6 Degrees of Freedom Control through Three Electromagnets and Three Linear Induction Motors

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Electromagnetic suspension, linear induction drive, magnetic levitation, motion control, and two-dimensional drive

Abstract

Configuration that the mover has three electromagnets and three linear induction motor (LIM) has been proposed for contactless flexible conveyance system. Hybrid electromagnet that uses permanent magnet can let power consumption converge to zero in steady state, and its stator becomes simple because the combination of three LIM's is used for two-dimensional drive. The normal attractive force of LIM can increase the carrying capacity of the mover, although it can be also disturbance force for the stabilization of the magnetic levitation system. Authors have experimentally confirmed that the proposed configuration can realize six-degrees of freedom control of the mover. Position sensing for the closed loop control of two-dimensional linear drive is difficult: one possible approach based on visual sensing combined with dual sample-rate digital observer is proposed and discussed.

1 Introduction

The combination of electromagnetic suspension technology (EMS) and linear motor is useful in the conveyance systems, but its movement is usually limited to single dimension. For more flexible conveyance system, we have proposed the coordination of a four-pole shaped hybrid electromagnet and two-dimensional linear synchronous motor[1]. It had, however, some disadvantages, such as its lack of damping in the yawing direction and complexity of its stator.We have proposed a mover that has 3 U-shaped electromagnets and three linear induction motors (LIMs)[2] in order to overcome these disadvantages. In this configuration, which is shown in figure 1, six-degrees of freedom of the mover can be controlled and the stator is simply composed of iron and conductor plate.

2 Control method of magnetic suspension

Three hybrid electromagnets that have permanent magnets on the surface and coils are used to suspend the mover and control its posture in this study. The hybrid electromagnets can let power consumption converge to zero in the steady state. The relationship between the coil current I_f, effective gap length g_e (air gap + thickness of secondary conductor d) of electromagnet and attractive force f_m has been calculated based on a simple magnetic circuit analysis. k is an attractive force coefficient, L_m is thickness of the permanent magnet and I_m is magnetmotive force of the permanent magnet. The equation is described as follows :

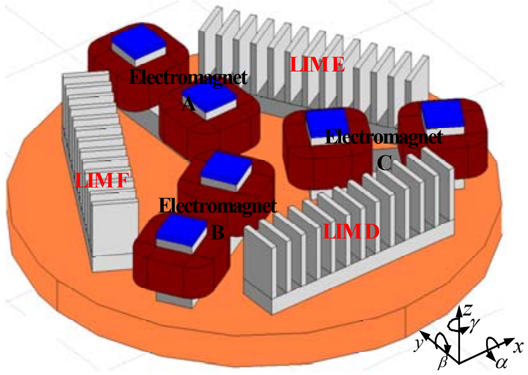

Figure 1 Configuration of the proposed mover.

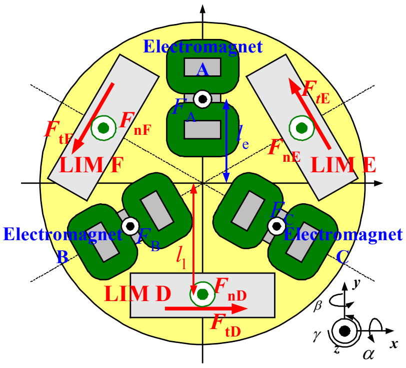

Figure 2 Location of Electromagnets and

$$f_m = k\left(\frac{I_f + I_m}{g_e + L_m}\right)^2 \tag{1}$$

As methods to control the posture of the mover, both of decentralized and centralized controls have been proposed. In the decentralized control, each of the three electromagnets controls its gap length suspending one-third of total mass. In the centralized control, total posture (z, α, β) is cont-rolled using coordinates transformations, which include the location of electromagnets. The location of electro-magnets and LIMs is shown in figure 2. The l_e is the distance between the center of the mover and its electromagnet, l_l is the one between the center of the mover and its LIM's.

2.1 Decentralized Motion Control

We call the conventional control method as the decentralized control, in which the gap of each magnet is controlled and stabilized separately by its own controller. The block diagram of decentralized control is shown in figure 3. In this study, the three hybrid electromagnets have same characteristics, so one can use the same controller in each gap length of A, B and C.

