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Study on Iron Loss in Two Kinds of Moving-magnet Linear Motors

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ABSTRACT

Linear motors are widely used in cryogenic fields to drive Stirling-type cryocoolers. Generally the Joule heat loss associated with copper lead is considered as the main loss in motors while the iron loss is ignored at a lower frequency operation, not only because it’s regarded as small enough but also it’s difficult to measure or calculate. This paper introduces an experimental method to measure the iron loss for linear motors. Two kinds of moving-magnet linear motors have been tested, one is known as single coil and magnet linear motor, and the other as double coils and magnets linear motor. Dependence of iron loss on frequency and displacement are investigated. Results show that there is a 1.6 power exponent relation between iron loss and frequency in the single-coil moving-magnet linear motor, and its iron loss come to be the same as copper loss at 75 Hz, it even grows to 1.65 times of copper loss at 100Hz. As for the double coils and magnets linear motor, there is a 1.3 power exponent relation between iron loss and frequency, and its iron loss percentage is only 15% at 120 Hz compared with 68% in the single-coil linear motor. Iron loss is proved to be significant in linear motors especially at higher frequency.

1. INTRODUCTION

Since linear compressors were introduced into cryogenic field at early 1980s by Oxford university (Davey, 1981), they have been widely used in Stirling and Pulse tube cryocoolers as pressure generators. Compared with the conventional rotary compressor, linear compressor is driven by linear motor which removes the transmission mechanism between rotary and linear movement. Because of this, linear compressor possesses merits of light weight, small size, long life and high efficiency, which make it suitable for space and military applications. In recent years, linear compressor has also turned to research for civil use such as in household refrigerators (Lee et al., 2000). In cryogenic applications, higher frequency and higher charging pressure means much larger cooling power density (Radebaugh, 2007), and it will bring advantages such as lighter weight, smaller size and faster cool down (Vanapalli et al., 2007). Although theoretical analysis shows that performance of a cryocooler operating at a higher frequency(e.g. 100Hz) could be as well as at a normal frequency(e.g. 30Hz), the practical result is not the case (Wu et al., 2010). That’s because some losses in the cryocooler, especially in the linear compressor, grow with frequency sharply. Iron loss is one of these losses. It seems important to understand the mechanism of iron loss and how to reduce it in order to improve the overall cryocooler efficiency.

2. THEORETICAL ANALYSIS

Iron loss is consisted of two parts: hysteresis loss and eddy current loss.
In a linear motor, outer and inner iron cores are employed to strengthen the magnetic field around the circuit. When the compressor is operating, the magnetic field generated by the coil will be alternating. Located in this alternating magnetic field, the iron core will be magnetized repeatedly, and this causes energy dissipation with the magnetic domain rubbing with each other all the time. All this energy turns into heat. This hysteresis loss in a linear motor is equal to the area of the magnetic hysteresis loop and can be expressed as

$$p_h = Vf \oint HdB = C_h V f B_m^n$$

(1)

Where $V$ is the volume of the iron core, $\oint HdB$ is the area of the hysteresis loop, $C_h$ is the hysteresis loss factor, $f$ is frequency and $B_m$ is the highest magnetic flux density, $n$ is a constant.

As iron core is electric and magnetic conductor, due to the law of electromagnetic induction, there will be induced electromotive force in the iron core when it’s located in alternating magnetic field. So the eddy current is caused, and there will be an amount of Joule heat which is called the eddy current loss. This loss can be expressed as

$$p_e = C_e V f^2 \tau^2 B_m^2$$

(2)

Where $C_e$ is the eddy current loss factor, $\tau$ is the thickness of the steel disc if it’s used as iron core.

The total iron loss is combined by the two parts above

$$P_{Fe} = p_h + p_e \approx C_{Fe} f^{1.3} B_m^2 G$$

(3)

Where $C_{Fe}$ is the iron loss factor and $G$ represents the weight of the iron (Tang and Shi, 2003).

The unknown factors $C_h, C_e, n$ and $C_{Fe}$ make the calculation of iron loss in a linear motor more difficult, for different iron materials and different motor structures, these factors will be different. So experimental methods are needed to measure iron losses in different kinds of linear motors.

3. EXPERIMENTAL OBJECTS AND APPROACH

3.1 Experimental objects

Two kinds of moving magnet linear motors are chosen to be our experimental objects here. They are motor I (single coil and magnet motor) and motor II (double coils and magnets motor).

![Figure 1: The axis symmetry cutaway view of a single coil and magnet linear motor](image1)

![Figure 2: The axis symmetry cutaway view of a double coils and magnets linear motor](image2)

Figure 1 shows the typical structure diagram of a motor I which is consisted of one coil and one magnet. This kind of linear motor owns advantages as follows: It has a compact structure and a large specific thrust which can meet the requirements of high efficiency and high power design. Also it has some disadvantages: The motor structure is somehow more complicated, it has a larger inherent electromagnetic offset force, and it has a longer axial dimension.
Figure 2 shows the structure diagram of a motor II which is consisted of two coils and two magnets. The two coils are oppositely wound, and the two magnets are oppositely magnetized. This kind of linear motor owns advantages as follows: It has less magnetic flux leakage, and the magnetic circuit is more symmetrical. While the disadvantages are: Higher magnetic reluctance in the air gap due to the larger space between inner and outer iron cores, and generally the inner iron core moves accompanied with the magnet which make a heavier active cell. What’s more, more coils are needed with the same specific thrust compared with motor I. It’s efficiency is regarded lower than the former type.

