MODELLING AND SIMULATION OF A MAGNETIC LEVITATION SYSTEM

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Abstract. The electromagnetic levitation system (MLS) is a mechatronic system already acknowledged and accepted by the field experts. Due to a synergic integration of the sensorial elements, the control subsystem and the actuating subsystem, the mentioned levitation system becomes an especially recommended subject in the academic curricula for mechatronic study programmes. This paper intends to initiate the investigation of different modelling, simulation and control possibilities for a magnetic levitation system starting from a real, physical reference model.

1. Introduction

The (electro)magnetic levitation system (MLS) is a mechatronic system accepted both for the specific mechatronic area [6] and for other engineering fields, as mentioned in numerous references [1], [2],[3]. At the same time, the MLS is a recommended subject for the academic curricula in mechatronic study programmes, due to the synergic integration of the sensorial elements, the control subsystem and the actuating subsystem [4], [5].

The current period is characterized by multiple requirements of achieving high precision mobile mechanical systems, managed by an intelligent control system and appointed to various industrial technologies: transportation, magnetic bearings, kinetic energy store systems, special actuators, haptic magnetic levitation, etc, [4], [8], [9].

The electromagnetic levitation represents a classical control subject matter for which various solutions were developed. Many of them converged on a voltage-control feedback linearization [4], [5]. This method requires a very accurate mathematical model for the analysed system. Different solutions for an advanced control were analysed in earlier reference papers; all of them outline the complexity of the investigated problem due to the multiple nonlinear effects and the essential role of these effects in modelling and simulating the system. In this context, the paper initiates the analysis of the possibilities to model, simulate and control a MLS starting from a real, physically built system.

2. A general description of the magnetic levitation system

The MLS considered in the current analysis is built of a ferromagnetic ball suspended in a voltage-controlled magnetic field. Figure 1 shows the diagram of the system. The mechatronic system is composed of the following subsystems:

- The electromagnetic actuator represented by the coil 1 (a ferromagnetic core coil);
- The position sensor, determining the position of the metallic ball 2 which is sustained with respect to the coil;
- Electrical circuits for power supply, amplification, control, etc.

The ferromagnetic ball has two degrees of freedom. The analysis envisages only the translation movement performed in the vertical plane, while neglecting the rotation of the ball around its own axis. The goal of the designed system consists in maintaining the ball at a reference level that is preset.

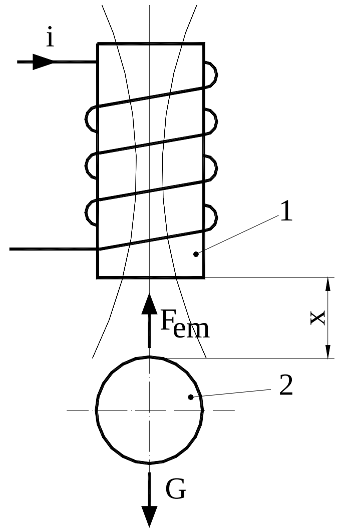


Fig.1 The magnetic levitation system

The ferromagnetic ball bears the influence of two forces:

- The field gravity “G”,
- The electromagnetic sustentation force F_{em} produced by the electromagnetic field generated in the coil 1.

One can define the equilibrium based on the known basic laws.

3. The mathematical model of the electromagnetic levitation system

One can build the mathematical model of the levitation system by writing appropriate differential equations in accordance to the typical mechanical- and electrical principles. The way the components are appreciated in the approaching mode can lead to simpler or more complex alternatives.

The formula for the energetic balance within the system is:

$$dW_e = dW_{mec} + dW_t + dW_m \tag{1}$$

where the terms represent the variation of the electrical energy (dW_e), the variation of the mechanical energy (dW_{mec}), the variation of the thermal energy (dW_t) and the variation of the magnetic energy (dW_m).

The variation of the magnetic energy when the magnetic fluxes are varying and bodies are moving within the magnetic field is:

$$dW_m = i \cdot d\Phi - F_{em} \cdot dx \tag{2}$$

The electromagnetic levitation force can be determined using the theorems of the generalized forces [17]:

$$F_{em} = -\left[\frac{\partial W_m}{\partial x}\right]_{i=ct} \tag{3}$$

The specific magnetic energy of a coil is:

$$W_m = \frac{\Phi \cdot i}{2} = \frac{Li^2}{2} \tag{4}$$

The inductivity L can be determined either by a direct calculus or by using the reluctance (or permeance) [17].

