Design of a Variable Structure Controller for an Electromagnetic Suspension System

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Abstract

This paper presents the design of variable structure algorithm for the position control of magnetic levitation system with particular emphasis on reference signal tracking. The model considered is a third order Maglev system characterized by inherent nonlinearity, instability, time-varying operating parameters and disturbances. System robustness is one of the major challenges to the Maglev development because of the stringent performance requirements necessary for the system to be attractive for human needs. An investigation is conducted on the robustness of the control strategy for levitation in maglev system. A nonlinear state transformation in the feedback path is adopted to obtain a linear second order system in the design of control law. Simulation results obtained on the robustness show the effectiveness of the controller for reference tracking in the presence of uncertainties in the operating parameters.

Key Words: Maglev, levitation, signal, electromagnetic, simulation, system

1. *Introduction*

Magnetic levitation (Maglev) systems have many applications such as in frictionless bearings, high-speed maglev passenger train, levitation of wind tunnel models, vibration isolation of sensitive machinery, levitation of molten metal in furnaces and levitation of metal slabs during manufacture (Walter et. al., 1996). These systems have nonlinear dynamics that are open loop unstable and, as a result, feedback control is required to stabilize them.

The maglev system presents significant challenges, because they are described by highly nonlinear differential equations which present additional difficulties in controlling the system. The challenge in a magnetically levitated vehicle is that of stability, because for any small change in the air-gap will obviously cause undesirable consequences. Therefore, it is an important task to construct high-performance feedback controller for regulating the position of the levitated object.

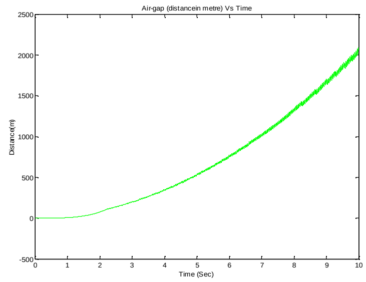
In recent years, a lot of works have been reported in the literature for controlling magnetic levitation systems by taking non-linearities of the system into account (Al-Muthairi et al., 2004; Walter et al., 1996; Gulterrez et al., 1988; Oleksiy et al., 2002; Shen et al., 2002; Zi-Jiang Yang et al., 2004). Simulation methods are very useful in supporting experimental methods and often enable the determination of variables which are difficult to obtain in experiments (Paolo et al., 2004; Robert et al., 1999).

Research efforts are presently directed at finding robust control algorithms for Maglev systems, because the systems are nonlinear and open loop unstable. Of particular interest is the control of maglev vehicle based on the theory of variable structure system (VSS). This paper presents computer simulation of control performances of maglev vehicle using the theory of variable structure (sliding mode) with reference signal tracking. The model of the system is discussed and the design objectives are achieved by the use of a state feedback transformation to obtain linear second order system, which satisfies the necessary performance characteristics of the actuator. A variable structure controller is designed to control the whole system and the robustness of the closed loop system against mass variation is discussed and simulation results are presented.

2. *Magnetic Levitation Model*

The Maglev system in this paper is illustrate in Fig 1

Fig 1: Schematic of an electromagnetic suspension system



The instantaneous flux linkage between the two magnetized bodies through the air gap z(t) is Φ_m. If the leakage flux is ignored, that is $\Phi_t = \Phi_m$, then

$$L = \frac{\mu_o N^2 A}{2z(t)} \qquad (0.1)$$

where μ_o is vacuum permeability, N is the number of turns of the magnet winding, and A is the pole face area. Furthermore, the inductance L varies with changes in the air gap. Also the attraction force at any instant of time is given by,

$$F(i,z) = \frac{\mu_o N^2 A}{4}\left(\frac{i(t)}{z(t)}\right)^2 \qquad (0.2)$$

Thus if the total resistance of the circuit is denoted by R, then the instantaneous voltage v (t) (across the magnet winding) controlling the excitation current i(t). From nonlinear equation of motion, the dynamic equations of the system are:

$$m\frac{d^2z(t)}{dt^2} = mg - \frac{k_2 i^2(t)}{z^2(t)} - f_d(t) \qquad (0.3)$$

$$v(t) = Ri(t) + L\frac{di(t)}{dt} \qquad (0.4)$$

The system is to regulate the current i, of the electromagnetic coil which will generate electromagnetic force F, that levitated mass m, (vehicle) at a fixed distance y. The values of the Constants are as shown in Table1. The state equations are:

$$\begin{aligned}
\dot{x} &= x_2(t) \\
\dot{x}_2 &= -\frac{k_2}{2m}\left(\frac{x_3}{x_1}\right) + g - \frac{1}{m} f_d \\
\dot{x}_3 &= -\frac{R}{k} x_1 x_3 + \frac{x_2 x_3}{x_1} + \frac{1}{k_2} x_1 u(t) \\
y &= x_1
\end{aligned} \qquad (0.5)$$

