

**Magnetic Levitation
Control Experiments
33-942S**



Feedback



Interactive Discovery Software



Electricity & Electronics



Control & Instrumentation



Process Control



Mechatronics



Telecommunications



Electrical Power & Machines



Test & Measurement

Technology Training for tomorrow's world



Magnetic Levitation Control Experiments

33-942S

(For use with MATLAB
R2006b version 7.3)

Feedback Instruments Ltd., Park Road, Crowborough, East Sussex, TN6 2QR, UK
Telephone: +44 (0) 1892 653322, Fax: +44 (0) 1892 663719
E-mail: feedback@fbk.co.uk, Website: www.fbk.com

Manual: 33-942S Ed01 122006
Feedback Part No. 1160-33942S

THE HEALTH AND SAFETY AT WORK ACT 1974

We are required under the Health and Safety at Work Act 1974, to make available to users of this equipment certain information regarding its safe use.

The equipment, when used in normal or prescribed applications within the parameters set for its mechanical and electrical performance, should not cause any danger or hazard to health or safety if normal engineering practices are observed and they are used in accordance with the instructions supplied.

If, in specific cases, circumstances exist in which a potential hazard may be brought about by careless or improper use, these will be pointed out and the necessary precautions emphasised.

While we provide the fullest possible user information relating to the proper use of this equipment, if there is any doubt whatsoever about any aspect, the user should contact the Product Safety Officer at Feedback Instruments Limited, Crowborough.

This equipment should not be used by inexperienced users unless they are under supervision.

We are required by European Directives to indicate on our equipment panels certain areas and warnings that require attention by the user. These have been indicated in the specified way by yellow labels with black printing, the meaning of any labels that may be fixed to the instrument are shown below:



CAUTION -
RISK OF
DANGER



CAUTION -
RISK OF
ELECTRIC SHOCK



CAUTION -
ELECTROSTATIC
SENSITIVE DEVICE

Refer to accompanying documents

PRODUCT IMPROVEMENTS

We maintain a policy of continuous product improvement by incorporating the latest developments and components into our equipment, even up to the time of dispatch.

All major changes are incorporated into up-dated editions of our manuals and this manual was believed to be correct at the time of printing. However, some product changes which do not affect the instructional capability of the equipment, may not be included until it is necessary to incorporate other significant changes.

COMPONENT REPLACEMENT

Where components are of a 'Safety Critical' nature, i.e. all components involved with the supply or carrying of voltages at supply potential or higher, these must be replaced with components of equal international safety approval in order to maintain full equipment safety.

In order to maintain compliance with international directives, all replacement components should be identical to those originally supplied.

Any component may be ordered direct from Feedback or its agents by quoting the following information:

- | | |
|------------------------|----------------------------|
| 1. Equipment type | 3. Component value |
| 2. Component reference | 4. Equipment serial number |

Components can often be replaced by alternatives available locally, however we cannot therefore guarantee continued performance either to published specification or compliance with international standards.

OPERATING CONDITIONS

WARNING:

This equipment must not be used in conditions of condensing humidity.

This equipment is designed to operate under the following conditions:

Operating Temperature 10°C to 40°C (50°F to 104°F)

Humidity 10% to 90% (non-condensing)

CE DECLARATION CONCERNING ELECTROMAGNETIC COMPATIBILITY

Should this equipment be used outside the classroom, laboratory study area or similar such place for which it is designed and sold then Feedback Instruments Ltd hereby states that conformity with the protection requirements of the European Community Electromagnetic Compatibility Directive (89/336/EEC) may be invalidated and could lead to prosecution.

This equipment, when operated in accordance with the supplied documentation, does not cause electromagnetic disturbance outside its immediate electromagnetic environment.

COPYRIGHT NOTICE

© Feedback Instruments Limited

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of Feedback Instruments Limited.

ACKNOWLEDGEMENTS

Feedback Instruments Ltd acknowledge all trademarks.

MATLAB is a registered trademark of Mathworks Inc.

IBM, IBM - PC are registered trademarks of International Business Machines.

MICROSOFT, WINDOWS XP, WINDOWS 2000, WINDOWS ME, WINDOWS NT, WINDOWS 98, WINDOWS 95 and Internet Explorer are registered trademarks of Microsoft Corporation.

Table of Contents

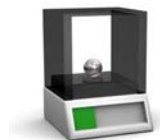
Manual overview	1
Introduction	2
Magnetic Levitation set description	3
Magnetic Levitation model	5
Exercise 1 - Nonlinear model testing.....	7
Model linearisation	10
Exercise 2 - Linear model	10
Maglev model identification	12
Model identification	13
Exercise 3 - Model identification	14
Maglev setup control	17
Plant control	17
PID controller	18
Maglev position control	19
Exercise 4 - PD control of ball position	19
Exercise 5 - Real time PD control of ball position.....	21
Exercise 6 -Real time PID control of ball position.....	24
Advanced Maglev control.....	25
Exercise 7 - WMV ball position model control	26
Exercise 8 - WMV ball position Real Time control.....	27
Additional Experiments	28
Exercise 9 - Stand alone controller tracking	28
Exercise 10 - External set point	29

Manual overview

The following manual refers to the Feedback Instruments Magnetic Levitation Control application. It serves as a guide for the control tasks and provides useful information about the physical behaviour of the system. A nonlinear model is proposed, linearisation methods and then identification algorithms are introduced. The models obtained are compared with the phenomenological model and the Magnetic Levitation setup (Maglev). Control algorithms are developed, tested on the models and then implemented in a real time application.

Throughout the manual various exercises are proposed to bring the user closer to the Maglev control problem. Depending on the knowledge level of the user some of the sections and exercises can be skipped. The more advanced users can try to model, identify and control the Maglev on their own from the beginning.

The relative difficulty of each exercise is indicated using the following icons:



easy level,



medium level,



expert level.

If any of the identification or controller design exercises appear to be too difficult or the results are not satisfactory you may go straight to the examples that are supplied and test them by changing the parameters of the controllers.

Introduction

The Maglev setup serves as a simple model of devices, which are becoming more and more popular in recent years i.e. Maglev trains and magnetic bearings. Maglev trains are recently tested and some lines are already available as for example in Shanghai. Magnetic bearings are used in turbines for the same reason as Maglev trains are being built, which is low friction in the bearing itself. Already many turbines are used commercially where the rotating shaft is levitated with magnetic flux. Some other magnetic bearings applications include pumps, fans and other rotating machines.

The magnetic levitation systems are appealing for their additional possibility of active vibration damping. This can be done by various control algorithms implementations and without any modifications to the mechanical parts of the whole system.

The Maglev unit allows for the design of different controllers and tests in real time using Matlab and Simulink environment.

Magnetic Levitation set description

The description of the Maglev setup in this section refers to the mechanical-electrical part and the control aspect. For details on how the signals are measured and transferred to the PC, refer to the '*Installation & Commissioning*' manual.

As shown in Figure 1, the Maglev unit consists of a Connection-Interface Panel with a Mechanical Unit on which a coil is mounted. An infra-red sensor is attached to the Mechanical Unit. Two steel spheres are included in the package.

