Development of a Control Platform for the Magnetic Suspension System

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Abstract

A highly integrated open control platform for control algorithms development of magnetic suspension system is proposed based on MATLAB/Simulink, dSPACE and DSP. The schema and work principle of the control platform are presented. A robust $H\infty$ controller as an example for the system is designed in detail to verify the control platform. Experimental results show that the control platform is successfully set up for carrying out research of complex control algorithms and education of control theory.

1 Introduction

Magnetic suspension system is an intrinsically unstable nonlinear system and has to require automatic control[1,2,3,4].Therefore, there is no doubt that it is an important issue today, and even more so in the future, to design and development of various control algorithms for magnetic suspension system.

A highly-integrated open control platform for control algorithms development of the magnetic suspension system is proposed based on MATLAB/Simulink, dSPACE and DSP, which consists of off-line simulation, hardware-in-the-loop simulation and real-time control. Where the off-line simulation is realized based on MATLAB/Simulink [5,6,7].The hardware-in-the-loop simulation is realized based on dSPACE[8,9,10]. And the real-time control is realized based on DSP [11,12]. The control platform can be realized to accelerate the verification of the correction and effectiveness of the control algorithms, and laboratory experiments in education of control theory and directly to provide the practical digital controller for industrial applications.

Research emphasis in this paper is the design and application of the control platform for magnetic suspension system. The schema and work principle of the control platform are presented. A robust controller as an example for the system is developed to verify the control platform. Experimental results show that the control platform is successfully set up for carrying out research of complex control algorithms and education of control theory.

2 Schema of Control Platform of Magnetic Suspension System

2.1 Magnetic Suspension System

A lab-scale single degree of freedom magnetic suspension plant has been developed to use as a test bed for mechatronic sensing and control experimentation as shown in Figure 1. The mechanical structure is designed to support the installation of position sensor, electromagnet, adjustable bracket and fans, where the adjustable bracket is used to support the controlled object steel ball for achieving a self-starting position. By finite element method(FEM), the electromagnetic field analysis and structure optimization of the electromagnet are carried out. The designed electromagnet is made of a 2024-turn coil of 0.8 mm wire wound around a steel cylinder of 17mm diameter and 73.6mm length as shown in Figure 2.

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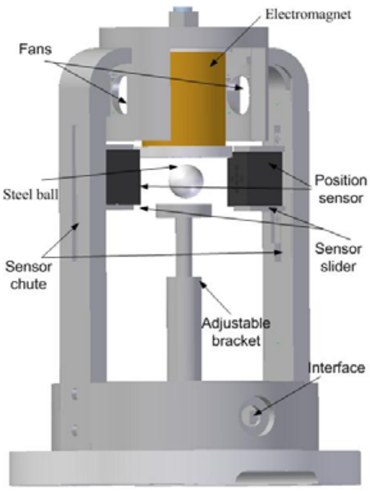


Figure 1: Lab-scale single DOF magnetic suspension plant

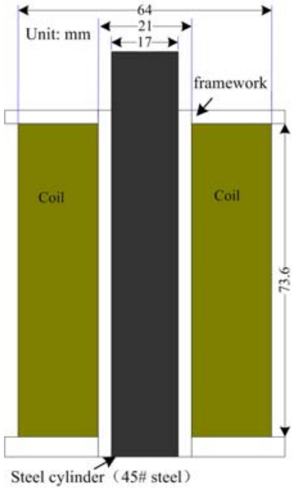


Figure 2: The Structure of the electromagnet

The design of the suspension plant presented here uses the electromagnetic attraction force. The modeling of the magnetic suspension plant is based on its electrical, mechanical, and electromechanical equations. The following transfer function model is obtained.

$$G(s)=\frac{U_o(s)}{I_c(s)}=\frac{-k_i k_a}{ms^2+k_x}=\frac{-388.2426}{0.046s^2-43.9787} \tag{1}$$

where I_c is the current of electromagnet as input of the system， U_o is the output voltage of the position sensor, m is the mass of the controlled object, k_i is current stiffness (*N/A*), k_x is displacement stiffness (*N/m*), and k_a is the sensor gain.

The parameters of the magnetic suspension system are shown in Table 1.

