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자기부상을 이용한 초정밀 위치작동기의 설계

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Magnetic Levitated Micro Positioing System. Part I: Design

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요 약

위치작동기의 정밀도를 결정하는 중요한 인자인 마찰력을 없애기위하여 자기부상을 이용한 초정밀시스템을 설계한다. 자기부상시스템은 근본적으로 불안정한 성질을 갖고있으므로 작동기의 안정성를 증가시킬수 있는 자기회로설계가 중요하다. 제안된 자기부상 위치작동시스템은 전자석을 고정하고 영구자석을 움직일수 있게하여, 간단하고 견고한 위치작동기가 설계되도록 상호간의 자기력을 이용한 Antagonistic 구조를 채택한다. 그리고 시스템의 동적모델을 구하여 안정성을 검토한다.

1 Introduction

There are two general types of levitation: electrostatic and magnetic. The arguments in favor of magnetic levitation are presented in Pelrine [1] and may be summarized as follows: it is generally possible to achieve higher field energy densities in air with magnetic fields, scaling laws favor magnetic forces on micron scale since magnetic forces scale with volume whereas electrostatic forces scale with surface area, magnetic levitation is more compatible with clean room operation since electrostatic fields tends to attract dust. For these reasons we have chosen to pursue magnetic levitation for the high precision micro-positioning system. Potentially, the device can be used for high precision microprobing, cellular biology, microsurgery, and industrial work in the micromechanical area. Henceforth, we call a magnetic levitation system as a maglev system for short.

We are examining a technology capable of providing high precision and speed with robust three-dimensional six degree-of-freedom motion using magnetic levitated manipulators. The major advantages of levitation are that the manipulator can operate as a rigid body rather than using jointed parts, and that friction can be dramatically reduced. This means that position errors don't compound, the dynamic behavior is simple to model, and harsh environments need not pose a problem since the device can be coated. The major disadvantage of levitation on small scales is that system behavior is nonlinear so control can be computationally intensive.

In Section 2, we present a magnetic force analysis in air core solenoid and permanent magnet pair system to grasp a system design concept. In Section 3, we introduce our unique maglev micro-positioning system. In Section 4, modeling of the maglev system dynamics is achieved. Section 5 summarizes the works performed in this research and suggests the related future works.

2 Force Analysis of a Solenoid and Permanent Magnet System

A magnetic levitation system uses two magnetic components, one of which must be active if motion control is to be accomplished [2]. We have chosen in our work to date to use rare earth passive magnets mounted on the micro-positioner and fixed air core electromagnets. This particular combination, which has also been used by Pelrine [1] and Hollis et. al. [3], permits the micro-positioner to work without a power or signal tether, uses a drive system which is very linear and thus predictable in behavior, and does not require any cooling component.

Air-core solenoid has a few advantages over an iron core in that it has no hysteresis, no eddy current loss, and no saturation of flux density. These characteristics all serve to increase the accuracy which can be achieved. Permanent magnets are being used in many applications of small magnetic systems because they can supply a sufficient force and they are suitable for compact design. Hence for the design of maglev system, one would prefer using air core solenoids paired with permanent magnets.

For a unit dipole moment $\mathbf{m}$ in a magnetic field $\mathbf{B}$, the force that the magnetic dipole moment experiences can be derived by applying the Lorentz force law, and this is expressed in a vector form as [4]

$$\mathbf{F} = (\mathbf{m} \cdot \nabla)\mathbf{B}. \tag{1}$$

Also, the torque on the dipole is expressed as [1]

$$\mathbf{T} = \mathbf{m} \times \mathbf{B}. \tag{2}$$

When the pole face axis points to the surface of the air core solenoid(i.e. $m_x = m_y = 0$), Eqs. (1) and (2) can be simplified to

$$F_x = m_z \frac{\partial B_x}{\partial z}, \tag{3}$$

$$F_y = m_z \frac{\partial B_y}{\partial z}, \tag{4}$$

$$F_z = m_z \frac{\partial B_z}{\partial z}, \tag{5}$$

$$T = -m_z B_y \mathbf{i} + m_z B_x \mathbf{j}, \tag{6}$$

where $\mathbf{i}$ and $\mathbf{j}$ are unit vectors in the x and y directions respectively.

According to Eqs. (3) - (5), we can discover that there are two types of forces present in an air core solenoid and permanent magnet system: radial force F_x, which is the same as F_y, and axial force, F_z. F_x has a constant value in a wide range. F_z has a maximum a little away from the surface of the solenoid and then decreases steeply. F_z is a function of both the supplied current and displacement, and has a big force in a small range. Usually, the maximum F_z is three or four times bigger than F_x. The general trends of those forces are drawn in Figure 1.

