

# Improved Loss Analysis Method Considering Core Anisotropy and AC Copper Loss in Linear Oscillating Actuator

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The linear oscillating actuator (LOA) operates as the driving mechanism for linear compressor, which shows high power density and efficiency. To ensure the high efficiency of linear compressor, it is important to accurately calculate the loss of LOA. Due to the complex structure of LOA with segmented outer core and permanent magnet, 3D finite element analysis (FEA) was executed to analyze the loss of LOA. Conventional loss calculation method of LOA includes DC copper loss and iron loss. This paper proposes a loss calculation method containing additional effect, core anisotropy and AC copper loss, on total loss of LOA. Methods to include effects in 3D FEA are introduced. Moreover, total loss error of conventional method and proposed method are compared to verify the effect.

**Index Terms**—AC copper loss, finite element analysis (FEA), linear oscillating actuator (LOA), rolling direction (RD).

## I. INTRODUCTION

THE linear oscillating actuator (LOA) is an electro-mechanical device that generates linear oscillatory motion along a single axis without the need for screws, gears, or crankshafts. LOAs are commonly used in refrigerators, which account 20-40% of household electricity consumption [1]. Efficiency is a critical factor, making LOA an ideal choice for this purpose. Therefore, assessing the loss of LOA is crucial to determining the overall efficiency of refrigerator.

To determine efficiency, it is essential to categorize the losses. Total loss is determined by subtracting the output power from the input power. Total loss consists of copper loss, which is calculated using the phase current and phase resistance, iron loss, and mechanical loss, which includes friction and windage losses [2].

This paper proposes additional components to be considered in LOA. Additional components are anisotropic property and AC copper loss.

## II. PROPOSED ADDITIONAL COMPONENTS

Fig. 1 shows the structure of the LOA, and its specifications are detailed in Table I. Due to the LOA's complex structure, which includes a segmented outer core and permanent magnet, 3D finite element analysis (FEA) was utilized.

### A. Anisotropic Property of Outer Core

Even if the core is manufactured by isotropic steel plate, anisotropy could occur by the directional property of the core which comes from the manufacturing process. The directional property is called rolling direction (RD). The RD exhibits high permeability and low iron loss, while deviations from RD toward the transverse direction (TD), tangential to RD, reduce permeability and increase iron loss.

Fig. 2 compares three different cases of loss data of the outer core material, 35PN230. Each case corresponds to the situation when magnetic flux flows in RD, TD, and the average direction of RD and TD. According to Fig. 2, loss density values vary depending on the directional characteristics.

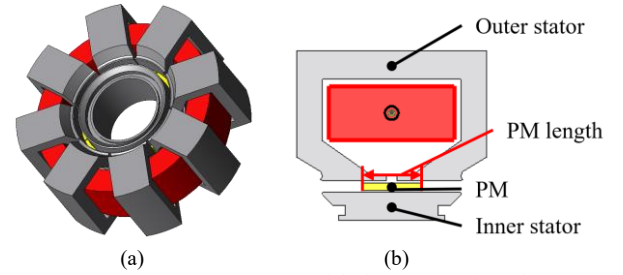


Fig. 1. LOA structures. (a) LOA 3D model. (b) Cross section of LOA.

TABLE I  
SPECIFICATIONS OF LOA

| Item                       | Unit      | Value      |
|----------------------------|-----------|------------|
| Phase resistance           | Ohm       | 10.394     |
| Input current              | $A_{rms}$ | 0.5        |
| Frequencies                | Hz        | 40, 51, 60 |
| Inner stator core material | -         | 50PN470    |
| Outer stator core material | -         | 35PN230    |
| PM material                | -         | 54SHS      |
| PM length                  | mm        | 18         |

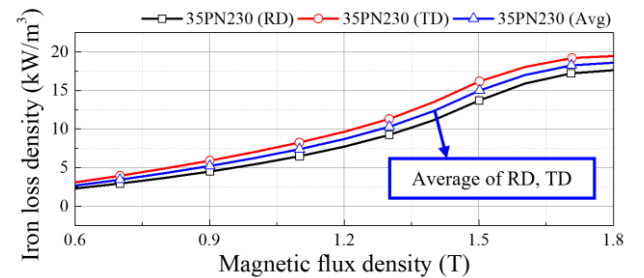


Fig. 2. Comparison of RD, TD and average iron loss density data of 35PN230 @ 50Hz.

In conventional method, only iron loss density data of average direction of RD and TD was used for calculating iron loss of the outer core shown in Fig. 3 (a). To include directional characteristics, the outer core was divided based on the direction of the magnetic flux. The magnetic flux directions and RD are shown in Fig. 3 (b). For the case of LOA, the outer core is manufactured as a single laminated plate, resulting in a single

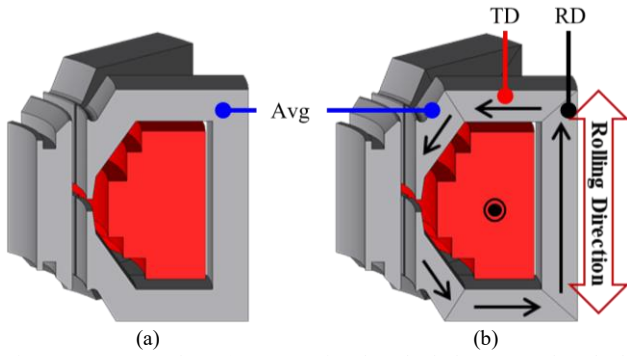


Fig. 3. 3D FEA topology. (a) Conventional method. (b) Proposed method.

