Design of a 2-DOF Control and Disturbance Estimator for a Magnetic Levitation System

Avadh Pati
Dept. of Electrical Engineering
M. N. N. I. T.
Allahabad, India
er.avadhmnnit@gmail.com

Vipin Chandra Pal
Dept. of Electrical Engineering
M. N. N. I. T.
Allahabad, India
vipin.vchandra@gmail.com

Richa Negi
Dept. of Electrical Engineering
M. N. N. I. T.
Allahabad, India
richa@mnnit.ac.in

Abstract—**This work proposes a systematic two-degree freedom control scheme to improve the reference input tracking and load disturbance rejection for an unstable magnetic levitation system. The proposed control strategy is a two-step design process. Firstly, a proportional derivative controller is introduced purposely to get the desired set-point response of the magnetic levitation system and then, an integral square error (ISE) performance specification is used for designing a set-point tracking controller. Secondly, a disturbance estimator is designed using the desired closed loop complimentary sensitivity function for the rejection of load disturbances. This leads to the decoupling of the nominal set-point response from the load disturbance response similar to an open loop control manner. Thus, it is convenient to optimize both controllers simultaneously as well as separately. The effectiveness of the proposed control strategy is validated through simulation.**

Keywords—Maglev System; PID; Maclaurin Series; Disturbance Estimator

I. Introduction

Magnetic levitation (maglev) systems have found wide applicability in various fields such as transportation (high speed maglev train), magnetic bearing system (contactless bearing), medical science (artificial heart pump), defense etc [1-8]. Magnetic levitation systems are nonlinear and unstable in nature. Designing a simple and efficient controller for a maglev system is a challenging task [9-31]. For stable and desired operation, various control strategies are reported in the literature. These controllers are generally applied either on the linearized model of magnetic levitation system or implemented in nonlinear environment [9-11]. In general, the Proportional Integral Derivative (PID) controller is the most common controller used in industrial applications and apart from this an extended version of PIDs, the Fractional Order Proportional Integral Derivative (FOPID) controller that provides more flexibility in design, has also been reported in [12-13]. The problem of disturbance and parameter uncertainty in conventional PID controllers has been tackled using expert knowledge based fuzzy PID control scheme [14]. The two degree freedom based PID control strategy using pole placement technique is discussed in [15] for the stabilization and improvement of the transient behavior of magnetic levitation systems.

Apart from this, many nonlinear control algorithms [16-18] are also reported for the said system. A feedback linearization based control technique and differential geometry based control strategy is implemented in [16] and [17] respectively. A nonlinear control algorithm is successfully applied on a maglev train system in [18]. The problem of disturbance and parameter uncertainty associated with maglev system has also been addressed through various nonlinear control schemes as discussed in [19-29]. The classical and Sliding Mode Control (SMC) scheme for maglev system is reported in [19-20]. SMC based integral variable structure grey control has been implemented on maglev system to avoid the chattering effect associated in the scheme [21]. In [22], an SMC based fuzzy controller is described for reducing the effects of parameter uncertainty and disturbance in maglev system and a Recurrent Elman Neural Network (RENN) estimator based robust dynamic sliding mode control has been used to estimate the nonlinear term [23-24]. The problem of uncertainty for maglev system has been stated in [25] where integral backstepping sliding mode control strategy is used and in [26-27] an adaptive backstepping algorithm has also been reported. The problem of noise associated with sensor output is tackled using robust output feedback technique in [28]. An H-infinity based control scheme is highlighted in [29-30]. An intelligent based adaptive PID fuzzy compensation technique is successfully implemented for the stabilization of a maglev system in [31].

These control methods have the ability to overwhelm the uncertainties and external disturbance in the system and improve the characteristics such as disturbance rejection and robustness to some extent. But all these methods are very complex in structure and tedious in adjusting the controller parameters. To overcome all these problems, an internal model control (IMC) scheme is found to be effective especially if system has some disturbance such as internal change in system parameters or external disturbances on system. IMC was initially proposed in [32]. The parameters of IMC are directly related to system performance and are used for adjusting characteristics like tracking, disturbance rejection and robustness in a completely independent way. Recently, a few publications [33-35] based on the IMC scheme have been reported for controlling magnetic levitation system. A feedback linearization based IMC technique is discussed in [33] and simulation based results are stated in [34] for controlling the speed of two mass maglev systems. A single degree of freedom IMC based PID control technique is applied in [35] for controlling the rotor of wind generator. The structure of IMC is very simple and easy to realize for stable systems but with the constraint that this scheme cannot be applied directly on unstable system due to the problem of internal instability [36]. Thus, some modification is needed for the control of unstable systems based on the two degrees of freedom IMC [37-40]. Smith predictor based 2-DOF control schemes are designed for unstable process for obtaining set-point response without overshoot [41-42]. But un-modeled dynamics uncertainty still raise problem in all existing 2-DOF control schemes and also failed online tuning of controller parameters in presence of process uncertainty.

