

# Fuzzy Control of a Magnetic Levitation System for a Linear Drive and Comparison with a State Control

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## Keywords

Fuzzy Control, Maglev, State Control

## Abstract

In this paper a fuzzy levitation controller for a one degree of freedom maglev application is designed and its performance is compared with the performance of a state controller. The comparison is based on both simulation and measurement results. The maglev application is a levitation/propulsion head of an autonomous transportation vehicle with a nominal air gap value of 2.5 mm. First a nonlinear model of the system is presented. After a short description of the state controller the design of the fuzzy controller is specified. Simulations with noisy signals indicate the noise sensitiveness of the fuzzy controller as a major drawback. Measurements acknowledge this fact. It is shown that for this application the state controller is a better choice because of its robust performance.

## 1 Introduction

The magnetic levitation technique combined with linear drives makes contactless and frictionless operation of a transport system possible. At the IEM a magnetic levitation conveyor vehicle is being designed. It is part of a new conveyor system which can replace conventional conveyor systems at airports. The frictionless operation guarantees lower maintenance costs and longer product life of the hardware.

Basic components of the vehicle are the light weight framework and four levitation/propulsion heads. A levitation/propulsion head consists of a linear homopolar motor [1], a controlled permanent magnet and a contactless energy transmission module. Because the energy needed for the whole vehicle is provided by contactless energy transmission, reduction of energy consumption is important. A controlled permanent magnet with a current which is set to zero by a controller is selected as magnetic bearing. The track is completely passive which makes it cheap and easy to manufacture.

Based on previous experiences with maglev systems a state control structure was the first choice for the levitation controller. Fuzzy levitation controllers are already successfully used to control magnetic bearings for rotating machines [2]. This is reason enough to analyse whether a fuzzy control can compete with a state control in a typical one degree of freedom maglev application. By means of simulations with a nonlinear model the fuzzy levitation controller is designed. Performance and stability of both controllers are compared based on simulations and experimental results.

## 2 Modelling

### 2.1 Test bench layout

Each levitation/propulsion head has its own independent levitation controller. A test bench with one levitation/propulsion head allowing only vertical displacement was built. Photo and layout are shown in Figure 1 and 2. The air gap with a nominal value of 2.5 mm is measured by an eddy current sensor. The homopolar motor is mounted in such a way that for the nominal air gap value the normal forces

are zero. For values less than the nominal value these normal forces contribute in levitating the vehicle, however for values greater than the nominal value the forces act as an extra load. Power electronics consist of a four-quadrant DC-DC converter build with discrete IGBT-modules. The DC bus voltage is 300 V and the current is limited between  $-10$  A to 12 A.



Figure 1: Photo of the test bench

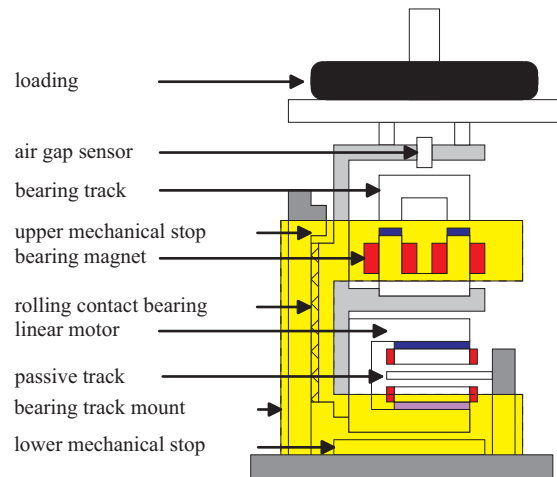


Figure 2: Layout of the test bench

## 2.2 Test bench model

In order to design a levitation controller a model of the system is needed. For the equation of motion special attention is paid to the implementation of the mechanical stops which determine the maximum and minimum air gap values. To implement the voltage equation

