

Analytic Estimation and Verification of Cogging Torque in SPMSM with Manufacturing Tolerance of Segmented Core

Dong-Hoon Ko¹, Yong-Min Lee¹, Soo-Hwan Park³ and Min-Ro Park^{1,2}

¹Department of Electrical and Communication Systems Engineering, Graduate School, Soonchunhyang University, Asan 31538, Korea

²Department of Electrical Engineering, Soonchunhyang University, Asan 31538, Korea

³Department of Mechanical, Robotics, and Energy Engineering, Dongguk University, Seoul 04620, Republic of Korea

This paper proposes a cogging torque calculation model that considers stator inner diameter tolerances using an analytical method. The purpose of this study is to present a faster calculation method that maintains sufficient accuracy compared to traditional finite element method (FEM) analyses when performing electromagnetic analysis with tolerances. First, the motor is equivalently modeled as a smooth core, and the air-gap flux density is calculated based on governing equations. Subsequently, the effects of slots and tolerances are incorporated using Complex Relative Permeance (CRP) to compute the air-gap flux density that reflects the influence of tolerances. Finally, the cogging torque is calculated, completing the proposed process. The validity of the proposed model is verified through comparisons with experimental data obtained from an actual prototype.

Index Terms—Analytic Method, Cogging Torque, Manufacturing Tolerance, Segmented Core

I. INTRODUCTION

Segmented cores enable high slot fill factors, which increase power density and make them widely applicable in various fields. However, during manufacturing with a high slot fill factor, coil interference may induce gaps in the segmented cores, leading to deviations in the stator's inner diameter and uncertainties proportional to the number of slots. These issues generate additional harmonic components (AHC), multiples of the pole count, in the cogging torque, causing discrepancies between the designed and actual performance of mass-produced motors.

Electromagnetic analysis is crucial for performance evaluation prior to full-scale manufacturing. While FEM-based analysis offers accuracy, incorporating stator tolerances significantly increases preprocessing complexity and computation time. Previous studies predominantly used FEM to assess the impact of tolerances on motor performance [1]. Another approach involves approximating the stator's inner diameter as an ellipse for electromagnetic analysis [2], but this method inadequately represents the air-gap flux density distribution arising from dimensional tolerances in each slot.

This study proposes a cogging torque prediction model that accounts for individual dimensional tolerances by employing scalar potential and Complex Relative Permeance (CRP). The proposed model's validity is demonstrated through comparisons with experimental prototype results.

II. ANALYSIS OF PROTOTYPE WITH SEGMENTED CORE

The ideal stator inner diameter of the designed model was set to 29.1mm, as shown in Fig. 1(a). However, dimensional tolerances were observed in most slots. Test results in Fig. 1(c) and (d) revealed 16th- and 18th-order AHC due to stator and rotor tolerances, respectively, while simulations showed only native harmonic components (NHC). These results indicate that dimensional tolerances caused deviations in the motor's performance from the designer's intent.

Predicting model performance before prototype fabrication

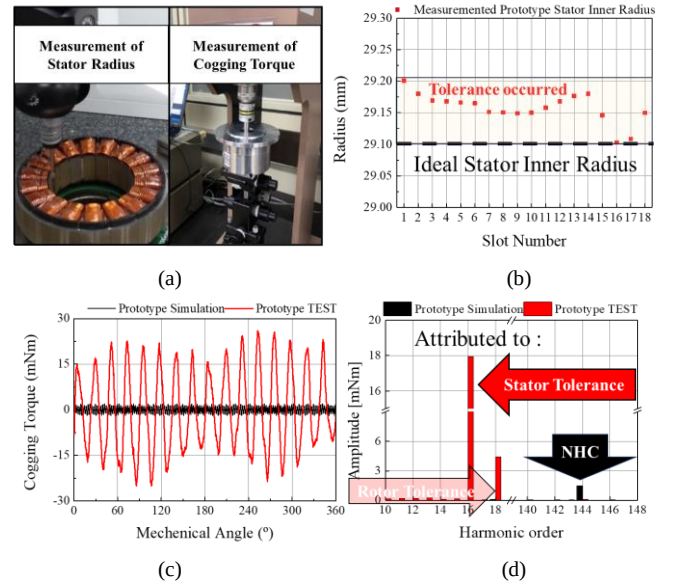


Fig. 1. Compare prototype measurements to ideal values (a) prototype experiment (b) stator inner radius (c) cogging torque (d) harmonic analysis is crucial. Although FEM-based electromagnetic analysis provides high accuracy, its complexity increases with variable count. To address this, this study introduces an analytical method for calculating cogging torque.

