the entire population and p_d^i is the previous best particle position.

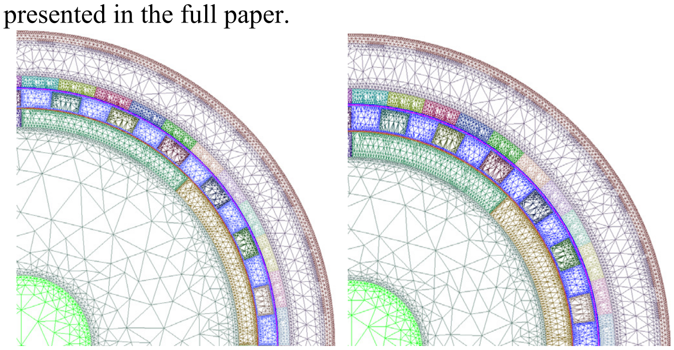
Since the PSO method has the capability in searching the global optimum with high probability and its convergence rate is fast, it is advantageous to be combined in FEM to determine the dimension changes of MGs.

B. Mesh Displacement with Dimension Modification

After an initial mesh is created and mesh refinement has been finished, the design optimization begins. The coordinates of the mesh will be adjusted according to the dimension displacement, which is determined by the PSO. A mesh adjusting method of FEM is adopted. Firstly, the boundaries of the shape to be optimized need to be parameterized. Assuming that the dimension displacement ΔR is known, the new boundary condition $R' = R + \Delta R$ is imposed. Secondly, inside the domain, a Laplace's equation is established, in which the vector displacement $\Delta \boldsymbol{r}$ in each point is variable [4]:

$$-\frac{\partial}{\partial x}\left(\frac{\partial \Delta \boldsymbol{r}}{\partial x}\right) - \frac{\partial}{\partial y}\left(\frac{\partial \Delta \boldsymbol{r}}{\partial y}\right) = 0 \quad (5)$$

After solving (5), the new mesh position $\boldsymbol{r}'$ at each optimization step is obtained by $\boldsymbol{r}' = \boldsymbol{r} + \Delta \boldsymbol{r}$. This mesh adjusting method is easy to implement in the design optimization of MGs. Fig. 4 shows the original mesh and the adjusted mesh results. Detailed optimization results will be presented in the full paper.



(a) (b)

Fig. 4. Mesh adjusting. (a) Original mesh. (b) Adjusted mesh.

IV. REFERENCES

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