Parameters	Symbol	Value	Unit
Mass of the steel ball	m	46×10^{-3}	kg
Radius of the steel ball	r_2	12.5×10^{-3}	*m*
Coil inductance	L	101.8	*mH*
Coil resistance	R	9.6	*Ω*
Coil turn	N	2024	/
Radius of core	r_1	8.5	*mm*
Sectional area of core	A	226.9801×10^{-6}	m^2
Ball position at operating point	x_0	20.5	*mm*
Coil current at operating point	I_0	0.8053	*A*
Current stiffness at operating point	K_i	0.7742	*N*/*A*
Position stiffness at operating point	K_x	-21.032	*N*/*m*
Position sensor gain	K_s	346.8	*V*/*m*
Power amplifier gain	K_a	1	*A*/*V*

Table 1: The parameters of the magnetic suspension system

2.2 Schema of Control Platform

The flexibility, quality, functionality, and development time are crucial factors for the control platform. At present, hardware-in-the-loop (HIL) simulation is a methodology tool that is gaining increasing importance for testing a controller's functionality and communication. MATLAB/Simulink provides many design and analysis facilities for controller design such as control system, robust control, µ-synthesis, and optimization tool boxes. In general, after a controller has been designed by MATLAB/Simulink, the final step is to implement it in real time and see whether or not it really performs. Digital signal processors (DSP) made by TI are commonly used to complete real time control. If the real time control performance meets the control requirements, then the actual controller is obtained.

Considering the above reasons, a high-integrated open control platform of magnetic suspension system is proposed based on MATLAB/Simulink, dSPACE and DSP. The schema of the proposed control platform is shown in Figure 3, which is composed of one controller (dSPACE/DSP), one position sensitive device (PSD), one electromagnet, one power amplifier, one current sensor, a PC with human-machine interface and software of MATLAB/Simulink, Control Desk and Code Composer Studio. DSP/dSPACE completes data acquisition and processing, control algorithm implementation, and communication with PC. The dSPACE with Control Desk is to realize HLP and DSP with Code Composer Studio is used to realize real time control. The system modeling and simulation are carried out in MATLAB/Simulink. PSD is used to measure the position of the controlled object. A Hall Effect sensor is used to measure the coil current. The power amplifier working with Pulse Width Modulation (PWM) is used to control the coil current based on symmetric half bridge in the main circuit of magnetic suspension system. Serial Communication Interface (SCI) is used to realize communication between DSP and PC. Human Machine Interface (HMI) based on Microsoft Foundation Class (MFC) is designed to help researchers monitor the operation information and it is convenient for verifying the controller parameters and realizing on-line modification.

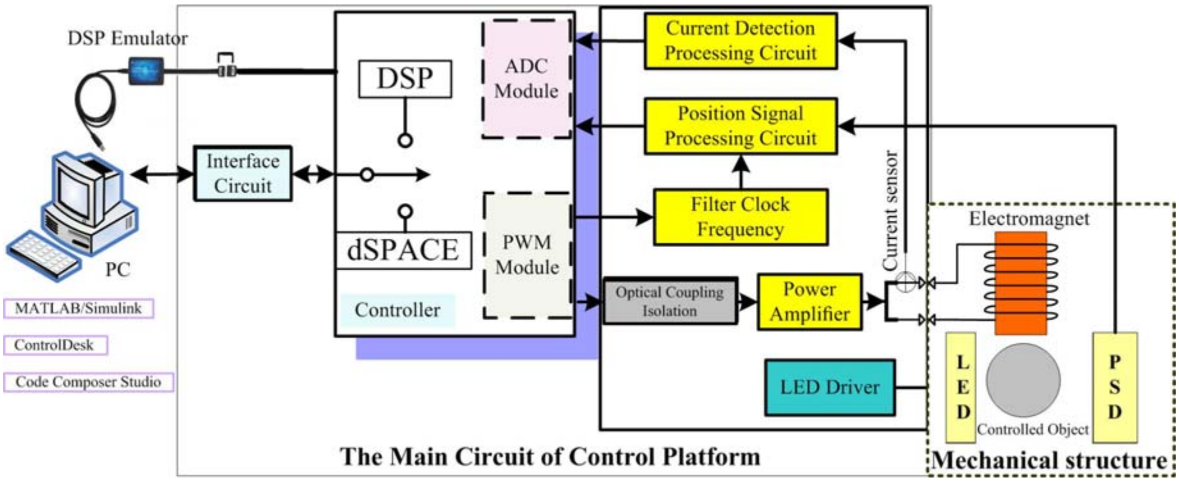


Figure 3: The schema of the control platform of magnetic suspension system

2.3 Gains and Ranges of the sensors

The gain and range of the position sensors are obtained as follows. The position sensor characteristic curve $U_z \times z$ with U_z the output voltage of the sensor is found and then a linear region is chosen, yielding the intervals $[U_{z\min}, U_{z\max}]$ and $[z_{\min}, z_{\max}]$ as seen in Figure 4. Finally, the position sensor gain can be obtained as $K_p = \dfrac{U_{z\max} - U_{z\min}}{z_{\max} - z_{\min}}$.

