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<th>WS / SS 20 . .</th>
<th>Additional Practical Exercise of Control Engineering*</th>
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<tr>
<td>Experiment hs-e</td>
<td><strong>Electro-hydraulic Servo System (Version B)</strong></td>
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<th>Name</th>
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* Please note that this exercise is not mandatory. It is only for exercise and repetition of the contents of the lecture Control Technique. Therefore, there are -in contrast to other practical exercises- no mandatory parts included.
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1 Introduction

In this section, a short introduction to the principles of control is given as described in [Lun01], [Oga02] or [Unb97].

Control of a technical system means to retain the output (i.e. the control value) of a system on a constant value (constant value control) or tracking a variable’s nominal value (asymptotic regulation control), independent of external disturbances. The loop produces an actuating signal based on the difference between the actual and desired value, so that the output of the system complies the reference signal. The term, closed loop control, always implies the use of feedback control action in order to reduce the control error.

The main goal of this practical exercise experiment is to introduce into ideas and methods of control engineering. In this experiment, we will analyze the EHS 160 (FEEDBACK INSTRUMENTS LTD) and design some controllers for special control values. The controllers (P-, PI-controller) are realized by a control panel with an analog circuit. In this experiment the original analog circuit is replaced by a PC and the settings are realized in MATLAB Simulink.

The electro-hydraulic system consists of a hydraulic drive unit, which is controlled by a electro-hydraulic servo-valve. The advantage of a hydraulic drive is its high power density. The pressure or the volumetric flow of the drive unit are controlled by the servo-valve, which is controlled by its input voltage. In this way, a small input power controls a much larger output power. Such control systems are used in many technical applications, e.g. in the adjustment of wing flaps of a plane or for vehicle dynamics control.
2 Fundamentals

In this chapter, the operational principle and the mathematical description of the two main components of an electro-hydraulic control system (servo-valve, hydraulic motor) will be described. The control will be realized using MATLAB Simulink. Finally, the interface between the control path and MATLAB Simulink will be explained, and the applied P- and PI-controller will be introduced.

2.1 Servo-valve

A servo-valve consists of a torque motor and a sliding spool, which is positioned by a torque motor. The volume flow rate $Q_V$ of the fluid (hydraulic oil) is controlled by the voltage $U_V$ on the torque motor.

![Image of electro-hydraulic valve](image)

Figure 2.1: Electro-hydraulic valve

In the neutral (Zero) position $U_V = 0$, the two output ports are at the same energy level (balanced position).

Each current corresponds to a certain displacement of the sliding spool and each displacement corresponds to a certain flow rate in the output ports. In this way, the flow rates of output port 1 and port 2 are controlled (Figure 2.2).

The servo-valve works as a adjustable flow resistance. Its time behavior can be approximately described as a PT₁ element. (Input: Voltage $U_V$, Output: Volumetric flow rate
$Q_V$). The transfer behavior is given by

$$F_V(s) = \frac{K_V}{1 + T_V s}.$$  \hspace{1cm} (2.1)

The time constant of the servo-valve is $T_V \approx 2.3$ ms, hence the cut-off frequency is $w_V \approx 435$ Hz.

![Figure 2.2: Electro-hydraulic valve]

Figure 2.2: Electro-hydraulic valve

Figure 2.3: Transfer behavior of the Servo-valve

Figure 2.4 shows typical characteristic curves for different valve laps conditions.

### 2.2 Hydro-motor

A hydro-motor converts hydraulic energy into mechanical energy. The mechanical energy is transferred to a rotating shaft. In this case, the flow rate $Q_V$ is converted to angular velocity $\Omega$. 

