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Nonlinear Control of a Magnetic Levitation System Using a New Input-Output Feedback Linearization

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Abstract: In this paper a nonlinear controller (NLC) is designed for a Magnetic Levitation System (MLS). The proposed NLC uses a new input-output based differential geometry feedback linearization method in conjugation with a linear state feedback controller in outer loop to levitate a ferromagnetic ball. The electromagnetic force, which is a function of input magnetizing current and position of the ferromagnetic material to be levitated by the applied input force, is estimated using real-time experimental data. The simulation results obtained show efficacy of the proposed NLC in comparison to a traditional PID controller.

Keywords: Magnetic levitation system, Nonlinear Control, Feedback Linearization.

1. INTRODUCTION

Magnetic levitation system (MLS) is an electromagnetic device which levitates ferromagnetic elements using principle of electromagnetism. MLS technology eliminates mechanical contacts between moving and stationary parts thereby reducing the friction. Due to reduction in friction, MLS offers many advantages such as low noise, ability to do work in high vacuum environment, high precision positioning platforms. MLS generally works on three kinds of forces namely propulsion, levitation and guidance force [1]. Propulsion force to push moving part forward, levitation force to lift up the moving part, and guidance force to avoid derailing. If magnetic force is attractive then it is magnetic suspension while repulsive force responsible for magnetic levitation.

MLS has numerous applications like ability to do work in high vacuum environment [2] .But due to the constant need of levitation, a MLS is subjected to continuously changing parameters and hence the mathematical model is highly nonlinear. There have been several attempts to model and control the MLS [3]. Despite the fact that magnetic levitation is nonlinear behaviour and it is described by nonlinear differential equation, mostly design approaches are based on linear model [4-6]. But in linear model tracking performance is deteriorates rapidly as increasing deviation with respect to nominal operating point. In order to have efficient tracking and reliable levitation nonlinear modelling is considered in this work. Hence an online parameters estimation based on experimental data is used for the system modelling.

In this work an effort is being made to model the MLS using the electromagnetic laws. Based on this developed model a nonlinear input-output feedback linearization in conjunction with a static-state feedback control law is designed. In addition to it, the electromagnetic force, which is a function of input magnetizing current and position of the ferromagnetic material to be levitated by the applied input force, is estimated using real-time data. The superiority of the proposed controller is established at the end with respect to a traditional PID controller. The contribution of the work are as follows

- To model a nonlinear model for the MLS system and estimate its parameters using curve fitting.
- Design and implement a new input-output based differential geometry feedback linearization method in conjugation with a linear state feedback controller in outer loop

2. DYNAMIC MODELING OF MLS

MLS considered for modelling consists of a ferromagnetic ball suspended in a voltage controlled magnetic field. Ferromagnetic core coil acts as actuator, sensor determining the position of ball with respect to core coil, ferromagnetic ball has single degree of freedom.

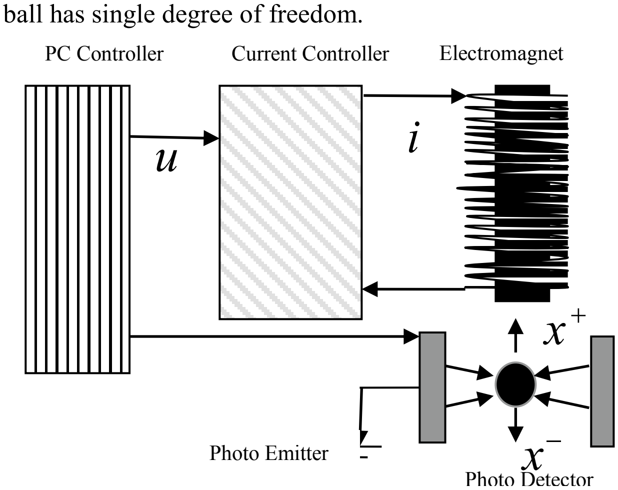

Fig. 1 Schematic diagram of the MLS

$F(x,i)$

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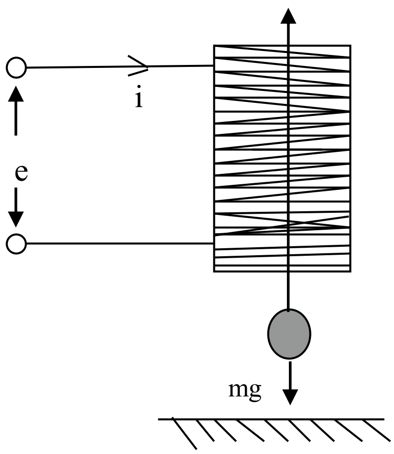

