11th International Symposium on Magnetic Bearings
August 26-29, Nara, Japan

Digital Control of Magnetic Levitation for Contactless Delivery Applications

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Abstract - In recent semiconductor making processes, high-class clean operations of delivery robots without contacts are required more and more. Magnetic levitation system can be applied to semiconductor fabrication applications, for example, which includes clamp-type robot, linear motors for propulsion, contact-less power supply for power sourcing and magnetic levitations for contact-less bearings. In this paper, electromagnetic suspension vehicle model and its decoupled control method is presented. The symmetry of the geometric configuration and space coordinates transformation techniques are used to eliminate the redundancy of electromagnetic force control. Then, each of the three motion states becomes a single-input and single-output (SISO) linear sub-system and a linear proportional, integral and derivative (PID) controller was designed for each sub-system and tested for the constructed electromagnetic suspension (EMS) vehicle simulator.

I. INTRODUCTIONS

The conventional delivery robots are supported by rigid contact bearings, and driven by the rotary motor and ball screw in order to achieve high acceleration and precision motion. However, because of friction, abrasion, mass inertia of the driven parts, the clearance between the connected parts and so on, the positioning accuracy and the response frequency is limited**.**

Magnetically suspended system, compared with linear driven system directly, has the advantages of non-contact motion which is free of particle generation and mechanical friction problem, therefore no abrasion and long lives. Moreover, the separation of a moving object from a stationary part almost eliminate heat generation problem that is caused by the rubbing activity of the mechanical components. This contact movement has been a main obstacle to performance improvement of the conventional mechanical system.

However, magnetically suspended stage is a multi-variable, strongly coupled, nonlinear and complicated system. In order to gain high speed and high accuracy, the dynamic decoupling control for each degree of freedom (DOF) is necessary. In this paper, the control system could be simplified by using the symmetry of the vehicle's mechanical configuration and coor-dinated transformation between input and output state spaces to eliminate the coupling of the 3 degree of freedom motions of the vehicle. An example of the electromagnetically suspended vehicle is shown in figure 1.

FIGURE1: A simulator for EMS vehicle

II. EMS VEHICLE MODEL

There are four U-shaped electromagnets top of the vehicle, and U-shaped guide rails in the EMS simulator of figure 1. The proposed electromagnetic suspension (EMS) vehicle has six degree of freedoms. Five degrees are constrained by four U-U shaped suspension magnets and rails. That is, three degrees are controlled by four perpendicular electromagnet, z-translation, x-rotation and y-rotation. The y-translation and z-rotation is controlled by guide rail's passive force. Another one DOF, x-translation, is controlled by linear motor.

As the suspension parts moving along the guide, there are longitudinal vibration for the electromagnetic force distribution which may not be the same if there are errors for the geometry configuration and changed currents. The errors can affect the orientation accuracy.

A. Force model of 1 DOF actuator

Before getting complex force model of the EMS vehicle, let's deduce force model of the one DOF electromagnetic actuator. The electromagnetic force generated by a U-shaped electromagnet is as follows:

$$F = \frac{1}{4} N^2 \mu_0 A \frac{I^2}{Z^2} \qquad (1)$$

Where N is number of coil turns, A is cross-sectional area of U-shaped core, I is coil current, Z is length of air gap and μ_0 is the permeability of free space($\mu_0 = 4\pi \times 10^{-7} [H/m]$). If we control the magnet with bias current I_0 and control current i_c with small deviation z with Z_0, then the force becomes as follows:

$$F = \frac{1}{4} N^2 \mu_0 A \frac{(I_0 + i_c)^2}{(Z_0 - z)^2} \qquad (2)$$

If we take approximated equations of equation (2) near bias current and nominal gap, we get :

$$F(z, i_c) = F(Z_0, I_0) + k_i (i_c - I_0) + k_x (z - Z_0) \qquad (3)$$

Where

$$k_i := \frac{\partial F(z,i_c)}{\partial i_c} \; k_x := \frac{\partial F(z,i_c)}{\partial z} \quad \text{for} \quad I = I_0, Z = Z_0 .$$

For $z = 0$ and $i_c = 0$, we get

$$k_i = \frac{1}{2} N^2 \mu_0 A \frac{I_0}{Z_0^2} \qquad (4\text{-a})$$

$$k_x = -\frac{1}{2} N^2 \mu_0 A \frac{I_0^2}{Z_0^3} \qquad (4\text{-b})$$

Thus we get the open-loop system as shown in shaded box in figure 2, where M is equivalent mass of the suspended vehicle. If we make suitable control $K(s)$ with feedback sensor gain of K_m, the EMS vehicle will be levitated well.

