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Comprehensive review and analysis of the electromagnetic levitation systems (modeling, controllers, nonlinearity sources)

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Abstract. Magnetic Levitation Systems (MLS) is a higher advanced technology without any mechanical contact that results in zero friction losses. Such technology offers a low cost of maintenance, precise operation, very clean working, not noisy and quiet, remotely controlled, and small size. These features make it utilize with various important applications in different fields and different industries sectors, it can be applied in the vibration absorber, Biomedical applications or devices, very fast transport technology, etc. It is very well known that the (MLS) are non-linear and unstable open-loop, hence, numerous approaches are considered for non-linear control techniques to present a variety of results. The aim of our analysis in this article is to introduce the system's nature and behavior and to learn about the system's components as well as to cover most of the applied controlling approaches that were suggested by researchers to acquire the best performance.

1 Introduction

The (MLS) is one of the substantial phenomena of the physical control molds because it matches with the diverse industrial fields. It has been successfully carried out and studied in various applications due to its energy efficiency such as high-speed train (maglev) technologies, vibration isolation systems, magnetic bearings, etc.

In such systems, objects levitate or suspend as a result of the magnetic field interaction influence between the magnetic object and the applied magnetic field. The effect of gravitational acceleration or any other acceleration can be canceled by the electromagnetic force. If the object is placed very far from the magnetic source, the magnetic field is too weak to support the weight of the object. If it placed so closely, the magnetic field becomes very strong and leads to move the object towards the source until it makes a contact with the magnet. (MLS) are the embodiment of an inherently unstable system so that objects can only be levitated and stabilized using a feedback control system to continuously adjust the electromagnet power of the system to stabilize the object at the desired location [1].

Magnetic levitation forces may be produced from various techniques such as electromagnetics, superconducting, and permanent magnet. However, the control of

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levitation forces using superconductors requires more complicated technology compared to electromagnetic levitation forces sources. On the other hand, applications in which the permanent magnet levitation forces can be used are more limited than the use of electromagnetic forces [2, 3].

It has been used in many industrial systems including in high-speed magnetic levitation trains, active magnetic bearings, electromagnetic cranes of the wind tunnel, models vibration isolation of precise machinery, levitation of molten metal in induction furnaces levitation of metal slabs during manufacture and high precision positioning of wafers in photolithography [4]. Furthermore, magnetic levitation technology has seen rapid growth since the 20th century and made it very useful in the field of real-life applications, such as transportation systems, wind tunnel levitation, magnetic bearing systems, and anti-vibration systems [5].

According to the rapid development of the industry, the serious work of many scientists, researchers, and engineers has been focusing on improving magnetic suspension technology because of its great advantages and wide and promising application areas.

It is well known that the magnetic force is of a non-linear nature. High accuracy high speed in performance are demanded in all engineering and scientific applications so that researchers and engineers had to work with great interest to formulate a thoughtful and serious mathematical modeling of the magnetic force affecting the system and deriving many sophisticated approaches and advanced methods and techniques to precisely control the system.

In this article, we try to cover most of the mathematical modeling methods and scientific formulas that describe the magnetic force accurately, as well as review the methods and techniques adopted in controlling the magnetic levitation system.

2 Magnetic Levitation System Construction

Generally, the (MLS) constructed from two subsystems, the first is a mechanical subsystem, and the second an electrical subsystem. The schematic diagram for the magnetic levitation system has been shown in Fig. 1. The system consists of a steel object (or magnetic object) and an electromagnet coil used to create an electromagnetic force to levitate an object in the target position, controlled, and a sensor is also required to measure the object position.

Since the value of the electromagnetic force which is generated in the electromagnet coil is related to the value current flowing through it, Therefore, the object vertical position (*X*) can be controlled by adjusting the current flowing through the electromagnet coil applying a controlled voltage across the electromagnet terminals, hence to achieve the stability of the system have to connect with the controller. The equilibrium state of two forces (the gravitational and electromagnetic) must be kept by this controller to keep the object in a desired distance from the coil.

