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LEVITATION AND THRUST CONTROL OF A COMPLETELY PASSIVE CORE EXCITED SOLELY BY ARMATURE CURRENTS OF A LINEAR SYNCHRONOUS MOTOR

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ABSTRACT
Electromagnetic suspension is an essential technique commonly used in industrial transport system without mechanical contacts. The reduction of the energy consumption in mover side is significant. Authors have proposed a 4-pole electromagnet with three-degrees of freedom in its control, which works well for independent levitation stabilization of a single electromagnet. They are also proposed a linear synchronous drive, in which the attractive force produced by armature flux of a linear motor is used as levitation force, for realizing a mover passive completely. The principle of the simultaneous control of levitation force and thrust are based in the separation of d- and q-axis current components. The basic idea, simulation results are described as well as its successful experimental verification.

INTRODUCTION
Electromagnetic suspension is an established technique commonly used in industrial transport system without mechanical contacts. The reduction of the energy consumption in mover side is significant: One practical solution is "zero-power control" by using permanent magnet on the mover side, so that the fundamental attractive force to suspend the mechanical load may be supplied by magnetomotive force of the permanent magnets and the onboard battery needs only to supply the compensating magnet currents to stabilize the levitation. We have proposed a 4-pole electromagnet with three degrees-of-freedom, which works well[1]. Another solution may be to remove the active components from the mover side, which is typically seen in studies of magnetic bearings and/or bearingless motors for rotary machines.

We propose a linear synchronous drive, in which the attractive force produced by armature flux of a linear synchronous motor is used as levitation force.

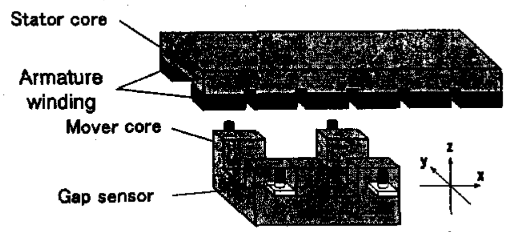


FIGURE 1. Proposed system configuration.

The first function of the armature control is, therefore, to stabilize the levitation dynamics in three degrees-of-freedom of the mover motion, *i.e.*, levitation, pitching and rolling. The second function is, of course, to produce the thrust. Since the mover is completely passive, *i.e.*, without field excitation of itself, the thrust is produced as a reluctance force.

SYSTEM CONFIGURATION
The fundamental configuration of the proposed system is illustrated in FIGURE 1. The mover has no active parts. The armature coils, below which the mover poles exist, are excited and their current are controlled. There is no active control in lateral and yawing directions, since the motion in these directions is substantially stable. Other unstable motion in vertical, pitching and rolling directions are stabilized through active control based on the gap-sensor feedback signals simultaneously. The simultaneous controls of levitation and thrust are possible based on the d- and q-axis coordinates transformation illustrated in FIGURE 2 (a).

The d-axis component of the armature current is used to control the levitation gap whereas the q-axis component is used to control thrust in our fundamental idea. The voltage equation of the d-axis component is as follows:

$$V_d = I_d R + L_d \frac{dI_d}{dt} - \frac{\pi v}{\tau_p}\Phi_q \qquad (1)$$

where v is mover speed and τ_p is a pole pitch. The voltage equation of q-axis component which mainly contribute to the thrust control is:

$$V_q = I_q R + L_q \frac{dI_q}{dt} - \frac{\pi v}{\tau_p}\Phi_d . \qquad (2)$$

The thrust is calculated from d- and q-axes flux as follows:

$$F_x = K(\Phi_d I_q - \Phi_q I_d) \qquad (3)$$

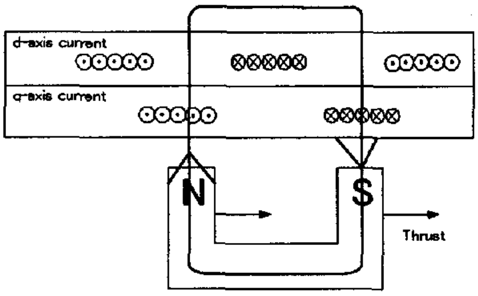
where the d- and q-axis flux is written as follows.