$$u = Ri + \frac{d\psi}{dt}$$

$\Psi$  is linearised at the nominal operating point

$$\psi_{lin} = \psi_0 + \left. \frac{\partial \psi}{\partial \delta} \right|_{\delta_0, i_0} (\delta - \delta_0) + \left. \frac{\partial \psi}{\partial i} \right|_{\delta_0, i_0} (i - i_0)$$

which results in the voltage equation

$$u = Ri + \left. \frac{\partial \psi}{\partial \delta} \right|_{\delta_0, i_0} \frac{d\delta}{dt} + \left. \frac{\partial \psi}{\partial i} \right|_{\delta_0, i_0} \frac{di}{dt}$$

The partial derivatives are calculated based on a finite element model of the magnet and stored as splines. A third spline needed for the equation of motion represents the force of the magnet for any value of air gap and current. The accurate nonlinear model of the test bench is implemented in Matlab/Simulink.

## 2.3 Validation

In order to validate the model, the system's response to a voltage step of 7.7 V is simulated and measured. The results in Figure 3 confirms the accuracy of the model. The ripple in the measured air gap after the magnet has hit the upper mechanical stop is due to the elasticity of the bearing track. This elasticity is neglected in the model. For the design of the state controller a linear model is deduced from the nonlinear model by linearising the system for the nominal operating point. The design of a fuzzy control does not need this linearisation step and uses the accurate model.

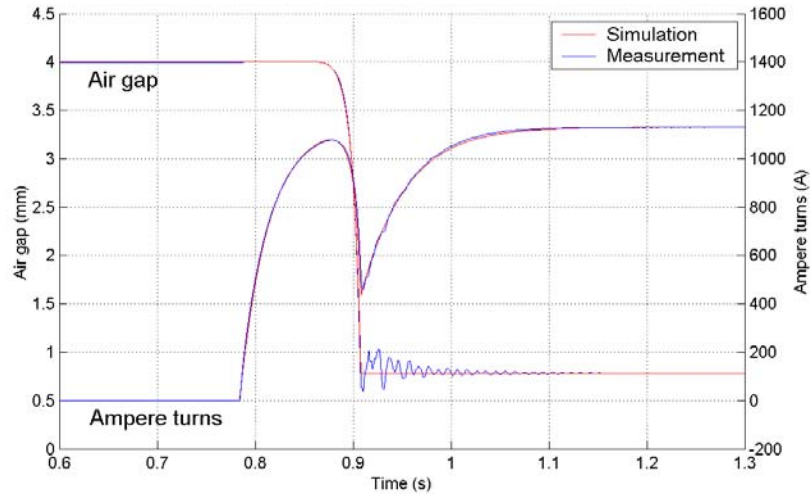


Figure 3: Model validation

### 3 Levitation Controller

#### 3.1 State controller

The state controller is an often used control structure for maglev applications. If connected with an integral element static offset is reduced to zero for all valuable operating points. The state controller with an integral element achieves a good performance with a relatively simple control structure. The control algorithm requires little calculating time which enables a high control frequency.