RD. The magnetic flux directions have angles of  $0^\circ$ ,  $45^\circ$ , and  $90^\circ$  with respect to the RD. Parts where magnetic flux passes parallel to RD have an angle of  $0^\circ$ , tangential to RD with an angle of  $90^\circ$ , and diagonal to RD have an angle of  $45^\circ$ . In the proposed method, iron loss was calculated by applying different iron loss density data according to the flux direction in each section.

### B. AC Copper Loss

AC copper loss is generated by armature and field excitation, affected by the skin and proximity effect. Conventional method models the coil as a single region, which makes it impossible to accurately determine the current distribution within the coil caused by magnetic field distribution.

Fig. 4 (a) shows magnetic flux path of LOA at 51Hz load. Due to the structure, magnetic flux saturation occurs near the slot opening area, leading to flux leakage around the region. This leakage flux causes an imbalance in the magnetic field distribution within the coil, which results in AC copper loss. Therefore, in the LOA's structure, it is essential to consider the detailed current distribution to accurately assess AC copper loss.

To include the effect of AC loss in 3D FEA, each conductor was modeled respectively as Fig. 4 (b) in the proposed method, to get the armature current density for a single coil. For the case of LOA, 760 conductors were modeled considering the fill factor and current density limitation. Based on the calculated current density, the AC copper loss was included in the proposed method loss analysis.

## III. EXPERIMENTAL SETUP AND RESULTS

Fig. 5 shows the experimental setup for measuring loss of the LOA. Loss measurements were conducted with  $0.5A_{rms}$  load current in three different frequencies with the PM stationary at the center position of the LOA due to measurement limitations. Since PM is fixed in a single position, mechanical losses were not considered.

Fig. 6 compares loss error of the conventional method and proposed method. According to Fig. 6, the proposed method showed lower error compared to the conventional method, indicating that the proposed method is more suitable for LOA.

## IV. CONCLUSION

This paper proposes additional components in loss analysis for the case of LOA. Additional components are anisotropic

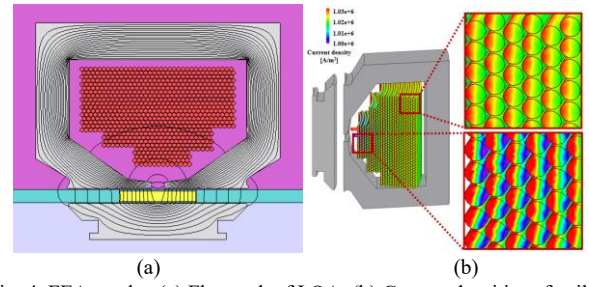


Fig. 4. FEA results. (a) Flux path of LOA. (b) Current densities of coil at load condition ( $I_{rms} = 0.5A_{rms}$ ,  $f = 51Hz$ ).

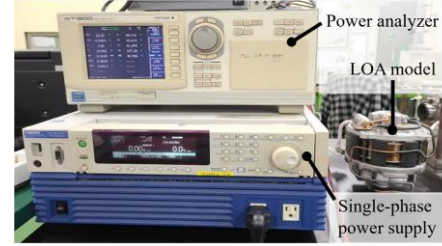


Fig. 5. Experimental setup for measuring loss of the LOA.

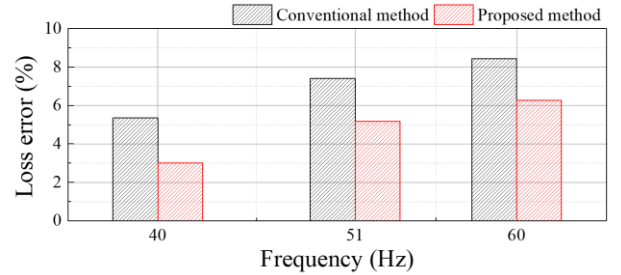


Fig. 6. Error comparison between conventional method and proposed method.

property of the outer core material and AC copper loss. Loss analysis with the proposed method enhances the reliability of 3D FEA.

Despite these improvements, some errors persist, potentially due to several reasons. One reason is the variations in specimen shapes during iron loss density tests, which can lead to different results even for the same material [3]. Another reason is the temperature difference between the 3D FEA and experimental environment. temperature differences affect the resistance and residual flux of the permanent magnet (PM), influencing magnetic losses and potentially causing demagnetization of PM, which further impacts overall electromagnetic losses. Finally, components such as PM eddy current loss should be considered for an accurate comparison of total losses between 3D FEA and experiments.

## REFERENCES

- [1] I. I. Abdalla, T. Ibrahim, and N. M. Nor, "Design and modeling of a single-phase linear permanent magnet motor for household refrigerator applications," in *Proc. IEEE Bus. Eng. Ind. Appl. Colloq. (BEIAC)*, Apr. 2013, pp. 634–639.
- [2] S. Zhu, Y. Hu, C. Liu, and K. Wang, "Iron loss and efficiency analysis of interior PM machines for electric vehicle applications," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 1, pp. 114–124, Jan. 2017.
- [3] D. M. Kim, J. W. Chin, J. P. Hong, and M. S. Lim, "Performance prediction of surface-mounted permanent magnet synchronous motor based on ring specimen test result," *IET Electric Power Applications*, vol. 13, no. 9, pp. 1280–1286, Sep. 2019.