$$\Phi_d = L_d I_d$$
$$\Phi_q = L_q I_q \qquad (4)$$

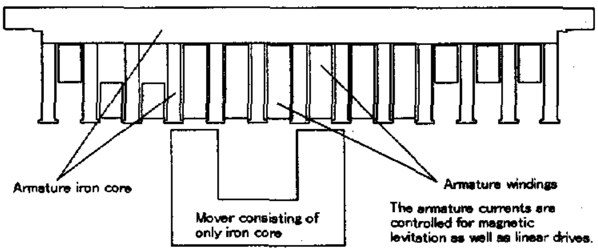
Hence, the thrust is proportional to the multiplication of the difference of L_d and L_q, I_d, and I_q.

$$F_x = K(L_d - L_q) I_d I_q \qquad (5).$$

That is to say, the thrust is "salient force," which is proportional to the multiplication of I_d and I_q, therefore, we can control it by keeping I_d constant and adjusting I_q corresponding to the thrust command. The detailed theory is explained in many standard textbooks on electrical machinery and its drives, *e.g.*, in [2]. The coordinates transformation between d- and q-axis and physically existing u-, v-, and w-phase windings will be described in the appendix in this paper.



(a) Fundamental control concept of Id- and Iq-separation in the 2-pole mover case.



(b) Cross-sectional view of the armature and the 2-pole mover core of the test bench.

FIGURE 2. Configuration of the principle and actual levitation system.

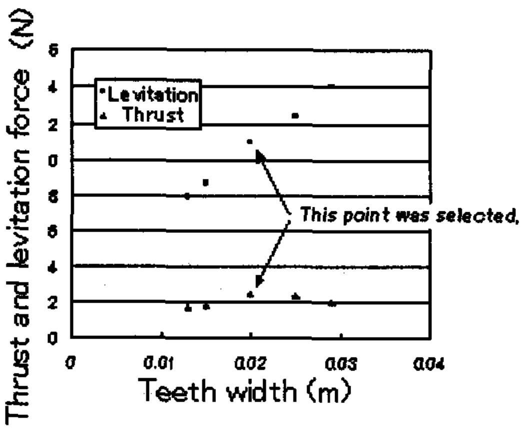


FIGURE 3. Teeth width dependency of thrust and levitation force. $I_d = 4$A, $I_q = 2$A.

TABLE 1. Specification of experimental machine.

Stator	Slot pitych	τ_s	0.018m
	Pole pitch	τ_p	0.054m
	Winding number	T	102 turns
Mover	Mass of mover	m	1.05kg
	Mass including sensors	m'	1.45kg

The mover pole pitch has been selected identical to the armature pole pitch. The teeth width is selected as 0.02m through the numerical results in figure 3 obtained from a two-dimensional field calculation. The specification of the resultant design of the experimental set is given in TABLE 1.

VERIFICATION OF THE PROPOSED SEPARATE CONTROL THROUGH TWO-DIMENSIONAL FIELD CALCULATION

It is obvious that the separate controls of d- and q-axis currents are valid in a rotary synchronous motor, but there may be differences between rotary and linear motors. Therefore, we should check the validity of the control scheme through two-dimensional electromagnetic analysis. When we input only d-axis current, the flux plot in FIGURE 4 (a) is obtained. It is obviously seen that we obtain the attractive force, which contributes directly to the levitation control, by such an excitation. Contrary to this, when we input only q-axis current, the flux plot in FIGURE 4 (b) is obtained. These flux lines do not affect the levitation force. These facts justify the idea of the separate control, in which we control I_d for levitation control and I_q for thrust separately.

The force calculation in FIGURE 5 supports this idea quantitatively, too. If we keep I_d constant, the levitation force is almost constant even if the position and I_q changes, and thrust is uniquely determined when we give a specific I_q.

The position dependency of the d- and q-axis inductances is also checked in FIGURE 6. If these values strongly depended on the position, we had to change the levitation controller gains as a function of the mover position. But L_d and L_q are fortunately almost constant. Therefore, we can design a simple levitation controller in the next section.