In general, the Hall Effect current sensor is approximately linear as seen in Figure 5. Thus, the sensor gain K_i can be calculated by the ratio of the output voltage variation to the input current variation.

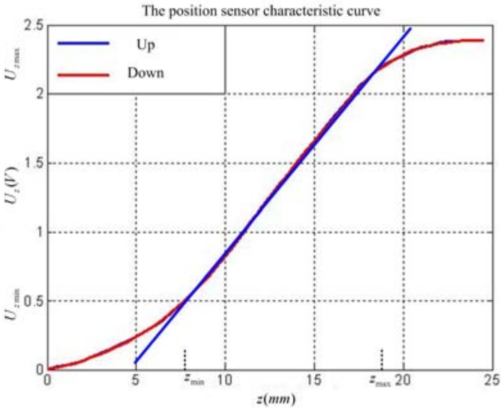


Figure 4: The position sensor characteristic curve

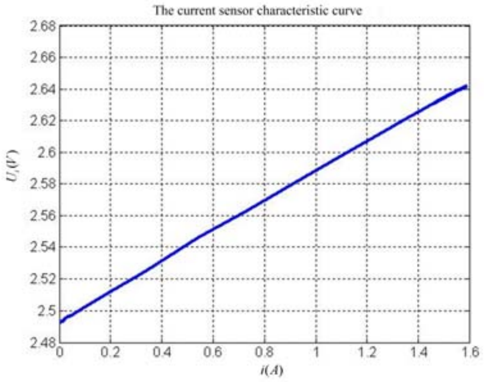


Figure 5: The current sensor characteristic curve

3 Work principle of the Control Platform

The work principle of the control platform of magnetic suspension system is illustrated in Figure 6. The work steps mainly include three parts: off-line simulation, hardware-in-the-loop simulation and real-time control.

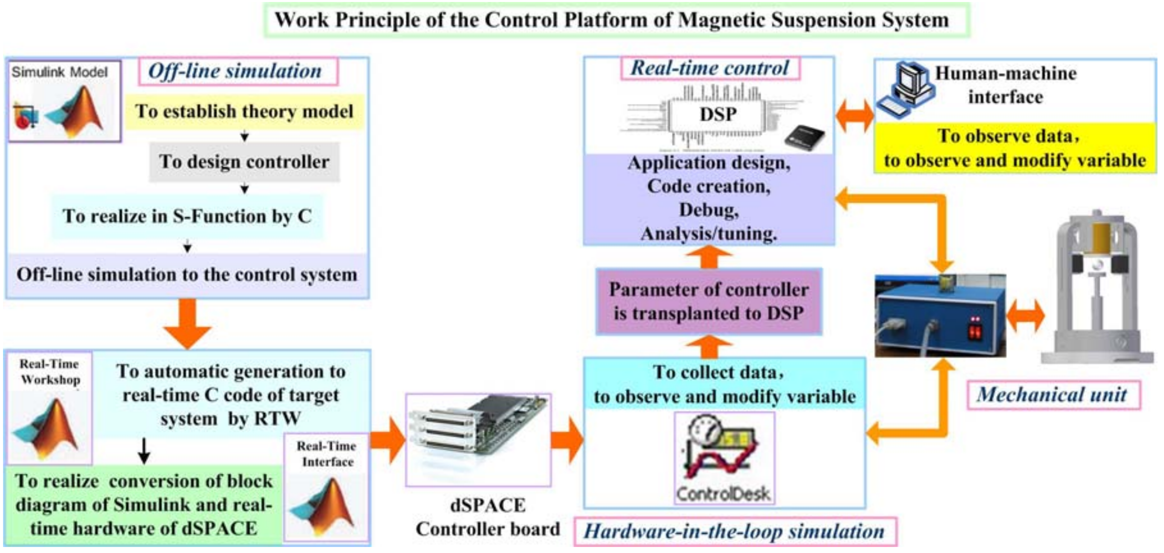


Figure 6: Work principle of the control platform

In off-line simulation part, the theoretical math model of the magnetic suspension system is established by analyzing the physical properties and system parameter identification. The simulation model of the system is built based on MATLAB/Simulink, and the algorithms are designed and realized in S-Function by C language in MATLAB/ Simulink. Simulation is repeated till the result is satisfied.

Hardware-in-the-loop simulation of the magnetic suspension system is realized based on dSPACE. The block model of Simulink and real-time C code of target system are generated by Real Time Workshop (RTW), and Control Desk based on dSPACE controller board. To connect the model to a dSPACE I/O board, just drag & drop the I/O module from the Real-Time Interface (RTI) block library and then connect it to the Simulink blocks. All settings, such as parameterization, are available by clicking the appropriate blocks. Real-Time Workshop generates the model code while RTI provides blocks that implement the I/O capabilities of dSPACE systems in the Simulink models. The real-time model is compiled, downloaded, and run automatically on the real-time hardware. Then the ControlDesk software can be operated interactively with real-time controller to collect and observe data, adjust the control parameters and track process response curve, etc. If needed, the automatic optimization parameters can be carried out based on MATLAB and MLIB/MTRACE.