2.2 Centralized Motion Control

The centralized control uses coordinates transformation to change gap length and currents of electromagnets to posture (z, α, β) and virtual currents (i_z,i_α,i_β). These coordinates transformations are described as follows.

$$\begin{pmatrix}\Delta z\\ \Delta\alpha\\ \Delta\beta\end{pmatrix} = \begin{pmatrix}-1/3 & -1/3 & -1/3\\ -2/3l_e & 1/3l_e & 1/3l_e\\ 0 & -1/\sqrt{3}l_e & 1/\sqrt{3}l_e\end{pmatrix}\begin{pmatrix}\Delta g_A\\ \Delta g_B\\ \Delta g_C\end{pmatrix} = T\begin{pmatrix}\Delta g_A\\ \Delta g_B\\ \Delta g_C\end{pmatrix} \tag{2}$$

$$\begin{pmatrix}\Delta i_z\\ \Delta i_\alpha\\ \Delta i_\beta\end{pmatrix} = \begin{pmatrix}1 & 1 & 1\\ 1 & -1/2 & -1/2\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{pmatrix}\begin{pmatrix}\Delta i_A\\ \Delta i_B\\ \Delta i_C\end{pmatrix} = H\begin{pmatrix}\Delta i_A\\ \Delta i_B\\ \Delta i_C\end{pmatrix} \tag{3}$$

By using these virtual variables, dynamic equations of motions are described. For example, linearized dynamic equation of z direction is described as follows :

$$Ms^2\Delta z = K_A\Delta i_z + 3K_B\Delta z \tag{4}$$

The controllers of z, α and β directions are designed depending on the linearized dynamic equations and assuming these equations are realized independently. The controller's gains are determined as is the case with decentralized control. The block diagram of the centralized control is illustrated in figure 4.

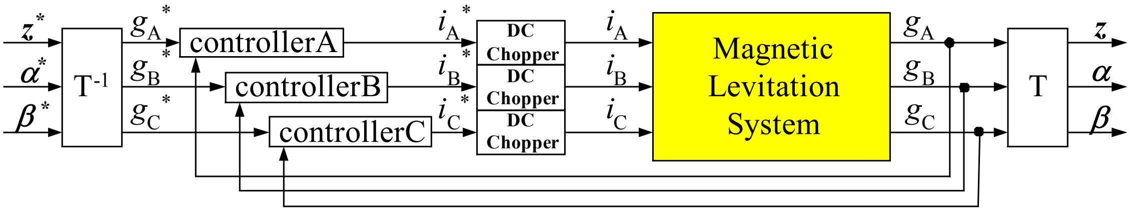

Figure 3 Block diagram of the decentralized control.

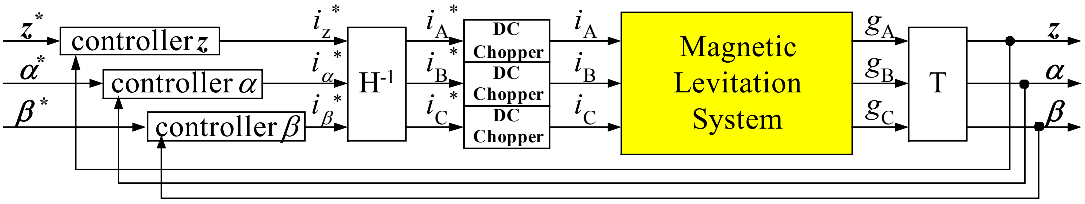

Figure 4 Block diagrm of the centralized control.

3 Two-Dimensional Drive Scheme using Three Linear Induction Motors

Three LIMs are used for controlling two-dimensional drive. When linear motor generates thrust, normal force is simultaneously generated in the vertical direction. In a steady state, we use normal attractive force of LIMs to suspend 10% of the mover's mass. In terms of suspension and propulsion, we prefer small gap length to get large attractive force and thrust. But the shorter the gap becomes, the smaller the range of motion becomes. In order to keep sufficient range of motion and obtain thrust large enough, we have determined the air gap length to 4.0[mm]. The speed of the mover is not high (lower than 0.05[m/s]) and slip frequency may be low in prospective experiments. We have, therefore, simply adopted slip frequency control as a control method of a LIM because thrust increases in proportion to its slip frequency in the region of low slip frequency. Approximated linearized thrust equation is described as follows :

$$F_t \approx K\,sf \qquad (5).$$

We have to measure the speed of each LIM's for the drive control. A coordinates transformation is used to estimate the velocity from the mover's velocity. This is described in equation (6) and the coordinates transformation from each LIM's thrust to forces and torque toward x, y, and γ direction described in equation (7).

