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Air gap control with a sliding mode control method

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Abstract— **in this work, the control of the levitation of a ferromagnetic object by using a planar magnetic bearing has been proposed and simulated. Such control is based on the correction of the magnetic force applied on the object as a function of its displacement by the action on the supplying current of the magnetic bearing. To achieve a control that permits a quick reaching of the desired object equilibrium position and to take into account the mass disturbance, the sliding mode control (SMC) method has been applied. To permit the correction of the dc supplying current, the bearing is energized by a four quadrants chopper. The bearing parameters required for the simulation have been experimentally and analytically defined. To the mass disturbing, an object of important mass has been considered. The control process for the considered mass has shown that the reaching of a same equilibrium position requires a higher supplying current in a short time.**

***Keywords*—** **Actuators, choppers, magnetic levitation, motion control, sliding mode control.**

I. INTRODUCTION

Magnetic bearings are widely used for the levitation in the domain of transportation (Maglev) [1-5]. Their disadvantage resides in the instability of the levitated object. To achieve a stable levitation, a control circuit must be associated to the system. The control process is based on the correction of the applied magnetics force by acting on the bearing excitation current according to the object displacement. The supplying bearing current may be increased until the magnetic force produced is equal to or greater than the gravitational force applied on the object. The variation of the current causes the fall of the object when the current is decreased or its sticking to the electromagnet when the current is increased. The feedback path control introduced aims to stabilize the object when the mass disturbance occurs. The magnetic levitation system is nonlinear in nature and is unstable in open loop. The system performance would be heavily affected by the mass disturbance. In [6-8] the bearing control has been treated for the case of alternative current supplying. In such control an approach based on the use of a PID regulator has been applied. To control a radial magnetic bearings the *LQ* and $H\infty$ approaches are applied [9-11]. To obtain robustness of the control system and to take into account the disturbance of the system the sliding mode control method is used [12-16]. The other advantage that favors the use of the SMC method is the exclusion of the use of conventional position detectors which can simplify the set-up. However, a sensorless levitation based on the detection of the position of the levitated object based on the resonance method can be used [16]. In [12], the method has been applied and experimentally validated for the control of a magnetic levitation system where the reference position of the levitated object has been considered as a disturbance.

In this work, the sliding mode control was used to control the air gap of a planar magnetic levitation where the disturbance of the system is assumed related to the changing of the mass of the levitated object (see Fig. 1). The SMC focuses on two domains; the selection of the sliding surface and the design of the sliding control law [12]. The sliding surface will decide the desirable behaviour of the operating system. The sliding control law will force the system state trajectories towards the sliding surface and stay on it [12].

In our application, the control process consists of the correction of the excitation current as a function of the object displacement x. If the object displaces to the bottom with a distance $-\Delta x$, the coil current i_0 must be increased with a quantity Δi. If the object moves upwards with a distance Δx, a current quantity Δi must be subtracted from the biased current i_0. To permit the sensing of the object displacement, a position sensor was used. To permit the changing of the excitation current that generates the applied magnetic force, a four quadrants chopper was used [17], [18]. The bearing parameters required for the simulation have been experimentally and analytically defined. To obtain the transfer function of the levitation system, the magnetic force expression has been linearized. In such linearization the

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dependence between the winding inductance of the bearing and the air gap changing has been considered.

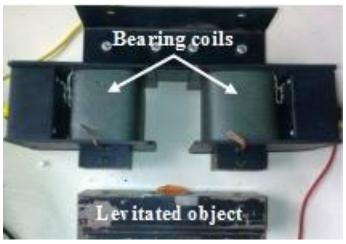

Figure1.View of the studied levitation system

II. MODELING OF THE LEVITATION PROBLEM

To build the mathematical models required for the simulation of the control, we have made call to the appropriate governing equations of the mechanical and electrical problems.

