Characteristic Analysis of Transverse Flux Type Linear Oscillating Actuator According to Slot Number

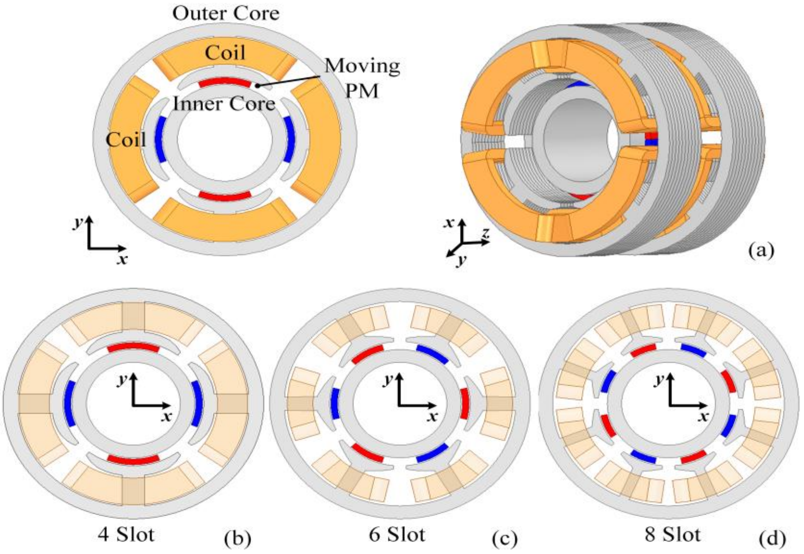
Chang-Woo Kim, Gang-Hyeon Jang, Kyung-Hun Shin, Sung-Won Seo, Jang-Young Choi

A transverse flux linear oscillatory actuator (TFLOA) for a compressor is proposed, which features a unique configuration consist of dual stator cores, single-phase winding coil and permanent magnet (PM) mover. It not only offers low manufacturing cost and good magnetic force density, but also provides high efficiency for its transverse flux flow. This paper deals with the design and electro-magnetic analysis of TFLOA according to a number of slots. For the same comparison, the use amount of the moving magnet, the outer diameter of the stator core, the moving stroke, and the frequency are selected equally. Finally, we compared the electro-magnetic characteristics such as no-load analysis, electromagnetic loss analysis, electromagnetic output and efficiency of each TFLOA and proposed the optimal TFLOA.

Keywords: Transverse flux machine, linear oscillating actuator, electromagnetic characteristic, electromagnetic loss analysis.

I. INTRODUCTION

Linear Oscillating actuators (LOAs) are machines that control linear reciprocating motion using a certain stroke cycles at a specific frequency [1-2]. Because of advantages such as their high transmission efficiency, simple structure, and low noise characteristics, LOAs are more suitable than traditional actuation methods that make use of rotatory motors and crankshafts, for devices such as electro-medical machines, electric hammers, linear pumps, refrigeration compressors [3–4]. LOA can be divided into longitudinal flux type LOA (LFLOA) and transverse flux type LOA (TFLOA) according to the direction of magnetic flux. Currently, most LOAs are manufactured LFLOA type. In general, TFLOA is known to have a higher power density than LFLOA. [5-6]. Therefore, This paper identifies the working principle of TFLOA. Next, In order to propose an optimal TFLOA, we analyzed the electromagnetic characteristics according to the number of stator slots. The electromagnetic characteristics, such as no-load analysis, electromagnetic loss analysis, electromagnetic output and efficiency, were compared and analyzed through a commercial finite element analysis program. Finally, we proposed the optimal number of slots for TFLOA.



