Robust Feedback Control Analysis of Magnetic Levitation System

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Abstract: The Magnetic Levitation System is one of the important benchmark laboratory models for the design and analysis of feedback control systems. Robust feedback control for magnetic levitation systems is considered problematic due to the parametric uncertainties in mass, strong disturbance forces between the magnets and noise effects inflowing from sensor and input channels. Therefore robustness is a key issue in designing a control system for a magnetic levitation as the models are never 100 percent accurate and the uncertainties in the model must be accounted. In this paper, H_∞ robust control is investigated to bring the magnetic levitation system in a stable region by keeping a magnetic ball suspended in the air in the presence of uncertainties. The paper first presents the complete non-linear and linear mathematical models and then it adopts the mixed sensitivity design method for H_∞ controller synthesis. The simulation results show that the designed controller meets robustness against model uncertainties and permits very precise positioning of the levitated object.

Key–Words: Modeling, Robust Control, Stability, Performance, Mixed Sensitivity, H_∞ Control, Robustness

1 Introduction

The Magnetic Levitation System is a benchmark laboratory model for the understanding of control systems. It is highly nonlinear and open loop unstable system. This unstable aspect of Maglev and its inherent nonlinearity make the modeling and control problems very challenging. Over the past few decades, the several control strategies using both classical and modern design methods have been used and implemented in Maglev [6, 8, 11–13]. Magnetic levitation system not only presents challenging problems for control engineering research, but also have many relevant applications, such as high-speed transportation systems (Maglev trains) and magnetic bearings [13–15]. From an educational viewpoint, this process is highly motivating and suitable' for laboratory experiments and classroom demonstrations, as reported in the engineering education literature [6, 12].

Robustness is an important objective in control system design as plants are vulnerable to unpredicted external disturbance and noise and there is always difference between mathematical model used for design and the actual plant. Therefore it is required to design a robust controller to guarantee the internal stability and performance of the system in presence of such uncertainties. The PID controller is generally used as a controller of magnetic levitation which is easily realized [6], but it can hardly meet the demands of good robustness because it is difficult to adjust three parameters of K_p, Ki and K_d, so there has been considerable interest in robust controller for magnetic levitation system. Control methods based on robust H_∞ control theory [1, 2, 8, 10] deal with robustness much more directly than other approaches

The main objective of this paper is to analyze robust feedback control for maglev. The emphasis is on explaining the H_∞ robust control design method and its relevance for maglev system. In this paper, weighting functions selection for controller synthesis is done with the help of the articles [8, 10]. Mathematical models for the Maglev system is established using articles [6, 12]. Some MATLAB functions are frequently used in this work for controller synthesis and system simulation using reference [5, 7, 9]. The paper presents few results and does not at all do justice to extensive real time simulation results. We also like to remind a number of approaches that could benefit under several forms of our current work [16–24].

We preview some of the contents of paper. In section (2), we established the non-linear and linear mathematical model of maglev system. Section (3) is devoted to the theory of robust control design method. It leads to the discussion of mixed sensitivity H_∞ control method. Minimization of the mixed sensitivity criterion results in optimal robustness of feedback control system. In section (4), we shown the robust controller synthesis for maglev system. The simulation are obtained to verify robust stability and performance for the system. Section (5) concludes this paper by some remarks and conclusion.

2 Mathematical Modeling of Magnetic Levitation System

Magnetic levitation system consists of magnetic, electrical and mechanical systems. The dynamic behaviuor maglev system can be modeled by the study of electromagnetic and mechanical sub systems.

2.1 Mathematical Model for Electromagnetic Sub-System

Consider a schematic of maglev plant and its electromagnetic network model as shown in Fig.(1). Apply

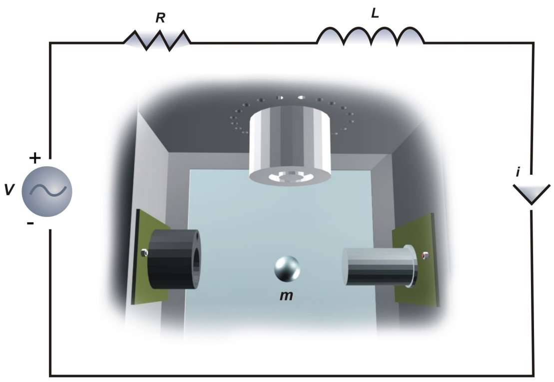

Figure 1: Maglev model [6]

kirchoffs voltage law in electrical system network (see Fig.1).

$$V = V_R + V_L \Rightarrow u(t) = iR + L(x)\frac{di}{dt} \qquad (1)$$

where u, i, R and L are applied voltage input, current in the electromagnet coil, coil's resistance and coil's inductance respectively.

