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Experimental Verification and Electromagnetic Characteristics Analysis of Permanent magnet Linear Oscillating Actuator by using Semi 3D Analysis Technique with Corrected Stacking Factor

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Abstract

This paper proposes a semi 3D analysis method, analyzes a permanent magnet linear device with radially laminated structure. After the magnetic flux density was calculated using 2-D FEM analysis, the magnetic flux density in the iron core was estimated by considering the volume of the divided core. Finally, the core loss analysis of the laminated core was performed using the modified Steinmetz equation and then compared with the FEM analysis results. Additionally based on the predicted magnetic flux density, electromagnetic characteristics were compared through the experiment.

Structure of Linear Oscillating Actuator (LOA)

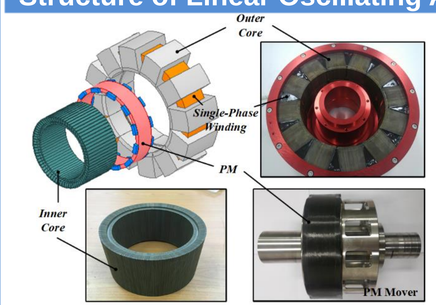

FIG. 1. Construction of LOA with radially lamination.

TABLE I REQUIRED DESIGN PARAMETER OF LOG FOR FPSE

Parameter	Value	Parameter	Value
Stroke	± 11 [mm]	PM weight	1 [kg]
Frequency	30 [Hz]	Maximum speed	3.46 [m/s]
Total piston weight	2.5 [kg]	Output Power	1500 [W]

- **In this model. Lamination of the radial direction perpendicular to the current flow direction of the coil is applied.**
- **Radially laminated cores consist of 12 lamination blocks be-cause of manufacturing limitations for the stator of this model.**
- **3D FEM analysis is essential for a more accurate analysis of radially stacked LOAs.**

Structure of Linear

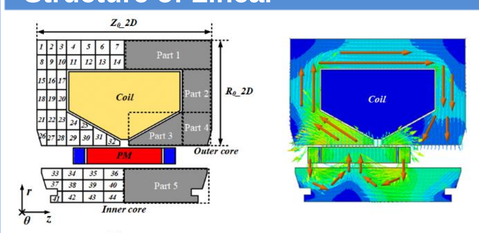

FIG. 2. (a) Analysis model for behavior and harmonics analysis of magnetic field and (b) Flux vector of LOA

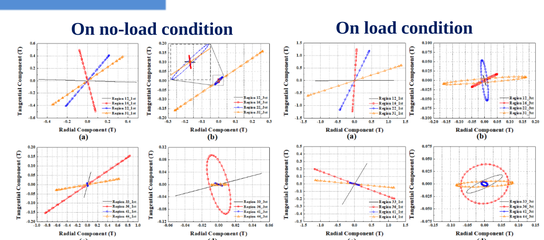

FIG. 3. 1st and 3rd harmonics magnetic behavior according to region : (a)-(b) Outer core regions, (c)-(d) Inner core regions

- **Fig 2 shows the 2D analysis model for semi 3d analysis.**
- **44 segmental analyzes were performed to analyze the magnetic flux flowing at each point.**
- **Fig 3 shows the analysis of magnetic field behavior according to odd harmonics at each point.**

Corrected Stacking Factor

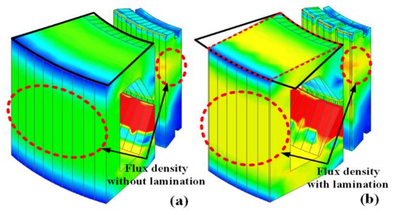

FIG. 4. Magnetic flux density at the rated condition (a) without lamination and (b) with lamination.