The hydro-motor used in this experiment is an axial piston motor. The transfer behavior of the motor can be modelled as a PT$_2$ element (angular velocity as output, volume flow rate as input), or a PIT$_2$ element (angle of rotation as output, volume flow rate as input).

a) The PT$_2$ transfer function for the angular velocity $y_{\Omega}$ as output can be described as

$$F_{M,\Omega}(s) = \frac{K_{M,\Omega}}{\omega_0^2 s^2 + 2D\omega_0 s + 1}. \quad (2.2)$$

b) The PIT$_2$ transfer function for the angle of rotation $y_{\phi}$ as output can be described
as

\[ F_{M,\varphi}(s) = \frac{K_{M,\varphi}}{s \left( \frac{1}{\omega_0^2} s^2 + \frac{2D}{\omega_0} s + 1 \right)} \]  \hspace{1cm} (2.3)

The parameters \( \omega_0 \) and \( D \) depend on the compressibility and viscosity of the oil, the moments of inertia of all rotating parts and on possible leakages of the oil.

The hydraulic tubes have a large resistance and can save potential and kinetic energy. In this experiment these effects will be neglected.

The angular velocity is measured by a tachometer, which generates a voltage \( U_T \) proportional to the angular velocity \( y_\Omega = K_T y_\Omega \). The angular position can also be proportionally transferred into a voltage.

### 2.3 MATLAB and RTI

MATLAB\(^1\) is a high performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment. Its basic data element is array. Simulink is a software package that enables to model, simulate and analyze a wide range of real-world dynamic systems, including mechanical, electrical and chemical systems. This program has a specially designed user interface, which allows to simplify complex systems into block diagrams. It can be used for linear and nonlinear, continuous and discrete system. The needed blocks can be chosen from the Simulink block libraries.

With the toolboxes „Real-Time Workshop“ and „Real-Time Windows“, values can be read in and read out via a PC-card into MATLAB Simulink(RTI\(^2\)815-card). A model in

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\(^1\) MATrix LABoratory

\(^2\) Runtime Infrastructure
Figure 2.7: Interface of MATLAB/RTI

Simulink will be connected into the loop as a controller. With the toolbox „Real-Time Workshop“ C-code of the Simulink model can be generated and compiled for the application of the Simulink Toolbox „Real-Time Windows“, so that the exchange of signals between Simulink and RTI-card can be realized. The RTI-Card is the hardware interface to the plant.

The signal can be supervised in real time on the Simulink graphical surface, and the parameters can be changed according to the conceptual formulation.

### 2.4 Controller

In this experiment a P-controller (Proportional-controller) and a PI-controller (Proportional-Integral-controller) with the time constant $T_I$ is used. The two controllers should be compared during the experiments.

The transfer function of a P-controller is

$$F_P(s) = \frac{y}{u} = K_P,$$

with its block diagram shown in figure 2.8.

The transfer function of a PI-controller is

$$F_{PI}(s) = \frac{y}{u} = K_{PI} \left(1 + \frac{1}{T_I \cdot s}\right),$$

with its block diagram shown in figure 2.9.
Figure 2.8: The block diagram of P-Controller

Figure 2.9: The block diagram of PI-Controller
3 Experimental Setup

3.1 Overview

The electro-hydraulic system used in this experiments is the EHS160 (FEEDBACK INSTRUMENTS LTD). It consists of the following hydraulic components: the hydraulic pump which delivers hydraulic energy (located at the adjoining room), the servo system (Figures 3.1 and 3.2) and the electrical patch with the outputs of the sensors and the electronic controller components (Figure 3.4). The servo system consists of a servo-valve, hydraulic ducts, hydro-motor and the sensors for angular velocity and angle. A PC will be used instead of the existing controller components.

![Figure 3.1: Model Control system EHS 160](image)

Fig 3.2 shows the system with responding numbers on its components.

**List of components**

1. Pump
2. Filter
3. Indicator: Supply Pressure
4. Accumulator tank
5. Indicator: volumetric flow in the return line
6. Adjustable throttle valve
7. Reservoir
8. Servovalve
9. Indicator: Pressure of Servovalve’s output 1
10. Hydromotor
11. Tachometer

12. Indicator: Pressure of servovalve’s output 2

13. Input input 4

14. Output pos’n error

15. Output $U_T$

16. Output $A_{0\theta}$

17. Output $AI_{\theta}$

**Figure 3.2**: Sketch of system EHS 160

Figures 3.3 and 3.4 show the RTI-Box and the control panel.