2.2 Mathematical Model for Mechanical Sub-System

Energy stored in the inductor can be written as

$$W_e = \frac{1}{2}L(x)i^2 \qquad (2)$$

Since power in electrical system (P_e) = Power in the mechanical system (P_m), where $P_e = \frac{dW_e}{dt}$ and $P_m = -f_m\frac{dx}{dt}$, Therefore

$$\begin{aligned} -f_m\frac{dx}{dt} &= \frac{dW_e}{dt} \\ \Rightarrow f_m &= -\frac{dW_e}{dt}\frac{dt}{dx} = -\frac{dW_e}{dx} \end{aligned} \qquad (3)$$

where f_m is known as electromagnet force. Now substituting (2) in the equation (3),

$$\begin{aligned} f_m &= -\frac{d}{dx}\left(\frac{1}{2}L(x)i^2\right) \\ &= -\frac{1}{2}i^2\frac{d}{dx}\left(L(X)\right) \end{aligned} \qquad (4)$$

Since $L(x) = \frac{k}{x}$, therefore, we have

$$\begin{aligned} f_m &= -\frac{1}{2}i^2\frac{d}{dx}\left(\frac{k}{x}\right) \\ &= -\frac{1}{2}i^2\left(\frac{-k}{x^2}\right) \\ \Rightarrow f_m &= \frac{k}{2}\left(\frac{i^2}{x^2}\right) \end{aligned} \qquad (5)$$

where k=electromagnet force constant, x=actual air gap between core face and ball surface.

If f_m is electromagnetic force produced by input current, f_g is the force due to gravity and f is net force acting on the ball, the equation of force can be written as

$$\begin{aligned} f_g &= f_m + f \\ &= m\left(\frac{d^2x}{dt^2}\right) + f \\ \Rightarrow m\frac{dv}{dt} &= -f_m + f_g \end{aligned} \qquad (6)$$

where m=steel ball mass and $v = \frac{dx}{dt}$=velocity of the ball movement

At equilibrium: $f_g = -f_m$ and $f = 0$

2.3 Non-Linear Model

On the basis of electro-mechanical modeling, the non-linear model of magnetic levitation system can be described in terms of following set of differential equations:

$$L\frac{di}{dt} + iR = u(t) \qquad (7)$$

$$\frac{dx}{dt} = v \qquad (8)$$

$$\begin{aligned} m\frac{dv}{dt} &= -f_m(x, i) + f_g \\ &= \frac{k}{2}\left(\frac{i^2}{x^2}\right) + f_g \end{aligned} \qquad (9)$$

2.4 Linear Model

To carry out controller design and analysis of maglev system, the obtained non-linear model has to be linearized. Such linearization is done in the equilibrium point, which can be calculated from:

$$g = f_m(x, i) \Rightarrow i_0, x_0. \tag{10}$$

The states of the system are i, v and x. At equilibrium, the force due to gravity f_g and the magnetic force f_m are equal and opposes each other so that the ball levitates. Considering nominal input voltage produces the corresponding coil current i_0 such that the ball reaches at its equilibrium where position $x = x_0$. We can linearized the model using Taylor's series expansion of $f_m(x, i)$ around the equilibrium point (x_0, i_0), where $x = x_0 + \delta x$ and $i = i_0 + \delta i$.

$$\begin{aligned} f_m(x,i) &\cong f_m(x_0,i_0) + \left(\frac{\partial f_m}{\partial x}\right)_{(x_0,i_0)} \delta x \\ &+ \left(\frac{\partial f_m}{\partial i}\right)_{(x_0,i_0)} \delta i \qquad (11) \\ f_m &\cong f_{m_0} - k_s \delta x + k_i \delta i \qquad (12) \end{aligned}$$

where $k_s = k\left(\frac{i_0^2}{x_0^3}\right)$ and $k_i = k\left(\frac{i_0}{x_0^2}\right)$.