A. *LINEARIZED MODEL OF THE MAGNETIC FORCE*

To obtain the expression of the magnetic force applied on the levitated object, an analytical modelling has been applied to the magnetic circuit related to the levitation system. By considering the *x* direction, the force is given by [12], [13]. The analytical modelling of the magnetic circuit related to the studied device has led to the magnetic force expression given by [13-14].

$$F = c.(\frac{i}{x})^2 \tag{1}$$

Really, the levitated object oscillates around the equilibrium position x with very small displacement. The applying of the Taylor series expansion to (1) leads to the linearized flowing expression [19].

$$F_m = K_x x - K_i i + F_0 \tag{2}$$

The coefficients K_x and K_i are respectively the displacement and current gains. They are analytically evaluated and given by [20].

$$\begin{cases} K_x = 2\ c.i_0^2/x_0^3 \\ K_i = 2\ c.i_0/x_0^2 \end{cases} \tag{3}$$

Here x_0 and i_0 are respectively the displacement of the levitated object and the excitation current at the equilibrium position.

B. *ELECTRICAL CIRCUIT MODELS*

The magnetic bearing coil is electrically represented by an inductance in series with a resistor. The evolution of the voltage in the coil is governed by the equation given by

$$u = R.i + \frac{d(L(x).i)}{dt} \tag{4}$$

Here R and L are respectively the coils resistor and the inductance. The nonlinear dependence between the inductance L and the object position x is expressed by [20].

From (4) we can write for the supplying voltage.

$$u = R.i + L_s\frac{di}{dt} + K.\frac{d}{dt}(\frac{i}{x}) \tag{5}$$

The voltage generated by the position sensor related to a displacement *x* of the levitated object is expressed by [19]

$$V_s = \alpha.x \tag{6}$$

Here α is the displacing sensor gain.

C. *MAGNETIC BEARING MECHANICAL MODEL*

The dynamic governing equation of the levitated object is given by

$$F_g - F_m = m\ddot{x} \tag{7}$$

Here m is the object mass, $\ddot{x}$ is the object moving acceleration and F_g is the gravitational force ($F_g = mg$, where g is the gravitational acceleration).

The substitution of (2) in (7) lead to the resulting force

$$F_r = -K_x x + K_i i = m\ddot{x} \tag{8}$$

In (8), the gravitational force F_g has been cancelled by the constant component of the magnetic force F_0related to the equilibrium position ($F_g = -F_0$).

Finally, the dynamic model of the levitation system is expressed by [14]

$$\begin{cases} \frac{dx}{dt} = v \\ u = R.i + \frac{d(L(x))}{dt} \\ m.\frac{dv}{dt} = m.g - F(x,i,t) = m.g - c(\frac{i}{x})^2 \end{cases} \tag{9}$$

III. DESIGN OF THE SWITCHING SURFACE

The state-space model of the magnetic levitation system (9) will be used in the design of the SMC schemes. Now, consider the following nonlinear changing of coordinates,

$$u = R.i + L_s\frac{di}{dt} + N\frac{d\O}{dt} \tag{10}$$

A. *MAGNETIC BEARING MECHANICAL MODEL*

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Here v represents the object displacing velocity.
In the given context, one can particularize the dynamic model of the levitation system for each mode of calculating the inductance. The states and the control input are chosen such that $x_1 = x, x_2 = v, x_3 = i$ and $u = e$.

B. DESIGN OF THE SWITCHING SURFACE

The state-space model of the magnetic levitation system (11) will be used in the design of the SMC schemes. Now, consider the following nonlinear changing of coordinates,

$$\begin{cases} y_1 = x_{1ref} - x_1 \\ y_2 = x_2 \\ y_3 = g - \frac{c}{m}\left(\frac{x_3}{x_1}\right)^2 \end{cases} \quad (12)$$

Here x_{1ref} represents the reference trajectory.

$$\dot{y}_3 = -\frac{2.c}{m}\left(\frac{x_3}{x_1^2}\right)\left(u - Ri + \frac{k.i}{x_1^2}.x_2\right)\frac{x_1}{(L_g x_1 + k)} - \frac{2.c}{m}\left(\frac{i^2.x_2}{x_1^3}\right) \quad (13)$$

It should be noted that the functions $f(x)$ and $g(x)$ correspond in the original coordinates to the following functions, respectively:

$$f(x) = \frac{2.c.R.i^2}{mx_1(L_g x_1 + k)} - \frac{2.c.k.i^2.x_2}{mx_1^3(L_g x_1 + k)} - \frac{2.c.i^2.x_2}{mx_1^3} \quad (14)$$

$$g(x) = \frac{2.c.i}{mx_1(L_g x_1 + k)} \quad (15)$$

To establish the sliding mode disturbance estimator, we define the switching surface function S as

$$s = y_3 + \sigma_1 y_2 + \sigma_2 y_1 \quad (16)$$

As a function of states x_1, x_2 and x_3 the switching surface function s can be written as

$$s = \left(g - \frac{c}{m}\left(\frac{x_3}{x_1}\right)^2\right) + \sigma_1 x_2 + \sigma_2\left(x_{1_{ref}} - x_1\right) \quad (17)$$

