Two-Dimensional FEA-Based Iron Loss Calculation Method for Linear Oscillating Actuator Considering the Circumferential Segmented Structure

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Linear compressors have a simpler mechanical structure and higher efficiency than rotary compressors because they have lower frictional loss. Therefore, the linear oscillating actuator (LOA) is an attractive option for compressors owing to its high power density and efficiency. However, the complex structure of LOA such as segmented outer stator and mover leads to conduct 3-D finite element analysis (FEA) for calculating accurate iron loss, but it requires high computation cost. Thus, we propose a method to calculate iron loss only using 2-D axisymmetric FEA considering the permeance in the stator core. To compensate for the alterations in the magnetic flux density resulting from the structure of the mover and outer stator of the LOA, two equivalent coefficients are applied in permanent magnets in the mover to correct the induced voltage and the outer stator to correct the magnetic flux density. Through the utilization of these two equalization methods, iron loss can be accurately calculated using only 2-D axisymmetric FEA. The proposed method can be used to accurately determine the efficiency of the LOA without 3-D FEA, thus, making the LOA design process more efficient.

Index Terms—**Equivalent coefficient, finite element analysis (FEA), iron loss, linear oscillating actuator (LOA), magnet pole ratio.**

I. Introduction

A COMPRESSOR is an electro-mechanical device that converts electrical power to mechanical power to compress gas and supply it at increased pressure, and it is widely used in home appliances such as refrigerators and air conditioners [1]. The compressors are classified into two types: linear and rotary, depending on the mechanism of the actuator. A rotary compressor loses energy during the power conversion process, that is, conversion from rotational to linear motion to compress the gas, and it has a complicated structure because it requires additional mechanical components [2]. On the other hand, a linear compressor which is operated with linear oscillating actuator (LOA) has a simpler mechanical structure and higher efficiency than a rotary compressor because it has lower friction loss [3]. Thus, the electromagnetic loss of LOA is an important factor in determining the overall efficiency of the linear compressor [4].

Fig. 1. shows the structure of an LOA, which consists of outer and inner stators, a single-phase winding, and a mover. The inner and outer stators are laminated to reduce the iron loss. Unlike the inner stator, the outer stator and mover are divided into several pieces owing to manufacturing constraints. The air regions created by the segmented outer stator structure can cause magnetic saturation that affects the electromagnetic performance of the LOA. This is caused by more magnetic flux passing through the segments of the outer stator owing to the absence of ferromagnetic material in the air regions [5]. Furthermore, the segmented mover structure affects magnetic flux distribution, which depends on the utilization of magnets. [6]. In order to calculate the performance of LOA, 2-D axisymmetric finite element analysis (FEA) is required to reduce the computation cost rather than using the 3-D FEA. However, 2-D axisymmetric FEA for electromagnetic field analysis cannot guarantee accuracy when analyzing LOA with a complex structure of outer stator and mover. This is because the effects of the magnetic flux distribution changes cannot be considered in 2-D axisymmetric FEA. Thus, an accurate iron loss can only be calculated by using 3-D FEA, resulting in high computational cost for the design process of LOA [7]. Therefore, an accurate cost-effective method for calculating the electromagnetic losses of the LOA is required.

Thus, in this article, we propose a computationally efficient analysis method for calculating iron loss of LOA only

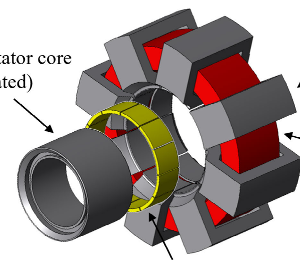

Fig. 1. Structure of the LOA.

Manuscript received 28 March 2023; revised 1 May 2023; accepted 3 May 2023. Date of publication 11 May 2023; date of current version 24 October 2023. Corresponding author: M.-S. Lim (e-mail: myungseop@hanyang.ac.kr).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TMAG.2023.3275152.

