Numerical Simulation of The Magnetic Levitation System in State-Space Form

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Abstract

The maglev system is a technology that uses the repulsive force between magnets to float or levitate an object or vehicle. Maglev trains use electromagnets to counter the gravitational force of an object, so that the object can float in the air. With this technology, the resulting loss between the workpiece and the base can be eliminated. The technology used in this train is Electromagnetic Suspension (EMS). The research began by modeling the maglev system in the form of state space. Furthermore, the stability system model that has been built is analyzed. Finally, it is analyzed how the numerical simulation of an open loop without control is analyzed. The result of this research is that the floating system (maglev) is an unstable system if it is run in an open loop, so the maglev system requires sensors and controls in its operation.

Keywords: *Maglev, electromagnetic suspension, numerical simulation, state space model.*

I. INTRODUCTION

As the times progress, the need for a transportation system that is faster, more efficient, comfortable and environmentally friendly, is therefore necessary. The latest generation of transportation is faster, more reliable and safer, as well as convenient, easy to maintain, environmentally friendly, and supports mass transportation. Magnetic levitation train or abbreviated as magnetic levitation (maglev) train is one of the best candidates to fulfill these requirements. This maglev replaces conventional train wheels with electromagnets and hovers over the tracks. This technology uses electromechanical thrust without direct contact with the rails. And this study will focus on the maglev system with the type of Electromagnetic Suspension (EMS) which will discuss the characteristics of the dynamic model in the form of state space and how the model behaves.

II. MATERIALS AND METHODS

The steps of the research method used are literature study, magnetic levitator system modeling, electromagnetic design, numerical simulation. In the literature study stage, all existing references are studied to get an overview of the maglev system that has been studied. all existing references are studied to get an overview of the maglev system that has been studied. The parameter assumptions used are in accordance with the following figure:

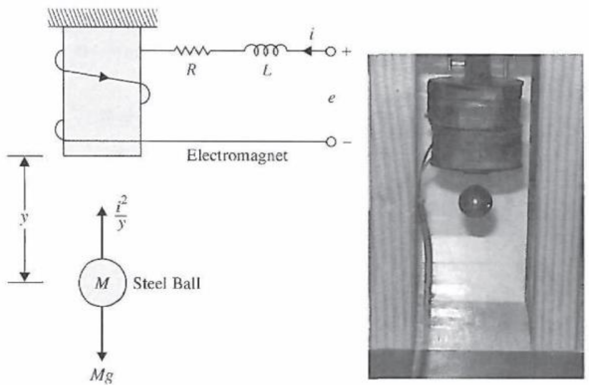

Figure 1. Ball-magnet Suspension System [9]

with

- e(t) : Input voltage
- y(t) : Ball position
- i(L) : Winding current
- R : Winding resistance
- L : Inductance of coil
- M : Mass of ball
- g : Acceleration of gravity

Then in the simulation the parameters used are as follows

Table 1. Simulation calculations with 4 pairs of electromagnets

Data	Value
Number of Pairs of EM	4
Elektromagnetic Mass (kg)	0.065
Total EM Mass (kg)	0.26
Train Weight (kg)	360
Lifting load per EM (kg)	0.085
$y(m)$	0.003
Winding	800
$\mu 0$	1.26E-06
K	0.00101
i (Ampere)	3.747
Voltage (V)	24
Inductance (L)	0.01
Resistance (R)	4.815

with the flow or diagram of the open-loop maglev system as follows

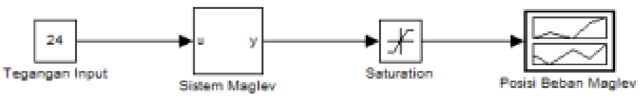

Figure 2. Block diagram of an uncontrolled open-loop maglev system [4].

III. Results and Discussions

A. Magnetic Levitator System Modeling

of research related to maglev system modeling has been carried out as in several references [6-14]. Where the maglev system is shown in Figure 9 above. Then defined for state variable [1,2,3]

$$x_1 = y(t);\ x_1 = \frac{dy(t)}{dt};$$

and

$$x_3 = i(t).$$

Then the state equation of the system is

$$\frac{dx_1(t)}{dt} = x_2(t) \quad (1)$$

$$M \cdot \frac{dx_2(t)}{dt} = M \cdot g - \frac{x_3^2(t)}{x_1(t)} \quad (2)$$

$$\frac{dx_3(t)}{dt} = -\frac{R}{L} x_3(t) + \frac{1}{L} e(t) \quad (3)$$

Then calculate the electromagnet attraction using the Lorentz equation

$$F = l \cdot i \cdot B \quad (4)$$

With

$$B = \frac{\mu_0 \cdot N \cdot i}{l} \quad (5)$$

Where:
F : Magnetic force (N)
l : Length of solenoid (m)
i : Strong electric current flowing through wire
B : Strong magnetic field (Tesla)
μ_0 : Vacuum permeability ($4\pi \cdot 10^{-7}$ Wb/Am)
N : Number of turns