In the proposed work, an analytical two degree of freedom control methodology based on [43-44] of analytical virtue is proposed for tackling the reference input tracking and load disturbance/process uncertainty for maglev systems. The proposed control strategy is a two-step design process. Firstly, a proportional derivative controller is introduced purposely to get the desired set-point response of the magnetic levitation system and then, for designing set-point tracking controller, an integral square error (ISE) performance specification is used. Secondly, a disturbance estimator is designed using the desired closed loop complimentary sensitivity function for the rejection of load disturbances.

II. Mathematical Modeling of Maglev Systems

The electrical equivalent circuit and schematic block diagram of a magnetic levitation system is shown in Figure 1(a) and Figure 1(b). This experimental setup is developed by feedback instrument Ltd [45].

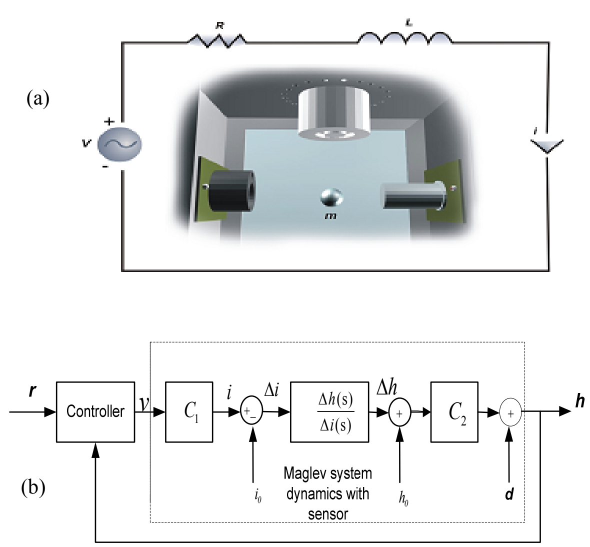

Fig. 1. (a) Electrical Circuit Model of Maglev System (b) Schematic Block Diagram of Maglev System.

TABLE I. PARAMETERS OF PHYSICAL MAGLEV SYSTEM [15, 45]

Description	Parameters	Value	Unit
mass of the steel ball	m	0.02	kg
Acceleration due to gravity	g	9.81	m/s^2
Equilibrium value of current	i_0	0.8	A
Equilibrium value of position	h_0	0.009	m
Control voltage to coil current gain	C_1	0.95-1.05	A/V
IR sensor gain	C_2	143.48	V/m
Offset		−2.8	V
Control input voltage level	v	-5 to 5	V
Sensor output voltage level	h_v	-3.75 to 1.25	V

The major components of maglev system are suspended steel ball, position Infra-Red (IR) sensors, actuator (including electro magnet and power amplifier). The steel ball is controlled through current i, as seen in Figure 1(a). The magnetic force acting on the steel ball depends on two parameters, firstly, the current i flowing in the coil and the second one is the distance h between coil and the steel ball. The non-linear model of magnetic levitation system [15, 45] which relates to the current i flowing in the coil and the position h of the steel ball is expressed as

$$\begin{aligned} m\ddot{h} &= mg - C\frac{i^2}{h^2} \\ &= mg - f(i,h) \end{aligned} \quad (1)$$

where $f(i,h) = \frac{Ci^2}{h^2}$, C is a constant value which depends on the parameters of coil, m is mass of the steel ball and g is acceleration due to gravity.

The magnetic levitation system expressed by (1) is nonlinear. For easy analysis and design of controller, the system is linearized about the equilibrium point ($i_0 = 0.8$ A & $h_0 = 0.009$ m). At the equilibrium point, the dynamical equation is taken as $\ddot{h} = 0$ and at this point the simplified expression is obtained as

$$C = \frac{mgh_0^2}{i_0^2} \quad (2)$$

The linearization is carried out with the following assumptions that position of ball is considered as $h = h_0 + \Delta h$ and current in the coil is taken as $i = i_0 + \Delta i$, where Δh is small deviation in position of ball with equilibrium position and Δi is the deviation in coil current from equilibrium current i_0.

By calculating the partial derivative of (1), the linearized model of maglev system is obtained as

$$\Delta\ddot{h} = \left(\left.\frac{\partial f(i,h)}{\partial i}\right|_{i_0,h_0} \Delta i + \left.\frac{\partial f(i,h)}{\partial i}\right|_{i_0,h_0} \Delta h \right) \quad (3)$$

Taking Laplace transform on both sides of (3), we get the transfer function as

$$\frac{\Delta h}{\Delta i} = \frac{-C_i}{s^2 - C_h} \tag{4}$$

where

$$\left.\begin{aligned} C_i &= \frac{2g}{i_0} \\ C_h &= \frac{2g}{h_0} \end{aligned}\right\} \tag{5}$$

In the electrical equivalent circuit of maglev system given in Figure 1(b), the current i flows in the coil and is proportional to the control voltage v, expressed as

$$i = C_1 v \tag{6}$$

Using (4) and (6), the transfer function of maglev system is obtained as

$$\frac{\Delta h}{\Delta v} = \frac{-C_1 C_i}{s^2 - C_h} \tag{7}$$

where Δv is small incremental control voltage around its mean value.