III. CALCULATION OF COGGING TORQUE CONSIDERING MANUFACTURING TOLERANCE

In this study, the air-gap flux density, including the effects of tolerances, is calculated as shown in Fig. 2, and the cogging torque is determined using the Maxwell stress tensor. First, the motor is equivalently modeled as a smooth core to calculate the air-gap flux density excluding the effects of tolerances and slots. Then, the CRP considering tolerances is calculated to obtain the air-gap flux density that reflects the effects of both slots and tolerances.

The calculation results from section A and B were compared with FEM and presented in Fig.3 and 4, respectively, to validate the effectiveness of the calculations in each section.

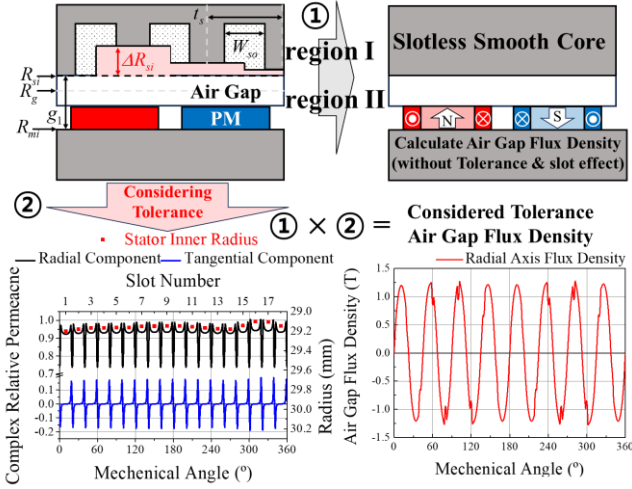


Fig. 2. Proposed method for calculating air-gap flux density with tolerances

A. Air-gap Flux Density considering Manufacturing Tolerance through Complex Relative Permeance

First, to calculate the air-gap flux density in the smooth core, the domain is divided into two regions as shown in Fig. 2, governed by the Laplace and Poisson equations. The magnetization vector and boundary conditions are applied to derive the general expression, the slotless air-gap flux density, B_{nos} , represented as [3]:

$$B_{r_nos}(r, \theta) = \sum_{n=1,3,5,\dots}^{\infty} K_B(n) \cdot f_{B_r}(r) \cdot \cos(np\theta) \quad (1)$$

$$B_{\theta_nos}(r, \theta) = \sum_{n=1,3,5,\dots}^{\infty} K_B(n) \cdot f_{B_\theta}(r) \cdot \sin(np\theta) \quad (2)$$

Next, the air-gap flux density, B_s , considering manufacturing tolerance and slot effect can be derived by multiplying the slotless air-gap flux density by the CRP, λ , which accounts for manufacturing tolerance as follows:

$$B_{r_s}(r, \theta) = B_{r_nos}(r, \theta) \lambda_a(r, \theta) + B_{\theta_nos}(r, \theta) \lambda_b(r, \theta) \quad (3)$$

$$B_{\theta_s}(r, \theta) = B_{\theta_nos}(r, \theta) \lambda_a(r, \theta) - B_{r_nos}(r, \theta) \lambda_b(r, \theta) \quad (4)$$

$$\lambda_a(r, \theta) = g_1(\theta) \cdot \frac{1 + \frac{k_c - 1}{k_0(\theta)} \sum_{n=1}^{\infty} [Q_n R_v(n, \theta) \cos(nS\theta)]}{r \ln \left(\frac{R'_{si}}{R_{mi}} \right) + \frac{k_c - 1}{k_0(\theta)} \frac{R'_{si}}{S} \sum_{n=1}^{\infty} \left[\frac{(-1)^n}{n} Q_n \right]} \quad (5)$$

