Testing Performance and Reliability of Magnetic Suspension Controllers

Adam Piłat*

** AGH – University of Science and Technology, Department of Automatics, Al. Mickiewicza 30, 30-059 Kraków, Poland (e-mail: ap@agh.edu.pl).*

Abstract: The aim of this paper is to present an experiment realized with the support of magnetic levitation system equipped with additional electromagnet. This extra unit allows to realize more experiments including identification and control, diagnose the performance of the closed loop system and design controllers for single axis of the active magnetic bearing. The test rig consists of two electromagnets, distance and current sensors and ferromagnetic object. The system is controlled by the personal computer or embedded system. The MATLAB/Simulink software allows to perform identification, signal analysis, controller design and real-time code generation for the selected target. The experimental controllers reliability test under external pulse excitation is presented.

1. INTRODUCTION

Magnetic levitation phenomena allows to suspend the ferromagnetic object without contact in a surrounding filed (Sinha 1987, Schweitzer 1993, Hurley 1997). The magnetic levitation is an example of nonlinear and unstable systems as an ideal tool for teaching and research purposes (Piłat 2002). Typically controlled magnetic levitation systems are based on a single electromagnet located at the top of the frame. The electromagnetic force generated by the electromagnet counteracts the gravity force and the object can levitate. The controlled magnetic levitation is based on distance sensor usually. The controller implemented in a programmable analogue (Piłat 2005) and/or digital form (Piłat 2002, Piątek 2007) controls the current in the electromagnet coil. The extra electromagnet located on the opposite side of the top electromagnet can be used for various purposes. First of all this electromagnet can generate external force with desired shape to act as an disturbance. Moreover, it can be used together with the gravity force to produce higher value of the external field force. Finally both electromagnets can work together as a single axis of the active magnetic bearing (Gosiewski 1999, Kozanecka 2000, Maslen 1999, Schweitzer et al. 1993, Taniguchi M., Ueyama H. 1996). With the lower electromagnet one can test the performance of the magnetic suspension realized by the upper one. Such important properties of the control loop like robustness and reliability can be investigated. The experimental results can verify theoretical and numerical calculation, realization method and used hardware -software tools.

2. MAGNETIC LEVITATION LABORATORY TEST-RIG AND ITS MODEL.

The Magnetic Levitation System (MLS)/Active Magnetic Suspension (AMS) with two Electromagnets (MLS2EM 2007) is a single degree of freedom system for demonstration of magnetic levitation phenomena (Fig. 1). MLS2EM is a nonlinear, open-loop unstable and time varying dynamical system. The basic principle of MLS2EM operation is to set the current in an upper electromagnet to keep a ferromagnetic object levitated. To levitate the sphere a real-time controller is required. The controller maintain the equilibrium stage of the gravitational and electromagnetic forces to keep the sphere in a desired distance from the upper electromagnet. The lower electromagnet is used for external excitation or as contraction unit.

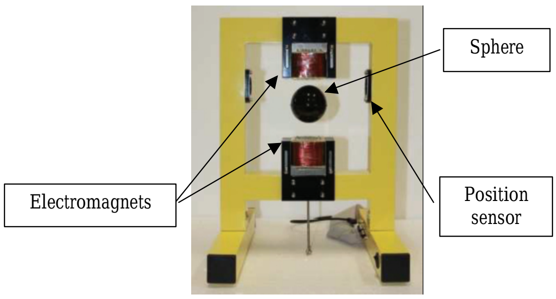


Fig. 1. MLS2EM laboratory set-up

The position of the sphere may be adjusted using the set-point control and the stability may be varied using the gain control. The band-width of lead compensation may be changed in a programmable way and the stability and response time investigated. The object position is determined through a distance sensor. Additionally the coil current are measured to identify and validate the electromagnetic force characteristics. The test-rig is connected to the PC via dedicated FPGA based I/O board (Piłat, Piątek 2008). The MATLAB/Simulink environment is used to design control strategy and generate real-time executable code The diagram of the dual electromagnet system is presented in Fig. 2a. The mechanical representation of upper part is presented in Fig. 2b, where stiffness and damping are shown in tuneable form. In the AMS it is realized ina programmable way by controller structure and parameters (Piłat 2009). Note, that the P force represents the sum of gravity force and lower electromagnet force if controlled.