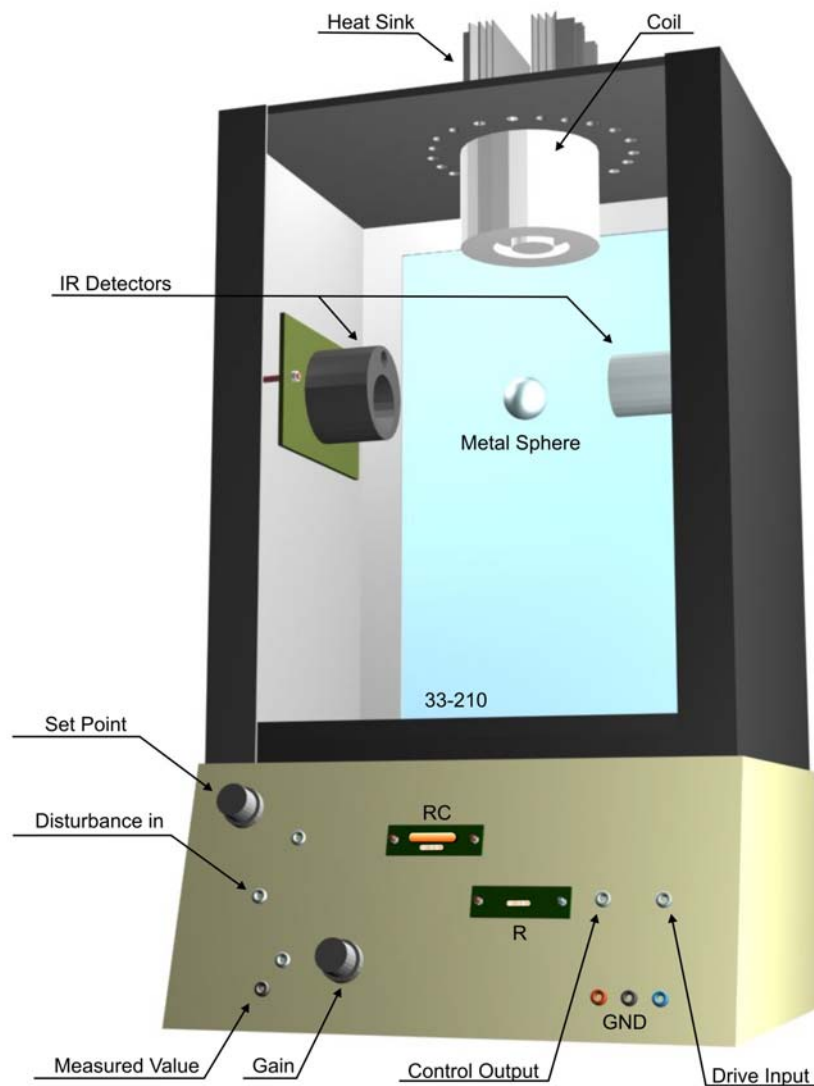


Figure 1 Maglev mechanical unit

Apart from the mechanical units electrical units play an important role in Maglev control. They allow measured signals to be transferred to the PC via an I/O card. The Analogue Control Interface is used to transfer control signals from the PC to Maglev and back. The mechanical and electrical units provide a complete control system setup presented in Figure 2.

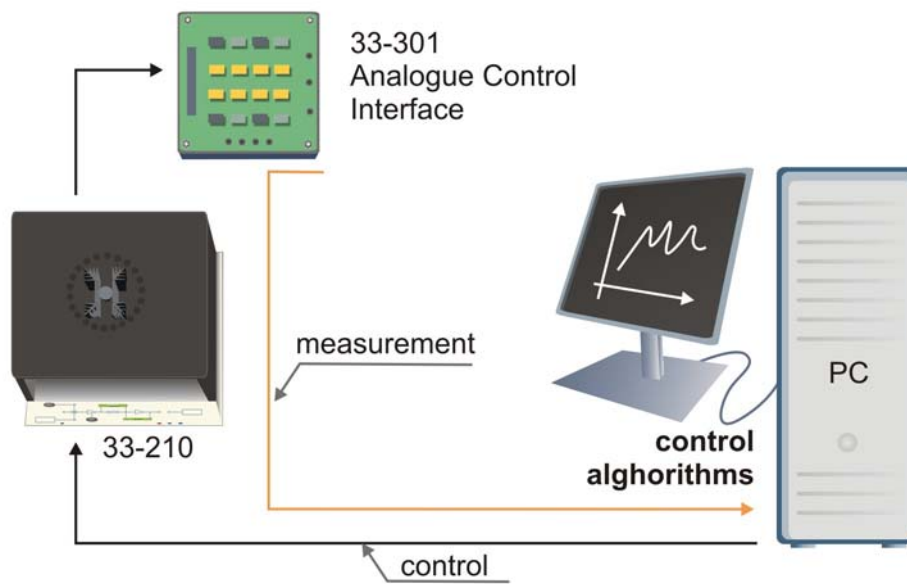


Figure 2 Maglev control system

In order to design any control algorithms one must first understand the physical background behind the process and carry out identification experiments. The next section explains the modelling process of the Magnetic Levitation.

Magnetic Levitation model

Every control project starts with plant modelling, so as much information as possible is given about the process itself. The mechanical-electrical model of Maglev is presented in Figure 3.

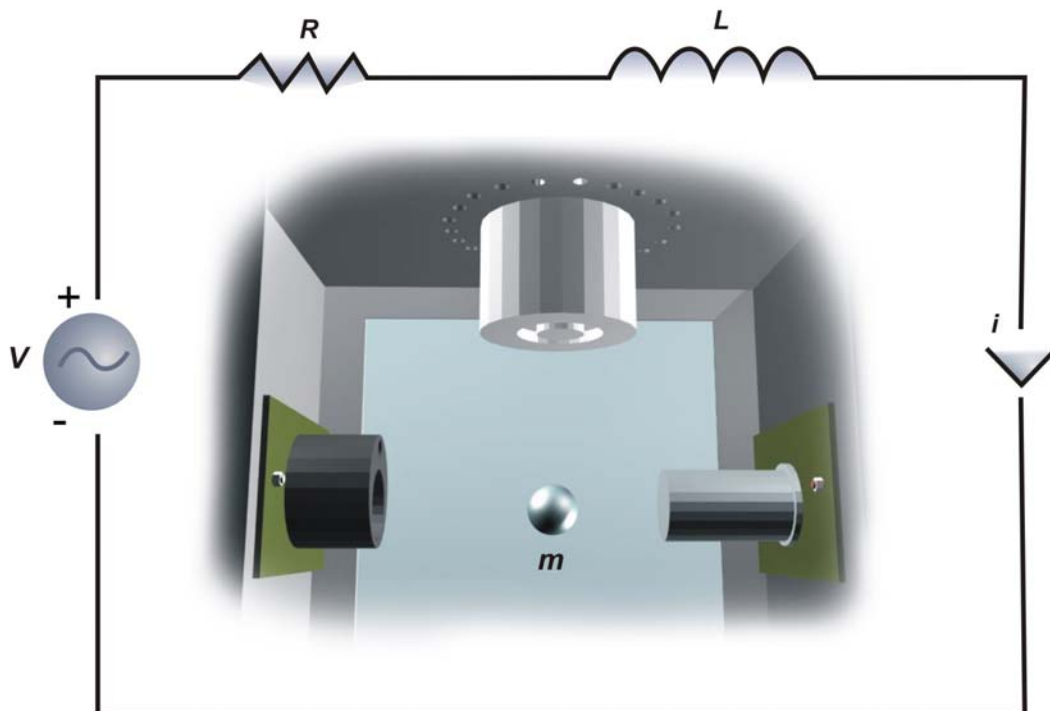


Figure 3 Maglev phenomenological model

Usually, phenomenological models are nonlinear, that means at least one of the states (i – current, x – ball position) is an argument of a nonlinear function. In order to present such a model as a transfer function (a form of linear plant dynamics representation used in control engineering), it has to be linearised.

According to the electrical-mechanical diagram presented in Figure 3 the nonlinear model equations can be derived.

The simplest nonlinear model of the magnetic levitation system relating the ball position and the coil current i is the following:

$$m \cdot \ddot{x} = m \cdot g - k \frac{i^2}{x^2} \quad (1)$$

where k is a constant depending on the coil (electromagnet) parameters. To present the full phenomenological model a relation between the control voltage u and the coil current would have to be introduced analysing the whole Maglev circuitry. However Maglev is equipped with an inner control loop providing a current proportional to the control voltage that is generated for control purpose:

$$i = k_1 \cdot u . \quad (2)$$

Equations (1) and (2) constitute a nonlinear model, which has been assembled in Simulink.

The bound for the control signal is set to $[-5V \dots +5V]$.

Maglev is a SISO plant – single input single output (Figure 4). Position is the model output and voltage is the control signal.



Figure 4 Maglev model for position control

Exercise 1 – Nonlinear model testing**Introduction**

For the initial exercise the user has been provided with the nonlinear Maglev model described by equations (1) and (2). The model can be opened in Simulink - *Maglev_NonlinModel.mdl*. It is possible that the assembled phenomenological model responds differently from the Maglev Unit. This might be caused by differences in the model structure itself as well as the value of the chosen parameters. However these differences can easily be detected during the course of identification. One can also modify the phenomenological model by adding gain or by certain parameter tuning.

Load Matlab and the menu system using the Windows Start menu (Figure 5).



Figure 5 Start menu

Matlab will run and the Simulink model menu will open (Figure 6). This contains links to the simulation-only models (Maglev Simulation Models), the real-time models (Maglev Servo Real-Time Models) and the manual documents.

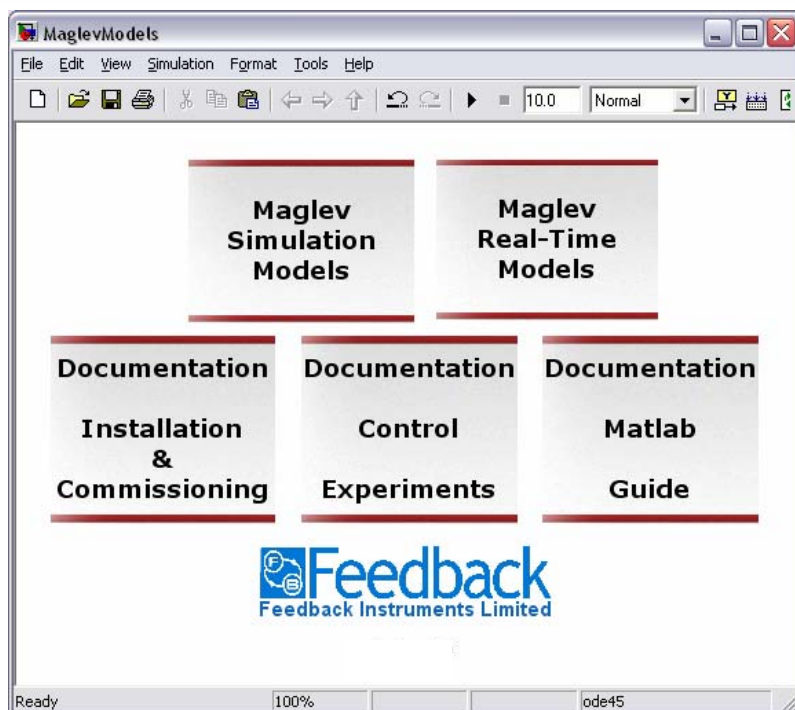


Figure 6 Simulink model menu

Double click on the 'Maglev Simulation Models' block in the main menu. A sub-menu containing all of the simulation-only models will open (Figure 7).

