Comparison of a Nonlinear Magnetic Levitation Train Parameters using Mixed H 2/H∞ and Model Reference Controllers

Mustefa Jibril, Mesay Tadese and Nuriye Hassen
School of Electrical and Computer Engineering, Dire Dawa Institute of Technology, Dire Dawa, Ethiopia

KEY WORDS
Maglev train
Mixed H 2/H∞ with regional pole placement
Model reference

Abstract: To improve the riding performance and levitation stability of a high-speed magnetic levitation (maglev) train, a control strategy based on mixed H 2/H∞ with regional pole placement and model-reference controllers are proposed. First, the nonlinear maglev train model is established, then the proposed system is designed to observe the movement of a suspension frame and a control strategy based on mixed H 2/H∞ with regional pole placement and model-reference control method are proposed. Test and analysis of the proposed system has been done using MATLAB toolbox for train levitation height, velocity and current consume. Comparative simulation results show that the mixed H 2/H∞ with regional pole placement control strategy has a better performance under the condition of step and random train levitation height.

Corresponding Author:
Mustefa Jibril
School of Electrical and Computer Engineering, Dire Dawa Institute of Technology, Dire Dawa, Ethiopia

INTRODUCTION

Maglev (derived from magnetic levitation) is a gadget of educate transportation that makes use of units of magnets: one set to repel and push the educate up off the track and some other set to transport the expanded educate ahead, taking benefit of the shortage of friction. Along certain "medium-range" routes (commonly 320-640 km [200 to 400 mi]), maglev can compete favorably with high-velocity rail and airplanes.

With maglev era, there's simply one shifting part: the educate itself. The educate travels alongside a guideway of magnets which manipulate the trains balance and velocity. Propulsion and levitation require no shifting components. This is in stark comparison to electric powered a couple of units that could have numerous dozen components in step with bogie. Maglev trains are consequently quieter and smoother than traditional trains and feature the ability for tons better speeds[1].

Maglev cars have set numerous velocity records and maglev trains can boost up and slow down tons quicker than traditional trains; the handiest sensible difficulty is the protection and luxury of the passengers. The energy wished for levitation is usually now no longer a big percent of the general strength intake of a high-velocity maglev gadget[2]. Overcoming drag, which makes all land shipping greater strength intensive at better speeds, takes the maximum strength. Vactrain era has been proposed as a way to conquer this difficulty. Maglev structures had been tons greater pricey to assemble than traditional educate structures, despite the fact that the less complicated production of maglev cars makes them inexpensive to fabricate and maintain. The Shanghai maglev educate, additionally called the Shanghai Transrapid has a pinnacle velocity of 430 km h^{-1} (270 mph). The line is the quickest operational high-velocity maglev educate, designed to connect Shanghai Pudong International Airport and the outskirts of central Pudong, Shanghai. It covers a distance of 30.5 km (19 mi) in only over 8 minutes. For the primary time, the release generated huge public hobby and media attention, propelling the recognition of the mode of transportation[3]. Despite over a century of studies and development, maglev shipping structures at the moment are operational in only 3 countries (Japan, South Korea and China). [quotation wished] The incremental blessings of maglev era have regularly been taken into consideration tough to justify towards fee and risk, specially wherein there's an present or proposed traditional high-velocity educate line with spare passenger wearing capacity as in high-velocity rail in Europe, the High Speed 2 with inside the UK and Shinkansen in Japan[4].

MATERIALS AND METHODS

Mathematical models

Nonlinear modelling of EDS maglev train: In order to develop the nonlinear modelling of EDS maglev train, we need to develop the mathematical modelling of the electromagnetic and mechanical subsystems separately[5].

