Centralized Gap Clearance Control for Maglev Based Steel-Plate Conveyance System

Ömer Faruk GÜNEY, Ahmet Fevzi BOZKURT, Kadir ERKAN
Department of Mechatronics Engineering, Yildiz Technical University, 34100, Istanbul, Turkey
oguney@yildiz.edu.tr

***Abstract*—The conveyance of steel-plates is one of the potential uses of the magnetic levitation technology in industry. However, the electromagnetic levitation systems inherently show nonlinear feature and are unstable without an active control. Well-known U-shaped or E-shaped electromagnets cannot provide redundant levitation with multiple degrees of freedom. In this paper, to achieve the full redundant levitation of the steel plate, a quadruple configuration of U-shaped electromagnets has been proposed. To resolve the issue of instability and attain more robust levitation, a centralized control algorithm based on a modified PID controller (I-PD) is designed for each degree of freedom by using the Manabe canonical polynomial technique. The model of the system is carried out using electromechanical energy conversion principles and verified by 3-D FEM analysis. An experimental bench is built up to test the system performance under trajectory tracking and external disturbance excitation. The results confirm the effectiveness of the proposed system and the control approach to obtain a full redundant levitation even in case of disturbances. The paper demonstrates the feasibility of the conveyance of steel plates by using the quadruple configuration of U-shaped electromagnets and shows the merits of I-PD controller both in stabilization and increased robust levitation.**

***Index Terms*—centralized control, control design, electromagnetic modeling, magnetic levitation, mechatronics.**

I. Introduction

In many industrial processes, especially in automobile manufacturing, steel plates are generally conveyed over rollers. In this case, during the conveyance, there could be some surface deterioration on steel plates due to mechanical contact with the rollers. Therefore, the quality of the finite products decreases. It is expected that the electromagnetic conveyance of the steel plates should provide precise positioning and vibration-free, noise-free, contact-free working conditions. As the magnetic levitation systems meet all these requirements, mechanical contactless transport applications will be used more widely in the near future. Moreover, the usage of electrical energy alone in these systems eliminates the necessity of energy conversion. Because of mechanical contactless nature of the magnetic levitation systems, the wear effect is removed and also the maintenance costs can be reduced [1-7].

Maglev systems have been widely implemented for many engineering fields, such as vibration isolation, high-speed trains, frictionless bearings and conveyance of steel plates. Because of the instability and nonlinearity of the electromechanical dynamics of the magnetic levitation systems, the design of a stabilizing active control is a vital issue of safe and comfortable levitation of the steel plates [7-14]. In the literature, several control methods for magnetic levitation systems were presented; sliding mode control [15-18], adaptive control [19-20] and control techniques combining these two techniques are some examples. However, excessive control signals and chattering problem of the sliding mode controller revealed non-satisfactory results in the transient response; and strong nonlinearity of electromagnets makes difficult the design of these controllers. In [21], an improved version of the sliding mode control approach called gray control method with integral variable-structure was recommended for magnetic levitation system position tracking. Gray predictive compensator estimates disturbances to reduce the steady-state error and the chattering problem. Despite this, signal function at the balancer and the non-continuous switching causes chattering problems. Some researchers have used the feed forward and feedback linearization techniques for the position tracking [22-24]. Since a certain model is required in these techniques, some nonlinear dynamics has been neglected which causes a reduction of the control performance [25-26]. The use of Fuzzy logic control and artificial intelligence applications for the position tracking in the magnetic levitation systems are presented in the literature [27-30]. As an alternative to the aforementioned control techniques, in order to overcome the model deviations, a disturbance observer was added to the controllers, which makes the system more robust [31-32].

