Laboratory
DC Motor Speed Control

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Course: **ACA**

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List of Figures

Abstract

The rotation speed of a DC motor will be closed-loop controlled in this laboratory.

The setup used to test this closed-loop controller is described at section 1.

A reasonable dynamical model of the process is needed to develop a good controller. The model used in this laboratory is based on the differential equations described in section 3. It's parameters will de determined experimentally by exploiting a typical step answer (see section 5).

The controller development approach is depicted in section 6.

The developped controllers will be implemented in a Beckhoff PLC as described in section 6.

1 Introduction

DC Motors are being widely used in numerous applications (low-power mechatronic systems like mobile robots). A motor from the company Maxon Motor AG is beeing used in this laboratory.

The datasheet of the motor considered here can be found in appendix A.

A picture of the plant can be found in figure 1.

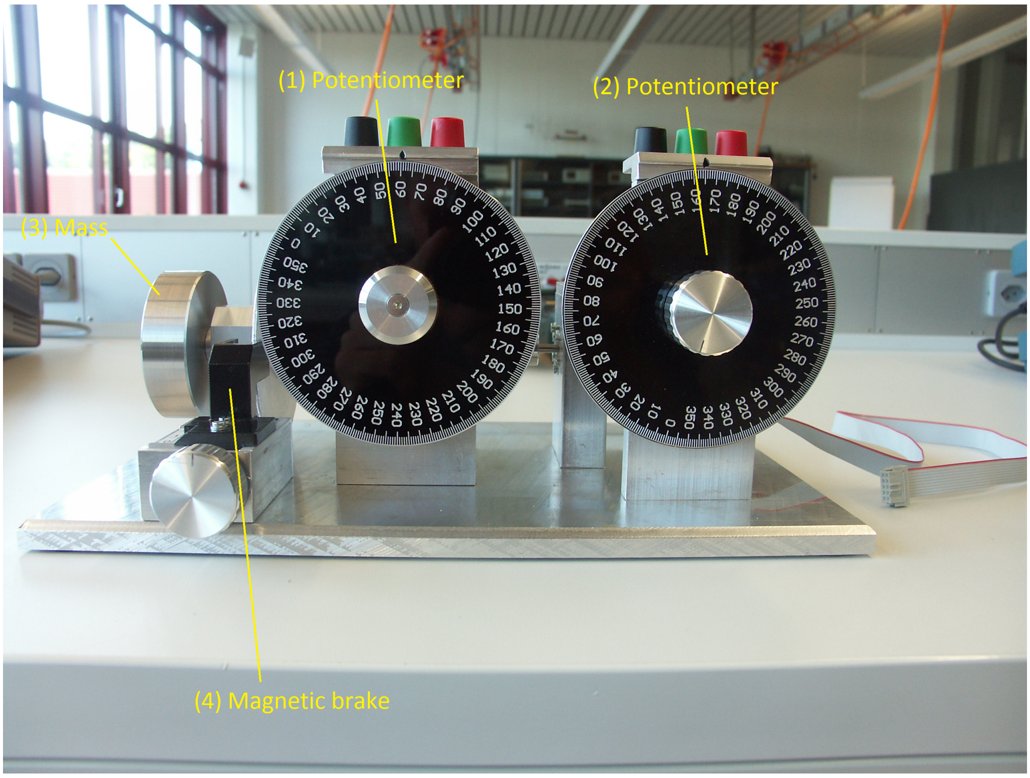


Figure 1: DC Motor experiment

Different masses (3) can be mounted on the plant. A magnetic brake (4) makes it possible to test different loads on the process.

2 Hardware

It's important to get familiar with the hardware of the experiment.

The DC motor being used is quite simple. Send it the enable signal, apply a positive or negative voltage and it rotates in the according direction. The motor voltage $u(t)$ can take values between -24 (V) and $+24$ (V).

The incremental encoder is a bit more complicated. It is mounted directly on the motor axis and keeps track of the motor's position by incremental counting of pulses from it's two sensors. The datasheet of this sensor can be found in the appendix B. This encoder has a resolution of 512 Impulses per turn.