By considering C_2, the gain of IR sensor, (7) is written as

$$\frac{\Delta h_v}{\Delta v} = \frac{-C_1 C_2 C_i}{s^2 - C_h} \tag{8}$$

Using values of Table I in (8), the transfer function of the linearized model of magnetic levitation system (plant) can be expressed as

$$G_{\mathrm{P}}(s) = \frac{-3518.85}{s^2 - 2180} \tag{9}$$

Further, the generalized form of transfer function of $G_{\mathrm{P}}(s)$ is given by

$$G_{\mathrm{P}}(s) = \frac{k_1}{(\tau_1 s - 1)(\tau_2 s + 1)} \tag{10}$$

where $k_1 = -1.6142$ and $\tau_1 = \tau_2 = 0.0214$

The maglev system (10) has two poles at ± 46.69 and it could be seen that it is unstable as one of its pole lies in right half of complex s-plane. Hence, the main objective is to design a suitable controller that stabilizes this unstable magnetic levitation system.

III. PROPOSED CONTROL STRATEGY

The proposed 2-DOF control strategies consist of three major control components, stabilizing controller $G_{\mathrm{C}}(s)$, set-point tracking controller $C(s)$ and disturbance estimator F for magnetic levitation system as shown in Figure 2. In the above suggested control scheme as given in Figure 2, the G_{P} is the unstable maglev system and G_{m} is the minimum phase part of G_{P}. The two main controllers are $C(s)$, the set point controller which is responsible for set-point tracking and $G_{\mathrm{C}}(s)$, the stabilizing controller which ensures the closed loop stability of magnetic levitation system. The parameters of stabilizing controller and set-point tracking controller and their bounds are calculated using Routh's stability criterion. The disturbance estimator F [44] is designed using the desired closed loop complimentary sensitivity function for rejection of load disturbances. Maclaurin series expansion method is used for calculation of PID structure of disturbance estimator F.

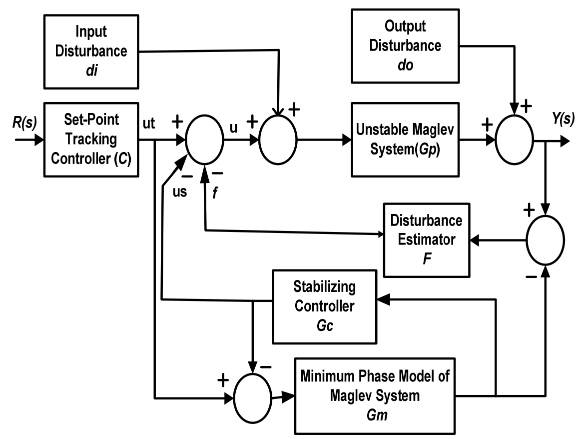

Fig. 2. Block diagram of 2-DOF control strategy

The design steps of all the three controllers $G_{\mathrm{C}}(s)$, $C(s)$ and $F(s)$ are described in Section III from *A* to *C*. The control efforts of $G_{\mathrm{C}}(s)$, $C(s)$ and F are specified as u_{s}, u_{t} and f respectively.

A. Stabilizing Controller

From Figure 2, using stabilizing controller (G_{C}) the minimum phase model (G_{m}) of maglev plant (G_{P}) is augmented as

$$G_{\mathrm{m}}^*(s) = \frac{G_{\mathrm{m}}(s)}{1 + G_{\mathrm{C}}(s) G_{\mathrm{m}}(s)} \tag{11}$$

The set-point transfer function of the overall system is obtained as

$$H(s) = \frac{C(s) G_{\mathrm{P}}(s)}{1 + G_{\mathrm{C}}(s) G_{\mathrm{m}}(s)} \cdot \frac{1 + F(s) G_{\mathrm{m}}(s)}{1 + F(s) G_{\mathrm{P}}(s)} \tag{12}$$

In special case when, $G_{\mathrm{m}}(s)$ is the perfect model of $G_{\mathrm{P}}(s)$ then the set-point transfer function is written as

$$H(s) = \frac{C(s) G_{\mathrm{P}}(s)}{1 + G_{\mathrm{C}}(s) G_{\mathrm{m}}(s)} \tag{13}$$

From (13), it is clear that, if uncertainty like dead time or any parametric variation is present in the magnetic levitation system, the set point transfer function will definitely achieve smooth set-point response. To avoid stability problem for the unstable magnetic levitation system (10), a proportional derivative (PD) form of stabilizing controller $G_C(s)$ is proposed and for simplicity it can be chosen as

$$G_C(s) = k_c + k_d s \tag{14}$$

Now, the characteristic equation of set-point transfer function (13) is written as

$$\tau_1\tau_2 s^2 + (k_d k_1 + \tau_1 - \tau_2)s + k_c k_1 - 1 = 0 \tag{15}$$

With the help of Routh's stability criterion, the tuning parameters of stabilizing controller $G_C(s)$ is computed as

$$\left.\begin{aligned} k_d &> (\tau_1 - \tau_2)/k_1 \\ k_c &> 1/k_1 \end{aligned}\right\} \tag{16}$$