Here σ_1 and σ_2 are positive scalars representing the feedback gain to be designed so that the error dynamics will have the desired response while the system is free of uncertainties and disturbances.
Note that the choice of the switching surface S guarantees that $y_1 = x_{1ref} - x_1$ converges to 0 as $t \to \infty$.
The sliding surface from any initial condition is obtained for the flowing condition [12].

$$s.\dot{s} \leq -\gamma|s| \quad (18)$$

Here γ is a positive constant that guarantees the system trajectories hit the sliding surface in finite time.
Using a sign function often causes chattering in practice. One solution is to introduce a boundary layer around the switch surface [12].

$$\dot{s} = \gamma.sign(s) \quad (19)$$

The differentiating of (22) with respect to time leads to the following equation

$$\dot{s} = (f(x) + g(x).u) + \sigma_1\left(g - \frac{c}{m}\left(\frac{x_3}{x_1}\right)^2\right) - \sigma_2 x_2 = \gamma.sign(s) \quad (20)$$

The resolution of (20) and (19) leads to the control law [15]

$$u = \frac{1}{g(x)}\left[\gamma.sign(s) + \sigma_2 x_2 + \sigma_1\left(g - \frac{c}{m}\left(\frac{x_3}{x_1}\right)^2\right) - f(x)\right] \quad (21)$$

IV . SIMULATION OF THE CONTROL AND OBTAINED RESULTS

The parameters and specifications of the considered magnetic levitation system are listed in Tab. I.

TABLE I

PARAMETERS OF THE STUDIED SYSTEM

Parameters	value
The levitated object mass	m=1.8kg, m=20kg
Gravity acceleration	g=9.81m/s^2
Equilibrium distance	x_0=5mm
Equilibrium current	i_0=1.15A
Force constant	C= 2.5133× 10^{-6}
Coil resistance	R=0.21978Ω
Coil inductance	L=0.03H

The association of the proposed supply circuit, the control loop and the magnetic bearing has been built in Matlab Simulink, the simplified configuration is presented in Figure.2. The four quadrants chopper is constituted by four switches (IGBT, diodes). This chopper permits the changing of the exciting current according to the two axes ($x, -x$).
To control the chopper, a pulse (0, 1) has been chosen for the switches 1 and 4 and a pulse (1, 0) for the switches 2 and 3. The four quadrants chopper has been excited in the discrete time by a dc voltage V_c=10V. The gains added to the regulator are respectively σ_1=50,σ_2=1500,γ=100 arbitrarily chosen in the manner to ensure a good stability of the system.
In the simulation process, the initial position (air gap) related to t= 0s has been arbitrary chosen x_0=3×10^{-3}m to avoid the joining between the levitated object and the electromagnet at the first time. The implementation of the control approach for the real measured mass of the levitated object $m = 1.8kg$ has led to the results of figures 3 to 4 that present respectively the variations of the air gap, the electromagnetic force, the exciting current, and the supplying voltage show that the stability has been reached after 2.4s.

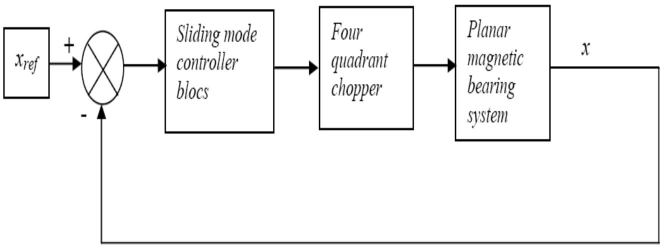

Figure2. Simulation blocs of the studied device.