Where y is the output, $x_1 = z$ is vertical air gap (m), x_2 is the vertical relative velocity (m/s^2), $x_3 = i$ (magnet current in A), g = 9.8 m/s^2 and k is force factor

$$\left(\frac{\mu_o N^2 A}{2}\right)$$

Variable Structure Controller Design

Variable Structure Control (VSC) system design consists of determining the controller gains as well as the switching logic such that the state will be brought from any initial point in the phase plane to the sliding surface, along which it slides towards the origin. The error vector is defined as

$$e = r - x \qquad (0.6)$$

Where $e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$, $r = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix}$ and $x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$

The reference position is r_1 while the reference speed is r_2. For position control along, r_2 is usually not specified and may therefore be assumed zero. Thus from equation (1.6)

$$e_1 = r_1 - x_1 \qquad (0.7)$$

$$e_2 = -x_2 \qquad (0.8)$$

Consider the control law

$$u = ke_1 \qquad (0.9)$$

Where control gain k switches according to the following logic (Utkin, 1977, 1978)

$$k = \begin{cases} \alpha, & \text{if } \mathrm{se}_1 > 0 \\ \beta, & \text{if } \mathrm{se}_1 < 0 \end{cases} \qquad (0.10)$$

Along the switching line defined in the error space as

$$s = c_1 e_1 + e_2 \qquad (0.11)$$

Where c_1 is a constant greater-than zero, called the sliding surface (Utkin, 1977, 1983; Ukin et al., 1999). In the neighbourhood of the switching line

$$e_2 = c_1 e_2 \qquad (0.12)$$

The condition for sliding along s= 0 is given by (Utkin, 1977, 1978)

$$\dot{s}s < 0 \quad (0.13)$$

Differentiating equation (1.11) yields

$$\dot{s} = c_1 \dot{e}_1 + \dot{e}_2 = 0 \qquad (0.14)$$

Differentiation of equation (1.7) while assuming that r_1 is constant, yields

$$e_1 = - x_1 \qquad (0.15)$$

Making use of equations (1.7), (1.8) and (1.12) yields

$$\begin{aligned} \dot{e} &= -a_{12} x_2 \\ &= a_{12} e_2 \\ &= - c\, a_{12} e_1 \qquad (0.16) \end{aligned}$$

Similarly, differentiation of equation (8) and substituting for $\dot{x}_2$ yields

$$\begin{aligned} \dot{e} &= -a_{22} x_2 - \beta k e_1 \\ &= a_{22} e_2 - ßk e_1 \\ &= - a_{22} c_1 e_1 - ßk e_1 \qquad (0.17) \end{aligned}$$

Substituting equation (1.15) and (1.16) into equation (1.14) yields

$$\dot{s} = -c^2 a_{12} e_1 - c_1 a_{22} e_1 - \beta k e_1$$

Therefore, the condition for sliding is given by

$$\dot{s}s = -[c^2 a_{12} + c a_{22} + ßk] s e_1 \qquad (0.18)$$

To satisfy condition (1.10) it is required that the following condition should hold.

$$se1 \begin{cases} se_1 > 0, \text{ then } \left[c^2 a_{12} + c a_{22} + ßk\right] \geq 0 \\ se_1 < 0, \text{ then } \left[c^2 a_{12} + c a_{22} - ßk\right] \leq 0 \end{cases} \qquad (0.19)$$

The values of control gain k which makes the above condition to hold is thus given by:

$$k := \begin{cases} \alpha \geq \Psi \, if \;\; se_1 > 0 \\ \beta \leq \Psi \;\; if \;\; se_1 < 0 \\ \Psi \;\; = \;\; - \;\; \left[c^2 a_{12} + \;\; a_{22} c \right) / \, b \end{cases} \qquad (0.20)$$

3. Simulation Results and Discussion

In this section results of simulation runs are presented. The fourth order RungeKutta integration algorithm coded in MatLab is employed to simulate the Magnetic Levitation System. It is proposed to exploit the useful properties of VSC to solve the problems of fast response, small overshoot, and high accuracy in air-gap distance of the Maglev and its robustness to parameter variation and disturbance rejection.

Fig 2. and Fig 3. Shows the open-loop response to non-zero condition where the air-gap (distance) is increasing probably will go out of range,

Fig 2: Open loop response of the system

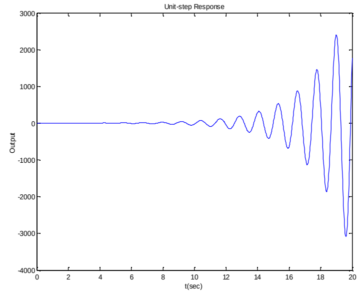


Fig 3: Open loop response of the system

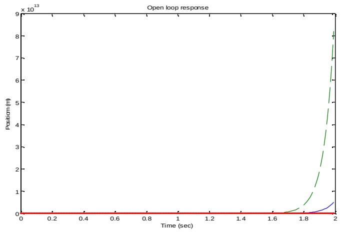
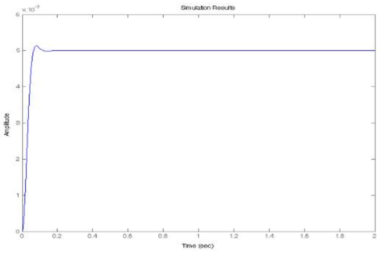


Fig 4 shows unstable step response of the open loop system.