For satisfying (16), when $k_1 = -1.6142$ (for maglev system (10)), the bounds on parameters of $G_C(s)$ are obtained as

$$\left.\begin{aligned} k_d &< 0 \\ k_c &< 0.62 \end{aligned}\right\} \tag{17}$$

From (17), an effective $G_C(s)$ can be chosen as

$$G_C(s) = -0.2s - 4 \tag{18a}$$

As $G_C(s)$ is not physically realizable, therefore a low pass filter is added, given by

$$J(s) = \frac{1}{(\lambda s + 1)} \tag{18b}$$

where λ is time constant and could be chosen between $(0.01 - 0.1)k_d$.

The final realizable form of $G_C(s)$ with low pass filter of time constant $\lambda = 0.01$, and is given as

$$G_C(s) = \frac{-0.2s - 4}{(0.01s + 1)} \tag{19}$$

B. Set-point Tracking Controller

The set-point tracking controller is designed with the help of ISE performance minimization. The main objective of proposed set-point of tracking controller $C(s)$ is to improve the system performance satisfying the criteria of norm bound as

$$\min \| W(s)(1 - H(s)) \|_2^2 \tag{20}$$

where W is the set-point weight function and could be taken as $1/s$ for the strict step change of the set point input and the load disturbance. The set-point tracking controller $C(s)$ is obtained analytically by substituting (10) and (13) into (20) as

$$\min \| W(s)(1 - H(s)) \|_2^2 = \left\| \frac{1}{s}(1 - \frac{k_1 C(s)}{\tau_1\tau_2 s^2 + (k_d k_1 + \tau_1 - \tau_2)s + k_c k_1 - 1} \right\|_2^2 \tag{21}$$

Using orthogonality property of H_2 norm, (21) is further simplified as

$$\min \| W(s)(1 - H(s)) \|_2^2 = \left\| \frac{1}{s} \right\|_2^2 + \left\| \frac{(\tau_1\tau_2 s^2 + (k_d k_1 + \tau_1 - \tau_2)s + k_c k_1 - 1) - k_1 C(s)}{s(\tau_1\tau_2 s^2 + (k_d k_1 + \tau_1 - \tau_2)s + k_c k_1 - 1)} \right\|_2^2 \tag{22}$$

The optimal set-point tracking controller $C(s)$ is obtained by minimizing the right hand side of (22). The simplified expression of $C(s)$ is obtained by considering the second term zero as

$$C(s) = \frac{\tau_1\tau_2 s^2 + (k_d k_1 + \tau_1 - \tau_2)s + k_c k_1 - 1}{k_1} \tag{23a}$$

Again, $C(s)$ given by (23a) is not proper and realizable in practice. Therefore, a second order low pass filter is added as

$$J_C(s) = \frac{1}{(\lambda_C s + 1)^2} \tag{23b}$$

where λ_C is time constant. The filter (23b) is added with (23a) for practically realizable form. The time constant of second order low pass filter can be chosen between $(0.01 - 0.1)k_d$. Hence, $C(s)$ can be written as

$$C(s) = \frac{\tau_1\tau_2 s^2 + (k_d k_1 + \tau_1 - \tau_2)s + k_c k_1 - 1}{k_1(\lambda_C s + 1)^2} \tag{24}$$

It can be seen from (19), $k_d = -0.2$ and $k_C = -4$ using (17), considering the same of values as in (19) and for $\lambda_C = 0.01$, the set-point tracking controller $C(s)$ for system (10) is obtained as

$$C(s) = -\left[\frac{4.579 \times 10^{-4} s^2 + 0.322s + 5.456}{1.6142 \times 10^{-4} s^2 + 0.0323s + 1.6142} \right] \tag{25}$$

C. Disturbance Estimator

The disturbance estimator is basically designed for improving the system performance when disturbance is encountered in the system in the form of internal parameter variation or external load disturbances. With the proposed disturbance estimator as shown in Figure 2, the load disturbance transfer functions are realized as

$$\left.\begin{aligned} H_{d_i} &= \frac{y_{d_i}}{d_i} = \frac{G_P(s)}{1 + F(s)G_P(s)} \\ H_{d_o} &= \frac{y_{d_o}}{d_0} = \frac{1}{1 + F(s)G_P(s)} \end{aligned}\right\} \tag{26}$$