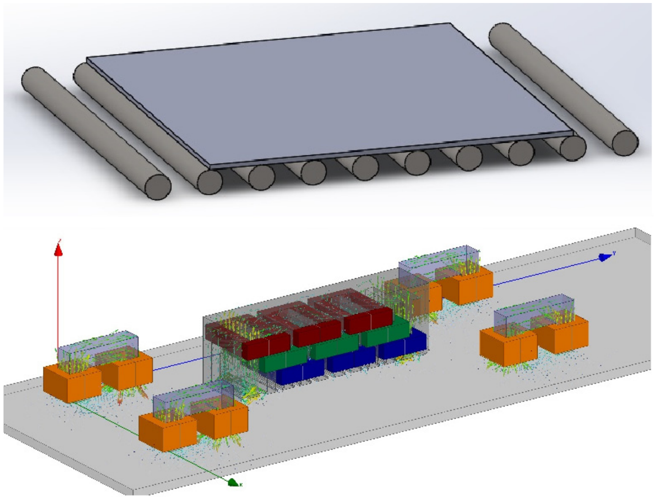

Figure 1. The conventional system and proposed maglev conveyance system.

In this study, firstly, the dynamics of the magnetic levitation system is analyzed in detail. Secondly, a FEM analysis is carried out to verify the analytical model. Then, a centralized I-PD controller is designed for control the positioning of the steel plate. Finally, the reference position tracking and disturbance response experiments are performed on the test

This work was supported in part by the Yildiz Technical University BAPK under Grant 2012-06-04-KAP01

Digital Object Identifier 10.4316/AECE.2017.03013

bench, to illustrate the validity of the proposed control method. The paper demonstrates the feasibility of the conveyance of steel plates by using the quadruple configuration of U-shaped electromagnets and shows the merits of I-PD controller both in stabilization and increased robust levitation.

II. System Modeling

The stabilizing control design issue is solved by linearizing the nonlinear electromagnet motion equations for tiny deviations around a specified equilibrium point and then and designing a linear controller.

The implementation of a one degree of freedom suspension is possible using either U-shaped or E-shaped electromagnets. However, to provide a balanced levitation of the steel plate, multiple arrangement of electromagnets is required. We proposed a magnetic levitation system that controls the 3-axes movement of the steel-plate (Fig. 1).

The analytical models of the electromagnetic attraction force and of the rotational torques produced by electromagnets via the coil currents are developed by the magnetic equivalent circuit method and verified using 3-D FEM. Results confirm that the used analytical model is consistent with the FEM model and it can be used to design the controllers.

The attraction force of a U-shaped electromagnet can be expressed by:

$$f_e(i,x) = \frac{\mu_0 N^2 S}{2}\left(\frac{i}{x}\right)^2 \qquad (1)$$

with following assumptions:

- Hysteresis, saturation and eddy currents are neglected;
- Ferromagnetic parts have infinite permeance;
- Electromagnets have no flux fringing or leakages

where, N is number of turns, S is area of flux carrying core surface and μ_0 is permeability of free space. Drawing of the U-shaped electromagnet shown in Fig. 2 and geometric details for configuration of magnets shown in Fig. 3.

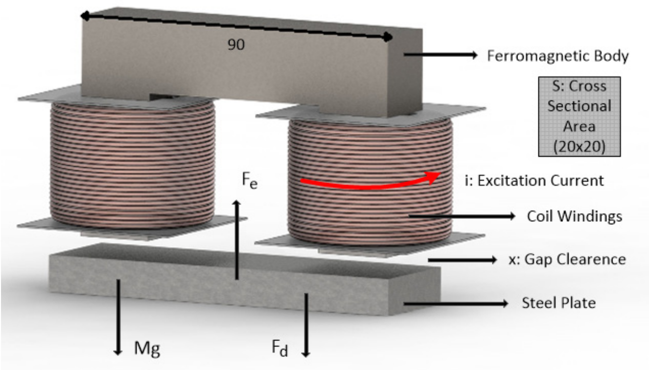

Figure 2. The U-shaped electromagnet

To determine the lateral and vertical force values, a 3-dimensional FEM analysis is carried out by Ansys Maxwell. The FEM analysis results demonstrate the nonlinear feature of the U-shaped electromagnet as it has been outlined in the analytical model. The FEM analysis of an U-shaped electromagnet with steel-plate graph can be seen in Fig. 4.

Fig. 5 shows the graph of the attraction force vs. current for a U-shaped electromagnet and the magnetic flux density map of the FEM analysis for the nominal operation point.