The incremental encoder is nicely explained on Wikipedia:

> An incremental rotary encoder provides cyclical outputs (only) when the encoder is rotated. They can be either mechanical or optical. ... The incremental rotary encoder is the most widely used of all rotary encoders due to its low cost and ability to provide signals that can be easily interpreted to provide motion related information such as velocity.
>
> The fact that incremental encoders use only two sensors does not compromise their accuracy. One can find in the market incremental encoders with up to 10,000 counts per revolution, or more.
>
> ...
>
> Incremental encoders are used to track motion and can be used to determine position and velocity. This can be either linear or rotary motion. Because the direction can be determined, very accurate measurements can be made.
>
> They employ two outputs called A & B, which are called quadrature outputs, as they are 90 degrees out of phase.

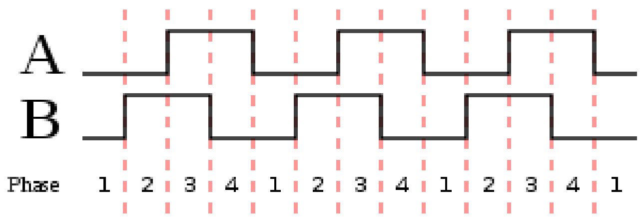


Figure 2: Sensor signals

> The two output wave forms are 90 degrees out of phase, which is what quadrature means. These signals are decoded to produce a count up pulse or a count down pulse. For decoding in software, the A & B outputs are read by software, either via an interrupt on any edge or polling, and the above table is used to decode the direction. For example, if the last value was 00 and the current value is 01, the device has moved one half step in the clockwise direction.

A Beckhoff PLC will be used to program the different controllers and test them experimentally. The following terminals will be used:

Phase	A	B
1	0	0
2	0	1
3	1	1
4	1	0

Figure 3: Coding for clockwise rotation

Phase	A	B
1	1	0
2	1	1
3	0	1
4	0	0

Figure 4: Coding for counter-clockwise rotation

- EL5101: This terminal is used to read the encoder signal (differential). Take care, the step counter value of the channel is an UINT which at some point will overflow and start at 0 again.
- EL7342: This terminal is used to drive the motor. The enable signal is connected to DCM Control Channel 1. The DC supply voltage of the motor is provided by DCM Velocity Channel 1.

Exercise 1: *Rotate the DC motor manually by one full revolution and check if you get the expected amount of steps from the encoder. You can observe this in the TwinCAT System Manager.*

□

Exercise 2: *Check if you can operate the motor manually (in free run mode) from the TwinCAT system manager. For this you first need to send it the enable signal, followed by the voltage to be applied. All these signals can be found in TwinCAT System Manager.*

□

3 Model

A simle modell of the DC Motor will be derived in this section

A schematic view of this motor can be seen in 5.

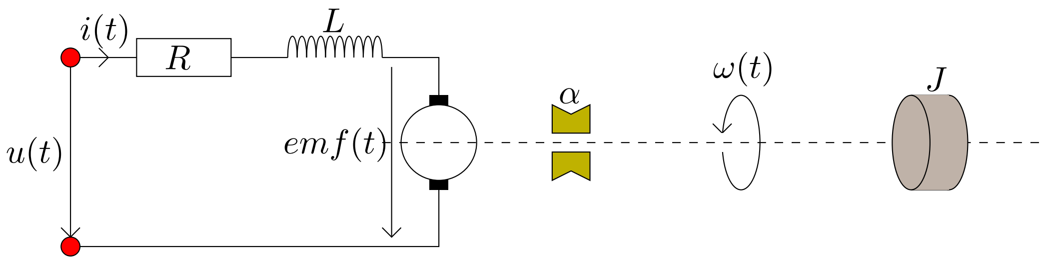


Figure 5: DC Motor Setup

The first differential equation links the current $i(t)$ and the voltage $u(t)$.

$$u(t) = Ri(t) + L\frac{di(t)}{dt} + \text{emf}(t) \tag{1}$$

where $\text{emf}(t)$ is the back-emf voltage expressed in (V).
Values for R and L can be found in appendix A.
It is assumed that $\text{emf}(t)$ is proportional to the rotation speed $\omega(t)$:

$$\text{emf}(t) = K_\omega \omega(t) \tag{2}$$

K_ω can be found in appendix A.