Fig. 2 Free body diagram of the MLS

Fig. 1 shows the schematic diagram of the studied MLS which consists of magnetic levitation mechanical unit (electromagnet, sensors, and ferromagnetic ball) with a computer interface card, a signal conditioning unit, connecting cables. There are two inputs to the system. Reference input signals (*u* and *i*) and disturbances–such as power supply fluctuations, coil temperature variation and external forces applied to the ball. Dynamic behaviour of MLS can be modelled by the study of electromagnetic and mechanical sub system [3]. In magnetic levitation there is magnetic force induced due to current flowing in the coil. The magnetic force and electric current of the coil deduced by Biot-Savart law and Kirchoff,s law respectively. Ferromagnetic ball experiences magnetic force as well as gravitational force. From the free body diagram shown in Fig. 2 the force equation using Newton's Laws of motion can be written as

$$F(x,i) - mg = ma \tag{1}$$

where

$F(x,i)$ = Electromagnetic force

m = mass of ferromagnetic ball

g = Acceleration due to gravity

From (1) it is known that electromagnetic force $F(x,i)$ is function of position and current which can be rewritten as

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

$$m\frac{d^2x}{dt^2} = F(x,i) - mg \tag{3}$$

$$m\ddot{x} = F(x,i) - mg \tag{4}$$

$$\ddot{x} = \frac{F(x,i)}{m} - g \tag{5}$$

Now we have to calculate *F (x,i)* for location of the ball with respect to the electromagnet. Magnetic field due to small segment of wire *dl* carrying a current *i* is

$$dB = \frac{\mu_o}{4\pi}\frac{idl \times r}{r^3} \tag{6}$$

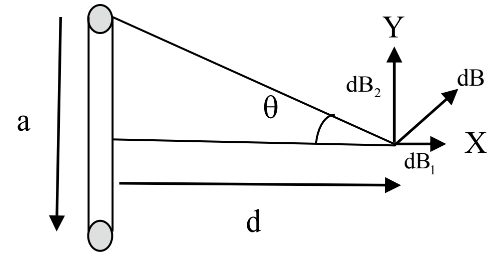

Fig. 3 Magnetic field for circular contour

Magnetic field due to circular path having current *i* and radius a is

$$B = \frac{\mu_o i}{2}\frac{a^2}{(a^2+d^2)^{3/2}} \tag{7}$$

Where

$r = \sqrt{a^2 + d^2}$

Due to field symmetry magnetic field in y direction is zero hence magnetic field exiting in only x direction.

For N=total number of turns, n is the number of turns per unit length. Effect of magnetic field from electromagnet is to introduce a magnetic dipole in the ball which itself becomes magnetized the force acting on ball is then composed of gravity and magnetic force acting on induced dipole. In Fig. 4 ADEF is a solenoid (or electromagnet) having N number of turns, solenoid of radius *r*, length *l*. Next, magnetic field on AD is in upward direction while downward at EF direction. Now consider *dx* at distance separation between two turns, then total current is *nIdx*. Magnetic control force between solenoid and ball can be found out by considering magnetic field as function of ball distance '*x'* from end of the coil which is given as

$$\left.\begin{aligned} sin\,\theta_1 &= \frac{r}{\sqrt{(l+x)^2 + r^2}} \\ sin\,\theta_2 &= \frac{r}{\sqrt{r^2 + x^2}} \end{aligned}\right\} \tag{8}$$

Total axial field from all turns $B = \int dB$ from (7) we can write,

$$B = \frac{\mu_o}{2} nI \int \frac{r^2}{(r^2 + l^2)^{3/2}} dx \tag{9}$$

$$\left.\begin{aligned} B &= \frac{\mu_o}{2} nI \int \frac{r}{\sqrt{r^2+l^2}}\frac{r}{\sqrt{r^2+l^2}}\frac{r}{\sqrt{r^2+l^2}} dx \\ B &= \frac{\mu_O}{2} nI \int sin\,\theta . sin\,\theta \frac{1}{\sqrt{r^2+l^2}}\frac{r}{r} dx \\ B &= \frac{\mu_O}{2} nI \int sin\,\theta . sin\,\theta . sin\,\theta \frac{1}{x} dx \end{aligned}\right\} \tag{10}$$

$$B = \frac{\mu_O}{2} nI \int (\sin\theta)^3 \frac{1}{r} dx \tag{11}$$

Integrating Eq. (11) from interval $\theta_1 \le \theta \le \theta_2$