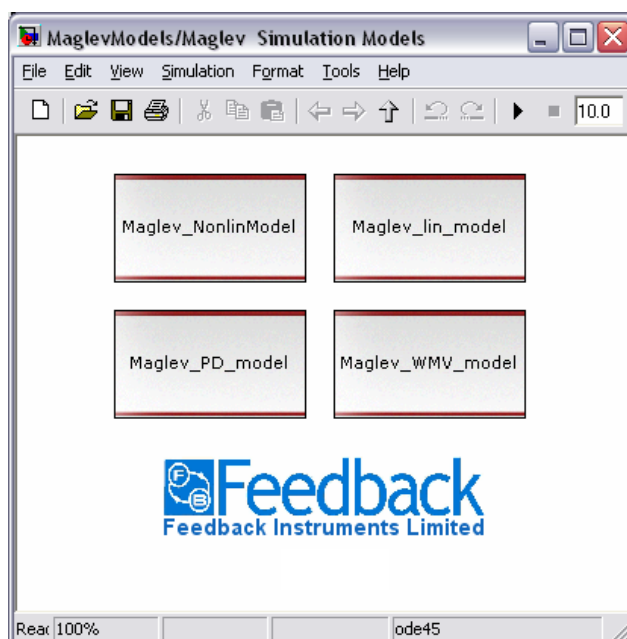


Figure 7 Simulation models menu

Double click the required model *Maglev_NonlinModel.mdl*. The Simulink model window will open.

Task

To begin with the user is advised to check the responses of the Maglev model (*Maglev_NonlinModel.mdl*). Of course without any control applied the ball will keep on falling so we can imagine what will happen with the model response with $u = 0$. Run the test with other values of control signal by changing the input selector value.

Example results and comments

Figure 8 presents the response of the Maglev model when no control voltage is applied.

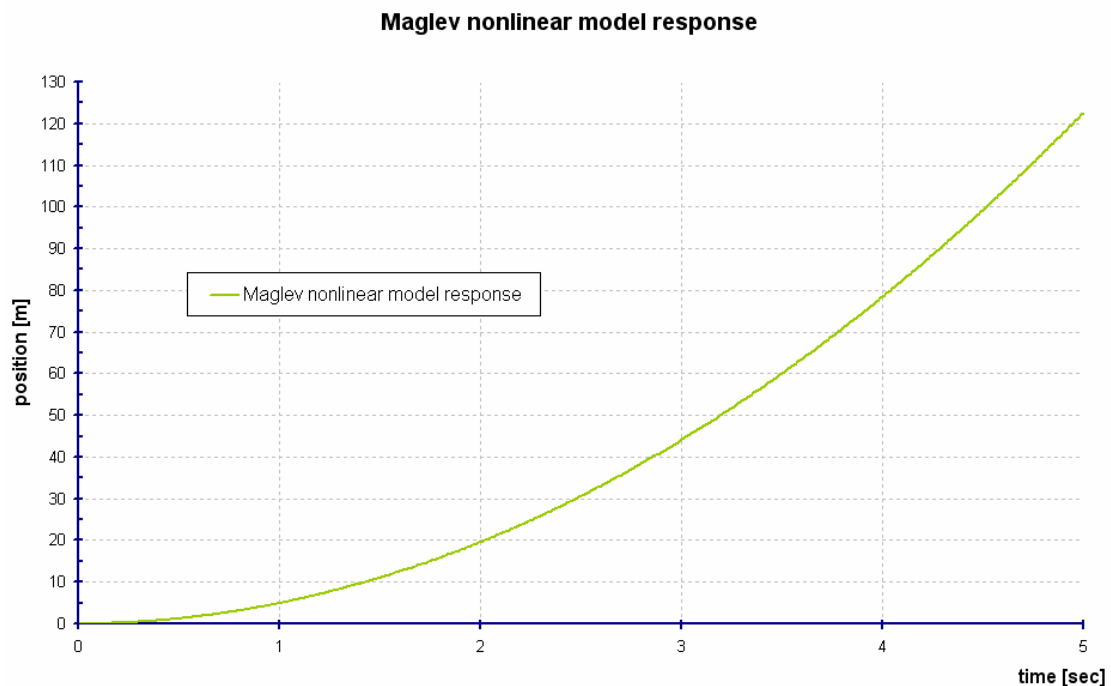


Figure 8 Maglev model response

Model linearisation

To carry out analysis of the model dynamics for open loop¹ systems using techniques such as Bode plots, poles and zeros maps, Nyquist plots, root locus (for closed loop² systems only), the model has to be linearised. Such a linearization is done in the equilibrium point of $x_0 = -1.5$ [V] (the position is expressed in volts), $i_0 = 0.8$ [A]:

$$\ddot{x} = g - f(x, i), \quad f(x, i) = k \frac{i^2}{m \cdot x^2} \quad (3)$$

equilibrium point can be calculated from:

$$g = f(x, i) \Rightarrow i_0, x_0. \quad (4)$$

The linearisation steps are the following:

$$\ddot{x} = - \left(\left. \frac{\partial f(i, x)}{\partial i} \right|_{i_0, x_0} \Delta i + \left. \frac{\partial f(i, x)}{\partial x} \right|_{i_0, x_0} \Delta x \right), \quad (5)$$

$$s^2 \Delta x = -(K_i \Delta i + K_x \Delta x), \quad (6)$$

$$s^2 \Delta x + K_x \Delta x = -K_i \Delta i, \quad (7)$$

$$\Delta x (s^2 + K_x) = -K_i \Delta i, \quad (8)$$

$$\frac{\Delta x}{\Delta i} = \frac{-K_i}{s^2 + K_x}, \quad (9)$$

where

$$K_i = 2mg/i_0 \text{ and } K_x = -2mg/x_0.$$

Exercise 2 – Linear model

Introduction

According to the equation (9) a linear model has been assembled in Simulink. You can run similar experiments on it as for the nonlinear model in Exercise 1.

Task

Run the linear (*Maglev_lin_model.mdl*) and compare the responses. Also, with the use of Matlab, the Bode diagrams, zeros and poles maps can be drawn to carry out initial dynamic response analysis of the Maglev system.

¹ Open loop system – the plant without a controller

² Closed loop system – the plant and controller with a negative feedback loop, see “Control” section for more information.

Example results and comments

Figure 9 presents the response of the Maglev model when no control voltage is applied.

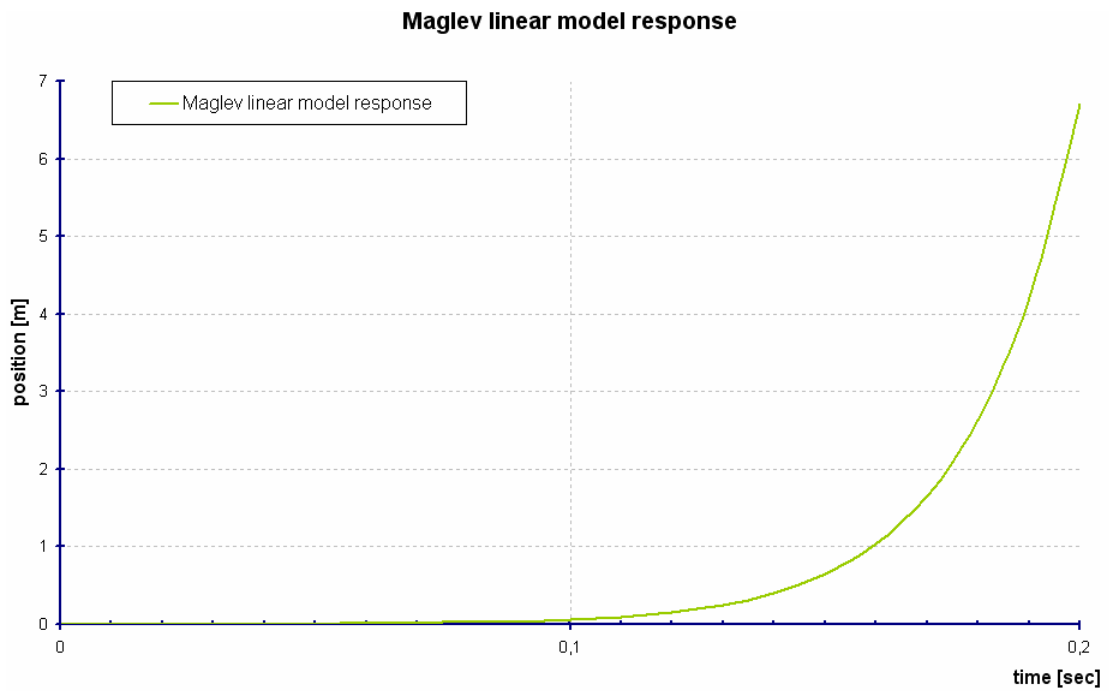


Figure 9 Linear model response

Maglev model identification

In the previous section a phenomenological model was derived and then linearised. A model can be identified through an identification experiment, upon which controllers will be designed, which is described in the “*Maglev Control*” section. This section however explains how the discrete Maglev model identification is carried out.

