MEM02: Hydraulic Servomechanism

Interdisciplinary Automatic Controls Laboratory - ME/ECE/CHE 389

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1 Introduction and Goals

Closing a feedback loop around a rotary hydraulic actuator to obtain actuator shaft position that is proportional to a varying electrical signal is the most fundamental of mechanical control problems. In fact, this is called, “the basic regulator problem,” i.e., making the output position of a relatively massive device follow a low-power input signal by addition of position feedback and a power amplifier. Often the performance can be further improved by adding to the outer position feedback loop an inner velocity feedback loop. Since the position is often the angular position of a shaft, the angular velocity will be measured by a tachometer and the inner loop is then called the “tachometer feedback loop.”

Virtually every undergraduate controls textbook discusses tachometer feedback performance improvement, including Ogata, Modern Control Engineering, 5th edition, page 164.

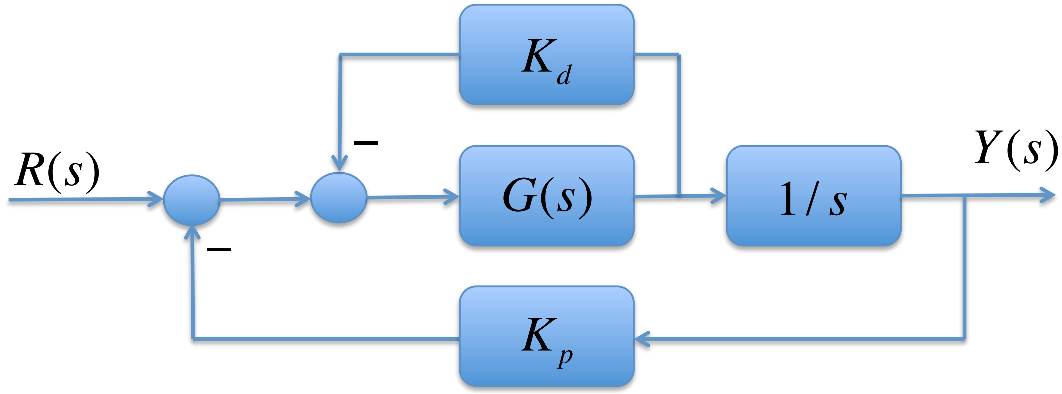

Figure 1: Block diagram of basic servomechanism-based regulator.

2 Description

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, the servo system (Figures 2 and 3). 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.

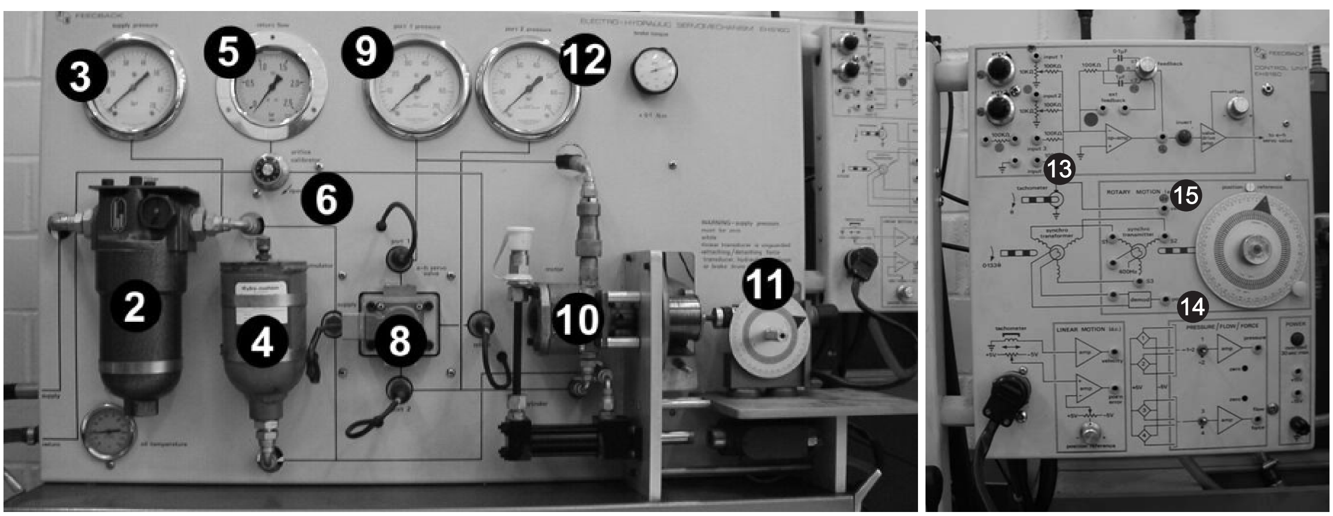

Figure 2: Feedback, Inc. hydraulic servomechanism.