Fig 4: Open loop step response



4. Analysis of Robustness

This section presents the effect of uncertainties of Maglev system, which may appear in different form as disturbance or parameter variations in the maglev model.

The response curves in Fig 5. With a settling time of 0.17 seconds

Fig 5: Step response

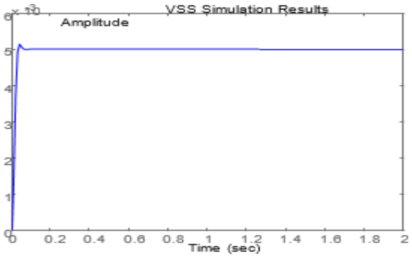
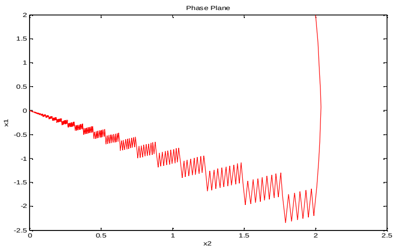


Fig 6. also has settling time of 0.15 and overshoot of $1\text{x}10^{-4}$ in both cases. Which are neatly identical and both exhibit no significant overshoot and good settling times, also the steady state response curves associated reveals that there are no significant changes with parameter variation and disturbances.

Fig 6 Step response



Further demonstration shown in Fig 7. to Fig 12. revealed that the system response was effectively controlled by sliding mode equation, which was specified by the value of c_1. The result shows that most significant parameter variation and external disturbances could be reliably controlled by the sliding mode dynamics. While the chattering phenomenon inherent in sliding mode control could be greatly improved by the feedback transformation of current and air gap ratio of the maglev system.

Fig 7: Phase plane

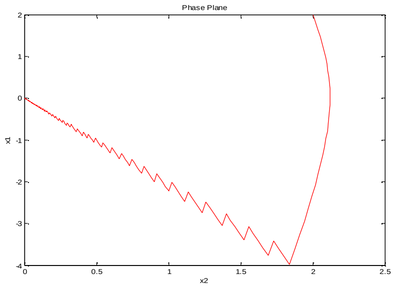


Fig 8: Phase plane

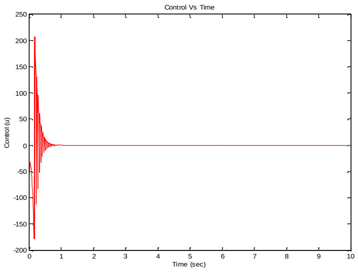


Fig 9: Control signal

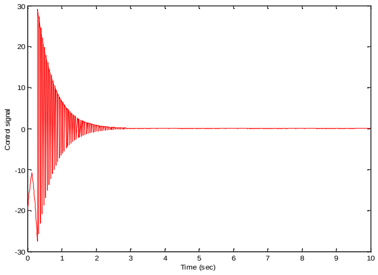


Fig 10: Control signal

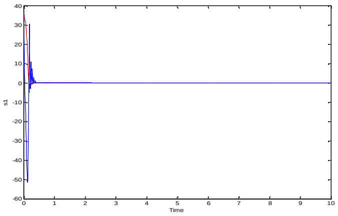


Fig 11: Sliding surface

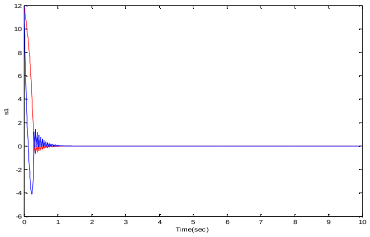
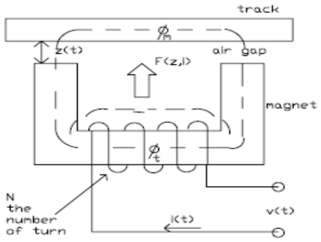


Fig 12: Sliding surface



Moreover, Fig 9. and Fig 10., for the range between 28 and -28, 62 and -56 of c_1 s phase portrait and sliding surface, shows the following observation are made:

i. As c_1 increases, the speed of response also increases with reduction of signal chattering.
ii. The rate of switching along the sliding surface reduces as c_1 increases.

5. Conclusions

In this paper, method for controlling the electromagnetic system, by state transformation the complex nonlinearities are reduced to achieved the aim of controlling the system. The nature and the properties of variable structure system has been demonstrated by way of simulation, such that structural changes facilitate exploitation of useful properties of each structure and can also produce new properties. It has also revealed the reduced control effort as well as reduced chattering of the control signal.

The proposed controller was applied to magnetic levitation system and simulation studies shown that operating a variable structure system in sliding mode makes it insensitive to parameter variation.

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Table 1: System parameters

Description	Symbol	Value	Units
Coil resistance	R	1.5	Ohm
Force Constant	k_2	5×10^{-4}	m^2N/A^2
Gravitational Constant	g	9.81	m/s^2
Mass of vehicle	m	3.3	kg
Nominal air gap	z	2.5×10^{-3}	m
No of turns	N	565	-
Pole area	A	78.6×10^{-5}	m^2

Sources: Adapted from Taghirad et. al., 1998