a) b)

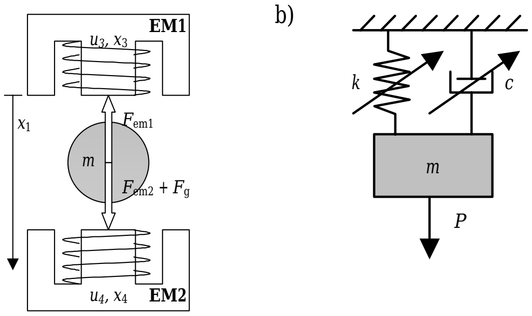


Fig. 2. Active magnetic suspension: a) MLS2EM diagram, mass-spring-damper equivalent of upper electromagnet.

The nonlinear model of the MLS2EM can be described by a set of four first order equations (1) corresponding to mechanical and electrical compounds (MLS2EM 2007).

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= m^{-1}[-F_{EM1}(x_1,x_3)+F_g+F_{EM2}(x_1,x_4)] \\
\dot{x}_3 &= f_{AEM1}(x_1,x_3,u_3) \\
\dot{x}_4 &= f_{AEM2}(x_1,x_4,u_4)
\end{aligned} \tag{1}$$

where: x_1 – object distance from the surface of the upper electromagnet, x_2 – object velocity, x_3 – upper coil current, x_4, bottom coil current, F_{EM1} – force generated by the upper electromagnet, F_{EM2} – force generated by the bottom electromagnet, F_g – gravity force, m – object mass, f_{Au}, f_{Al} – characteristics of the power actuator units supplying both electromagnets, u_3, u_4 - control signals applied to appropriate actuator. Power actuators are available in two configurations: MLS2EM uses PWM control by the digital interface operates with a fixed base frequency and variable duty cycle. The MLS2Emi (MLS2Emi 2008) operates with hardware current feedback controller (*ICtrl*) adjustable by analog voltage signal. Both power actuators generate the requested coil current, although are controlled in a different way. Because of their hardware structure the dynamical response of the same coils vary (Fig. 3). Working with the *ICtrl* unit one can obtain fastest coil current response than for *PWM* unit.

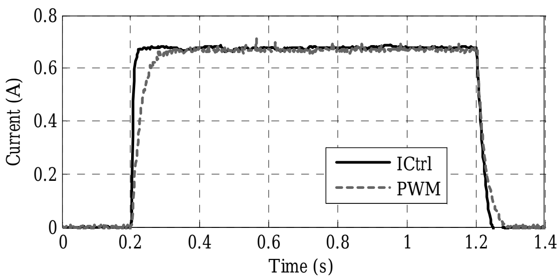


Fig. 3. Comparison of current responses for two types of coil actuators *PWM* and *ICtrl*.

The applied power actuator affect the dynamics of the closed loop system while the object is stabilized and externally excited. For object movement in the range of 5% of the whole operational area and for locations close to electromagnet surfaces the electrical equations plays an important role. For the stabilization at the desired distance far from the electromagnet – usually at 50% of the total air gap, both electrical equations can be neglected and system equations are simplified to two. In this case the current control mode is achieved, so the electromagnetic force is directly controlled. In the next chapter the MLS2Emi will be used due to the immediate external force excitation.

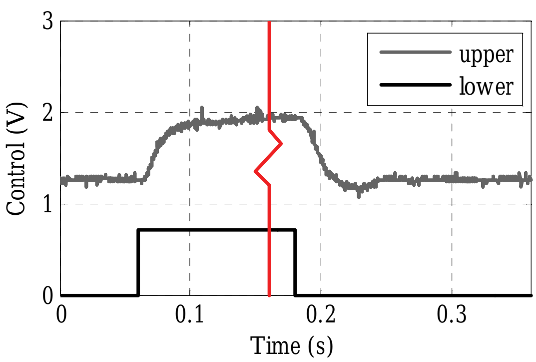
3. TESTING ML CONTROLLERS

The active magnetic levitation controller can be designed and verified under a few typical quality criteria. They strongly depend on the application of the magnetic levitation based device and are designed under a single or a combination of a few quality indexes like: integrals of squared error, minimization of used energy, attraction to desired position with the minimal (or requested) time, fixed values of stiffness and damping of the closed loop. A several controllers were tested under a few of previously listed criteria (Piłat 2002). Particularly, when using dual AMS it is possible to test the performance and reliability of the applied controller. Thus the next two examples show how the PD controller operates under external force excitation and the mixed structure (PD+NN) controller (Piłat, Turnau 2009) stabilizes the object at desired position.

