Measurement and Analysis of an Electromagnetic Levitation Micro-Actuator Based On Repulsive Force

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Abstract. Based on the repulsive force magnetic field method, a novel electromagnetic levitation micro-actuator was designed. The electromagnetic levitation micro-motion method was presented in one structure with integration of drive, measurement and control. After the vertical stress of the micro-actuator was analyzed, the mathematical models of movement state were derived. The measurement and control system for the micro-actuator was constructed with eddy current sensors and a DSP controller. The experimental results show that the micro-actuator has the advantages with better stability and actuation ability.

1. Introduction
The actuator with high positioning accuracy must be provided in order to realize high-precision micro motion, the micro-actuator technologies at home and abroad are summarized [1-4], the main drive types are piezoelectric drive [5], electrostatic drive [6], gas levitation drive and other types from the drive principles and methods. Compared with other micro-actuators, the electromagnetic drive technology is easy to realize high-precision micro-motion in a single drive structure because the motion body and the drive module are not in contact. Electromagnetic actuators at home and abroad can be mainly divided into two categories: one is that the levitation force and the drive force are provided by the same component, this structure requires using complicated control algorithm for decoupling, the programming is very complicated, but also brings enormous calculation load to control chips, the control effect of the chip is reduced. The other is the method with using a suction of electromagnet to achieve levitation, its levitation force and drive force are controlled by independent components, but its structure is unstable and the control volume fluctuates greatly. For this reason, this paper designs an electromagnetic levitation micro-actuator based on repulsive force, and carries out mechanical analysis and testing under vertical take-off and landing motion state.

2. Design of Micro-actuator

2.1. Structural Design
The structure diagram of magnetic levitation micro-actuator designed in this paper is shown in Figure.1. The vertical and horizontal 180 turns of wire are stacked orthogonally and bonded with epoxy resin to form a wire array on the bottom surface [7], the outer frame above the wire array is used to place eight coil windings to ensure the horizontal stability of the permanent magnet array. The
permanent magnet array is placed inside the frame. The array is composed of 7×7 small magnetic blocks with different magnetic pole directions. According to the Halbach array principle [8], it is composed of two-dimensional vector superposition method [9], and the outer-ring size is 80×80 mm. Permanent magnet select neodymium-iron-boron permanent magnets with high coercive force and residual magnetism, the residual magnetism is 1.35T, the coercive force is 880 kA/m, the maximum magnetic energy product is 320kJ/m³.

The simplified Halbach arrays in groups of three are embedded around the motion body; there are two groups in one side and totally eight groups, and the surrounding coil windings form a horizontal drive system. Above the moving body is used to place experimental reflection measuring mirrors and drive connection devices. Cooperated with corresponding high-precision eddy current displacement sensor, implement measurements with multiple degrees freedom. After the digital processing system controls the motion, a new magnetic levitation micro-drive method that integrates drive, measurement and control is set up in a mechanism.

2.2. Drive principle
The driving force of vertical work of actuator comes from the wire array, electromagnetic force and permanent magnet force and the permanent magnet array, the two are in a repulsive relationship by adjusting the current density of the wire array, the height and carrying capacity of the permanent magnet array can be controlled. As shown in Figure.1.

In the vertical and horizontal directions, the wire arrays are divided into four groups. A1, B1, C1, D1 are vertical directions, and A2, B2, C2, D2 are horizontal directions. The currents in two directions cause the wire arrays to generate five super magnetic field strengths in the surface air gap, these five super magnetic field strengths is corresponding to the magnetic field intensity distribution of the permanent magnet array, and there are repulsive forces among them, and suspend it by adjusting the current intensity. Under the condition of stable levitation, the 3 free degree motions in the vertical direction are achieved by controlling the current of circuit control array.

