Static Characteristic Analysis and Force Optimization of a Short-stroke DC Planar Motor with Three Degree of Freedom

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***Abstract*—This paper deals with the static characteristic analysis and force optimization of a novel 3-DOF short-stroke DC planar motor. The translation displacement of ±1mm in the *x* and *y* directions and the rotation degree of ±3° about the *z* axis can be achieved. The air-gap flux density, static force, torque and back-EMF are obtained analytically and compared with the 3D finite element simulation. Then the static force is optimized by changing some main parameters. Finally, the measured results of planar motor prototype are in good agreement with the analytical calculation and the simulation.**

***Index Terms*—FEM, multi-degree-of-freedom, optimization, planar motor, static characteristic.**

I. INTRODUCTION

Generally, conventional motors with multiple degrees of freedom are manufactured by stacking several single degree of freedom motors. However, it is difficult for such motors to improve their positioning accuracy and frequency response due to multiple moving parts, complicated dynamic characteristics and complex control strategy. By contrast, planar motors have only one moving part and can be directly driven in a plane coordinate system. In recent years, various types of planar motors have been proposed [1]-[7]. Due to its excellent static and dynamic characteristics, there is a great application potential for planar motors in semiconductor manufacturing machines, scanning probe microscope and precision measurement system.

In this paper, static characteristic and force optimization of a novel 3-DOF short-stroke DC planar motor are investigated. Fig. 1 shows the basic structure of the planar motor. The planar motor adopts moving magnet scheme which has moving magnets and stationary coils. The double-sided PM structure is applied in order to make the magnetic field gentle and increase the electromagnetic force. The mover consists of 24 pieces of PMs and two back irons. The stator consists of four square DC coils and a braced frame. The four coils are glued to the braced frame on the same level.

The novel DC planar motor is driven by four groups of Lorentz driving units and its driving principle is the same as voice coil actuator. In particular, no matter what direction of motion the mover is driven in, all the four coils always work together at the same time. Therefore, when force level is close, the current of coil in the proposed DC planar motor is decreased compared with common separating coil layout. And the heat distribution of motor is more uniform, which is a crucial factor in some precision positioning systems.

II. ANALYTICAL MODEL AND STATIC CHARACTERISTIC

By using magnetic charge method and image method, the *z*-component amplitude of air-gap magnetic field can be expressed as the following equation:

$$B_{zm} = \frac{2\mu_0 M_{\mathrm{r}}}{\pi} \times \left(\mathrm{arctg}\frac{l^2}{\frac{h}{2}\sqrt{2l^2+(\frac{h}{2})^2}} + \mathrm{arctg}\frac{l^2}{(\frac{h}{2}\pm H)\sqrt{2l^2+(\frac{h}{2}\pm H)^2}} + \mathrm{arctg}\frac{l^2}{(\frac{h}{2}\pm 2H)\sqrt{2l^2+(\frac{h}{2}\pm 2H)^2}}\right) \quad (1)$$

where μ_0 is relative permeability of vacuum; M is magnetization of permanent magnet; l is the half length of square permanent magnet; h is the total length of air gap; H is the distance between two back irons.

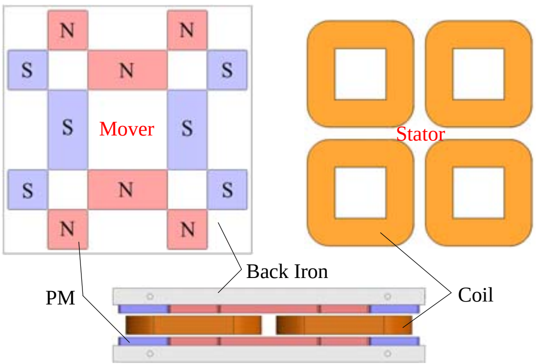

Fig. 1. Basic structure of the 3-DOF short-stroke DC planar motor

Assuming the velocity of the mover in the *x* direction is v_x, the expression of the back-EMF of one coil with N turns is as follows:

$$E = 2NB_{zm}l_{ef}v_x \quad (2)$$

where l_{ef} is the length of effective coil edge.

When the mover translates in the *x* (or *y*) direction, each coil has two effective edges. The force generated by two effective edges is parallel to *x* (or *y*) axis. The force generated by two non-effective edges is perpendicular to *x* (or *y*) axis and offset by other coils. So, the analytical expression of one coil force based on the Lorentz law is as follows:

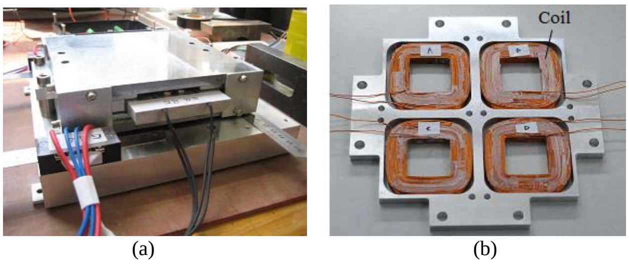

Fig. 2. Prototype and coils of the DC planar motor: (a) prototype and (b) coils.