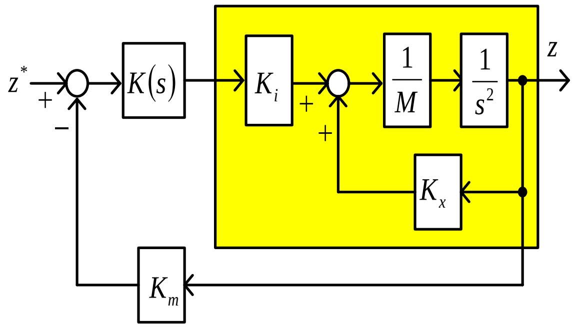


FIGURE 2: 1 DOF control model of suspended object

B. Dynamic Equations of the EMS vehicle

In order to simplify description, the dynamics analytical model of the EMS vehicle is shown in Fig.3.

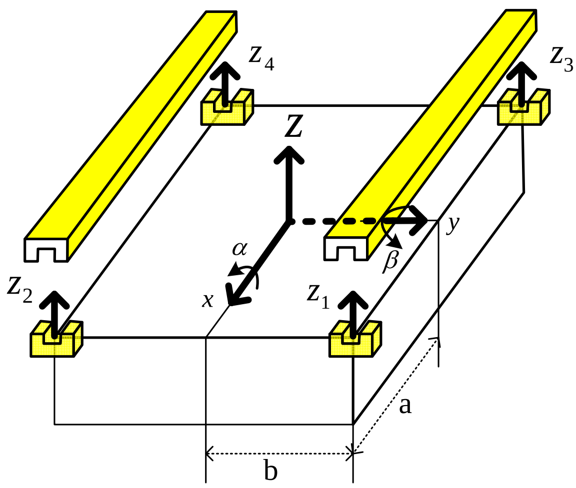


FIGURE 3: Electromagnetic suspension vehicle

Supposing that the magnetically suspended vehicle is a rigid body and Cartesian coordinates original point is located on the center O of the vehicle in normal position. When the vehicle is moving, the center of the vehicle may be deviated the balanced position and translated to O' because of vibration.

Define the generalized coordinates of O' as follows:

$$q = [z \quad \alpha \quad \beta]^T \tag{5}$$

And the vehicle's generalized coordinates of the electromagnet is:

$$q_B = [z_1 \quad z_2 \quad z_3 \quad z_4]^T \tag{6}$$

Based on system dynamic theory, the 5-DOFs dynamic equation of the vehicle with four magnetic actuators in z direction can be expressed as follows:

$$M\ddot{z} = F_1 + F_2 + F_3 + F_4 \tag{7-a}$$

$$J_\alpha \ddot{\alpha} = (F_1 - F_2 + F_3 - F_4)b \tag{7-b}$$

$$J_\beta \ddot{\beta} = (-F_1 - F_2 + F_3 + F_4)a \tag{7-c}$$

In the above equations, $F_n(n = 1,2,3,4)$ is the electromagnetic force of the magnets, M is the mass of the moving vehicle, J_α, J_β is moment of inertia that the vehicle rotate around x–, y – axis respectively, a and b are the distance between the electromagnets.

For the convenience of analysis, equation (7-b) and (7-c) can be expressed as:

$$M_\alpha \ddot{x}_\alpha = F_1 - F_2 + F_3 - F_4 \tag{8 - a}$$

$$M_\beta \ddot{x}_\beta = -F_1 - F_2 + F_3 + F_4 \tag{8 - b}$$

Where, M_α, M_β are equivalent masses that the vehicle rounds about x–, y–axis that pass through center, x_α, x_β are equivalent displacement in these two directions, and

$$M_\alpha = \frac{J_\alpha}{b^2}, M_\beta = \frac{J_\beta}{a^2}, x_\alpha = b\alpha, x_\beta = a\beta \tag{8 - c}$$

Then state-space model of the magnetically suspended vehicle is

$$\begin{bmatrix} M & 0 & 0 \\ 0 & M_\alpha & 0 \\ 0 & 0 & M_\beta \end{bmatrix} \begin{bmatrix} \ddot{z} \\ \ddot{x}_\alpha \\ \ddot{x}_\beta \end{bmatrix} = [T] \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \tag{9 - a}$$

Where T represents motion state matrix of the system, that is

$$T = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ -1 & -1 & 1 & 1 \end{bmatrix} \tag{9 - b}$$

The $q' = [z \quad x_\alpha \quad x_\beta]^T$ represents equivalent micro-displacement, and $F_n(n = 1,2,3,4)$ still represents electromagnetic force produced by four electromagnets.