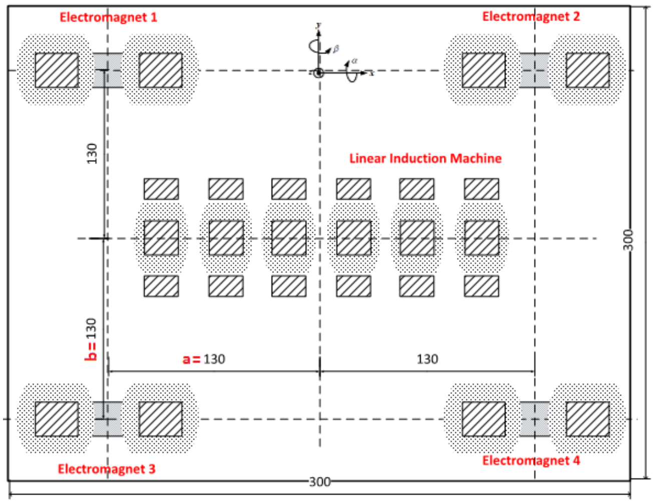

Figure 3. Geometric details for the magnetic levitation system

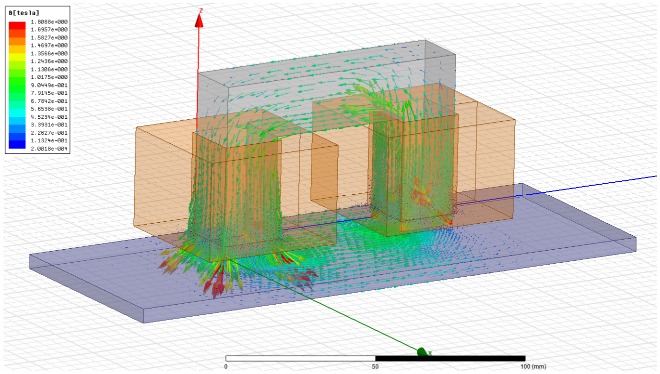

Figure 4. FEM analysis for an U-shaped electromagnet with steel-plate

At the nominal operating point (4 mm) required attraction force value is equal nearly 26 N for 1.5 A.

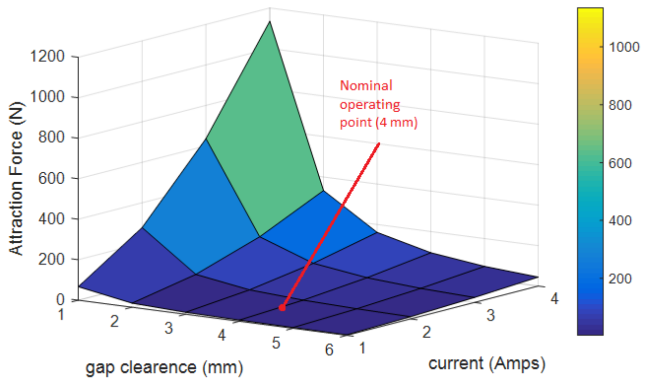

Figure 5. FEM analysis for electromagnetic force vs current

Governing nonlinear mechanical and electrical dynamics for U-type electromagnet can be described as:

$$m\frac{d^2x}{dt^2} = f_e(i,x) - mg - f_d \qquad (2)$$

$$V = Ri + \frac{d\lambda}{dt} = Ri + \frac{\partial\lambda}{\partial i}\frac{di}{dt} + \frac{\partial\lambda}{\partial x}\frac{dx}{dt} \qquad (3)$$

where the flux linkage $\lambda = 2N\Phi$ and Φ is the magnetic flux of the core.

The nonlinear force equation is linearized for tiny deviations around a specified equilibrium point, (i_0, x_0), to lead the linear controller design as illustrated by:

$$f_{e0}(i_0, x_0) = k\left(\frac{i_0}{x_0}\right)^2 = mg \tag{4}$$

The linearized dynamics of the system can be expressed:

$$m\frac{\mathrm{d}^2\Delta x}{\mathrm{d}t^2} = -K_x\Delta x + K_i\Delta i - f_d \tag{5}$$

$$K_x = -\left.\frac{\partial f_e}{\partial x}\right|_{\substack{i=i_0\\x=x_0}} \quad \& \quad K_i = \left.\frac{\partial f_e}{\partial i}\right|_{\substack{i=i_0\\x=x_0}} \tag{6}$$

