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    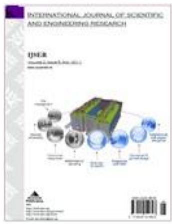 

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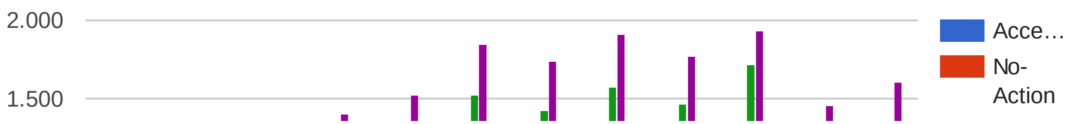

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A Study on the Effect of an Attractive and a Repulsive Forces with Feedback Control on a Magnetic Levitation System

Bambang Pramujati, Hendro Nurhadi, Desmas A Patriawan

Abstract - This research was conducted to observe the effect of an attractive force and a repulsive force on a magnetic levitation (maglev) with the addition of a feedback control system. Initially, the study was conducted by observing the displacement gap from both type of maglev without an application of a control system. Closed loop control experiments were performed by implementing a Proportional-Integral-Derivative (PID) controller in order to maintain the displacement gap. Stable responses from both simulation control and experiments indicated that the PID controller can be employed to control the gap between the magnet and the levitated object. However, the results of the repulsive maglev control show faster response and smaller steady state error in comparison with the attractive maglev control.

Index Terms - magnetic levitation, displacement gap, repulsive-attractive force, electromagnetic, feedback control system, PID controller

1. INTRODUCTION

Nowadays, traffics in many cities around the globe becoming issues and problems that need to be resolved. As the number of population increases rapidly, private vehicles and air services are no longer able to serve as mass rapid transport anymore [1]. The number of vehicles on the road, not only contributes worsen the traffic jammed but also produces polluted environment. Therefore, the availability of transportation system to serve the public movement which is more efficient, safe, efficient and eco-friendly vehicles are imperative these days. Obviously, the new generation of this vehicle must suited to mass transportation and magnetic levitation (maglev) train is one of the best option for such transportation system [1][2].

With the development of industrial technology, many researchers have focused their work to further improve maglev technology. Maglev train uses magnetic force to levitate vehicle a short distance away from a guide as well as to propel the vehicle [3]. In comparison, conventional train uses friction between wheel and train to drive the train forward. Therefore, maglev trains tend to move more quietly as well as more smoothly that the wheeled ones. In addition, these trains can reach very high speed since there is no friction between train and the guide.

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Magnetic forces can be generated by using several methods such as electromagnetics [4] and superconducting [5]. In her research, Lilienkamp et al [4], utilized a permanent magnet and an electromagnetic field to generate levitation forces. The result of this research was then used by others as a basis for developing a stable magnetic levitation forces [6]. Superconductor YBa2Cu3O7-x (YBCO) and permanent magnet can also be used to produce levitation forces. The YBCO presents superconducting state at temperatures below 92 K, which can be achieved within a liquid nitrogen bath [7]. However, levitation forces generated using superconducting are difficult to be controlled as compared to electromagnetic source. Maglev system with electromagnets can be used as handling objects without contact which yield significant advantages over conventional handling [8].

In general, based on the source of levitation forces, a maglev system can be classified into an attractive system and a propulsive system. The attractive system uses an attractive forces to maintain the gap between the moving components and the fixed components, while the repulsive systems uses repulsive forces to to push the moving components above and the fixed components and then maintain the gap between them [9]. Both of the systems have a different characteristics from one to another which is shown in Table 1 [10].

