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Design and Analysis of a Control System For a Multi-Magnet Levitation System

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ABSRACT - This paper deals with some analytical and experimental aspects to control a multi-magnet suspended vehicle. Because the response of a multi-magnet vehicle shows mutually coupled interaction, an analytical description of the vehicle dynamics is necessary. For numerical computations, a linearized modelling of vehicle dynamics is dicussed and computer simulation is carried out. And for the experiment, a test vehicle suspended by four magnets has been made and investigated by local control of each magnet. Two algorithms by PID and state feedback control law are used and compared with each other. Some kinds of disturbance characteristics and coupling effects of the width change of the test vehicle are experimented.

I. Introduction

With the increase of requiring new transportation system with high speed and good ride quality, considerable attention has been given to magnetically levitated vehicle because of its operational and environmental advantages. Among the two types of magnetic suspension the one using attraction force(electromagnetic suspension) seems to be dominant up to date since it has simple design aspects and flexible operational conditions. Various kinds of electormagnetic suspension system have been studied and experimented in some countries.[1]

In contrast to single magnet suspension, a multi-magnet suspended vehicle has a number of degrees of freedom to be controlled.[2-4] That is, not only maintaining the constant air gap between the guideway and magnet but also reducing the transient rolling, pitching and yawing motions should be considered under any possible disturbances. The dynamics of the suspended vehicle becomes, therefore, an important role in the analysis of multi-magnet system. This significant feature of multi-magnet system leads the problem to multivariable control and it is essential to analyze the dynamic interaction between the various modes of translational and rotational motion.

The purpose of this paper is to discuss some analytical and experimental design aspects of a multi-magnet levitation vehicle.

II. Vehicle Dynamics

A magnetically suspended vehicle is a free body in space and has six degrees of freedom associated with translational motion and rotation. Translational motions arise from suspension, propulsion and guidance. Rotational motions are roll, pitch and yaw. In practice, some torsion torques exist due to the finite rigidity of the vehicle. In this study, vehicle movement is assumed to be restricted in the heave direction, i.e. the propulsion and lateral motions are not considered here. Also, the guideway is assumed to be rigid. For the analytical simplicity, a moving reference coordinate is chosen assuming that the center of mass coincides with its geometric center. (Fig. 1)

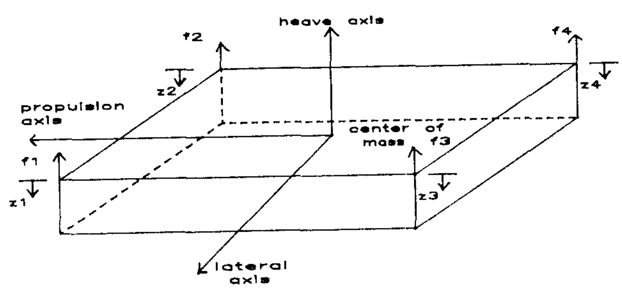

Fig. 1. Reference coordinate of a vehicle

Since yawing movement is small compared with the heave motion, the equations of motion for small perturbations around the nomial operating point can be described as follows.[2]

$$
\begin{aligned}
F_z &= M\, z \\
T_r &= I_{xx}\phi \\
T_p &= I_{yy}\theta
\end{aligned}
\qquad (1)
$$

where F_z ; total lift force
T_r, T_p ; roll and pitch torques
I_{xx}, I_{yy} ; inertia terms correspoding to x and y axes
M ; mass of the vehicle

Letting f1, f2, f3, f4 be lift forces of the corner magnets, total lift force, torques, roll and pitch angles for small perturbations are described as[2]

$$F_z = f1 + f2 + f3 + f4$$

$$
\begin{aligned}
T_r &= (- f1 + f2 - f3 + f4)\, B \\
T_P &= (f1 + f2 - f3 - f4)\, L \qquad \text{—— (2)} \\
z &= (z1 + z2 + z3 + z4) / 4 \\
\phi &= (- z1 + z2 - z3 + z4) / (2b) \\
\theta &= (z1 + z2 - z3 - z4) / (2l)
\end{aligned}
$$

where L, B ; distances between centers of magnets along x and y axes respectively

