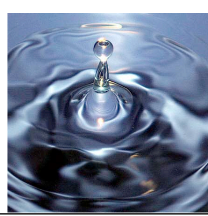
Design and Modeling of Fluid Power Systems
ME 597/ABE 591

Dr. Monika Ivantysynova
MAHA Professor Flud Power Systems

MAHA Fluid Power Research Center
Purdue University



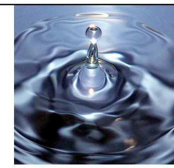
Dr. Monika Ivantysynova, Maha Professor Fluid Power Systems

- Mivantys@purdue.edu
- http://www.purdue.edu/ME
- Phone: 765 447 1609
- Fax: 765 448 1860

@ Maha Fluid Power Research Center, 1600 Kepner Drive
Lafayette, IN 47905

http://engineering.purdue.edu/Maha

Course Description

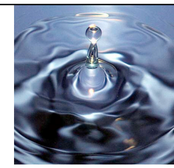


ME 597/ABE 591 Design and Modeling of Fluid Power Systems
1 Semester, 3 classes/week, credits 3
Prerequisites: ABE 435 or ME 309, ME 375 or consent of instructor.

This course provides an introduction into modeling and design of fluid power components and systems. Modeling techniques based on physical laws and measured performance characteristics will be applied to design and analyze component and system performance.

Fundamentals:
- **design principles of displacement machines,**
- **flow and pressure control,**
- **motion control using resistance control,**
- **motion control using displacement controlled actuators,**
- **variable speed transmissions,**
- **modeling of flow in lubricating gaps,**
- **transmission line models,**
- **secondary controlled systems,**
- **load sensing systems.**

Course Objectives



1. To learn to design fluid power systems and to understand the function of components and how to model their steady state and dynamic behavior.

2. To determine steady state and dynamic characteristics of fluid power components and systems based on measurements.

3. To learn *how* to model fluid power components and systems based on physical laws and when *to use these models*.

4. To learn how to design advanced energy saving hydraulic actuators and to predict their performance.

Note that for all physical quantities the SI system of units will be used consequently in this course.

Contents

1. Introduction and overview of components, circuit and system design methods

2. Fluid properties, bulk modulus, viscosity, solubility of gas, types of fluids

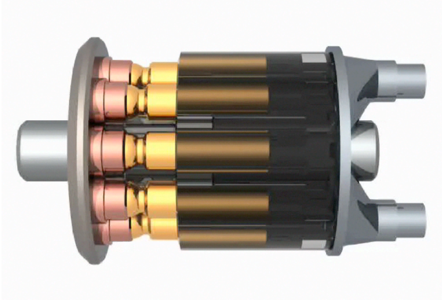
3. Modeling of transmission lines, impedance model of lines, accumulators

4. Displacement machines design principles, scaling laws, power density, volumetric and torque losses

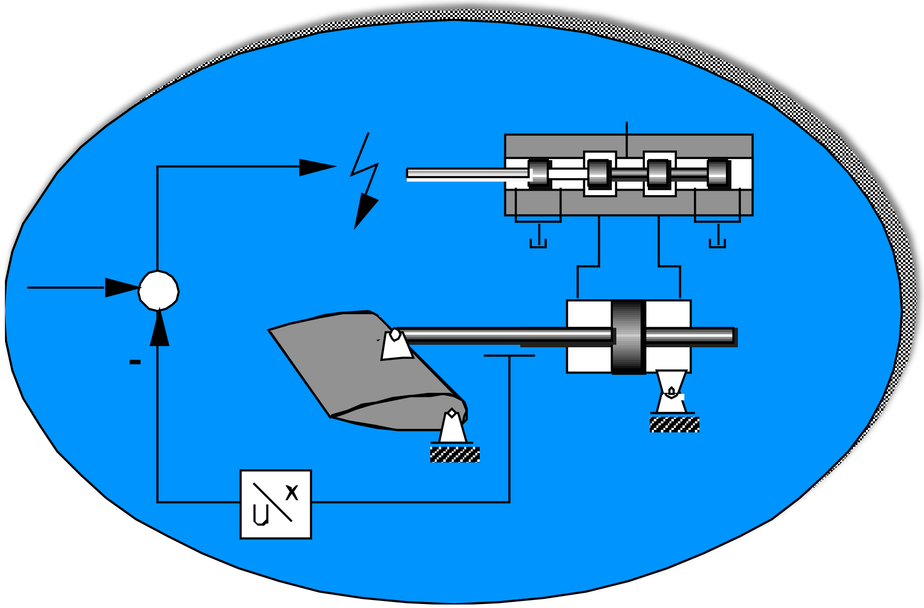
5. Displacement machines classification, piston machines, vane type machines, gear machines