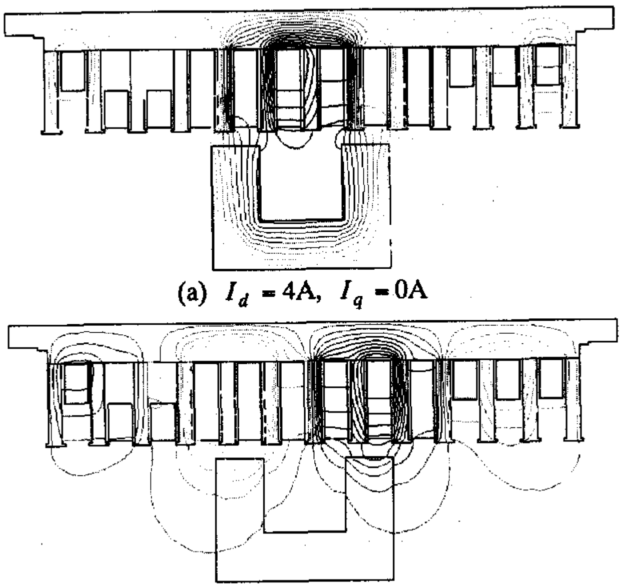


FIGURE 4. Magnetic flux plot.

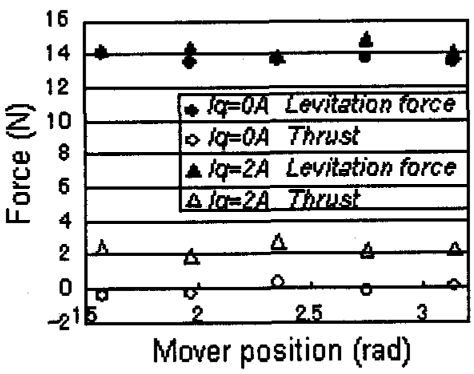


FIGURE 5. Position dependency of thrust and levitation force when I_d =*const.*, I_q = 0 or 2A, and the gap length is 6mm.

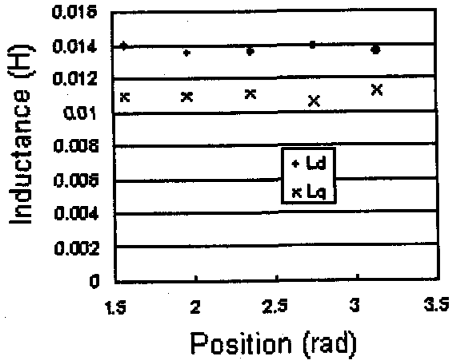


FIGURE 6. Position dependency of d-axis and q-axis inductance.

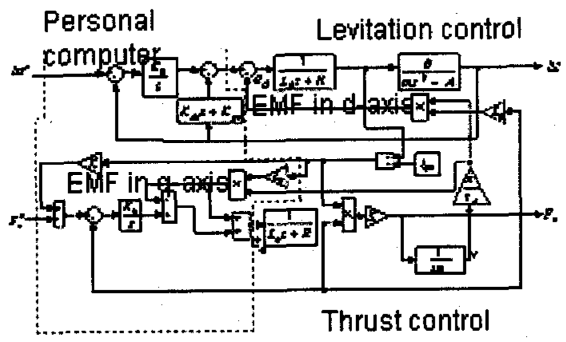


FIGURE 7. Block diagram drawn through Simulink for calculating the behavior of the simultaneous control of levitation and thrust.

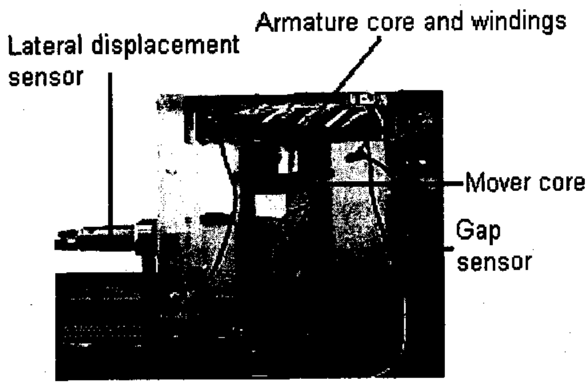


FIGURE 8. Outline of the experimental bench set.