Figure 1 shows a single axis magnetic levitation system is used, as well as electromagnetic and mechanical equations. Apply Kirchhoff's voltage equation for the electric circuit:

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

where u, I, R and L is applied voltage input, current in the electromagnet coil, coil's resistance and coil's inductance, respectively. Energy stored in the inductor can be written as:

$$W_{IStored} = \frac{1}{2}Li^2 \quad (2)$$

Since, power in electrical system (P_e) = Power in the mechanical system (P_m). Where:

$$P_e = \frac{dW_{IStored}}{dt}$$

and:

$$P_m = -f_m \frac{dx}{dt}$$

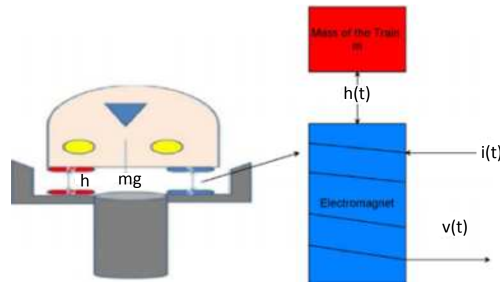

Fig. 1(a, b): (a) EDS Model and (b) Single axis magnetic suspension system

therefore:

$$f_m = -\frac{dW_{IStore}}{dt}\frac{dt}{dx} = -\frac{dW_{IStore}}{dx} \quad (3)$$

where, f_m is known as electromagnet force now substituting (Eq. 2) in Eq. 3:

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

Since, the inductance L is a nonlinear function of train position (x), we shall neglect the leakage flux and eddy current effects (for simplicity), so that, the inductance varies with the inverse of train position as follows:

$$L = \frac{K}{x} \quad \text{Where in } K = \frac{\mu_0 N^2 A}{2} \quad (5)$$

Where:

μ_0 = The inductance constant
A = The pole area
N = The number of coil turns
k = Electromagnet force constant

$$\left.\begin{aligned} f_m &= -\frac{1}{2}i^2\frac{d}{dx}\left(\frac{k}{x}\right) \\ &= -\frac{1}{2}i^2\left(-\frac{k}{x^2}\right) \\ \therefore f_m &= \frac{K}{2}\left(\frac{i^2}{x^2}\right) \end{aligned}\right\} \quad (6)$$

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 train, the equation of force can be written as:

$$\left.\begin{aligned} f_g &= f_m + f \\ &= f_m + m\left(\frac{d^2x}{dt^2}\right) \\ \Rightarrow m\frac{dv}{dt} &= f_g - f_m = mg - \frac{K}{2}\left(\frac{i(t)}{x(t)}\right)^2 \end{aligned}\right\} \tag{7}$$

where, m = train mass and v = dx/dt = dh/dt which is velocity of the train movement. At equilibrium the force due to gravity and the magnetic force are equal and oppose each other so that the train levitates. i.e., $f_g = -f_m$ and f = 0. On the basis of electro-mechanical modeling, the nonlinear model of magnetic levitation system can be described as follows: the general form of an affine system[6, 7]:

$$\frac{dx}{dt} = f(x) + g(x).u \tag{8}$$

Is obtained by denoting variables for state space representation as follows:

$$\left.\begin{aligned} x_1 &= h = x \\ x_2 &= \frac{dh}{dt} = v \\ x_3 &= i \end{aligned}\right\} \tag{9}$$

Substitute Eq. 9 or the state variables in to Eq. 1 and 7:

$$\left.\begin{aligned} u(t) &= x_3.R + L.\dot{x}_3 \\ m.\dot{x}_2 &= m.g - \frac{K}{2}\left(\frac{x_3}{x_1}\right)^2 \end{aligned}\right\} \tag{10}$$

Then the nonlinear state space model is:

$$\left.\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= \left(g - \frac{K}{2m}\right)\left(\frac{x_3}{x_1}\right)^2 \\ \dot{x}_3 &= \frac{u}{L} - x_3.\frac{R}{L} \end{aligned}\right\} \tag{11}$$

Nonlinear model in matrix form is given by Table 1:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{pmatrix} = \begin{pmatrix} x_2 \\ \left(g - \frac{K}{2m}\right)\left(\frac{x_3}{x_1}\right)^2 \\ -\frac{R}{L}.x_3 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{L} \end{pmatrix} u \tag{12}$$

Table 1: Physical parameters of EMS maglev train

Parameters	Values
M	15,500 (kg)
R	50 (Ω)
L	1 (H)
i_0	200 (A)
x_0	26 (mm)
k	0.01 (Nm^2/A^2)
g	9.8 (m sec^{-2})