C. Decoupled control the EMS vehicle

From matrix T, it can be seen that the vehicle adopts magnetically suspended bearings to control three DOFs, that is to say, there is one redundant control variable. This redundant control variable can improve the vehicle's mechanical characteristics and coherence of each bearing's controller. Four same magnetically suspended bearings are used in vertical direction, means that using one more bearing to support a rigid body. In fact, three points not in a line can determine on plane. Besides, electromagnetic force of each motion state in vertical and horizontal direction is co-coupled, so classic control theory could not adopted to analyze the system. This paper designs a controller primarily aiming at the symmetrical construction of the stage. By coordinates transformation and redundancy elimination, the 4 motion variables (z_1, z_2, z_3, z_4) of the system can be decoupled as 3 independent controlled variables (z, x_α, x_β) from the 4 input current variables i_1, i_2, i_3, i_4.

Assuming that the magnetically suspended vehicle is rigid, and the vehicle can move only a small displacement around the normal poison, then the coordinate transformation can be expressed as follows:

$$z = \left(z_1 + z_2 + z_3 + z_4\right) \big/ 4 \qquad \text{(10 - a)}$$

$$\alpha = \left(z_1 - z_2 + z_3 - z_4\right) \big/ 4b \qquad \text{(10 - b)}$$

$$\beta = \left(- z_1 - z_2 + z_3 + z_4\right) \big/ 4a \qquad \text{(10 - c)}$$

$$z_1 + z_4 = z_2 + z_3 \qquad \text{(10 - d)}$$

Then there is a relation between displacement q_B of every suspending point detected by transducer and displacement q' can be decomposed by every motion coordinate as follows:

$$q_B = Mq' \qquad \text{(11 - a)}$$

Where,

$$M = \begin{bmatrix} 1 & 1 & -1 & 0 \\ 1 & -1 & -1 & 0 \\ 1 & 1 & 1 & 0 \\ 1 & -1 & 1 & 0 \end{bmatrix} \qquad \text{(11 - b)}$$

From equation (3) and (4), it can be deduced that electromagnetic force produced by every electromagnet and corresponding current loop and displacement of the corresponding point is a linear relation. Thus electric current decomposed and generated in every motion direction by every control current loop has such a relation:

If $F_j\,(j = z, \alpha, \beta)$ represents electromagnetic force decomposed in very locomotion direction, from (3), (9), (11), such an equation can be deduced as follows:

$$\begin{aligned} F_{j,(j=z,\alpha,\beta)} &= TF_{n,(n=1,2,3,4)} \\ &= T\left(k_x q_B + k_i i_{n,(n=1,2,3,4)}\right) \qquad (12) \\ &= k_x TMq' + k_i TMi_{j,(j=z,\alpha,\beta)} \end{aligned}$$

If we provide the control current proportional to the electromagnetic force, equation (12) implies that the EMS vehicle is linearly independent for each axis. So we can design three single-input and single-output controllers for open-loop unstable suspended system independently. Figure 3 shows the proposed control system. In this figure, the controller $K(s)$ of figure 2 is substituted by a proportional, integral and derivative (PID) controller.

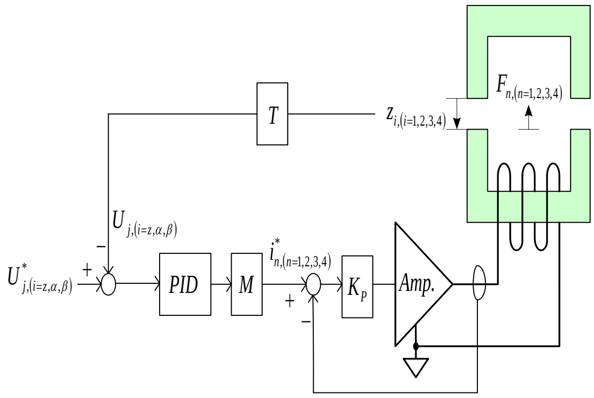


FIGURE 4: Decoupled control of EMS vehicle

IV. EXPERIMENTAL RESULTS

A. Experimental test setup

For the experiment, total mass of 200kg including 4 levitation electromagnets are levitated under small deviation of electromagnet placement as shown in figure 1. The main position controller is designed in the Matlab/Simulink environment and implemented via Real-time control toolbox using the commercial dSPACE control desk. Figure 5 shows the constructed experimental setups, where monitoring and tuning of parameters of the controller can be achieved easily.

An additional DSP controller was used for current controller of the electromagnets. The controller was implemented using a VC-33 digital signal processor of Texas Instruments. Integral controllers on a loop can cause unexpected oscillation thus make system unstable. So the current controller was implemented using proportional control only. This scheme of a PID controller as main position controller and only proportional controller for subsystem can get stable system operation.