Two linear motors with the same specific thrust 25N are employed in this experiment.

3.2 Experimental method
When the compressor is operating, some input electrical power is transformed into mechanical energy through the linear motion of active cell. Supposed the active cell be steady, there will be no output mechanical energy, all the input electrical power will be transformed into heat inside the linear motor, in another word, into copper loss and iron loss. The copper loss (I^2R) is simple to calculated via measuring the resistance of the coil and the input current. By subtracting the copper loss from the total power supply, the iron loss of the linear motor is obtained.

A fixed steel block is used here in place of the plate spring, shown in Figure 3. The active cell is fastened with the stator by this block, screw joint is employed between the two parts so that the piston displacement can be adjusted. Figure 4 shows the schematic diagram of this experiment. A variable-frequency power sources is employed to control the input power and frequency, the input power and the current value is obtained from a power meter, and the coil resistance is read from a multimeter. The iron loss is expressed as follows

\[ p_{Fe} = p_c - p_{Cu} = p_c - I^2 R(T) \]

(4)

where the \(R(T)\) means the dependence of coil resistance on temperature is taken into account.

4. RESULTS AND ANALYSIS
Experiments are carried out on these two kinds of linear motors, dependence of iron loss on frequency and piston displacement are investigated.

Figure 5 shows the dependence of total input power, copper loss and iron loss on frequency in the two different kinds of linear motors, while the current is fixed at 3 A. It’s simple to understand that the copper loss under the same input current keeps steady, but the iron loss increases obviously as \(f\) grows higher, which makes the total power dissipation increase with \(f\) at the same trend. With the same specific thrust 25 N, motor I has a coil resistance only 1.2\(\Omega\), while it’s 3.4\(\Omega\) in motor II. That’s why the copper loss in these two motors are so different. But the iron loss prove to be another situation. It’s shown in Figure 5 that for motor I, the copper loss is little but the iron loss increases with \(f\) significantly. At lower frequency (below 20 Hz), the iron loss is so small that it could be ignored compared with copper loss. As \(f\) goes higher, the iron loss increases with \(f\) at a power exponent, it even catches up with the copper loss at 75 Hz. What’s more, iron loss grows to 1.65 times as the copper loss at 100 Hz and 2.2 times at 120 Hz. So frequency has a great influence on the iron loss as well as the total motor loss in motor I.
In comparison, the iron loss is much smaller than the copper loss in motor II, both of its iron loss and total power consumption increase more slightly than that of motor I. That’s mainly because in this kind of linear motor, the two coils are oppositely wound, so the generated magnetic field in the inner and outer iron cores by one coil is mostly cancelled by the other. As a result, the hysteresis loss is expected to be almost zero. Comparisons between the two different kinds of linear motors show that for frequencies under about 100 Hz, the total motor power consumption in motor I is lower than that of motor II, the situation is the opposite for frequencies above about 100 Hz. And the rising tendency is more significant in the motor I.

Figure 5: Dependence of total motor loss on frequency in two types of linear motors

Figure 6: Dependence of iron loss on frequency at two displacements in two types of linear motors

Figure 6 shows the dependence of iron loss on frequency and piston displacement in two kinds of linear motors. It’s shown that there is a week dependence on displacement in motor I. And for motor II, its iron loss is smaller at 5mm than 0mm. Fitting curves were made and show that in motor I, there is a 1.6 power exponent relationship between its iron loss and frequency. As for motor II, the factor is 1.3, which is smaller than the other one. It’s indicated that iron loss has a strong dependence on the motor type, and the iron loss in motor I grows more significantly as $f$ increases. Figure 7 shows the iron loss percentage in two kinds of linear motors. It’s shown the percentage in motor I is much higher than motor II. In motor I, the iron loss exceeds the copper loss after 75 Hz, and the iron loss percentage increases to 68% at 120 Hz. In comparison, the iron loss percentage is much lower in the motor II which is only 15% even at 120 Hz.
Figure 7: Dependence of iron loss percentage on frequency at two displacements in two types of linear motors

5. CONCLUSIONS

Iron loss in a linear motor is significant. The dependence of iron loss on piston displacement is week while the frequency has a strong influence on the iron loss. The type of a linear motor applied to a linear compressor is important. Effective ways should be sought out to reduce iron loss in a linear motor in order to improve the overall efficiency of a linear compressor.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Subscripts</th>
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<tbody>
<tr>
<td>B</td>
<td>magnetic induction</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>factor</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>frequency</td>
<td>Cu</td>
</tr>
<tr>
<td>H</td>
<td>magnetic field intensity</td>
<td>Fe</td>
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<tr>
<td>p</td>
<td>power</td>
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<tr>
<td>V</td>
<td>volume</td>
<td>e</td>
</tr>
<tr>
<td>G</td>
<td>weight</td>
<td>m</td>
</tr>
</tbody>
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τ       | thickness     | |

Subscripts:
- Cu: copper
- Fe: iron
- h: hysteresis
- e: eddy current
- m: maximum

REFERENCES


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