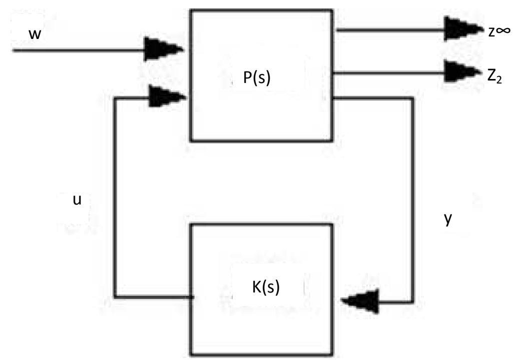

Fig. 2: Mixed H 2/H∞ configuration

Proposed controllers design

Mixed H 2/H∞ with regional pole placement controller: The mixed H 2/H∞ control problem is to minimize the H 2 norm of overall state feedback gains k such that what also satisfies the H8 norm constraint. Mixed H 2/H∞ synthesis with regional pole placement is one example of multi-objective design addressed by the LMI. The control problem is sketched in Fig. 2. The output channel z is associated with the H∞ performance while the channel z_2 is associated with the H 2 performance[8].

The LMI regions for the pole placement are found using the command lmireg and we select the half plane region and the output region is:

$$2.0000 + 1.0000i \text{ and } 1.0000 + 0.0000i$$

And, we use this region for the mixed H 2/H∞ controller synthesis.

Model-reference controller design: The designing of neural model reference control uses two neural networks:

- A Neural network controller
- A neural network controller for the plant model (Fig. 3)

There are three sets of controller inputs:

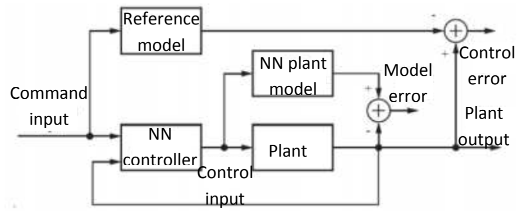

Fig. 3: Block diagram of the model reference controller

Table 2: Neural network architecture

Network architecture	Values	Parameters	Values
Size of hidden layer	6	Delayed plant input	2
Sample interval(sec)	1	Delayed plant output	3
Training data			
Training sample	100	Maximum Plant output	3
Maximum plant input	1	Minimum Plant output	1
Minimum plant input	1	Max interval value (sec)	3
Min interval value (sec)			1.5
Training parameters			
Training epochs			100

- Delayed reference inputs
- Delayed controller outputs
- Delayed plant outputs

The neural network architecture, training data and training parameters for model reference and predictive controllers are shown in Table 2[9].

RESULTS AND DISCUSSION

Here in this study the comparison of the performance of the maglev train with mixed H 2/H∞ with regional pole placement controller and model-reference controller is done for the train levitation height, velocity and current consume using step and random reference levitation height.

Comparison of the maglev train with Mixed H 2/H∞ with regional pole placement controller and model-reference controller for a step reference input: The simulation result of the maglev train with Mixed H 2/H∞ with regional pole placement controller and model-reference controller levitation height, velocity and current consume for a step input are shown in Fig. 4-6, respectively.

Train levitation height response simulation shows that the maglev train with mixed H 2/H∞ with regional pole placement controller has small rising time with less percentage overshoot and better settling time than the maglev train with model-reference controller[10].

Train levitation velocity response simulation shows that the maglev train with mixed H 2/H∞ with regional pole placement controller has minimum velocity as compared to the maglev train with model-reference controller. The maglev train current consumption response simulation shows that the maglev train with mixed H 2/H∞ with regional pole placement controller has small rising time with the same percentage overshoot and better settling time than the maglev train with model-reference controller[11].