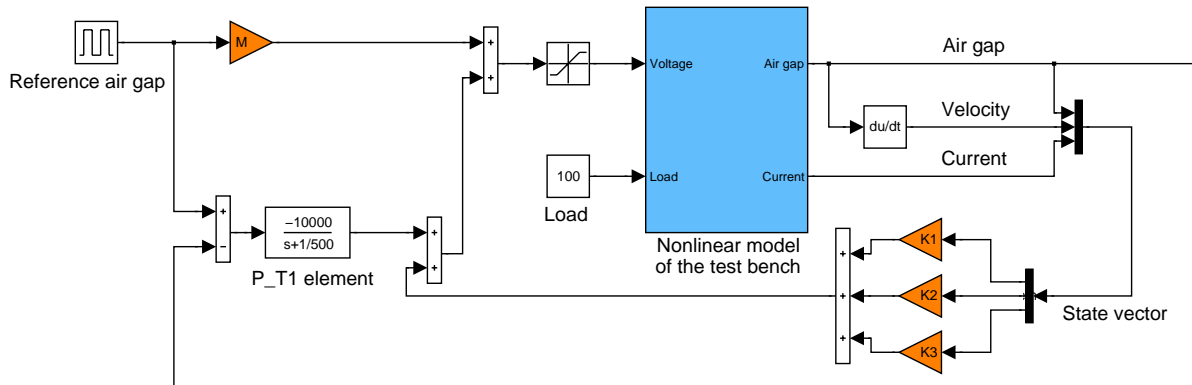


Figure 4: Block diagram of the state control

The block diagram of the levitation state controller connected with a P-T1-element is shown in Figure 4. Air gap, air gap velocity and current are the elements of the state vector. The gains K1, K2, K3 and M are calculated from the linear model. Fine tuning is iterated based on simulations done with the nonlinear model.

#### 3.2 Fuzzy controller

A fuzzy control system can be considered as a real time expert system [3], which performs the control tasks in a human-like way. The system under control is described in terms of some linguistic variables. The control tasks are performed by using some rules set forth in a rule base. The inference rule used is a fuzzy inference scheme. It takes three steps to design a fuzzy controller: fuzzyfication, inference rules and defuzzyfication. In the first step the values obtained through a sensor are transformed into values of the corresponding linguistic variable. The second step performs the fuzzy inference giving the linguistic values of the control variables. In the third step these linguistic values are transformed to the numerical value of the control variable in order to perform the required task. After executing the three steps, the controller is fine tuned in an iterative way.

There are two possibilities using a fuzzy approach in maglev applications: 1) the first level controller is a fuzzy controller or 2) the first level controller is a conventional controller e.g. PID controller where at the level underneath a fuzzy algorithm is used to adapt the parameters of the first level controller. In this paper the first possibility is analysed ([4], [5]). The linguistic "input" variables (=fuzzy sets) of the controlled permanent magnet are air gap deviation and air gap deviation velocity.

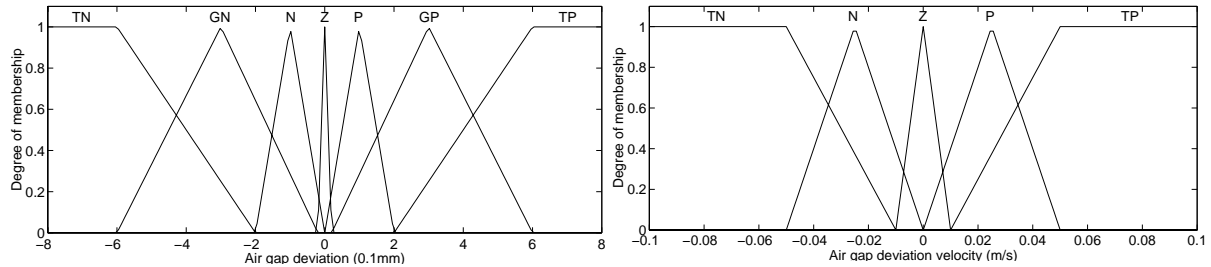


Figure 5 : Fuzzy set of air gap deviation and air gap deviation velocity  
[T: top, G: great, N: negative, Z: zero, P: positive]

The air gap deviation fuzzy set has seven membership functions and the air gap deviation velocity has five (figure 5). Above a certain number of membership functions the control accuracy is just slightly increased, where as too few membership functions make an accurate control impossible. Also with increasing number of membership functions the rule base becomes bigger therefore increasing the calculation time. The use of triangular membership functions which become narrow around zero results in an accurate control with a small number of membership functions. The linguistic "output" variable is the voltage applied to the magnet related to the dc link voltage. Its fuzzy set has seven membership functions as shown in figure 6. In this study Mamdani's fuzzy inference method with a