$$\frac{\mathrm{d}i}{\mathrm{d}t} = -\frac{R}{L}i + \frac{K_v}{L}\Delta x + \frac{1}{L}\Delta V \tag{7}$$

$$K_v = \left.\frac{\partial \lambda}{\partial x}\right|_{\substack{i=i_0\\x=x_0}} \quad \& \quad L = \left.\frac{\partial \lambda}{\partial i}\right|_{\substack{i=i_0\\x=x_0}} \tag{8}$$

where K_x and K_i are the gap and current stiffness coefficients and K_v is the coefficient of motion back emf.

The moving platform may be able of 3-DoF movements. The nonlinear motion equations for the mechanical dynamics of each of the 3 axes can be developed considering following geometric structure:

$$m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} = f_{e1} + f_{e2} + f_{e3} - mg - f_{dz} \tag{9}$$

$$J\frac{\mathrm{d}^2\alpha}{\mathrm{d}t^2} = a\left(f_{e1} + f_{e2}\right) - a\left(f_{e3} + f_{e4}\right) - T_{d\alpha} \tag{10}$$

$$J\frac{\mathrm{d}^2\beta}{\mathrm{d}t^2} = b\left(f_{e1} + f_{e2}\right) - b\left(f_{e3} + f_{e4}\right) - T_{d\beta} \tag{11}$$

A transform matrix can be used to transform the airgap of each electromagnet to linear displacement at the z-axis and angular displacements at the α and β axes. The transform matrix can be defined considering sensors placements as:

$$T_1 = \begin{bmatrix} z \\ \alpha \\ \beta \end{bmatrix} = \frac{1}{4}\begin{bmatrix} -1 & -1 & -1 & -1 \\ \frac{1}{a} & \frac{1}{a} & -\frac{1}{a} & -\frac{1}{a} \\ \frac{1}{b} & -\frac{1}{b} & \frac{1}{b} & -\frac{1}{b} \end{bmatrix}\begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \\ \Delta x_4 \end{bmatrix} \tag{12}$$

In the same manner, a current transform matrix is defined for the conversion of the currents of each electromagnet coil into global axes currents:

$$T_2 = \begin{bmatrix} i_z \\ i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{4}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \end{bmatrix}\begin{bmatrix} \Delta i_1 \\ \Delta i_2 \\ \Delta i_3 \\ \Delta i_4 \end{bmatrix} \tag{13}$$

Total system dynamics can be obtained using Eqs. (2) and (3). The linearized dynamics can be developed as:

$$\frac{\mathrm{d}^2\Delta z}{\mathrm{d}t^2} = K_{xz}\Delta z + K_{iz}\Delta i_z - f_{dz} \tag{14}$$

$$\frac{\mathrm{d}i_z}{\mathrm{d}t} = -\frac{R}{L}i_z + \frac{K_v}{L}\frac{\mathrm{d}\Delta z}{\mathrm{d}t} + \frac{1}{L}\Delta V_z \tag{15}$$

$$\frac{\mathrm{d}^2\Delta\alpha}{\mathrm{d}t^2} = K_{x\alpha}\Delta\alpha + K_{i\alpha}\Delta i_\alpha - T_{d\alpha} \tag{16}$$

$$\frac{\mathrm{d}i_\alpha}{\mathrm{d}t} = -\frac{R}{L}i_\alpha + \frac{K_v}{L}\frac{\mathrm{d}\Delta\alpha}{\mathrm{d}t} + \frac{1}{L}\Delta V_\alpha \tag{17}$$

Linearized β-axis dynamics is expressed by equations which are symmetrical with Eqs. (16) and (17).

III. Controller Design

The magnetic levitation systems are designed by multiple arrangements of the electromagnets are multi inputs – multi outputs (MIMO) systems and highly nonlinear systems due to characteristics of the electromagnets. From the point view of the controllability, it is an unstable system, thereby, an active control algorithm is compulsory. We proposed an I-PD control for a 3-DoF levitation system with quadruple configuration under centralized concept. The I-PD control algorithm for one degree of freedom is shown in Fig. 6 and the transfer function block diagrams of the maglev system for the linearized z-axis dynamics is shown in Fig. 7.