B. Test results.

The levitation control command of 5mm gap was made from initial air-gap length of 11mm ($z^* = 5(mm)$, $\beta^* = 0$, $\alpha^* = 0$). The reference gap command was provided smoothly using low pass filter of commanded input in order to prevent the suspended vehicle unstable. The experimental test result is shown in figure 6. We can conclude that the decoupled controller and independent PID controller make good stability and performance.

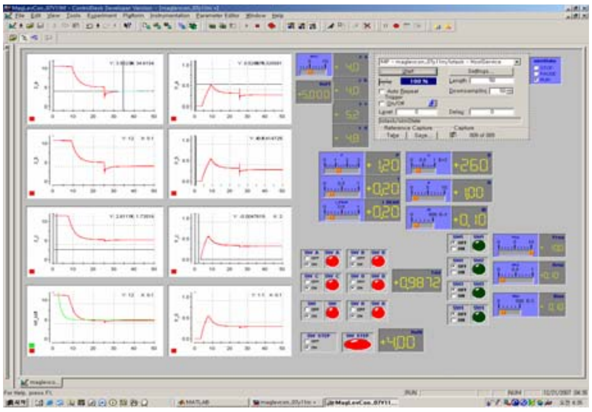
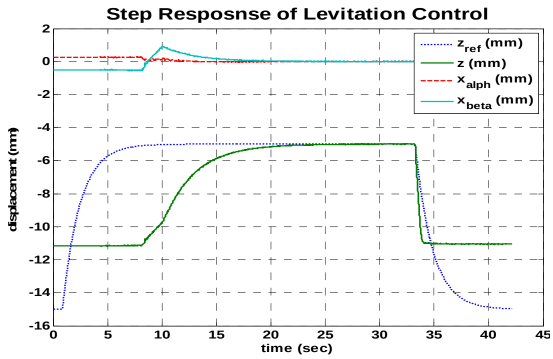


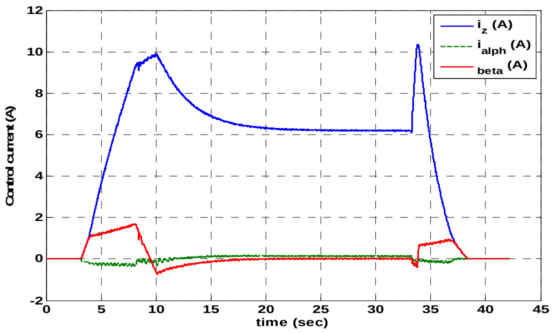
FIGURE 5: Experimental Test setup

V. CONCLUSIONS

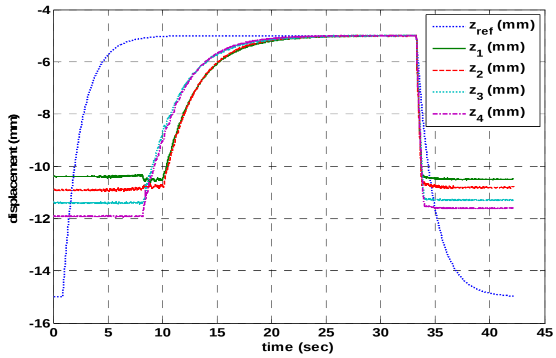
In recent semiconductor making processes, high-class clean operations of delivery robots without contacts are required more and more. Magnetic levitation system can be applied to semiconductor fabrication applications, for example, which includes clamp-type robot, linear motors for propulsion, contact-less power supply for power sourcing and magnetic levitations for contact-less bearings. In this paper, electromagnetic suspension vehicle model and its decoupled control is presented. The symmetry of the geometric configuration and space coordinates transformation techniques are used to eliminate the redundancy of electromagnetic force control. Then, each of the three motion states becomes a SISO linear sub-system and a linear PID controller was designed to the each sub-system and tested for the constructed simulator.



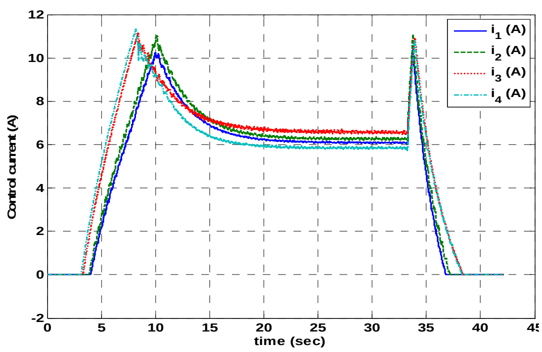
(a) Displacement (q coordinates)



(b) Current (q coordinates)



(c) Displacement (q_B coordinates)



(d) Current (q_B coordinates)

FIGURE 6: Step response of levitation control

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