3.1 Example – testing the PD controller

To demonstrate the performance of the closed loop system the PD controller stabilising the ball at x_{10} = 0.008 [m] for k = 248.2 [N/m] and c = 8.12 [Ns/m] what corresponds to eigen values $\lambda_1 = \lambda_2 = 71$, was tuned with the following parameters k_1 = -418.9906, k_2 = -7.9781 (Piłat 2009). The system responses under the external excitation by lower electromagnet are presented below. These figures were combined with two parts for better overview of system reaction on rising and falling edge of the external excitation signal. Fig. 4a show the time diagrams of control signals applied to both electromagnets while Fig. 4b coil currents. The object position is marked on the Fig. 4c where the mode change from critical (around 8mm) to aperiodic is well visible.

a)



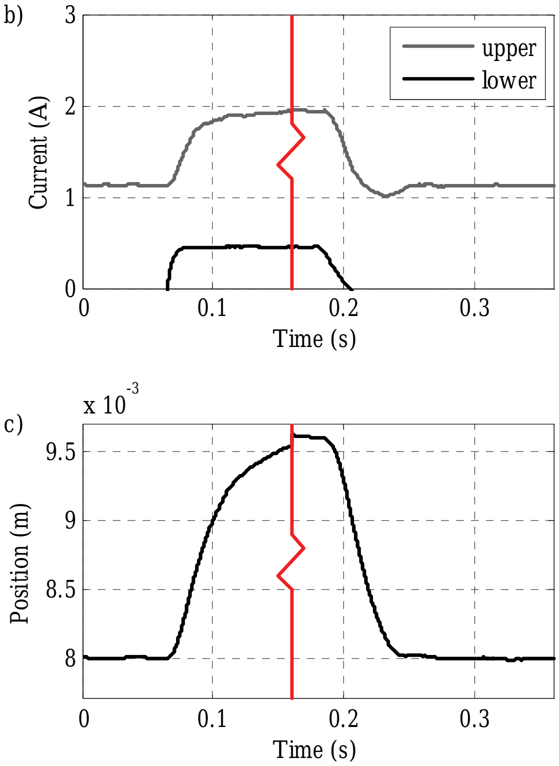


Fig. 4. Test the stabilization mode under PD critical gain adjusted.

To illustrate the aperiodic and oscillatory modes the k_2 parameter has been changed by |2|. The system responses are given in Fig. 5 and Fig. 6 respectively. One can observe the appropriate dynamics of the active magnetic levitation system. The proposed test shows all features of the state feedback control when the poles of the closed loop system are programmed with respect to the required dynamics characterized by active magnetic suspension stiffness and damping.