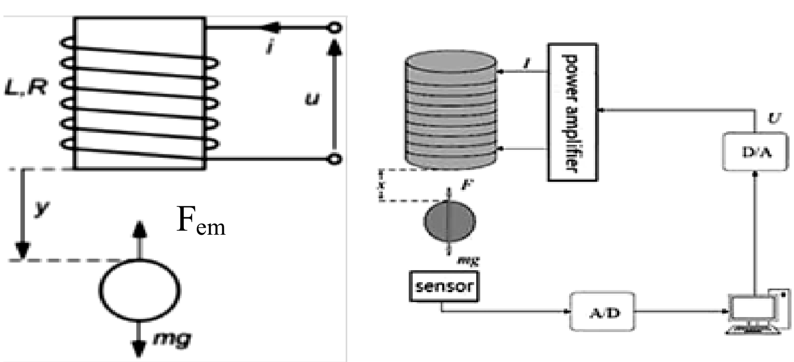

Fig. 1. Magnetic levitation system construction [6, 7].

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Predominantly the position sensor output is an analog voltage signal which required a signal conditioning circuit and analog to digital converter before entering the microcontroller.

The signal from the microcontroller requires Adjustment from digital to analog again and amplified by the power amplifier before going to the electromagnetic coil.

3 System Analysis

The schematic of the magnetic levitation model and the free body diagram of a levitated object as shown in Figure (1). where X is the vertical location of the object measured from the lower point of the coil, v is the velocity of the object in the vertical axis and i is the coil current. And R, L denotes the coil resistance and the coil inductance respectively, m is the mass of the object, g is the gravitational acceleration, F_{em} is the electromagnetic force generated by the coil, u is the voltage input of the coil.

3.1 Nonlinear Model

The relationship between electromagnetic force, coil current, and the object position are nonlinear. In this paper, will analyze the main causes of nonlinearity and where it comes from

there are two substantial causes of nonlinearity, first is the nonlinear nature of the magnetic force, second is the nonlinear uncertainty of inductance behavior with respect to object position X.

The dynamic behavior of a magnetic levitation system can be modeled by the study of electromagnetic and mechanical subsystems.

3.1.1 Nonlinear Magnetic Force

Magnetic force generated (F_{em}) in the coil is responsible for levitating the object, there are several different expressions to describe it. this difference a result of the object kind whether it is just steel ball or permanent magnet, and also depends on the nonlinearity of the coil inductance.

But generally, to determine the magnetic force there is an analytical method that depends on the differentiation of magnetic stored energy in the electromagnet system with respect to the distance and an experimental method for each system and finding experimental parameters for each case separately.

Some of the most well-known expressions that authors of the researches utilized are:

- Levitated object is a Steel ball

There are eight expressions used to describe the magnetic force (F_{em})

1. The most common system is used when the levitated object is a steel mass and magnetic force (F_{em}) as in the following articles: [1, 6, 8, 9]

$$F_{em} = \frac{\partial E}{\partial x} = C\frac{i^2}{x^2} \quad (1)$$

$$C = L_o X_o /2, \text{ C: constant} \quad (2)$$

E: The energy stored in the electromagnet is defined as: $E = \frac{1}{2} L(x)i^2$

L_o: is the additional inductance contributed by levitated object presence.

X_o: is the equilibrium position.