For example, the vertical motion on the Z-axis can be realized by increasing or decreasing the size of the currents in two horizontal and vertical directions simultaneously; and the current of the A1, B1, C1, D1, A2, B2, C2, and D2 can be changed by the grouping and can realize micro-rotation around the X and Y axes. In Fig. 2 (a), Z⁺ and Z⁻ indicate positive and negative motion along the Z axis. Figure 2(b) takes rotation around the Y axis as an example.
The characteristic of the micro-actuator structure is to adopt a stereoscopic Gaussian magnetic field formed by wire array and synchronously followed by Halbach permanent magnet array. This characteristic of magnetic field dynamic following make the centroid time of the actuator correspond to the center of the 5-point driving force, and ensure that the arm of the bottom driving force is constant at any position. The structure of the multi-point support ensures that the effect position of the magnetic field accurately provides good stability, and it is easy to achieve the motion trajectory planning and position adjustment of micro-actuator. This design structure overcomes other electromagnetic driving methods when the micro-actuator has a rotational displacement, because the feedback of the original transverse electromagnetic force make the micro-actuator subjected to an electromagnetic force that opposes the rotary direction, thus causing the micro-actuator to vibrate or even lose stability, and cannot be realized, and cannot achieve large-angle rotation.

3. Mechanics Analysis of Vertical Drive

The vertical module is responsible for the rotation around the X and Y axis and the micro-motion of the Z axis. Considering that during the process of the actuator motion, the damping caused by the magnetic field change is small and no contact, so the actuator is regarded as a rigid body for modeling. The suspended height 0.5 mm as the steady state, at this time the plane where the sports body centre is the initial plane, the drive current at 0.5mm stable height is 0.56A.

The driving forces generated by the peak of the surface magnetic field of the wire array are $f_{1z}$, $f_{2z}$, $f_{3z}$, $f_{4z}$. The horizontal driving forces on the left and right sides are marked $f_{L}$ and $f_{R}$. The mechanical relationship of angle tilt stability along the Y-axis is shown in Figure 3:

$$G \tan \theta = f_y$$

The Z-axis vertical motion equation is listed by the relationship among the moments:

$$f_{1z} + f_{2z} + f_{3z} + f_{4z} - Mg = M \frac{\partial^2 z_z}{\partial t^2}$$

(1)
In the formula: M is the mass of the motion body of the permanent magnet array and is 0.9Kg; \( \theta \) is the rotary angle 0~3°; L is half of the side length of the actuator and is 4cm, \( l_1, l_2 \) are force arm from driving force to centroid and are 3cm; \( J_x \) and \( J_y \) are rotary inertia, \( 2.7 \times 10^{-3} \text{Kg} \cdot \text{m}^2 \). \( Z_x \) and \( Z_y \) are the vertical displacement generated in the direction of the driving force when rotating around the X, Y axis, because the rotary angle designed as 0~3°, after the measurement, the maximum displacement generated in the direction of the Z axis is regarded equal as arc length, and it can be treated as a straight line motion.

In Fig. 3, \( G \sin \theta, f_x \cos \theta, f_y \cos \theta \) along the axis direction of the motion body are the opposite acting forces, in order to avoid side slipping of the drive in the rotary process, this pair of forces must be balanced at all times. The relationship is as follows:

\[
f_L \cos \theta + G \sin \theta = f_R \cos \theta \tag{2}
\]

From this we see that save \( f_x \cos \theta \) and increase \( f_y \cos \theta \) can also keep balance. Let \( \theta = 0 \) and the relationship can be obtained from (2):

\[
G \tan \theta = f_R \tag{3}
\]

This relationship can transform the complex electromagnetic force \( f_x \cos \theta \) into the relationship between the gravity \( G \) and the rotation angle \( \theta \), transform the complex calculation of the electromagnetic force into function of the \( \theta \) angle, and at the same time, the software control algorithm can be simplified, which reflects the superiority of the structural design.

According to electromagnetic field theory analysis and the Maxwell's equation to obtain the drive force mathematics model of permanent magnet array and energized wire, the parameter value of physical model is put into, and obtain the relational expression among air gap height \( \text{Gap} \), current \( I \) and the driving force \( F \) (4):

\[
\text{Gap} = 6.4(\ln I - \ln F) + 14.4978 \tag{4}
\]

The expressions and designed parameters of \( f_u, f_z, f_v, f_u \) introduced by formula (4) is put into the form (1), simplify and obtain mathematical model.

\[
I_{1,2,3,4} e^{-z} - 673.75 = 68.75 \frac{\partial^2 z}{\partial t^2} \tag{5}
\]

4. Test System Design

The structure diagram of test system of actuator is shown in Figure 4. The signal processing uses the TMS320F2812DSP digital processing chip as the core of the controller, C language is used to write the control algorithm, the 16-bit 250KSPS AD7656 and DAC7744is used to achieve data acquisition and control output conversion, voltage range±10V. The upper computer monitoring system uses LabView real-time measurement software and integrate 12-bit 16-channel high-speed data acquisition card 6023E to collect, observe and save the measurement data in real time, and carry out subsequent analysis.