The studied bibliographical references specify the fact that the permeance of the air gap (entrefer) – the region between the coil and the ferromagnetic core - corresponds to the pole area exclusively when the polar surface is much wider than the entrefer thickness [18]. Therefore, different bibliographical references approach in different ways the determination of the inductivity for a magnetic levitation system.

The coil inductivity L depends upon the position "x" of the ferromagnetic ball in accordance to the relationship (5) [2]:

$$L(x) = L_0 + L_1 \cdot e^{-\left(\frac{x}{x_0}\right)^2} \qquad (5)$$

where: L_0 – is the coil inductivity when the ball is absent; L_1 – is the coil inductivity when the ball is present (x=0); x_0 – is the characteristic length of the coil.

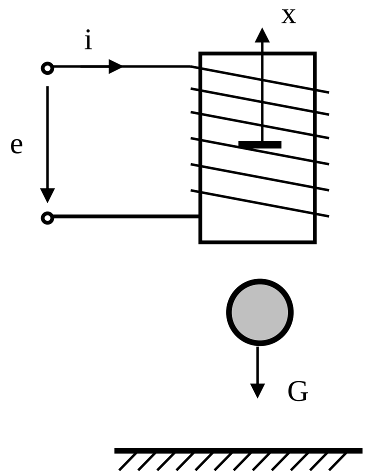


Fig.2 A new way of considering the "x" parameter

In another approach, the inductivity L is a nonlinear function defined as:

$$L(x) = L_1 + \frac{2K}{x} \qquad (6)$$

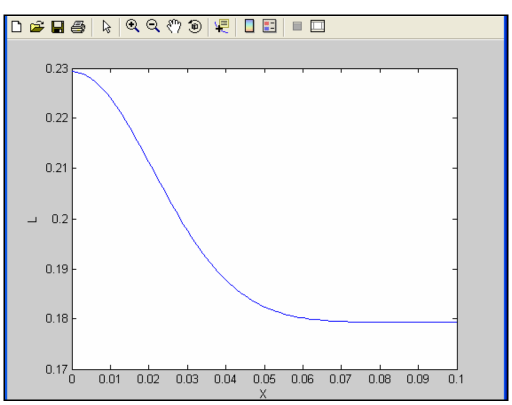
where L_1 is a system parameter.

The reference [4] considers the coil inductivity as being:

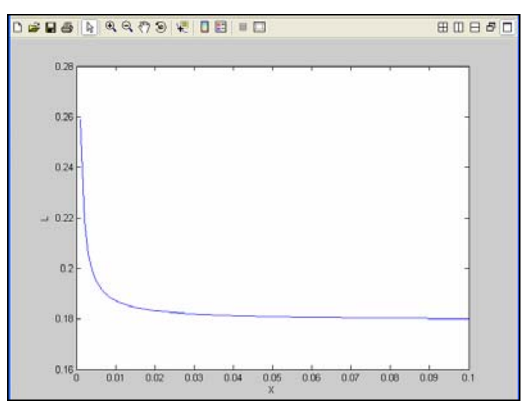
$$L(x) = L_1 + \frac{L_0}{1 + \left(x/a\right)} \qquad (7)$$

x = is the reference position of the ball; $L_1 = L(\infty)$, $L_0 = L(0) - L(\infty)$; a = a positive constant.

Figures 3a and 3b show a comparison of the inductivity variation based on the relationships (5) and (6).



a)



b)

Fig.3 The variation of the inductivity

Derived from the relationships (4) - (7), one can determine in different ways the electromagnetic sustentation force.

