MECH420

Sensors and Actuators

Laboratory Manual for Experiment 5

Fall 2020

The University of British Columbia

Department of Mechanical Engineering

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Laboratory Exercise #5: Hydraulic Demonstration System Containing Actuator, Servo-valve and Analog Sensors

Learning Objectives

The objectives of this laboratory exercise are:

- To understand the main components of a hydraulic control system, particularly a servo-valve-controlled positioning and motion control system
- To understand how the sensor signals (e.g., pressure and flow rate) in a hydraulic control system are used in the operation of the system
- To understand the nonlinear static and dynamic behavior of hydraulic control system elements.

Background

Hydraulic control systems offer medium to large actuation forces, where they typically outperform comparable electrical drives with respect to their system dynamics. Hydraulic systems are therefore widely used in industry and in industrial products. This laboratory exercise will give an introduction to hydraulic servo-systems using the example of a typical hydraulic piston-cylinder actuator and a servo-valve with associated sensors, for linear motion [5.1].

1. Hydraulic Control System

A schematic diagram of a basic hydraulic control system is shown in Figure 5.1. The hydraulic fluid (incompressible oil) is pressurized using a pump, which is driven by an AC motor. The motor converts electrical power P_e into mechanical power P_m, and the pump converts mechanical power into hydraulic power P_h. Losses in the power conversion can be expressed in terms of the conversion efficiency η_{em} of the motor, which is typically high, and the efficiency η_{mh} of the hydraulic pump, which is typically much lower. This conversion may be represented by:

$$\eta_{em} P_e = P_m \;, \quad \eta_{mh} P_m = P_h$$

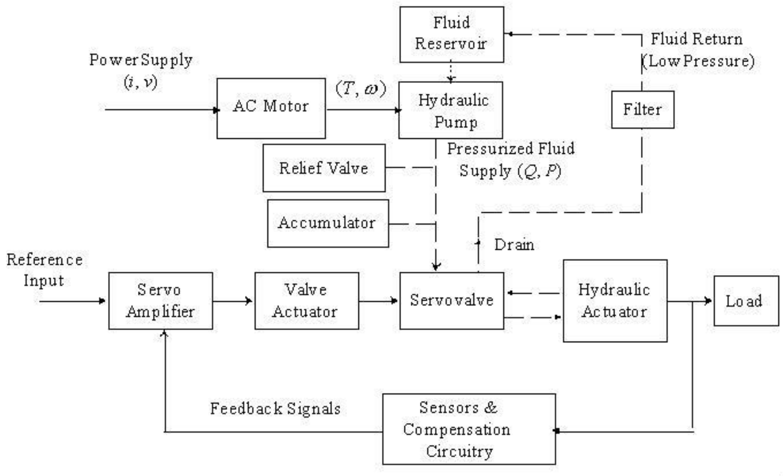


Figure 5.1 Schematic diagram of a hydraulic control system [5.1].

The pressure of the fluid from the pump is regulated and stabilized by a relief valve and an accumulator. A hydraulic valve provides a controlled supply of fluid into the actuator. In feedback control, the valve actuation uses motion signals, to achieve the desired response — hence the name *servo-valve*. Usually, the servo-valve is driven by an electric *valve actuator,* such as a *torque motor* or a *proportional solenoid*, which in turn is driven by the output from a *servo amplifier*. The servo amplifier receives a reference input command (corresponding to the desired position of the load) and also a measured response of the load (in feedback). The hydraulic actuator (typically a piston-cylinder device for rectilinear motions or a hydraulic motor for rotary motions) converts fluid power back into mechanical power, which is available to perform tasks (i.e., to drive a mechanical load). The low-pressure fluid at the drain of the hydraulic servo-valve is filtered (to any impurities) and returned to the reservoir, and is again available to the pump.

The computer-controlled hydraulic system that is available for the present experiments is shown in Figure 5.2. In this system, in addition to the position of the mechanical load, the pressure on both sides of the piston of the hydraulic actuator and also the flow rate Q_s of the fluid streaming into the valve, are measured.