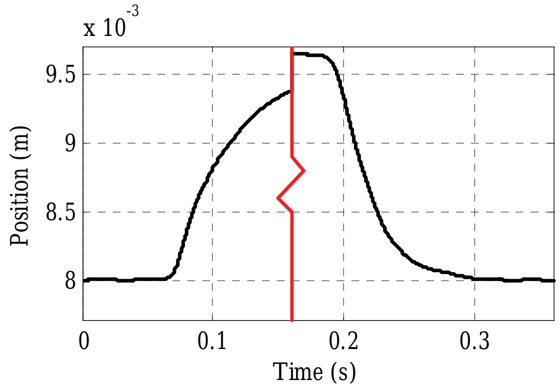


Fig. 5. PD aperiodic mode

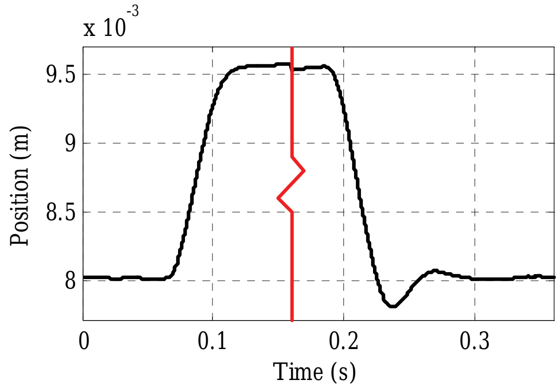
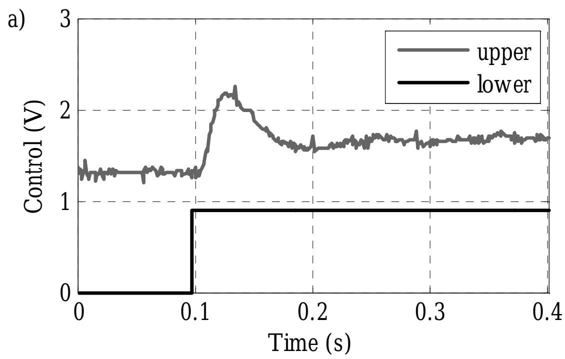


Fig. 6. PD Oscilatory mode

3.2 Example – testing PD+NN controller

The realized PD+NN (mixed structure PD and Neural Network) controller is an example of on line tuning control system. The proposed test with external excitation allows to observe changes in the system behaviour as well the NN structure modifications. The proposed controller produces the control signal as the weighted sum of 60%PD and 40%NN. The cooperation of both algorithms results in a robust control of active magnetic levitation. Fig. 7 presents time responses from experimental tests. All of them are focussed on the rising edge of the external excitation force – generated by the lower electromagnet. Fig. 7a show the moment when the lower electromagnet is turned on while the upper electromagnet controller is stabilizing the ball at the desired level. The EM2 is excited by the current pulse signal (Fig. 7b) and the object is pulled down. The levitated object has been attracted towards the lower electromagnet (EM2) what is well visible in Fig, 7c. the reaction of the controller returns the levitated sphere to the desired level in 150ms. Looking at the control signal generated by the upper electromagnet (EM1) – see Fig. 7a one can notice that more current is required to counteract the action of the lower one. As mentioned above, this control signal is a weighted sum of two control signals presented in Fig. 7d.



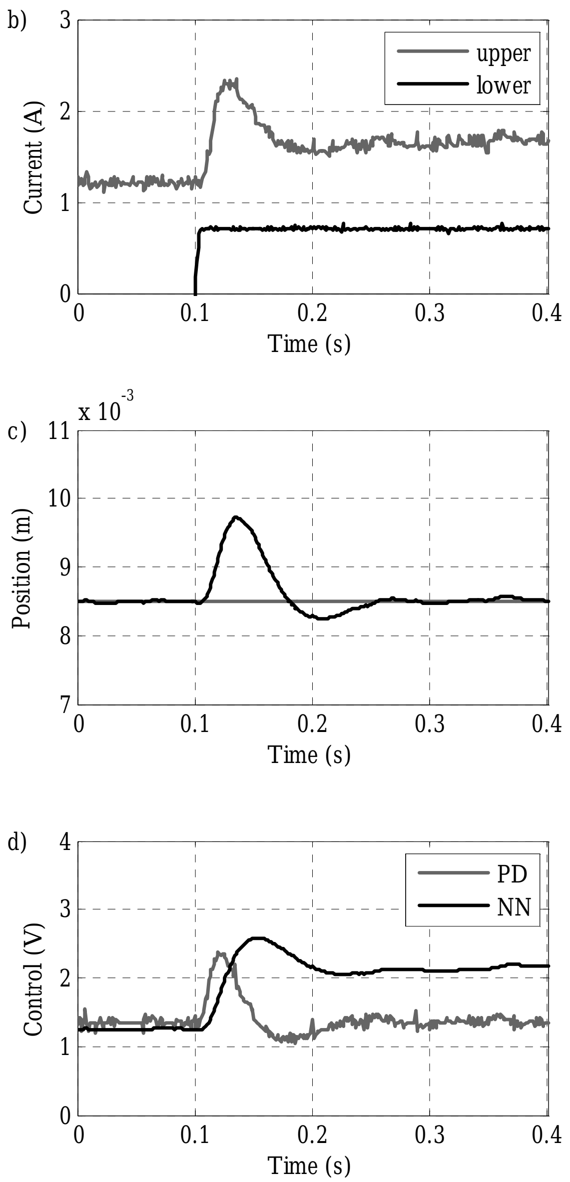


Fig. 7. External force switch on while PD+NN stabilizes the ball at the desired level.