TABLE 1. COMPARISON OF MAGLEV SYSTEM [10]

Maglev system	Types of magnets	Battery on carries	Controllability
Attractive	DC electromagnet	Large size	Good
	Hybrid magnet	Medium size	Fair
	AC electromagnet	No	Good
Repulsive	DC electromagnet	Medium	Good
	Permanent magnet	No	Poor

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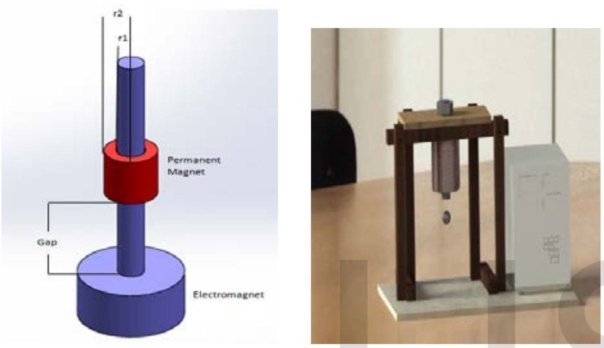
This research is aimed to study the effect of those two forces on a levitation system with the application of feedback control, i.e. Proportional Integral and Derivative (PID).

2. Design Of Maglev System

As mention earlier in this paper, maglev system can be divided into two different systems, i.e. attractive and repulsive systems, as shown in Fig 1.. Both systems shown in Fig 1 were designed and constructed using the same specifications, with the only difference was the generating force. Two main parts for maglev system are the electromagnetic and the permanent magnet. A stable levitation can be obtained as long as the force between the permanent magnet and the electromagnet at the equilibrium state.



(a) repulsive maglev (b) attractive maglev

Fig 1. Maglev system [11]

The force generated by permanent magnet is highly influenced by the material as well as the size of the permanent magnet. Table 1 shows the characteristics of several type of magnetic materials. It can be seen that the Nd2Fe14B or neodymium has the highest values as compared to the other types of permanent magnets, and therefore, neodymium material was used in the modeling of maglev system.

Table 1. Commercial characteristics of the magnetic [12].

	B_r (T)	J_S (T)	$_iH_c$ (kA m^{-1})	$_BH_c$ (kA m^{-1})	$(BH)_{max}$ (kJ m^{-3})
$SrFe_{12}O_{19}$	0.41	0.47	275	265	34
Alnico	1.25	1.40	54	52	43
$SmCo_5$	0.88	0.95	1700	660	150
Sm_2Co_{17}*	1.08	1.15	800	800	220
$Nd_2Fe_{14}B$	1.28	1.54	1000	900	300

The magnetic force generated by a permanent magnet can be calculated using the following equation:

$$F_{PM} = BH \times Volume \quad (1)$$

where F_{PM} is the force generated by permanent magnets, BH is the magnetic field generated by the magnet material. The force can be obtained using vector multiplication with the volume of the object levitator. The calculation yields different values of magnetic forces as shown in Table 2. Although *Rare Earth-Iron Alloys* also known as neodymium produces the largest magnetic force, this material is very difficult to find and its price is very expensive (the case in Indonesia).

Table 2. Forces calculated for different magnetic materials

Magnetic materials	Force
Ferro Oxide ($SrFe_{12}O_{19}$)	0.034 N
Alnico	0.043 N
Rare Earth –Cobalt Alloys ($SmCo_5$)	0.15 N
Rare Earth-Iron Alloys ($Nd_2Fe_{14}B$)	0.3 N

Stable levitation is also affected by the electromagnetic force, which can be generated either from a toroid or a solenoid. In this paper, the electromagnetic force was generated from the solenoid. The generated force depends upon the magnitude of magnetic field. Ampere's law approach can be employed to determine the magnetic field in the solenoid, ie:

$$B_{EM} = \mu_0 i_0 n \quad (2)$$

where n is the numbers of turns per unit length, $\mu_0$is the permeability of air and $i_0$is the current through the solenoid wire [13].

Using the Lorentz force law, the electromagnetic force can then be determined as,

$$\overrightarrow{F_{EM}} = q\vec{v} \times \vec{B} \quad (3)$$

where q is positive electric charge and $\vec{v}$ is vector velocity. The direction of the force given in Eq (3), can be obtained by the right hand rule. The force relationship above can also be presented in the form of a vector product of

$$\overrightarrow{F_{EM}} = \vec{I}L \times \vec{B} \quad (4)$$

where $\vec{I}$ is the current through the length of the wire L.