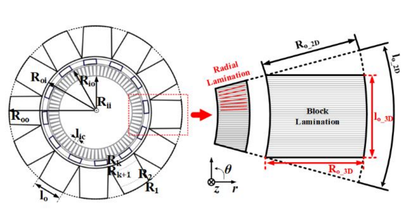

FIG. 5. Analysis model for finding of the corrected stacking factor

- **2-D cylindrical coordinate system does not take into account the radially laminated core**
- **Based on Fig. 5 , the corrected stacking factor of equation is derived.**
- **The calculated stacking factor is applied to derive the final magnetic flux density considering the laminated core volume.**

$$\alpha_s = \frac{\pi(R_{k+1}^2 - R_k^2)}{n_c l_o (R_{k+1} - R_k)} \qquad B_{3d} = \alpha_s \times B_{2d}$$

Core Loss Analysis

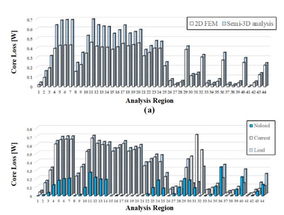

FIG. 6. Core Loss Analysis results in each region

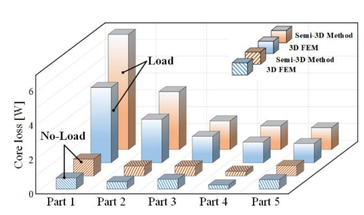

FIG. 7. Core loss results of the 3D FEM or the proposed Semi 3D analysis

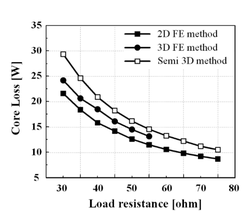

FIG. 8. Analysis results according to load resistance variation

- **On the load resistance 40 Ω, results by the semi 3D method, 2D FE method and 3D FE method for the core loss have a result of 23.3W, 16.3W, and 19.4W**
- **This difference arises from the consideration of magnetic field behavior.**
- **The predicted 3D magnetic flux density (B_3d) and applied to the modified Steinmetz equation to obtain the core loss**

$$P_{core\_semi3d} = \sum_{l=1,odd}^{\infty} \alpha_l \left(k_{hl} f_l B_{3d}^{\ n_{si}} + k_{el} f_l^{\ 2} B_{3d}^{\ 2} + k_{al} f_l^{\ 1.5} B_{3d}^{\ 1.5} \right)$$

Experimental Result and Discussion

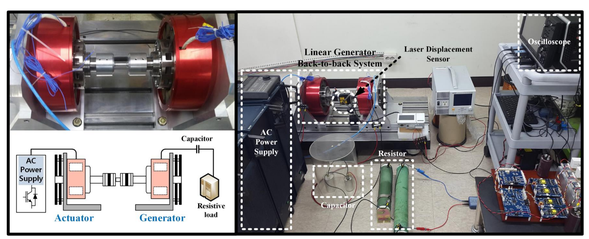

FIG. 9. Manufactured model of LOG and back-to-back experimental set.

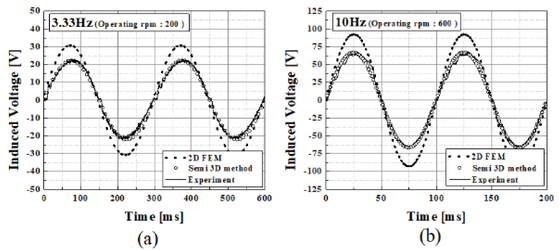

FIG. 10. Back-EMF waveform considering stacking factor at (a) 3.33Hz (b) 10Hz

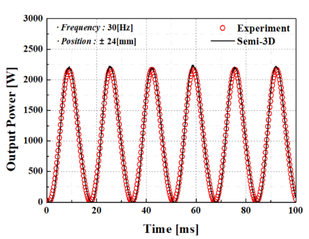

FIG. 11. Comparison of FEA result with experimental result: output power.

- **The analytical results were verified by comparison with 2D and 3D FEM results and experimental results.**
- **In terms of electromagnetic characteristics, the back-EMF is reduced due to the saturation of the iron core. Therefore, the inverse of the stacking factor was applied to the 2D analysis results of no-load induced voltage.**
- **The back-to-back test system was composed by linear actuator, linear generator, AC power supply, capacitor and load resistance.**
- **The two linear machine was connected linear coupling, and the air bearing was used for reduced friction loss**
- **The experimental results are agreement with the semi 3D analysis result.**