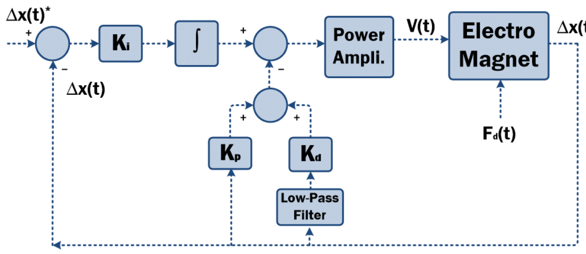

Figure 6. I-PD control scheme for one degree of freedom.

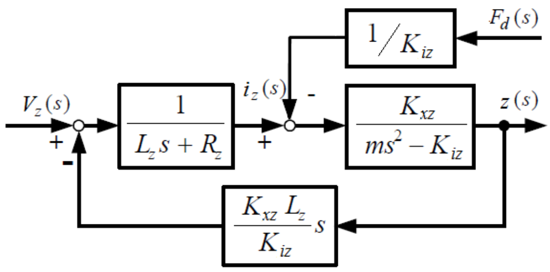

Figure 7. Transfer function block diagram of the maglev system.

In the centralized control, it can be considered that each axis can be controlled independently, by transforming the attraction forces of the electro-magnets assuming that the coupling effect is negligible. By controlling each DoF, each gap clearance can be controlled using the transformation matrices (Fig. 8).

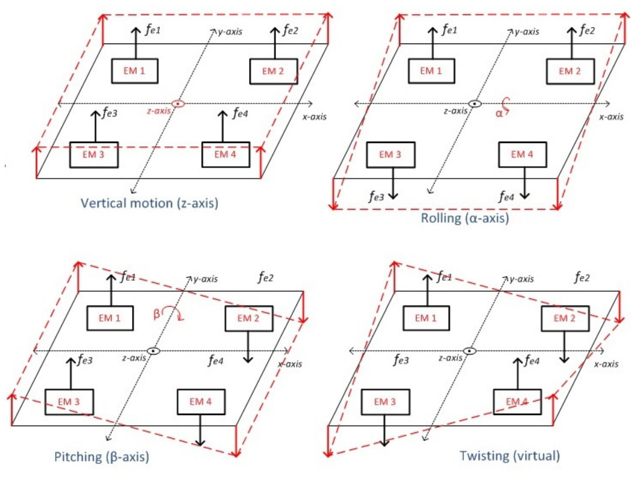

Figure 8. Transform of the attraction forces of electromagnets to the motion axes

The attraction forces produced by electromagnets provided motions on axes (*z*, α, β). For the conventional PID control loops, major changes in the reference signals cause large input signals generated by the proportional and derivative gains in the controller that resulted in so called derivative kick effect. The control algorithm with the I-PD controller has a structure whose inner loop includes the proportional and the derivative gain blocks that include the low-pass filter. In this structure, the proportional and derivative gains are directly multiplied by the position feedback signal that prevents large signals being the input to the actuator and eliminates the derivative kick effect [34].

When the linearized system dynamics is investigated, it might be assumed that there is no mutual coupling between the electromagnets. So is concluded that each axis can be controlled separately. Since all of the electromagnets have same structural properties, the controller design is identical.

By using the transform matrix, symbolized with T_1 in Eq. (12), the gap clearances between steel-plate and each electromagnet may be converted to linear z-displacement and angular α-, β-displacements. Calculated angular and linear displacements are transferred to controller as feedback. Then, the I-PD controller outputs are converted to winding voltages using the T_2 transform matrix. The I-PD control algorithm that controls the each degree of freedom is shown in Fig. 9.