The complementary sensitivity function of the closed loop between the system input and output for the load disturbance rejection is derived as

$$T_d = \frac{f}{d_i} = \frac{F(s)G_P(s)}{1 + F(s)G_P(s)} \tag{27}$$

The desired complementary sensitivity function should be equal to unity in an ideal case. The disturbance estimator $F(s)$ should detect the resultant system output whenever the input disturbance d_i enters into the system input and then it should obtain an inversely equivalent signal f to counteract it (Figure 2). However, the actual asymptotic tracking constraints are as follows

$$\lim_{s \to p_k} H_{d_o}(s) = 0,\ k = 1, 2, ..., m \tag{28}$$

$$\lim_{s \to 0} H_{d_o}(s) = 0 \tag{29}$$

where p_k is the process model right hand side pole (RHP) and m is the number of these RHP poles. To ensure the internal stability of closed loop system for the load disturbance rejection, the constraints (28) and (29) are required to be fulfilled. Hence based on the H_2 optimal performance objective of the IMC theory [36], the practically desired closed loop complementary sensitivity function is formulated as

$$T_d(s) = \frac{\sum_{k=1}^{m} a_k s^k + 1}{(\lambda_f s + 1)^{\ell + m}} \tag{30}$$

where λ_f is the adjustable parameter, ℓ is the relative degree of the maglev model, m is the number of RHP poles in the maglev model and a_k is calculated by the asymptotic constraints of (28)-(29).

Hence the desired disturbance estimator can be inversely calculated by (27), as

$$F(s) = \frac{T_d(s)}{1 - T_d(s)} . \frac{1}{G_P(s)} \tag{31}$$

For the system (10), closed loop complementary sensitivity function (30) for the load disturbance rejection is written as

$$T_d(s) = \frac{a_1 s + 1}{(\lambda_f s + 1)^3} \tag{32}$$

Now, substituting (10) and (32) in (31), the desired disturbance estimator is realized as

$$F(s) = \frac{(\tau_1 s - 1)(\tau_2 s + 1)(a_1 s + 1)}{k_1[(\lambda_f s + 1)^3 - (a_1 s + 1)]} \tag{33}$$

where

$$a_1 = \tau_1 \left(\left(\frac{\lambda_f}{\tau_1} + 1 \right)^3 - 1 \right) \tag{34}$$

However it is not difficult to find out that there exist a RHP zero-pole cancelling at $s = 1/\tau_1$ in (32), which tends the desired disturbance estimator to work unstably. The Maclaurin series expansion is used to calculate the disturbance estimator of (33).

Let,

$$F(s) = M(s)/s \tag{35}$$

Using the Maclaurin series expansion, we get

$$F(s) = \frac{1}{s}\left[M(0) + M'(0)s + \frac{M''(s)}{2!}s^2 + ... + \frac{M^{(k)}}{k!}s^k + ... \right] \tag{36}$$

On application of Maclaurin series expansion on (33), the first three terms can be used to constitute a standard PID controller structure as

$$F_{\text{PID}}(s) = \left(K_P + \frac{1}{T_I s} + T_D s \right) \tag{37}$$

where $K_P = M'(0), T_I = 1/M(0),\ T_D = M''(0)/2$

Remark**:** It should be noted that the pure derivative term in (37) can be physically realizable by cascading it with a first order low-pass filter whose time constant can be chosen between $(0.01 - 0.1)T_D$.

As for the design aspects of the disturbance estimator for magnetic levitation system (10), disturbance terms such as input disturbance $H_{d_i}(s) = \frac{1}{s}$ is applied at 3 second and output disturbance $H(s)_{d_o} = \frac{0.5}{s}$ is applied at t = 20 second.

Taking the above disturbances condition $H_{d_i}(s)$ and $H(s)_{d_o}$ on maglev system (10), the disturbance estimator (33) is obtained in PID structure whose parameters are obtained using (36) and (37) as

$$\left. \begin{aligned} M(0) &= -38.23 \\ M'(0) &= -2.47 \\ M''(0) &= -0.0307 \end{aligned} \right\} \tag{38}$$

For the practical realization of PID controller, a low pass filter whose time constant T_F is chosen between $(0.01\text{-}0.1)T_D$.

By incorporating the parameters of PID obtained in (38) and low pass filter with time constant $T_F = 0.005$ second, the disturbance estimator for maglev system (10) is calculated as

$$F(s) = -\left[\frac{0.0307s^2 + 2.47s + 38.23}{s(0.005s + 1)} \right] \tag{39}$$

The final control effort applied to maglev system (10) is sum of responses of all three control efforts u_s, u_t and f obtained for (19), (25) and (39) respectively and is expressed as

$$u = u_t - u_s - f \tag{40}$$

The detailed discussion of simulation results of proposed control strategy is presented below in Section IV.

IV. Simulation Results and Discussion

The simulation result is carried out for the unstable magnetic levitation system (10) and various results are plotted to show the effectiveness of proposed control strategy. Figure 3 gives the tracking response when system is associated with external disturbance. The external disturbances are given at 3 second and 20 second.