Substituting equation (5) into equation (4) gives

$$F = \frac{l \cdot i \cdot (\mu_0 \cdot N \cdot i)}{l} \quad (6)$$

The multiplication of vectors is considered to be one (cos 0 = 1), so

$$F = i^2 \cdot \mu_0 \cdot N \quad (7)$$

If K is a coefficient that relates the magnetic force that attracts the ball with the formula $K = \mu_0 \cdot N$, then equation (7) becomes

$$F = i^2 \cdot K \quad (8)$$

Then assume that the magnetic attraction is inversely proportional to the gap between the magnet and the steel ball, then the equation for the magnetic attraction becomes

$$F=i2\cdot Ky \quad (9)$$

And by reviewing the equation n (2) then the mechanical dynamic equation for the maglev system is

$$M \cdot \frac{d^2y(t)}{dt^2} = M \cdot g - K\frac{i^2(t)}{y(t)} \quad (10)$$

The linearization of the system around the equilibrium distance $y_0(t)$ is constant, so the term $\frac{d^2y_0(t)}{dt^2} = 0$, and the nominal value of i(t) is found from the substitution of

$$i_0(t) = \sqrt{\frac{Mgy_0}{K}} \quad (11)$$

Substituting $x_3 = i(t)$ and algebraic operations on equation (3), it will produce the following equation (12)

$$e(t) = R \cdot i(t) + L\frac{di(t)}{dt} \quad (12)$$

The final form of the state equation is written with the coefficient matrix A and B state space as follows [7,8]

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{g}{y_0} & 0 & -\frac{K}{M{y_0}^2 i} \\ 0 & 0 & -\frac{R}{L} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} \quad (13)$$

These A and B matrices will be used in numerical simulations so that the characteristics of a maglev system are known.

B. Electromagnetic Design

In the design of the electromagnetic system, the magnetic train is designed to be able to lift the train body. Power supply and other instrumentation equipment are not located on the carriage. The number of electromagnets used in this study amounted to 4 units. If it is assumed that each electromagnet has a mass of 65 grams and the train frame on each side is 50 grams, then the total mass of the train is 360 grams. The calculation of the mass of each component is described in Table 2 below.

Table 2. Calculation of the estimated mass of each component of the maglev train

Component	Mass/ unit	Unit	Sub-total mass
Elektromagnetic	65 grams	4	260 grams
Train Frames	50 grams	2	100 grams
Total			**360 grams**

These four electromagnets are expected to be able to lift a total mass of 360 grams, so each electromagnet is able to lift a load of 85 grams, the following is the calculation:

M = Total mass/ Number of electromagnets
M = 360 grams /4
M = 85 gram

Free body diagram on the maglev apparatus (Figure 3) is a representation of equation (10) and equation (12) below.

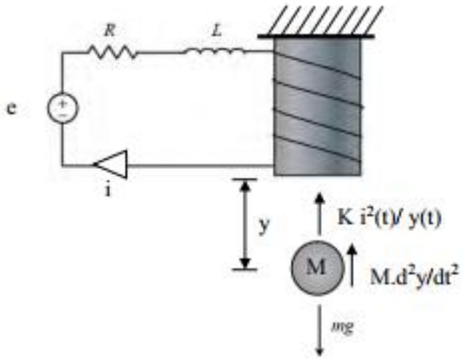

Figure 3. Free Body Diagram of Maglev Mechanical and Electrical Systems.