There are a few important things that the control system designer has to keep in mind when carrying out an identification experiment:

- *Stability problem* – if the plant that is identified is unstable, the identification has to be carried out with a working controller, which introduces additional problems that will be discussed further on. If the plant is stable and does not have to work with a controller the identification is much simpler.
- *Structure choice* – a very important aspect of the identification. For linear models it comes down to choice of the numerator and denominator order of the transfer function. It applies both for continuous and discrete systems.

As far as the discrete models are concerned the structures are also divided in terms of the error term description: ARX, ARMAX, OE, BJ³.

- *Sampling time* – the sampling time choice is important both for identification and control. It cannot be too short nor can it be too long. Too short sampling time might influence the identification quality because of the quantisation effect introduced by the AD. Furthermore the shorter the sampling time the faster the software and hardware has to be and more memory is needed. However short sampling time will allow for elimination of aliasing effects and thus anti aliasing filters⁴ will not have to be introduced. Long sampling times will not allow for including all of the dynamics.
- *Excitation signal* – for the linear models the excitation choice is simple. Very often designers use white noise however in industrial applications it is often disallowed. It is attractive however because of the fact that it holds very broad frequency content thus the whole dynamics of the plant can be identified. If the dynamics are not too complex several

³ More information about these structures can be obtained during the System Identification courses.

⁴ These are the basics of the Digital Signal Processing course. For more insight the user is asked to study more on signal processing and digital control.

sinusoids with different frequencies can be summed to produce a satisfactory excitation signal.

- *Identification method* – usually two methods are used, the Least Mean Square (LMS) method and the Instrumental Variable method. The LMS method is the most popular and is implemented in Matlab. This method minimizes the error between the model and the plant output. The optimal model parameters, for which the square of the error is minimal is the result of the identification.

Model identification

The following exercise includes all of the above facts and provides an identification experiment, which results in a discrete model of the Maglev unit. The model to be identified describes the relation between the control voltage u and the ball position expressed in volts.

Any Maglev identification tasks are difficult for the reason of instability. In order to carry out an identification experiment a controller has to be applied, otherwise the ball will fall and system dynamics cannot be identified. It is best if the working controller is discrete for the discrete model identification purpose. That is why a discrete version of the PD is used in this experiment.

The Maglev is unstable and has to be identified with a running, stabilising controller⁵ i.e. closed loop identification⁶. The controller introduces output noise and control signal correlation, which leads to model corruption. This correlation can be broken by introducing an additional excitation signal r , which is added to the control signal u (Figure 10).

If the power of the signal r is substantial compared to the noise power n , the proper model should be identified.

⁵ The Maglev control aspect is explained in the 'Maglev Control' section.

⁶ Closed loop system identification is a broad topic and more advanced users are advised to refer to identification literature to get more insight.

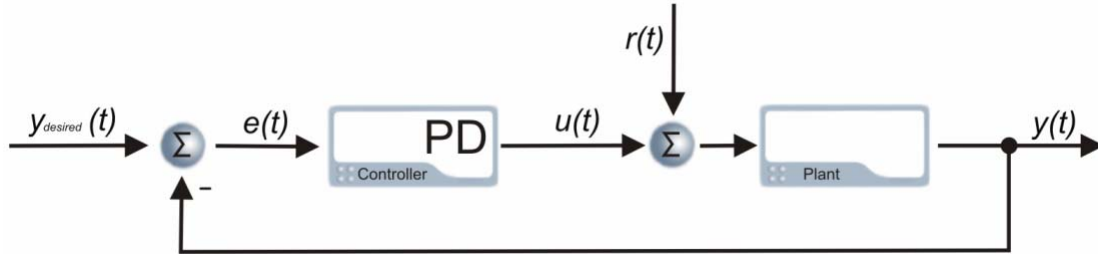


Figure 10 Unstable system identification

Such an approach will only allow for the linear model identification of the transfer function between the voltage control signal u and the position x expressed in Volts, for small deviations of the position around the equilibrium point of $x_0 = -1.5$ [V].

More intelligent identification methods should be applied for complete nonlinear Maglev model identification (gradient methods).

A closed-loop system describing the relation between signal r and y is identified:

$$T(z^{-1}) = \frac{G(z^{-1})}{1 + C(z^{-1}) \cdot G(z^{-1})}, \quad (10)$$

where $T(z^{-1})$ is the complete system discrete transfer function describing the relation between, $C(z^{-1})$ is the discrete controller transfer function and $G(z^{-1})$ is the Maglev model discrete transfer function. The relation (10) can be transformed to yield the Maglev model:

$$G(z^{-1}) = \frac{T(z^{-1})}{1 - C(z^{-1}) \cdot T(z^{-1})} \quad (11)$$

Such approach is presented in Exercise 3 to yield a complete Maglev model.

Exercise 3 – Model identification



Introduction

Most of the control real time simulations are carried out with a sampling time of $T_s = 0.001$ [s]. The model identification is carried out however with a sampling time of 0.01 [s] so the model can be used for Advanced Controller Synthesis (WMV controller). For the identification the Matlab System Identification Toolbox is used.

The identification experiment is carried out using the model called *MaglevIdent.mdl*. This model controls ball levitation and adds an extra excitation signal to the controller output. The response is recorded. The excitation signal is a random signal. The experiment lasts 30 seconds and two signals are collected in the form of vectors and are available in the Workspace.

Task

Run the model in Simulink. Be prepared to uphold the ball with your hand without position measurement disturbance. You have 10 seconds until the identification is carried out. The IR sensor cannot be covered at that point with your hand. Make sure the ball will not fall down during the identification. If so, reduce the “*signal_gain*” value and repeat the experiment.

For instructions on identification experiments refer to the ‘*Matlab Guide*’ manual.

One of the possible closed loop system model orders is oe331. When you identify the complete transfer function $T(z^{-1})$ extract the Maglev transfer function according to equation (10). Use the *Mextract.m* file to perform that transformation. Type ‘*help Mextract*’ to view help on this file. The model is also transformed into a continuous form.

The obtained continuous model will be used in the PID controller design section. The discrete model version is used for the WMV controller synthesis.

Example results and comments

Since the Maglev model is unstable it is difficult to make the comparison of the step response. That is why performance of the closed loop system is compared $T(z^{-1})$ for the model and experiment data Figure 11. Use the *ModelTest.mdl* for that purpose. This experiment will run a PD controller used for the identification on the Maglev Unit. In parallel same controller is used for model control. During the experiment the desired position value is changed in a step manner. You can compare the closed loop Maglev Unit and identified model performance. To test your model replace the implemented in *ModelTest.mdl* Maglev model with the model that you have acquired in the identification procedure.