In terms of the C code above, real-time control part will implement application design of the control algorithm by using DSP. The IDE software of Code Composer Studio (CCS) from TI company is used to debug and analyze the application code by connecting the DSP board [11]. The controller parameters are transplanted to the DSP from the results of off-line and hardware-in-the-loop simulation and are downloaded into the flash in the DSP. TMS320C28x™ DSP is used due to highly integrated, high-performance for demanding control applications. HMI is applied in communication with DSP by SCI interface and serial port in PC. HMI developed by Visual C++ 6.0 MFC is made to show the dynamic real-time curves of the received data in order to observe the operation of magnetic suspension system intuitively, being convenient for verifying and modifying on-line the controller parameters. The developed human-machine interface of the control platform is shown in Figure 7. If the real-time control result is satisfied, the control algorithm is successfully developed.

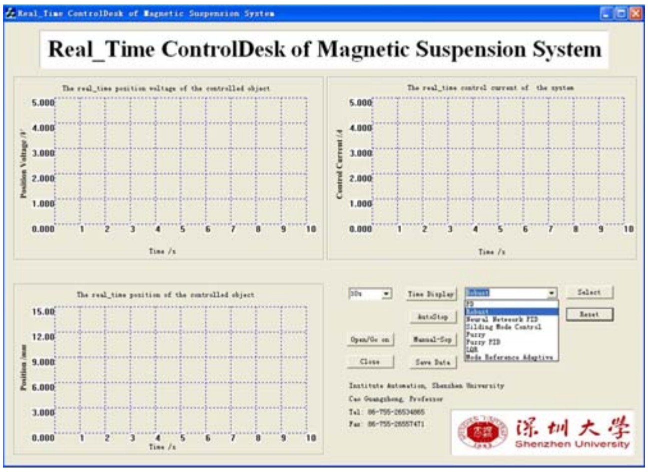


Figure 7: Human-machine interface of magnetic suspension system

4 Design of the Controller

As an example, a robust $H\infty$ controller for the magnetic suspension system is investigated and the design process is demonstrated based on the control platform.

4.1 Design of robust $H\infty$ controller for the magnetic suspension system

Figure 8 illustrates the work principle of robust H∞ controller for the magnetic suspension system.

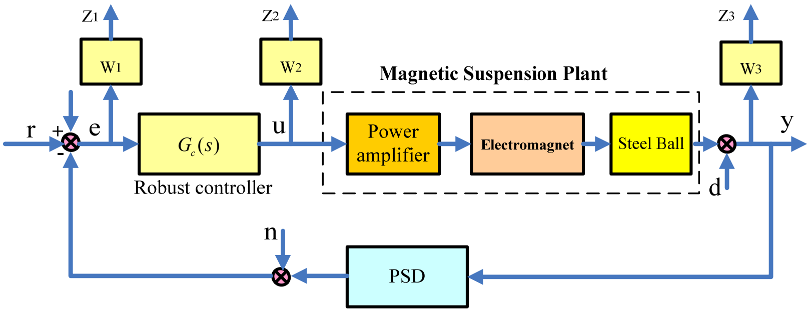


Figure 8: Work principle of robust $H\infty$ controller for the magnetic suspension system

For the magnetic suspension system, the effect of robust $H\infty$ controller determines controller $G_c(s)$ by a reasonable selection of W_1 、 W_2 and W_3 to realize stable suspension of the controlled object [13,14,15].

$W_1(s)$ is selected with as a low pass filter as follows,

$$W_1(s)=\frac{a}{s+b}\,,（a>0,b>0） \tag{2}$$

In order to not add extra controller order， $W_2(s)$ can be defined as a constant as follows,

$$W_2(s)=c\,,（c>0） \tag{3}$$

$W_3(s)$ is selected with high pass as follows,

$$W_3(s)=\frac{ms^2+ns}{k}\,,（m>0,n>0,k>0） \tag{4}$$

The performance of the robust control system depends on the properly chosen weighting functions. The weighting functions describe the influence of particular signals on the behavior of the control system. The proper selection of the weighting functions is very important. The weighting functions are respectively chosen by experimental comparison and analysis as follows,

$$W_1(s)=\frac{50}{s+0.001}\,,\quad W_2(s)=10^{-5}\,,\quad W_3(s)=\frac{0.001s^2+0.001s}{100} \tag{5}$$