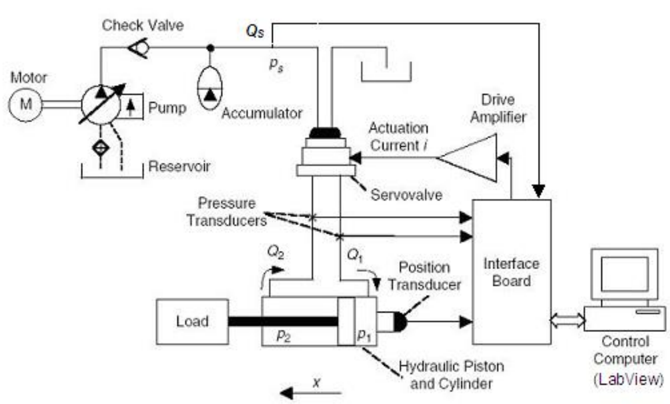


Figure 5.2 A computer-controlled hydraulic system [5.1].

2. The Hydraulic Control Elements

2.1 The Pump

The pump unit consist of a gear pump driven by an AC induction motor. It provides a relatively constant system pressure p_s of about 1,000 psi for a volumetric flow rate Q_p, which varies within specific limits.

2.2 The Accumulator

The accumulator is located downstream from the hydraulic pump. The task of the hydraulic accumulator is to take up any excess quantity of pressurized hydraulic fluid, which can be fed back into the hydraulic circuit when needed. Such a storage device can supply hydraulic fluid to satisfy the peak demand, compensate for temperature-related variations, supply energy during emergency conditions (power loss) or dampen pump-induced pressure oscillations. In addition, it filters pressure fluctuations of the system that might be due to variable loads, which can harm the system.

The accumulator is a container of variable volume, to accommodate the excess fluid. The two most common types of hydraulic accumulators are the gas charged accumulator and the spring-loaded accumulator. The fluid tank of a gas-charged accumulator contains a bladder that is filled with gas under high pressure. The pressure of the hydraulic system compresses the gas and the hydraulic fluid fills the resulting void in the tank. In the cylinder of a spring-loaded accumulator, a spring force acts on a piston against the fluid pressure and therefore provides a variable fluid volume.

The accumulator is a nonlinear element. However, as a first order approximation, the fluid volume stored in the accumulator is proportional to the pressure p_A inside the accumulator relative to the atmospheric pressure, as given by:

$$V_A = C_A \; p_A$$

where, C_A denotes the fluid capacitance. Some accumulators require a specific base pressure p_{A0} to start taking up liquid according to the relation:

$$\begin{aligned} p_A > p_{A0}: &\quad V_A = \frac{p_A - p_{A0}}{C_A}, \\ p_A \le p_{A0}: &\quad V_A = 0. \end{aligned}$$

The flow rate of fluid into the accumulator is therefore proportional to the change in pressure inside the accumulator. This may be expressed as:

$$q_A = \frac{\mathrm{d}V_A}{\mathrm{d}t} = C_A \frac{\mathrm{d}p_A}{\mathrm{d}t}$$

Compare this with the physical equation of an electric capacitance, which involve current and voltage, analogously to volume flow rate and pressure.

It can be assumed that the pressure inside the accumulator corresponds to the system pressure in the pipe at its inlet. Thus, the accumulator can be fully described by its fluid capacitance C_A and its base pressure p_{A0}.

2.3 Hydraulic Valves

Fluid valves are used to regulate three quantities of a fluid flow:

1. Flow direction

2. Flow rate
3. Fluid pressure.

The valves that accomplish the first two functions are termed *flow-control valves*. The valves that regulate the fluid pressure are termed *pressure-control valves*. Valves are also classified by the number of flow paths present under operating conditions. For example, a four-way valve has four paths in which flow can enter and leave the valve.

Spool valves are used extensively in hydraulic servo systems. A schematic diagram of a four-way spool valve is shown in Figure 5.3. The moving unit of the valve is called the spool. It consists of a spool rod and one or more expanded regions (or lobes), which are called lands. Input displacement d , which is applied to the spool rod using an actuator (torque motor or proportional solenoid), regulates the flow rates Q_1 and Q_2 to and from the hydraulic actuator, respectively, and also the corresponding pressure difference $P = P_1 - P_2$ available to the actuator. *Note*: Depending on the operational regime of the hydraulic system, the flow rates and pressures cannot be set independently.

