Further advances in applying continuum design sensitivity analysis in combination with commercial electromagnetic software to aid design optimization

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***Abstract*—The paper reports on new developments in the application of Continuum Design Sensitivity Analysis to design optimization. Fast convergence, the ability to use existing electromagnetic software without the need to access source codes and independence of computing times on the number of design variables are the distinctive features of the proposed implementation. The computationally challenging problem of reducing cogging torque in a brushless direct current motor has been selected to illustrate the advantages of the approach in 2D and 3D optimizations.**

I. Introduction

Continuum Design Sensitivity Analysis (CDSA) has recently gained momentum as an alternative optimization technique. The physical meaning of pseudo sources of an adjoint system in a CDSA when applied to shape optimization was explored in [1] and the approach was reported to avoid the need to access source codes of commercial programs. Moreover, the computing times required to find an optimal solution are not affected by the number of design variables. The initial, very encouraging, results have prompted the researchers to pursue this technique further as it appears to be very competitive compared, for example, with stochastic methods [2].

Brushless Direct Current (BLDC) motors are rapidly gaining popularity. They are used in industries such as Appliances, Automotive, Aerospace, Consumer, Medical, Industrial Automation Equipment and Instrumentation. The exterior BLDC motor considered here has the same shape as a permanent magnet DC motor without brushes and a commutator and has the permanent magnets rotating outside.

In a permanent magnet motor the cogging torque (a term used to describe non-uniform angular velocity) appears as motion "jerkiness", especially at low speeds, and is undesirable because it introduces vibration and noise. It is thus of great practical importance to gain deeper understanding of the phenomenon and find ways to reduce it [3].

In this paper further advances are reported on the application of CDSA, in combination with commercial electromagnetic software [4], with the aim of aiding the efficient design optimization of electromagnetic devices. A BLDC motor was used as an example due to its increasing range of use and because reduction of cogging torque is a difficult problem for electromagnetic simulation and modelling. Both 2D and 3D models are considered.

II. Results

A BLDC motor with 8 permanent magnets and 12 salient stator poles is considered and optimization is carried out with the aim of minimizing the cogging torque. The outer radii of

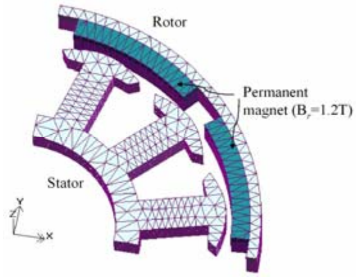
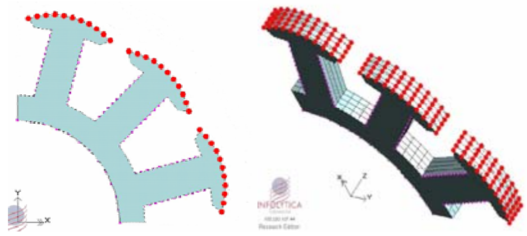


Fig. 1. 3D model used for optimization.



(a) 33 vertices in 2D (b) 165 vertices in 3D

Fig. 2. Design variables in 2D and 3D optimization.

stator teeth, magnet and rotor yoke are 13.8mm, 15.3mm and 16mm, respectively. The depth of the teeth is 2.5mm whereas that of the magnet and yoke is 3.8mm. Only one-eighth of the problem needs to be modelled owing to symmetry (Fig. 1).

To investigate the fringing effect on the cogging torque, an optimization of the pole face shape is performed using CDSA in conjunction with commercial software (MagNet 6). Design variables are defined at finite element vertices forming the outline of the stator pole, as in Fig. 2. In order to take into account manufacturing limitations, a geometrical constraint that the pole face shapes should be the same and symmetric is imposed on the design variables when moving points in radial direction. Since the reduction of cogging toque is accomplished by minimizing the variation of the co-energy stored in a magnetic system versus the rotor positions, the objective function can be defined as

$$F = \sum_{i}^{nr} (W_i - W_o)^2 \quad (1)$$

where nr is the number of rotor positions considered, W_i the stored co-energy computed at the i-th position and W_o the constant target value. Due to the 15^o periodicity of the cogging torque, the objective function is calculated every 1.5^o from 0^o to 15^o in both 2D and 3D nonlinear FE analyses.