**Figure 3.3**: RTI-815 (I/O Board)
3.2 Functional Description

An electric driven hydraulic pump transports the oil from the reservoir through a flexible pressure tubing to the pressure side of the servo-valves. The supply pressure $p_V$ in the power unit will be held at a constant value by a pressure relief valve. The outputs of the servo-valve control the hydromotor through two hydraulic tubes. The hydromotor transforms the hydraulic pressure or a hydraulic oil flow into a moment or angular velocity. Another engine or a load can be driven by the drive shaft of the hydro-motor. A flywheel mass on the driving shaft of the hydromotor can be braked by a shoe brake. A following tachometer changes the angular speed into a voltage proportionally to the angular speed.

The speed voltage or the position voltage are the inputs to the PC. The controller will be realized by the software package MATLAB Simulink. (Take the control of speed for example, the speed voltage should follow a reference signal.) The controller sends out a voltage to the servo-valve as a control signal depending on the control error (the difference between reference value and measured value).

Oil flows out of Servo system, through the servo-valve and return line, and back to the reservoir. Electro-hydraulic systems show both the advantages of the electrical and the hydraulic system (high response speed, large power and reliability).

3.3 Controller Description

The block diagrams used in the MATLAB Simulink will be introduced in the following section. The name of the Simulink Blocks are bold and if they are in German, a translation
in brackets follows. Subsequently a short description of the function of each block is given.

3.3.1 Characteristic Curve

![Figure 3.5: Characteristic Curve](image)

1. Spannung (Voltage) $U_V$: Input block for output voltage
2. Spannung (Voltage) $U_T$: Graphic indicator to visualize the speed voltage
3. Display 1: Numerical indicator for the speed voltage
4. Display and test Scope: Numerical and graphic indicator for the input signal

3.3.2 Frequency Response

1. Sinusgenerator (Sine-wave generator) $U_V$: Signal generator for output voltage
2. $U_V$ Referenz (Reference): Reference signal same as $U_V$
3. Vergleich: $U_V$ Referenz, $U_T$ (Comparison between $U_V$ Reference and $U_T$: Graphic indicator of the speed voltage and the reference value
4. Display 1: Numerical indicator for the speed voltage
5. Display and test Scope: Numerical and graphic indicator for the input signal
3.3.3 Position Control

1. *Führungsgröße (Spannung) (Reference value (Voltage))*: Input block for the reference signal

2. *Verstärkung I-Anteil (Gain of the I-part)*: Input block for integral gain
3. Verstärkung P-Anteil (Gain of the P-part): Input block for proportional gain

4. Spannung $U_V$ (Voltage): Graphic indicator of the output voltage

5. Regelabweichung (Control error): Graphic indicator of the signal: Reference value - Position

6. Regelgröße (Control value): Graphic indicator of the position voltage

7. Display 1: Numeric Indicator of the position voltage

3.3.4 Speed of Rotation Control

![Figure 3.8: Speed of rotation control](image)

1. Führungsgröße (Reference value (Voltage)): Input block for the revolution speed voltage

2. Verstärkung I-Anteil (Gain of the I-part): Input block for the I-Gain

3. Verstärkung P-Anteil (Gain of the P-part): Input block for the P-Gain

4. Spannung $U_V$ Voltage): Graphic indicator of output voltage

5. Regelabweichung (Control error): Graphic indicator of signal: Reference value - Position Voltage

6. Regelgröße (Control value): Graphic indicator of position voltage

7. Display 1: Numeric indicator of position voltage
4 Preparation for the Experiment

The following exercises should be prepared and answered at home for preparation of the lab. It is strongly recommended to investigate some hours of preparation. In the lab, related questions will be answered, (but the material will not be explained in detail). Furthermore, questions concerning the theoretical background of this experiment will be discussed, even if not specified in this description.