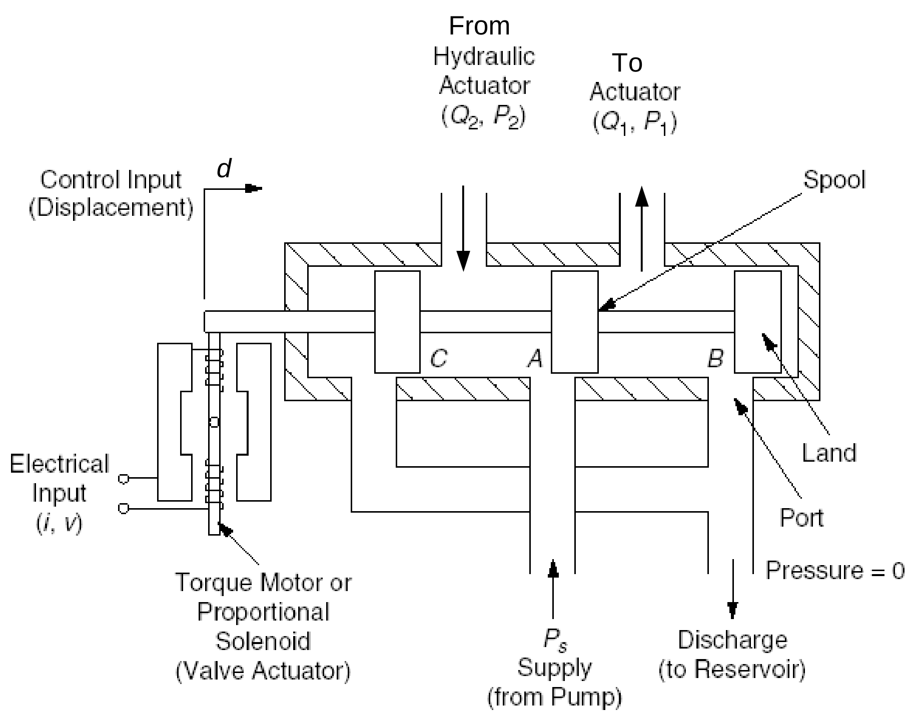


Figure 5.3 A four-way spool valve [5.1].

The symbol for such a 4-way spool valve that is used to set a flow direction is shown in Figure 5.4. In addition to the fully open and closed port positions, any intermediate position can be achieved by choosing the appropriate control current for the valve actuator, in the range:

$$-60 \text{ mA} < i < +60 \text{ mA}$$

In the present setup, a control voltage V_V is sent from the PC to a signal conditioning circuit that translates it linearly into current.

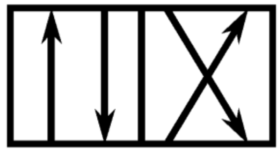


Figure 5.4 The symbol of a four-way spool valve (example).

The partially opened valve ports produce flow resistance, controlling the flow rate-pressure drop according to the relationship:

$$q_i = K\sqrt{\Delta P_i}\ ,$$

where K is the valve constant (which depends on the control signal, which in turn governs the degree of valve opening) and ΔP_i is the pressure drop across the corresponding port of the valve. The manufacturer gives the flow load characteristic of the valve in the form shown in Figure 5.5.

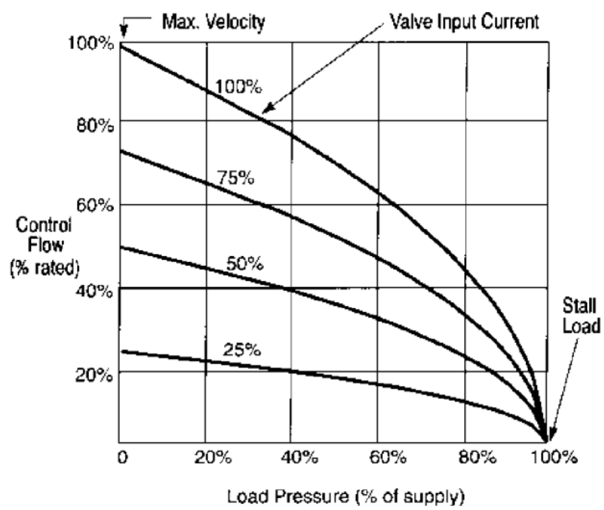


Figure 5.5 Flow-load characteristics of a four-way spool valve.