Analysing the controller behaviour one can observe a reaction of PD for external force – highest value of control and reaction of NN to reduce the stabilisation error to zero. Note that the NN controller has changed its structure to compensate the steady-state error (for more details see (Piłat, Turnau 2009). The proposed test allows to validate the robustness of the designed controller.

3. CONCLUSIONS

The active magnetic levitation system with additional electromagnet is a practical laboratory test rig to develop, test and demonstrate a wide range of control techniques for magnetic levitation. The tested system fits well requirements of the modern automatic control teaching where the programmable features of the closed loop are requested to demonstrate a wide rage of automatic control facilities. With the proposed test a reliability, robustness and expected performance of the designed controllers has been proved experimentally.

Acknowledgement

This research was supported in parts by: AGH grant 11.11.120.768, *PBZ/MEiN/01/2006/48, INTECO Ltd.*

REFERENCES

Bania P. (1999): Model i sterowanie magnetyczną lewitacją. Praca Dyplomowa. Katedra Automatyki AGH, Kraków.

Clarence de W. Silva (2000), Vibration Fundamentals and Practice, CRC Press.

Gosiewski Z (1999). Magnetic bearing for rotating machinery – control and tests, BNIL, Warszawa (in Polish)

Hilton E., Allaire P., Baloh M. (1998): Magnetic Suspension Test Controller for a New Continuous Flow Ventricular Assist Device. 6th International Symposium on Magnetic Bearings, 5-7 August, Massachusetts, USA, pp. 87 ÷ 94.

Hurley W.G., Wölfle W.E. (1997), Electromagnetic Design of a Magnetic Suspension System. IEEE Transactions on Education, vol. 40, No. 2, May, pp. 124 ÷ 130.

Kozanecka, D. (2000). Digitaly controlled magnetic bearing. (in Polish). Zeszyty Naukowe Politechniki Łodzkiej, Łódź

Maslen E. (1999): Magnetic Bearings. University of Virginia, Department of Mechanical, Aerospace and Nuclear Engineering, Charlottesville, Virginia.

MLS2Em (2007), Magnetic Levitation System Users Guide, INTECO Ltd. Kraków.

MLS2Emi (2008), Magnetic Levitation System Users Guide, INTECO Ltd. Kraków.

Piatek P. (2007) Wykorzystanie specjalizowanych architektur sprzetowych do realizacji krytycznych czasowo zadan sterowania. Ph.D. Thesis, AGH University of Science and Technology, Cracow, Poland, (in Polish).

Piłat A. (2002), Control of Magnetic Levitation Systems, Ph.D. Thesis, AGH University of Science and Technology, Cracow, Poland, (in Polish).

Piłat A. (2005a), Programmable analog hardware for control systems exampled by magnetic suspension, Computer Methods and Systems, 14–16 November, Kraków, Poland, pp. 143–148

Piłat A., Turnau A. (2005b), Self-organizing fuzzy controller for magnetic levitation system, Computer Methods and Systems, 14–16 November, Kraków, Poland, pp. 101–106

Piłat A, Piątek P. (2008), Multichannel control & measurement board with parallel data processing, Recent advances in control and automation, Warsaw, Academic Publish-ing House EXIT, pp. 373 ÷ 380

Piłat A. (2009), Stiffness and damping analysis for pole placement method applied to active magnetic suspension. AGH Automatyka, vol.1

Piłat A., Turnau A. (2009), Neural adapted controller learned on-line in real-time, 14th MMAR, 19 – 21 August, Miedzyzdroje, Poland

Sinha. P.K. (1987), Electromagnetic suspension dynamics and control, London, Peter Perginus.

Schweitzer G, Traxler A., Bleuer H. (1993), Magnetlager,

Taniguchi M., Ueyama H. (1996): Cutting Performance of Digital Controlled Milling AMB Spindle. 5th International Symposium on Magnetic Bearings, 28-30 August, Kanazawa, Japan, pp. 375 –379.