2l, 2b ; distances between gap sensors along x and y axes respectively

In mose cases the four magnets are considered to have the identical characteristics and the attraction force generated by j-th magnet may be given by

$$
\begin{aligned}
f_j &= -K_i i_j + K_z z_j \qquad \text{—— (3)} \\
\frac{di_j}{dt} &= \frac{K_z}{K_i}\frac{dz_j}{dt} - \frac{R}{L} i_j + V_j / L
\end{aligned}
$$

K_i and K_z are coefficients representing force-distance characteristics of a magnet. Equations (1)-(3) consist of the open loop system of a multi-magnet suspended vehicle, which can be regarded as a non-uniform transformation of the applied magnet forces into the outputs of gap sensors. The transformation is given by

$$
\begin{bmatrix} F_z \\ T_r \\ T_P \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -B & B & -B & B \\ L & L & -L & -L \end{bmatrix} \begin{bmatrix} f1 \\ f2 \\ f3 \\ f4 \end{bmatrix}
$$

$$
\begin{bmatrix} z \\ \phi \\ \theta \end{bmatrix} = \begin{bmatrix} 1/M & 0 & 0 \\ 0 & 1/I_{xx} & 0 \\ 0 & 0 & 1/I_{yy} \end{bmatrix} \begin{bmatrix} F_z \\ T_r \\ T_P \end{bmatrix} \qquad \text{—— (4)}
$$

$$
\begin{bmatrix} z1 \\ z2 \\ z3 \\ z4 \end{bmatrix} = \begin{bmatrix} 1 & -b/2 & l/2 \\ 1 & b/2 & l/2 \\ 1 & -b/2 & -l/2 \\ 1 & b/2 & -l/2 \end{bmatrix} \begin{bmatrix} z \\ \phi \\ \theta \end{bmatrix}
$$

If some torsional motion exists, the following equations about trosional movement is added to the equations (1), (2) and (3).

$$
\begin{aligned}
T_t &= I_t \xi \\
T_t &= (f1 - f2 - f3 + f4)\, D \qquad \text{——(5)} \\
\xi &= (z1 - z2 - z3 + z4) / (2d)
\end{aligned}
$$

where ξ is torsion angle and D(or 2d) is the diagonal distance between the centers of magnets(or sensors). The resulting transformation matrix in equation (4) becomes uniform. This is omitted here.

After stable suspension is achived, modes of coupling can be analyzed by the following Lagrange's equations.[3] The coordinate with arbitrary center of mass is shown is Fig. 2.

$$
\begin{bmatrix} M & 0 & 0 \\ 0 & I_P & 0 \\ 0 & 0 & I_r \end{bmatrix} \begin{bmatrix} z \\ \phi \\ \theta \end{bmatrix} +
$$

$$
\begin{bmatrix} 4k_z & 2k_z(L_2-L_1) & 2k_z(l_2-l_1) \\ 2k_z(L_2-L_1) & 2k_z(L_1^2+L_2^2) & k_z(L_1-L_2)(l_1-l_2) \\ 2k_z(l_2-l_1) & k_z(L_1-L_2)(l_1-l_2) & 2k_z(l_1^2+l_2^2)+4k_1h_1^2 \end{bmatrix}
$$

$$
\begin{bmatrix} z \\ \phi \\ \theta \end{bmatrix} = \begin{bmatrix} F_z \\ T_P \\ T_r \end{bmatrix} \qquad \text{—— (6)}
$$

The first matrix is inertia matrix and the second is stiffness matrix. So natural frequencies for different position of the center of mass can be derived by solving

$$
\det\{ -\omega^2 A + B \} = 0 \qquad \text{—— (7)}
$$

where A and B are inertia and stiffness matrix respectively.

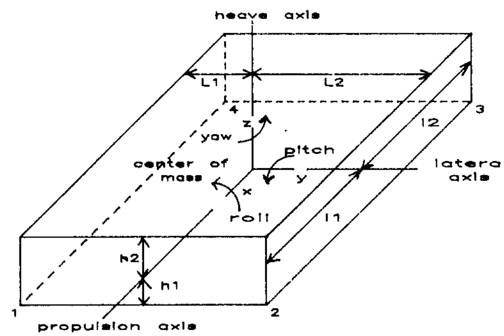

Fig 2. Reference coordinate for coupling analysis

III. Control of A Multi-Magnet System

The electromagnetic suspension system is inherently unstable and has highly nonlinear force-distance characteristics. First consideration of the control is to obtain adequate stability margin under any possible disturbances. And then, ride quality must be considered.