- Based on the relationship (5):

$$F_{em} = -\left[\frac{\partial W_m}{\partial x}\right]_{i=ct} = -\frac{i^2}{2}\cdot\frac{\partial L(x)}{\partial x} = -\frac{i^2}{2}\cdot\frac{\partial}{\partial x}\left(L_0 + L_1\cdot e^{-\left(\frac{x}{x_0}\right)^2}\right) = \frac{i^2}{2}\cdot\left(\frac{2x}{x_0^2}\cdot L_1\cdot e^{-\left(\frac{x}{x_0}\right)^2}\right) \quad (8)$$

- Based on the relationship (6):

$$F_{em} = -\left[\frac{\partial W_m}{\partial x}\right]_{i=ct} = -\frac{i^2}{2}\cdot\frac{\partial L(x)}{\partial x} = -\frac{i^2}{2}\cdot\frac{\partial}{\partial x}\left(L_1 + \frac{2K}{x}\right) = C\left(\frac{i}{x}\right)^2 \quad (9)$$

In the given context, one can particularize the dynamic model of the levitation system for each mode of calculating the inductivity; this dynamic model is expressed by the equations (10) to (12):

$$\frac{dx}{dt} = v \quad (10)$$

$$e = Ri + \frac{d[L(x)i]}{dt} \quad (11)$$

$$m\frac{dv}{dt} = mg - F_{em} \quad (12)$$

where: “x” – represents the ball position with respect to the reference position; “v” – represents the speed of the ball; “i” – represents the current intensity in the electromagnet winding; “e” – represents the supply voltage of the coil; “R” – represents the resistance of the electromagnet winding; “L” – represents the winding inductivity; “g” – represents the gravity acceleration (which is constant); “m” – represents the ball mass.

A development of the defined mathematical model can be achieved based on the system status, if considering the status variables $x = [x_1 \quad x_2 \quad x_3]^T = [x \quad v \quad i]^T$ and $u = e$. Using the typical systems linearization principle (the expansion in Fourier series and the preservation of the first order terms), one can linearize the acquired nonlinear model.

4. The simulation of the magnetic levitation system

The optimal design of the system, including the control subsystem, requires a “balance” between the modelling/ simulation procedure and the experimental procedure [6]. Starting from the previous established equations, one can achieve within the Matlab/ Simulink environment the simulation of the system’s running mode. Figure 4 shows the diagram of this simulation. The block “Levitation” was achieved with the aim of introducing it in a specific working library. Figure 5 shows the model of the realized block, while Figure 6 shows the simulation results.