Digital Object Identifier 10.1109/TMAG.2023.3275152

TABLE I
SPECIFICATIONS OF LOA

Item	Unit	Value
Stroke	mm	11
Output power	W	61.69
Frequency	Hz	51
Outer stator outer radius	mm	73.45
Inner stator outer radius	mm	31.7
PM length	mm	18
Rated current	A_{rms}	0.4
Inner stator core material	-	50PN470
Outer stator core material	-	35PN230

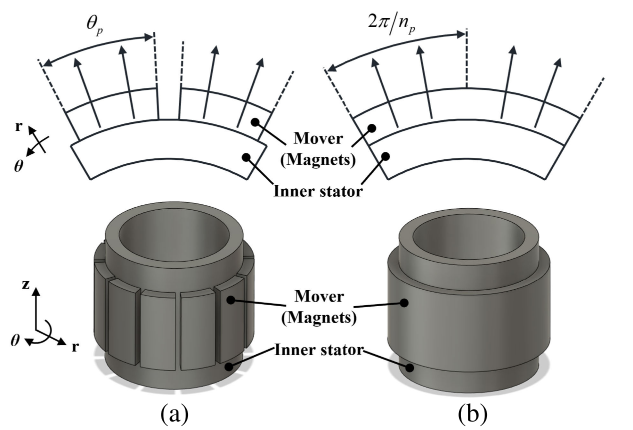

Fig. 2. Structure of the (a) segmented mover and (b) ring-type mover.

using 2-D axisymmetric FEA. This method reduces the computational cost while improving the accuracy of iron loss calculations through the following steps. First, the residual magnetic flux density of the permanent magnet is corrected by applying the magnet pole ratio, considering the segmented mover structure. Second, 2-D axisymmetric FEA is performed using the corrected residual magnetic flux density to calculate the magnetic flux density at each element. Then, the magnetic flux density at each element is corrected by applying an equivalent coefficient, considering the segmented outer stator structure. Subsequently, the iron loss is calculated based on mapped data according to the amplitude and phase angle of the current and frequency using the corrected magnetic flux density per element. With the proposed method, accurate iron loss calculations can be performed with lower computational costs than those associated with 3-D FEA.

II. Electromagnetic Loss Analysis Considering the Segmented Structure of LOA

The specifications of the LOA are listed in Table I. As home appliances require high efficiency in continuous operation, the efficiency of the LOA should be high either. Therefore, the LOA operates at a low current density to reduce copper loss, and the magnetic saturation of the stator is also low accordingly.

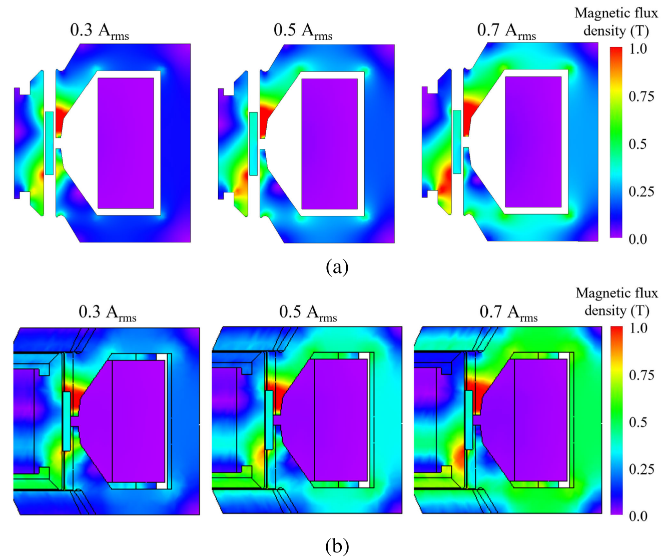

Fig. 3. Contour plot of magnetic flux density. (a) Two-dimensional axisymmetric FEA. (b) Three-dimensional FEA.