4 Slot (b) 6 Slot (c) 8 Slot (d)

Figure 1. Analysis model of TFLOA (a) TFLOA configuration, (b) 4 slot, (c) 6 slot, (d) 8 slot

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Table 1. Specifications of TFLOA

Parameters	Value	Parameters	Value
Outer core diameter	100 mm	Core axial length	20mm X 2
PM thickness	2.5 mm	PM length	44 mm
PM mass	66 g	Air gap length	0.5mm / 0.5mm
Moving Stroke	15 mm	Frequency	100 Hz

II. ANALYSIS MODEL

Figure 1 shows the analysis model of TFLOA. The TFLOA consists of an outer stator core, an inner core, a permanent magnet (PM) and a coil. PMs are used as the moving part, which enables high frequency operation. In the TFLOA, the direction of current flow is parallel to the direction of the moving part(z-axis oscillating motion). As a result, the operation of this machine cannot be explained using the 2-D coordinate system. Hence, TFLOAs are analyzed using the 3-D FEA, for more accurate characterization of their behavior.

Figure 1 (b), (c), (d) shows the analysis model of 4-slot core, 6-slot core, 8-slot core, respectively. For the same comparison, the use amount of the moving magnet, the outer diameter of the stator core, the moving stroke, and the frequency are designed equally. Table 1 shows the details of the specifications of the TFLOA.

2.1 No-Load Analysis

In order to compare the electromagnetic performance of the TFLOA under the same conditions, the back electromotive forces

(EMFs) of the three models are designed to be the same. The magnetic flux density distributions of these models are shown in figure 2. Figure 3 shows the no-load analysis of these models. In the case of the 8-slot model, the back EMF waveform is distorted due to the saturation of the teeth, and the value of the detent force is also similar because the same magnet amount is used.

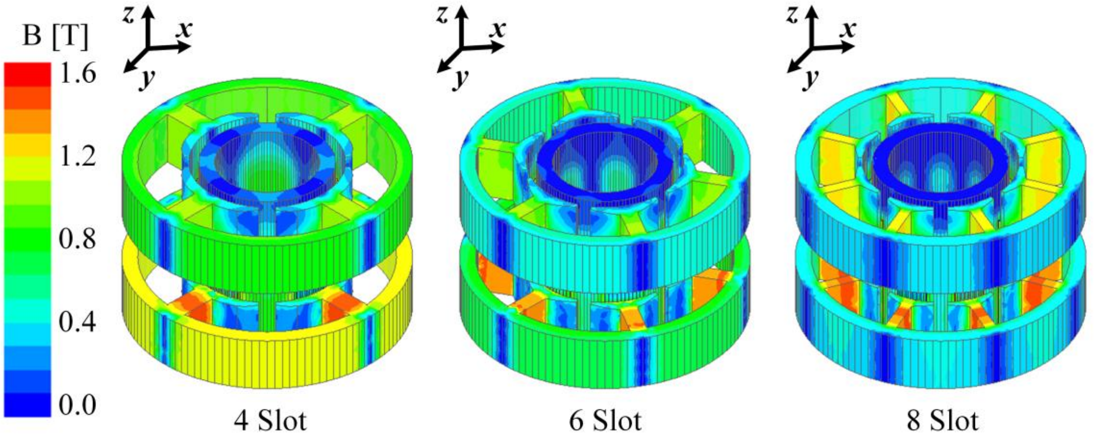


Figure 2. Comparison of magnetic flux density distribution according to the slot numbers.

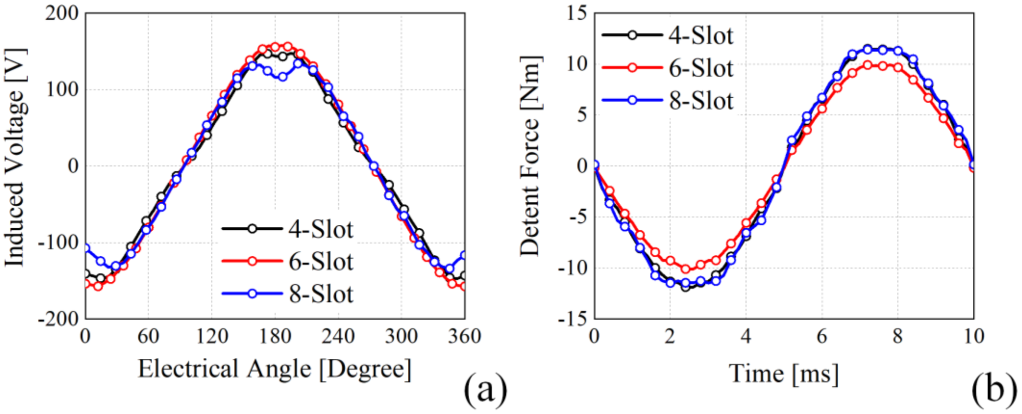


Figure 3. Comparison of no-load characteristics according to slot numbers; (a) back EMF, (b) detent force.