2. The introduced magnetic force denoted as

$$Fem = -\frac{1}{2}\frac{L_o i^2}{a\left(1+\frac{x}{a}\right)^2} + \frac{d\lambda_B(x)}{dx}\, i \quad (3)$$

$$\frac{d\lambda_B(x)}{dx} = 4a_4x^3 + 3a_3x^2 + 2a_2x + a_1 \quad (4)$$

a_4, a_3, a_2, a_1 : experimental coefficients

3. As for the articles [10] they found a slightly different expression despite adopting the same method of analysis, because they relied on a different expression of inductance, as will be detailed later.

$$F_{em} = \frac{\partial E}{\partial x} = \frac{L_o i^2}{2a\left(1+\frac{x}{a}\right)^2} \quad a\text{: is an experimental coefficient} \quad (5)$$

4. The author of the article [24] is alone who utilize the following expression

$$F_{em} = \frac{B^2 A}{\mu_o} \quad (6)$$

B: The air gap magnetic flux density of the suspension electromagnet.
A: is the pole area of the suspension electromagnet.
μ_o : is the vacuum permeability = $4\pi\times10^{-7}$ H/m.

5. The author's point of view [11] the following expression is the most appropriate

$$F_{em} = i^2 \frac{p_1}{p_2}\, exp\left(-\frac{x}{p_2}\right) \quad (7)$$

where p_1, p_2 : experimental coefficients

6. In [12] the magnetic force was:

$$F_{em} = \frac{i^2}{b_0+b_1y+b_2y^3+b_3y^4} \quad (8)$$

b_0, b_1, b_2, b_3 : are experimental coefficients

7. In [7, 13] not very far but was interested in treating if the distance was $x = 0$

$$F_{em} = K_m \frac{i^2}{2(x+a)^2} \quad (9)$$

$K_m = mg\left(\frac{i_o}{x_o}\right)^2$, *a:* is an experimental coefficient, which is commonly determined by experimentation to prevent that the force is infinite when $x = 0$ at the bottom of coil.

8. In [12] was written two different expressions, the first as mentioned above and the second is:

$$F_{em} = \frac{i^2}{2}\left(\frac{2x}{x_o^2} L_1 e^{-\left(\frac{x}{x_o}\right)^2}\right) \quad (10)$$

- Levitated object is a Permanent magnet

Due to the interference between the magnetic flux from the permanent magnet and the flux resulting from the flow of current in the coil. The analytical formula for the magnetic interaction force between the coil and the permanent magnet is very difficult hence most authors resort to the experimental or approximation procedures to determine it.

1. [14] The force actuated by the electromagnet is formulated as

$$F_{em} = C\frac{i}{x^3} \tag{11}$$

2. [15] The magnetic force is supposed to be of the form:

$$F_{em} = K_i' i^2 \tag{12}$$

$$K_i' = \frac{2L_o}{x} \tag{13}$$

L_o: is the inductance of the coil when the object at the equilibrium point.

3. [16] The magnetic force is supposed to be of the form:

$$Fem = (\alpha . z + \beta). i \tag{14}$$

where α and β are constants that should be identified based on the system properties. The force model in [16] was experimentally verified for the levitation system and successfully estimated the magnetic force over a range of 32 mm with a maximum estimated error of 3.2%.

4. In [2] although permanent magnets was a levitated mass, they tend to use the following expression

$$F_{em} = -\frac{1}{2}\frac{L_o i^2}{a\left(1+\frac{x}{a}\right)^2} \tag{15}$$

a: experimental coefficient.

5. The magnetic force in [17] is supposed to be of the form:

$$F_{em} = \frac{i}{a_2 x^2 + a_1 x + a_o} \tag{16}$$

a_2, a_1, a_o : experimental coefficients

6. [18, 19] The force between the electromagnet and a magnetic ball is given as:

$$F_{em} = C\frac{i}{x^4} \tag{17}$$

3.1.2 Nonlinear variation of inductance

As explained above, the second reason for the system's nonlinearity comes from the non-linear vary of inductance, there are several expressions. There are many well-known expressions, most of which are experimental.

The levitated steel mass contributes to the inductance of the electromagnet coil. As the object approaches the magnet-coil, the coil inductance rise. As the object moves farther from the magnet-coil, the inductance reduces, reaching a minimum value when the mass is much far.