$$\begin{pmatrix} v_D \\ v_E \\ v_F \end{pmatrix} = \begin{pmatrix} 1 & 0 & l_l \\ -1/2 & \sqrt{3}/2 & l_l \\ -1/2 & -\sqrt{3}/2 & l_l \end{pmatrix} \begin{pmatrix} v_x \\ v_y \\ \omega_\gamma \end{pmatrix} = P \begin{pmatrix} v_x \\ v_y \\ \omega_\gamma \end{pmatrix} \tag{6}$$

$$\begin{pmatrix} F_x \\ F_y \\ T_\gamma \end{pmatrix} = \begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ l_l & l_l & l_l \end{pmatrix} \begin{pmatrix} F_{tD} \\ F_{tE} \\ F_{tF} \end{pmatrix} = L \begin{pmatrix} F_{tD} \\ F_{tE} \\ F_{tF} \end{pmatrix} \tag{7}$$

4 Command response (z direction, decentralized control).Simulation and Experimental Results

The two magnetic levitation control methods are compared experimentally. The experiments of linear drives interacting with magnetic suspension will be also reported.

4.1 Control System and Experimental Bench

Levitation and drive are controlled by a DSP-system. The DSP system enables constant sampling- and control- cycles. In this case, that cycle was 500[μs]. The configuration of control system is shown in figure 5. Three different gap-lengths of electromagnet are detected by LED sensor. Measured gap lengths are taken into the DSP through an A/D board, command currents of three electromagnets are calculated and the currents are given to electromagnets by DC chopper. The position in the *y* direction are detected by supersonic sensor for linear drive controls. Command currents are calculated and given to LIM E and LIM F. Coefficients of the test bench are shown in table 1 and a photograph of the experimental system is shown in figure 6

Table 1 Coefficients of the facility

M	14.2[kg]	k	1.57×10^{-5}[Nm^2/A^2]
G_0	5.70[mm]	I_m	15.0[A]
L_m	3.00[mm]	d	2.00[mm]
J_α	0.0569[kgm^2]	J_β	0.0621[kgm^2]
J_γ	0.1431[kgm^2]	l_e	0.0850[m]
l_l	0.100[m]	τ	0.0700[s]

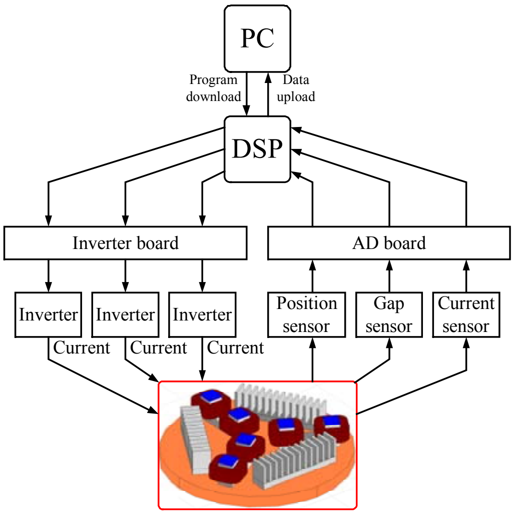

Figure 5 Suspension control system.

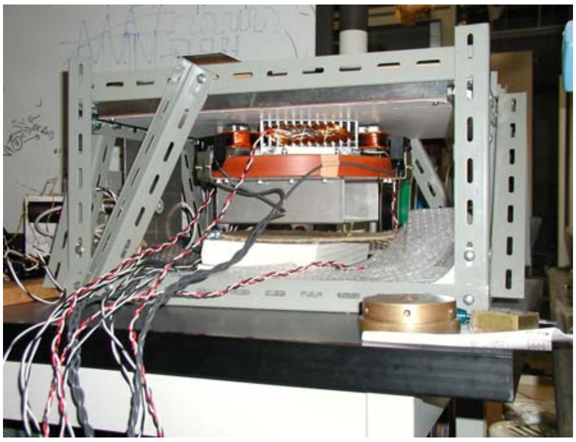

Figure 6 Photograph of the test bench.

4.2 Experiments of Magnetic Suspension

Command responses of the *z*-direction in the decentralized and the centralized controls are shown in figures 7 and 8, respectively. The command responses of the β-direction in decentralized and centralized controls are shown in figures 10 and 11. Command values in the *z*- and $\beta-$ directions are changed from 0[mm] to 0.5[mm] and from 0[rad] to 0.588[rad] at 1.5[s]. When we compare figures 9 and 10, the command responses in the *z* direction are the same in decentralized and centralized controls. But when we compare figures 9 and 10, the response in centralized control can converge to command value more quickly, since we can design the controller explicitly considering rotational dynamics. When one uses the centralized control, one can let the controller robust to rotational disturbance. We have, therefore, applied centralized control to suspend the mover in the following one-dimensional drive experiments.