3. The Hydraulic Actuator

Rotary hydraulic actuators (hydraulic motors) operate much like hydraulic pumps, except that the direction of the flow is reversed and the mechanical power is delivered by the shaft, rather than taken in. High-pressure fluid enters the actuator. As it passes through the hydraulic motor, the fluid power is used to turn the rotor, and the pressure drops along the flow path in the actuator. The low-pressure fluid leaves the motor and returns to the reservoir.

A rectilinear hydraulic actuator that is commonly used in hydraulic control systems is the hydraulic ram or piston-cylinder actuator. A schematic diagram of the hydraulic ram used in the current setup is shown in Figure 5.6.

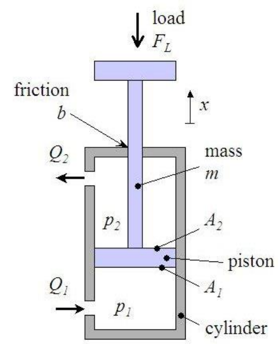


Figure 5.6 Double-acting piston-cylinder hydraulic actuator.

This is a double-acting actuator because the fluid pressure acts on both sides of the piston to move it in either direction. However, the area on which the pressure acts is different in the two sides. The area of the piston available to extend the ram corresponds to the cross-sectional area of the cylinder, which is reduced by the small area $\pi D_S^2/4$ of the displacement sensor that is mounted at that face of the piston:

$$A_1 = \frac{\pi}{4}\left(D_1^2 - D_S^2\right)$$

On the opposite side, the effective area of the piston corresponds to the cross-sectional area of the cylinder, reduced by the cross-sectional area of the rod:

$$A_2 = \frac{\pi}{4}(D_1^2 - D_2^2)$$

The force balance for the piston shows how the pressures p_1 and p_2 in the two actuator compartments are related to the forces from the piston itself F_p and from an external load F_L acting on the system:

$$p_1 A_1 - p_2 A_2 = F_P + F_L$$

The force of the piston is given by:

$$F_P = m\frac{\mathrm{d}^2 x}{\mathrm{d}t^2} + b\frac{\mathrm{d}x}{\mathrm{d}t} + mg\cos\phi + F_{P0}$$

This equation of motion (Newton's 2nd law) includes the mass m of the moving parts, the viscous damping constant given by b, the gravitational forces acting on the piston, and a dry friction term F_{P0}. Only the component of the gravitational force in direction of the piston axis is taken into account for a piston that is tilted by an angle ϕ relative to its vertical position. For simplicity we will ignore the inertia effects, assuming that they are small for the intended slow operation of the actuator. Hence, the force of the piston is given by:

$$F_P \approx b\frac{\mathrm{d}x}{\mathrm{d}t} + mg\cos\phi + F_{P0}$$

This force includes the viscous damping force and gravity. The flow rates into or out of the actuator are related to the velocity of the piston through the corresponding actuation areas:

$$\frac{q_1}{A_1} = \frac{q_2}{A_2} = \frac{\mathrm{d}x}{\mathrm{d}t} = u$$

The hydraulic actuator used in the current setup has the following dimensions:

$D_1 = 4.0$”, $D_2 = 2.5$”, $D_s = 0.5$”.

4. The Variable Load

In general terms, the load that is driven by the hydraulic actuator can be represented by a load force F_L, which may include dynamic effects such as compliance, inertia, and dissipative effects.

In the present system, the load consists of a linear spring. The spring can be connected to the rod of the hydraulic actuator. As the ram expands (increasing x) towards the position L_L , in which the spring is fully extended, the spring relaxes, while the spring is compressed when the ram retracts into the cylinder (decreasing x). The spring force is a linear function of the displacement x, as given by:

$$F_L = k(L_L - x)$$

The spring constant (stiffness) is given by:

$$k = \frac{|\Delta F_L|}{|\Delta x|}$$

5. The Control Sensors for the Hydraulic System

The variables flow, pressure, and displacement appear in the equations describing a hydraulic control system. It follows that measuring these quantities is useful for controlling the hydraulic system.