$$J\frac{d\omega(t)}{dt} = K_M i(t) - M_l - \alpha\omega(t) \tag{3}$$

where M_l is the load. J is the inertia. The friction is approximated by $\alpha\omega(t)$.
α can be changed with the magnetic brake.
It is supposed that:

$$K_M = K_\omega \tag{4}$$

If we neglect L, the transfer function $G(s) = \frac{\Omega(s)}{U(s)}$, where

$$\omega(t) \circ\!\!-\!\!\bullet \ \Omega(s)$$
$$u(t) \circ\!\!-\!\!\bullet \ U(s)$$

, can be derived as follows:

$$G(s) = \frac{K}{1+\tau s}$$

4 Problem formulation

In this Laboratory, the rotation speed $\omega(t)$ will be controlled.

Exercise 3: *Draw the block diagram of the process, uncontrolled. What is the control signal? The process output? What are possible disturbances?*

□

Exercise 4: *Draw the block diagram of the closed-loop controlled process.*

□

5 Parameter identification

Some of the parameters in $G(s)$ are not well known. For this reason, K and τ will be determined experimentally by applying a step signal to the motor voltage input from 5 [V] to 15 [V].

Exercise 5: *In TwinCAT PLC Control (use the provided template project) and TwinCAT System Manager:*

- *connect the global variables (globUint...) in the template project with the hardware in- and outputs.*
- *in PROGRAM WriteOutputs convert the value of global variable globVoltMotorVoltage from volt to INT and save it in globIntMotorVoltage. Make sure the value does not exceed the INT value range! Use the constant SCALE_VOLT_INT for the conversion.*
- *use the provided visulization to control the motor voltage and create a step signal like described above. Use the TwinCAT scope to measure the step response of the velocity and export the acquired data.*

□

Exercise 6: *In Matlab display the acquired data of the motor voltage and velocity in the same plot and determine K and τ graphically. Simulate the previously carried out experiment with the determined parameters in Matlab. Draw in the same plot the acquired data and the simulation results. Verify if the experiment and simulation match well.*

Useful Matlab functions:

- *Use help <NAME_OF_FUNCTION> to get the description of a function.*
- *Use tf(...) to create transfer functions.*
- *Use lsim(...) to simulate the output of a transfer function to a given input signal.*

□

6 P Controller

In this section a P controller will be designed and experimentally tested. The controller design is normally done in three steps:

1. Create the specification (stability, stationary accuracy, rise time, oscillations)
2. Define the controller structure.
3. Calculate the parameters of the controller.

In this experiment we focus on points 2. and 3.

6.1 Controller structure

Exercise 7: *For a P controller derive first the closed loop transfer function.*

□

Exercise 8: *Derive the reference tracking closed loop transfer function $T_r(s)$ of the controlled process.*

□

Exercise 9: *Express the steady state error as a function of the controller gain K_p. Compute K_p for the following cases:*

1. *Case 1: A steady state error of 40 % is required.*
2. *Case 2: A steady state error of 5 % is required.*

□

Exercise 10: *In Matlab simulate the process output, when excited with a step from 0 RPM to 3000 RPM, of the closed loop transfer function of the controlled process with the above computed K_p for a steady state error of 5 % and 40 %. Also simulate the process output for the reference tracking closed loop transfer function $T_r(s)$ with the same step signal. Compare the two simulations, are both of them sensible in a real world application?*

□

6.2 Controller parameters

Exercise 11: *Program and test the developed controller (with K_p for a steady state error of 40 %) experimentally and document the results (command signal, reference signal and process output). Test the controller with a reference value step from 1500 RPM to 2500 RPM. How does the DC supply voltage behave when you change the position of the magnetic brake? Is the controller stable? Compare the simulation results with the experimental results. Document these results.*

□

7 PI Controller

In this section a PI controller will be first analyzed and experimentally tested.