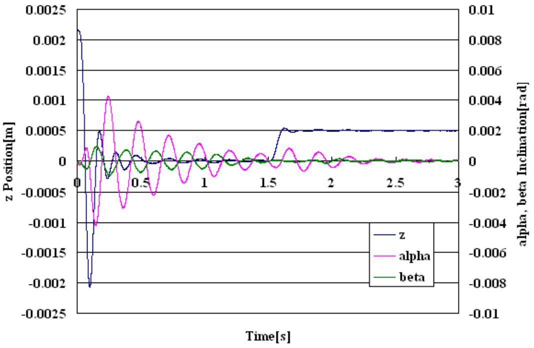

Figure 7 Command response (*z*-direction, decentralized control).

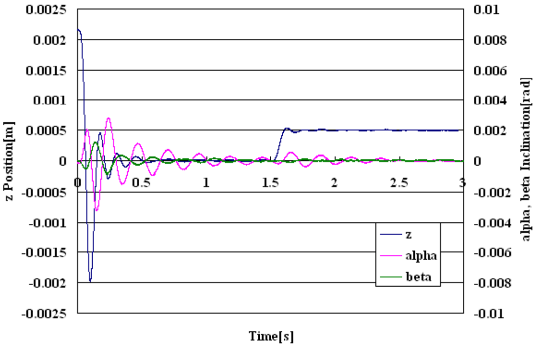

Figure 8 Command response (*z*-direction, centralized control).

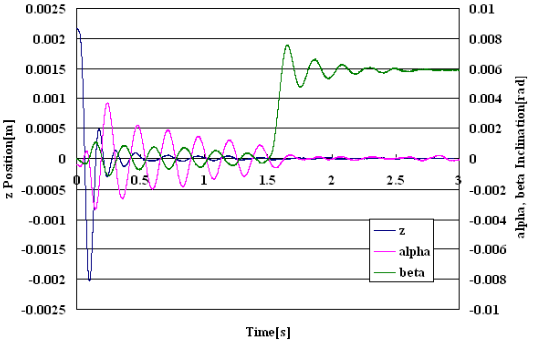

Figure 9 Command response (*β*-direction, decentralized control).

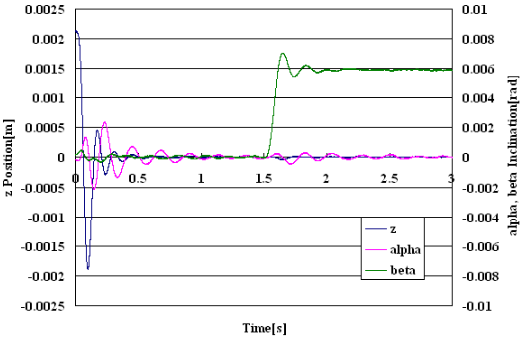

Figure 10 Command response (*β*-direction, centralized control).

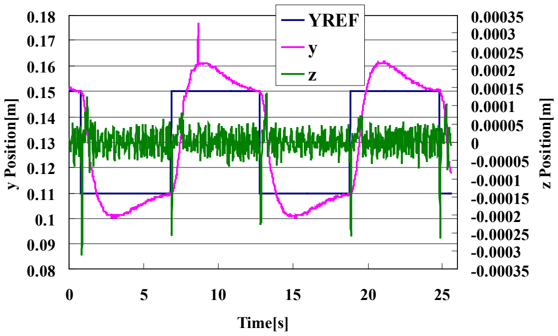

Figure 11 Vibration in *z*-direction with *y*-direction drive.

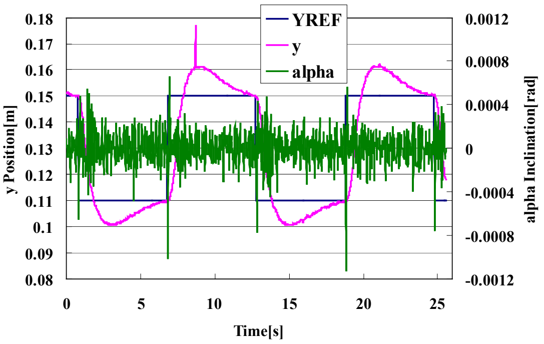

Figure 12 Vibration of *z*-direction with *y*-direction drive.