6. Steady state characteristics, measurement methods and modeling

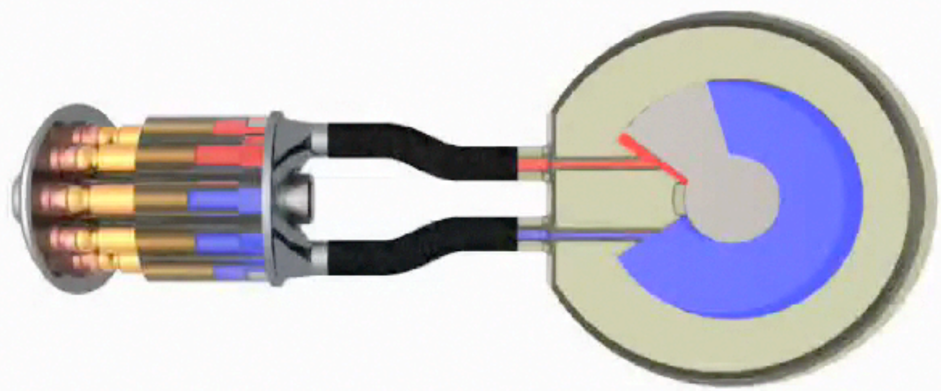
7. Gap flow models



Contents



Contents



Literature

Ivantysyn, J. and Ivantysynova, M. (2001), *Hydrostatic Pumps and Motors.* Akademia Books International. New Dehli. ISBN-81-85522-16-2

Fitch, E.C. and Hong, I.T. (1998), *Hydraulic Component Design and Selection.* BarDyne, Inc. Oklahoma, USA

Watton, John (2009), Fundamentals of Fluid Power Control. Cambridge University Press, New York

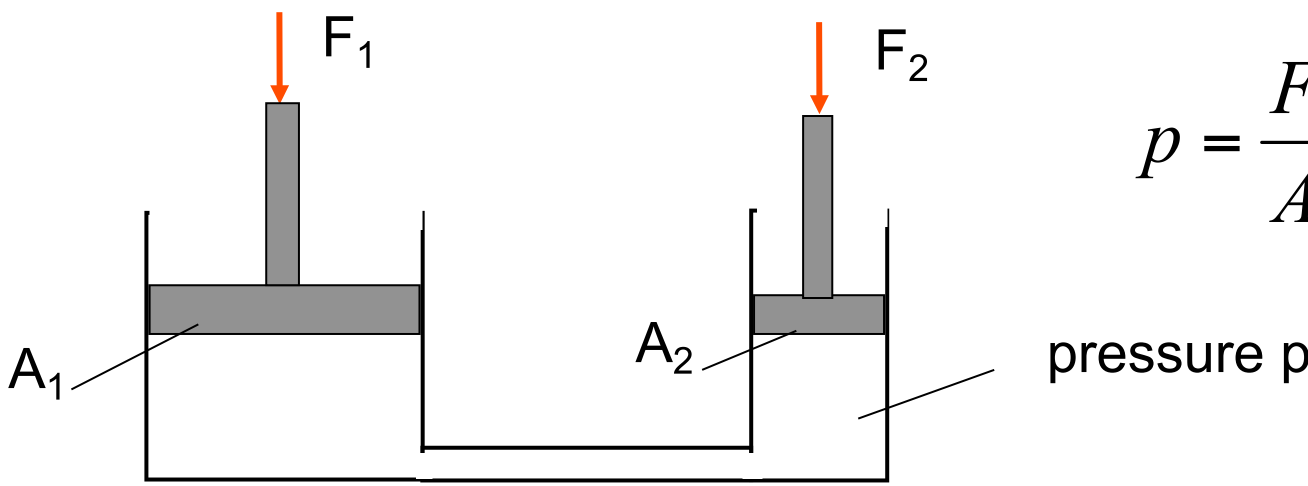
H. E. Merritt. *Hydraulic Control Systems*. John Wiley & Sons, Inc.