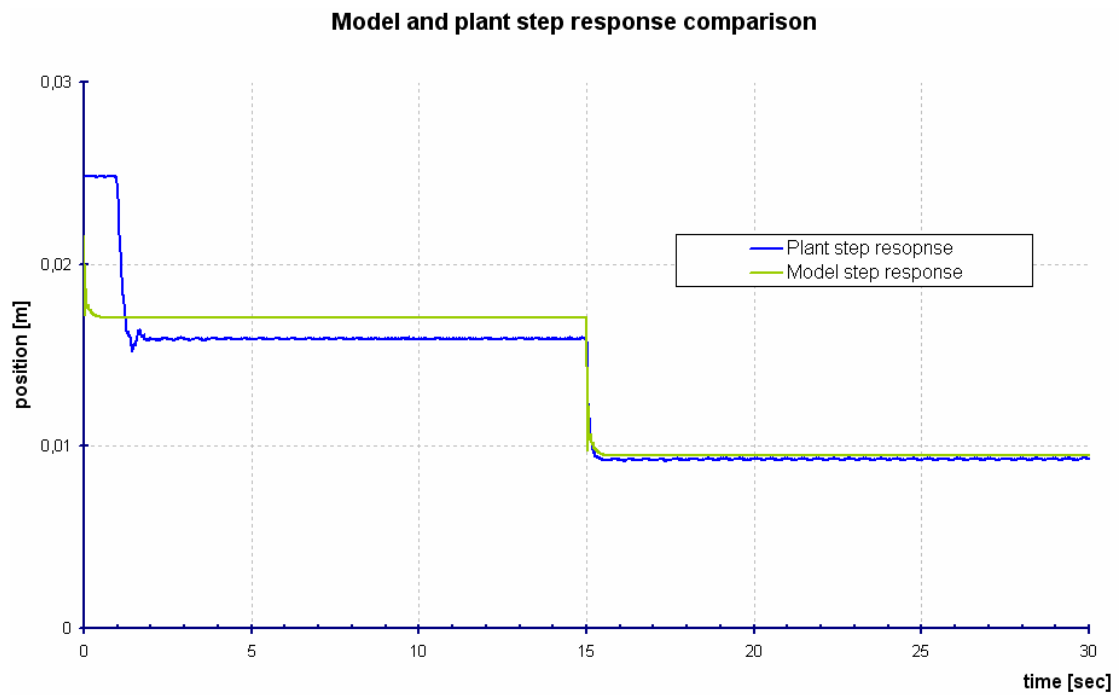


Figure 11 Model and plant closed loop response

Maglev setup control

The Maglev control aspect covers one area, which is the position control. Matlab provides various analysis methods for linear systems as far as dynamics are concerned (root locus, frequency analysis tools – Bode diagrams, Nyquist plots, pole and zero maps etc.). With the information that Matlab provides about the dynamics of the system, controllers can be designed. The following sections explain how the PID controller works, and how it can be tuned.

Plant control

There are numerous control algorithms however the PID control is the most popular because of its simplicity. A general schematic of a simple control closed loop system is presented in Figure 12.

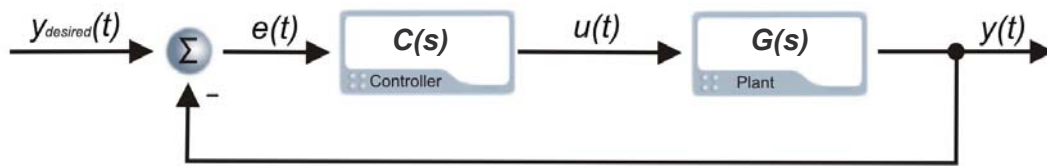


Figure 12 Simple control system – closed loop

Assuming that the plant is represented by its linear model its transfer function can be described as:

$$G(s) = \frac{B(s)}{A(s)} \quad (9)$$

where s is the Laplace operator. The idea of control algorithms is to find such a controller (transfer function, discrete transfer function, any nonlinear), which will fulfil our requirements (certain dynamic response, certain frequency damping, good response to the dynamic changes of the desired value etc.). Every controller's input is the $e(t)$ error signal. Sometimes disturbance signals are also measured. Depending on the present and past values of the error signal, the controller performs such an action (changes the $u(t)$ control signal) that the $y(t)$ is as close to the $y_{desired}(t)$ value as possible at all times.

There are a lot of controller design and tuning methods. All of them consider the behaviour of the '*closed loop system*' (plant with a controller Figure 12) and provide

controller parameters according to the assumed system characteristics. With the known plant transfer function $G(s)$ it is possible to find satisfactory parameters of the $C(s)$ controller such that the closed loop system will have the desired characteristics described by the transfer function $T_c(s)$:

$$T_c(s) = \frac{C(s) \cdot G(s)}{1 + C(s) \cdot G(s)} \quad (10)$$

PID controller

A PID controller consists of 3 blocks: **P**roportional, **I**ntegral and **D**erivative. The equation governing the PID controller is as follows:

$$u(t) = P \cdot e(t) + I \cdot \int e(t) dt + D \cdot \frac{de(t)}{dt} \quad (11)$$

$$e(t) = y_{desired}(t) - y(t) \quad (12)$$

With the means of the Laplace transform such a structure can be represented as a transfer function:

$$U(s) = \left(P + \frac{I}{s} + D \cdot s\right) \cdot E(s) \quad (13)$$

$$C(s) = \frac{U(s)}{E(s)} = \left(P + \frac{I}{s} + D \cdot s\right) = \frac{Ds^2 + Ps + I}{s} \quad (14)$$

Each of the PID controller blocks (P , I and D) plays an important role. However for some applications, the Integral or Derivative part has to be excluded to give satisfactory results. The Proportional block is mostly responsible for the speed of the system reaction. However for oscillatory plants it might increase the oscillations if the value of P is set to be too large.

The Integral part is very important and assures zero error value in the steady state, which means that the output will be exactly what we want it to be. Nevertheless the Integral action of the controller causes the system to respond slower to the desired value changes and for systems where very fast reaction is very important it has to be omitted. Certain nonlinearities will also cause problems for the integration action.

The Derivative part has been introduced to make the response faster. However it is very sensitive to noise and may cause the system to react very nervously. Thus very often it is omitted in the controller design. Derivative part output filtering may reduce the nervous reaction but also slows the response of the controller down and sometimes undermines the sense of using the Derivative part at all. Proper filtering

can help to reduce the high frequency noise without degrading the control system performance in the lower frequency band.

There are several PID tuning techniques. Most often Ziegler-Nichols rules are used or a relay experiment is undertaken. Very often the closed loop system roots are analysed and set in the desired position by proper choice of P , I and D values. Matlab delivers a root locus tool, which helps in such designs. To gain an understanding of root locus controller design and its effects on the system, a motor velocity control exercise is proposed.

Maglev position control

As a first control task, PD position control of the Maglev is chosen. The following exercises will guide you through the controller design, testing on the model and on the real time application.

Exercise 4 – PD control of ball position



Introduction

To design a PD controller a model of the plant is needed. For this purpose we can use a discrete model and design a discrete PD controller, or use a continuous model (equation 9) and design a continuous PD controller, however when a controller is implemented on some kind of a control unit it has to be used in a discrete form. The continuous model can also be obtained from the identified discrete model using Matlab 'd2c' function.

For controller design the continuous model obtained in the identification experiment is used.

Task

Design a PD controller using the transfer function obtained in the identification experiment or one described by equation (9). Input the transfer function in Matlab using the ' tf ' command. The discrete model obtained in *Maglev Model Identification* section can be transformed into a continuous model before the controller design.

For instructions on controller tuning refer to the '*Matlab Guide*' manual.

Example results and comments

The root locus of the identified model with the PD control with $P = 4$, $D = 0.2$ is presented in Figure 13.

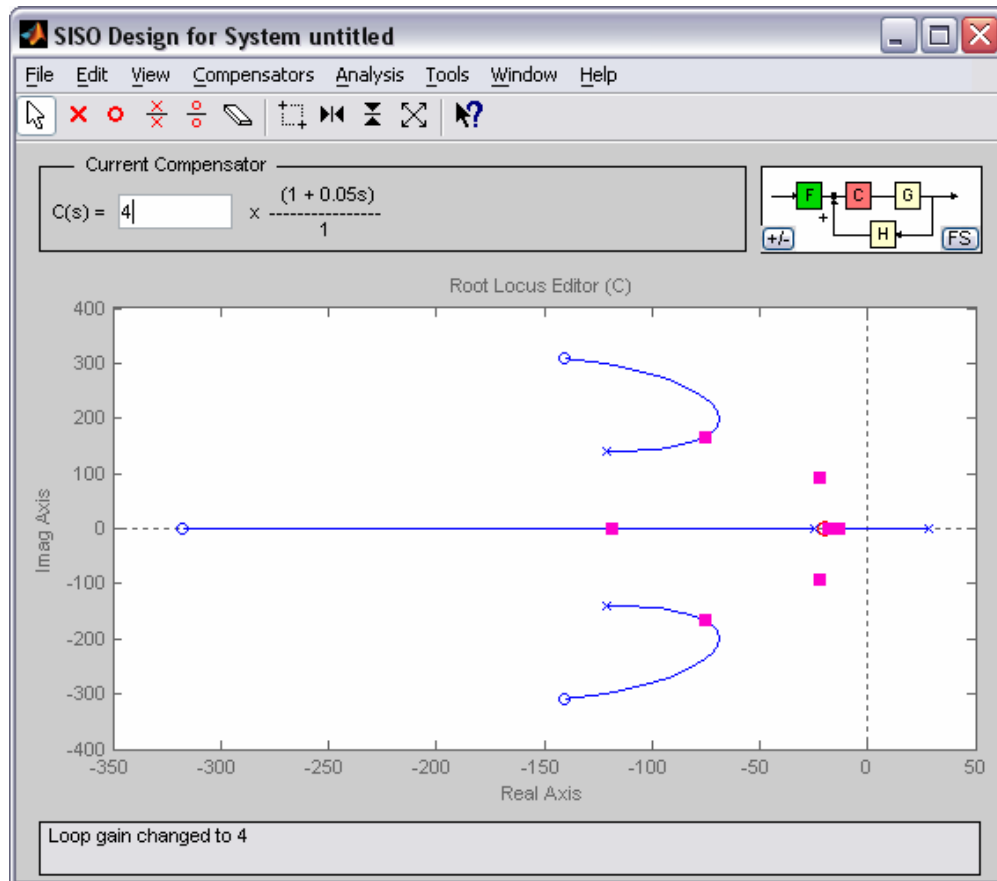


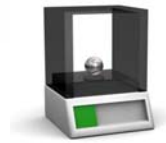
Figure 13 Root locus with PD controller

You can move the poles, zeros and the gain to obtain for example faster step response of the closed loop system. Then you can export the controller into Workspace and test it on the model of the Maglev with *Maglev_PD_model.mdl*.