As mentioned earlier, a multi-magnet system has in practice mutually coupled dynamics. Change in any one of input forces will cause a response in all the output variables. In the case where the center of mass coincides with its goemetric center, the non-interacting dynamics could be obtained and it is possible to control each degree of freedom(heave, roll and pitch) by appropriate linear combinations of lift forces. This control scheme is called integrated control and is shown in Fig. 3.

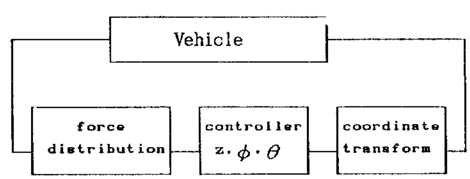

Fig. 3. Integrated control

In most cases, the force f_i is independently controlled by the nearest gap sensor output z_i regardless of mutual coupling. This type of control is called local control and is shown in Fig. 4.

In this analysis, a simple state feedback controller for local control is simulated for the experimental vehicle. Fig. 5 shows the response of a test vehicle(see in section IV) when the external force of 20[N] is applied at corner 3. The feedback gains of four controllers are all the same.

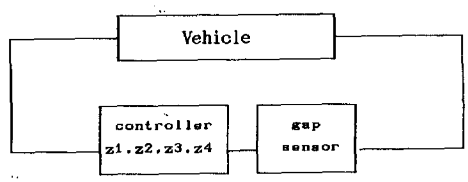

Fig. 4. Local control

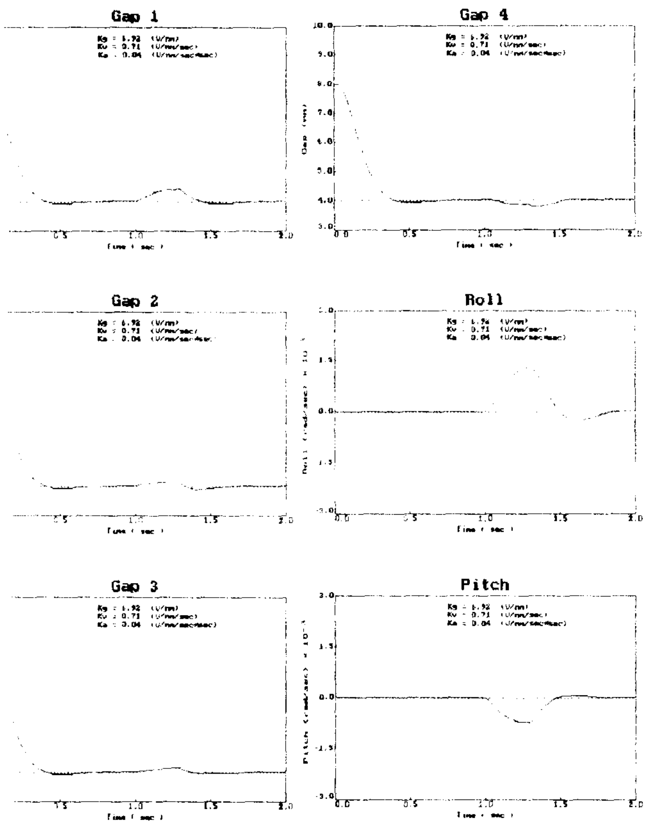

Fig. 5. Simulation results of a test vehicle

IV. Experimental Results

For the experiment, a 40Kg test vehicle suspended by four magnets is made(shown in Fig. 6) and the specification of the magnet is listed below.

Mass : 8.5[Kg]
Nominal air gap : 4[mm]
Nominal current : 0.8[A]
Nominal Force : 89[N]

The four magnets in the test vehicle are controlled independently through four controllers in the form of local control. No effort is made for decoupling the dynamics of the vehicle. Fig. 7 shows the vehicle responses when state feedback and PID control laws are adopted respectively. For the state feedback control, gap, velocity and acceleration are fed back. And velocity is derived from the integration of acceleration. Though reliable suspension is achieved in both controls, state feedback controller shows the better response. This is because suspension stiffness in PID control is mainly dependent on high frequency noise contained in the differentiator.