A block diagram of maglev system is necessary to develop the model and hence determine the forces acting on the maglev system. Magnetic force creates a springy action on the levitate object and hence can be considered as a spring. Fig 2 shows the block diagram of repulsive maglev system, while Fig 3 depicts the block diagram of an attractive maglev system.

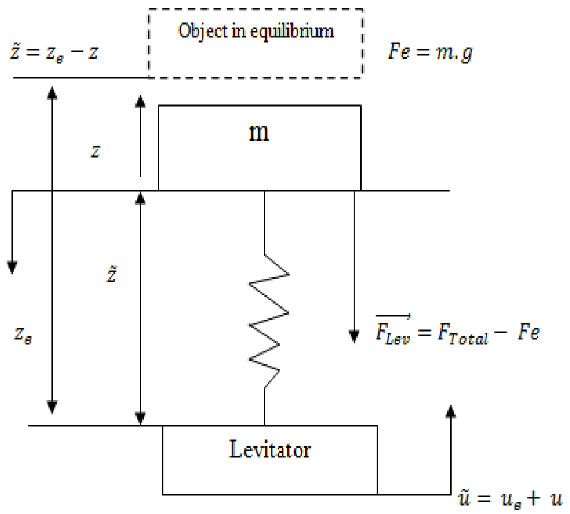


Fig 2. Block diagram for a repulsive system

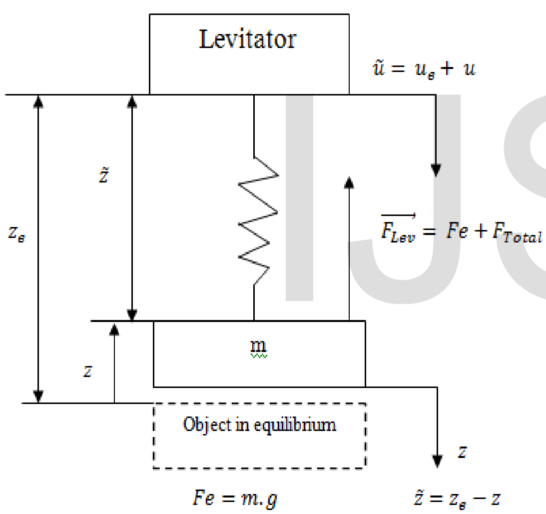


Fig 3. Block diagram for an attractive system

Force equation is linearized around the operating point (u_e, z_e, F_e), in which the levitation force of the operating point must of $F_e = m.g$. The result of the linearized equation for repulsive maglev system becomes,

$$m\ddot{z} = k_u u - k_z z \qquad (5)$$

where k_u is force-input factor and k_z is force-displacement factor. Whereas in the attractive maglev system has the following equation,

$$m\ddot{z} = k_u u + k_z z \qquad (6)$$

Force-input factor in the maglev system is given by the force in the permanent magnet and electromagnet, while force-displacement factor is generated by the gravitational force on the object levitation. The transfer function of the maglev system H_{SYS} can be derived from equation (5) for repulsive maglev and equation (6) for attractive maglev in the Laplace conjugate domain. Assuming the initial conditions are zero, then the equation in the Laplace form for repulsive system is,

$$H_{sysR} = \frac{I(s)}{J(s)} = \frac{k_u}{ms^2 + k_z} \qquad (7)$$

while the transfer function for attractive model is given by,

$$H_{sysA} = \frac{I(s)}{J(s)} = \frac{k_u}{ms^2 - k_z} \qquad (8)$$

The objective of the maglev system is to provide a stable vertical gap between the magnet and the levitated object. Therefore, a good feedback control system need to be designed and implemented to achieve such objective. A proportional integral and derivative PID controller was employed as the feedback control system in this research. Its three-term functionality offers treatment for both transient and steady-state responses. The transfer function of a PID controller is often expressed in the ideal form of

$$G_{PID} = \frac{U(s)}{E(s)} = K_P\left(1 + \frac{1}{T_I s} + T_D s\right) \qquad (9)$$

Therefore the control moves or manipulated variables can be determined using the following equation.

$$u_{PID}(t) = K_p\, e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \qquad (10)$$

Equation (10) can also be expressed in discretized form as,

$$u_{PID}(t_k) = K_P\, e(t_k) + K_i \sum_{k=1}^{n}(e(t_k).\Delta t_k) + K_d \frac{\Delta e(t_k)}{\Delta t_k} \qquad (11)$$

PID parameters can be determined using several approaches and one of them is Ziegler Nichols tuning method.