1. The most common and used formula is as follows [20]

$$L(x) = L_1 + \frac{2c}{x} \tag{18}$$

$$C= L_o X_o /2 \tag{19}$$

L_1: is the inductance of the electromagnet coil in the absence of the levitated object, or minimum value when the ball is far away from the coil i.e. $x = \infty$. L_o: is the additional inductance contributed by levitated object presence. X_o: is the equilibrium position.

2. Another approximation for L(x) is given by [10]

$$L(x) = L_1 + \frac{L_o}{1+\left(\frac{x}{a}\right)} \tag{20}$$

a: experimental coefficient
L_1: is the inductance of the electromagnet coil in the absence of the levitated object, or minimum value when the ball is far away from the coil i.e. x=∞.
L_o: is the additional inductance contributed by levitated object presence.

3. [15] proposed

$$L(x) = L_o\left[1 + \frac{\Delta x}{x} + \left(\frac{\Delta x}{x}\right)^2\right] \tag{21}$$

4. [21] They saw the best approximation it is

$$L = L_o + L_1 e^{-ax} \tag{22}$$

3.2 Sensors

Sensors detect the variation of the object position and send a feedback signal to the controller and then to the driver's circuit to ensure levitate the object and fixed it at the required position. There are a lot of position sensors kinds such as optical sensors, ultrasonic sensors, inductive sensors, capacitive sensors and Hall effect sensors. [1, 6] utilized Optical sensor. While [3, 14] utilized Hall effect sensors. [22] linear capacitive type proximity sensor. [23] non-contact inductive eddy current sensor.

3.3 System order

To design an efficient controlled it is necessary to represent all parts of the system in the mathematical model. Therefore, most authors consider the system to be the third order.

The authors acknowledged that a good controller must be able to control the position of the levitated object even when the object weight may changes. it is well known that in the open-loop poles, the first pool and the second pool, related to the object's weight. whereas the third pole is related to the coil resistance and inductance will still unchanged regardless of any change in the weight of the levitated object, and the dampin8g influence of coil inductance to the current dynamic response can be ignored. This means that the third pole can be annulled by using the virtual pole cancellation technique [3, 8, 9].

4 System Controller Approaches

The magnetic levitation system is one of the highly nonlinear, open-loop unstable systems. the system is described by nonlinear differential equations, this means the execution of appropriate controller design is a very difficult job. A robust and accurate controller is indispensable to stabilize the system and ensure levitate the object at the desired position.

1. Authors, fundamentally relied on the PID controller of all its sorts, either conventional form or modified PID, Two Degree of Freedom PID, and Fractional Order PID, as the main controller of the system to achieve the required position. Some of them developed the PID controller design by adopting intelligent controllers like fuzzy, genetic, and neural PID controller, while others used the PID controller as a secondary controller to compare the performance with it [8].
2. Authors [14, 15] are used LQR controller to compare the system performance with PID controller, while [1] are used LQR as an optimization approach to improve the PID controller.
3. [5] developed sliding mode or adaptive sliding mode controller to overcome the system non-linearity and achieve stability.
4. [9] proposed an integral-tilted-derivative (I-TD).

5 Conclusions

The magnetic levitation system is a suspension or levitation of an object without any physical effect just magnetic force which is produced by coil or solenoid. the system Moreover it is inherently unstable also has a problem of parameter's uncertainty. A simplified magnetic levitation system is employed in automatic control laboratories for research objectives. In this study the nonlinearity causes and uncertainty source are considered. Hence there is a several notes can present.

1. The main reason for the nonlinearity is the magnetic nonlinear force that is arising from the nonlinearity of the coil inductance. [1, 4, 8, 9].
2. In most of the research's articles, the levitated object is a steel ball rather than the magnetic ball, so that an analytical manner was adopted to obtain the magnetic force due to the simplicity to understand and consider it.
3. To avoid the problem of interference of position sensor, the optical position sensors are widely utilized in the magnetic levitation system.
4. To overcome the complex nature of the magnetic levitation system and simplify the system, researchers resorted to the virtual pole cancellation technique to revoke the third pole.
5. Although very widespread and high important applications of the magnetic levitation system in various sectors, The PID controller is still considered the most widely used or as a comparison reference with the other controllers.

