

Robust Design Optimization of SPMSM based on Manufacturing Uncertainty Analysis of Prototype

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This paper investigates robust design optimization (RDO) for surface-mounted permanent magnet synchronous motors (SPMSMs) to mitigate additional harmonic components (AHC) of cogging torque caused by manufacturing uncertainties. A prototype motor is analyzed using finite element analysis (FEA) and experimental validation, revealing discrepancies due to manufacturing uncertainties. Sensitivity analysis identifies significant variables influencing AHCs, which are then used to develop a kriging surrogate model. This surrogate model facilitates computationally efficient optimization to minimize AHCs while maintaining performance. The optimized design is validated experimentally, demonstrating reduced sensitivity to manufacturing uncertainties and improved motor performance.

Index Terms— Cogging torque, manufacturing uncertainty, robust design optimization.

I. INTRODUCTION

SERVO MOTORS are widely used in various applications due to their ability to deliver precise and fast motion control under diverse operating conditions with varying loads. To achieve high performance, especially under repeated acceleration and deceleration, servo motors must be compact, lightweight, and exhibit low friction. Surface-mounted permanent magnet synchronous motors (SPMSMs) are commonly employed as servo motors due to their high efficiency and torque density [1]. However, SPMSMs face challenges related to cogging torque, a form of torque pulsation caused by the interaction of permanent magnets with slotted stator structures. This cogging torque acts as a frictional torque, hindering accurate motion control and overall system performance. To address this issue, design improvements are often implemented to minimize cogging torque and enhance the motor's controllability. However, during the manufacturing process, uncertainties in the dimensions of the stator and rotor, such as alignment deviations, concentricity errors, and size variations, can introduce additional harmonic components (AHC) of cogging torque [2]. Studies have shown that manufacturing tolerances, such as rotor eccentricity and magnetization faults, significantly influence the harmonic components of cogging torque, leading to degraded performance [3]. Furthermore, worst-case analysis frameworks have been proposed to estimate the impact of manufacturing uncertainties on cogging torque, demonstrating the necessity of robust optimization to mitigate these effects [4].

This study focuses on analyzing the impact of manufacturing uncertainties in the stator and rotor on the AHC of cogging torque. Using a prototype motor, the cogging torque is analyzed through both finite element analysis (FEA) and tests. The test results reveal the presence of AHCs that are not accounted for in the FEA simulations, which assume ideal manufacturing conditions. By comparing these results, the study identifies uncertainties in the stator and rotor such as air gap uniformity, misalignment, and dimensional variations that significantly contribute to the generation of AHCs. Also, sensitivity analysis

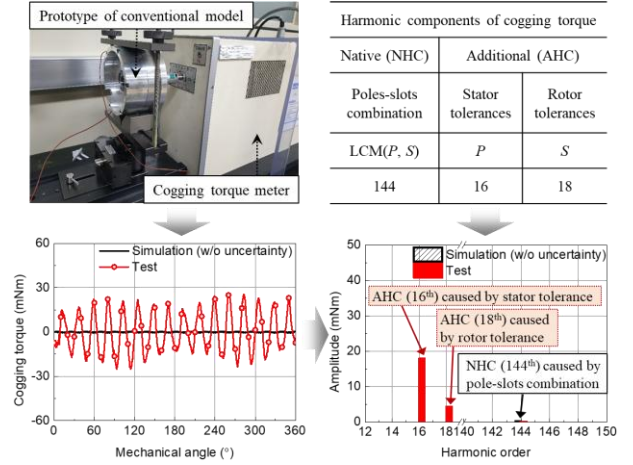


Fig. 1. Cogging torque of prototype

is conducted using the prototype motor to evaluate the degree to which individual manufacturing uncertainties contribute to AHC. Statistically significant uncertainties are identified and prioritized for optimization. These significant variables are then used to develop a robust design optimization (RDO) framework that minimizes AHC while maintaining motor performance. To achieve this, a design of experiments (DoE) approach is employed to capture interaction effects between critical uncertainties. Finally, robust design optimization is performed, explicitly considering the manufacturing uncertainties that contribute to AHC. The optimized design is validated through experiments and compared with the original prototype, demonstrating improved performance, reduced sensitivity to manufacturing uncertainties, and lower AHC of cogging torque.

II. MANUFACTURING UNCERTAINTY IN PROTOTYPE

In Fig.1, the cogging torque of the prototype obtained from FEA and test are compared. The FEA result of ideal prototype without applying manufacturing uncertainty shows very small value of the cogging torque based on 144th harmonics. However, the test results of the fabricated prototype show a large value of cogging torque including the AHCs of 16 and 18th. It is shown that the AHCs of cogging torque are produced due to manufacturing uncertainty of both stator and rotor.