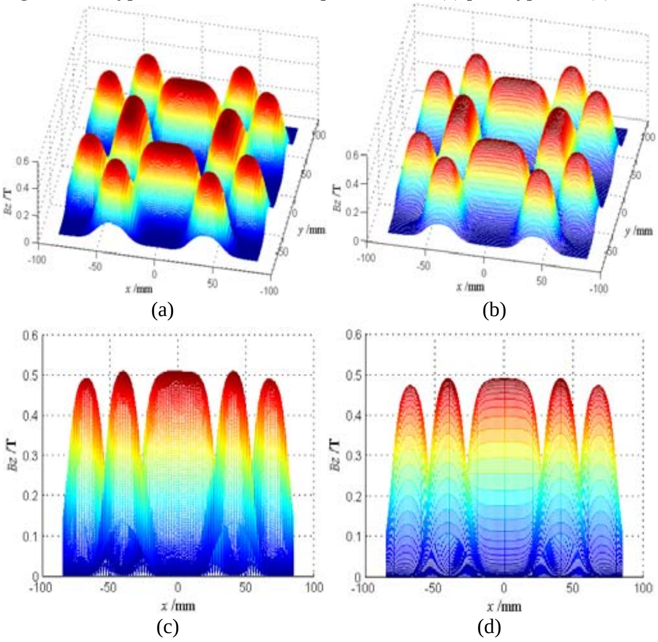

Fig. 3. 3D distribution of the air-gap magnetic field in no-load condition: (a) 3D simulation (b) 3D analytical method (c) side view of 3D simulation and (d) side view of 3D analytical method.

$$F = 2NB_{zm}Il_{ef} \tag{3}$$

where I is the input current of coil.

Taking four coils into account, the analytical expression of total force can be expressed as:

$$F = 8NB_{zm}Il_{ef} \tag{4}$$

When mover rotates about the z axis, each square coil has four effective edges. The torque expression can be derived as

$$T = 4 \cdot \sqrt{2}F \cdot \frac{3\sqrt{2}}{4}\tau = 12NB_{zm}Il_{ef}\tau \tag{5}$$

where τ is the pole pitch.

III. Simulation and Experimental Verification

The prototype machine of the short-stroke DC planar motor and four groups of coils are shown in Fig. 2. The armature reaction of the DC planar motor is neglected due to ironless structure and long air-gap. Fig. 3 shows the simulation results and the analytical results of magnetic filed in no-load condition. Simulation results are obtained by FEM software--Ansoft3D. By contrast, it can be concluded that the magnetic field analysis using magnetic charge method and image method is in good agreement with FEM.

The static force experiment shows that the static force characteristic versus current in the x and y directions both increase linearly with the increment of current and the experimental values of force agree with the analytical model and finite element simulation. The amplitude of measured force is 52.3[N] when the input current is 1.8[A]. The force coefficient is 29.06[N/A]. The amplitude of analytical force is 50.69[N], the model error is only 3.08%.

As shown in Fig. 4, when the mover travels within the stroke of ±1mm, it can be calculated that the measured force ripple is 0.36% in the x direction and 0.72% in the y direction. The analytical force ripple is 0.25% in both directions. In summary, the novel DC planar motor has linear force-current relationship and low force ripple which is less than 1% within the stroke of ±1mm.

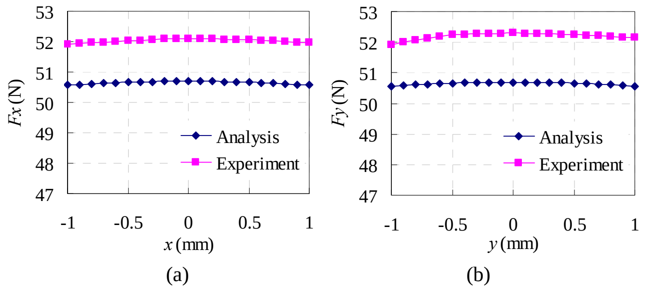

Fig. 4. Static force characteristic versus displacement: (a) in the x direction and (b) in the y direction.

IV. Conclusion

The novel DC planar motor has low force ripple that is less than 1% within the stroke of ±1mm. And, the motor has a linear thrust-current relationship. Furthermore, the force in the moving direction and the torque are not appreciably affected by the rotation angle.

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