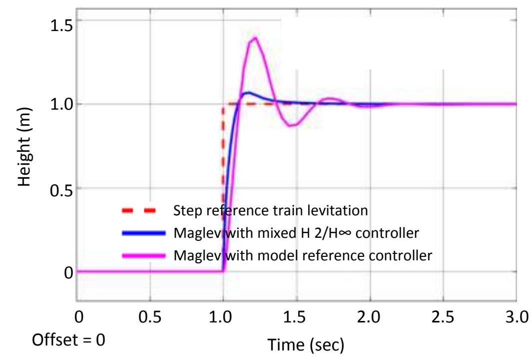

Fig. 4: Step response of train levitation height

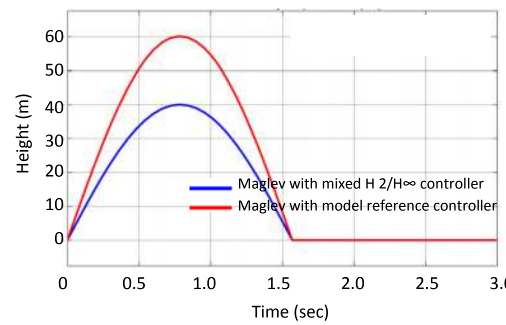

Fig. 5: Step response of train levitation velocity

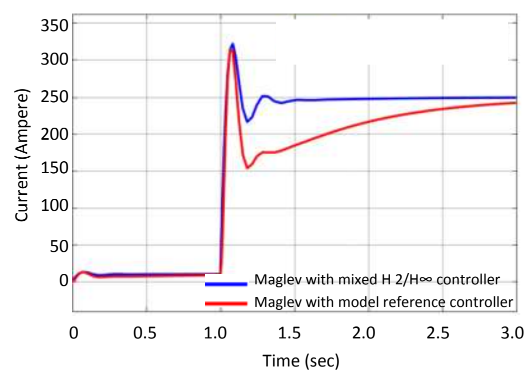

Fig. 6: Step response of maglev train current consume

Comparison of the maglev train with mixed H 2/H∞ with regional pole placement controller and model-reference controller for a random reference input: The simulation result of the maglev train with mixed H 2/H∞ with

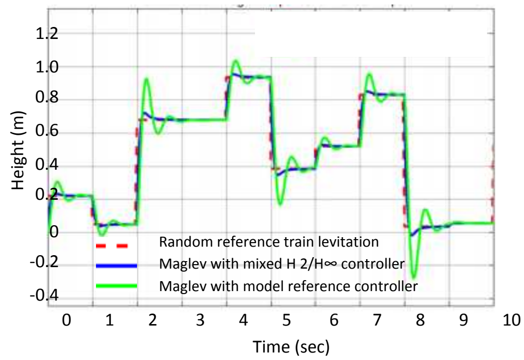

Fig. 7: Random response of train levitation height

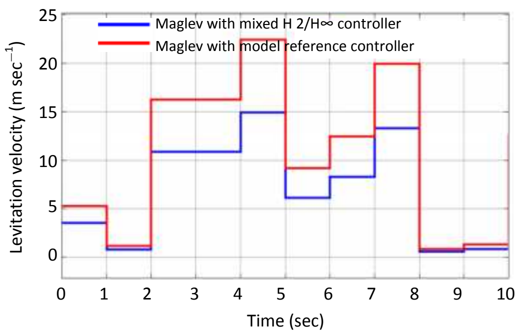

Fig. 8: Random response of train levitation velocity

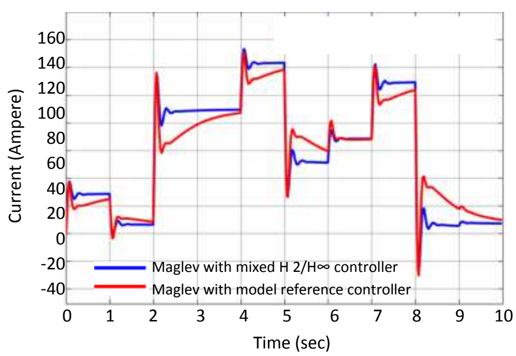

Fig. 9: Random response of maglev train current consume

regional pole placement controller and model-reference controller levitation height, velocity and current consume for a random input are shown in Fig. 7-9, respectively.

Train levitation height response simulation shows that the maglev train with mixed H 2/H∞ with Regional Pole Placement Controller has a small different in rising time with less percentage overshoot and improved settling time than the maglev train with model-reference controller[12].