The choice of sensor requires not only higher sensitivity but also better linearity and measurement range, and can meet the large-scale and high-precision measurement requirements; this paper selects the eddy current sensor, four displacements change of the motion body in the frame surface and horizontal and vertical directions around the actuator are measured. The sensor converts the change of
displacement to the voltage change of feedback; the voltage signal collected by the controller will be calculated according to the calibrated voltage displacement (U-D) relationship, the operation results as controlled objects. Relationship of 8-channel sensor is shown in Table 2.

Table 2: Relation of voltage-displacement

| Sensor (U-D) relation | 1. $3 \frac{1}{2}$: $D = 13.12 - 1.23U$ | 2. $4 \frac{1}{2}$: $D = 12.23 - 1.77U$ | 3. $5 \frac{1}{2}$: $D = 13.34 - 1.797U$ |
|-----------------------|--------------------------------|--------------------------------|--------------------------------|
|                       | $D = 13.232 - 1.34U$          | $D = 12.59 - 1.05U$            | $D = 12.387 - 1.84U$          |

Fig. 4 Diagram of the micro-actuator measurement system

Combined with the mathematical model obtained from the force analysis above, through simulation analysis, it can be concluded that the open loop of the system has the following frequency characteristics: the phase angle allowance is 40 degrees and the cut-off frequency is 7.54 rad/s. The design of the Z-axis controller is given here, and the controller in the vertical direction is based on the principle of lag-lead compensation. It has the advantages of lagging correction and advance correction. The main purpose is to compensate the control accuracy on a stable basis. The structure diagram of controller is shown in Figure 5.

Fig. 5 Diagram of the micro-actuator controller

Therefore, considering that the actuator must have both a wide range of stability and steady-state accuracy, the controller increases the gain of the low-band system to reduce the steady-state error; the mid-band corrects the slope of the amplitude-frequency characteristic to -20 dB/dec, and occupies a wider band. The phase allowance is increased to 50 to 75 degrees to increase stability. The damping ratio of the system is designed to be 0.71. The sampling period of collection digital controller design is 100 μs (the rate is 10 kHz), and obtain digital compensation controller:
$$G_z(z) = 770.141 \frac{(z - 0.9475)(z - 0.93525)(z - 0.95476)(z - 0.1911)}{770.141(z - 0.9475)(z - 0.93525)(z - 0.95476)(z - 0.1911)}$$ (6)

5. Test Experiment

In order to verify the actuator's stability and drive capability, closed-loop control test experiments were conducted. Firstly, the surrounding the coil windings closed loop control circuit work, and then the current flows in the wire array to make the motion body float, this process is a transient unstable process due to the circuit power-up, therefore, the motion body is into a 1mm stable suspension state through the adjustment of the surrounding coil current. Then, the controller outputs a step signal with arbitrary amplitude and width in the Z-axis direction, and synchronously acquires the eddy current sensor signals in the X and Y-axis direction to monitor the stability of the Z-axis, the experimental result is shown in Figure 6.

![Experimental result of the micro-actuator stability](image)

As can be seen from the figure, the closed-loop compensation control of the Z-axis enables the motion body after each step signal arrives, and enters a relatively stable state after not more than two passes through the target value. As can be seen from the output data of the X-axis and Y-axis, under the control of the feedback signal of the eddy current sensor, the surrounding coil windings can compensate the deflection caused by electrical noise and other disturbances timely, and remain stable. After calculation, the average value of the signal output from the X-axis deviated from the stable point is 8.5 μm, and the standard deviation is 1.211 μm, compared with the motion range of the Z axis, it can be considered as agonistic. It does not cause large output fluctuations of the X-axis coil winding. The signal output by the Y-axis will have some deviations each time the Z-axis step signal appears, it is more obvious at the beginning of the motion and the last negative step, the standard deviation is 1.321 μm.

