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IRON LOSS ANALYSIS OF LINEAR MOTOR FOR LINEAR COMPRESSOR

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ABSTRACT

A refrigerator consumes 20~40% of the total electric energy in a house. And most of the electricity in the refrigerator is consumed for operating the compressor. Therefore, developing a high efficiency compressor is necessary to increase the energy efficiency.

To increase the efficiency of the linear motor, a new linear motor design with a reduced electrical loss is needed. Also, the loss analysis is preceded to design the linear motor having higher efficiency.

In this paper, the iron loss analysis is implemented by using the analytical and numerical methods. The iron loss analysis of the linear motor is performed by using ANSYS, the commercial FEA tool and tested iron loss curve made by the manufacturer. The proposed methods are applied to the iron loss analysis of the linear motor. For the validation of the iron loss analysis result, the experiment measuring the iron loss of the linear motor is performed and this result is compared with that of ion loss analysis result.

1. INTRODUCTION

The linear compressor mentioned in this paper is composed of linear oscillating motor directly coupled with piston and springs for resonance operation. So the linear motor must have a high efficiency for the high efficiency linear compressor. The loss of the linear motor entirely means the electrical loss. The reason is that the linear motor does not need energy conversion system such as screw, chain, bearing and gear systems. The electrical loss of the linear motor is mainly divided into copper loss and iron loss. And the iron loss is distributed to the eddy current loss and hysteresis loss due to the alternating flux and excess loss due to the motion of the magnetic material. To increase the efficiency of the linear motor, a new linear motor design with a reduced electrical loss is needed. Also, the loss analysis is preceded to design the linear motor having higher efficiency [1].

Although the iron loss analysis is one of the most important parts for the loss analysis of the linear motor, it is very difficult to analyze. Therefore, most researchers perform the iron loss calculation by using the experiment. However the experimental method needs much time and cost because of alternating each new designed motor with the previous one. Hence, the iron loss analysis without the experiment is needed.

In this paper, the iron loss analysis is implemented by using the analytical and numerical methods [2]-[3]. Also, the iron losses considered in this paper include the eddy current loss and hysteresis loss. For the iron loss analysis of the linear motor, three methods, which are Method Ⅰ, Method Ⅱ and Method Ⅲ, are proposed. Method Ⅰ is performed by using ANSYS, the commercial FEA tool. Method Ⅱ and Method Ⅲ are performed by using ANSYS and tested iron loss curve made by the manufacturer. The proposed methods are applied to the iron loss analysis of the linear motor. For the validation of the iron loss analysis results, the experiment measuring the iron loss of the linear motor is performed and this result is compared with that of each iron loss analysis method.

Finally, the iron loss of the linear motor is calculated and the iron loss analysis result is validated.

2. IRON LOSS ANALYSIS

2.1 Iron Loss Analysis Method Ⅰ

The main source of the iron loss in the motor is an alternating magnetic field generated by the ac coil. This alternating magnetic field can potentially produce the eddy current loss in any conductive material and hysteresis loss in any ferromagnetic material subjected to this field

The iron loss analysis method Ⅰ is performed to FEA method by using ANSYS, the commercial tool. Generally, the FEA tool to solve the electromagnetic problem can be considered to calculate the eddy current loss. But the calculation of the hysteresis loss isn't possible. The hysteresis loss analysis is able to the experiment. Therefore, the iron loss analysis method Ⅰ considers the eddy current loss generated in the magnetic materials. The eddy current loss analysis is the steady state time harmonic analysis.

Two dimensional eddy current phenomena are described by the diffusion equation. For the steady state time harmonic case, this equation, in terms of the magnetic vector potential is

$$\frac{1}{\mu}\frac{\partial^2 A}{\partial x^2}+\frac{1}{\mu}\frac{\partial^2 A}{\partial y^2}=-J_0+j\omega\sigma A \tag{1}$$

This equation considers along with time stepping procedures.

In Equation (1), the eddy current density is

$$J_e = j\omega\sigma A \tag{2}$$

The eddy current density represented to Equation (2) is calculated by using FEA, ANSYS.

By using the eddy current density, the eddy current loss is calculated. The eddy current loss is written in terms of the current density as

$$P_e=\frac{1}{2\sigma}\int_V J_e\cdot J_e^{'}dV \tag{3}$$

where J_e is the eddy current density and σ is the conductivity of the material.