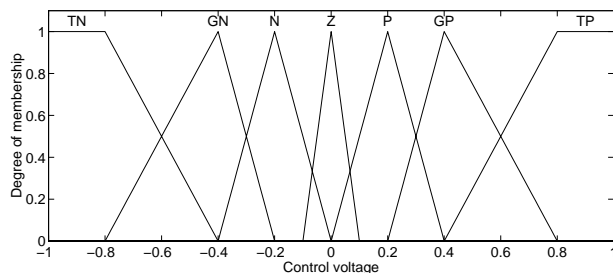


Figure 6: Fuzzy set of control voltage

adv \ ad	TN	GN	N	Z	P	GP	TP
TN	TP	TP	TP	TP	TP	GP	P
N	TP	TP	TP	GP	P	Z	N
Z	TP	GP	P	Z	N	GN	TN
P	P	Z	N	GN	TN	TN	TN
TP	N	GN	TN	TN	TN	TN	TN

Figure 7: Rule base of Fuzzy-Fast

max/min rule is used. For the simulation two controllers have been developed. One called "Fuzzy-Fast", the other "Fuzzy-Slow". The rule base of Fuzzy-Fast includes 35 rules and is shown in figure 7. Fuzzy-Slow does not allow high speed which is achieved by making a slight change to the rule base of Fuzzy-Fast. The element of the first (resp. last) row of Fuzzy-Slow's rule base is Top Positive (resp. Top Negative). The transfer characteristics are shown in figure 9. Figure 12 displays the block diagram of the fuzzy controller.

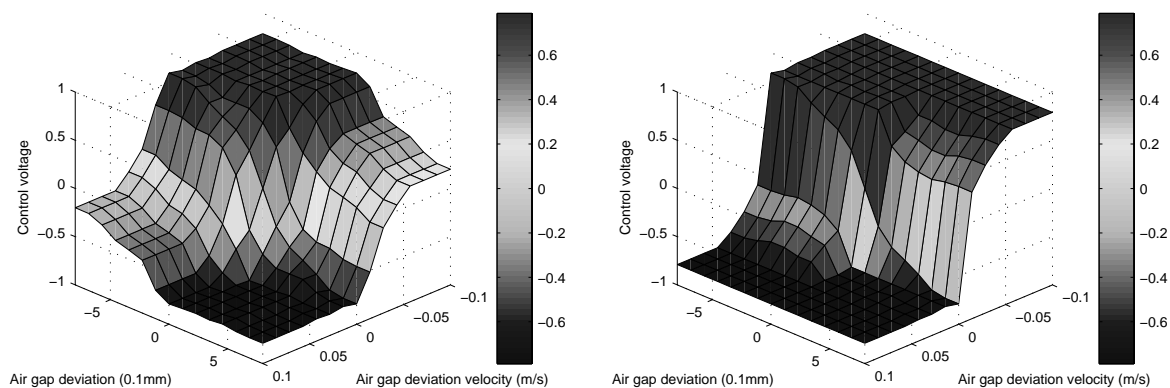


Figure 9: Transfer characteristic of Fuzzy-Fast (left) and Fuzzy-Slow (right)

## 4 Simulation and comparison

The complete controlled system is simulated with the Matlab/Simulink software. All simulations are done with the nonlinear model, using a fixed-step solver. The chosen fixed step size equals the sampling time of the real time application (40  $\mu$ s).

### 4.1 Simulation with noise-free signals

The first simulation is done with ideal components. The sensor signals contain no noise and the DC-DC converter has no time delay. Two cases are discussed. In the first one, the response of the system with two different loads on a target air gap sequence is simulated. Figure 10 shows the air gap and the current signals.

