Investigations on a Three-dimensional Model of the Moving-coil Linear Motor Applied in the Space-borne Micro Compressor

Y B Zhao\textsuperscript{1,2}, D Ding\textsuperscript{1,2} and X C Mao\textsuperscript{1,2}

\textsuperscript{1}Shanghai Institute of Measurement and Testing Technology, Shanghai, 201203, China
\textsuperscript{2}Shanghai Key Laboratory of Online Test and Control Technology, Shanghai, 201203, China

zhaoyb@simt.com.cn

Abstract. In order to optimize the magnetic circuits of the linear motor applied in the space-borne pulse tube cryocooler, a three-dimensional magnetostatic field model of the moving-coil linear motor in the micro compressor is established. The effects of several key dimensions on the distributions of the magnetic flux density inside the air gap are simulated and discussed by finite element method. The simulated results show that the magnetic flux density decreases with the increase of both width and thickness of air gap. According to the analysis, it will greatly facilitate the design, fabrication and future practical applications of the micro moving-coil linear compressor.

1. Introduction
The core component of a linear compressor is the linear motor. According to different moving parts, it can be divided into three main types: moving-iron, moving-coil and moving-magnet types. In recent years, both the moving-coil and moving-magnet linear compressors have wide applications in a number of scientific and industrial fields. Especially, the moving-coil linear motor realizes the complete elimination of the radial force due to its structural characteristics, and it does not generate axial force and torque on the current-carrying coil when it is open, and thus having several advantages such as high efficiency, low noise and high reliability. Therefore, it has become the preferred power source for space-borne pulse tube cryocoolers in the past thirty years [1--3].

The micro moving-coil linear compressor is designed based on the modified scaling principle [4], which assumes that the magnetic induction intensity $B$ at the electrified inductor should be fixed. However, the magnetic induction intensity inside the air gap may be weakened due to the reduction in the size of the linear motor. Therefore, its magnetic circuit should be optimized before component processing and experimental testing. In this paper, a three-dimensional magnetostatic field model of the moving-coil linear motor in the micro compressor is established. The influences of several key dimensions on the magnet circuits are simulated and discussed.

2. Model setup
Figure 1 shows a schematic of the typical Oxford-type moving-coil dual-opposed linear compressor, in which the permanent magnet, the return iron and the moving coil form the magnetic structure of the
linear motor. In order to study the characteristics of the magnetic field and then optimize the magnetic circuit configuration, a three-dimensional theoretical model of the micro magnetic structure is established, as shown in figure 2, which consists of four essential parts: the permanent magnet, the pole piece, the magnetic pole and the air gap. All of four parts are designed to be hollow cylinders for simplifying the calculation process.

![Figure 1. The typical Oxford-type moving-coil dual-opposed linear compressor](image1)

**Figure 1.** The typical Oxford-type moving-coil dual-opposed linear compressor

![Figure 2. The 3-D model of the micro magnetic structure](image2)

**Figure 2.** The 3-D model of the micro magnetic structure

![Figure 3. The cross-sectional drawing of the magnetic structure](image3)

**Figure 3.** The cross-sectional drawing of the magnetic structure

Figure 3 shows the cross-sectional drawing of the 3-D micro magnetic structure model, in which several important dimensional parameters are marked, including the width of air gap $w_g$, the thickness of air gap $t_g$, the width of permanent magnet $w_m$, the width of pole piece $w_p$ and the inner and outer radiuses of permanent magnet and pole piece $r_{im}$, $r_{om}$, $r_{ip}$, and $r_{op}$, respectively. In the whole simulation, both the inner and outer radiuses of the magnetic pole are equal to those of the permanent magnet, and the width of the magnet pole should keep the same with that of the air gap.

**Table 1. Initial dimension parameters of the simulated magnetic structure**

| Dimension parameter       | Value (mm) |
|---------------------------|------------|
| Width of air gap $w_g$    | 7          |
| Thickness of air gap $t_g$| 2.4        |
| Width of magnet $w_m$     | 9.3        |
| Outer radius of magnet $r_{om}$ | 19   |
| Inner radius of magnet $r_{im}$ | 5     |
| Outer radius of pole piece $r_{op}$ | 27.5 |
| Inner radius of pole piece $r_{ip}$ | 21.4 |
| Width of pole piece $w_p$ | 21.6       |
Table 1 gives the initial dimension parameters of the simulated micro magnetic structure in the basic model, which is scaled down from mid-size moving-coil dual-opposed linear compressors developed in the authors’ laboratory based on the scaling principles [5].