2.2 Iron Loss Analysis Method Ⅱ

Calculation of the iron loss of the magnetic material is traditionally made with sinusoidal flux density of varying frequency and magnitude. The total iron loss density (p_{iron}) is commonly expressed in the following form for sinusoidal varying magnetic flux density (B) with angular frequency (f).

$$p_{iron}=p_h+p_e=k_hB^{\alpha}f+k_eB^2f^2 \quad \left[W/m^3\right] \tag{4}$$

To calculate the iron loss by using Equation (4) k_h k_e α has to be applied to the known value. These values are obtained by the iron loss curve. Figure1 is the iron loss curve tested by Epstein test apparatus

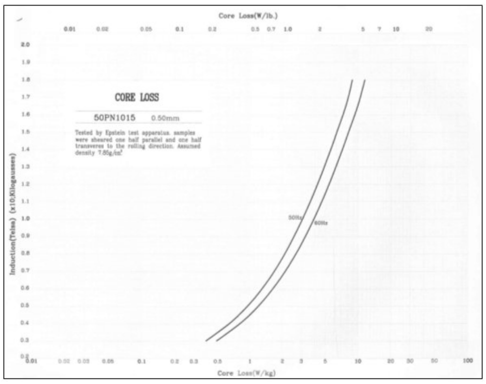


Figure 1: Iron loss curve

The sample to perform the experiment is sheared one half parallel and one half transverse to the rolling direction. The material shown in Figure 1 is the iron core. The type of this iron core is called to S24. Through the curve fitting by using the iron loss curve, k_h, k_e, α is calculated.

The iron loss curve, which is given by the manufacturer, is the data by the reliable experiment. So this iron loss curve is reliable data. Then, some assumption is required.

First, the short circuit between one flat core and another aren't considered, while stacking the core.

Second, the alternating flux is only considered beside of the rotating flux.

So, Method Ⅱ for the iron loss analysis is performed by using ANSYS which is used to get the flux density of each element and tested iron loss curve which is used to get k_h, k_e, α. The iron loss analysis by using this method refers to Equation (4). The iron loss expression in Equation (4) is valid only for sinusoidal flux density.

For the eddy current it is convenient to represent the average loss density as a function of the time rate of change of the vector flux density.

$$p_e = \frac{2k_e}{T}\int_0^T \left(\frac{dB}{dt}\right)^2 dt \ \left[W/m^3\right] \tag{5}$$

where T is the period.

The radial (x) and circumferential (y) components of flux at time step t_n in the volume element m are evaluated as $B_{mx,n}$ and $B_{my,n}$. The continuous form, equation (5) can be rewritten as the discrete form to use the FEA method. The total eddy current loss can be obtained from equation (5) as

$$\begin{aligned} P_e &= \frac{p}{2}\sum_{m=1}^{M} A_m l_{fe} \frac{2k_e}{T} 2\int_0^{T/2}\left(\frac{dB}{dt}\right)^2 dt \\ &= 2pNk_e l_{fe} f^2 \sum_{m=1}^{M}\left\{A_m\left[\sum_{n=1}^{N}\left(B_{mx,n}-B_{mx,n-1}\right)^2+\sum_{n=1}^{N}\left(B_{my,n}-B_{my,n-1}\right)^2\right]\right\} \quad [W] \end{aligned} \tag{6}$$

where N, $T/2$, l_{fe}, A_m and M is the total number of steps in the half time period, the core length, the area of element m and the total number of elements in the core.

Similarly, the total hysteresis loss can be expressed as

$$P_h = 2\pi f k_h l_{fe}\sum_{m=1}^{M}\left[A_m B_{m,\max}{}^{\alpha}\right] \ [W] \tag{7}$$

2.3 Iron Loss Analysis Method Ⅲ

The iron loss analysis method Ⅲ is evaluated by the frequency analysis of the magnetic flux density distribution by the time-stepping FEM and the iron loss curves, which are provide by manufacturer. Iron loss in each element is evaluated using iron loss curve and total iron loss is obtained by the summation of the losses in all elements. In this method, the iron loss curve considered to that of the iron loss analysis method Ⅱ is used.

The iron loss analysis method Ⅲ considers Equation (4) similar to the iron loss analysis Ⅱ.

$$p_{irion} = aB_{\max}{}^2 + bB_{\max} + c \ \ [W/kg] \tag{8}$$

The unknown values a, b and c are evaluated by the curve fitting of the iron loss curve. The iron loss density (p_{iron}) at each element is calculated from Equation (8). The maximum flux density ($B_{\max}$) is considered to distributing $B_{\max}{}^{x}$, $B_{\max}{}^{y}$, $B_{\max}{}^{sum}$, respectively.