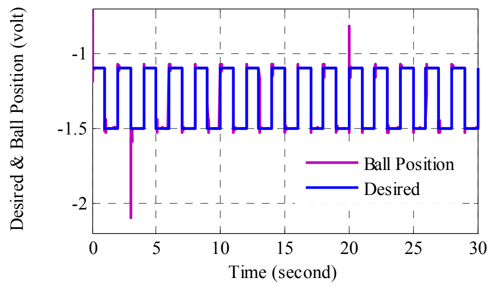

Fig. 3. Desired & Ball Position (with proposed)

From the simulation results shown in Figure 3, it is clear that the proposed control scheme could stabilize the maglev system (10) and track the desired reference trajectory (square wave). It is also seen that when the system is subjected to input and output disturbances at 3 second and 20 second, the designed controller forces the disturbed plant to track the desired reference input trajectory and eliminate the effect of disturbances.

The control parameters such as stabilizing controller $G_C(s)$, set-point tracking controller $C(s)$ disturbance estimator $F(s)$ and final control effort as u_s, u_t ,f and u respectively are plotted in Figure 4.

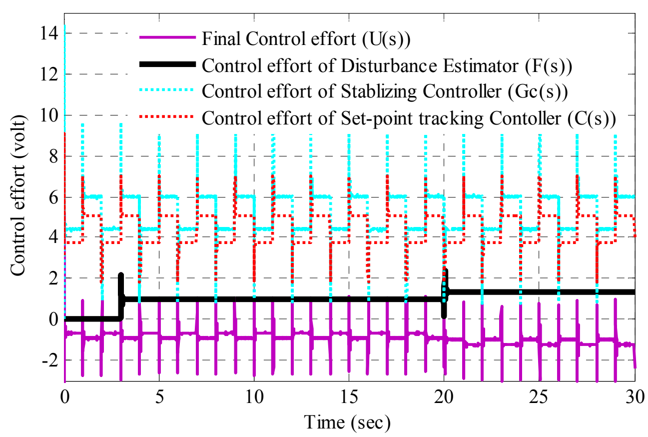

Fig. 4. Control efforts

From Figure 4, it is clearly noticed that the designed control scheme has ability to track the desired set-point input reference trajectory and remove the effect of external disturbances. The disturbance estimator works only when the system is subjected to external disturbances, as clearly seen at time 3 second and 20 second. The overall control effort is always maintained in a desirable voltage range (±5 volt) as necessary for stable operation.

To show the effectiveness of the proposed scheme, it has been compared with conventional PID control [45] and their comparative results are plotted in Figure 5 for similar condition as considered in Figure 3.

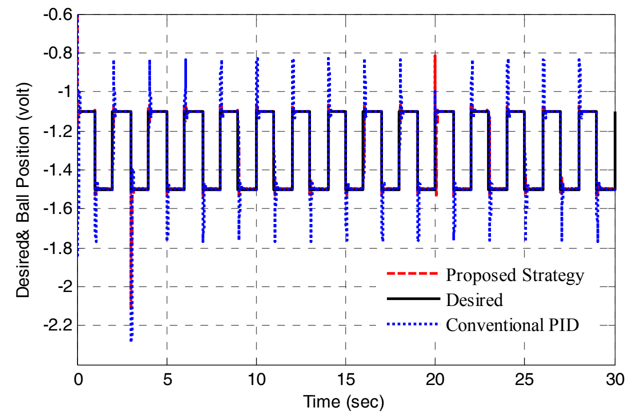

Fig. 5. Desired & Ball Position (Comparative)

Figure 5 depicts that the designed control strategy has better adaptability to avoid the effect of disturbance compared to conventional PID control. The conventional PID control has spikes and shows poor tracking for the set-point reference trajectory when the system is subjected to external disturbance/parameter uncertainty whereas the proposed two DOF control strategy stabilizes the maglev system and tracks the reference trajectory even if the system is subjected to external disturbance and also shows remarkable improvement in system performances (settling time and peak overshoot) over conventional PID control.

V. Conclusion

In this work a systematic DOF control scheme is presented to improve the reference input tracking and load disturbance rejection for an unstable magnetic levitation system. Here, both set-point tracking response and load disturbance response can be tuned separately using the proposed scheme. The stabilizing and tracking controller are applied in such a way that the unstable magnetic levitation system gets stabilized and at the same time the set-point tracking controller also forces the system to track the desired trajectory. The disturbance estimator is designed using the desired closed loop complimentary sensitivity function for rejection of load disturbances and it is realized in PID form using Maclaurin series expansion. The disturbance estimator comes into existence only when the system is subjected to internal/external disturbances. This technique leads to a remarkable improvement of regulatory capacity for reference input tracking as well as load disturbance rejection. The effectiveness of designed control strategy is shown by comparing it with conventional PID controller.