The material of the permanent magnet is selected as the NdFeB alloy. Its coercive force and maximum energy product are as high as 890 kA/m and 280 kJ/m³, respectively, and its magnetization is in the axial direction. Both the pole piece and the magnetic pole are made of pure iron, and the air gap is filled with the working fluid of helium.

The governing equations for the 3-D micro magnetic structure model are based on Maxwell’s equations, including the Faraday’s law of electromagnetic induction, the Gauss’s law, the flux continuity theorem and the Ampere’s loop law, which are given by:

\[
\nabla \times E = -\partial B / \partial t
\]
\[
\nabla \times H = J + \partial D / \partial t
\]
\[
\nabla \cdot B = 0
\]
\[
\nabla \cdot D = \rho
\]

where \(E, B, H, D, J, \rho\) and \(\tau\) represent the electric field intensity, magnetic flux density, magnetic field intensity, electric displacement, conduction current density and volume charge density, respectively.

Each component in the model is divided into the tetrahedral mesh. The minimum length of the mesh in the air gap is set as 0.2 mm, while that in the permanent magnet, the pole piece and the magnetic pole is 0.5 mm. The total number of mesh elements is up to 140175 in the basic model and no noticeable difference about the simulated result is observed when the minimum length of the mesh in the air gap is decreased to 0.1 mm.

3. Simulated results and discussions

3.1. Width of air gap

The magnetic flux density to be investigated is inside the air gap, and therefore the size of air gap will have great impact on the distribution of magnetic field. Table 2 gives the dimensional parameters of the micro magnetic structure in Cases A1–A6, in which the width of air gap ranges from 1 mm to 11 mm, and the width of pole piece varies accordingly on the condition that other parameters remain constant. Case A4 is used as the basis of optimization, and its specific parameters are provided in table 1. The distributions of the magnetic flux density inside the air gap with different widths of air gap are calculated, and the effect of \(w_g\) on the specific thrust is also investigated.

| Case number | \(w_g\) (mm) | \(t_g\) (mm) | \(w_p\) (mm) | \(w_m\) (mm) | \(r_{om}\) (mm) | \(r_{op}\) (mm) | \(r_{im}\) (mm) | \(r_{ip}\) (mm) |
|-------------|--------------|--------------|--------------|--------------|----------------|----------------|----------------|--------------|
| A1          | 1            | 2.4          | 15.6         | 9.3          | 19             | 27.5           | 5              | 21.4         |
| A2          | 3            | 2.4          | 17.6         | 9.3          | 19             | 27.5           | 5              | 21.4         |
| A3          | 5            | 2.4          | 19.6         | 9.3          | 19             | 27.5           | 5              | 21.4         |
| A4          | 7            | 2.4          | 21.6         | 9.3          | 19             | 27.5           | 5              | 21.4         |
| A5          | 9            | 2.4          | 23.6         | 9.3          | 19             | 27.5           | 5              | 21.4         |
| A6          | 11           | 2.4          | 25.6         | 9.3          | 19             | 27.5           | 5              | 21.4         |

Figures 4(a)–4(f) show the contours of the simulated magnetic flux densities inside the air gap in Cases A1–A6, respectively. It can be observed that, the magnetic flux density monotonously increases in radial direction from outside to inside in each case, except that there exist slightly uneven distributions in Cases A1 and A3. Therefore, the moving coil should be placed closer to the magnetic pole so as to get higher specific thrust. In addition, the magnetic flux density inside the air gap is between 1.02 T and 1.18 T in the basic case, and its mean value is about 1.10 T, which is basically the
same with the tested value in the mid-size moving-coil linear compressor developed in the authors’ laboratory. It proves the assumption in the scaling principles that the magnetic field intensity is kept constant.

Figure 4. The contours of the simulated magnetic flux density in Cases A1–A6

It can also be found that the magnetic field intensity decreases with the increase of the width of air gap in figure 4. Figure 5 shows a detailed comparison of the radial distributions of the average magnetic flux densities in Cases A1–A6, where the radial location represents the distance between the test point and the inner boundary of air gap. The simulated values have been averaged in axial direction. The results show that the magnetic flux density drops sharply when \( w_g \) increases from 1 mm to 5 mm, and then decreases gradually when \( w_g \) increases from 5 mm to 11 mm. The reason is that the magnetic lines of force become more concentrated in the air gap with the smaller \( w_g \). Moreover, it is worth noting that the difference between the maximum and minimum magnetic flux density also decreases with the increase of the width of air gap.