$B_{\max}{}^{sum}$ is represented as

$$B_{\max}{}^{sum} = \sqrt{\left(B_{\max}{}^{x}\right) + \left(B_{\max}{}^{y}\right)} \tag{9}$$

The total iron loss is calculated by the summation of the iron loss at each element.

$$P_{iron} = \sum_{n=1}^{m} p_{iron}{}^{n} \cdot weight^{n} = \sum_{n=1}^{m} p_{iron}{}^{n} \cdot (\rho^{n} \cdot A^{n} \cdot l_{fe}) \ [W] \tag{10}$$

where m, A, l_{fe}, ρ is total number of elements, area of the element, core length, density.

3. IRON LOSS ANALYSIS OF LINEAR MOTOR

3.1 FEA of Linear Motor

The iron loss analysis methods considered in this paper use the FEA tool, ANSYS, to get the flux density of each element. To analyze the iron loss of the linear motor by using each iron loss analysis method, FEA is performed.

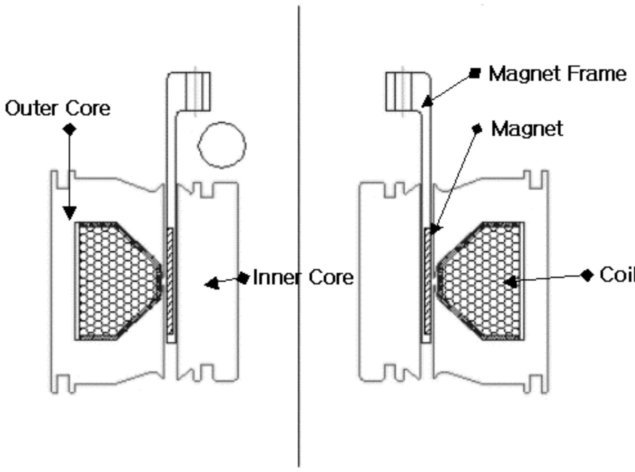


Figure 2: Linear motor

The structure of the linear motor for the iron loss analysis is shown in Figure 2. As shown in Figure 2, the linear motor is composed to the inner core, outer core, inner ring, magnet and coil.,

In this part, the static analysis by using ANSYS is considered. The material property of each part in the linear motor for the FEA is represented in Table 1. B-H curve of the core and blade is shown in Figure 3.

Table 1: Material property of each part in the linear motor

	Relative Permeability	Current Density (Js)	Resistivity (ρ)
Inner Core	B-H Curve	•	•
Outer Core	B-H Curve	•	•
Coil	0.98	0.68A and 600 Turns	1.75e-8
Magnet	•	•	•
Inner Ring	1	•	7.20e-7
Air	1	•	•

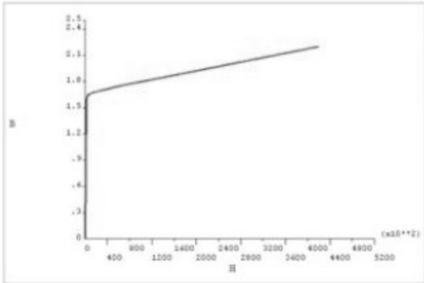
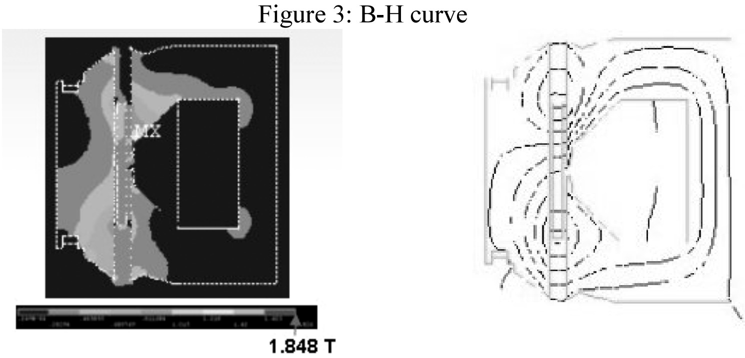


Figure 3: B-H curve



(a). Flux density (b). Flux line

Figure 4: FEA result

The flux density and flux line, which flow through the core nicely, is shown in Figure 4.(a), (b).

To use the FE model of the linear motor, the validation has to be needed. For the validation of the FE model of the linear motor, the experiment of the linear motor is performed. In the experiment, the force and the flux density in the air gap are measured. Also, the experimental result is compared with the FEA result. Then, the situation of the experiment has to be considered to same as that of FEA.