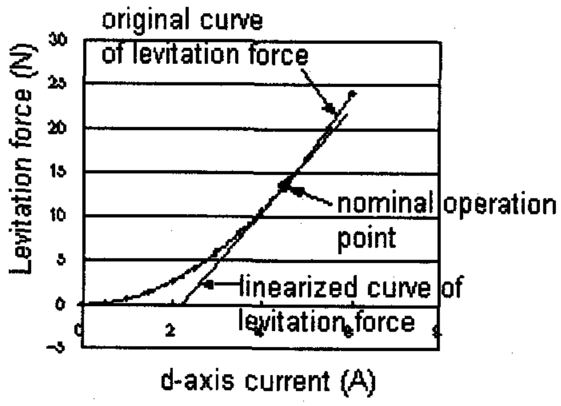


FIGURE 9. Relationship between d-axis current and levitation force when the gap length is 6mm.

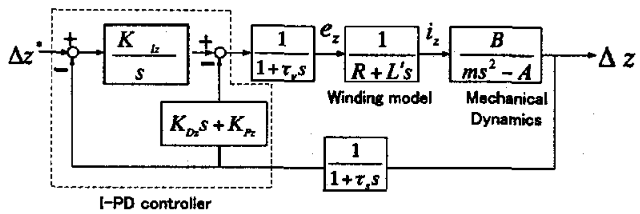


FIGURE 10. Block diagram of levitation control.

CONTROLLER DESIGN

Although there are some interactions between thrust and levitation controls as shown in FIGURE 7, they are substantially weak. We can design levitation and thrust controllers separately in the following procedures.

Levitation Control

The levitation control has the following three steps:

(1) coordinates transformation from the real coils to virtual vertical-, pitching-, and rolling coils,
(2) design of I-PD controllers based on simplified plant linear models in each motion direction, and
(3) reversed coordinates transformation from virtual to real coils.

Since the principle of (1) & (3) has already been experimentally proved in our previous publications [1], the test bench is designed with 2-pole magnet configuration as illustrated in FIGURE 8 only for investigating the I_d - and I_q - separate control.

The levitation force has a nonlinear dependency on gap length, and this characteristic has been linearly approximated around the nominal operating point as illustrated in FIGURE 9. By this simplification, the d-axis current is controlled through a simple I-PD controller illustrated in FIGURE 10. The controller parameters have been determined by the method called *Kessler's damping optimization*[3]. FIGURE 11 shows a simulation result of the gap length response, which is a typical example of the response of the levitation controller designed through Kessler's method.

Thrust Control of the Linear Motor

The drive in x-direction is realized by controlling q-axis current separately from d-axis current. The thrust controller has been realized as a simple I-controller and the controller gain has been determined also based on Kessler's canonical form. A simulation result is shown in FIGURE 12. Although the controller is a simple I-controller, the thrust response converges sufficiently fast, since the time constant of I_q is substantially small in the d/q-separation control.

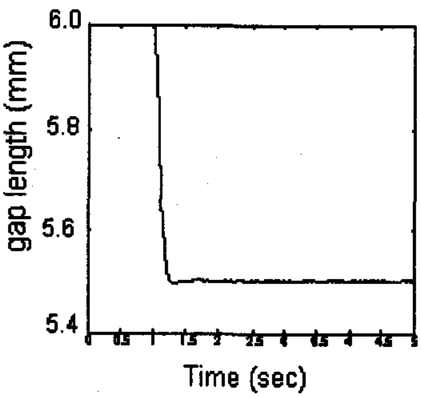


FIGURE 11. Simulation result of the levitation control when the gap set value is given as 5.5mm.

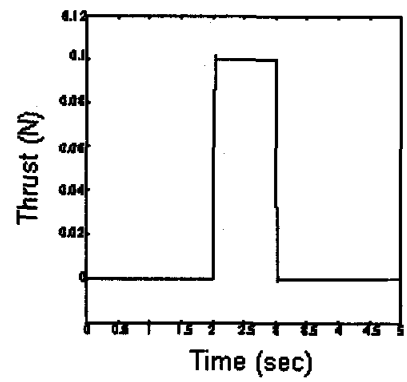


FIGURE 12. Simulation result of thrust control.