A. 2D Optimization

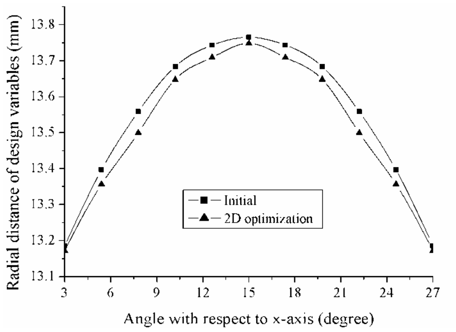


Fig. 3. Variation of design variables with respect to shaft center.

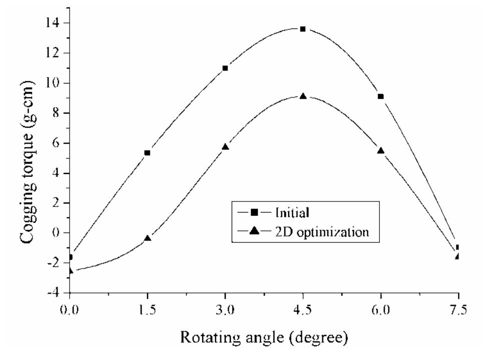


Fig. 4. Cogging torque waveform before and after 2D optimization.

After 10 iterations, an optimum pole shape was obtained as shown in Fig. 3. Even though the maximum variation of design variables with respect to the initial shape is less than 0.09 mm, the cogging torque of Fig. 4 has been reduced by nearly 30% of its initial value, based on this 2D FE analysis.

B. 3D Optimization

In order to accomplish a 3D shape optimization, the stator has been decomposed into four independent layers with a thickness of 0.3125 mm and the common surface of adjacent layers is allowed to be deformable in order to facilitate the conformity of the FE mesh with the continuing shape changes. After 11 iterations, the optimal pole face shape was achieved. Fig. 5 shows the difference between the pole face shapes optimized using 2D and 3D analyses on a cutting plane parallel to the z-axis and located at 10.2^o from the x-axis. After creating a 3D model by the extrusion technique according to the 2D optimized pole shape, a comparison of the cogging torque waveforms obtained from the 2D and 3D optimised pole shapes is shown in Fig. 6. It is revealed that the 3D optimised pole reduces the cogging torque by 25% of the initial value whereas the 2D analysis suggests only a 13% reduction due to the neglected fringing effect.

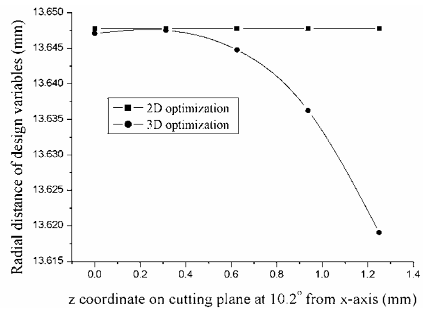


Fig. 5. Comparison of optimised shapes from 2D and 3D analyses.

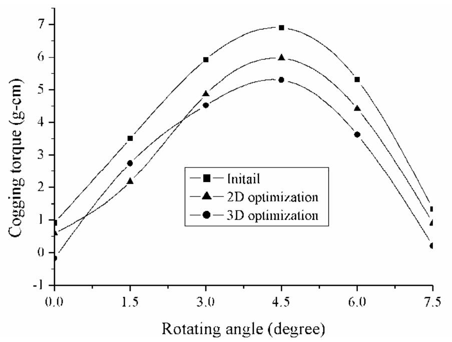


Fig. 6. Cogging torque waveforms for the initial, 2D and 3D optimal shapes.

III. CONCLUSIONS

Continuum Design Sensitivity Analysis is a very efficient optimization technique offering much reduced computational effort due to the fact that computing times do not depend on the number of design variables. Reduction of cogging torque in a brushless dc motor by shaping a pole face has been accomplished and importance of 3D modelling emphasised.

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