Now governing equations for linear maglev model can be written as:

$$\begin{aligned} L\frac{d}{dt}\delta i + R\delta i &= u \qquad (13) \\ m\frac{dv}{dt} - k_s\delta x + k_i\delta i &= 0 \qquad (14) \\ \frac{d}{dt}\delta x &= v \qquad (15) \end{aligned}$$

Using equations (13), (14) and (15), we can formulate the state space model of maglev system as:

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix}\delta i \\ v \\ \delta x\end{bmatrix} &= \begin{bmatrix}-\frac{R}{L} & 0 & 0 \\ -\frac{k_i}{m} & 0 & \frac{k_s}{m} \\ 0 & 1 & 0\end{bmatrix}\begin{bmatrix}\delta i \\ v \\ \delta x\end{bmatrix} \\ &+ \begin{bmatrix}\frac{1}{L} \\ 0 \\ 0\end{bmatrix} u \qquad (16) \\ Y &= \begin{bmatrix}0 & 0 & 1\end{bmatrix}\begin{bmatrix}\delta i \\ v \\ \delta x\end{bmatrix} \qquad (17) \end{aligned}$$

The equations (16) and (17) constitute the state space model $\dot{X} = AX + BU$ and $Y = CX + DU$ where $A = \begin{bmatrix}\frac{R}{L} & 0 & 0 \\ -\frac{k_i}{m} & 0 & \frac{k_s}{m} \\ 0 & 1 & 0\end{bmatrix}; B = \begin{bmatrix}\frac{1}{L} \\ 0 \\ 0\end{bmatrix}; C = \begin{bmatrix}0 & 0 & 1\end{bmatrix}$ and $D = 0$.

In order to obtain the A, B, C and D matrices for the linear maglev model, we consider the physical parameter's value from the following table (1).

Table 1: Physical parameters of Magnetic Levitation system

Parameter	Unit	Value
m	Kg	0.068
R	ohms (Ω)	10
L	Henry (H)	0.4125
k	Nm^2/A^2	6.53×10^{-5}
i_0	Ampere (A)	0.8
x_0	meter (m)	0.012

3 Design Philosophy

Consider the feedback system as shown in Fig.(2). The problem of interest is to synthesize a controller $C(s)$ for the uncertain plant $\tilde{G}(s)$ so that the closed-loop system achieves specified performance in presence of disturbance d and noise n. The block diagram shows a nominal plant $G(s)$ that is disturbed by multiplicative uncertainty $\Delta(s)$, which is an unknown but stable transfer function.

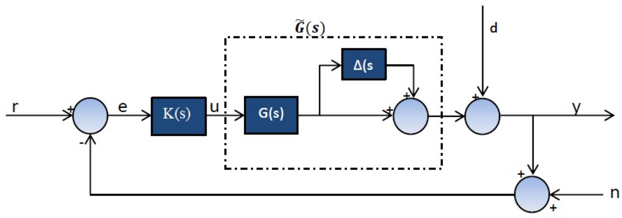

Figure 2: Feedback system with multiplicative uncertainty model

By convention, the nominal open loop transfer function, sensitivity and complementary sensitivity transfer function are defined as [1–5]

$$\begin{cases} L(s) = G(s)K(s) \\ S(s) = \frac{1}{1+L(s)} \\ T(s) = \frac{L(s)}{1+L(s)} \end{cases} \tag{18}$$

Since sensitivity transfer function $S(s)$ determines the steady-state behavior and disturbance attenuation of the feedback system. Therefore, by specifying an upper bound on the norm of $S(s)$, the disturbance attenuation and steady-state specifications can be addressed as follows:

$$\left|\overline{\sigma}\left(S(j\omega)\right)\right| \leq \left|W_p^{-1}(j\omega)\right|, \forall\omega \tag{19}$$

where $\overline{\sigma}(S(j\omega)$ is the maximum singular value of $S(s)$ and weighting function W_p is the bound that reflects the desired disturbance attenuation for each frequency ω. Good disturbance rejection is required particularly in the low frequency region where disturbance is significant.