III. COMPARISON OF ELECTROMAGNETIC CHARACTERISTICS

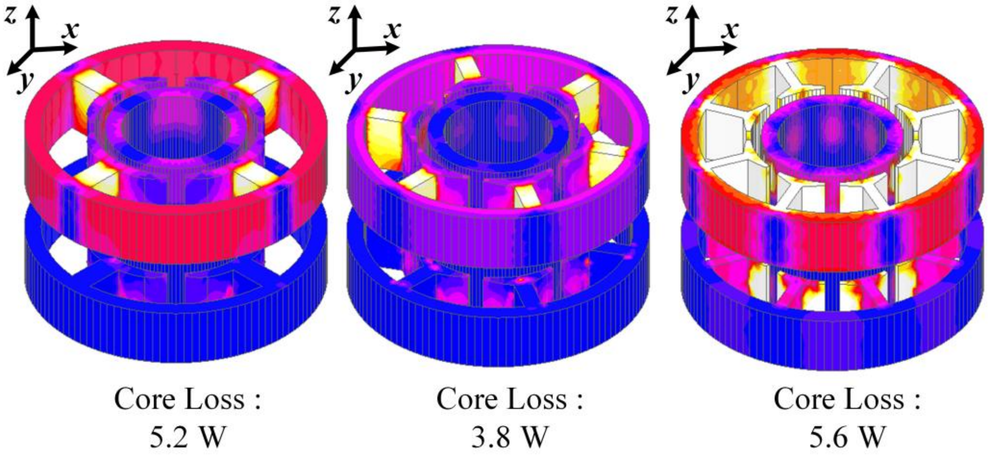
In order to compare the electromagnetic characteristics of TFLOA, electromagnetic loss analysis is performed. The electromagnetic losses of TFLOA consist of core loss, PM loss, and copper loss. This section discusses this.

3.1 Core Loss

The core loss calculated based on the Steinmetz equation as

$$P_{core} = P_h + P_e + P_a = k_h f_c B_c^{n_{st}} + k_e f_c^2 B_c^2 + k_a f_c^{1.5} B_c^{1.5} \quad (1)$$

Here, P_h, P_e, and P_a are the hysteresis loss, eddy current loss, and excess loss, respectively. k_h, k_e, k_a, and n_{st} are the hysteresis loss coefficient, eddy current loss coefficient, excess loss coefficient, and Steinmetz constant, respectively. f_c and B_c are the frequency of the magnetic flux density in the core, respectively. Figure 4 shows the core loss of TFLOA calculated from equation (1). It can be confirmed that more core loss occurs in the portion where the magnetic flux density is high.



Core Loss : 5.2 W

Core Loss : 3.8 W

Core Loss : 5.6 W

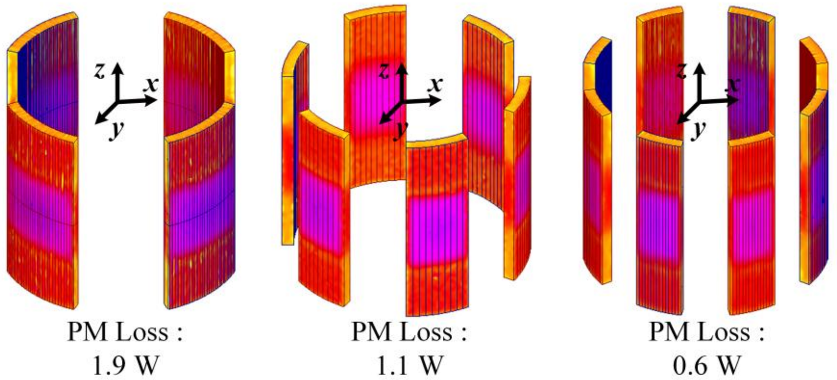
Figure 4. Comparison of core loss according to slot number.