Table 3. Ziegler Nichols tuning formulae [14]

Controller type	K_P	T_i	T_d
P	0.5 K_{cr}	∞	0
PI	0.45 K_{cr}	1/1.2 P_{cr}	0
PID	0.6 K_{cr}	0.5 P_{cr}	0.125 P_{cr}

where Kcr and Pcr represent the ultimate gain and frequency, respectively.

3. Results And Discussion

In order to control the gap between the levitator and the levitated object as shown in Fig 4, the gap has to be measured and this can be done using hall-effect sensor. This sensor able to detect the magnetic field as well as the distance between object and the magnet. The change in the

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gap width of the maglev system is used as an indicator whether or not the system is stable. Gap setpoint was set to be 10 mm and the controller should be able to maintain the desired distance. Based on the experiments data, the gap of 10 mm can be achieved by making an electromagnet to produce a force of 0.66 N.

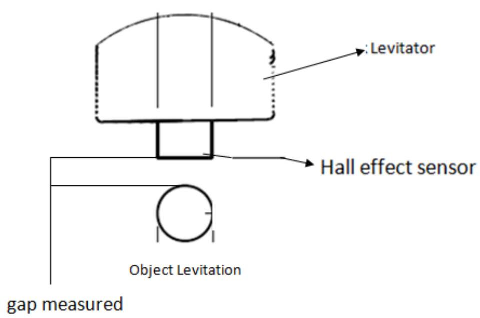

Fig 4. Measured gap between a levitator and a levitated object

The experiment uses magnetic ferrite oxide since this type of magnet can be easily found in the market, although it produces the least electromagnetic force. The required force can be produced by a magnetic system which has number of winding of 600 and 60 A current.

The open loop test responses for both repulsive and attractive maglev systems are depicted in Fig 5 and Fig 6, respectively. These results can be used to determine the appropriate controller parameters for the system as well as to evaluate the stability of the maglev system.

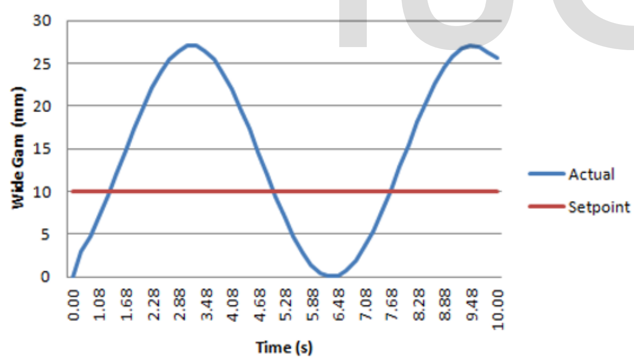

Fig 5. Open loop test response of a repulsive maglev

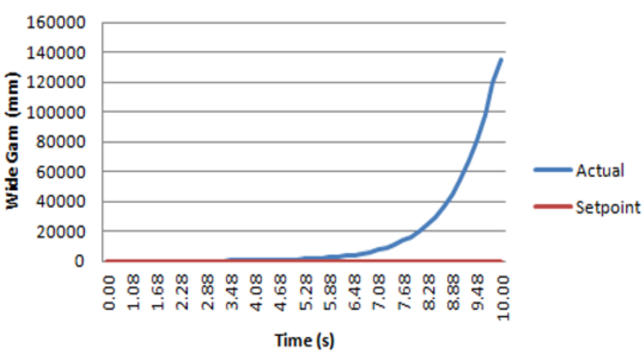

Fig 6. Open loop test response of an attractive maglev

It can be seen in Fig 5 that the change in position of the gap for the repulsive maglev system resulted in not only produces oscillate response but also yields a fairly large error. However, Fig 6 shows different responses of attractive maglev when it is subjected to a step input test. The response indicates that the gap was maintained only in the beginning of the test and then eventually unable to keep the levitated object in place. Both responses suggest that the two systems were unable to keep the gap width in accordance with the setpoints, despite of the generated different responses. Therefore, closed loop feedback control is required to improve their both transient and steady state responses.