$$\lambda_b(r, \theta) = g_1(\theta) \cdot \frac{\frac{k_c - 1}{k_0(\theta)} \sum_{n=1}^{\infty} [Q_n R_b(n, \theta) \sin(nS\theta)]}{r \ln \left(\frac{R'_{si}}{R_{mi}} \right) + \frac{k_c - 1}{k_0(\theta)} \frac{R'_{si}}{S} \sum_{n=1}^{\infty} \left[\frac{(-1)^n}{n} Q_n \right]} \quad (6)$$

This study, the stator inner diameter R_{si} is divided by angle to incorporate tolerances, and the divided diameter is expressed $R'_{si} = R_{si} + \Delta R_{si}$, all parameters derived from the stator inner diameter such as g_1 , k_0 , R_a , and R_b are computed on a per-angle basis, thereby effectively applying the tolerances.

Fig. 3 shows the airgap flux density considering the manufacturing tolerance calculated analytic method and FEA.

B. Cogging Torque considering Manufacturing Tolerance

The cogging torque can be calculated using Maxwell stress tensor, and is expressed in (7)

$$T_c = r \int (B_{r_s} B_{\theta_s} / \mu_0) dA \quad (7)$$

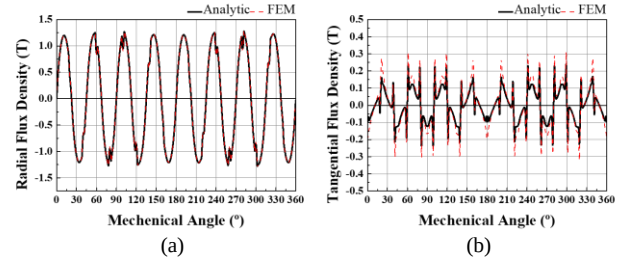


Fig. 3. Air-gap Flux density from analytic method and FEM (occur tolerance) (a) radial flux density (b) tangential component

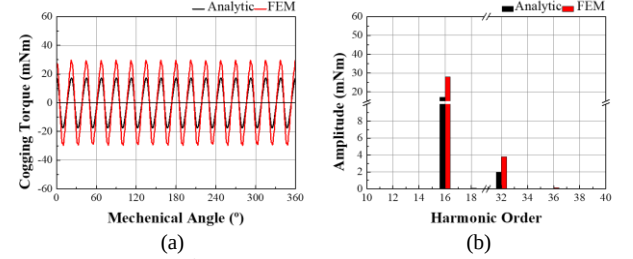


Fig. 4. Cogging torque from analytic method and FEM (occur tolerance) (a) cogging torque (b) harmonic analysis

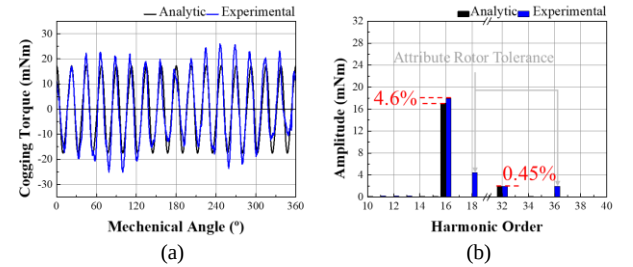


Fig. 5. Cogging torque from analytic method and experimental result (a) cogging torque (b) harmonic analysis

Figs. 4 and 5 show the cogging torque obtained by the proposed analytical method, FEA, and experiments, with closely similar results. The comparison with experiments reveals acceptable errors of 4.6% for the 16th harmonic and 0.45% for the 32nd harmonic, attributed to stator tolerances.

IV. CONCLUSION AND FUTURE WORK

This study proposed an analytical method for calculating motor performance considering the tolerances. The proposed method achieved fast computation times for tolerance-applied models and demonstrated its effectiveness by providing highly accurate cogging torque estimation, as validated through comparisons with prototype experimental results. Additional equations and analyses will be provided in the full paper.

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