REFERENCES

[1] D. Rogg, "General survey of the possible applications and development tendencies of magnetic levitation technology", IEEE Transactions on Magnetics, Vol. 20, No. 5, pp. 1696–1701, 1984

[2] H. Yaghoubi, "The Most Important Maglev Applications", Journal of Engineering, Vol. 2013, Article ID 537986, 2013

[3] S. Yamamura, "Magnetic levitation technology of tracked vehicles present status and prospects", IEEE Trans. on Magnetics, Vol. 12, No. 6, pp. 874–878, 1976

[4] P. Sinha, "Design of a magnetically levitated vehicle", IEEE Trans. on Magnetics, Vol. 20, No. 5, pp. 1672–1674, 1984

[5] A. R. Eastham, W. F. Hayes, "Maglev systems development status", IEEE Aerospace and Electronic Systems Magazine, Vol. 3, No.1, pp. 21–30, 1988

[6] H. W. Lee, K. C. Kim, J. Lee, "Review of Maglev Train Technologies", IEEE Trans. on Magnetics, Vol. 42, No.7, pp. 1917-1925, 2006

[7] K. A. Mirica, S. T. Phillips, C. R. Mace, G. M. Whitesides, "Magnetic levitation in the analysis of foods and water", Journal of Agricultural and Food Chemistry, Vol. 58, No. 11, pp. 6565–6569, 2010

[8] K. X. Qian, P. Zeng, W. M. Ru, H. Y. Yuan, "New concepts and new design of permanent maglev rotary artificial heart blood pumps", Medical Engineering and Physics, Vol. 28, No. 4, pp. 383–388, 2006

[9] W. Barie, J. Chiasson, "Linear and Nonlinear State-space Controllers for Magnetic Levitation", International Journal of Systems Science, Vol. 27, No.11, pp. 1153-1163, 1996

[10] M. Ahsan , N. Masood, F. Wali, "Control of a Magnetic Levitation System Using Non-Linear Robust Design Tool", 3rd IEEE International Conference on Computer, Control & Communication (IC4), pp. 1-6, Karachi, Pakistan, September 25-26, 2013

[11] R. Song, Z. Chen, "Design of PID Controller for Maglev System Based on an Improved PSO with Mixed Inertia Weight", Journal of Networks, Vol. 9, No. 6, pp. 1509-1517, 2014

[12] C. I. Muresan, C. Ionescu, S. Folea, R. D. Keyser, "Fractional order control of unstable processes: the magnetic levitation study case", Nonlinear Dynamics, Vol. 80, No. 4, pp. 1761-1772, 2014

[13] A. Tepljakov, E. Petlenkov, J. Belikov, E. A. Gonzalez, "Design of Retuning Fractional PID Controllers for a Closed-loop Magnetic Levitation Control System", 13rd International Conference on Control, Automation, Robotics & Vision (ICARCV 2014), pp. 1345-1350, Marina Bay Sands, Singapore, December 10-12, 2014

[14] A. Sakalli, T. Kumbasar, E. Yesil, H. Hagras, "Analysis of the Performance of Type-1, Self-tuning Type-1 and Interval Type-2 fuzzy PID Controller on the Magnetic Levitation System", IEEE Internatinal Conference on Fuzzy System (FUZZ-IEEE), pp. 1859-1866, Beijing, China, July 6-11, 2014

[15] A. Ghosh, T. R. Krishnan, P. Tejaswy, A. Mandal, J. K. Pradhan, S. Ranasingh, "Design and implementation of a 2-DOF PID compensation for magnetic levitation systems", ISA Transactions, Vol. 53, No. 4, pp. 1216–1222, 2014

[16] M. Golob, B. Tovornik, "Modeling and control of the magnetic suspension system", ISA Transactions, Vol. 42, No. 1, pp. 89-100, 2003

[17] R. Uswarman, A. I. Cahyadi, O. Wahyunggoro, "Control of a Magnetic Levitation System Using Feedback Linearization", IEEE International Conference on Computer, Control, Informatics and Its Applications (IC3INA), pp. 95-98, Jakarta, November 19-21, 2013

[18] A. E. Hajjaji, M. Ouladsine, "Modeling and Nonlinear Control of Magnetic Levitation Systems", IEEE Transactions on Industrial Electronics, Vol. 48, No. 4, pp. 831-838, 2001

[19] D. Cho, Y. Kato, D. Spilman, "Sliding mode and classical controllers in magnetic levitation systems", IEEE Control Systems, Vol. 13, No. 1, pp. 42-48, 1993

[20] N. F. AL-Muthairi, M. Zribi, "Sliding Mode Control of a Magnetic Levitation System", Mathematical Problems in Engineering, Vol. 2004, No. 2, pp. 93–107, 2004

[21] H. K. Chiang, C. A. Chen, M. Y. Li, "Integral variable-structure grey control for magnetic levitation system", Electric Power Applications, Vol. 153, No. 6, pp. 809-814, 2006

[22] C. A. Chen, H. K. Chiang, J. C. Shen, "Fuzzy Sliding Mode Control of Magnetic Ball Suspension System", International Journal of Fuzzy System, Vol. 11, No. 2, pp. 97-106, 2009

[23] F. J. Lin, S. Y. Chen, K. K. Shyu, "Robust Dynamic Sliding-Mode Control Using Adaptive RENN for Magnetic Levitation System", IEEE Transactions on Neural Networks, Vol. 20, No. 6, pp. 938–951, 2009