The transfer function of the robust *H*∞ controller is derived by using Robust Control Toolbox in MATLAB as follow

$$G_c(s)=\frac{-1533s^2-7.403\times10^4s-8.233\times10^5}{s^3+477.3s^2+1.055\times10^5s+105.5} \tag{6}$$

To implement the robust control algorithm in MATLAB/Simulink, dSPACE or DSP, the discrete transfer functions of the robust controller are derived when the sampling time is △T=0.0008, △T=0.00085 and △T=0.0013 respectively, and then $G_c(s)$ are obtained as follows

$$G_c(s)|_{\Delta T=0.0008s}=\frac{-0.5176z^3+0.4978z^2+0.5174z-0.498}{z^3-2.628z^2+2.312z-0.6839} \tag{7}$$

$$G_c(s)|_{\Delta T=0.00085s}=\frac{-0.5443z^3+0.5222z^2+0.5441z-0.5224}{z^3-2.606z^2+2.274z-0.668} \tag{8}$$

$$G_c(s)|_{\Delta T=0.0013s}=\frac{-0.7588z^3+0.712z^2+0.7582z-0.7127}{z^3-2.41z^2+1.952z-0.542} \tag{9}$$

4.2 Off-line Simulation Model

The simulation program of the robust *H*∞ controller for the magnetic suspension system is designed based on S-Function by C in MATLAB/Simulink as shown in Figure 9.

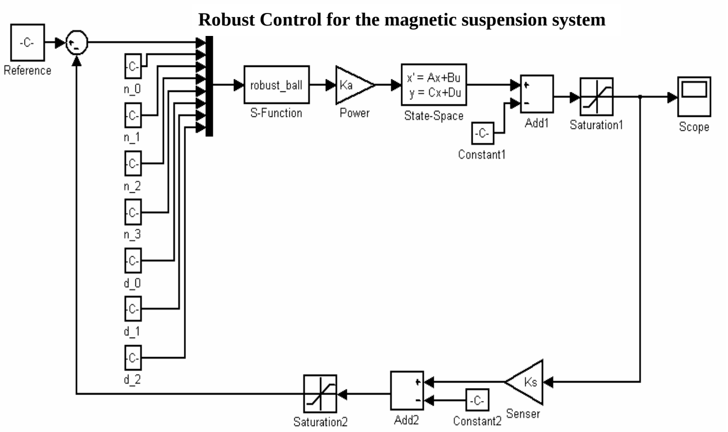


Figure 9: Off-line simulation of robust *H*∞ control for the magnetic suspension system

Where Reference is reference position voltage of the steel ball, robust_ ball is the robust $H\infty$ controller of the system, and n_0 , n_1 , n_2 , n_3 , d_0 , d_1 and d_2 are numerator and denominator of the pulse transfer function of the robust $H\infty$ controller respectively.

4.3 Hardware-in-the-loop simulation Model

A. Design of simulation model

The model of hardware-in-the-loop simulation based on dSPACE for the magnetic suspension system is designed as shown in Figure 10.

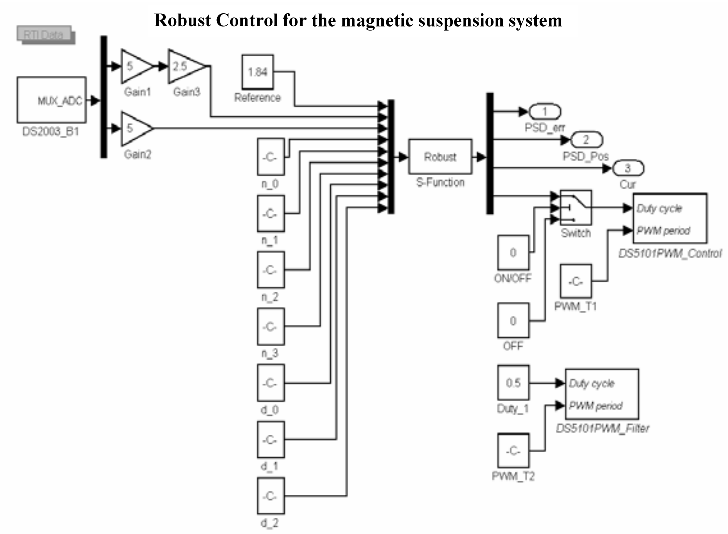


Figure 10: The hardware-in-the-loop simulation based on dSPACE for the magnetic suspension system

The controller’s input signals are from the current sensor and the position sensor. The signals of the current sensor and the position sensor are connected to two A/D ports of dSPACE. One PWM signal to drive the power amplifier is connected to one D/A ports of dSPACE. Here the robust $H\infty$ controller is realized by using S-Function program.