To see the disturbance characteristics, two kinds of experiment is carried out. Fig. 8 shows the response of the vehicle in case of 10[Kg] increase of mass (25% of total mass) between corner 1 and 2. As shown in the figure, stable suspension is obtained with some transient roll and pitch. The other experiment is under the steady state, an impulsive force of 10[N] is acted on corner 3 and the response is shown in Fig. 9. It is found that both controllers are very sensitive to impulsive external force, and that the stability may not be guaranteed under the impulsive disturbances. However, adjusting the filtering bandwidth of acceleration(or differentiator in PID control) could improve the stability margin.

Fig. 10 shows the response when the width of the vehicle is increased by 20[cm].

In result, it is realized that suspension stiffness and the adaptibility to intantaneous mass change cannot be achieved at the same time by the fixed gain feedback control.

V. Conclusion

In this paper, a basic technology about multi-magnet system control has been discussed. Because of a number of degrees of freedom in the suspended vehicle, system dynamics is described on the basis of a linearized model. And simple PID and state feedback control is simulated and experimented. Experimental results show that with these controllers, a proper stability margin has been achieved without any decoupling techniques except when the impulsive external forces are applied. But, decoupling by state feedback will improve the system performance.

In future, the effects of nonlinearity, decoupling the mutual interaction, positioning of the center of mass and the problem of guideway flexibilty should be considered. These studies are currently in progress.

VI. Acknowledgment

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Rferences

1. P. K. Shina " Electromagnetic suspension dynamics and control", Peter Peregrinus Ltd., 1987.
2. P. K. Shina and B. V. Jayawant, " Analytical and design aspects of magnetically suspended vehicle", Automatica, Vol. 15, 1979, pp. 539-552.
3. A.D.G. Hazlerigg and P. K. Shina "Design of a multi-variable controller for a magnetically suspended vehicle", IEE Conf., Publn., No. 117, 1974, pp. 673-684.
4. E. Gottzein, K. Brock, E. Schneider and J. Pfefferl "Control aspects of a tracked magnetic levitation high speed test vehicle", Automatica, Vol.13, 1977, pp. 205-223.