7.1 Controller analysis

Exercise 12: *What is the transfer function of the PI Controller?*

□

Exercise 13: *Derive the closed loop transfer function for a PI Controller. How does this transfer function simplify if T_i is chosen such that $T_i = \tau$?*

□

Exercise 14: *Derive the reference tracking closed loop transfer function $T_r(s)$ of the controlled process for $Ti \neq \tau$. How does this transfer function simplify if $Ti = \tau$?*

□

Exercise 15: *Prove that the steady state error is equal to zero for any value of K_p and T_i.*

□

7.2 PI controller parameters computation and experimental testing

Exercise 16: *Design a PI controller using the Kuhn approch.*

□

Exercise 17: *Test this controller in simulation using Matlab/Simulink. Realistic boundaries on the control signal should be taken into account in this simulation. A realistic reference signal should be programmed as well (for example a step of a few hundreds (rpm)). Test the controller with and without the anti-reset windup activated in the PID block (set $K_D = 0$). Explain why it is important to have this option activated if an integral is present in the controller.*

□

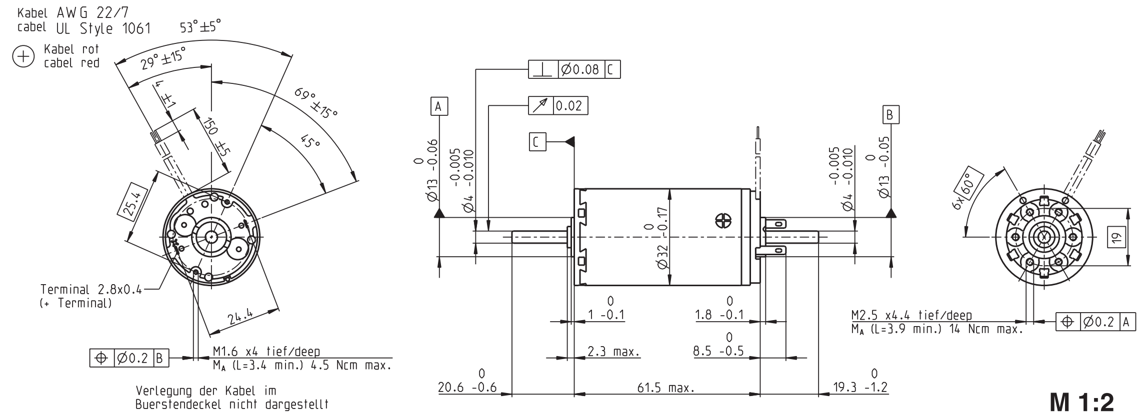
Exercise 18: *Program and test a PI controller experimentally.*

□

A Maxon Motor 236655

maxon A-max

A-max 32 ∅32 mm, Graphite Brushes, 15 Watt



M 1:2

Stock program
Standard program
Special program (on request)

Order Number									
with terminals		236651	236652	236653	236654	236655	236656	236657	236658
with cables		353220	353221	353222	353223	353224	353225	353226	353227
Motor Data									
Values at nominal voltage									
1 Nominal voltage	V	6.0	9.0	12.0	18.0	24.0	30.0	36.0	48.0
2 No load speed	rpm	5830	4930	4670	5270	5930	5870	5830	3870
3 No load current	mA	153	83.2	58.4	44.8	38.6	30.5	25.2	11.7
4 Nominal speed	rpm	3800	2980	2860	3550	4180	4140	4090	2080
5 Nominal torque (max. continuous torque)	mNm	31.4	33.1	36.0	37.5	36.7	37.1	36.8	36.9
6 Nominal current (max. continuous current)	A	3.42	2.02	1.55	1.21	0.998	0.798	0.656	0.328
7 Stall torque	mNm	99.7	87.4	95.9	118	127	128	125	81.3
8 Starting current	A	10.4	5.12	3.98	3.66	3.34	2.66	2.15	0.698
9 Max. efficiency	%	75	75	77	79	80	80	80	76
Characteristics									
10 Terminal resistance	Ω	0.577	1.76	3.02	4.92	7.19	11.3	16.7	68.8
11 Terminal inductance	mH	0.0657	0.209	0.416	0.739	1.04	1.66	2.43	9.71
12 Torque constant	mNm / A	9.58	17.1	24.1	32.2	38.2	48.2	58.3	117
13 Speed constant	rpm / V	996	559	396	297	250	198	164	81.9
14 Speed / torque gradient	rpm / mNm	59.9	57.6	49.5	45.5	47.1	46.3	47.1	48.4
15 Mechanical time constant	ms	27.6	23.5	22.4	21.8	21.7	21.5	21.5	21.5
16 Rotor inertia	gcm²	43.9	39.0	43.3	45.9	44.0	44.4	43.6	42.4

