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DESIGN AND SIMULATION OF NONLINEAR CONTROL SYSTEM FOR MAGNETIC LEVITATION OF STEEL BALL

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Abstract: ***The importance of control system in mechanical, electrical and electronics has been improved a lot in recent years. The main motto of research and development is to minimize the size of system equipment and produce more efficient output from it, with less expenditure. The two main concepts involved in this paper are, nonlinear control and magnetic levitation. Nonlinear control systems are those control systems where nonlinearity plays a significant role, either in the controlled process (plant) or in the controller itself. In this paper, a new class of PID controller is introduced. The system to be controlled is assumed to be modeled or approximated by second-order transfer functions.***

Magnetic levitation is a method by which an object is suspended with no support other than magnetic field. Magnetic pressure is used to counteract controller for magnetic levitation system. In this paper we are looking forward to represent the work on classical control as well as nonlinear control for magnetic levitation system. In order to design any controller, the mathematical modeling of the system is mandatory. This paper is mainly concerned about mathematical modeling of maglev, Design of a classical controller for the system and introducing nonlinear function i.e., Sigmoidal function as a function of error. MATLAB and Simulink are the tools used in order to find the responses of plant.

Keywords: Magnetic levitation, mathematical modeling, Sigmoidal function (Nonlinear), Controller Design

1. INTRODUCTION

The conception of magnetic forces is the basis of all magnetic levitation. The creation of a magnetic field can be caused by a number of things. The first thing that it can be caused by is a permanent magnet. These magnets are a solid material in which there is an induced North and South Pole. These will be described further a little later. The second way that a magnetic field can be created is through an electric field changing linearly with time. The third and final way to create a magnetic field is through the use of direct current. There are two basic principles in dealing with the concept of magnetic levitation. The first law that is applied was created by Michael Faraday. This is commonly known as Faraday's Law, which states that if there is a change in the magnetic field on a coil of wire, there is seen, a change in voltage [1].

1.1 Earnshaw's Theorem

Earnshaw's theorem proves that it is not possible to achieve static levitation using any combination of fixed magnets and electric charges. Static levitation means stable suspension of an object against gravity. There are, however, a few ways of to levitate by getting round the assumptions of the theorem.

1.2 Overview of Levitation

Levitation is defined as: "rising of a body above ground without support and without physical medium between source and destination". There are two types or methods of magnetic levitation, Electro Dynamic Levitation (EDL) and Electro Magnetic Levitation (EML). Electromagnetic levitation is also known as attracting levitation because it uses the attractive forces of magnets. Electro Dynamic Levitation is also referred to as repulsive levitation because it uses the repulsive forces of like poles of magnets. The phenomena of levitation have fascinated from philosophers through the ages and in recent times it has attracted much attention from scientists as a means of eliminating physical contact. Although the area of frictionless bearings is important, it is the application of contactless suspension to high speed ground transportation which has received the most attention, recent days [2].

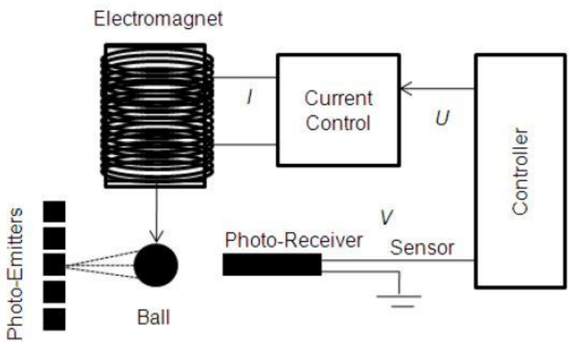

Fig. 1.1 Block diagram of Maglev system

Maglev system considered in the current analysis consisting of a steel ball suspended in a voltage-controlled magnetic field. Coil acts as electromagnetic actuator, while an optoelectronic sensor determines the position of the steel ball. By regulating the electric current in the circuit through a controller, the electromagnetic force can be adjusted to be equal to weight of the steel ball, thus the ball will levitate in an equilibrium state. But it`s a nonlinear, open loop, unstable system that demands good dynamic model and stabilized controller [3]