Use a sinusoidal signal for the set value of the ball position $x_{desired}(t)$. Change the frequency and see how the output follows the desired value. Decrease and increase the values of the proportional, integral and derivative gains in the PID controller. See how that influences the tracking of the desired value.

The controller that has been obtained in the above exercise can be tested on the Maglev setup. The following exercise will guide you through it.

Exercise 5 – Real time PD control of ball position



Introduction

Just as in exercise 4 the ball position will be controlled. This time it will be tested in real time. For this exercise use the *Maglev_PD.mdl* presented in Figure 14.

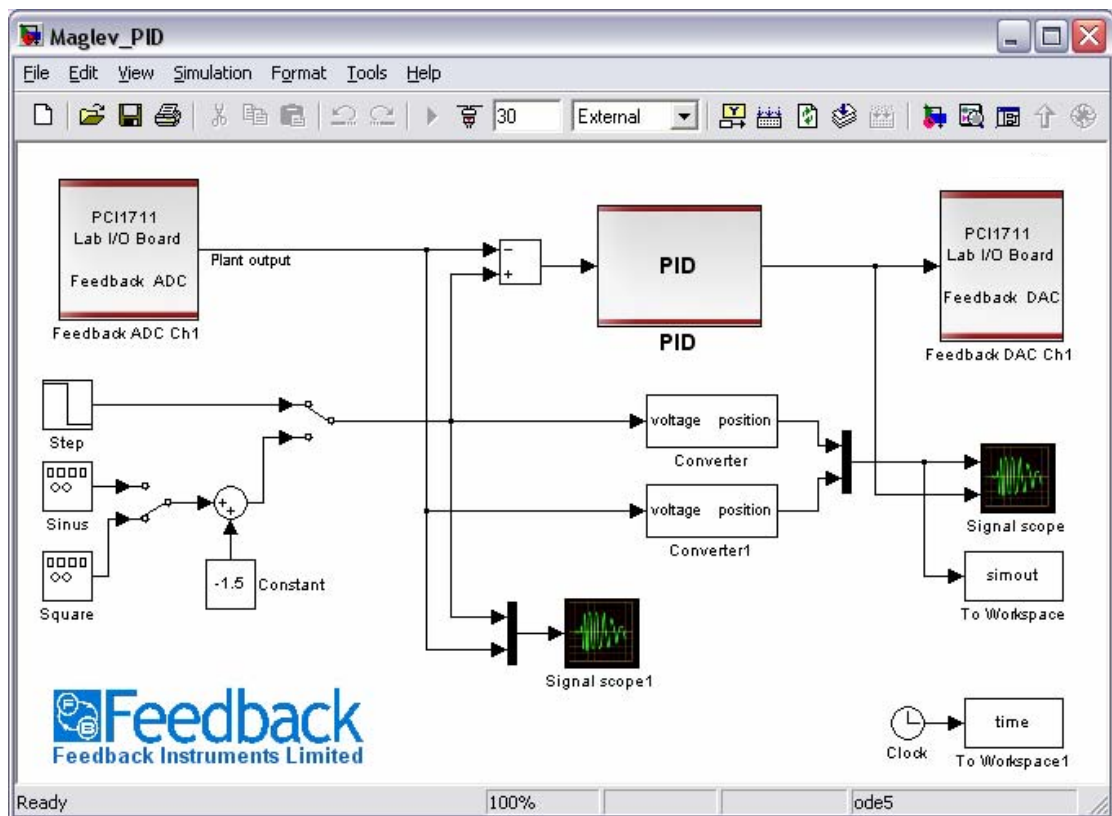


Figure 14 Real time Maglev position control

As you open the *Maglev_PD.mdl* you will notice that this simulation is directed to an external module, which is indicated in the upper part of the simulation window. The PD controller has been already designed, however you can change its parameters according to the results obtained in exercise 5.

Before you run the real time simulation make sure the PMS setup is properly connected. Refer to the '*Installation & Commissioning*' manual for more instructions on real time simulations.

Task

The task is to change the sinusoidal or rectangular $x_{desired}(t)$ signal frequency and see how the cart reacts to it. Change the controller P and D values to see how the signal $x_{desired}(t)$ is tracked by the system output.

You should already gain some experience in exercise 5 on how the values of these gains can be changed.

Example results and comments

Figure 15 and Figure 16 present real time simulation results of the PD ball position control. Two P and D gain values have been selected. You should notice that the bigger the D value the faster the response but the more nervous the control signal u . Very energetic control signal changes can often lead to control unit brake down.

Without integral part the error will not be brought down to 0 but the system performance is fast, which in magnetic levitation experiments and unstable plants is important.

Maglev position control: $P=4$, $D=0.2$

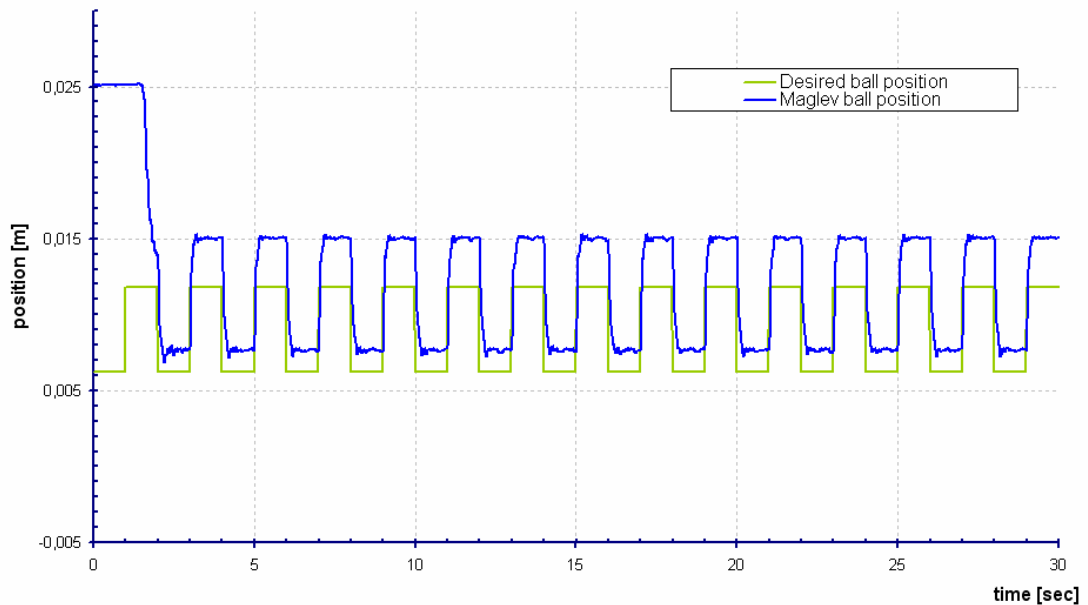


Figure 15 PD control with $P = 4$, $D = 0.2$

The result presented in Figure 15 proves how efficient controllers can be when an identification experiment is incorporated in their design. Figure 16 shows how wrong controller tuning may degrade the system performance.