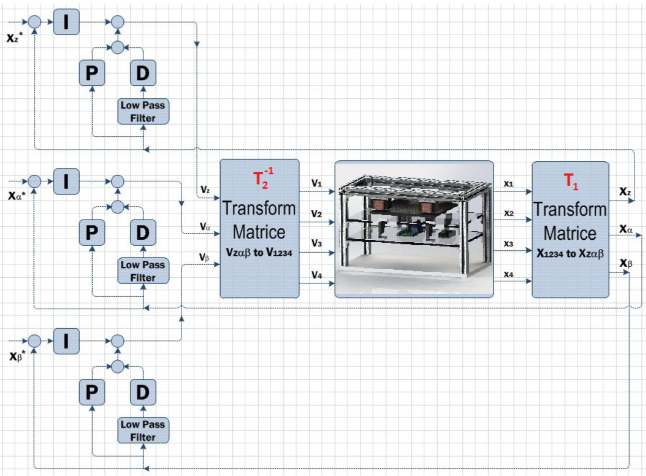

Figure 9. I-PD Controller design for each degree of freedom

As known, the control performance decreases due to the sensor measurement noise which results in excessive change of pure derivative output. To reduce the effects of the noise, a low-pass filter is inserted in series with the derivative term of each controller. With respect to the noise levels that we observed, it is enough to use a first-order low pass filter. But there is a critical issue that should be considered intensively i.e. the rational value of the low-pass filter's time constant. If the time constant is picked too small, that will allow entering of too much noise into the measurement which will reduce the control performance. Besides, if the time constant is picked too high, the derivative gain will be delayed too much and the system will become non-stable. So, choosing filter's time constant is as important as determining the controller gains [33]. K_p - K_d - K_i parameters indicate proportional, derivative, integral gains of the I-PD controller. These gains can be calculated using Manabe's canonic polynomial approach [34]. Controller gains are determined by following expressions:

$$K_p = \frac{L_z^2 \gamma_3^2 \gamma_2 K_{xz} R_z + R_z^3 m}{L_z^2 \gamma_3^2 \gamma_2 K_{iz}} \tag{18}$$

$$K_i = \frac{R_z^4 m}{L_z^3 \gamma_3^3 \gamma_2^2 \gamma_1 K_{iz}} \tag{19}$$

$$K_d = \frac{R_z^2 m}{L_z \gamma_3 K_{iz}} \tag{20}$$

The basic idea behind this approach is to determine a suitable stable characteristic polynomial using equivalent time constants and stability indices (gamma). The controller parameters that will achieve this are found by taking the first stability index value of 2.5 and the others of 2.

Parameters with index "z" in Eqs. (18), (19) and (20) represent the valid values for the *z*- axis. For the inclination movements, corresponding indices will be changed based on axes α and β so the values will change too.

The controller parameters values are given in Table 1.

TABLE 1. CONTROLLER PARAMETERS VALUES

Axis	*Kp*	*Ki*	*Kd*
z - axis	1380	460	3
α - axis	110	80	2
β - axis	110	80	2

IV. RESULTS AND DISCUSSIONS

The system control is implemented on a digital controller consisting in a computer, a data acquisition card and sensor boards. The Analog-Digital Converter converts the outputs of the airgap and current sensors. The computer determines the control outputs according to the control algorithm. Then, the Digital-Analog Converter converts the digital control outputs to analog signals to send to the power amplifier (Fig. 10).

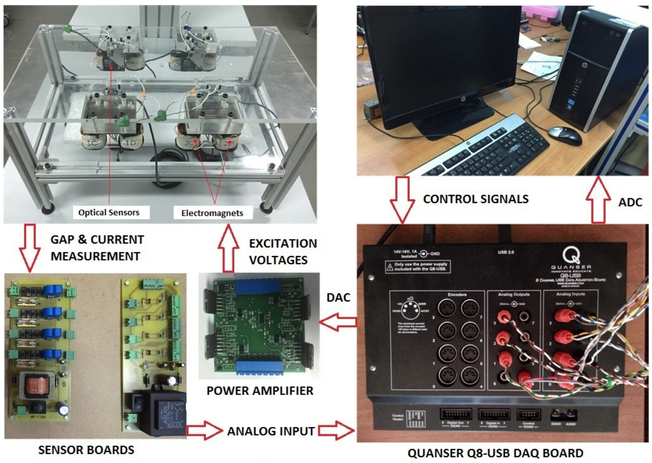

Figure 10. The flowchart of the system control

The experimental setup parameters are given in Table 2.