And if the free body diagram in Figure 10 is static at the equilibrium distance (y_0), then equation (10) becomes equation (11) namely. Equation (11) is used to determine the amount of current (i) that will be needed to lift the mass load (M) in the range of equilibrium distance (y) with the coefficient that connects the magnetic force that attracts the ball ($K = \mu_0 \cdot N$). The other data are as follows:

M = 85 grams
y = 3 mm (0,003 m)
$K = \mu_0 \cdot N$ = 1,257 x 10-6. 800 windings
= 0,00101

The amount of current required for each electromagnet to lift a load of 85 grams is 1,574 Ampere. And the efficiency of this equipment is assumed to be 42%. The reduction in efficiency is also accounted for by the transfer of mechanical, electronic, material and manufacturing energy. So the current value required is 1.57A/42% = 3.747 Ampere. Then refers to the electromagnetic circuit for the RLC (Resistance Inductance Capacitance) circuit which is arranged in series, where the RLC circuit consists of resistance R, inductance L and capacitance C. Assuming the value of C is much smaller than R and L, the calculation only uses a circuit The RL is presented in Figure 4 as follows.

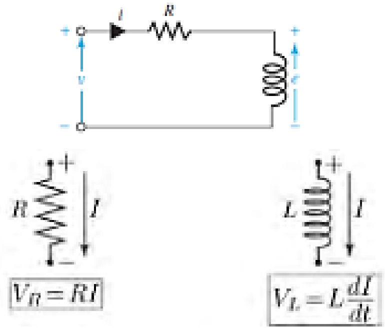

Figure 4. Relationship between Current and Voltage on Resistance and Inductor [9]

From Figure 11, for the voltage on the resistance V_R is

$$V_R = R \cdot i \quad (14)$$

While for the voltage formula V_L is formulated as follows

$$V_L = L\frac{di}{dt} \quad (15)$$

Then the impedance is obtained by identifying it in equation (12) resulting in the following equation (16)

$$Z = \frac{V_R + V_L}{i} - \frac{L}{i}\frac{di}{dt} \quad (16)$$

And because of the limitations of this study, the value of L/i di/dt ignored. Although this value can affect the current and impedance of the circuit. From the observations of this study, the current flowing decreased by 33% due to the inductance circuit compared to the circuit without inductance. The current value is added 33% to balance the resistance calculation. Then the resistance value R becomes

$$R = \frac{V_R + V_L}{1.33 \cdot i} \quad (17)$$

So to create a current of 3.747 Ampere at a voltage of 24 volts, a certain resistance value R and inductance L is required. adopting equation (17), the resistance R can be known VR + VL = 24, because this circuit is arranged in series and the voltage source is 24 volts. The resistance value R obtained is 4.815 ohms. This 4.815 ohm resistance is used as a reference for selecting the diameter and length of the copper wire. The larger the wire diameter, the lower the resistance. This is inversely proportional to the length of the wire. The longer the wire, the greater the resistance. The resistance value of 4.815 ohms is the maximum value when measuring the pure resistance of a solenoid using an ohmmeter. The calculation data above can be summarized in Table 3 above.

C. Numerical Simulation

This numerical simulation uses equation (10) and equation (12) to see the response of the system. The two equations are rewritten in the following state-space form.

$$M \cdot \frac{d^2y(t)}{dt^2} = M \cdot g - K\frac{i^2(t)}{y(t)}$$

$$e(t) = R \cdot i(t) + L\frac{di(t)}{dt}$$

C.1 Maglev System Modeling in State-Space Form

From the data in Table 3, it is entered into numerical software, namely Matlab with the following state-space equation form.

$$\dot{x} = Ax + Bu \quad (18)$$

$$\dot{y} = Cx + Du \quad (19)$$

With

$$x = \begin{bmatrix} \Delta y \\ \Delta \dot{y} \\ \Delta i \end{bmatrix} \quad (20)$$

In equation (20) it is the state variable used to maglev system, u is the input voltage (Δi) and y (output) is Δy. As for the matrices A and B are maglev systems in equation (13) above. In table 2 there are variable resistance, inductance, mass, gravity and magnetic coefficient. Then these variables are written into matrices A and B. Matrix A is the dynamic maglev system, while matrix B is the control input in the form of current (Δi) and matrix C is the output of the observed system, namely the gap distance so that it is worth [1 0 0] .

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 3270 & 0 & -68{,}7005 \\ 0 & 0 & -248 \end{bmatrix},$$

$$B = \begin{bmatrix} \Delta y \\ \Delta \dot{y} \\ \Delta i \end{bmatrix}, \qquad C = [1\ 0\ 0]. \quad (21)$$

C.2 Stability of the Maglev System

The next step is to determine whether the open-loop system is stable or not (without any control). The method used is the analysis of the location of the eigenvalues of the matrix system A (the same as polishing the transfer function). The eigenvalue of this matrix A is the s value of the equation $det(sI - A) = 0$ [6,15]. Then the eigenvalue of matrix A is

$$Eig\ (A) = \begin{bmatrix} 57{,}1839 \\ -57{,}1839 \\ -248 \end{bmatrix} \quad (22)$$

From these eigenvalues, the open-loop system without control is an unstable system. The positive value of 57.1839 indicates that the pole is in the right-half plane. Giving gain to the system will also not make the system stable. Figure 5 shows that a pole located in the right-half plane will remain in the right-half plane if gain is given. So this system needs feedback so that it becomes a closed-loop system and is stable.