Maglev position control: $P=2.5$, $D=0.05$

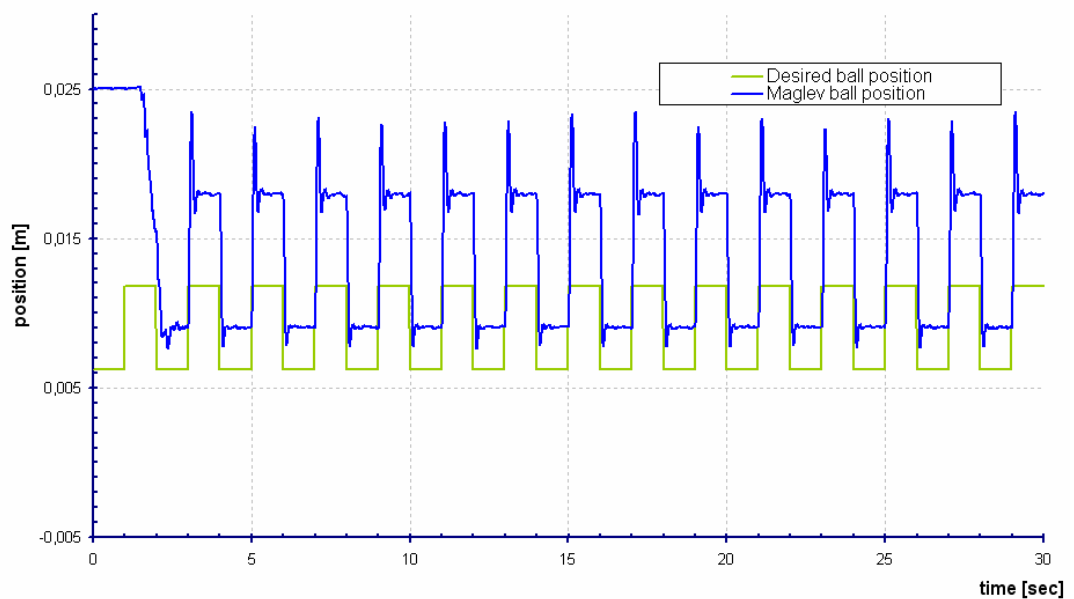


Figure 16 Real time control simulation results, with different P and D gains

Exercise 6 –Real time PID control of ball position



Introduction

The integral action in magnetic levitation system can improve the system performance in terms of error minimisation. However because of the fact that the system is not self starting the integral action has to be turned on when the ball is already stabilised by the PD controller. Otherwise the huge error of ball position would be integrated by the controller resulting in unrealistic control values. This would cause system destabilisation.

In this exercise a PID controller is also compared against the PD.

Task

Use the *Maglev_PID.mdl* to test the PID controller on the Maglev Unit. In this exercise the error integration is turned on after 15 seconds. Within that time the ball should be levitated by the PD controller.

Example results and comments

Figure 17 presents the results of an experiment where integration is turned on after 15 seconds of PD control.

Maglev position control: $P=4$, $D=0.2$ and $I=2$ after 15 sec

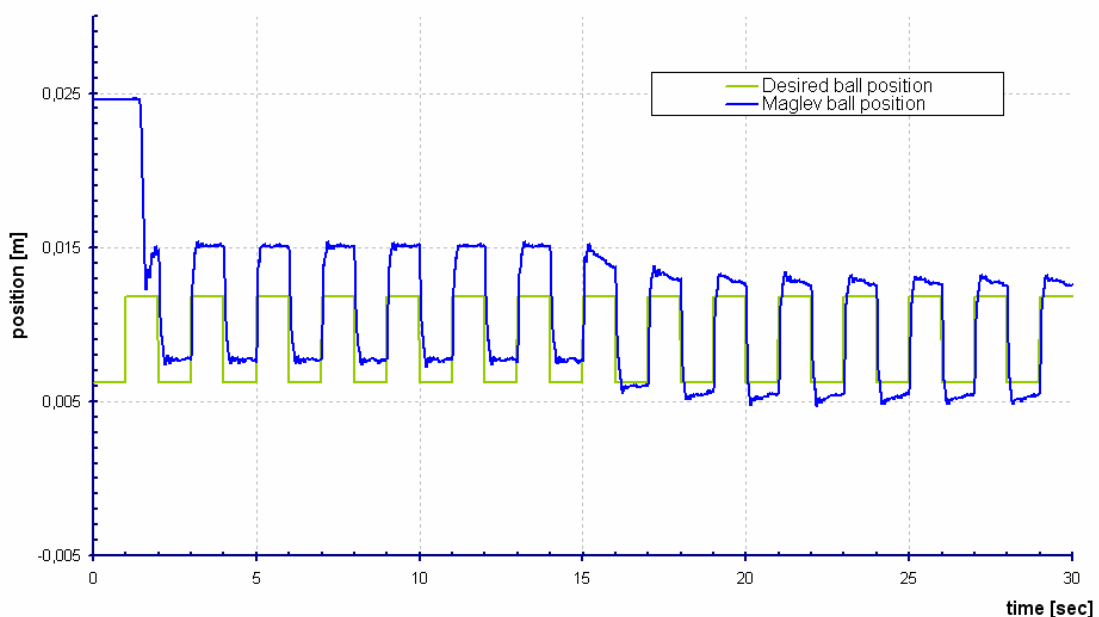


Figure 17 PID ball levitation control

Advanced Maglev control

Many advanced active magnetic levitation controllers could be implemented if the system was linear. Some linear algorithms assuring better performance (faster response) than the PID of linear systems, may have significant problems with the nonlinearity.

Nevertheless a linear Weighted Minimum Variance controller is proposed. With small ball movement it should be able to handle the nonlinearity. The theory behind the Minimum Variance controller is on graduate level and will not be explained in this manual.

The controller is of discrete and linear type. It is described by two polynomials $S(z^{-1})$ and $R(z^{-1})$:

$$WMV(z^{-1}) = \frac{S(z^{-1})}{R(z^{-1})}, \quad (15)$$

$S(z^{-1})$ and $R(z^{-1})$ are acquired through diophantine equation solution:

$$C(z^{-1}) = A(z^{-1}) \cdot F(z^{-1}) + z^{-k} \cdot H(z^{-1}), \quad (16)$$

$$R(z^{-1}) = A(z^{-1}) \cdot F(z^{-1}) + q^1 \cdot C(z^{-1}), \quad (17)$$

$$S(z^{-1}) = H(z^{-1}). \quad (18)$$

To solve the equation degrees nF and nH of polynomials $F(z^{-1})$ and $H(z^{-1})$ have to be determined:

$$nF = k - 1, \quad (19)$$

$$nH = \max(nA - 1, nC - k). \quad (20)$$

Polynomials $A(z^{-1})$ and $B(z^{-1})$ describe the discrete plant model:

$$G_d(z^{-1}) = z^{-k} \frac{B(z^{-1})}{A(z^{-1})} \quad (21)$$

Its task is to minimize the variance of the ball position signal subjected to the distortions around the working point. One of the parameters of the controller is its weighting factor 'q', which can be varied during the simulation to change the performance of the system.

Exercise 7 – WMV ball position model control



Introduction

The WMV controller synthesised based upon the Maglev discrete model resulting from the identification experiment is tested on a model first. The sampling time in this case is chosen to be 0.01 [s]. The WMV control is designed in 'Maglev_WMV_model.mdl'.

Task

Test the tracking performance of the WMV controller under different weighting factor values on the Maglev model in simulation. Use the slider gain to change the weight value.

Use the *WMV_synthesis.m* file to synthesise the WMV controller **before** you run the experiment. Change the default model in the file (polynomials) if you want to use the model obtained in the identification experiment. The file uses a default model unless you want to change it.

Type *help WMV_synthesis* to view help on WMV controller synthesis with that file.

Example results and comments

Figure 18 presents the results of the simulation for sinusoidal desired position signal for different controller weights.

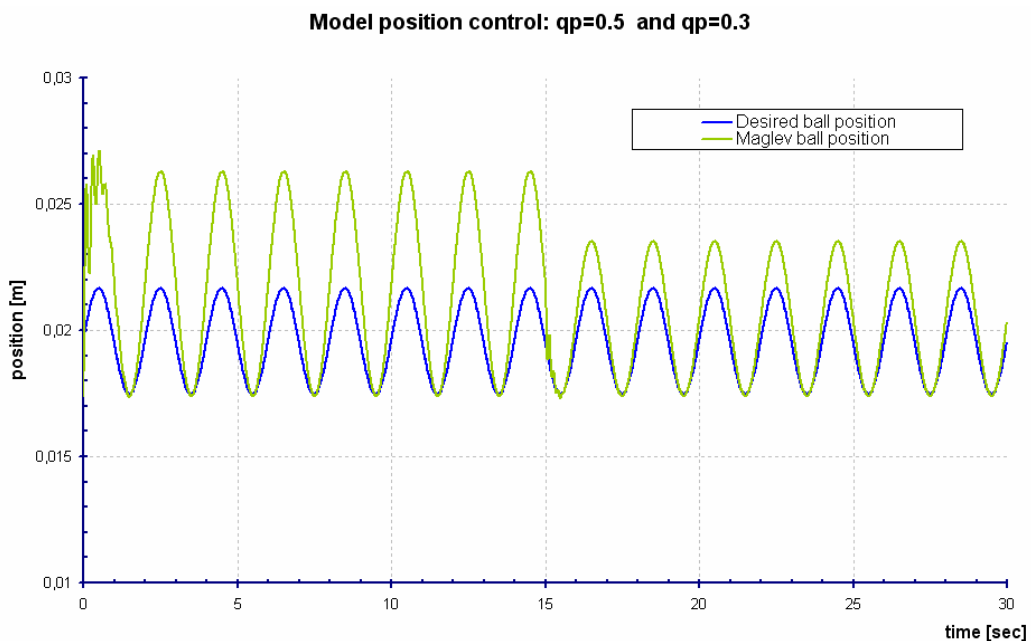


Figure 18 WMV performance on Maglev model

Exercise 8 – WMV ball position Real Time control



Introduction

Similar to exercise 7 the WMV control can be tested in Real Time on the Maglev Unit. The WMV real time control is designed in '*Maglev_WMV.mdl*'. The sampling time in this case is chosen to be 0.01 [s].