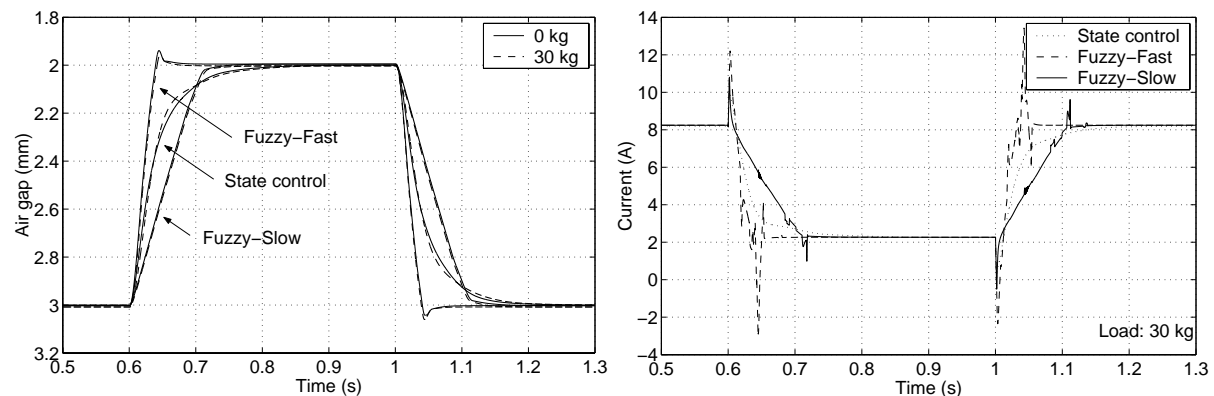


Figure 10: Input response (left: air gap signals, right: current signals)

Fuzzy-Fast reaches the target value (2 resp. 3 mm) in less than 40 ms. This high dynamic performance is due to high peak currents and so Fuzzy-Slow was developed to reduce these peak values. Both fuzzy controllers act faster than the state controller and the performance of each controlled system with different loads is nearly identical. In the second simulation, the system with a constant air gap reference value of 2.5 mm was loaded and unloaded. Figure 11 shows the response of the system for the two different loads. In this case fuzzy controller used is Fuzzy-Slow. Again the

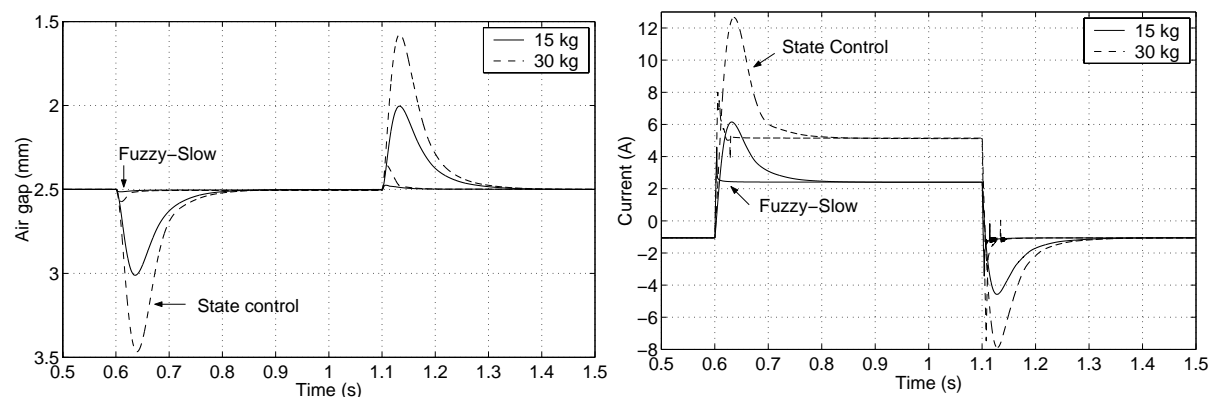


Figure 11: Disturbance response (left: air gap signals, right: current signals)

good dynamic performance of the fuzzy controller appears. The air gap deviation of the fuzzy controller is 6 times smaller than the deviation of the state controller (unloading 30 kg). The current peak values of the fuzzy controller are smaller than those of the state controller. Based on simulations with ideal components one can say that the performance of the fuzzy controller is superior to the performance of the state controller. Unfortunately ideal components do not exist and therefore simulations using components with real behaviour must follow to analyse the robust performance of both controllers.