The topics of the essential theoretical background are:

- Behavior of transfer elements (differential equation, transfer function, step response),
- Interconnection of transfer elements, block diagram,
- Magnitude and phase plot polar plot, Bode diagram, and
- Special Nyquist criterion.

The following exercises are to be done in advance, especially at home, to be well prepared for this lab (please bring your answers to on the practical exercise date.).

Part A: Preparation of theoretical background

A1) What is control? State max. 3 sentences. (Ref. [Oga02] p.6,7; [FPEN06] p.16,17)

A2) What is a system? State max. 3 sentences. How can the elements of systems be expressed and combined graphically? (Ref. [Oga02] p.3; [FPEN06] p.17)

A3) Give 3 different ways to describe or model a system. (Ref. [Oga02] p.53,54)

A4) Questions related to time domain

1. What is step/impulse response of a system? (Ref. [FPEN06] p.803,804)
2. What are $P$, $I$, $D$, $PTn$ elements? Please give two possible different behaviors between $PT1$ and $PT2$ elements. (Ref. [FPEN06] p.108,112)
3. What is convolution integral? (Ref. [FPEN06] p.76,77)

A5) Questions related to frequency domain

1. What is Laplace transformation? Give three examples of Laplace transformations from the elements given in A4). (Ref. [Oga02] p.17,18; [FPEN06] p.85)
2. Give the definitions of transfer function, poles and zeros. (Ref. [FPEN06] p.77,95)
3. What is a Bode-diagram? (Ref. [Oga02] p.497)

A6) State at least 3 different methods to check the stability of a SISO system. (Ref. [FPEN06] p.131,230,340)
A7) State the functions of the three different parts in a PID-controller. (Ref. [Oga02] p.685)

Part B: Preparation related to the experiment

B1) The control path consists of a servo-valve, a hydro-motor and a rotary encoder. Write down the transfer function of the control path. Combine the transfer functions given in the related equations. The control value is the angle of rotation of the hydro-motor. What is the effect of the integral element in the transfer function on the behavior of the control path?

B2) Draw the block diagram of the control loop for the rotation speed and for the angle of rotation (control with P-controller). Inscribe the transfer functions of each block and indicate the parameters.

B3) Give the reference transfer function of rotation speed and angle of rotation (control with P-controller).

B4) 1. Draw the Bode diagram of the transfer function of the hydro-motor qualitatively with the angular velocity as the controlled value (general PT$_2$-System).

2. What is the definition of gain and phase margin (Ref. [FPEN06, Oga02])? Under which conditions is the PT$_2$-System with the transfer function

\[ F(s) = \frac{K}{\frac{1}{\omega_0}s^2 + \frac{2D}{\omega_0}s + 1}, \quad D > 0, \ K > 0 \]  \hspace{1cm} (4.1)

stable? Give your answer according to the Bode diagram and polar plot.

3. A servovalve is used in the control path $F(S)$ (Equation 4.1). What is the effect of the servo-valve in this series connection?
5 Experiments

The preparation (the supply of hydraulic oil and electricity) for the experiment will be done by the tutor. The PC with the software (MATLAB Simulink) is turned on and connected with the control panel. The output \( A_0 \) of the interface box is connected with input 4 of the control panel and the output \( U_T \) of the control panel is connected with the input \( A_1 \) on the interface box.

The Matlab/SIMULINK-models for these experiments can be found in the path C:\MATLABxxx\WORK. After loading the corresponding Matlab /SIMULINK-models, the following steps have to be carried out.

1. Compile the model with Strg+B (create the C-Code to control the interface box)
2. Click the button Connect to target to connect to the interface box.
3. Click the button Start real-time code to start the model. Only after the third step, signals can be sent and received.

