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The Characteristics of LGE Linear Oscillating Motor

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ABSTRACT

This paper summarizes the characteristics of LGE linear oscillating motor from the viewpoint of electro-magnetic loss. Through the results of finite element analysis, the magnetic flux and loss due to magnet and coil current, respectively, are shown and estimated. The magnetic flux of magnet and current generates the eddy-current and hysteresis losses in not only electrical steels but also mechanical parts. The linear motor efficiency is defined from aspect of electro-magnetic efficiency. The static efficiency of motor is inversely proportional to the cooling capacity, because the current is almost proportional to the capacity. However, the dynamic efficiency of motor is proportional to the cooling capacity. For the high efficiency in small capacity region, the magnetic losses (core losses) due to moving-magnet should be reduced as much as possible. Furthermore, these moving-magnet losses are deeply related to the materials of mechanical structures around motor.

1. INTRODUCTION

LG Electronics has developed an energy efficient linear compressor for the household refrigerators utilizing a free piston mechanism. The conventional reciprocating compressors have crank mechanism that converts the rotational motion of motor into reciprocating one for the piston, which causes much friction loss. The linear compressor is composed of linear oscillating motor directly coupled with piston and springs for resonant operation. Also, the linear oscillating motor applied for direct-drive is a short-stroke, single-phase, radial magnetized permanent magnet motor. In order to achieve a low side force, a high power density and efficiency, the linear motor employs a tubular structure, 2-airgap, and moving high energy permanent magnets.

The stator is composed of outer and inner core, bobbin, and annular winding. The outer stator is fixed by the stator cover and frame made of sheet metal and aluminum alloy, respectively. To obtain the easy alliance between the piston and the magnet mover, the cylinder and the piston are placed in the inner stator. So, they are located inside the motor and severely affected by the coil and magnet field. A conventional rotational motor is multi-pole type and its coil and magnet flux is confined in electrical steel core. However, the linear oscillating motor in this paper has one pole magnet and its coil and magnet flux leak to the mechanical parts. This leakage flux generates the eddy-current and hysteresis losses in ferromagnetic material and electric conductor, cylinder, piston, stator cover, and frame and so on. Therefore, these losses reduce the advantage of linear compressor with low friction loss.

In this paper, the characteristics of LGE linear oscillating motor will be reviewed, and defined the motor efficiency from aspect of electro-magnetic loss. Through the results of finite element analysis, the flux and the magnetic loss due to magnet and coil current are presented, respectively. Finally, the efficiency of the linear motor system according to the capacity modulation of the compressor will be mentioned.

2. LGE LINEAR OSCILLATING MOTOR

There are various linear motor topologies which might be employed in oscillating applications. Figure 1(a) shows the configuration of the linear motor we have chosen. In order to achieve not only a low side force but a high power density and efficiency, linear motor employs a cylindrical structure, and moving high energy magnets. The motor is moving magnet type and driven the single-phase source. The stator is divided into outer and inner one by the moving magnets. The outer stator, as shown in Figure 1 (b), has C-shaped core block laminated electrical steel, whereas the inner stator, as shown in Figure 1(c), is laminated in the radial direction. An annular winding is housed in C-core blocks. The radial magnetized magnets, as shown in Figure 1(d), are segmented and mounted on a nonmagnetic supporter. The oscillating force is generated by the pull and push force between the magnets and the pole of stator core due to coil's alternating current.

The flux of linear motor is generated by the magnets and coil current. When the magnets are at the motor center, the magnet flux doesn't flow at outer yoke and all leak to both poles, as shown in Figure 2(a). Whereas, the magnets flux begin to flow at outer yoke as the magnets are out of the outer stator center. When the magnets lines up the pole, the magnet flux is maximized at outer yoke. Therefore, the alternating flux is generated by the oscillating magnets. Like the magnet flux, the alternating coil flux is the same principle, as shown in Figure 2(c). After all, the amplitude of total flux depends on the phase difference between the magnet displacement and the coil current, as given in Equation (1):

$$\Phi_t(t) = \sqrt{\Phi_A^2 + 2\Phi_A\Phi_m\cos\theta + \Phi_m^2}\,\cos(2\pi ft) \qquad \text{---------} \quad (1)$$

where Φ_t : total flux, Φ_A : coil flux, Φ_m : magnet flux, Θ : phase difference, and f : excitation frequency. Figure 3 shows the phase diagram of magnet flux and the coil flux according to the phase difference which depends on the relation of the system and excitation frequency.