References

1. K. Anurag, S. Kamlu, Proceedings of the Second International Conference on Inventive Systems and Control (ICISC 2018), 444-447 (2018)
2. V.A. Oliveira, E.F. Costa, J.B. Vargas, IEEE Transactions on Education **42(4)**, 315-322 (1999)
3. B. Pramujati, H. Nurhadi, D. Patriawan, International Journal of Scientific & Engineering Research **6(6)**, 56-60 (2015)
4. Y. Eroğlu, G. Ablay, 9th International Conference on Electrical and Electronics Engineering, ELECO, 785- 789 (2018)

5. J. He, Y. Jia, Journal of Robotics, Networking and Artificial Life **1(2)**, 169-173 (2014)
6. Y. Qi, Zh. Zhong, Y. Liu, Proceedings of the International Symposium on Big Data and Artificial Intelligence December, 312–315 (2018)
7. Fatih Adıgu¨zel, Ersin Dokumacılar, Onur Akbati, Transactions of the Institute of Measurement and Control **40**, 10 –1 (2018)
8. Maher Alwajih, Shabana Urooj, Part of the Smart Innovation, Systems and Technologies book series **78**, 175-182 (2018)
9. Zhenyu Yang, Gerulf Pedersen, Proceedings of the IEEE International Symposium on Intelligent Control Munich, Germany, 3098- 3103 (2006)
10. M. Ahsan, N. Masood, F. Wali, 3rd IEEE International Conference on Computer, Control and Communication (IC4), 62-67 (2013)
11. Bushra Hanif, Inam-Ul-Hasan Shaikh, Ahsan Ali, Mehran University Research Journal of Engineering & Technology **38(4)**, 885-900 (2019)
12. A. El Hajjaji, M. Ouladsine, Ieee Transactions on Industrial Electronics **48(4)**, 831-838 (2001)
13. F.B. Carbajal, A.F. Contreras, A.V. González, G.S. Navarro, Revista Facultad de Ingeniería **2013(66)**, 70-81 (2013)
14. M.H.A. Yaseen, H.J. Abd, Results in Physics **8**, 153-159 (2018)
15. M.H.A. Yaseen, Results in Physics **7**, 4379-4387 (2017)
16. E. Shameli, M.B. Khamesee, J.P. Huissoon, Microsyst Technol **13**, 831–835 (2007)
17. H.-K. Chiang, C.-A. Chen, M.-Y. Li, IEE Proceedings - Electric Power Applications **153(6)**, 809 – 814 (2006)
18. Myung - Gon Yo on, Jung -Ho Moon, International Journal of Engineering Research & Technology (IJERT) **5(03)**, 94- 97 (2016)
19. Jung-Ho Moon, Myunggon Yoon, International Journal of Engineering Research & Technology (IJERT) **5(08)**, 384-387 (2016)
20. Pallav Sumit Kumar Pandey, Vijaya Laxmi, *PID Control of Magnetic Levitation System based on Derivative Filter, Annual International Conference on Emerging Research Areas: Magnetics, Machines and Drives* (Kottayam, India, 2014)
21. A.R. Acero, J.A. Orozco Quiceno, J.A. Jiménez Bulies, Conference: III International Congress of Mechatronic Engineering and Automation At: Cartagena **14(1)**, 28-38 (2016)
22. S. Banerjee, D. Prasad, J. Pal, *Design, Implementation, and Testing of an Attraction type Electromagnetic Suspension System* (Indian Institute of Technology, Kharagpur, 2002)
23. J. Zhang, T. Tao, X. Mei, G. Jiang, D. Zhang, Proceedings of the Institution of Mechanical Engineers Part I Journal of Systems and Control Engineering **225**, 85-98 (2015)
24. Junqi Xu, Yougang Sun, Dinggang Gao et al, IEEE Access **6**, 31571 – 31579 (2018)