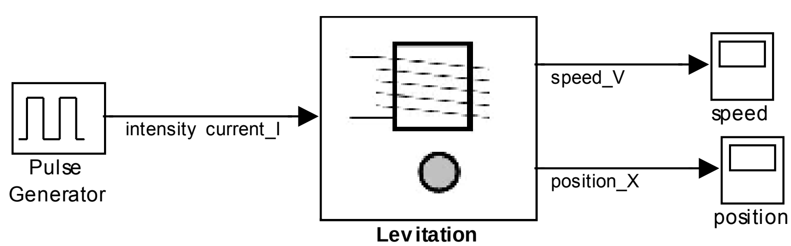


Fig.4 The simulation within the Matlab/ Simulink environment

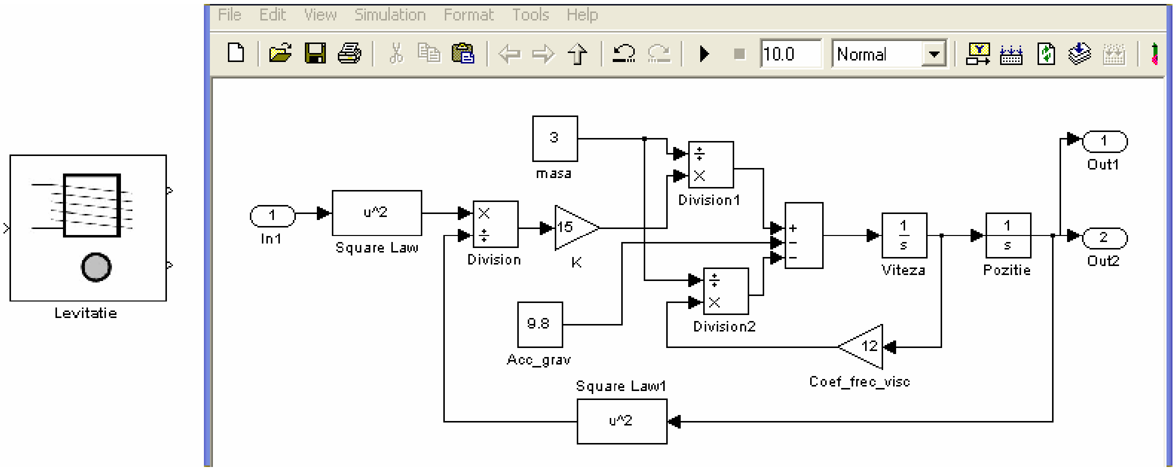


Fig. 5 The mask and the created "Levitation" block

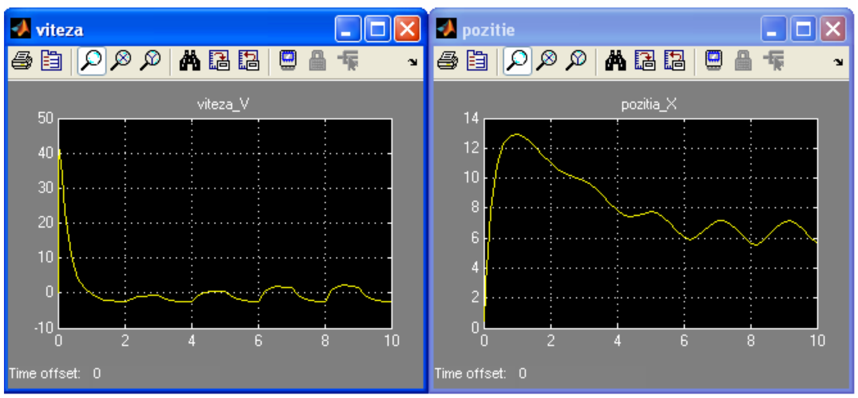


Fig.6 The results of the simulation process in Matlab/ Simulink

A research group including the authors built and studied the magnetic levitation system shown in Figure 7 within the Sensors and Actuators Laboratory [7].

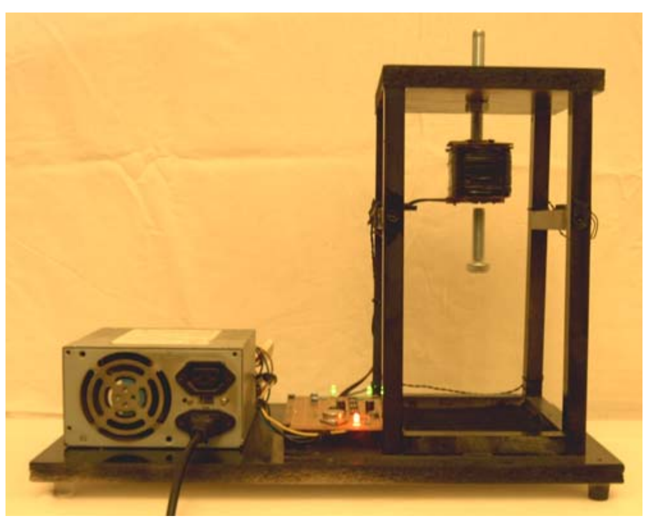


Fig. 7 General view of the electromagnetic levitation system built and studied within the Sensors and Actuators Laboratory

The proposed control scheme is a typical scheme used in many other similar studies and papers [1], [6].

The authors considered a development of the control methods in connection with the LabView and dSPACE environments. Figure 8 schemes the structural diagram for the latter solution.

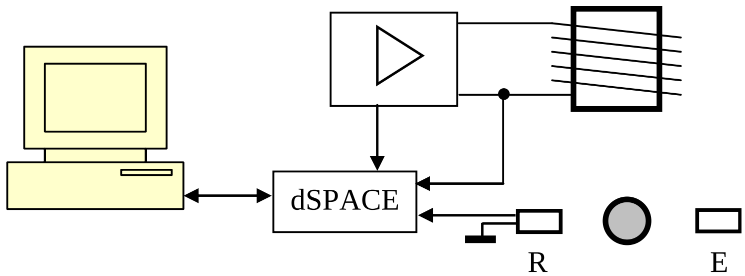


Fig.8 A solution for the control of the levitation system using the dSPACE equipment

5. Conclusions

The electromagnetic levitation system is a multiple applicability structure; this applicability can be educational or practical, industrial. The former set of applications envisages the control and regulation, the perturbations removal, the intelligent control, the design, the modelling and simulation of the systems, while the latter set of applications regards different transportation systems, constructive elements, positioning systems, etc.

The analysis described in this paper together with the experimentally built system facilitates a study of the system functionality and the determination of the optimal mathematical model for design purposes.

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