5.1 The Flow Sensor

The volumetric flow rate to the hydraulic actuator is measured downstream from the accumulator using a turbine flow meter (sensor model: FTB-904 by Omega Engineering Inc.). The rotational speed of a small turbine in the fluid stream is picked up magnetically, and converted into a voltage signal through the signal conditioning provided by the manufacturer. The output signal (0 V – 10 V) for the range of the volumetric flow rate (0 GPM – 16 GPM, with GPM: gallon per minute) is linear over the range 1.75 GPM – 16 GPM (accuracy: 0.5 %) according to the data sheet of the sensor. At lower flow rates the error is typically higher.

5.2 The Pressure Sensors

Two pressure sensors are located in the hydraulic system. They capture the pressure at the inlet into the expansion chamber (p_1) and at the inlet to the contraction chamber (p_2) of the linear actuator. These pressure sensors use a metal diaphragm that deflects in response to the applied pressure. This deflection is measured by strain gauges, which are integrated with the diaphragm and arranged in a Wheatstone bridge. The amplified output signal has a sensitivity of 10 V/2500 psi; assume zero offset.

5.3 The Displacement Sensor

The position of the piston in the hydraulic cylinder is measured by an integrated magnetostrictive linear position sensor (For example, see Section 6.10.3 of the textbook [5.1]). The permanent magnet of the sensor is displaced along the magnetostrictive wire together with the piston. The output of this sensor, given in counts, is proportional to the position.

6. Experiments

System component list

a. Hydraulic Servo-valve
b. Electric drive amplifier of the hydraulic servo-valve
c. Hydraulic actuator
d. Variable load (spring)
e. Hydraulic fluid system with AC motor, pump, tank, accumulator, etc.
f. Flow sensor
g. Pressure sensors
h. Displacement sensor
i. Computer with LabVIEW system
j. LabVIEW interface board (4 analog input channels, 1 analog output channel)

Part A: Introduction of the Hydraulic System

The provided video will introduce the components of the hydraulic system and their locations. It will also demonstrate the system and perform all necessary operations required for the experimental procedures of this laboratory exercise.

Part B: Calibration of the Displacement Sensor

Experimental Procedure

We open the LabVIEW program “X:\Lab 5” and select the “Part B” tab. We start the program and slowly drive the ram to its two end positions ($x = 0$ and $x = L$) by dragging the “Valve Command Signal” slider. We measure the total displacement L and record the voltage output v of the linear displacement sensor (which is the valve voltage) for the two end positions of the sensor.

Analysis

Derive the linear calibration relation $x(v)$ for the displacement sensor signal from the measured data, using end-point calibration.

Part C: Characterization of the Servo-valve

Experimental Procedure

Now we select the "Part C" tab. We move the ram between its extreme positions at different constant valve control signals in the range 0.25 V and 0.70 V and record the sensor signals at a rate of 20 Hz, 10 times in and out. We do this by entering the desired control voltages in the boxes on the front panel and pressing the run button.

Analysis

1. Calculate the ram velocity from the displacement information by numerical differentiation. From the velocity information, calculate the flow rates Q_1 and Q_2. Convert the flow meter signal into a flow rate Q_S according to the manufacturer information and plot it as a function of time, together with Q_1 and Q_2.
2. What does the system do during periods where $Q_S = Q_1$ or $Q_S = -Q_2$?
3. As stated above, the relationship between the flow rate through the valve and the corresponding pressure across the valve is nonlinear. For the periods when the flow rate $Q_1 < 0$, the ram is retracting and fluid from chamber 1 is draining through the valve into a reservoir at atmospheric pressure. This means the pressure p_1 in chamber 1 corresponds to the pressure across the valve. The valve position is set by the control signal V_V, and the flow rate relates to the pressure as a function of V_V: $Q_1 = K_i(V_V - V_{V0})\sqrt{p_1}$.

   For 5 of the periods when the flow rate $Q_1 < 0$ calculate the average flow rates Q_1 and find the corresponding pressures. Find the relation between the flow rate and the induced pressure drop across the servo-valve as a function of the valve control voltage sent from the PC. For this purpose, plot $Q_1/p_1^{1/2}$ as a function of the control voltage V_V for the 5 values. Determine the unknown values V_{Vo} and K_i in the relation:

   $$Q_1 = K_i(V_V - V_{V0})\sqrt{p_1}$$

   This relation describes the flow resistance (nonlinear) of the valve path.