The linear motor driven in resonant frequency is designed to achieve the maximum efficiency. Due to their inherent high efficiency and power density, the moving magnet type linear motor is particularly attractive. However, the coil and magnet field directly affect the mechanical parts. Figure 4 shows the model for finite element analysis, which has the motor and the main mechanical parts, cylinder, piston, stator cover, frame. The motor losses, to be accurate the electro-magnetic losses, are generated at not only the electrical steel core but also the mechanical parts. This reason is that most mechanical parts are made of ferromagnetic materials and electric conductor. Therefore, it is reasonable that the motor efficiency is defined in terms of the electro-magnetic one. As shown in Table I, the electro-magnetic losses of linear motor system are classified as the conduction and the magnetic loss. From a different viewpoint, the electro-magnetic losses are separated from the static loss due to coil current and the dynamic loss due to moving magnet. The magnetic losses are composed of the eddy-current loss and the hysteresis loss in the ferromagnetic material and electric conductor. The motor efficiency is defined and given in Equation (2):

$$\eta = \frac{P_{input} - P_{StaticLoss} - P_{DynamicLoss}}{P_{input}} \times 100\ [\%] \qquad \text{--------} \quad (2)$$

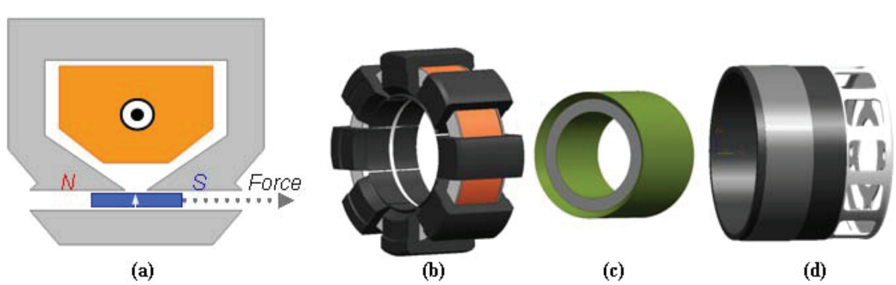


Figure 1: Linear oscillating motor
(a) Overview, (b) Outer stator, (c) Inner stator, (d) Magnet frame

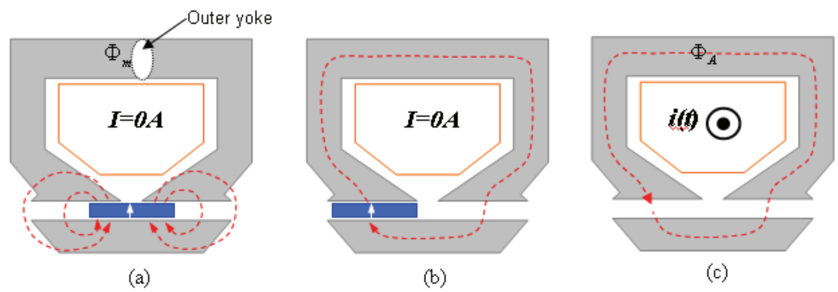


Figure 2: Magnetic flux path of linear motor
(a)(b) Moving magnet, (c) Coil currents

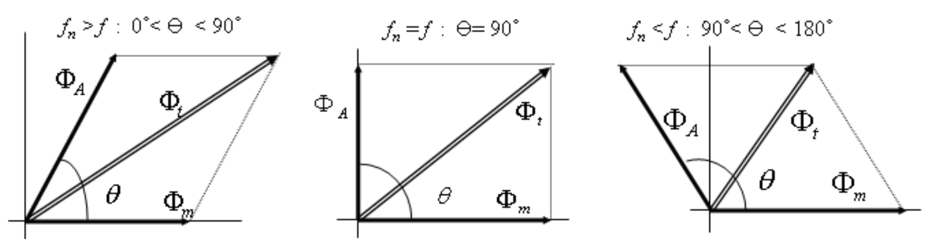


Figure 3: Phase diagrams of magnet and coil flux

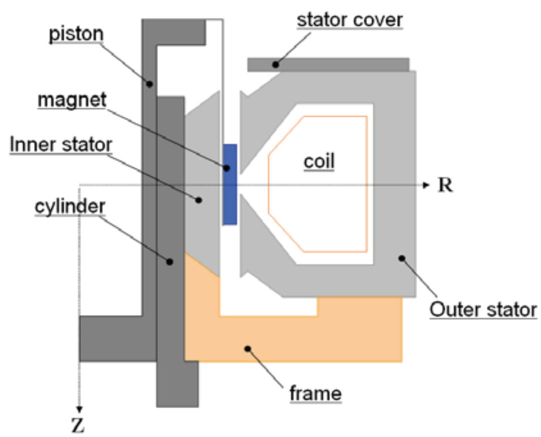


Figure 4: Analysis model of linear motor system

Table 1: Loss of linear motor system

		parts	parameter
Static loss (current loss)	Conduction loss	Al or copper wire	R_{dc}
	Magnetic loss (Core loss)	-Electrical steel -Frame, piston, cylinder, stator cover etc.	R_{ac}
Dynamic loss (magnet loss)		-Electrical steel -Frame, piston, cylinder, stator cover etc.	C_{magnet}