Specifications

Thermal data

17	Thermal resistance housing-ambient	7.5 K / W
18	Thermal resistance winding-housing	2.1 K / W
19	Thermal time constant winding	17.7 s
20	Thermal time constant motor	791 s
21	Ambient temperature	-20 ... +85°C
22	Max. permissible winding temperature	+125°C

Mechanical data (ball bearings)

23	Max. permissible speed	6000 rpm
24	Axial play	0.12 - 0.22 mm
25	Radial play	0.025 mm
26	Max. axial load (dynamic)	7.6 N
27	Max. force for press fits (static)	110 N
	(static, shaft supported)	2000 N
28	Max. radial loading, 5 mm from flange	32 N

Mechanical data (sleeve bearings)

23	Max. permissible speed	6000 rpm
24	Axial play	0.12 - 0.22 mm
25	Radial play	0.012 mm
26	Max. axial load (dynamic)	5.0 N
27	Max. force for press fits (static)	110 N
	(static, shaft supported)	2000 N
28	Max. radial loading, 5 mm from flange	10.5 N

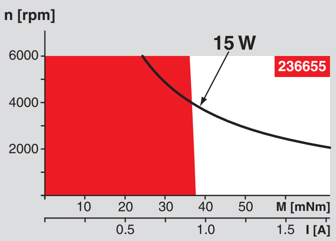
Other specifications

29	Number of pole pairs	1
30	Number of commutator segments	13
31	Weight of motor	211 g

Values listed in the table are nominal.
Explanation of the figures on page 49.

Option
Sleeve bearings in place of ball bearings

Operating Range



Comments

Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

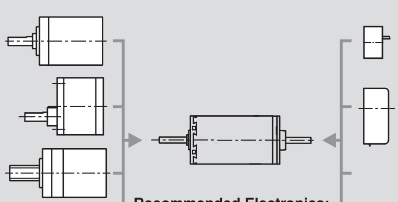
maxon Modular System

Overview on page 16 - 21

Planetary Gearhead
∅32 mm
0.75 - 6.0 Nm
Page 229 / 231 / 232

Spur Gearhead
∅38 mm
0.1 - 0.6 Nm
Page 236

Spindle Drive
∅32 mm
Page 249 / 250 / 251



Encoder MR
256 - 1024 CPT,
3 channels
Page 263

Encoder HED_5540
500 CPT,
3 channels
Page 267 / 268

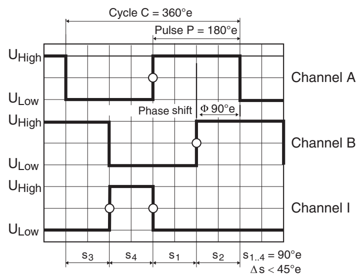
Recommended Electronics:

LSC 30/2	Page 282
ADS 50/5	282
ADS_E 50/5	283
EPOS2 Module 36/2	304
EPOS2 24/5	305
EPOS2 50/5	305
EPOS2 P 24/5	308
Notes	**18**

May 2011 edition / subject to change

B Maxon Encoder 225785

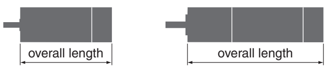
Encoder MR Type L, 256 - 1024 CPT, 3 Channels, with Line Driver



Direction of rotation cw (definition cw p. 48)

- Stock program
- Standard program
- Special program (on request)