3.2 PM Loss

The eddy current loss occurring in the PMs can be calculated as follow :

$$P_{eddy} = \frac{\omega_n}{2\pi} \int \int \frac{J_e^2}{\sigma} dVdt \quad (2)$$

Here, P_{eddy}, and J_e are the eddy current loss in the PMs and the eddy current density in the PMs, respectively. Figure 5 shows the PM loss. As the number of slots increases, the number of divided magnets increases, so that the magnet loss can be confirmed to be reduced.



PM Loss : 1.9 W

PM Loss : 1.1 W

PM Loss : 0.6 W

Figure 5. Comparison of PM loss according to slot number

3.3 Copper Loss

The copper loss can be calculated from the phase resistance and current as follows;

$$P_{cu} = R_{ph} I_{rms}^2 \quad (3)$$

Here, P_{cu}, R_{ph}, and I_{rms} are the copper loss, phase resistance, and value of the phase current, respectively. The copper loss consists of a phase resistance term and a phase current term. Therefore, accurate resistance calculation is essential for copper loss analysis. the phase resistance, and is calculated as follows:

$$R_{ph} = \rho_0 \left[1 + \alpha_r (T - T_0)\right] \frac{l_w}{S_c} \quad (4)$$

In (4), ρ_o is the resistivity of copper at room temperature, T_0, α_r is the temperature coefficient of resistivity, T is the operational temperature of the TFLOA, and l_w and S_c are the total length of the coil winding and the cross-sectional area of the coil, respectively. l_w can be calculated by multiplying the single-coil length of the TFLOA by the number of turns. Figure 6 shows a stator winding model for calculating the single-coil length of the TFLOA, where L_z is the axial length of the device and L_{end} is the length of the end turn. Hence, the single-coil length, l_{TFLOA}, can be calculated as follows:

$$l_{TFLOA} = 2L_z + 2\pi L_{end} \quad (5)$$

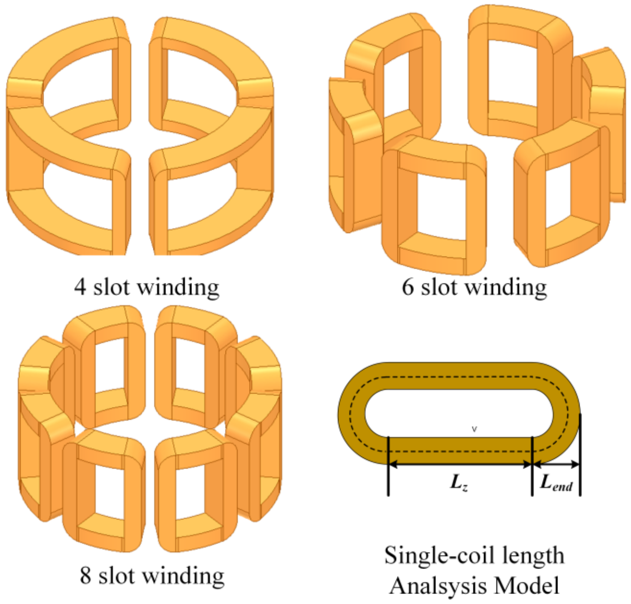


Figure 6. Stator winding model for calculating the single-coil length of the TFLOA

Using (3), (4), and (5), we calculated the phase resistance of the TFLOA. The phase resistances of 4, 6, and 8 slots TFLOA are calculated as 17Ω, 27 Ω, and 48 Ω, respectively. It can be seen that the resistance increases as the number of slots increases.

3.4 Output Power and Efficiency

Figure 7 shows the magnetic force and output power according to the applied current of TFLOA according to slot number. Detailed analysis results can be confirmed on the Table 2.

At low currents, the output characteristics of the three models are similar, but as the current increases, the difference in copper loss increases, and as the number of slots increases, the output and efficiency become worse.