List of components:

1. Pump
2. Filter
3. Indicator: Supply pressure
4. Accumulator tank
5. Indicator: volumetric flow in the return line

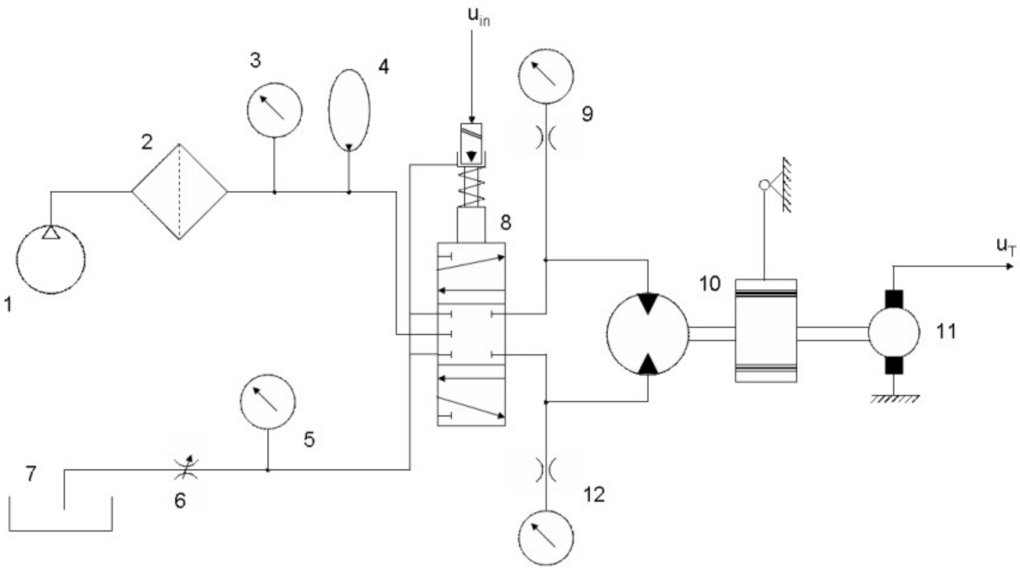

Figure 3: Feedback, Inc. hydraulic servomechanism.

6. Adjustable throttle valve
7. Reservoir
8. Servovalve
9. Indicator: Pressure of servovalves output 1
10. Hydromotor
11. Tachometer
12. Indicator: Pressure of servovalves output 2
13. Input (Input 4 (u_{in} in Figure 3))
14. Output (position error)
15. Output (velocity (u_T in Figure 3))

An electric driven hydraulic pump (1) transports the oil from the reservoir (7) through a flexible pressure tubing to the pressure side of the servo-valves (8). The supply pressure in the power unit (measured by (3)) will be held at a constant value by a pressure relief valve. The outputs of the servo-valve control the hydromotor (10) 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 (not installed). A following tachometer (11) changes the angular speed into a voltage proportionally to the angular speed. The position error voltage (14) or the speed voltage (15) are the inputs to the PC. The controller will be realized by LABVIEW. The controller sends out a voltage to the servo-valve (8) as a control signal (13) depending on the control error (the difference between reference value and measured value). Oil flows out of the servo system, through the servo-valve and return line, and back to the reservoir (7). Electro-hydaulic systems show both the advantages of the electrical and the hydraulic system (high response speed, large power and reliability).

3 Modeling

The two main components of a hydraulic servomechanism are the servo-valve and the hydraulic motor. Their descriptions are provided below.

3.1 Servo-valve

A servo-valve (Figure 4) 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_{in} on the torque motor. In the neutral (Zero) position $u_{in} = 0$, 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 4). The servo-valve works as a adjustable flow resistance. Its dynamics can be approximately described by a first-order model (Input: Voltage u_{in}, Output: Volumetric flow rate Q_V). The transfer function is given by

$$G_{valve}(s) = \frac{K_V}{1 + \tau_V s} \tag{1}$$

The time constant of the servo-valve is $\tau_V \approx 2.3$ ms, which implies a cut-off frequency of $\omega_V \approx 435$ Hz.

