

Efficient Prediction of Electromagnetic Excitation Force for SPMSM Using Analytical Model-Based Deep Transfer Learning Considering Axial Leakage Flux

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Surface-mounted permanent magnet synchronous motors (SPMSMs) for robot actuators are typically designed in a pancake form due to the limited space within actuator systems. In order to control the robot manipulator in precision, vibration characteristic is one of the main issue in designing the SPMSMs for robot actuators. As the radial and tangential electromagnetic force which are considered as an excitation force in stator are affected by the air-gap magnetic flux density, electromagnetic analysis considering the axial leakage flux is important in pancake formed SPMSMs. Thus, 3-D finite element analysis (FEA) is necessary to calculate electromagnetic excitation force density (EEF) for SPMSMs, but it requires high computation cost. Therefore, analytical model-based deep transfer learning is proposed in this paper. The proposed method incorporates a large amount of analytical model-based radial and tangential electromagnetic force and a small amount of 3-D FEA-based electromagnetic force, so that the EEFD can be predicted accurately with reduced computation cost. By using the proposed method, the low vibration and high performance SPMSMs for robot actuator can be designed rapidly considering the axial leakage flux. The results of analysis using the proposed method will be validated through simulation and experimental results.

Index Terms—analytical method, excitation force, deep transfer learning, surface-mounted permanent magnet synchronous motors, vibration.

I. INTRODUCTION

SURFACE-MOUNTED PERMANENT MAGNET SYNCHRONOUS MOTORS (SPMSMs) are generally used for robot actuators because of their high torque density and linearity in torque control [1]. The potential of torque density for SPMSMs is determined by the winding factor which is affected by the pole and slot combination, and it also determines the time and spatial order of electromagnetic excitation force (EEF) which is the source of vibration in SPMSMs [2]. Thus, the main issues in designing the SPMSMs for robot actuator are maximizing the torque density while minimizing the vibration characteristics for high precision control of robot manipulator [3].

Since the pancake shaped SPMSMs are highly affected by the effect of axial leakage flux, the performance of SPMSMs can be accurately calculated using 3-D finite element analysis (FEA). However, it requires high computation cost, so that it is not efficient using 3-D FEA in design optimization of SPMSMs for considering the effect of axial leakage flux. Therefore, research on analysis of electromagnetic characteristics for SPMSMs considering the axial leakage flux has been conducted. In [4], the effect of axial leakage flux was considered on the operating point of the permanent magnet. It was effectively worked in rated torque, but the accuracy was lowered in high torque region. Park *et al.* considered axial leakage flux in the ratio of no-load back-electromotive force calculated by 3-D FEA and 2-D FEA, but 3-D FEA was necessary in this method, so that it is not efficient in use of the method when designing the SPMSMs [5].

In this paper, a data-driven method for considering the effect of axial leakage flux is proposed for predicting the EEF for

SPMSMs. Deep transfer learning (DTL) is used in this study, which utilizes a large amount of low cost dataset and a small amount of high cost dataset [6]. The former dataset is set as the analytical model (AM) based EEF, and the latter dataset is set as the 3-D FEA-based excitation force. Although the results of AM are inaccurate compared to the 3-D FEA, these results are suitable for modeling trends similar to those calculated with 3-D FEA. Then, the gap between the AM-based results and ground truth is compensated by using the dataset computed with a small amount of 3-D FEA, which ultimately allows accurate prediction of the EEF of the SPMSMs with very low computation cost. Eventually, the SPMSMs with low vibration and high performance for robot actuator can be designed efficiently using the proposed method.

II. EFFECT OF AXIAL LEAKAGE FLUX IN ELECTROMAGNETIC EXCITATION FORCE

In airgap for SPMSMs, radial and tangential electromagnetic force are produced because of the result of interacting field magnet and armature current. The tangential force acting on rotor is same with the shaft torque, and the radial and tangential force acting on stator are considered as the EEF which are the source of vibration. According to Maxwell stress tensor method, the radial and tangential EEF can be expressed as follows in terms of the radial and tangential air-gap magnetic flux density:

$$f_r = \frac{1}{2\mu_0} (B_r^2 - B_t^2) \quad (1)$$

$$f_t = \frac{1}{2\mu_0} B_r B_t \quad (2)$$

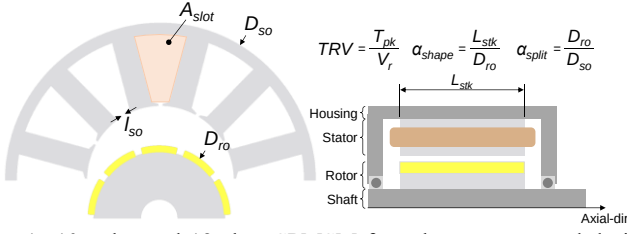


Fig. 1. 10-poles and 12-slots SPMSM for robot actuator and design variables concerned with electromagnetic excitation force.