[24] F. J. Lin, H. J. Shieh, L.T. Teng, P. H. Shieh, "Hybrid Controller With Recurrent Neural Network for Magnetic Levitation System", IEEE Transactions on Magnetics, Vol. 41, No. 7, pp. 2260-2269, 2005

[25] H. K. Chiang, W. T. Tseng, C. C. Fang, C. A. Chen, "Integral backstepping sliding mode control of a magnetic ball suspension system", 10th IEEE International Conference on Power Electronics and Drive Systems (PEDS), pp. 44– 49, Kitakyushu, April 22-25, 2013

[26] W. Zhou, B. Liu, "Backstepping Based Adaptive Control of Magnetic Levitation System", Proceedings of the 2nd International Conference On Systems Engineering and Modeling (ICSEM-13), pp. 435-438, Paris, France, 201

[27] F. J. Lin, L. T. Teng, P. H. Shieh, "Intelligent Adaptive Backstepping Control System for Magnetic Levitation Apparatus", IEEE Transactions on Magnetics, Vol. 43, No. 5, pp. 2009-2018, 2007

[28] Z. J. Yang, K. Kunitoshi, S. Kanae, K. Wada, "Adaptive Robust Output-Feedback Control of a Magnetic Levitation System by K-Filter Approach", IEEE Transactions on Industrial Electronics, Vol. 55, No. 1, pp. 390–399, 2008

[29] J. C. Shen, "H∞ Control and Sliding Mode Control of Magnetic levitation System", Asian Journal of Control, Vol. 4, No. 3, pp. 333-340, 2002

[30] T. Saravanan, G. Saritha, R. Udayakumar, "Robust H- Infinity Two Degree of Freedom Control for Electro Magnetic Suspension System", Middle-East Journal of Scientific Research, Vol. 18, No.12, pp. 1827-1831, 2013

[31] C. M. Lin, Chih-Min Lin, C. W. Chen, "SoPC-based adaptive PID control system design for magnetic levitation system", IEEE Systems Journal, Vol. 5, No. 2, pp. 278-287, 2011

[32] C. E. Garcia, M. Morari, "Internal model control: A unifying review and some new results", Industrial & Engineering Chemistry Process Design and Development, Vol. 21, No. 2, pp. 308-323, 1982

[33] D. S. Liu, J. Li, W. S. Chang, "Internal Model Control for Magnetic Suspension System", Proceedings of the International Conference on Machine Learning and Cybernetics, pp. 482-487, Guangzhou,China, August 18-21, 2005

[34] A. Detchrat, V. Tipsuwanporn, A. Numsomran, S. Suvikath, "IMC-Based PID Controllers Designs for Two-mass systems", Proceeding of Multi-Conference of Engineers and Computer Scientists (IMECS), pp.1-4, Hong Kong, March 14-16, 2012

[35] Z. Zhongqiao, W. Xiaojing, Z. Yanhong, X. Liang, C. Yanglin, "The Research on IMC-PID Control in Maglev Supporting System", The Open Automation and Control Systems Journal, Vol. 6, No. 1, pp. 797-802, 2014

[36] M. Morari, E. Zafiriou, Robust Process Control, Englewood Cliffs, NJ, Prentice Hall, 1989

[37] H. P. Huang, C. C. Chen, "Control System synthesis for open-loop unstable process with time delay", IEE Proc. Part D, Vol. 144, No. 4, pp. 334-346, 1997

[38] Y. Lee, J. Lee, S. Park, "PID controller tuning for integrating and unstable processes with time delay", Chemical Engineering Science, Vol. 55, No. 17, pp. 3481-3493, 2000

[39] X. P. Yang, Q. G. Wang, C. C. Hang, C. Lin, "IMC-based control system design for unstable processes", Ind. Chem. Res., Vol. 41, No. 17, pp. 4288-4294, 2002

[40] W. Tan, H. J. Marquez, T. Chen, "IMC design for unstable processes with time delay", J. Process Control, Vol. 13, No. 1, pp. 203-213, 2003

[41] H. J. Kwak, S. W. Sung, I. B. Lee, J. Y. Park, "Modified Smith predictor with a new structure for unstable processes", Ind. Eng. Chem. Res., Vol. 38, No. 2, pp. 405-411, 1999

[42] S. Majhi, D. P. Atherton, "Obtaining controller Parameters for a new Smith predictor using autotuning", Automatica, Vol. 36, No.1, pp. 1651-1658, 2000

[43] W. D. Zhang, D. Gu, W. Wang, X. Xu, "Quantitative performance design of a modified Smith Predictor for unstable processes with time delay", Ind. Eng. Chem. Res., Vol. 43, No. 1, pp. 56-62, 2004

[44] T. Liu, W. Zhang, D. Gu, "Analytical design of two-degree-of-freedom control scheme for open-loop unstable processes with time delay", Journal of Process Control, Vol. 15 No. 5, pp. 559-572, 2005

[45] Feedback Expermental Manual, Magnetic Levitation Control Experiments, Feedback Instruments Limited, UK, 2011