2. MATHEMATICAL MODELING

The physical system, as shown in figure below, consists of a steel ball that is to be levitated under an electromagnet. For the purposes of theoretical analysis and system behavioral study, realistic but arbitrary system parameters were selected. For the electromagnet, the required parameters were assumed to be a resistance, an inductance, a magnetic constant and mass of the steel ball and any hysteresis effects of the electromagnet were assumed to be negligible. The electrical model of magnetic levitation can be represented as follows [6].

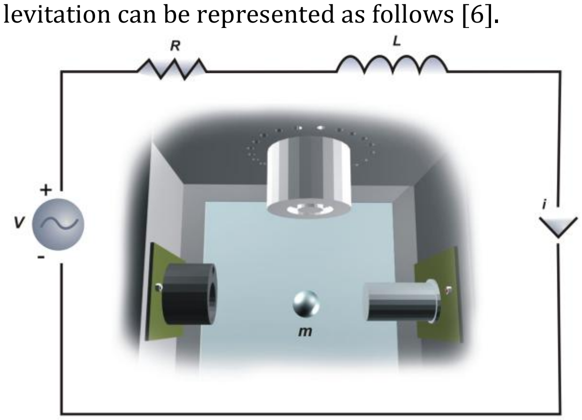

Fig.2.1 Electrical Representation of Maglev

The magnetic levitation system shown in above figure, keeps a steel ball suspended in the mid-air by counteracting the ball's weight with the electromagnetic force. x(t) is the distance between the steel ball and the electromagnet. x_0 is the reference position or it is the proper levitation distance. The electromagnetic force f (i,x), acts the ball, which can be expressed as the following dynamic formula in upward direction according to Newton's law.
The parameters taken into consideration are,

m =	mass of the ball= 0.020 Kg
L =	the winding inductivity
C =	magnetic constant determined experimentally=$1.477*10^{-4}Nm^2/A^2$
X =	ball position with respect to reference point,(mm)
V =	Speed of the ball
g =	acceleration due to gravity= $9.81m/m^2$

$$m\frac{d^2x(t)}{dt} = mg - f(i,x)$$

Where m is the weight of the ball and g is the gravitational constant.
Linearization can be done by using Taylor series [5].
After performing required simplifications and calculations, the obtained Laplace equation is

$$\frac{\Delta x}{\Delta i} = \frac{24.41}{(s+29.79)(s-29.79)}$$

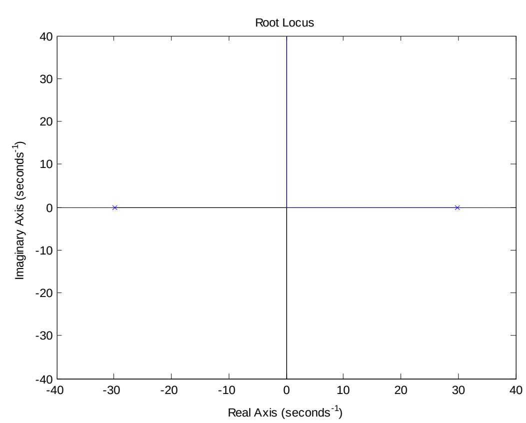

Fig.2.2 Investigation of stability of the system

2.1 Controller Design for Magnetic Levitation System

The magnetic levitation control aspect covers one area, which is the position control. Now there are numerous control algorithms however PID control is the most popular because of its high accuracy and simplicity. Various methods were investigated regarding he tuning of the controller. Such as Ziegler and Nichols method, good gain method, Skogestad's method etc. We will be using the Skogestad's method for tuning and designing of PID controller for the system.