Figure 5. Radial distributions of the average magnetic flux densities in Cases A1–A6

The specific thrust \( F_{LM} \) is given by:

\[
F_{LM} = BL_w \propto Bw_g
\]
where $L_w$ represents the effective length of coil. The linear motor in the micro compressor employs the long coil design, and therefore $L_w$ is proportional to $w_g$. As a result, the specific thrust is directly proportional to both the magnetic field intensity and the width of air gap. Figure 6 shows the relative specific thrust in Cases A1–A6, in which the result in Case A4 is set to the standard value of 1. With the increase of the air gap width, the magnetic flux density decreases as shown in figure 5, but the specific thrust shows an upward trend due to the greater increase of the effective coil length. Especially when the air gap width increases from 1 mm to 5 mm, the relative specific thrust rises by a wide margin from 0.39 to 0.91. However, the rising amplitude of the relative specific thrust drops sharply when the air gap width continues to increase. Therefore, based on the design principle to minimize the size of the linear motor under the sufficient motor force, Cases A3 and A4 are considered to be two ideal choices. However, as shown in figure 4(c), there exists slightly uneven distribution of the magnetic flux density in Case A3, and thus Case A4 is the best choice, and 7 mm is the optimum width of air gap, which is the same as the initial setup.

3.2. Thickness of air gap

The thickness of air gap $t_g$ also needs to be optimized. Table 3 gives the dimensional parameters in Cases B1–B6. Only the air gap thickness is changed on the condition that other key parameters are constant. The working condition of B4 is exactly the same as A4.

| Case number | $w_g$ (mm) | $t_g$ (mm) | $w_p$ (mm) | $w_m$ (mm) | $r_{cm}$ (mm) | $r_{op}$ (mm) | $r_{im}$ (mm) | $r_{ip}$ (mm) |
|-------------|------------|------------|------------|------------|---------------|---------------|---------------|---------------|
| B1          | 7          | 0.6        | 21.6       | 9.3        | 19            | 25.7          | 5             | 19.6          |
| B2          | 7          | 1.2        | 21.6       | 9.3        | 19            | 26.3          | 5             | 20.2          |
| B3          | 7          | 1.8        | 21.6       | 9.3        | 19            | 26.9          | 5             | 20.8          |
| B4          | 7          | 2.4        | 21.6       | 9.3        | 19            | 27.5          | 5             | 21.4          |
| B5          | 7          | 3.0        | 21.6       | 9.3        | 19            | 28.1          | 5             | 22.0          |
| B6          | 7          | 3.6        | 21.6       | 9.3        | 19            | 28.7          | 5             | 22.6          |

Figure 7(a)–7(f) shows the distributions of the internal magnetic flux density inside the air gap in Cases B1–B6. The magnetic flux density also shows a trend of increasing outward from inside. However, it is worth noting that, for the two small thicknesses in Cases B1 and B2, the distribution of the flux density is seriously uneven, especially when the air gap thickness is only 0.6 mm. In addition, a small number of spots appear in Case B6. As a result, when the air gap is too large or too small, there may be uneven distributions of magnetic flux density.

Figure 7. The contours of the simulated magnetic flux density in Cases B1–B6
Figure 8 further compares the distribution of flux density along the radial direction in Cases B2–B6. Due to the seriously uneven distribution in Case B1, it is not within the scope of discussion. As the air gap thickness increases, the magnetic flux density generally decreases uniformly. When the air gap thickness is greater than 2.4 mm, the average magnetic flux density in the air gap range is less than 1.1 T, so the premise of the modified scaling principle is not satisfied. Since the magnetic flux density distribution is uneven in Case B2, it is only necessary to further compare the specific thrust characteristics of Cases B3 and B4. According to the above design, the thickness of each layer of the coil is about 0.53 mm, and when the thickness of air gap is 2.4 mm, four layers of coils can be wound, and 1.8 mm is only enough to wind three layers. It is calculated that the ratio of the specific thrust in Cases B3 to B4 is about 1.16. Therefore, 2.4 mm can be considered as the optimal air gap thickness, which is still consistent with the initial design value.

Figure 8. Radial distributions of the average magnetic flux densities in Cases B2–B6

4. Conclusions
In this paper, a three-dimensional magnetostatic field model of the moving-coil linear motor in the space-borne micro compressor is established to optimize magnetic circuits in the structure. The effects of some key dimensions such as air gap width on the distributions of the magnetic flux density inside the air gap are simulated and analysed.

The simulated results show that the magnetic flux density monotonously increases in radial direction from outside to inside. Therefore, the moving coil should be placed closer to the magnetic pole so as to get higher specific thrust. In addition, the magnetic flux density decreases with the increase of both width and thickness of air gap. Moreover, when the air gap is too large or too small, there may be uneven distributions of magnetic flux density.

According to the analysis, it proves that the modified scaling principle in designing the space-borne micro compressor is reasonable. The corresponding experiment will be conducted in the future to validate the simulation results.

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