B. Selection of sample time

Code execution period of the system based on dSPACE is 18.65*us* measured by experiment. The minimum sampling time is selected as 0.000373*s* (20*18.65*us*), so simulation step size of the system is selected as 0.0008*s* and 0.00085*s* for hardware-in-the-loop simulation.

C. Experimental panel

Experimental panel is built by using ControlDesk/dSPACE as shown in Figure 11. It consists of current plotter, position plotter, position error plotter and regulator parameters of robust controller.

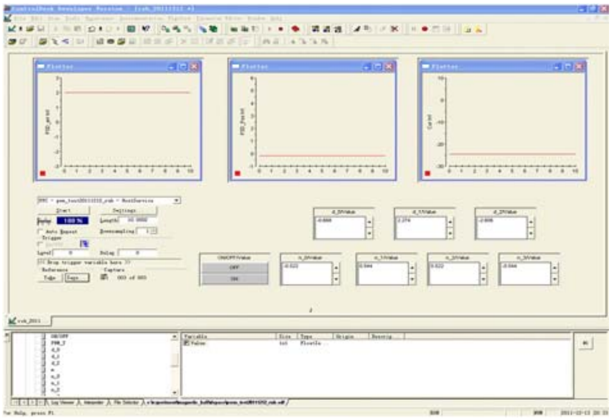


Figure 11: Comprehensive experiment panel of the magnetic suspension system based on dSPACE

4.4 Real-time control

The flow diagram of real-time digital control based on DSP is shown in Figure 12.

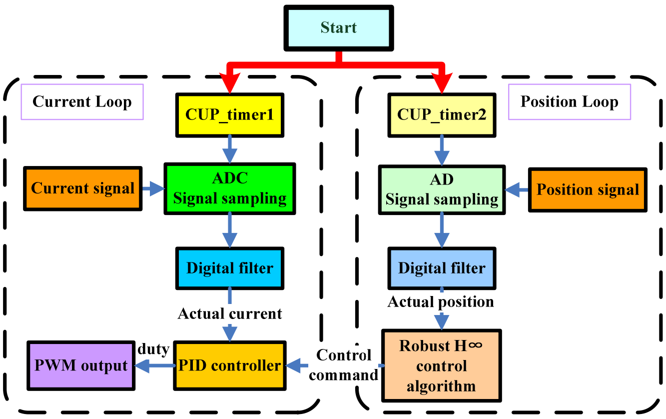


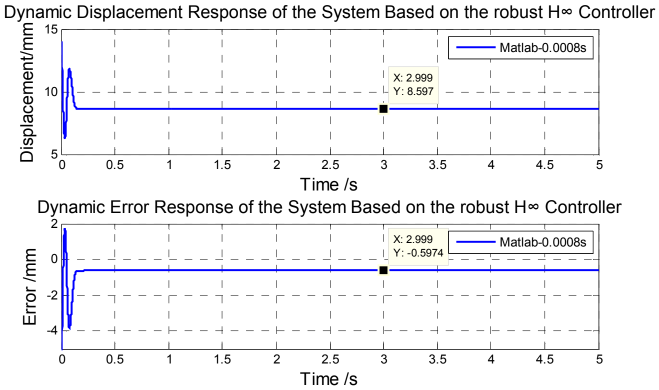
Figure 12: The flow diagram of real-time digital control based on DSP

In Figure 12, the digital robust $H\infty$ control of magnetic suspension system is located in the closed position loop. And the parameters of the robust $H\infty$ controller are transplanted from the results of off-line and hardware-in-the-loop simulation. Then the real-time control system is tested by using CCS and HMI.

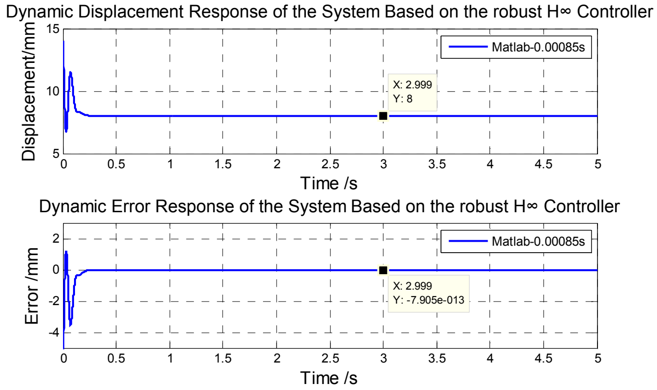
5 Experimental Results

To verify the performance of the designed robust $H\infty$ controller, simulation and experiment studies have been carried out.