Now parallel PID controller has the following transfer function,

$$u(s) = \left[k_{p_p} + \frac{K_{p_p}}{T_{i_p}s} + K_{p_s}T_{d_p}s\right]e(s)$$

Serial-parallel transformations are as follows

$$K_{p_p} = K_{p_s}\left(1 + \frac{T_{d_s}}{T_{i_s}}\right)$$

$$T_{i_p} = T_{i_s}\left(1 + \frac{T_{d_s}}{T_{i_s}}\right)$$

$$T_{d_p} = T_{d_s}\left(\frac{1}{1 + \frac{T_{d_s}}{T_{i_s}}}\right)$$

Using above equations, we get,

$$K_{p_p} = 145.74$$

$$T_{i_p} = 0.066s$$

$$T_{d_p} = 0.0165s$$

Maglev system is given by

$$u(s) = \left[\frac{2.4s^2 + 145.74s + 2208}{s}\right]e(s)$$

Standard equation is as follows

$$u(s) = \left[K_p + \frac{K_i}{s} + K_d s\right]e(s)$$

Comparing maglev equation with standard equation

K_p=145.74

K_i=2208

K_d=2.4

Plant with Classical PID Controller

The Proportional Integral and Derivative (PID) controller remains the most widely used in industries for the past few decades. For obtaining the step response of the magnetic levitation system we use Simulink model. The controller is introduces and negative feedback is given as shown in the below figure. Input is step signal, now the output reference tracking of the whole system is observed [7].

3. PROPOSED CONTROLLER DESIGN

PID controller design is simple in structure and easy to design, it continues to be an important method in control engineering. Linear PID controllers are the most popular and the most commonly used industrial controllers. The popularity and widespread use of PID or three-term controllers is attributed primarily to their simplicity and performance characteristics, where the I term ensures robust steady-state tracking of step commands while the P and D terms provide stability and desirable transient behavior. PID controllers have been utilized for the control of diverse dynamical systems ranging from industrial processes to aircraft and ship dynamics. Linear PID controller is often adequate for controlling static processes. The requirements for high-performance control with changes in operating conditions or environmental parameters are often beyond the capabilities of simple PID controllers. So for plants with high performance and dynamic change in operating conditions the design of advanced controllers give better results than classical controller approach [8].

Since the conventional PID is a linear controller, it is efficient only for a limited operating range when applied in nonlinear processes. So here comes the need of designing advanced controller for dynamic processes. Nonlinear controller design is one of the advanced methods for real time processes. There are different methods for designing a controller by using nonlinear approach [9].
Here the design is done by using sigmoidal function, which is represented as nonlinear function. The controller design by nonlinear method present in this thesis consists of a nonlinear gain 'K' in cascade with a linear constant gain PID controller

$$K(s) = k_p + \frac{k_i}{s} + k_d s$$

Where k_p, k_i and k_d are the positive or zero proportional, integral, and derivative gains, respectively.

The sigmoidal function represents nonlinear gain k as the function of the error e, as shown below.

$$k = k_0 + k_1 \left\{ \frac{2}{1+\exp(-k_2 e)} - 1 \right\}$$

Where $k_0, k_1 and\ k_2$ are user-defined positive constants, the gain k is lower-bounded by $k_{min} = k_0 - k_1$ when $e = -\infty$, is upper-bounded by $k_{max} = k_0 + k_1$ when $e = +\infty$, that is $k_{min} < k < k_{max}$, and furthermore $k=k_0$ when $e = 0$. Thus k defines the central value of k, k_1 [10].

Popov Stability Criteria:

Let us consider plant transfer function as P,

$$P = \frac{24.41}{(s+29.79)(s-29.79)}$$

Controller transfer function is given by

$$C = K_p + \frac{K_i}{s} + K_d s$$

By substituting designed K_p, K_i and K_d values in above equation, we get

$$C = 145.74 + \frac{2208}{s} + 2.4s$$

$$C = \frac{2.4s^2 + 145.74s + 2208}{s}$$

Therefore the product of plant and controller transfer functions is given by

$$PC = \frac{58.58s^2 + 3550.92S + 53897.28}{S(S^2 - 887.75)}$$

Negative frequencies of the Nyquist plot to be considered for finding k_{max} value.