4.3 Experiment of Position Feedback Control in One-Dimensional Linear Drive

We can control the position of the mover in the *y*-direction using LIM E and LIM F. The position in the *y*-direction converged to the command value smoothly, but the two LIM's cause vibration to *z*-, $\alpha-$ and $\beta-$ directions. The responses of *z*- and $\alpha-$ directions are shown in figures 11 and 12, respectively. Compared with static magnetic levitation, the vibration becomes larger since the normal forces of LIM's change in unstabilizing way depending on their gap length.

4.4 Difficulty in Position Sensing in the Two-Dimensional Drive and its Strategy

We have accomplished only fundamental experiments of one-dimensional linear drive in the last section, since the position detection in the three-degrees-of-freedom x-, y-and γ- directions in the proposed two-dimensional drive is substantially difficult in practice. We can apply the technique of visual position sensing system as shwon in figure 13, although the sampling frame rate of ordinary video systems is only approximately 30 fps, whose dynamic range in its frequency response may be too narrow as a sensor for motion controls. We have, therefore, developed an observer theory for solving such problems of speed controls in general motor drive systems with a slow position sensor and a fast digital controller, based on digital signal processing theory with multiple sample rates. The application of the multiple sample rate observer [3] combined with visual servo-technology will give an appropriate solution also to our two-dimensional three degrees-of-freedom linear drive control.

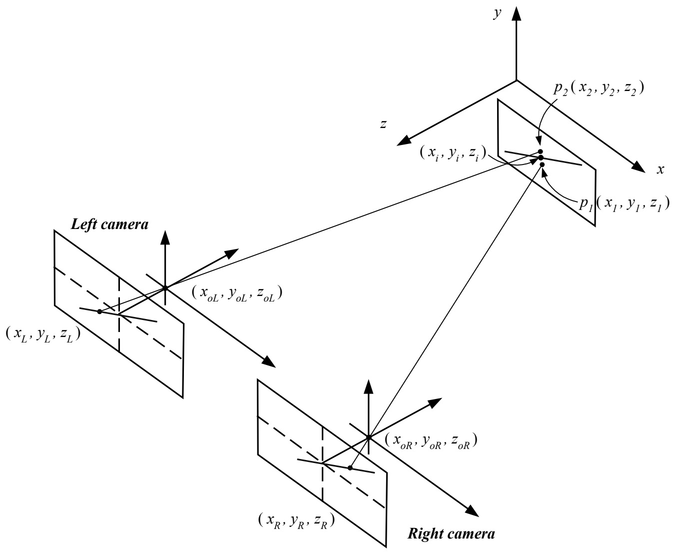

Figure 13 Principle of visual popsition sensing.

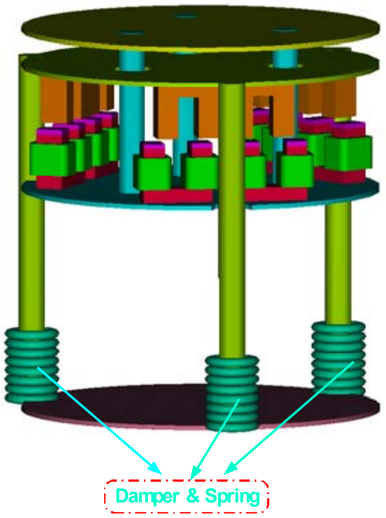

Figure 14 Application to oscillation suppression.

5 Conclusions

The structure of a mover that has three LIM's and three electromagnets to control six-degrees of freedom was proposed for a flexible contactless conveyance system. The decentralized and the centralized controls were proposed as methods of its levitation control, and both were compared in the experiments. The centralized control gives better dynamic response, if one can assume sufficiently rigid iron plate on ground as well as the mover bodies, since the centralized controller directly stabilize the rotational motors based on their dynamic model described explicitly in advance. The centralized levitation control system is, therefore, a preferable for such a conveyance system, which has a compact mover driven by linear induction motors, since their attractive normal force generated by the linear motors with their thrust control simultaneously are often considerable disturbances for the magnetic levitation.

The combination with the electromagnetic levitation with the static magnetomotive force by permanent magnets has also enabled the zero-power control [4] whose mechanical response seems like negative stiffness in its low frequency region between DC and cut-off frequency of the electromagnetic levitation controller in its frequency domain. This fundamental feature would be also used for a novel active oscillation-suppressing system in multiple direction combined with an appropriate passive and positive mechanical suspension and the fundamental structure of the magnetic levitation system illustrated in figure 14, which enables the active stabilization and motion control separately in multiple directions [5].

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