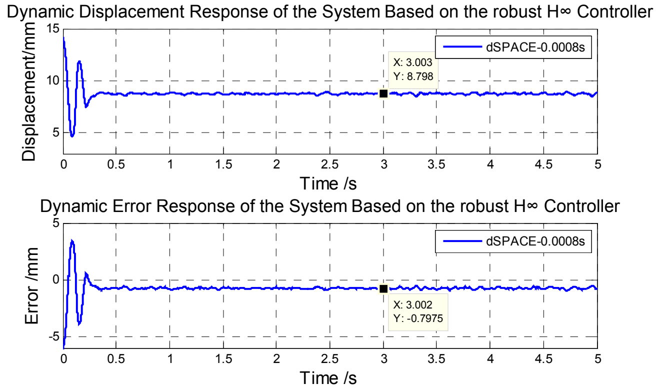
Assuming the initial position of the controlled steel ball is 14*mm* and the steady position is 8*mm*.The dynamic displacement responses of the off-line simulation, hardware-in-the-loop simulation and real-time control are got as shown in Figure 13(a), (b), (c), (d) and (e) respectively.



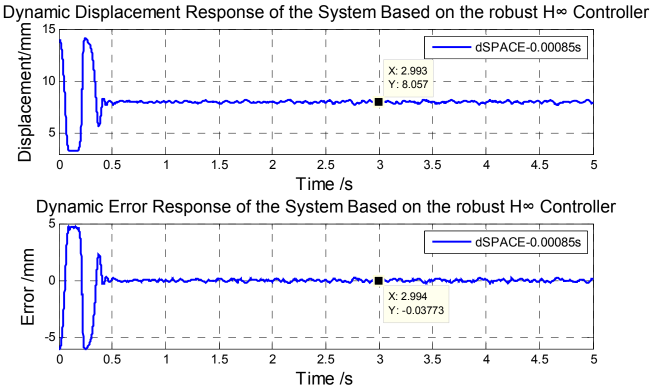
(a) Off-line simulation based on sampling time △T=0.0008*s*



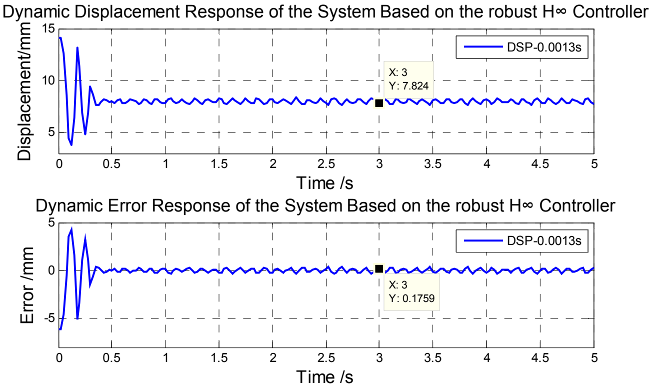
(b) Off-line simulation based on sampling time △T=0.00085s



(c) Hardware-in-the-loop simulation based on sampling time △T=0.0008s



(d) Hardware-in-the-loop simulation based on sampling time △T=0.00085s



(e) Real-time control based on DSP (sampling time △T=0.0013s)

Figure 13: The dynamic displacement and error responses of the magnetic suspension system

The statistical indexes of the experimental results in Figure 13 are listed in Table 2.

Controller	Overshoot	Settling time	Steady-state error
MATLAB_0.0008s	65%	0.27s	7.46%
MATLAB_0.00085s	63%	0.33s	0.00%
dSPACE_0.0008s	46%	0.33s	10.04%
dSPACE_0.00085s	76%	0.49s	0.96%
DSP_0.0013s	52.48%	0.425s	1.70%

Table 2: Control performance of the robust $H\infty$ controller based on the proposed control platform

From Figure 13 and Table 2, the results of simulation and experiment show that the system has a good dynamic and steady state performance based on the robust $H\infty$ controller.

By using the control platform, many control algorithms such as PD, LQR, Fuzzy PID, Fuzzy, Robust, Sliding mode control, Neural network PID, Model reference adaptive control and so on, have been researched and the corresponding controllers have been developed in the laboratory. Figure14 is the photo of the accomplished control platform. Figure15 is the dynamic displacement responses of the suspended ball under the various controllers developed in the platform.