TABLE 2. EXPERIMENTAL SETUP PARAMETERS

Constant parameter	Value	Unit
Length of steel-plate	300	mm
Width of steel-plate	300	mm
Thickness of steel-plate	4	mm
Mass of steel-plate	2.7	kg
Inertia for α and β axes	0.02	$kg.m^2$
Distance between magnets	260	mm
Number of turns	200	turns
Resistance of the coils	1.3	Ohms
Inductance of the coils	0.023	Henry

In the experiments, nominal airgap value is set for the overall system as linearization point value of 4 mm. As can be seen in Fig. 11, the system can track the given reference value successfully. In this figure, zero point corresponds to 4 mm, reference position tracking input is given as 1 mm.

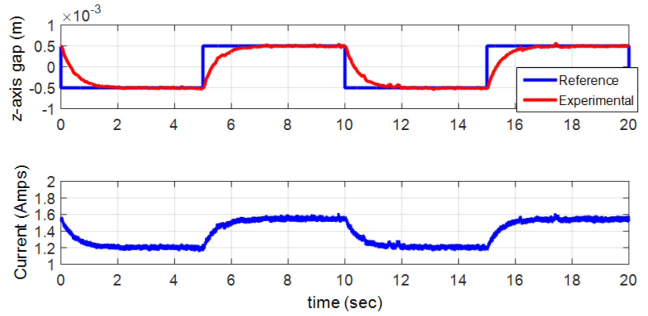

Figure 11. Position tracking performance of the levitated steel-plate

The position error in the steady-state is shown in Fig. 12. The system is able to track the reference position with precision that does not exceed 50 μm band. This value is very important and satisfactory for the precise positioning of the steel plate.

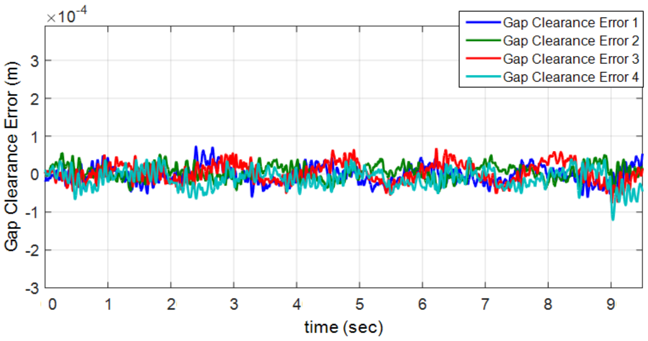

Figure 12. Position tracking error of the levitated steel-plate

To test experimentally the loading condition, a load of 400 grams was added as a disturbing effect at the 3rd second while the airgap was still at 4 mm (Fig. 13).

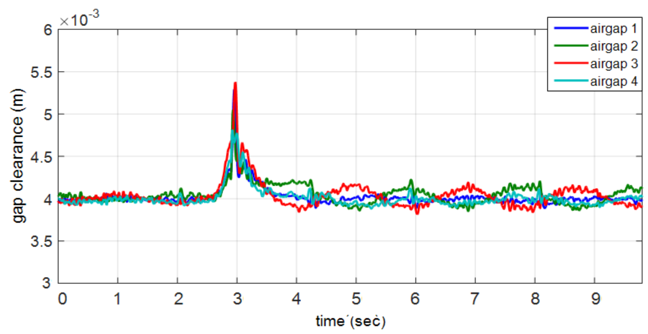

Figure 13. Position tracking performance with disturbance input

The system sets the nominal airgap again by making a small overshoot during the loading of the steel plate so that this load is levitated in air by consuming a little more energy (Fig. 14). Position control experiments has been performed considering that the steel plate is inclined in the x-axis (Fig. 15). In industrial applications, the transportation of the steel plate at a certain slope angle may not be usable, but the control of the slope angle of the plate is important in order to stabilize its vertical axis motion. The coil currents and the axial currents required to levitate the plate in these airgap values are shown in Fig. 16.