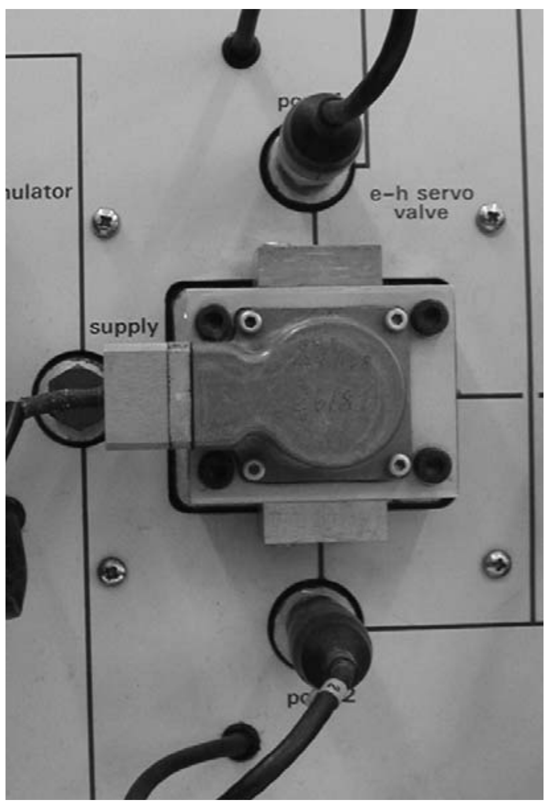

Figure 4: Feedback, Inc. hydraulic servomechanism. Servo-valve.

3.2 Hydro-motor

A hydro-motor (Figure 5) 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 y_Ω. The hydro-motor used in this experiment is an axial piston motor. The dynamics of the motor can be described by a second order model (Input: Volumetric flow rate Q_V, Output: Angular velocity y_Ω). The transfer function for the angular velocity y_Ω as output can be written as

$$G^{\Omega}_{motor}(s) = \frac{K_\Omega}{\frac{s^2}{\omega_n^2} + \frac{2\zeta}{\omega_n} + 1} \tag{2}$$

Therefore, the transfer function for the angular position y_ϕ as output (the input is still the volumetric flow rate Q_V) can be written as

$$G^{\phi}_{motor}(s) = \frac{K_\Omega}{s\left(\frac{s^2}{\omega_n^2} + \frac{2\zeta}{\omega_n} + 1\right)} \tag{3}$$

The parameters ω_n and ζ 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_Ω ($u_T = K_T y_\Omega$). The angular position error can also be proportionally transformed into a voltage.

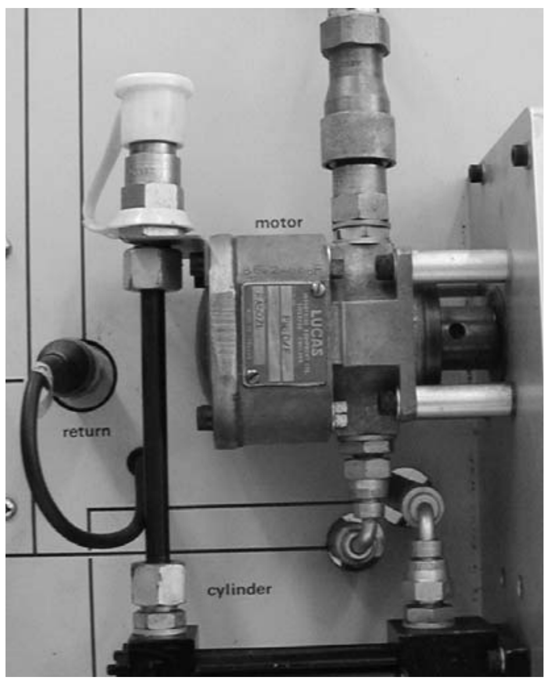

Figure 5: Feedback, Inc. hydraulic servomechanism. Hydro-motor.

4 Lab Objective

In this laboratory you will obtain a transfer function of the hydraulic servomechanism based on a system identification method. Then using the obtained transfer function you will design controllers to regulate both the angular velocity and the position of the the servo motor. Finally, you will test your controllers experimentally.