EXPERIMENTAL VERIFICATION

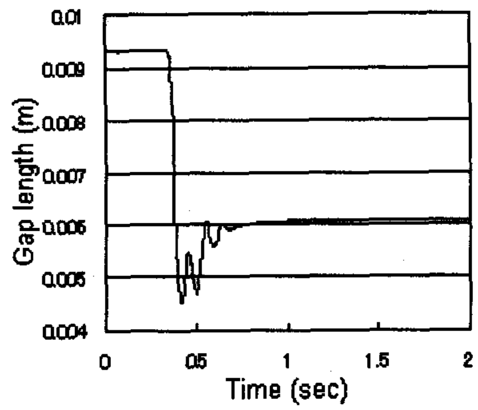
We made the test bench in FIGURE 8 for testing one-degree-of-freedom levitation control and one-dimensional drive, where the controller has no stabilizing function in pitching and rolling directions.

These degree-of-freedoms are mechanically supported in this machine.

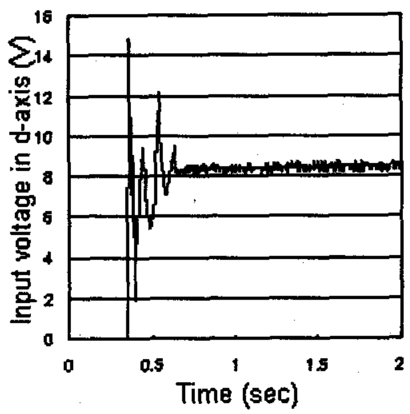
FIGURE 13 (a) is the gap response of the levitation controller when it starts the operation. Although the transient curve is more oscillating than the calculated transient curve in FIGURE 11, the levitation is successful. The main reasons for the difference from theoretical calculations may be the friction force of the mechanical pitching/rolling support, the modeling error of magnetic circuits and the effect of the time constant of the *quasi*-differential controller.

FIGURE 13 (b) indicates that the d-axis input voltage is kept constant so that the ohmic voltage drop in the armature winding can be compensated, when the stable levitation is once established. The transient input voltage is also limited to an acceptable extent.

We drove the mover in a pole pitch by controlling I_q while it was levitating, and observed the movement. The movement was smooth and there was no oscillation in vertical as well as longitudinal directions. The gap length was measured and plotted in FIGURE 14. We can see in this curve that the simultaneous separate controls of levitation and thrust were successful in this experiment.



(a) Step response of gap length



(b) Input voltage in d-axis.

FIGURE 13. Levitation test (Gap command was 6mm.)

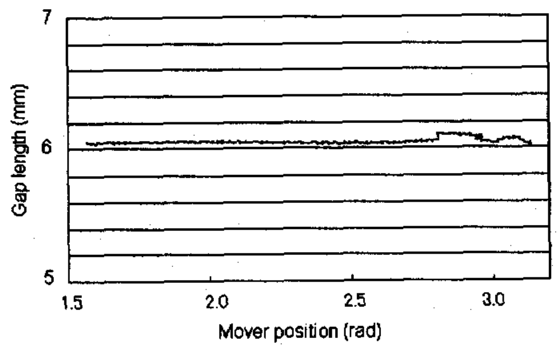


FIGURE 14. The gap length behavior when the mover is driven in x-direction.

CONCLUSIONS

We have proposed a linear synchronous motor, in which the attractive force produced by armature excitation of a linear synchronous motor is used as its levitating force. The designs of a levitation controller without substantial interaction with linear motor thrust controls have been described, and calculated results both from electromagnetic field analysis and controller simulations have supported the fundamental concept. Finally, a successful experimental data have verified the possibility of the simultaneous separate controls of levitation and thrust for a completely passive core combined with a linear synchronous motor. A practical form for an industrial application, including an appropriate arrangement of gap sensors, must be furthermore investigated.

REFERENCES

[1] Koji Yakushi, Takafumi Koseki and Satoru Sone, "3 Degree-of-Freedom Zero Power Magnetic Levitation Control by a 4-Pole Tpye Electromagnet", International Power Electronics Conference IPEC-Tokyo 2000, Vol. 4, pp. 2136-2141, April, 2000, Tokyo, Japan.