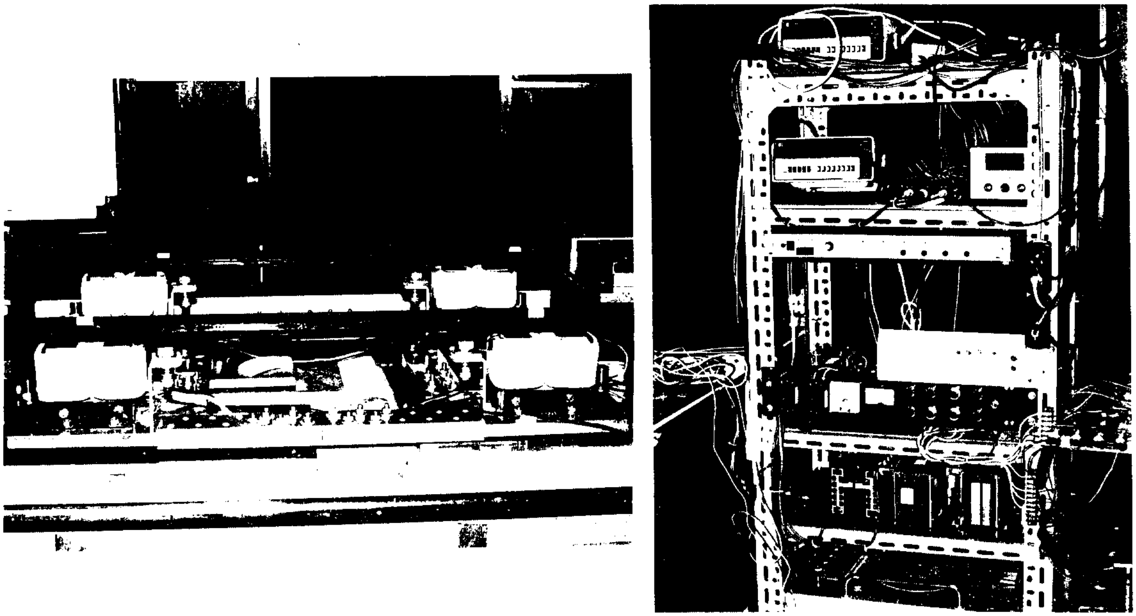
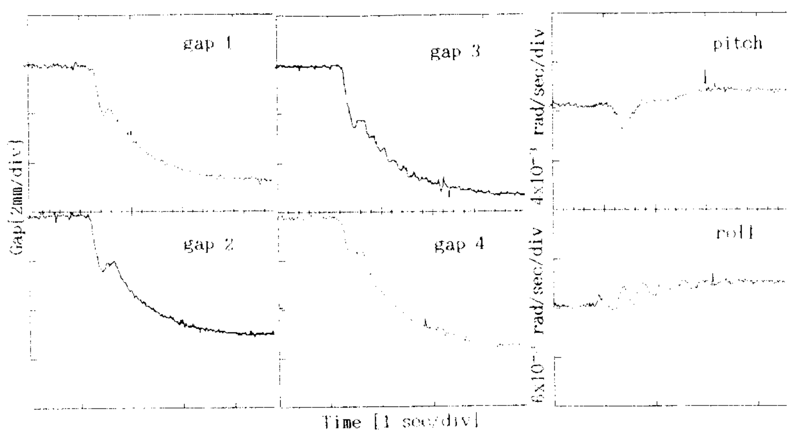
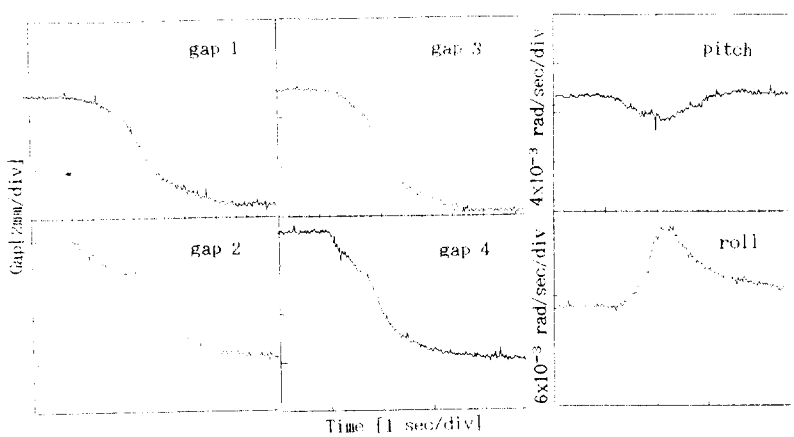