TABLE I

SPECIFICATIONS AND DESIGN VARIABLES OF 10-POLES AND 12-SLOTS SPMSM

Item	Unit	Value
Permanent magnets	-	N45H
Stator/rotor core	-	50PN470
Peak torque range	Nm	8.0 to 15.0
TRV range	Nm/mm ³	88,000 to 95,000
α_{shape} range	-	0.8 to 1.2
α_{split} range	-	0.45 to 0.55
Slot open range	mm	0.2 to 1.0

As the radial air-gap magnetic flux density can be derived from the AM, radial and tangential EEF according to the armature loading and design variables such as size of rotor and stator, and slot opening can be calculated rapidly using AM.

Fig. 1 shows the shape of 10-poles and 12-slots SPMSM, and the specifications and design variables are listed in Table I. Since the design variables are concerned with the magnetomotive force of field magnets and magnetic reluctance of air-gap and stator core, the EEF are highly affected by these design variables. However, AM only considers the radial and tangential magnetic flux path and ignores the magnetic reluctance in stator, so that it cannot consider the effect of axial leakage flux and magnetic saturation in electrical steel. Fig. 2 shows the difference between no-load radial and tangential EEF calculated with AM and 3-D FEA. It can be seen that the harmonic components for each EEF calculate from AM are increasing linearly because AM does not consider the magnetic saturation, and the results are different from the results calculate from 3-D FEA because AM does not consider the axial leakage flux.

III. PREDICTION OF ELECTROMAGNETIC EXCITATION FORCE USING AM-BASED DTL

Although AM-based radial and tangential EEF have errors, the computation cost required for calculation is very small, making it easy to construct a low-fidelity large dataset in an instant. On the other hand, 3-D FEA-based radial and tangential EEF are relatively accurate, but due to its high computation cost, it is suitable for constructing a small amount of high-fidelity dataset. In this paper, AM-based DTL is proposed by utilizing these two datasets for efficiently predicting the EEF for SPMSM. Fig. 3 shows the flowchart for the proposed method. First, a deep neural network (DNN) is trained with low-fidelity dataset. The input vector of the DNN consists of the design variables and armature current of SPMSM, and the output vector consists of the amplitude of spatial harmonic for EEF of twice the fundamental frequency. Then, the weights and bias for trained DNN are set as the initial value for the other DNN, and

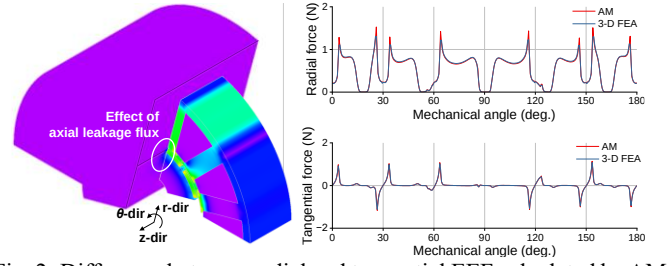


Fig. 2. Difference between radial and tangential EEF calculated by AM and 3-D FEA due to the axial leakage flux.

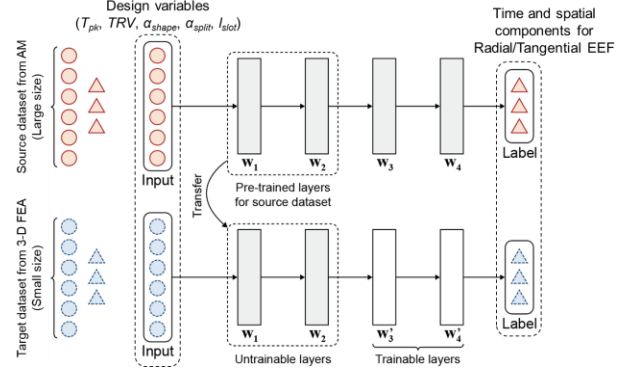


Fig. 3. Flowchart for proposed AM-based DTL method for efficiently predicting the EEF according to design variables.

it is trained with the high-fidelity dataset. As a result, the additionally trained DNN can predict high-fidelity EEF accurately although the size of high-fidelity dataset is very small. As a result, the SPMSM with high performance and low vibration can be designed.

IV. CONCLUSION AND FUTURE WORK

This paper proposes an analytical method-based deep transfer learning method for efficiently predicting the electromagnetic excitation force of SPMSM. By using the method, the SPMSM for robot actuator with low vibration can be efficiently designed without using 3-D FEA. In the full paper, the validation for the proposed method will be conducted through simulations and experimental results.

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