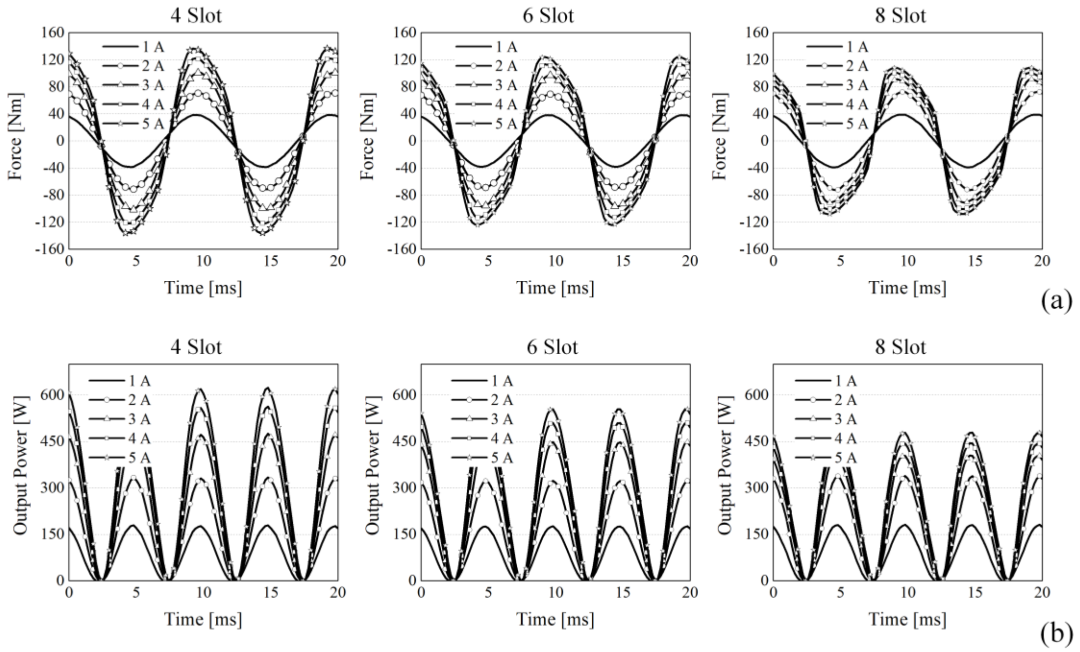


Figure 7. Comparison of magnetic force and output power according to slot number

Table 2. Analysis results of TFLOA

4 Slot	Force	Output Power	Core loss	PM loss	Copper loss	Efficiency
1 A_{max}	38.39 Nm	179.1 W	5.25 W	1.9 W	8.5 W	92.3 %
3 A_{max}	100.9 Nm	475.4 W	23.7 W	4.3 W	76.8 W	82.2 %
5 A_{max}	136.5 Nm	623.9 W	53.5 W	6.0 W	213.3 W	69.6 %
6 Slot	Force	Output Power	Core loss	PM loss	Copper loss	Efficiency
1 A_{max}	38.10 Nm	176.01 W	3.82 W	1.1 W	13.6 W	90.5 %
3 A_{max}	96.93 Nm	448.2 W	18.6 W	1.8 W	122.6 W	75.8 %
5 A_{max}	124.07 Nm	554.58 W	41.1 W	4.5 W	340.5 W	59.1 %
8 Slot	Force	Output Power	Core loss	PM loss	Copper loss	Efficiency
1 A_{max}	38.84 Nm	181.1 W	5.6 W	0.6 W	24.9 W	85.3 %
3 A_{max}	91.2 Nm	338.5 W	23.1 W	1.3 W	224.3 W	62.2 %
5 A_{max}	107.9 Nm	478.7 W	46.5 W	3.5 W	623.0 W	41.5 %

IV. CONCLUSION

In this paper, we compared the electro-magnetic properties of TFLOA according to the number of slots. The turns of stator are selected to have the same back EMF for all three models. Next, the electro-magnetic characteristics of TFLOA are compared when the same current is applied. As the number of slots increases, the number of magnet divisions also increases, so the permanent magnet loss is reduced. However, it can be confirmed that the efficiency is lowered because the copper loss is greatly increased due to the increase of the coil usage. Therefore, the optimal slot numbers of TFLOA can be confirmed.

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