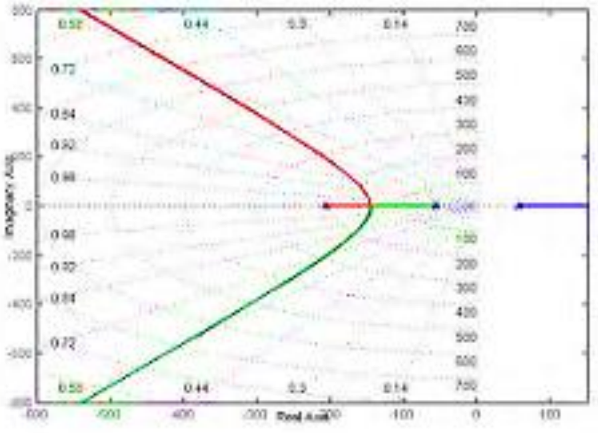

Figure 5. Root Locus of Uncontrolled Open-loop Maglev System

C.3 Numerical Simulation of Uncontrolled Open Loop

After obtaining the stability of the system, then the maglev system model is numerically simulated for an uncontrolled open loop with the following block diagram on figure 5 above. Figure 5 is a block diagram that will be simulated. The input voltage to the maglev system is 24 volts. Then the load is observed on the graph box plot at the far right.

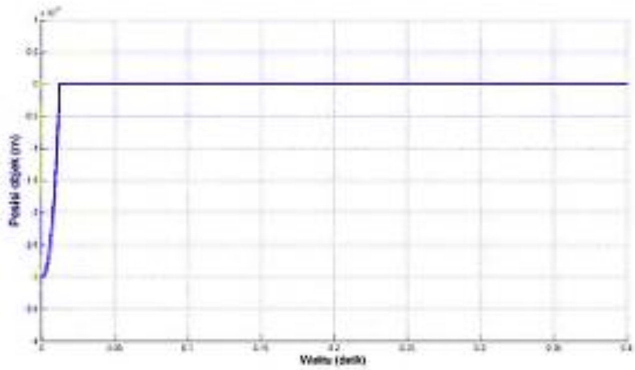

Figure 6. Object response with an initial condition of 3 mm.

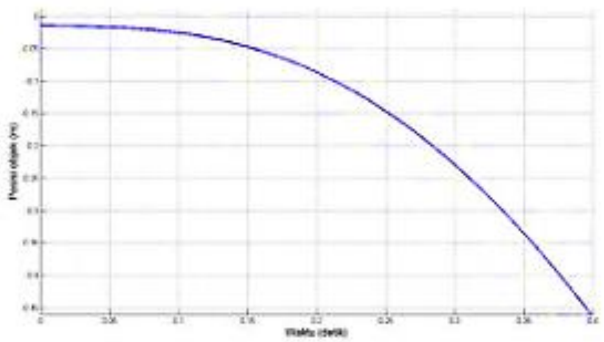

Figure 7. Object response with an initial condition of 15 mm.

Figure 6 and Figure 7 above are the simulation results of the block diagram in Figure 5 with input data from Table 2. Figure 6 shows an object placed 3 mm from the electromagnet will stick. Figure 7 shows an object placed at a distance of 15 mm from the falling electromagnet. Objects fall because the electromagnetic force is not strong enough to attract objects from a distance of 15 mm. One effort to stabilize this system is to use a controller in a closed-loop system. From a previous study [4], concluded that the maglev equipment in the study was stable using PD (Proportional-Derivative) control.

IV. CONCLUSIONS

The modeling carried out is a maglev system model in the form of state-space which is then carried out for system stability using eigenvalue location analysis. From the results of the eigenvalues, the results of an open-loop system without control include an unstable system. Giving gain to the system will also not make the system stable. So, this system needs feedback so that it becomes a closed-loop system and is stable. After that, the results of the numerical simulation for an uncontrolled open loop are also shown with the analysis that the magnetic drift system (maglev) is an unstable system if it is run in an open-loop, so that the maglev system requires sensors and controls in its operation.

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