A. Equivalent Method Considering the Segmented Mover

The segmented mover structure causes variability in the magnetic flux density, which is dependent on the utilization of magnets. However, the variability in the magnetic flux density is not considered in 2-D axisymmetric FEA. Thus, in this section, we propose a method of correcting the residual magnetic flux density of a permanent magnet by applying the magnet pole ratio to improve accuracy. The magnet pole ratio can be calculated from the ratio of the circumferential direction volume between ring-type and segmented mover. The segmented and ring-type mover structures are illustrated in Fig. 2(a) and (b), respectively. The magnet pole ratio can be calculated as

$$\alpha_p = \frac{\theta_p}{2\pi/n_p} = \frac{\theta_p n_p}{2\pi} \tag{1}$$

where α_p is the magnet pole ratio, θ_p is the pole arc and n_p is the number of poles. Then, the corrected residual magnetic flux density can be calculated as

$$B_r' = \alpha_p B_r \tag{2}$$

where B_r' is the corrected residual magnetic flux density and B_r is the residual magnetic flux density. When performing 2-D axisymmetric FEA, the corrected magnetic flux density is applied in permanent magnets.

B. Equivalent Method Considering the Segmented Outer Stator

Unlike the axisymmetric analysis, which assumes revolving the sheet of the outer stator in the circumferential direction, the outer stator is divided into several blocks. Therefore, more magnetic flux passes through the segments of the outer stator owing to the air regions that are diamagnetic. Fig. 3. shows a comparison of the magnetic flux density contour plot of 2-D axisymmetric FEA and 3-D FEA. In 2-D axisymmetric FEA, the magnetic flux density is calculated using the volume of

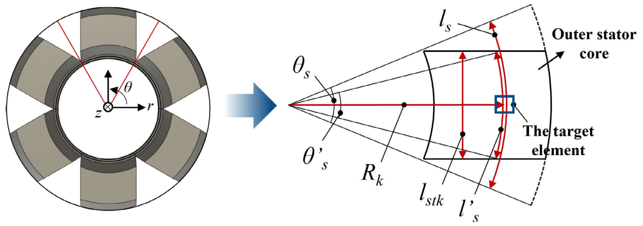

Fig. 4. Simplified model to determine the equivalent coefficient.

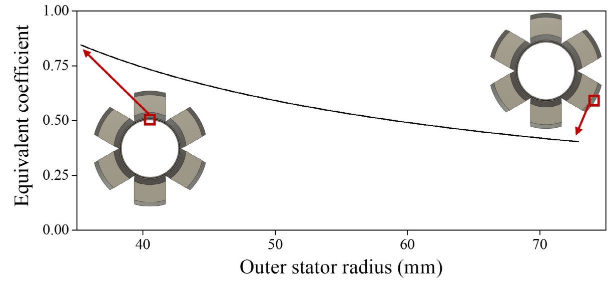

Fig. 5. Equivalent coefficient according to the radius of the outer stator.

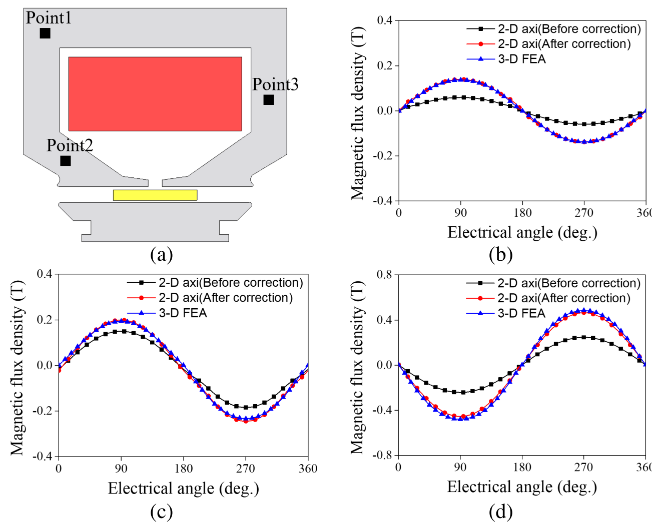

Fig. 6. Two-dimensional axisymmetric FEA before and after correction and 3-D FEA results of the magnetic flux density. (a) Location of the indicated magnetic flux density and waveform at (b) point1, (c) point2, and (d) point3.