[2] Werner Leonhard: "Control of Electrical Drives, 3rd Edition, " Springer Verlag

[3] C. Kessler: "Ein Beitrag zur Theorie mehrschleifiger Regelungen," Regelungstechnik (Jahresgang 1960) Heft 8, pp.261-266, 1960

APPENDIX

Coordinates Transformation Between d- & q-Voltage/Current Components and Three-Phases

The d- and q-axis inductances L_d and L_q are assumed constant independently from the mover position and they have no interaction each other in the system illustrated in FIGURE 2. The d- and q-axis current components i_d and i_q are written by using the transformation matrix

$$\mathbf{T} = \sqrt{\frac{2}{3}}\begin{pmatrix} \cos\theta & \cos\left(\theta - 2\pi/3\right) & \cos\left(\theta + 2\pi/3\right) \\ -\sin\theta & -\sin\left(\theta - 2\pi/3\right) & -\sin\left(\theta + 2\pi/3\right) \end{pmatrix}, \quad \text{(A.1)}$$

as follows:

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \mathbf{T}\begin{pmatrix} i_u \\ i_v \\ i_w \end{pmatrix} \quad \text{(A.2)}$$

where i_u , i_v and i_w are the three-phase current components. The voltage equation is written in the same form:

$$\begin{pmatrix} e_d \\ e_q \end{pmatrix} = \mathbf{T}\begin{pmatrix} e_u \\ e_v \\ e_w \end{pmatrix} . \quad \text{(A.3)}$$

The reversed relationship is written by using the transformation matrix

$$\mathbf{T}' = \sqrt{\frac{2}{3}}\begin{pmatrix} \cos\theta & -\sin\theta \\ \cos(\theta - 2\pi/3) & -\sin(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) & -\sin(\theta + 2\pi/3) \end{pmatrix}, \quad \text{(A.4)}$$

as follows:

$$\begin{pmatrix} i_u \\ i_v \\ i_w \end{pmatrix} = \mathbf{T}'\begin{pmatrix} i_d \\ i_q \end{pmatrix} \quad \text{(A.5)}$$

and

$$\begin{pmatrix} e_u \\ e_v \\ e_w \end{pmatrix} = \mathbf{T}'\begin{pmatrix} e_d \\ e_q \end{pmatrix}. \quad \text{(A.6)}$$

If the three phases are symmetrical, *i.e.*, $i_u + i_v + i_w = 0$, then

$$\begin{pmatrix} e_d \\ e_q \end{pmatrix} = \begin{pmatrix} R & 0 \\ 0 & R \end{pmatrix}\begin{pmatrix} i_d \\ i_q \end{pmatrix} + \begin{pmatrix} L_d & 0 \\ 0 & L_q \end{pmatrix}\begin{pmatrix} \dot{i}_d \\ \dot{i}_q \end{pmatrix} - \begin{pmatrix} 0 & \omega L_q \\ \omega L_d & 0 \end{pmatrix}\begin{pmatrix} i_d \\ i_q \end{pmatrix} \quad \text{(A.7).}$$

The fictitious impedances on d- and q-axes and real three-phase impedances have the following relationship:

$$\begin{pmatrix} e_u \\ e_v \\ e_w \end{pmatrix} = \mathbf{R}\begin{pmatrix} i_u \\ i_v \\ i_w \end{pmatrix} + \mathbf{L}_{33}\begin{pmatrix} \dot{i}_u \\ \dot{i}_v \\ \dot{i}_w \end{pmatrix}, \quad \text{(A.8)}$$

$$\mathbf{R} = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix}, \quad \text{(A.9)}$$

and

$$\mathbf{L}_{33} = \begin{pmatrix} L_{uu} & L_{uv} & L_{uw} \\ L_{vu} & L_{vv} & L_{vw} \\ L_{wu} & L_{wv} & L_{ww} \end{pmatrix} = ?'\begin{pmatrix} L_d & 0 \\ 0 & L_q \end{pmatrix}\mathbf{T}. \quad \text{(A.10)}$$

The values in FIGURE 6 were calculated from three-phase inductances based on this equation (A.10).