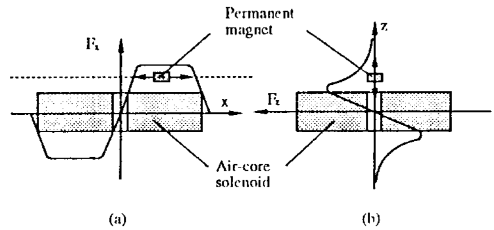

Figure 1: Force characteristics in a solenoid/magnet system (a) in the radial direction. (b) in the axial direction.

One thing to note from Figure 1 is that the force generated inside the air core behaves like a positive spring force and negative spring force outside the air core. This fact reveals that a manipulator inside the air core can be stabilized in open loop by using the push-pull mechanism, or antagonistic structure. For example, for the case when the magnet is inside core as shown in Figure 2(a), the manipulator is returning to an z-direction equilibrium point, where the manipulator weight, Mg balance to a recovery force, F_z. The z position of the manipulator is controlled by changing the input current. For the case when the magnet is outside of the air core as shown in Figure 2(b), the manipulator is returning to an equilibrium point arbitrarily determined in the middle of two solenoids where the two repelling forces, F_zs are the same to each other. Employing this antagonistic structure we can drive the manipulator to the desired position in the x, y and z direction.

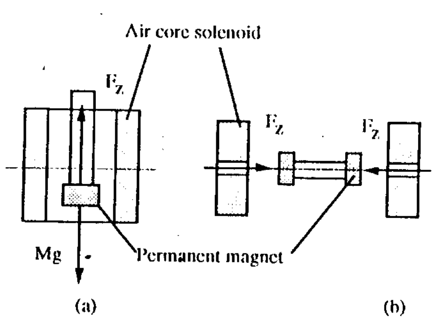

Figure 2: Antagonistic structure produced with a solenoid and permanent magnet pair (a) when the permanent magnet is inside the air core. (b) when the permanent magnet is outside the air core.

Since a basic design concept for a maglev positioning system was addressed, we proceed to its embodiment design in the next Section.

3 Design of Magnetic Levitated Micro Positioning System

The unstable features in maglev system pose a big control effort. Hence, most concern of maglev design is focused on how to utilize efficiently the force characteristics in order to increase the system stability. The more stable degree of freedom is assured, the less control effort is needed. For this purpose, we opt to use the repulsive forces with a manipulator shaped as shown in Figure (3). A stability problem in the direction of x, y is solved using two pairs of the solenoid and permanent magnet, top and bottom in the center of each side. The manipulator is stable in the $x - y$ direction because the recovery forces are increased as Δx or Δy increases due to the antagonistic structure. On the other hand, it is unstable in the θ direction because the radial forces generate torques which help to rotate in a way that $\Delta\theta$ increases. To control θ direction, another solenoid and permanent magnet pairs need to be used. Attractive or repulsive forces should to be generated depending on the magnitude of $\Delta\theta$ which can be obtained by measuring two points along the side of the manipulator. To this end, a pair of solenoid and permanent magnet is diagonally attached across the side. These can be understood in terms of Figure 3(a).

Also using the four solenoid and permanent magnet pairs at the centers of the four legs, another stability problem in the direction of z, ϕ, and ψ is solved. The manipulator tends to recover against the ϕ directed movement, for example, because the axial force inside the core has the antagonistic property. The same phenomena happens in the direction of ϕ. These can be understood in terms of Figure 3(b). Therefore, it can be said that the proposed maglev system is internally stable in all directions except the θ direction.

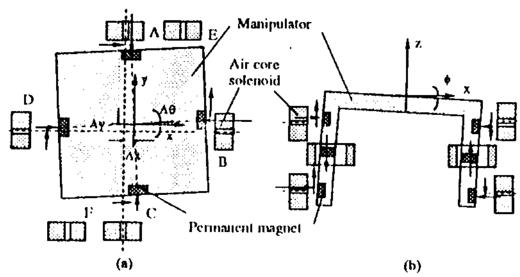

Figure 3: View of the manipulator with air core solenoid and permanent magnet pairs. (a) Top view. (b) Side view.

In conclusion, a magnetic levitated manipulator is designed such that stability in 5 degree of freedom, i.e., x, y, z, ϕ, ψ direction, is assured. The only θ directed rotation needs to be stabilized.