The transfer function from input r to control signal u is given by

$$\frac{u}{r} = Q(s) = \frac{K(s)}{1 + G(s)K(s)} = K(s)S(s) \qquad (20)$$

To ensure that the control signal is bounded, we need to introduce a non-zero weighting function W_u on the control signal. Hence, constraint on the control u can be considered with a bound W_u as shown by (21)

$$|\overline{\sigma}\left(K(j\omega)S(j\omega)\right)| \le \left|W_u^{-1}(j\omega)\right|, \forall\omega \qquad (21)$$

The relationship between the perturbed system $\tilde{G}(s)$, nominal system $G(s)$ and uncertainty $\Delta(s)$ for the block diagram shown in Fig. (2) is given by [3–5]

$$\tilde{G}(s) = G(s)\left(1 + \Delta(s)\right) \qquad (22)$$

The frequency structure of the uncertainty $\Delta(s)$ is characterized by a proper, stable and minimum phase transfer function $W_\Delta(s)$ satisfying

$$\left|\frac{\tilde{G}(j\omega)}{G(j\omega)} - 1\right| = |\Delta(j\omega)| \le |W_\Delta(j\omega)|, \forall\omega \qquad (23)$$

where the magnitude response of $W_\Delta(j\omega)$ is an upper bound of the magnitude of the model uncertainty $\Delta(j\omega)$. If practical systems operate under perturbation, we need a robustness test to ensure the stability under such perturbation. The size of small stable perturbation $\Delta(s)$ for the system becomes unstable is given by:

$$|\overline{\sigma}(\Delta(j\omega))| = \frac{1}{\overline{\sigma}(T(j\omega))} \qquad (24)$$

Thus, using equation (24), the upper bound on $\|T(s)\|_\infty$ can be specified as

$$|\overline{\sigma}(T(j\omega))| \le \left|W_\Delta^{-1}(j\omega)\right|, \forall\omega \qquad (25)$$

Weighting function W_Δ is used to ensure good robustness and noise rejection, particularly in the high-frequency range where the noise and modeling errors are usually significant.

Now let's consider the robust performance problem where we want to find an internally stabilizing control such that [1–5]

$$\overline{\sigma}\left(W_p S\right) + \overline{\sigma}\left(W_\Delta T\right) < 1 \qquad (26)$$

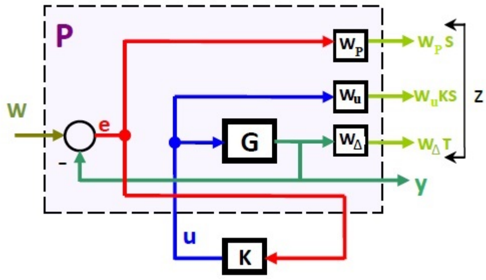

Figure 3: Block Diagram of Augmented Closed loop map

We're going to reframe this as an H_∞ control problem. We first rewrite our system as shown below in Fig.(3). This figure shows the interconnection of an augmented plant with the controller K. The augmented plant is denoted by P and we write it as a block transfer function matrix:-

$$P(s) = \left[\begin{array}{c|c} P_{11}(s) & P_{12}(s) \\ \hline P_{21}(s) & P_{22}(s) \end{array}\right]$$

The augmented plant of Fig.(3) has w and u as its inputs and z and y as outputs. The output z is the vector of regulated variables W_pS, W_uKS and $W_\Delta T$. The reference command r and $e = r - y$ of the feedback block diagram of Fig.(2) corresponds to w and y of Fig.(3). The input-output relationship of the system shown in Fig.(3) can be written as

$$\begin{bmatrix} z \\ y \end{bmatrix} = P\begin{bmatrix} w \\ u \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix}\begin{bmatrix} w \\ u \end{bmatrix} \qquad (27)$$

$$u = K(s)y \qquad (28)$$

Putting value of (28) in (27), the closed-loop transfer function from w to z can be found as

$$F_l(P, K) = P_{11} + P_{12}K(I - P_{22}K)^{-1}P_{21} \qquad (29)$$

The mapping $F_l(P, K)$ is known as linear fractional transformation (LFT).