Train levitation velocity response simulation shows that the maglev train with mixed H 2/H∞ with Regional pole placement controller has a smaller velocity as compared to the maglev train with model-reference controller. The maglev train current consumption response simulation shows that the maglev train with mixed H 2 /H∞ with regional pole placement controller has the same rising time with smaller percentage overshoot and better settling time than the maglev train with model-reference controller[13].

CONCLUSION

In this study, a mixed H 2/H∞ with regional pole placement and model reference levitation control approach was developed to deal with levitation height control. The mathematical model of the magnetic-levitation train systems was constructed. The proposed controllers could improve robustness against train levitation height by utilizing the Robust control method and Neural network-based technology. The system with the proposed controllers has been tested using MATLAB toolbox for train levitation height, velocity and current consume. Comparative simulation results show that the maglev train with mixed H 2/H∞ with regional pole placement controller has a better performance under the test of step and random train levitation height than the maglev train with model reference controller[14].

REFERENCES

01. Chen, C., J. Xu, W. Ji, L. Rong and G. Lin, 2019. Sliding mode robust adaptive control of maglev vehicle's nonlinear suspension system based on flexible track: Design and experiment. IEEE Access, 7: 41874-41884.
02. Sun, Y., J. Xu, H. Qiang, C. Chen and G. Lin, 2019. Adaptive sliding mode control of maglev system based on RBF neural network minimum parameter learning method. Measurement, 141: 217-226.
03. Humaidi, A.J., H.M. Badr and A.H. Hameed, 2018. PSO-based active disturbance rejection control for position control of magnetic levitation system. Proceedings of the 2018 5th International Conference on Control, Decision and Information Technologies (CoDIT), April 10-13, 2018, IEEE, Thessaloniki, Greece, pp: 922-928.
04. Khimani, D., S. Karnik and M. Patil, 2018. Implementation of high performance nonlinear feedback control on magnetic levitation system. IFAC-PapersOnLine, 51: 13-18.
05. Oh, S.Y. and H.L. Choi, 2018. Robust approximate feedback linearisation control for nonlinear systems with uncertain parameters and external disturbance: Its application to an electromagnetic levitation system. Int. J. Syst. Sci., 49: 2695-2703.

06. Wang, Z., Z. Long and X. Li, 2018. Levitation control of permanent magnet electromagnetic hybrid suspension maglev train. Proc. Inst. Mech. Eng. Part I. J. Syst. Control Eng., 232: 315-323.
07. Adiguzel, F., E. Dokumacilar, O. Akbati and T. Turker, 2018. Design and implementation of an adaptive backstepping controller for a magnetic levitation system. Trans. Inst. Meas. Control, 40: 2466-2475.
08. Bidikli, B. and A. Bayrak, 2018. A self-tuning robust full-state feedback control design for the magnetic levitation system. Control Eng. Pract., 78: 175-185.
09. Sadek, U., A. Sarjas, A. Chowdhury and R. Svecko, 2017. Improved adaptive fuzzy backstepping control of a magnetic levitation system based on symbiotic organism search. Appl. Soft Comput., 56: 19-33.
10. Al-Araji, A.S., 2016. Cognitive non-linear controller design for magnetic levitation system. Trans. Inst. Meas. Control, 38: 215-222.
11. Eroglu, Y. and G. Ablay, 2016. Cascade sliding mode-based robust tracking control of a magnetic levitation system. Proc. Inst. Mech. Eng. Part I. J. Syst. Control Eng., 230: 851-860.
12. Ginoya, D., C.M. Gutte, P.D. Shendge and S.B. Phadke, 2016. State-and-disturbance-observer-based sliding mode control of magnetic levitation systems. Trans. Inst. Meas. Control, 38: 751-763.
13. Liu, Z., Z. Long and X. Li, 2015. Maglev Train Overview. In: Maglev Trains, Liu, Z., Z. Long and X. Li (Eds.)., Springer, Berlin, Germany, pp: 1-28.
14. Safaei, F., A.A. Suratgar, A. Afshar and M. Mirsalim, 2015. Characteristics optimization of the maglev train hybrid suspension system using genetic algorithm. IEEE Trans. Energy Conversion, 30: 1163-1170.