## 4.2 Simulation with noisy air gap signals

From a noisy sensor signal measured on another test bench a suitable noise source is derived and added to the system as shown in the block diagram (figure 12). A moving average filter is introduced

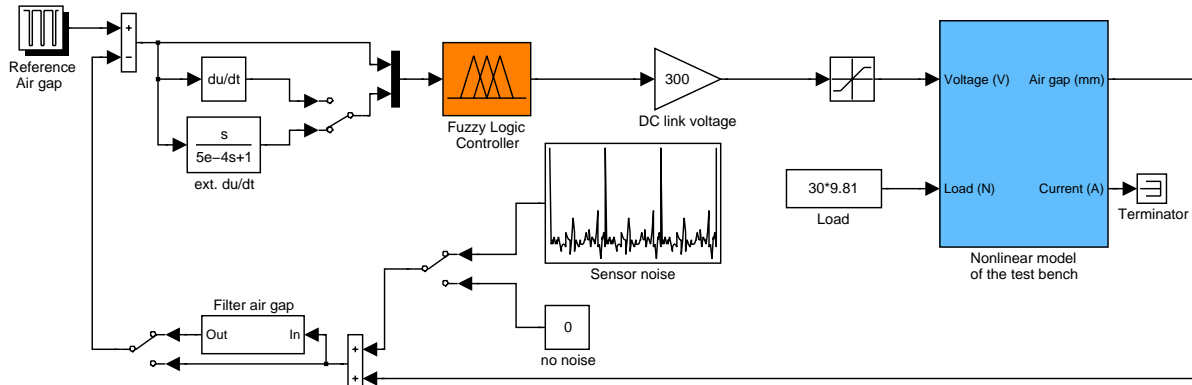


Figure 12: Block diagram of the fuzzy controller

and the derivative is built with a D-T1 element to reduce the impact of quantisation noise. The simulations of section 4.1 are then repeated with the Fuzzy-Slow and state controller with a 30 kg load.

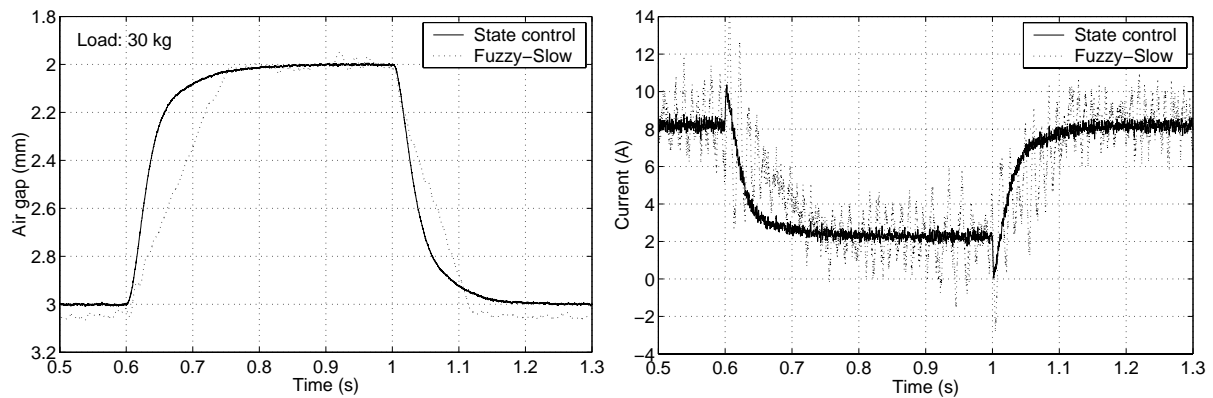


Figure 13: Input response (noisy air gap signal)