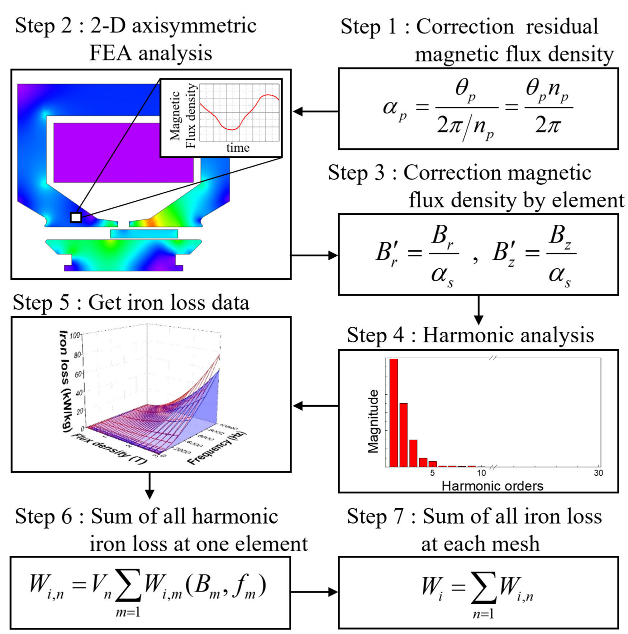

Fig. 7. Process for calculating iron loss using proposed method.

element that is rotationally integrated for a given 2-D cross section based on a specified axis. Therefore, the segmented structure of the outer stator and saturation effect cannot be considered in 2-D axisymmetric FEA. Thus, the electromagnetic performance such as flux-linkage or iron loss of the LOA should be calculated using 3-D FEA. However, 3-D FEA requires higher computational costs than 2-D axisymmetric FEA. Therefore, 2-D axisymmetric FEA-based equivalent analysis of iron loss is proposed in this section, taking into acount the segmented outer stator structure. Fig. 4. shows a simplified model to determine the equivalent coefficient. The equivalent coefficient, which is the ratio of the circumferential direction volume of the ring-type to that of segmented outer stator cores, can be calculated as

$$\alpha_s = \frac{l_s'}{l_s} = \frac{R_k\theta_s'}{R_k\theta_s} = \frac{2\arcsin\left(\frac{l_{\text{stk}}}{2r}\right)}{2\pi/n_c} = \frac{n_c}{\pi}\arcsin\left(\frac{l_{\text{stk}}}{2r}\right) \quad (3)$$

where α_s is the equivalent coefficient, n_c is the number of segmented outer stator cores, l_{stk} is the stack length of the segmented outer stator core, R_k is the radius of the target element, l_s is the circumferential length of the entire core, l_s' is the circumferential length of the segmented outer stator core, θ_s is the angle of the entire outer stator core, and θ_s' is the angle of the segmented outer stator core. Fig. 5. shows the calculated equivalent coefficient according to the outer stator radius. The corrected magnetic flux density can be calculated as

$$B_r' = \frac{B_r}{\alpha_s}, \quad B_z' = \frac{B_z}{\alpha_s} \quad (4)$$

where B_r is the radial magnetic flux density, B_r' is the corrected radial magnetic flux density, B_z is the axial magnetic flux density, and B_z' is the corrected axial magnetic flux density. Fig. 6(a) shows the location of the indicated magnetic flux density. Fig. 6(b)–(d) shows the 2-D axisymmetric FEA before correction, 2-D axisymmetric FEA after correction and 3-D FEA results of the magnetic flux density, respectively. It can be seen that corrected magnetic flux density results obtained using the proposed method have a higher accuracy.