3. FIELD AND LOSS ANALYSIS OF LINEAR MOTOR SYSTEM

The distributions of magnet flux are different according to the magnet position. If the magnet is at motor center, Z=0mm, the magnet flux doesn't flow at outer yoke, whereas most flux return to pole, airgap, and inner stator. The leakage flux flows to the mechanical parts and has a slight change in its direction and amplitude. However, the main flux has the alternating flow through the outer yoke, airgap, and inner stator. After all, the magnetic loss due to moving magnet is affected by the stator core, mainly. Figure 6 shows the distributions of magnetic flux and the eddy current at stroke=14mm, 60Hz. Though the Piston/Cylinder and stator cover are ferromagnetic material, the hysteresis loss cannot be considered in finite element analysis. The eddy-current loss due to the edge flux is generated at the piston of the cylinder edge.

Figure 6 shows the distributions of magnetic field due to the coil current at fixed magnet, Z=0mm. The direction and amplitude of main flux depend on the coil current, and other flux leaks to mechanical parts. The amplitude of leakage flux change according to the coil current, and therefore the change of leakage flux generates the eddy-current and hysteresis loss. Especially, the eddy-current loss of the aluminum alloy frame is significantly greater. Figure 7 shows the core loss due to coil current according to MMF. The core loss of compressor assembly is much greater than the one of motor assembly, about 5~6 times. The result of static test shows that the main magnetic loss of linear motor system is generated at mechanical parts.

Table 2 gives the results of loss analysis. The hysteresis losses in mechanical parts cannot be calculated and therefore are estimated through the dynamic and static test results. The magnetic losses of current in the mechanical parts are significantly greater. The dynamic losses of moving-magnet are similar portion in the electrical steel core and others. The moving-magnet loss of full capacity operation has greater portion than the one of small capacity region.

4. EFFICINCY OF LINEAR MOTOR SYSTEM

For the linear compressor, the cooling capacity is modulated by the controlled stroke of the free piston. When the stroke is fully operated, the cooling capacity is maximized. The cooling capacity is proportionally modulated by the under-stroke operation of the piston. However, the stroke of piston isn't proportional to the cooling capacity because of the dead volume at the under-stroke operation. The motor speed of under-stroke operation slightly decreases, and therefore the magnetic loss of moving magnet is about the same. Figure 8 (a) shows the static, dynamic, and total efficiency of linear motor system according to the capacity modulation of the linear compressor. At the small capacity modulation, the dynamic efficiency of moving magnet decreased and the static efficiency of coil current rapidly increased. Because of this trend of static efficiency, LGE linear motor can employ the aluminum wire for stator. Figure 8 (b) shows the magnetic and electrical loss according to the cooling capacity ratio. The magnetic loss included the loss of moving magnet and current, is 1.6 times larger than the electrical loss of coil wire heat because of the eddy-current and hysteresis loss of mechanical parts with ferromagnetic and conductive material.

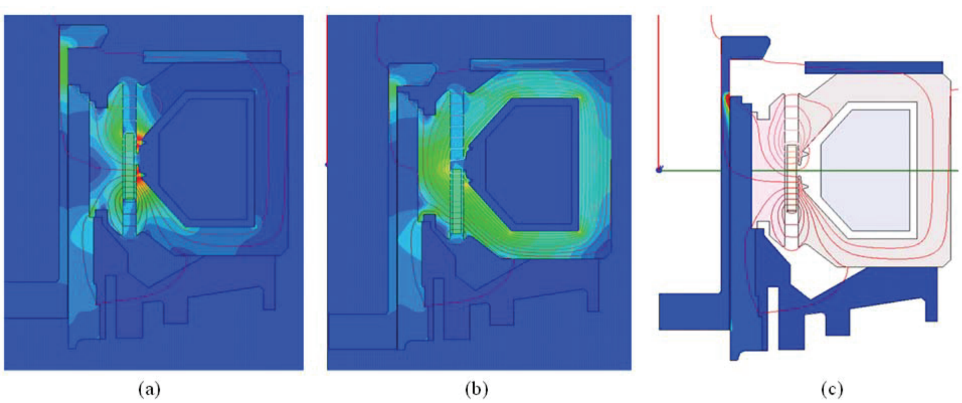


Figure 5: Distributions of magnet field and eddy current loss
(a) Z=0mm, (b) Z=+7mm, (c) Eddy current loss