To validate FE model of the linear motor, some experiments, which is the measurement of the force and the flux density in the air gap are performed.

First, through the experiment, the electromagnetic force of the linear motor is measured.

Table 2 shows the result considering the comparison of the experiment and FEA. As shown in Table 3, the error is very small.

Table 2: Comparison between the result of experiment and FEA

	FEA [%]	Experimental [%]	Error [%]
Force	101.6	100	1.64

Second, the experiment measuring the flux density of the air gap is performed to validate of the FE model. The experiment set is shown in Figure 5.

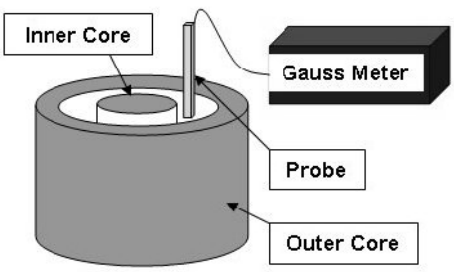


Figure 5: Experimental set

To measure the flux density, the sufficient air gap is needed. And the gauss meter is used to measure the flux density of the air gap. The gauss meter used in this experiment is the type of MG-5DAR made by Walker Scientific Inc. Measuring range is composed to ± 100.0 [Gauss], ± 1.000k [Gauss], ± 10.00k [Gauss]. Also, the accuracy of the equipment is 0.05% of the equipment range.

Table 3 shows the result comparing the experiment to FEA. As shown in Table 3, the error between FEA and the experiment is smaller than 5%.

Table 3: Comparison between the result of the experiment and FEA

Current [Arms]	Experiment [%]	FEA [%]	Error [%]
0.15	100	103.7	3.3
0.21	100	103.9	3.7
0.25	100	104.1	4.0

Through the experiments measuring the force and the flux density in the air gap of the linear motor, the FE model of the linear motor is validated. Therefore, the FE model of the linear motor can be used to the iron loss analysis.

3.2 Experiment of Iron Loss

For the validation of the iron loss result calculated by each analysis method, the experiment to measure the iron loss is performed. The experimental set is shown in Figure 6.

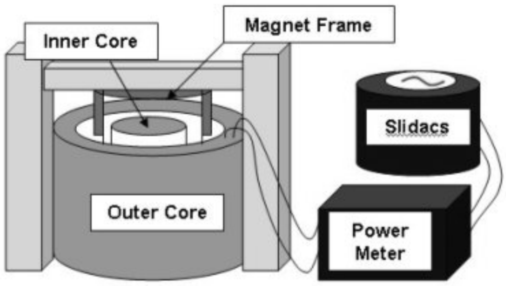


Figure 6: Experimental set

As shown in Fig 5, the experimental set is composed to the slidacs, power meter and frame. The frame is used to fix the magnet frame combined with the magnet. The upper part of the frame is attached to the magnet frame. The power meter displays the measured voltage, current, power and power factor. The experimental result is given by changing the input current from 0.7[Arms] to 1.1[Arms].

By subtracting the copper loss which is calculated to measure the resistance of the coil from the power measured by the power meter, the iron loss of linear motor is calculated.

3.3 Comparison between Iron Loss Analysis Result and Experimental Result

To validate the iron loss analysis result of linear motor by using each iron loss analysis method, the comparison between iron loss analysis result and the experimental result.

Table 4 shows the error between the iron loss analysis result and the experimental result.

Table 4: Error between iron loss analysis result and experimental result

Current [A]	Method Ⅱ [%]	Method Ⅲ-1 [%]	Method Ⅲ-2 [%]
0.7	0.2	9.0	11.0
0.8	5.3	0.6	1.8
0.9	2.1	0.6	2.3
1.0	5.4	6.9	4.0
1.1	2.0	6.0	2.8

4. CONCLUSIONS

In this paper, each iron loss analysis method, which is Method Ⅰ, Method Ⅱ and Method Ⅲ, is applied to the iron loss analysis of the linear motor. For the validation of the iron loss analysis results, the iron loss of the linear motor is measured by experiment. And experimental result is compared with that of each iron loss analysis method. The error is almost smaller than 10%. From these results, it is verified that each iron loss analysis method considered in this paper is good enough to analyze the iron loss of the linear motor.

NOMENCLATURE

A	Magnetic vector potential	P_h	Hysteresis loss
J_e	Eddy current density	P_e	Eddy current loss
N	Coil turn number	α	Steinmetz constant
σ	Electrical conductivity	f	frequency
k_h	Hysteresis constant	k_e	Eddy current constant

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