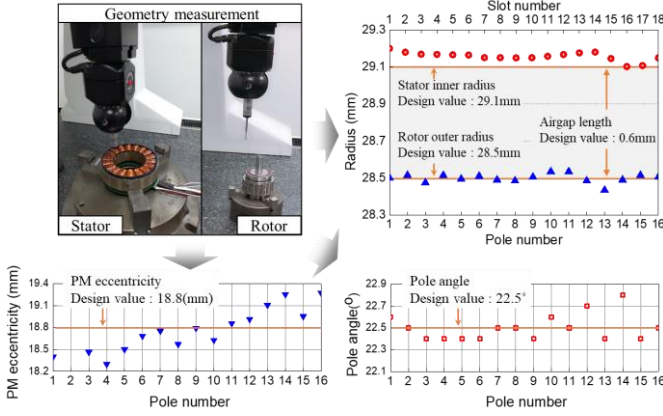


Fig. 2. Geometry measurement setup and measured value

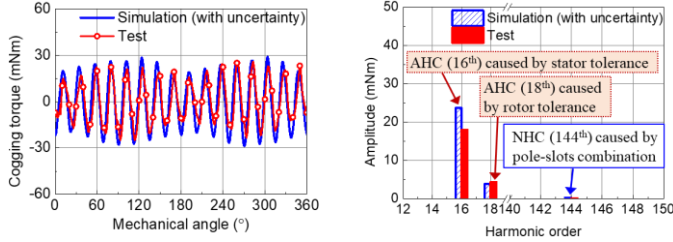


Fig. 3. Cogging torque from simulation considering uncertainty and test result

To identify the cause of the AHCs, the geometric dimensions of the manufactured conventional motor as shown in Fig. 2 were measured and it was confirmed that the design and measured value were different. In addition, the measured geometric dimensions were reflected in the simulation model and the FEA was performed, and it was confirmed that the measured cogging torque and the simulation cogging torque with the uncertainty reflected were similar. Therefore, in the next section, a robust optimal design is performed by considering the analyzed uncertainty information.

III. ROBUST DESIGN OPTIMIZATION

In this section, a RDO is conducted to reduce the AHC of cogging torque. The overall design process is illustrated in Fig. 4. First, a sensitivity analysis is performed to identify the design variables and uncertainty variables that significantly affect the AHC of the cogging torque. Based on the results, these key variables are used to construct a surrogate model. The surrogate model is then employed to perform the RDO, aiming to minimize the AHC of cogging torque.

A. Sensitivity analysis

The sensitivity analysis identified design and uncertainty variables with statistically significant effects on the AHCs of cogging torque. Manufacturing uncertainties were incorporated using inner and outer arrays in the DoE, where the inner array represented controllable design variables with negligible uncertainty, and the outer array included variables influenced by manufacturing imperfections. Orthogonal arrays were used to reduce computational costs, and statistical significance was determined based on a p-value threshold. Variables with p-values below the specified level were selected for surrogate modeling and optimization, ensuring that only the most impactful factors were considered.

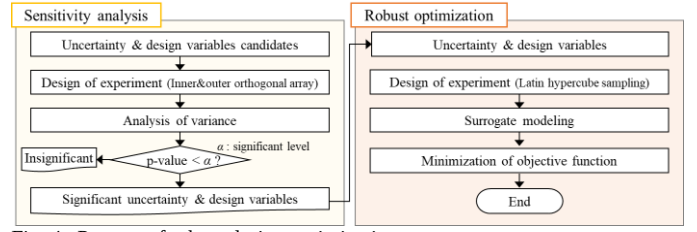


Fig. 4. Process of robust design optimization

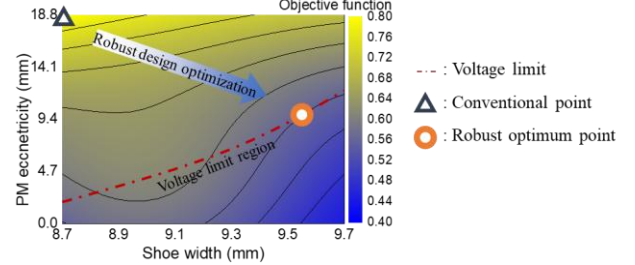


Fig. 5. Object function according to design variables

B. Robust design optimization

Kriging surrogate models for the objective function and constraints are constructed using sample data and Gaussian correlation functions. The primary goal of these surrogate models is to significantly reduce the computational cost associated with optimization processes. Using these surrogate models, RDO is performed. For the optimization, a gradient-based approach is applied. This method iteratively searches for the optimal point. To validate that the obtained solution is the global optimum, a contour map of the objective function is generated, providing a visual representation of the solution's convergence to the global optimum as shown in Fig. 5.

IV. CONCLUSION AND FUTURE WORK

This paper focuses on robust design optimization (RDO) of SPMSMs to reduce cogging torque caused by manufacturing uncertainties. Key variables influencing harmonic components are identified using FEA and experiments, optimized with a kriging model. Detailed analysis, design process, and results will be included in the full paper. Also, the optimized model will be fabricated, and its cogging torque will be experimentally measured. To validate the proposed robust design optimization, the measured cogging torque will be compared with the simulation results.

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