Order Number	225783	228452	225785	228456	225787
Type					
Counts per turn	256	500	512	1000	1024
Number of channels	3	3	3	3	3
Max. operating frequency (kHz)	80	200	160	200	320
Max. speed (rpm)	18750	24000	18750	12000	18750



maxon Modular System

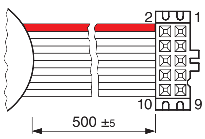
+ Motor	Page	+ Gearhead	Page	+ Brake	Page	Overall length [mm] / ● see Gearhead				
RE 30, 60 W	80					79.4	79.4	79.4	79.4	79.4
RE 30, 60 W	80	GP 32, 0.75 - 4.5 Nm	229			●	●	●	●	●
RE 30, 60 W	80	GP 32, 0.75 - 6.0 Nm	231/232			●	●	●	●	●
RE 30, 60 W	80	GP 32 S	249-251			●	●	●	●	●
RE 35, 90 W	81					82.4	82.4	82.4	82.4	82.4
RE 35, 90 W	81	GP 32, 0.75 - 4.5 Nm	229			●	●	●	●	●
RE 35, 90 W	81	GP 32, 0.75 - 6.0 Nm	231/232			●	●	●	●	●
RE 35, 90 W	81	GP 32, 4.0 - 8.0 Nm	234			●	●	●	●	●
RE 35, 90 W	81	GP 42, 3 - 15 Nm	237			●	●	●	●	●
RE 35, 90 W	81	GP 32 S	249-251			●	●	●	●	●
RE 40, 150 W	82					82.4	82.4	82.4	82.4	82.4
RE 40, 150 W	82	GP 42, 3 - 15 Nm	237			●	●	●	●	●
RE 40, 150 W	82	GP 52, 4 - 30 Nm	240			●	●	●	●	●
A-max 32	110/112					72.7	72.7	72.7	72.7	72.7
A-max 32	110/112	GP 32, 0.75 - 6.0 Nm	231/233			●	●	●	●	●
A-max 32	110/112	GS 38, 0.1 - 0.6 Nm	236			●	●	●	●	●
A-max 32	110/112	GP 32 S	249-251			●	●	●	●	●
EC-max 40, 70 W	168					73.9	73.9	73.9	73.9	73.9
EC-max 40, 70 W	168	GP 42, 3 - 15 Nm	238			●	●	●	●	●
EC-max 40, 120 W	169					103.9	103.9	103.9	103.9	103.9
EC-max 40, 120 W	169	GP 52, 4 - 30 Nm	241			●	●	●	●	●
EC-i 40, 50 W	190					42.0	42.0	42.0	42.0	42.0
EC-i 40, 50 W	190	GP 32, 1 - 6 Nm	233			●	●	●	●	●
EC-i 40, 50 W	190	GP 32 S	249-251			●	●	●	●	●
EC-i 40, 70 W	191					52.0	52.0	52.0	52.0	52.0
EC-i 40, 70 W	191	GP 32, 1 - 6 Nm	233			●	●	●	●	●
EC-i 40, 70 W	191	GP 32 S	249-251			●	●	●	●	●

Technical Data

Supply voltage V_{CC}	5 V ± 5%
Output signal	TTL compatible
Phase shift Φ	90°e ± 45°e
Index pulse width	90°e ± 45°e
Operating temperature range	-25 ... +85°C
Moment of inertia of code wheel	≤ 1.7 gcm²
Output current per channel	max. 5 mA

The index signal I is synchronised with channel A or B.

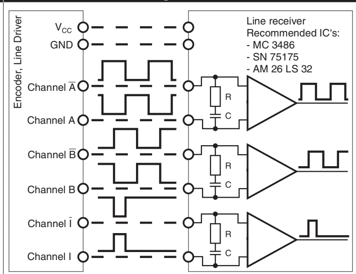
Pin Allocation



1. N.C.
2. V_{CC}
3. GND
4. N.C.
5. Channel $\bar{A}$
6. Channel A
7. Channel $\bar{B}$
8. Channel B
9. Channel $\bar{I}$ (Index)
10. Channel I (Index)

DIN Connector 41651
flat band cable AWG 28

Connection example



Terminal resistance R = typical 120 Ω
Capacitor C ≥ 0.1 nF per m line length