5 System Identification by Frequency Response

A very popular way of identifying a linear system, i.e. a system with transfer function of the form

$$G(s) = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots + b_0}{a_n s^n + a_{n-1}s^{n-1} + \cdots + a_0} \tag{4}$$

is to measure the steady-state response of the system to sine waves of varying frequency. For linear systems, a sinusoidal input will always generate a sinusoidal output of the same frequency in steady state. This approach is illustrated in Figure 6. Linear systems only include the operators of addition, subtraction, gain, integration and differentiation, all of which preserve the frequency of a sinusoidal input. By repeating this process at different frequencies, we can construct the frequency response of the system. The measured gain and phase shift between the input and output signal constitute the frequency response. The transfer function of the system can then be inferred from the experimental Bode plot. For review of frequency response and bode plots see the lectures available on the web.

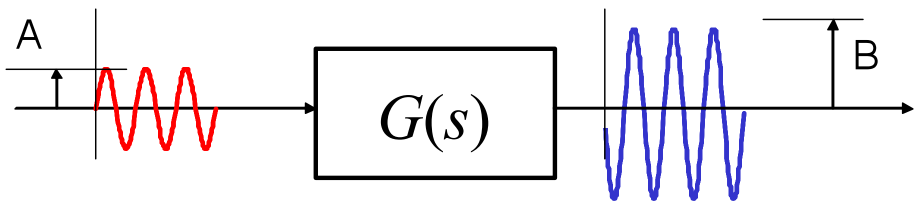

Figure 6: Sinusoidal excitation of a linear system.

Open Loop Frequency Response: Lab Procedure
NOTE: There should be no need to adjust the hardware

1. Use the lab view file (`ME389_MEM02_Control.vi`) as a signal generator to send input sine wave to the servo motor
2. Use the matlab file (`Collect_AnalogSignals.m`) to record the input output signals for analysis
3. Once you have collected enough data, you can use matlab file (`BuildBode.m`) to generate the frequency response plot (bode plot).
   - This file uses a routine to fit a sine wave to the input and output signals.
   - From the fitted sine waves we can easily determine the gain and phase shift. See Figure 7 below for an example.

Note: The hydraulic servo inverts the input signal before spinning the servo.

Q1: Plot the experimental Bode plot (both magnitude and phase) for the system. Use marks to show the obtained experimental points (not a curve). Write down the identified first-order transfer function. Compare in the same plot the frequency response of the identified model (use a curve) with the experimental frequency response (use marks for the experimental points).

Q2: Plot in the same figure the obtained experimental step response and that predicted by the identified first-order transfer function when the amplitude of the step is 0.75V. How well the predictions by the identified model match the experimental data?

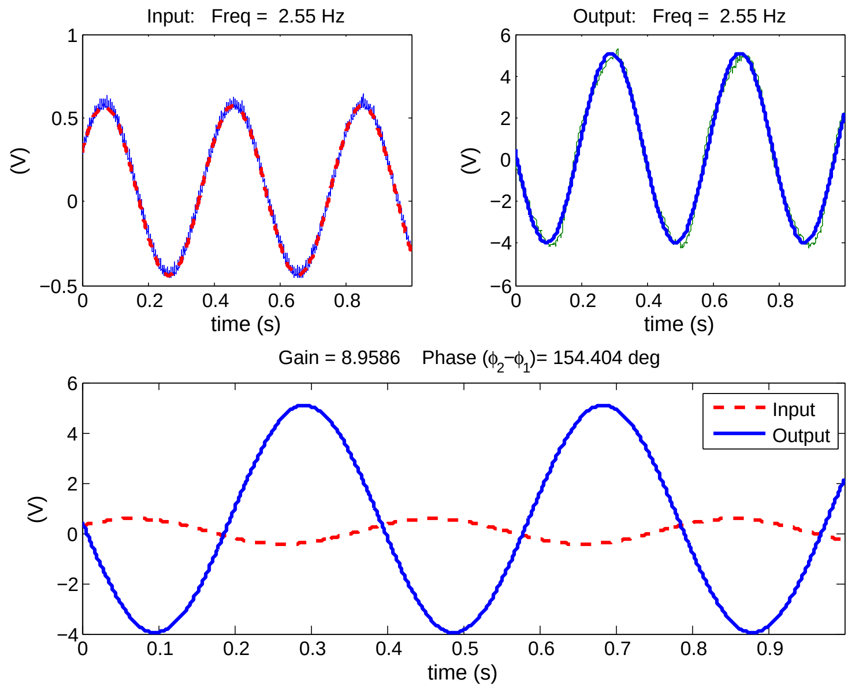

Figure 7: Example of input and output sine wave.