4 Modeling of System Dynamics

The proposed maglev system uses three different forces for stabilizing in 6 degree of freedom; levitating force, centering force, and stabilizing force. The stability in the direction of x and y is guaranteed by the centering force. The stability in the direction of z, ϕ and ψ is guaranteed by the levitating force. Since only the θ

direction is unstable mode, we derive a linearized one degree of freedom model. We can develop, of course, a complete analytical model which includes the other degrees of freedom that are assumed to be stable and decoupled from the one unstable degree of freedom. However, for simplicity, we will derive one degree of freedom model in the θ direction. To this end, the manipulator is assumed to be a rigid body in simple plane motion which can be treated as a special case of general rigid body dynamics. This assumptions eliminates the terms involving the product of angular velocities due to the time rate of change of angular momenta that would otherwise appear in the complex rigid body dynamics by the Euleran equations [5]. Another assumption is that the radial forces are much smaller than the axial forces and hence, they are ignored in the system modeling. This can be justified by using a relatively larger air core solenoid than permanent magnet so that small radial force produces.

The equation of the θ direction motion can be obtained from the momentum equation for a rigid body,

$$\Sigma \mathbf{T} = \dot{\mathbf{H}}, \tag{7}$$

where $\mathbf{T}$ designates the external torque while $\mathbf{H}$ designates the angular momentum. The angular momentum equation, when expanded, transforms into the Euler's equation,

$$\Sigma T_z = I_{zz}\dot{\omega}_z - (I_{xx} - I_{yy})\omega_x\omega_y, \tag{8}$$

where T_z is external torque, I_{xx}, I_{yy}, and I_{zz} are the principal moments of inertia, and ω_x, ω_y, and ω_z are the three angular velocities of the rigid body. Since we assume an $X-Y$ plane of motion for our system, $\omega_x = \omega_y = 0$ and we let I_{zz}=J and $\omega_z = \dot{\theta}$. Therefore, the Euler's equation can be reduced to only one equation,

$$\Sigma T_z = J\ddot{\theta}. \tag{9}$$

According to Figure 4, Eq (9) is

$$J\ddot{\theta} = -2F_{AC}(X - a\theta) + 2F_{BC}(Y + a\theta)$$
$$+2F_{CC}(X + a\theta) - 2F_{DC}(Y - a\theta))$$
$$-F_{ES}b - F_{FS}b, \tag{10}$$

where F_{AC}, F_{BC}, F_{CC}, and F_{DC} are the centering forces applied to the magnets positioned at A, B, C, and D respectively; F_{ES} and F_{FS} are the stabilizing forces applied to the magnets positioned at E and F; a is the distance from the center to the edges of the manipulator and and b is the distance to the points E and F respectively. Since two pairs of the air core solenoid and permanent magnet are used top and bottom around the edges of the manipulator, the torque due to the centering forces is amplified by a factor of two.

The centering forces, F_{AC}, F_{BC}, F_{CC} and F_{DC} can be assumed that they proportionally increase as the air gap between the solenoid and permanent increases. Therefore, the expressions of the centering forces are

$$F_{AC} = KY, \tag{11}$$
$$F_{BC} = KX, \tag{12}$$
$$F_{CC} = -KY, \tag{13}$$
$$F_{DC} = -KX, \tag{14}$$

where K is a positive value and same as a spring constant. Since the stabilizing forces, F_{ES} and F_{FS} are assumed to be only function of current, they can be expressed as

$$F_{ES} = K_i I_1, \tag{15}$$
$$F_{FS} = K_i I_2, \tag{16}$$

where I_1 and I_2 represent the stabilizing currents. K_1 and K_2 are the constant relating the stabilizing force and the current. With the substitutions from Eqs. (11) to (16), Eq. (10) simply become

$$J\ddot{\theta} = -bK(I_1 + I_2). \tag{17}$$

Eq. (17) indicates the motion in the direction of θ is decoupled from x or y direction and can be controlled by only each currents.

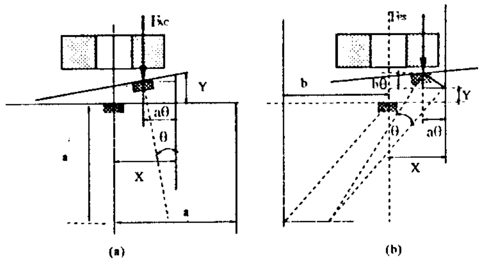

Figure 4: The manipulator undergoes X and Y translation and θ rotation (a) in the magnet positioned at A. (b) in magnet positioned at E.

5 Conclusion

A 6 degree-of-freedom magnetic levitated high precision micro positioning system is designed to get rid of the friction which is one of most important factors limiting the resolution and accuracy of positioning devices. Since magnetic levitation system is inherently unstable, most concern is focused on a magnetic circuit design so as to increase the system stability. The proposed levitation system is constructed using antagonisitic structure which permits a simple design and robust stability. Hall effect sensors will be used for positioning sensing devices. The proposed maglev system is simply modeled to check the stability in the direction of θ. Digital control for experiment will be implemented in the near future.

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