Part D: Load-dependent System Performance

Experimental Procedure

Now we select the "Part D" tab. We connect the spring to the actuator. We move the ram between its extreme positions again. We move it in and out twice using settings for the control parameters that we used in the previous experiment. We observe the sensor signals over time and record them at a rate of 20 Hz.

Analysis

Use the calibration equation from Part B and calculate the forces F_1 and F_2 by using the measured pressures. Use this to calculate the spring force from the force balance on the piston. For this purpose, plot $F_1 - F_2$ as a function of the position x, and determine the spring stiffness k.

Part E: Dynamics of the Hydraulic System

Experimental Procedure

Now we select the “Part E” tab. We drive the piston at a constant velocity (constant V_V). We apply a sudden change in the control signal to the valve and record the system response at a reasonable sampling rate (around 250 Hz is recommended). We do this by pressing the run button.

Analysis

1. For a step command to the valve, provide a plot showing both signals over time.
2. Assuming that the flow sensor signal corresponds to the step response of a linear first order system, determine the time constant. (*Note*: In class, we have discussed the step response of a 1st order system, and how to determine the time constant from it. See Figure 3.1(a) of the textbook [5.1], or any other relevant book, for the necessary information).

7. Additional Exercises (No additional exercises for this experiment)

Reference

[5.1] *Sensors and Actuators: Engineering System Instrumentation*, 2nd Edition, C. W. de Silva, CRC Press, Taylor & Francis, Boca Raton, FL, ISBN: 978-1-4665-0681-7, 2016.

Lab 5: Hydraulic Demonstration System with Actuator, Servo-valve and Analog Sensors

Objectives

- To understand the main components of a hydraulic positioning and motion control system, particularly: hydraulic piston-cylinder actuator, servo-valve with electric valve actuator, sensors
- To understand how the sensor signals (position, pressure, flow rate) in a hydraulic control system facilitate the operation of the system
- To understand the nonlinear static and dynamic behavior of hydraulic control system elements.

Lab 5: Sensors

Flow Sensor: Turbine-type

Flow velocity is obtained using miniature turbine and tachometer → proportional to volume flow rate (cross-section is constant)

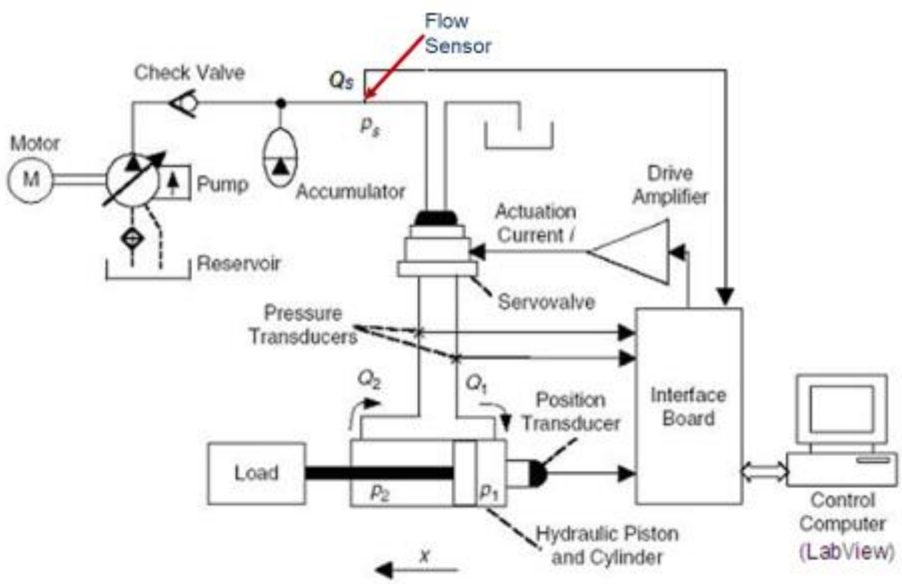
Pressure Sensors: Diaphragm-type

Metal diaphragm that deflects with pressure, which is measured by strain gauges. Integrated with a Wheatstone bridge and signal conditioning