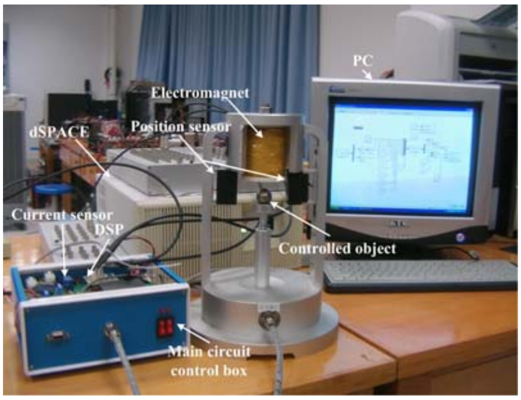


Figure 14: The photo of the control platform

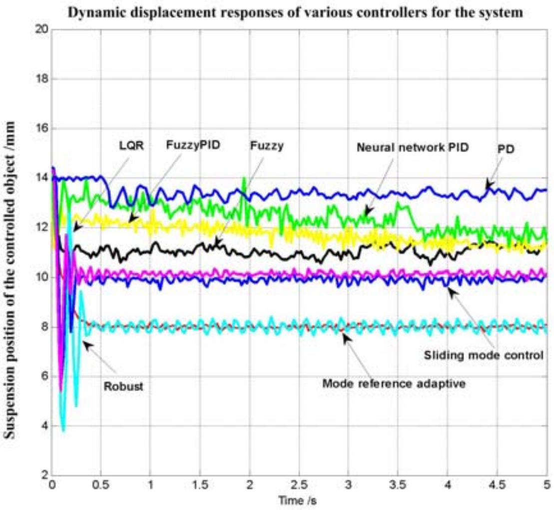


Figure 15: Dynamic displacement responses under the various controllers for the system

6 Conclusions

A kind of control platform of magnetic suspension system is successfully developed. Experimental results indicate that the proposed control platform is an efficient and convenient tool to design and verify of various control algorithms for the magnetic suspension system and further to obtain the corresponding digital controllers for education and many industrial applications.

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References

[1] K.A. Lilienkamp and K.H. Lundberg. Low-cost magnetic levitation project kits for teaching feedback system design. In *Proc. 2004 Amer. Control Conf.*,June 2004.

[2] Artigas, J.I., Barragán, L.A., Llorente, S., Marco, A. and Lucía, O.. Low-cost magnetic levitation system for electronics learning. *E-Learning in Industrial Electronics (ICELIE), 2010 4th IEEE International Conference on*, 2010.

[3] Lundberg, K.H., Lilienkamp, K.A., Marsden, G.. Low-cost magnetic levitation project kits. *IEEE Control Systems Magazine* , VOL. 24, 2004.

[4] Morales, R., Feliu, V. and Sira-Ramirez, H.. Nonlinear Control for Magnetic Levitation Systems Based on Fast Online Algebraic Identification of the Input Gain. *IEEE Transactions on Control Systems Technology*, 19(4), July 2011.

[5] Simulink®, the Mathworks Inc.. http://www.mathworks.cn/

[6] Vilma A.Oliveira, Eduardo F.Costa and Jerson B.Vargas. Digital Implementation of a Magnetic Suspension Control System for Laboratory Experiments. IEEE Transactions on Education, 42(4), Nov 1999.

[7] R. Morales and H. Sira-Ramírez. Trajectory tracking for the magnetic ball levitation system via exact feedforward linearisation and GPI control. *International Journal of Control*, Vol.83 (6), 2010.

[8] Dspace, Technologiepark 25, D-33100 Paderborn, Germany. http://www.dspace.com/en/inc/home.cfm

[9] Ma Peibei, Wu Jinhua, Ji Jun and Xu Xinlin. Software Environment and Application of dSPACE Real-Time Simulation Platform. *Acta Simulata Systematica Sinica*, No.4, 2010.

[10] Winfred K.N. Anakwal, Namik K. Akyil L and Jose A. Lopezl. Control of a Magnetic Suspension System Using TMS320C31-Based dSPACE DS 1102 and Simulink. *Proceedings of the 2005 IEEE International Conference on Mechatronics*, Taiwan, July 10-12, 2005.

[11] Texas Instruments, http://www.ti.com.cn.

[12] Vilma A.Oliveira, Eduardo F.Costa and Jerson B.Vargas. Digital Implementation of a Magnetic Suspension Control System for Laboratory Experiments. IEEE Transactions on Education, 42(4), Nov 1999.

[13] Kemin Zhou, John C.Doyle and Keith Glover. Robust and optimal control. *Prentice-Hall*, New Jersey， 1996.

[14] S.B. Kim, S.H. Kim and Y.K. Kwak. Robust control for a two-axis gimbaled sensor system with multivariable feedback system. *IET Control Theory Appl.*, Vol.4 (4), 2010.

[15] Selim Sivrioglu, Kenzo Nonami and Hirochika Ueyama. Advanced Mixed $H_2/H\infty$ Control Design For Active Magnetic Bearing Systems. *Proceedings of the Fifth International Symposium on Magnetic Bearings*, Japan, August 1996.