Now we have to find a controller K such that the H_∞ norm of $F_l(P, K)$ is bounded by a known constant γ. The constant γ represents the desired performance level of this closed loop system. In other words, we want to find K such that $F_l(P, K)$ is internally stable and satisfying [4, 5]

$$\|F_l(P, K)\|_\infty < \gamma. \qquad (30)$$

This problem is known as classical H_∞ controller synthesis problem. This synthesis problem is also often referred to as a mixed sensitivity problem. It has the name because the closed loop map $F_l(P, K)$ can be written as

$$F_l(P, K) = \begin{bmatrix} W_p S \\ W_u K S \\ W_\Delta T \end{bmatrix} \quad (31)$$

where S and T are the output sensitivities of the nominal closed loop system. Using the properties of the singular values, it can be shown that

$$\begin{aligned} \overline{\sigma}\left(\begin{bmatrix} W_p S \\ W_u K S \\ W_\Delta T \end{bmatrix}\right) &\leq \overline{\sigma}(W_p S) + \overline{\sigma}(W_\Delta T) \\ &\leq 2\overline{\sigma}\left(\begin{bmatrix} W_p S \\ W_u K S \\ W_\Delta T \end{bmatrix}\right) \end{aligned} \quad (32)$$

So if we solve the mixed sensitivity problem with $\gamma = 1/2$, then we can guarantee that

$$\|F_l(P, K)\|_\infty < 1/2. \quad (33)$$

and this is sufficient to ensure robust performance for all ω. Moreover, the H_∞ controller synthesis (if successful) always generates an internally stable closed loop map.

4 H_∞-Controller Synthesis for Magnetic levitation System

The robustness of Maglev feedback control system refers to the ability to keep stability of controlled object under the uncertainty. The control objective of magnetic levitation system is to maintain the stable levitation of ball without contact in equilibrium position by adjusting the coil current of electromagnet. Based on this objective, applying robust control design method as discussed in section (3), the control of magnetic levitation can be set as mixed sensitivity H_∞ control, whose control system structure is shown in Fig.(3), where $P(s)$ is augmented object model, $K(s)$ is controller model, $W_p(s)$ is weighting performance function introduced to restrain the influence to control error by noise and interference, $W_u(s)$ is weighting output function of controller introduced to restrain input extremity, $W_\Delta(s)$ is weighting model perturbations function introduced to meet robust stability.

4.1 Selection of Weighting Functions

The most crucial and difficult task in robust controller design is a choice of the weighting functions. Even though in some articles there are attempts to outline the algorithm for finding appropriate functions, it is still a very monotonous and laborious process especially when a given model has complex non-linearities which obviously are omitted in a linear model.

The basic requirement for the selection of weighting functions are discussed in section (3). It is also necessary that the weighting functions are stable and the non minimum phase system, and their order can not be too high, otherwise the order of the controller will be increased because the order of H_∞ controller is the sum of controlled object and of weighting function. So we should select the lowest order weighting function whichever possible on the premise of ensuring design requirements.

After extensive simulation and fine tuning, the weighting function $W_p(s)$ for sensitivity S, $W_u(s)$ for KS and $W_\Delta(s)$ for complementary sensitivity T are chosen as follows:

$$\begin{cases} W_p(s) = \frac{0.4451s+0.4999}{s+1.006} \\ W_u(s) = 1e^{-8} \\ W_\Delta(s) = \frac{0.1774s+8.717}{s+39.03} \end{cases} \quad (34)$$

The entire procedure of choosing these weights is done with the help of the article [8, 10].

Remark 1 *We consider the case of parameter uncertainty in the system for* 10% *mass variation. Initially, changing* 10% *of mass in* `MATLAB` *simulation, the weighting function* $W_\Delta(s)$ *is selected.*

4.2 Controller Design

The H_∞ optimal control problem is to find stabilizing controller K that satisfy inequality (33). This controller design framework includes performance specification, disturbance rejection, control input limitations and robustness requirements. In the initial design step, the nominal plant model G is obtained from equations (16) and (17) developed in section (2). H_∞ controller is generated using nominal plant G and weighting functions $W_p(s), W_u(s)$ and $W_\Delta(s)$. The controller K is obtained by the `MATLAB` function 'mixsyn' as follows [7, 9]:

`[K,CL,GAM]=mixsyn`(G, W_p, W_u, W_Δ)

where K is the controller, CL is the closed loop for the system and GAM=γ.