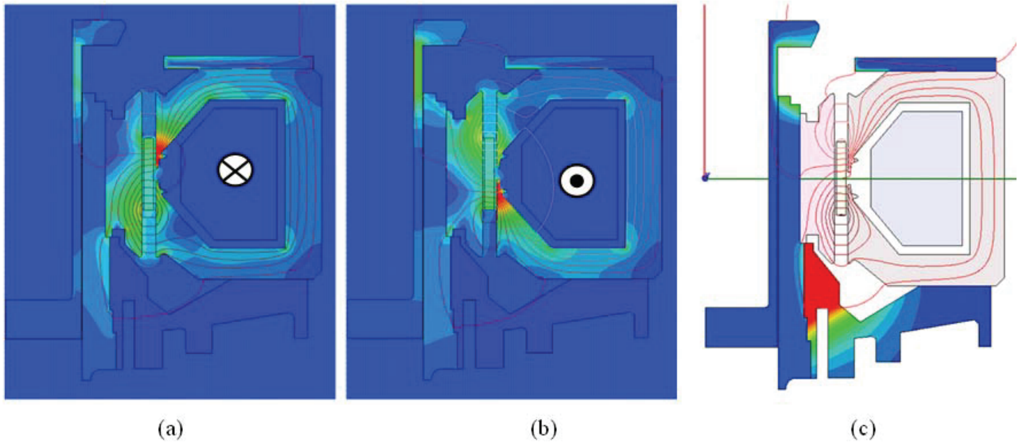


Figure 6: Distributions of coil current field and eddy current loss
(a) Negative current, (b) Positive current, (c) Eddy current loss

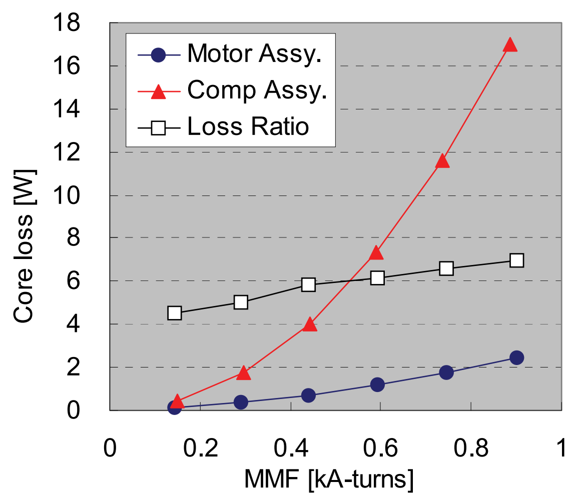
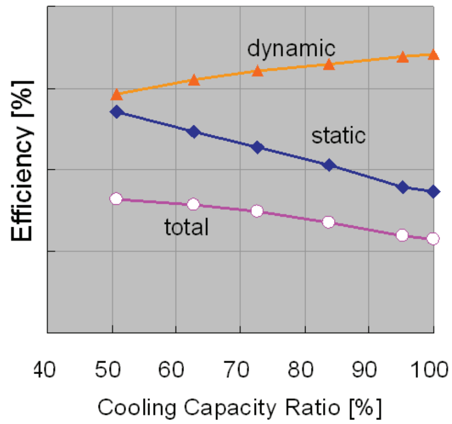


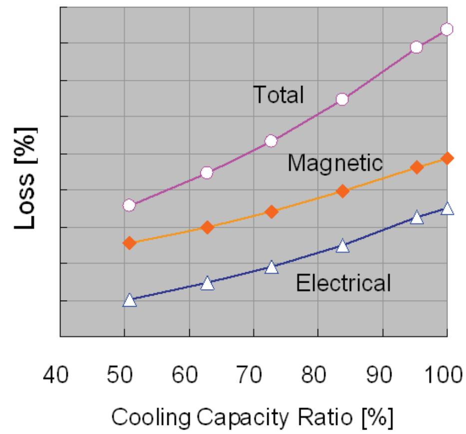
Figure 7: Core loss of static test

Table 2. Results of loss analysis [%=loss/total magnetic loss]

		100% Cooling	50% Cooling
Moving magnet	@ Electrical steel core	23	38
	@ others	25	33
AC current	@ Electrical steel core	9	5
	@ others	43	24
Moving magnet + AC Current @ resonance	@ Electrical steel core	34	45
	@ others	66	55



(a)



(b)

Figure 8: Efficiency (a) and loss (b) according to cooling capacity ratio

5. CONCLUSIONS

In the LGE Linear oscillating motor, the magnetic flux of coil current and moving-magnet generates the eddy-current loss and hysteresis loss in not only the electrical steel core but also the ferromagnetic material and electric conductor, cylinder, piston, stator cover, and frame and so on. The efficiency of linear motor has to be defined from aspect of electro-magnetic efficiency. These loss characteristics of linear motor reduce the advantage of linear compressor with low friction loss. Unfortunately, the dynamic motor efficiency is proportional to the cooling capacity. For the high efficiency in small capacity region, the moving-magnet losses should be reduced as much as possible.

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