6 Velocity Controller Design

Q3: Using the identified model $G(s)$ of the plant obtained either in Section 5 for the angular velocity in response to the voltage command, compute the step response of the open loop system for $0 <= t <= 2$ using the Matlab command "step." Use the Matlab command "stepinfo" to summarize the characteristics of the step response.

Q4: Consider a P controller (K(s)=Kp). Plot the position of the closed-loop poles as a function of the controller gain. Give an expression for the steady state error in the closed loop step response. Will this controller guarantee zero steady-state error? How could you reduce the steady-state error? Could you destabilize the closed-loop system by pursuing a smaller steady-state error (use root-locus to answer this question)? Could you drive the closed-loop system response into saturation by pursuing a smaller steady-state error. Compute the step response of the closed-loop system for a "small" gain of Kp=1 and for a "big" gain of Kp=100. Plot both the input and the output of the plant.

Q5: Consider a PI controller (K(s)=Kp+Ki/s). Give an expression for the steady state error in the closed-loop step response. Will this controller guarantee zero steady-state error? Choose Kp and Ki such that the overshoot is less than 10% and the settling time is less than 0.5 s. Justify the choice of Kp and Ki (no tuning or tweaking). Compute the step response of the closed-loop system for $0 <= t <= 4$ using the Matlab command "step." Use the Matlab command "stepinfo" to summarize the characteristics of the step response. Does the step response undershoot (goes below zero)? Explain why in the positive case.

Q6: Test developed PI controller experimentally. Compare simulated and experimental step responses in the same plot. Compare simulated and experimental sinusoidal responses in the same plot.

Closed-loop Velocity Control: Lab Procedure

1. Use a modified version of the lab view file (`ME389_MEM02_Control.vi`) to implement developed controller.

7 Position Controller Design

Q7: Using the identified model $G(s)$ for the angular velocity in response to the voltage command, obtain the model $H(s)$ for the angular position in response to the same voltage command.

Q8: Using $H(s)$, compute the step response of the open loop system for $0 <= t <= 2$ using the Matlab command "step." Use the Matlab command "stepinfo" to summarize the characteristics of the step response.

Q9: Consider a P controller ($K_1(s) = K_p$). Plot the position of the closed-loop poles as a function of the controller gain (use root locus). Give an expression for the steady state error in the closed loop step response. Will this controller guarantee zero steady-state error? Obtain K_p to guarantee an overshoot of 10%. Justify the choice of Kp (no tuning or tweaking).

Q10: By root locus, show that you can improve performance by adding tachometer feedback ($K_2(s) = K_d$) as proposed in Figure 1. Use previously designed proportional controller $K_1(s) = K_p$. Improved performance is evidenced by reduced overshoot without extending the risetime, or reduced risetime without incurring increased overshoot. What value of K_d will allow you to demonstrate this improved performance?

Q11: Test developed PD controller experimentally. Compare simulated and experimental step responses in the same plot. Compare simulated and experimental sinusoidal responses in the same plot.

Closed-loop Position Control: Lab Procedure

1. *Use a modified version of the lab view file (`ME389_MEM02_Control.vi`) to implement developed controller.*

A Files

The necessary files to carry out the lab can be found in `T:\ME389_MEM02_HydraulicServo\`. You have read permissions of these files, but not write permissions. Copy the files to the local `C` drive. The files are separated in three directories

1. `\HydraulicControl_VIs` - *Includes LabView files for controlling the hardware*
   - `ME389_MEM02_Control.vi` - *Used for system identification and experimental control*
   - `ME389_MEM02_Control_DataCollection.vi` - *Also for experimental control, but this version saves the LabView output to a file for later analysis with MATLAB*
2. `\HydraulicServo_WorkingData` - *MATLAB files for plotting frequency response and output of LabView files*
   - `Collect_AnalogSignals.m` - *Use this file to collect input output data with MATLAB. It saves the data to a .mat file with name* `Common_Name.mat`*. You can specify* `Common_Name` *which will be helpful when building the bode plot.*
   - `BuildBode.m` - *Use this file to find gain and phase difference of input and output signals. There is some example data in the directory. Try out* `BuildBode.m` *with the test data.*
   - `plot_HydraulicServo.m` - *Use this to plot data from the control experiment. It loads the LabView data, converts it to matlab, then plots and saves the data .mat form.*
3. `HydraulicServo_Simulation` - *MATLAB files for simulation*
   - *Can simulate the system with MATLAB or Simulink.*