Using the above `MATLAB` code, we obtain the optimized parameter $\gamma = 0.4686$, which satisfy our desired inequality $\|F_l(P, K)\|_\infty < \gamma = 1/2$. The 5^{th} order controller is obtained and the controller transfer can be written as:

$$K(s) = \frac{-(2.801\times10^{10})s^4-(2.33\times10^{12})s^3-(6.234\times10^{13})s^2-(5.626\times10^{14})s-(5.235\times10^{14})}{s^5+4432s^4+(7.989\times10^6)s^3+(8.105\times10^9)s^2+(3.025\times10^{11})s+(2.961\times10^{11})}$$

We now turn to examine this controller solution K and see if it really solved our problem. We first plot the robust performance level given by $\overline{\sigma}(W_pS) + \overline{\sigma}(W_\Delta T) < 1$. The plot shown in Fig.(4) is the combined robust performance level. Since the plot is below the 0 dB line, it shows that the robust performance condition is clearly satisfied. The next plot shown in the Fig.(5) illustrates the desired design specifications bounds as mentioned in (30) and (31). The plots meet our specification requirements, so the H_∞ synthesis has indeed solved the robustness problem of feedback control of maglev. Finally, we check our design by plotting the step responses for our closed loop design. The plot shown in the Fig.(6) shows the controlled ball position of linearized magnetic levitation system.This type of step response is what we want to see in our robust feedback system.

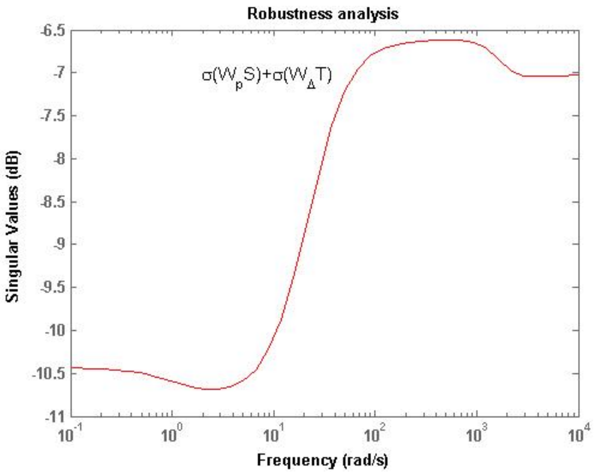

Figure 4: $\overline{\sigma}(W_pS) + \overline{\sigma}(W_\Delta T)$ versus ω

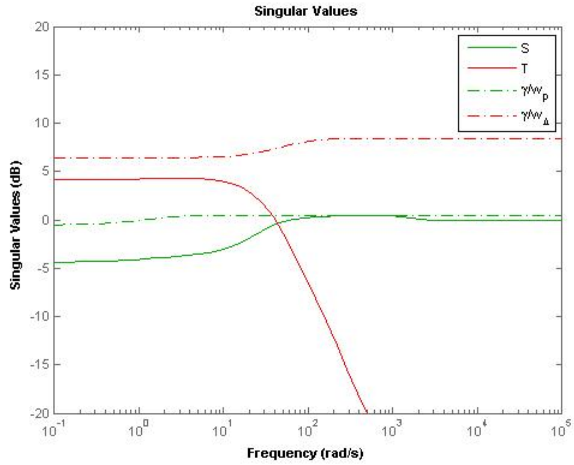

Figure 5: Design specification requirements

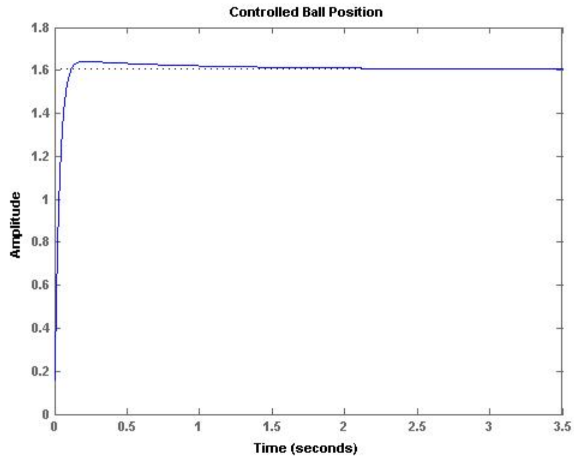

Figure 6: Stable ball position in Maglev system

5 Conclusion

In this paper, robustness analysis for the feedback control of magnetic levitation system is investigated. The basic ideas and technical formulations for the analysis of robust feedback control are presented. Firstly, the mathematical model of magnetic levitation system is established and then the control method based on H_∞ mixed sensitivity is analyzed and robust controller is designed. The simulation results show that the designed controller meets the requirement for the robust stability and performance. In other words, controller presents robustness against model uncertainties and permits very precise positioning of the levitated object.

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