Position Sensor: Magnetostrictive

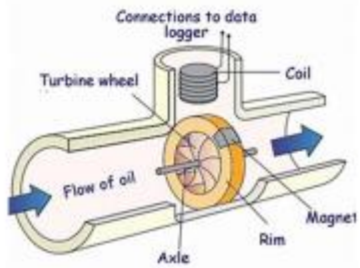
Ultrasound-based time of flight method. Interrogation current pulse travels along magnetostrictive wire (*waveguide*). It interacts with magnet (at sensed object) and generates an ultrasound (strain) pulse (magnetostrictive action). Return pulse is timed

Lab 5: Overview of the Hydraulic Control System

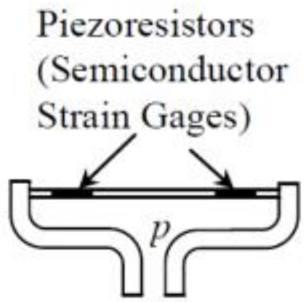


Lab 5: Sensors

Flow Sensor: Turbine-type

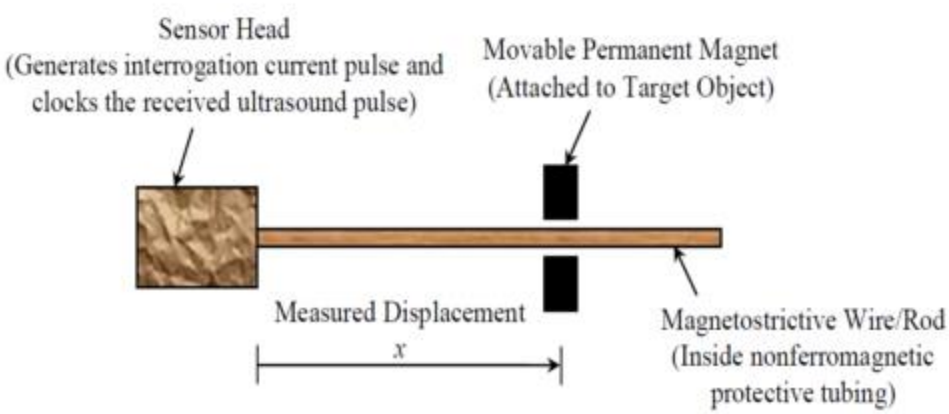


Pressure Sensors: Diaphragm-type

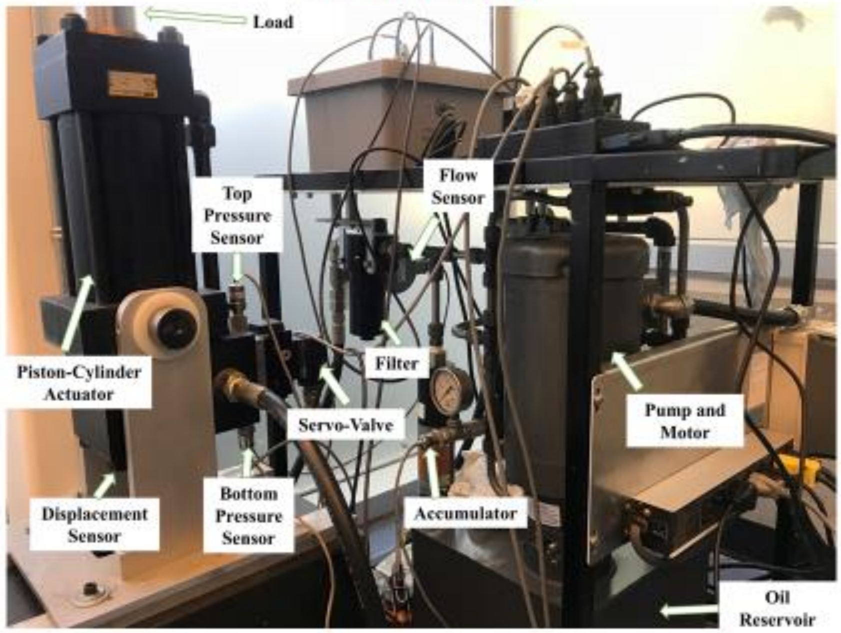


Lab 5: Sensors

Position Sensor: Magnetostrictive



Lab 5 Setup


Load
Top Pressure Sensor
Flow Sensor
Filter
Piston-Cylinder Actuator
Servo-Valve
Pump and Motor
Displacement Sensor
Bottom Pressure Sensor
Accumulator
Oil Reservoir