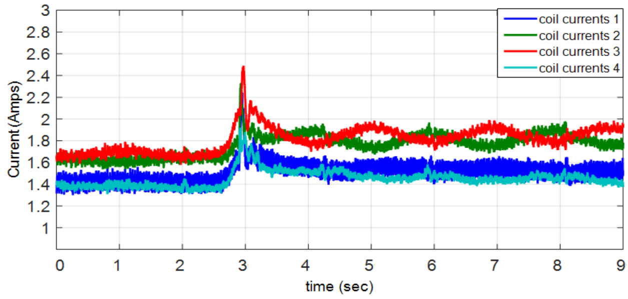

Figure 14. Current vs. time graph while position tracking

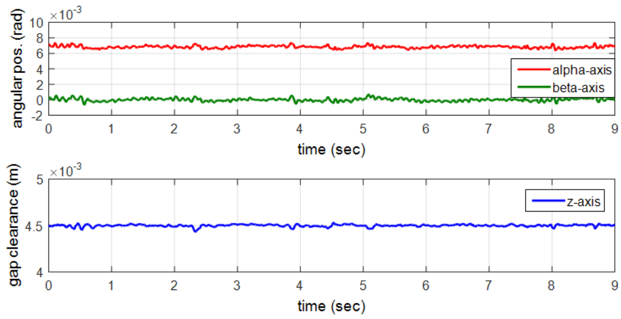

Figure 15. Position tracking performances in axial movements

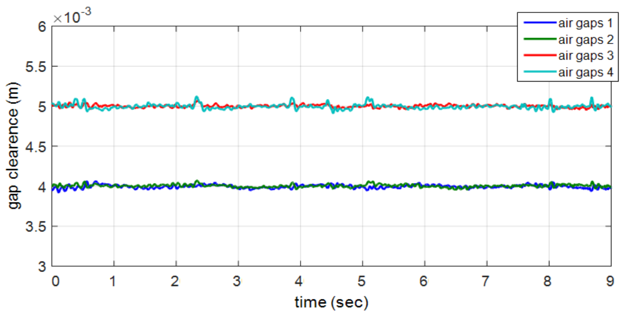

Figure 16. Gap clearance on each magnet while axial movements

The coil currents are converted in real time to the axis currents using the transformation matrices and the feedback of the control loop to levitate the steel-plate with desired slope angle (Figs. 17 and 18).

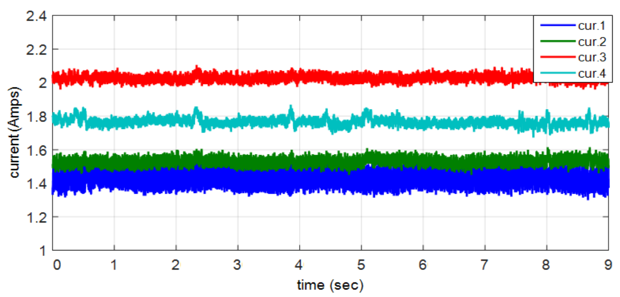

Figure 17. Currents on electromagnets while axial movements

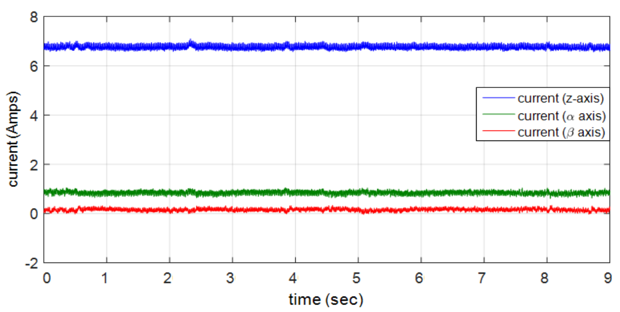

Figure 18. Currents on axes while axial movements

V. Conclusion

Multi-degrees of freedom gap clearance control of quadruple configuration of the electromagnets has been successfully achieved. In the design of the controllers, the canonical polynomial approach of Manabe has been adopted. The experimental results show no overshoot with a precise gap clearance control. Furthermore, the reference tracking error is bounded by the band of 50 μm. The approach is robust to external disturbance such as the change of the steel plate mass. This control approach is quite easy to implement and may be applied to other type of motion control systems with good robustness, stability and performance.

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