C. Proposed Method

The process of calculating the iron loss using the proposed method is shown in Fig. 7. First, the residual magnetic flux density is corrected by applying the magnetic pole ratio. Second, the corrected residual magnetic flux density was employed to conduct 2-D axisymmetric FEA and calculate the magnetic flux density at each element for a given frequency. Third, to reflect that the magnetic flux density increased according to the LOA structure, the magnetic flux density

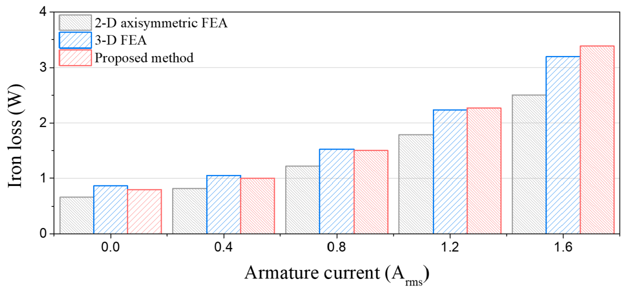

Fig. 8. Comparison between 2-D axisymmetric FEA, 3-D FEA and proposed method.

Fig. 9. Experimental setup for measuring iron loss of the LOA.

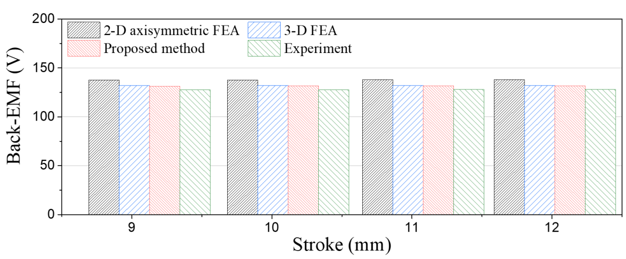

Fig. 10. Comparison of simulation and experiment results for the Back EMF according to stroke.

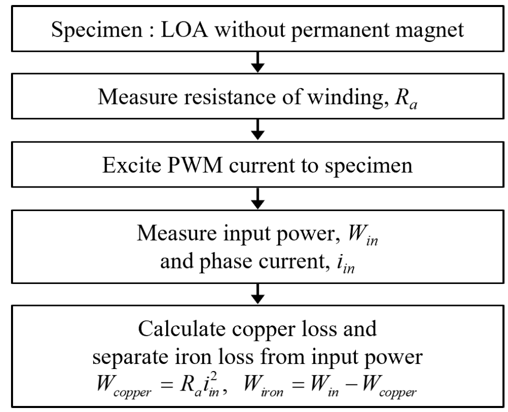

Fig. 11. Flowchart for verifying iron loss.

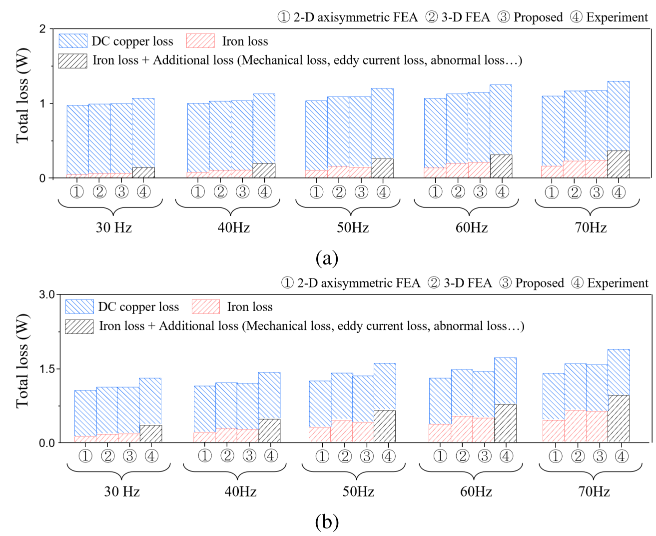

Fig. 12. Comparison of simulation and experiment results for total loss according to armature current. (a) 0.3 A_{rms}. (b) 0.5 A_{rms}.