Therefore plot is given by

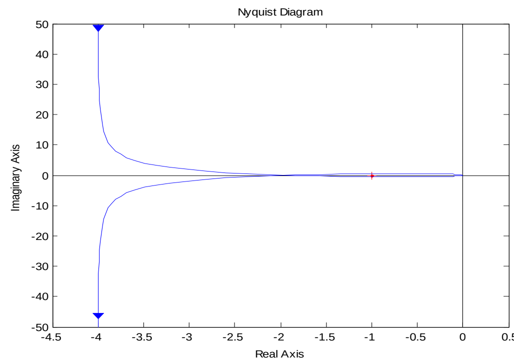

Fig.3.1 Nyquist plot of Plant-controller transfer function with negative frequencies

So from above plot k_{max} is the value at which both the graphs intersect each other at real axis.
Therefore k_{max} is 1.96.

Depending on k_{max} value, the values of sigmoidal function i.e, K_0, K_1 and K_2 to be selected in such a way to satisfy the given conditions $k_{max} = k_0 + k_1$[4], $k_{min} = k_0 - k_1$ and $k_{min} < k < k_{max}$. Hence $k_0, k_1 and\ k_2$ values are selected as

$$k_0 = 0$$
$$k_1 = 1.96$$
$$k_2 = 2$$

Substituting above values in sigmoidal function we get nonlinear gain '*k*' which is the function of error.

Hence the obtained nonlinear gain should be cascaded with classical PID to achieve nonlinear controller for the plant.

4. SIMULATION AND RESULTS

Linear PID controller for magnetic levitation gives better response, quick setting time with high precision. But the system response is up to certain limit of extend. In real world applications process won't be stable. Definite uncertainties will be affecting the system throughout the process. So for such kind of uncertainties classical PID doesn't hold good. To overcome this kind of problem, some advanced control strategies should be taken into consideration.

Fig.4.1 Response of maglev system with classical PID design

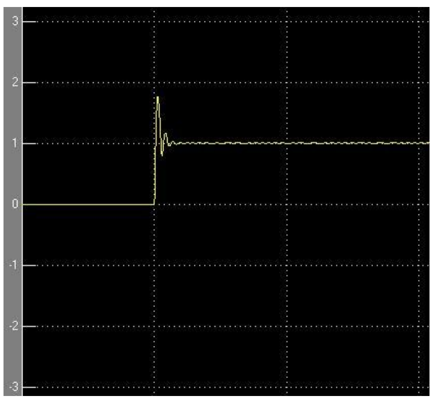

Fig.4.2 Response of magnetic levitation system with nonlinear gain

The above mentioned graphs give brief idea of the responses of magnetic levitation system with linear and nonlinear gains.

- If the output is observed, in the graph with nonlinear gain the overshoot comparatively with classical PID control
- Setting time less observed with linear model.
- Nonlinear design gives stable responses even if some sort of uncertainties act on it.
- As the gain '*k*' in nonlinear approach is function of error, even for the dynamic systems the response will be better.

5. CONCLUSION

Nonlinearity always drags the performance and stability of the system. It's the control engineer who has to design an appropriate controller for the system to perform effectively even when uncertainties acts on it. In this paper sigmoidal function is the nonlinearity which is taken as a constraint and designed an appropriate controller to react with such type of nonlinearities. Adding these type of constraints to the system gives an idea to the control engineer that how to design a controller for real time processes when unwanted disturbances acts on system.

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BIOGRAPHIES

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Eadala Sarath Yadav is presently working as Junior Research Follow, Manipal Institute of Technology, Manipal University, Manipal. He did M.Tech in control systems from MIT, Manipal and B.Tech in Electronics and Instrumentation Engineering from Sree Vidyanikethan Engineering College, Tirupati. His area of interest includes advanced control design, process control, Nonlinear and optimal control. Before joining as JRF, he worked as Assistant professor in Vignan Institute of technology and science, Hyderabad.

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