Task

Test the tracking performance of the WMV controller under different weighting factor values on the Maglev Unit in real time. Use the slider gain to change the weight value.

Use the *WMV_synthesis.m* file to synthesise the WMV controller **before** you run the experiment. Change the default model in the file (polynomials) if you want to use the model obtained in the identification experiment. The file uses a default model unless you want to change it.

Type *help WMV_synthesis* to view help on WMV controller synthesis with that file.

Example results and comments

Figure 19 presents the results of the real time WMV control for sinusoidal desired position signal for different controller weights.

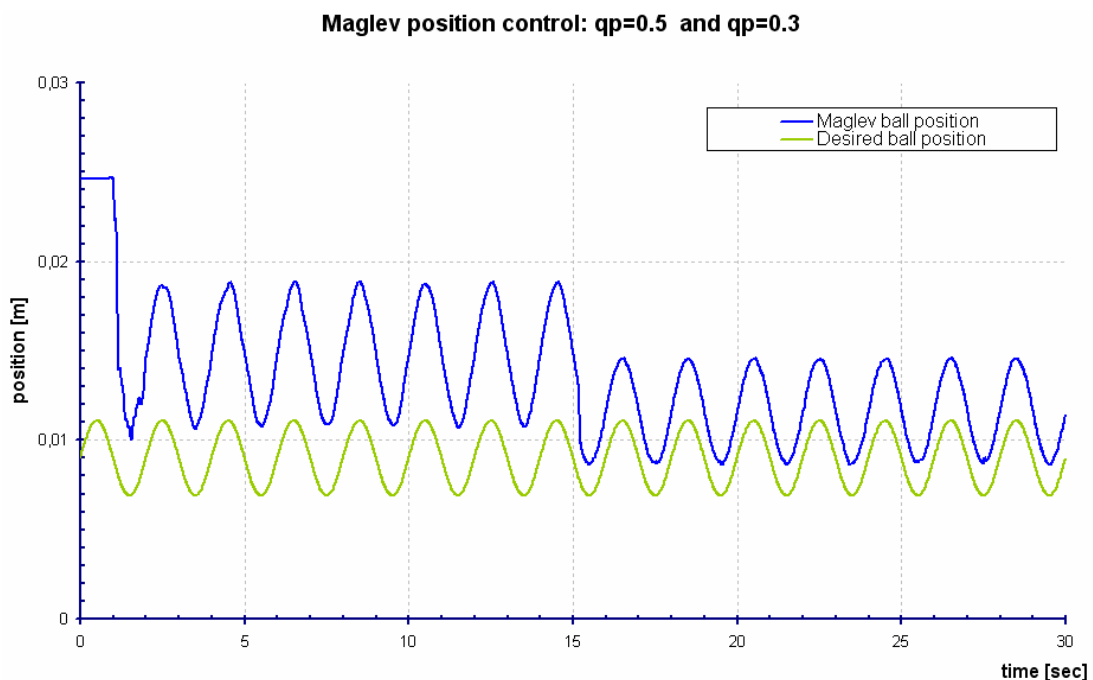


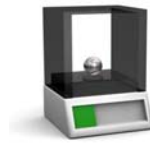
Figure 19 WMV performance on Maglev Unit

Additional Experiments

Additional experiments are extensions to the experiments presented in the Maglev Control section of the manual. First of the additional exercises allows for tracking of the analogue controller used on Maglev Unit as a stand alone setup.

The second gives an opportunity of Simulink ball control but the position set point value is read from the Maglev Unit.

Exercise 9 – Stand alone controller tracking



Introduction

It is possible to use the connection panel of the Maglev Unit and track the performance of the inbuilt, electronic levitation controller.

Task

Use the *Analogue_PD_Trace.mdl* for this exercise. Make sure that before you run the experiment the Maglev Unit is setup for stand alone mode with electronic controller assembled on the control panel. Connect the Measured Value to AD1, Set Point to AD2 and Control Output to AD3 of the 33-301. Run the simulation. Use the scopes to track the values of the measurement and the control signal.

Example results and comments

Figure 20 presents the results of the analogue controller tracking.

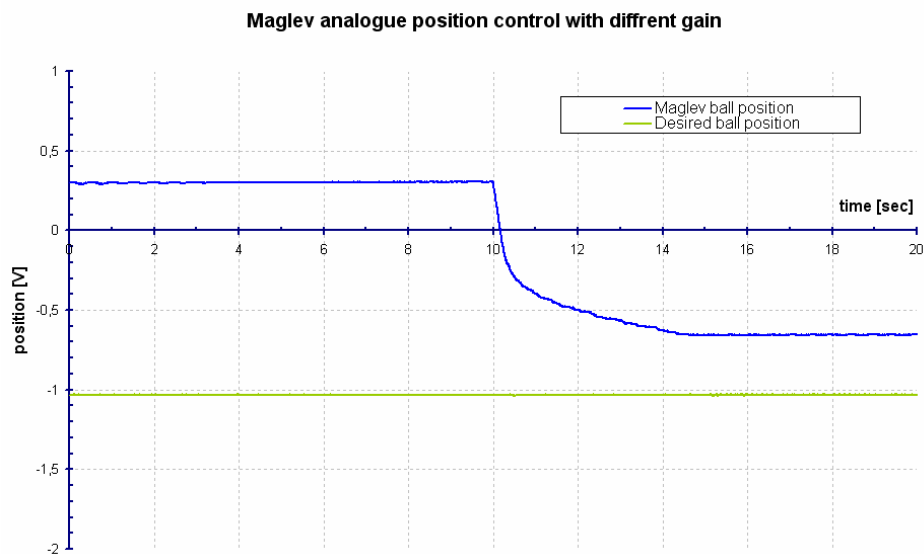


Figure 20 Analogue controller tracing

Exercise 10 – External set point

Introduction

The connection panel is used this time only for set point setting. The set point signal is transferred to Simulink to give a desired position value.

Task

Use the *PD_ExternalSetpoint.mdl* for this exercise. Connect the Measured Value to AD1, Set Point to AD2 of the 33-301. Run the controller and use the set point potentiometer to vary the desired value of the ball position.

Example results and comments

Figure 21 presents the results of the external set point exercise.

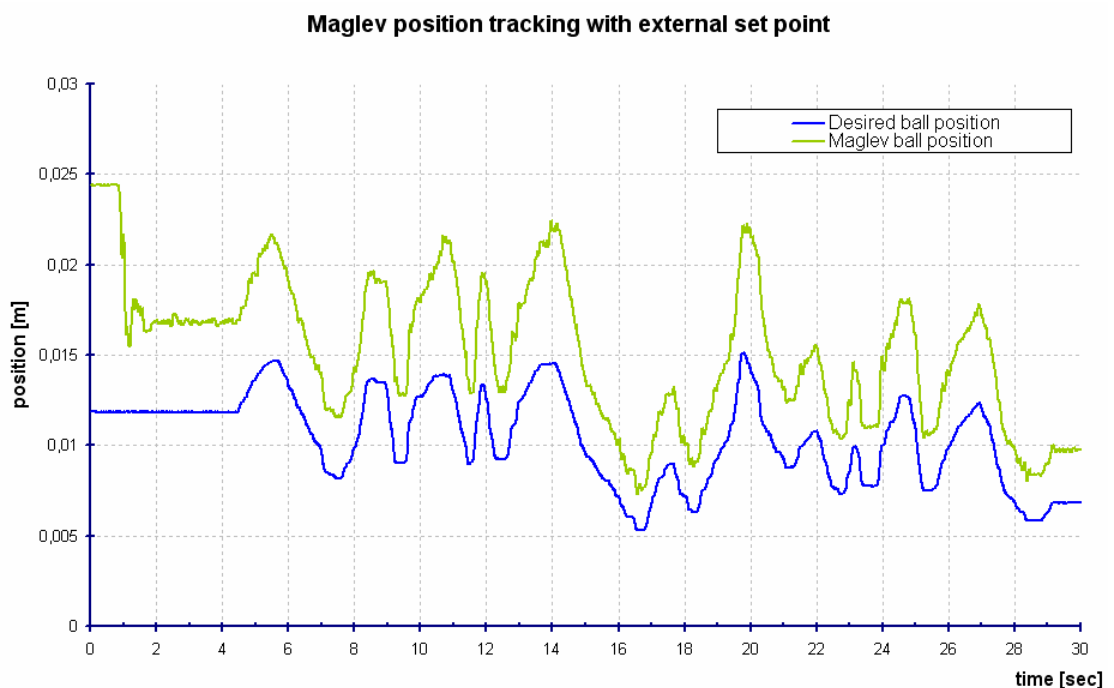


Figure 21 External set point signal use