was corrected by applying the equivalent coefficient. Firth, the harmonic analysis of the corrected magnetic flux density was conducted to evaluate the amplitude at each frequency. From the iron losses data of the material, the iron loss corresponding to the magnetic flux density and frequency of each harmonic component were calculated. Then, the iron losses for each element were calculated by summing the iron losses of all the associated harmonic components. Consequently, the total iron loss is calculated by summing the iron losses for all elements [8]. Fig. 8. shows the comparison between 2-D axisymmetric FEA and 3-D FEA and proposed method. It can be seen that predicted iron loss results obtained using the proposed method have a higher accuracy.

III. Experimental Verification

In this section, experimental results of iron loss calculations are presented. Fig. 9. shows the experimental setup for measuring the iron loss of the LOA. In order to verify the Back EMF, LOA were fabricated for the experiments. Fig. 10. comparison between the simulation and experimental results for Back EMF according to stroke. Upon the movement of the mover at a constant velocity of 1 m/s, Back EMF was measured. It can be seen that the errors were within 2.9%, so that the results from the electromagnetic FEA have consistency with the experiment. In order to verify the total loss, LOA without permanent magnets was fabricated for the experiment. The flowchart of the verification process of the iron loss is shown in Fig. 11. The iron loss was determined by subtracting the dc copper loss from the input power measured after exciting the winding with sinusoidal current. Fig. 12(a) and (b) show comparison between the simulation and experimental results for total loss obtained at armature currents of 0.3 and 0.5 A_{rms}. The experimental results include additional losses such as eddy current loss arising from the conductors, ac copper loss and mechanical loss due to the vibration of segmented core. Also, resistance of winding owing to the temperature rise during the test, while the simulation was performed under the constant temperature condition. As the additional losses were not separated in the iron loss of experiment, the total loss of the proposed method is larger than that of the experiment. However, it can be seen that the proposed method is accurate compared to 3-D FEA. Therefore, the proposed method can be widely applied for the calculation of iron loss in LOA, as the iron loss that takes into account the circumferential segmented structure of LOA can be predicted with a significantly low computational cost.

IV. Conclusion

Accurate calculation of iron loss requires high computational costs since 3-D FEA is essential for considering the circumferential segmented structure of LOA. Thus, in this article, computationally efficient analysis of 2-D axisymmetric FEA-based iron loss considering the segmented mover and outer stator structure of the LOA was proposed. First, residual magnetic flux is corrected applying by magnet pole ratio, considering the segmented mover structure. Magnet pole ratio can be calculated from the ratio of circumferential direction volume of between ring-type and segmented mover. Then, the residual magnetic flux density was corrected by applying the magnet pole ratio, followed by performing 2-D axisymmetric FEA was performed using the corrected residual magnetic flux. Subsequently, the magnetic flux density for each element is corrected applying by equivalent coefficient, considering the segmented outer stator structure. Equivalent coefficient can be calculated from the ratio of circumferential direction volume of between ring-type and segmented outer stator core. Then, the magnetic flux density for each element was corrected using an equivalent coefficient, and iron loss was calculated with the corrected 2-D axisymmetric FEA magnetic flux density for each element, and the method was verified to be reasonable through comparison with 3-D FEA. Finally, a specimen was fabricated for experimental verification, and simulation and experiment results of Back EMF and iron loss were compared. By using the proposed method, the efficiency of the LOA can be accurately estimated at the design stage because the magnetic flux density increased according to the LOA structure is considered via the proposed method, and the computation cost can be reduced when designing a high-efficiency LOA. Furthermore, the proposed method is adaptable and can be effectively utilized in the design of other LOA with varying dimensions.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) through the Korea Government (MSIT) under Grant RS-2023-00207865.

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