Fig. 6. The test vehicle and its drives

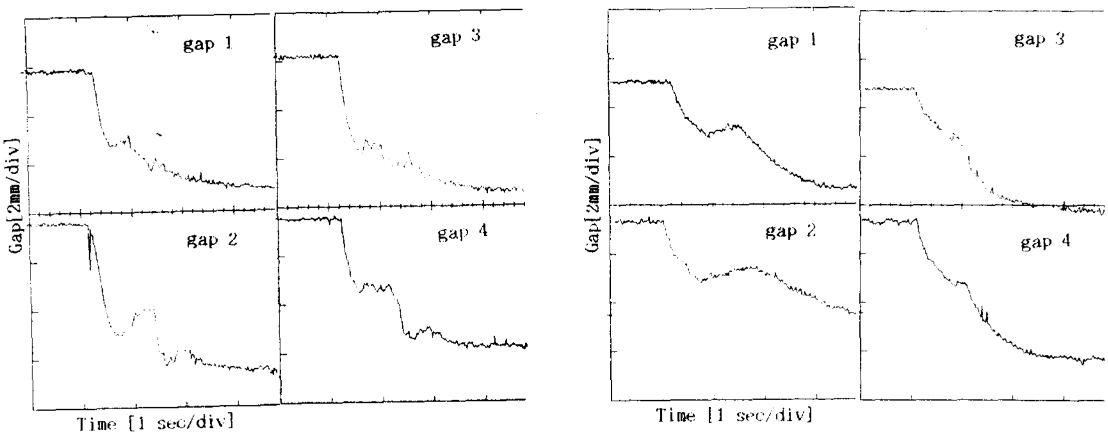


(a) State feedback



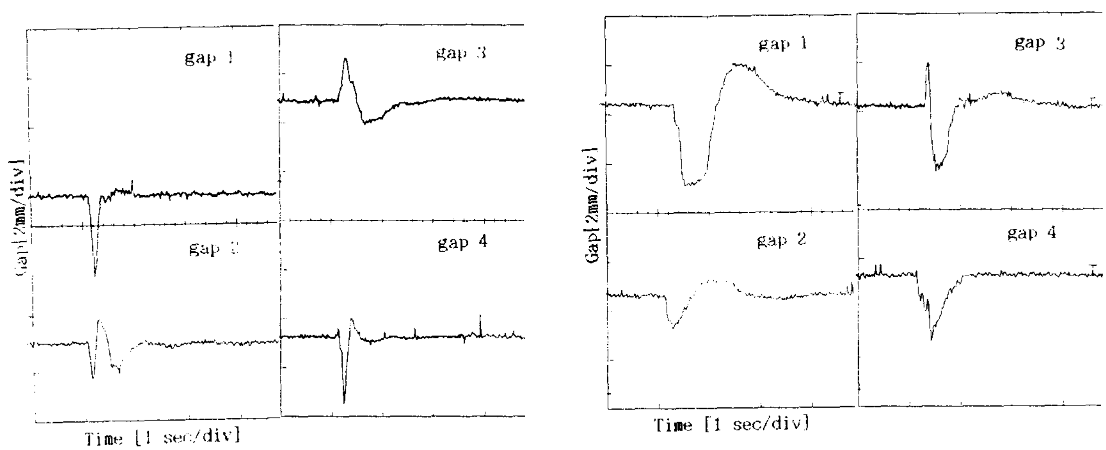
(b) PID

Fig. 7. The response of the vehicle(with no load)



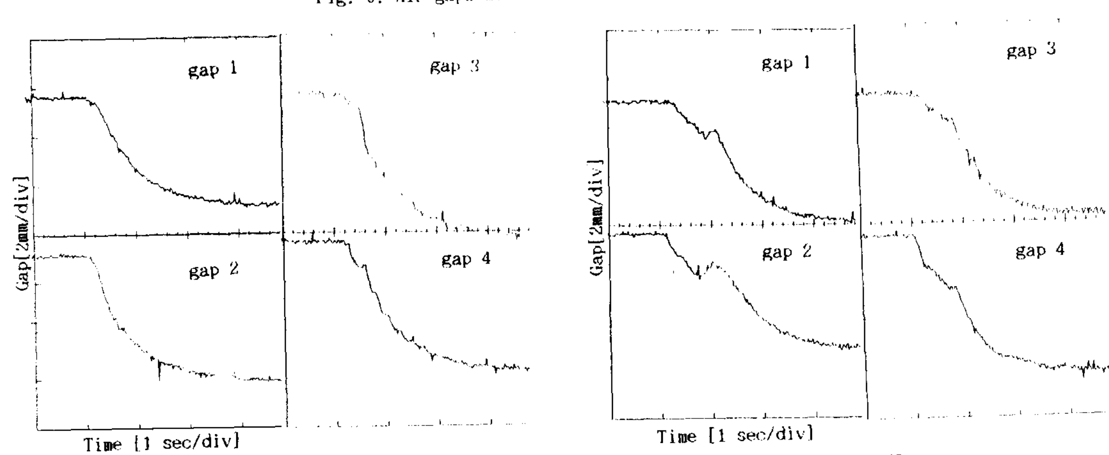
(a) State feedback (b) PID

Fig. 8. Air gaps at four corners for mass increase



(a) State feedback (b) PID

Fig. 9. Air gaps at four corners for impulsive force



(a) State feedback (b) PID

Fig. 10. Air gaps at four corners for width change