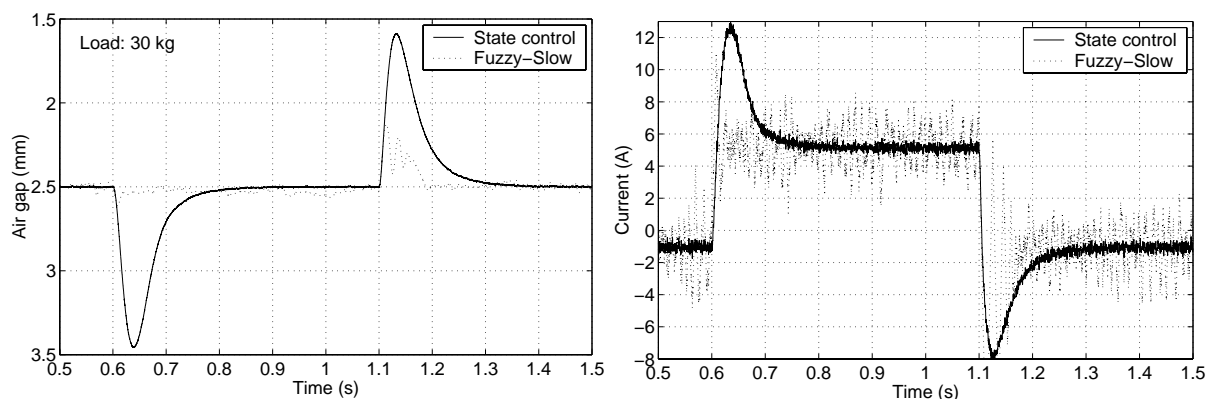


Figure 14: Disturbance response (noisy air gap signal)

The comparison between figures 13/14 and figures 10/11 shows that the performance of the state controller is not affected by the noisy air gap signal when it is correctly filtered. The performance of the fuzzy controller suffers drastically under noisy conditions, causing large air gap deviations and offset errors to occur. The reason for this poor performance lies in the calculation of the air gap deviation velocity. The disturbed velocity signal causes wide spread control voltage values which in turn cause large current oscillations and the bad levitation performance. Therefore a smooth velocity

signal is needed. To achieve this goal the first possibility is the use of higher order filters. However the higher order leads to more phase delay which in turn decreases the performance. The better solution would be to prevent noisy signals in the first place by screening noise sources and concentrating on better cabling. Based on simulations carried out with noisy signals, it is has been concluded that the use of the discussed fuzzy controller is only realistic in a system with very low noise levels.

## 5 Measurement results

Both control algorithms are implemented on a state-of-the-art DS1103 PPC Controller Board. The real-time code is generated by Real-Time Interface (dSPACE) together with Real-Time Workshop (The Mathworks). With ControlDesk (dSPACE) variables can easily be displayed and stored. It is also possible to adjust control parameters on-line until a satisfying dynamical performance is obtained.