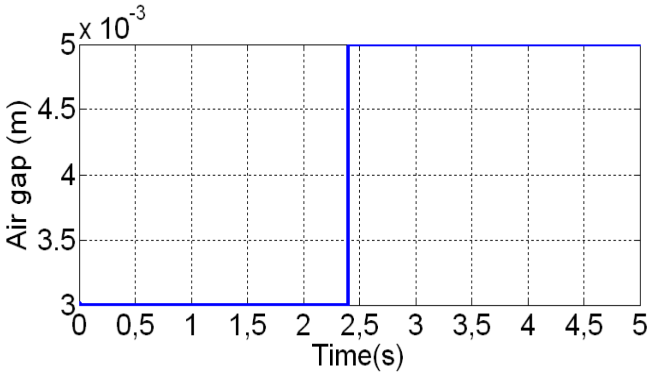

Figure 3.Variations of the air gap during the control process of the planar levitated object for *m*=1.8kg

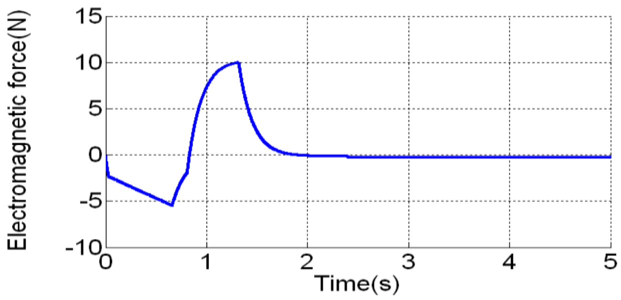

Figure 4.The variation of the electromagnetic force for *m*=1.8Kg

To introduce the mass disturbance, we have assumed a mass *m*=20kg for the levitated object. The simulation process has led to the results of figures 5 and 6. These last shows that the stability of the computing process for the Same reference position (air gap x=5×10^{-3}m) has been reached after 5.8s. From these results, we conclude that the sliding mode controller can keep the air gap at the same value for very important mass disturbances but with a short stability time. When the stability is occurred, all the curves (forces, current) are reached the stability with disturbance mass.

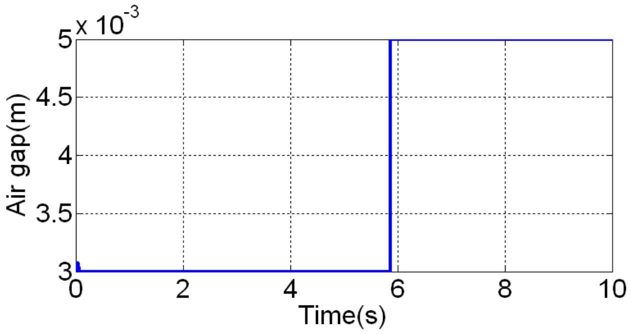

Figure5.The variation of the air gap of the planar levitated object for *m*=20kg

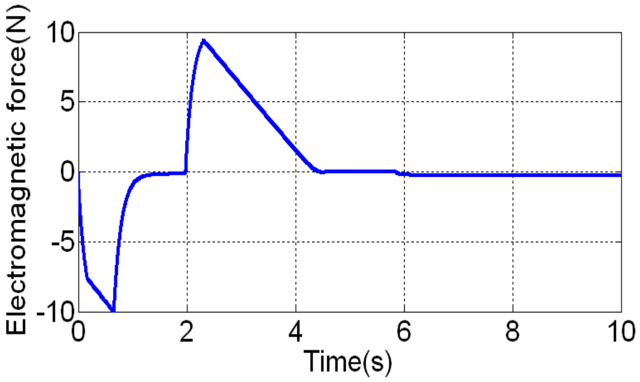

Figure6.The variation of the electromagnetic force for *m*=20kg

V. Conclusion

In this work, an approach for controlling the magnetic levitation of a planar ferromagnetic object based on the sliding mode control has been presented. To permit this control, the mathematical models that govern the magnetic, electrical and mechanical problems related to the studied system have been developed. Basing on the fact that the object exerts small displacements around the equilibrium position, the magnetic force expression has been linearized.

The performance of the SMC controller in trajectory tracking is superior for different disturbance signal in form (mass variation) applied to the planar levitated object. The obtained results show that the sliding mode control enables system stability even for large supply and load variations, gives good dynamic response and has simple implementation. These features make this control technique a valid alternative for standard control approaches like speed control. We can also conclude that the performance of the SMC controller in disturbance attenuation is good.

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