In order to verify the driving ability of the actuator under different loads, repeated experiments are performed under the condition that the surface of the motion body is loaded with different load (0g, 50g, 100g, 150g), and the current I, the driving force F, and the air gap height Gap four experimental data were measured., the results are shown in Figure 7.
It can be seen that as the weight increases, the starting current of the actuator also increases; the errors of the four groups of curves are summarized. The experimentally measured air gap height is close to the theoretical analysis result of the same experimental conditions, and is in the range of 0.8 to 2.25 mm. The theoretical and experimental values are in good agreement in a wide range of 0.8 to 2.25 mm, maximum error is 5μm, and standard deviation is 0.754μm.

The measured suspension starting current of the electromagnetic levitation micro-actuator is larger than the theoretical analysis starting current; the reason is that there is a large damping between suspension and actuator surface before the suspension movement starts. As the load supported by the suspension increases, the starting current of the electromagnetic levitation micro-actuator gradually increases. When the platform is no load, the starting current is only 0.61A, when the platform is loaded with 100g, the required starting current is 0.736A, when the platform is loaded with 150g, the required starting current increases to 0.764A. It is envisaged that the starting current will increase significantly as the suspension bears more load. As the actual air gap increases, nonlinearity and controlled effect decreases, and it is the result of the combined effects of the nonlinearity of the magnetic field and the increase in the heating resistance of the wire.

Compared with the experimental sampling values and the theoretical analysis results, it shows that the relationship between experimental characteristic parameter curve and theoretical characteristic parameter curve is good goodness of fit, it further illustrate the rationality of the structure design of this actuator, the system has better driving ability and adaptation for the changed controlled object.
6. Conclusion
This paper introduces a electromagnetic levitation micro-actuator with magnetic field synchronization and following multiple free degree, which solves the coupling problem among driving forces from the structural design. Through the force analysis of the equilibrium position during multiple free degree motion, the characteristic relationships of driving force, driving current and motion displacement are obtained, and the mathematical equation of the motion state is deduced. A set of test system with drive, measurement and control is established, the stability and drive capability of this actuator are verified via experiments.

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Reference
[1] M. Sitti. Survey of Nanomanipulation Systems [C]. Proc.of the IEEE Conf.on Naotechnology. USA: the Institute of Electrical and Electronics Engineers, 2001: 75-80.
[2] Chen Dixiang, Pan Mengchun ,Luo Feilu. Design of Motion Control Platform for the MagneticField Measuring System of Magnetic Levitation Vehicles [J]. Journal of Test and Measurement Technology, 2008, 22 (1): 13–16. (in Chinese)
[3] Trumper D L, Williams M, Nguyen T. Magnet Arrays for Synchronous Machines [C]. IEEE Industry Applications Society Annual Meeting. Canada: IEEE Industry Applications Society, 1993: 9–18.
[4] Hakho L, Alfreda M P, and Robert M W. Micromanipulation of Biological Systems with Microelectromagnets [J]. IEEE Trans. Magn., 2004, 40 (4): 2991-2993.
[5] Wang Hua, Zhang Xianmin,Deng Junguang,Research on a Precision Positioning Stage Based on Piezoelectric Actuators [J]. Journal of Test and Measurement Technology, 2003, 39 (10): 79–85. (in Chinese)
[6] Qiao Dayong, Yuan Weizheng, Ma Zhibo, et al. Research on an Electrostatic Repulsive-Force Based Vertical Micro Actuator [J]. Chinese Journal of Sensors and Actuators, 2006, 19 (6): 2664 - 2664. (in Chinese)
[7] Chen Benyong, Pan Kerong, Yang Tao, et al. Analysis and modeling of an electromagnetic levitation micro-actuator [J]. China Mechanical Engineering, 2008, 19 (21): 2637-2642. (in Chinese)
[8] Q Han, C Ham, R Phillips. Four- and Eight-piece Halbach Array Analysis and Geometry Optimisation for Maglev [C]. IEE Proc. Electr. Power Appl., United Kingdom: the Institution of Engineering and Technology, 2005, 152 (3): 535-542.
[9] Trumper D L, Kim W J, Williams M E. Magnetic arrays: USA, 5631618 [P]. 1997 - 05 - 20.