The following experiment have to be done:

5.1 Get the static characteristic curve (Valve - Motor - Tachometer)

Determine the characteristic curve \( U_T = f(U_V) \) of the control path for different inputs.

1. Install the brake.
2. Open the file kennlinie.mdl.
3. The voltage \( U_V \) can be changed by changing the value in the block Spannung \( U_V \). The value of \( U_T \) can be read out by the block Spannung \( U_T \) (The y-coordinate should go from -4 to 4 V).
4. Enter the values of \( U_V \) from Table 6.1. Read and note down each stationary value of the tacho voltage \( U_T \). Use the brake to keep the pressure drop \( \Delta p = p_o - |p_1 - p_2| = 40 \) bar (the pressure difference between the supply and the valve output) constant.
5.2 Measuring of the frequency response and its description in the Bode Diagram

1. Remove the brake. Be Careful! The brake may be hot!
2. Open the file `frequenzgang.mdl`.
3. The input voltage $U_V$ is given by a sinewave generator with the frequencies 2, 5, 10, 20, 40, 60, 80 Hz and the amplitude 0.5 V. A signal identical to $U_V$ will be compared with the voltage $U_T$. The phase shift and amplitude gain of the reference signal will be adjusted until its shape is the same as that of $U_T$. (With the button **Parameters** you may scale the abscissa in the entry **Time-Range**).
4. Read off the phase shift and amplitude gain for each frequency.

5.3 Position control with a P-controller

Connect the output `pos'n error` on the control panel with the input $AI_\theta$ of the interface box.

1. Open the file `positionsregelung.mdl`.
2. Set the gain of the I-controller to zero.
3. The reference value will be chosen between -2 V and +2 V. The gain of the P-controller has to be varied until there is satisfactory result (give reasons!). Observe the control value (**Scope**).
4. Apply the brake in a way, so that there is a disturbance and a clear control error by using P-controller.

Note: The gain of the P-controller has to be smaller than 1

5.4 Control of the angular velocity

Connect the output $U_T$ of the control panel with the input $AI_\theta$ of the interface box (RTI).

a) Use of a P-controller:
1. Remove the brake.

2. Open the file `drehzahlregelung.mdl`.

3. Set the gain of the I-controller to zero.

4. The reference value will be chosen between -3 V and +3 V. The gain of the P-controller has to be varied until there is satisfactory result (give reasons!). Observe the control error (`Scope`).

b) Use of a PI-controller:

1. The reference value will be chosen between -1 V and +1 V.

2. The gain of the I-controller and the P-controller has to be varied until there is a satisfactory result (give reasons!). Observe the control error (`Scope`).
6 Documentation

1. In Section 5.1, the static characteristic curve for the plant with rotation speed as control value is recorded. The control path consists of the servo-valve, the hydro-motor and the tachometer. Enter the measured value in the Table 6.1 and plot the characteristic curve.

Table 6.1

<table>
<thead>
<tr>
<th>$U_V$ [V]</th>
<th>-0.8</th>
<th>-0.6</th>
<th>-0.4</th>
<th>-0.2</th>
<th>-0.1</th>
<th>-0.05</th>
<th>0</th>
<th>0.05</th>
<th>0.1</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_T$ [V]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

Explain why the characteristic curve is like this and give two possible reasons for its nonlinearity.

2. Enter the results of Section 5.2 in Table 6.2.

Table 6.2

<table>
<thead>
<tr>
<th>$w$ [Hz]</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>F_0</td>
<td>$ [V]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varphi$ [rad]</td>
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<td></td>
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Draw the Bode diagram (MATLAB File bode_plotten.m to draw the Bode diagram will be given) and the polar plot by hand. Explain how to read the gain and phase margin.

3. Give reasons for the choice of the control parameter in Section 5.3 to control the angle of rotation.

4. When there are disturbances, which controller is preferable (P or PI)? Give reasons.
References