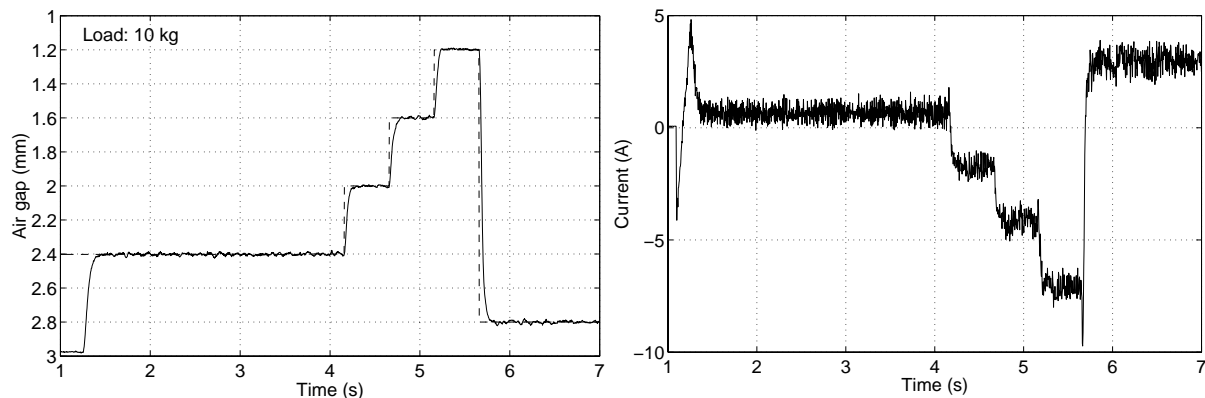


Figure 15: Lift-off and step response (State control)

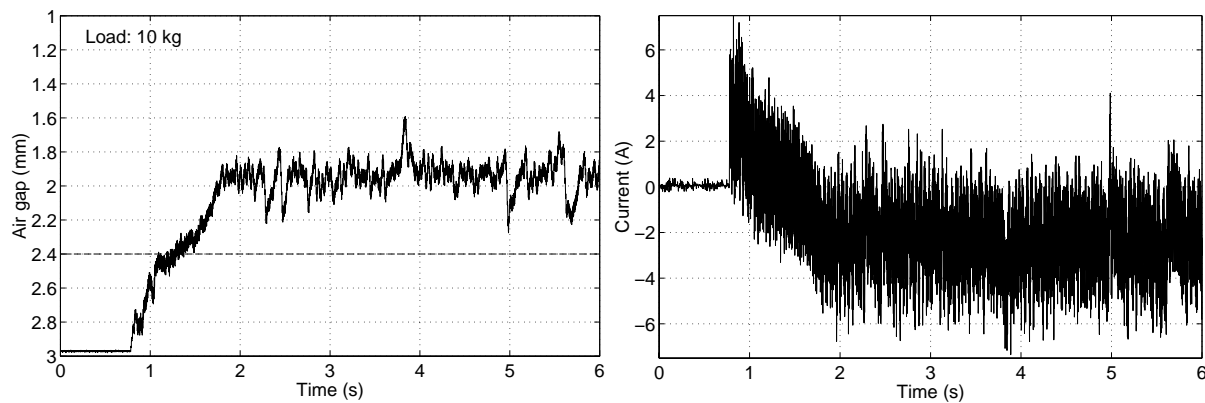


Figure 16: Lift-off (Fuzzy-Slow)

The sampling time is  $40 \mu\text{s}$  and 16 bit ADC-converters are used. Measurement results of the state controller are shown in figure 15. It can be seen that the step response of the system is very good over the complete air gap range and the state controller has a stable and robust performance. The results from the simulations can be verified with the measurement results. The practice tests of the fuzzy controller are considerably worse than those obtained from the simulation results. Figure 16 shows a lift-off from 3 mm to 2.4 mm. There is a big offset error and no real stable performance.

## 6 Discussion and Conclusion

The promising simulation results (with noise-free signals) presented in the papers [4] and [5] and the fact that a fuzzy controller of the presented type works well in magnetic bearings for rotating machines [2], were the reasons for making a comparison between a state controller and a fuzzy controller for a 1 DOF maglev application.

The presented fuzzy controller emerges as very noise sensitive. One should notice that the air gap range of the application (0.75 .. 4 mm) is much greater than the air gap range of magnetic bearings. Because the system noise of eddy current sensors grows with increasing measurement range it is hard to get a noise-free air gap signal which is absolutely necessary to derive a useful velocity signal. The presented fuzzy controller with air gap deviation and air gap deviation velocity as the only input signals is not a good option for this application unless more complex filters are used and there is a better EMC design to prevent noisy signals.

To protect converters from damage, in practice the coil current is always measured. It is thought that the robustness of a fuzzy controller could be an important benefit when the current is used as a third input signal. However completing the rule base becomes much harder than in the case of having only two input signals.

In the future the authors will focus on the use of the state controller for this application.

## 7 References

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