Using tuning of Ziegler Nichols method, the PID controller parameters were obtained. Although tuning method was used to determine the controller parameter, it is common that fine tuning during the application is necessary and its results were Kp of 10, Ki of 2.5 and Kd of 4. Prior to the application of PID controller, proportional and derivative (PD) controller was employed to maintain the gap between levitated object and the levitator. Manipulated variable of PD controller can be determined using the following discretized equation,

$$u_d(t_k) = K\left(e(t_k) + T_d\,\frac{\Delta e(t_k)}{\Delta t_k}\right) \qquad (12)$$

Fig 7 shows the response of closed loop control of an attractive maglev system having different PD controller parameters. It can be seen that good control performances were achieved, however there exist steady state errors for all responses. It is understood since the only controller that will be able to force the steady state error to zero is proportional and integral (ideal PI controller).

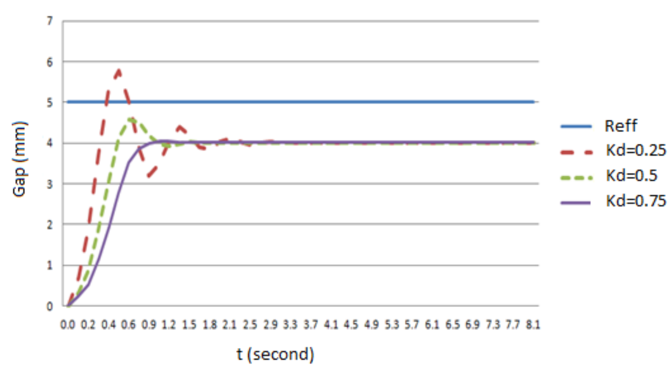

Fig 7. Responses of an attractive maglev system using PD controller

PID controller was then implemented for both repulsive and attractive maglev system to improve their transient as well as the steady state responses. The obtained responses indicate that better closed loop performance was achieved for repulsive maglev system as compared to the attractive ones. For repulsive maglev system, gravitational force drives the levitated object approaches the levitator and hence it provides a faster response. On the other hand, gravitational force opposes the motion of levitated object approaching the levitator in attractive maglev system.

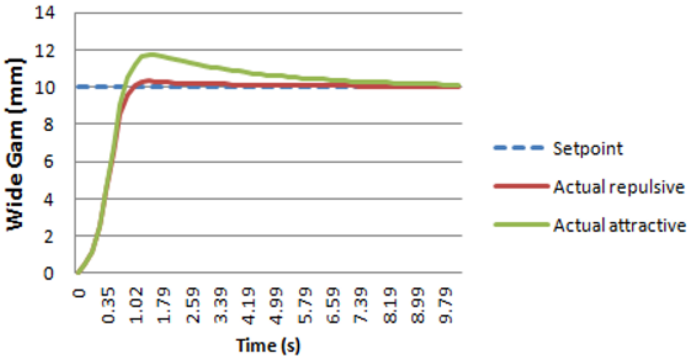

Fig 8. PID application on both a repulsive and an attractive maglev

4. Conclusion

Open loop test responses for both repulsive and attractive maglev system result in two very different responses. The repulsive maglev generates an oscillate response which yields different width of the gap from time to time between the object levitation with levitator. Response of an attractive maglev system shows stable response for a short period of time and then the gap increases exponentially. Therefore, the application of feedback control system is required in order to generate a stable levitation.

The addition of feedback control system significantly improve the performance of the maglev system. Ziegler-Nichols tuning strategy was used to obtain the controller parameters and the obtained parameters were Kp: 10, Ki: 2.5 and Kd: 4. Two different responses were achieved due to the effect of the gravitational force. An attractive maglev system yields a faster response than the repulsive maglev system.

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