Manring, Noah D. (2005), *Hydraulic Control Systems. John Wiley & Sons, Inc. Hoboken, New Jersey*

Fluid Power Systems

Pascal‘s Law → Hydrostatic Systems, Power Transmissions & Actuators

„Any change of pressure at any point of an incompressible fluid at rest, is transmitted equally in all directions.“ formulated 1651 by Pascal



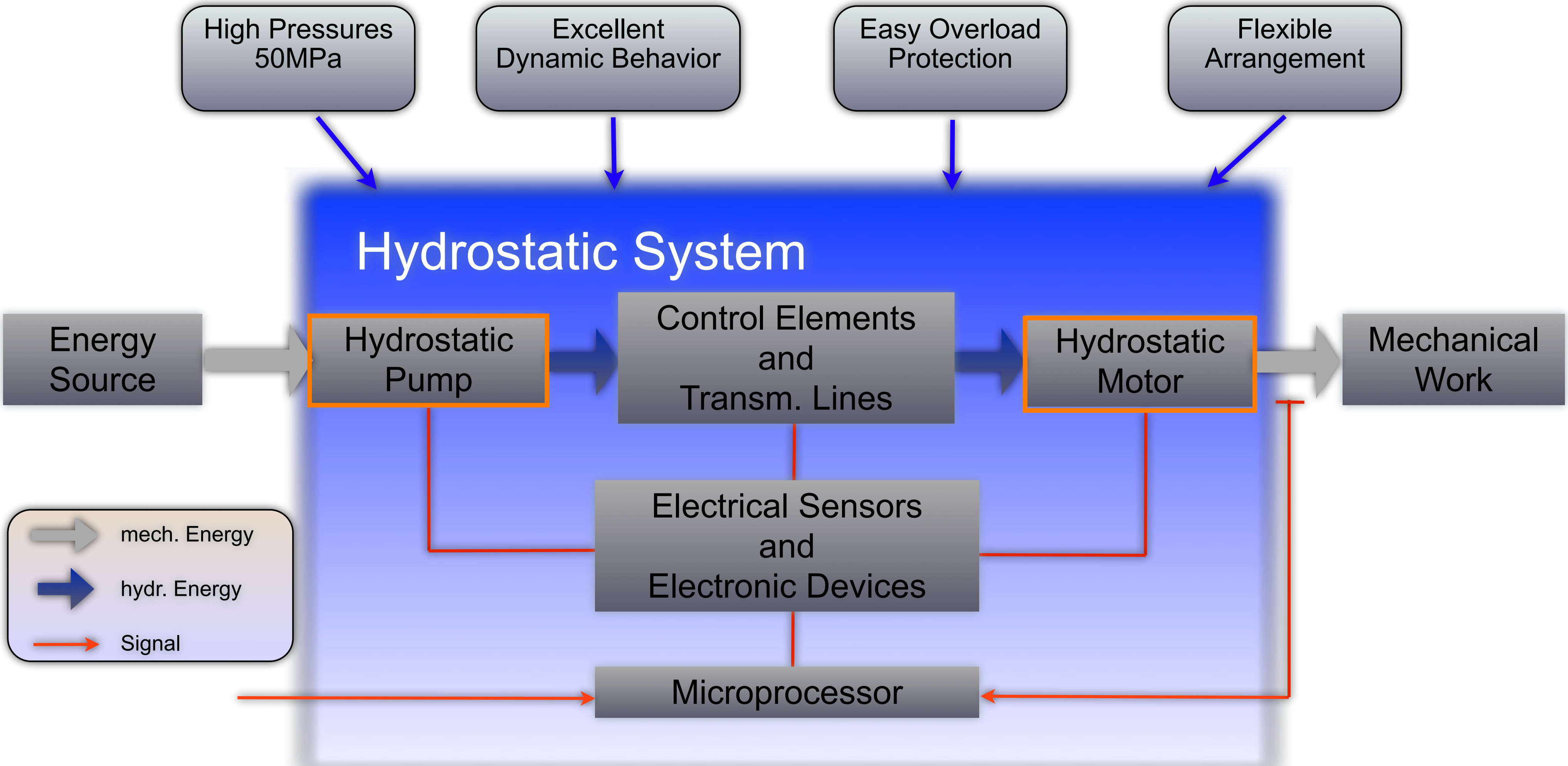
$$p = \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

Thus it is possible to transmit forces using the static pressure of a fluid. The hydrostatic pressure is given by the ratio of the force acting on a fluid column and the related area.

→ we can build machines to multiply forces!

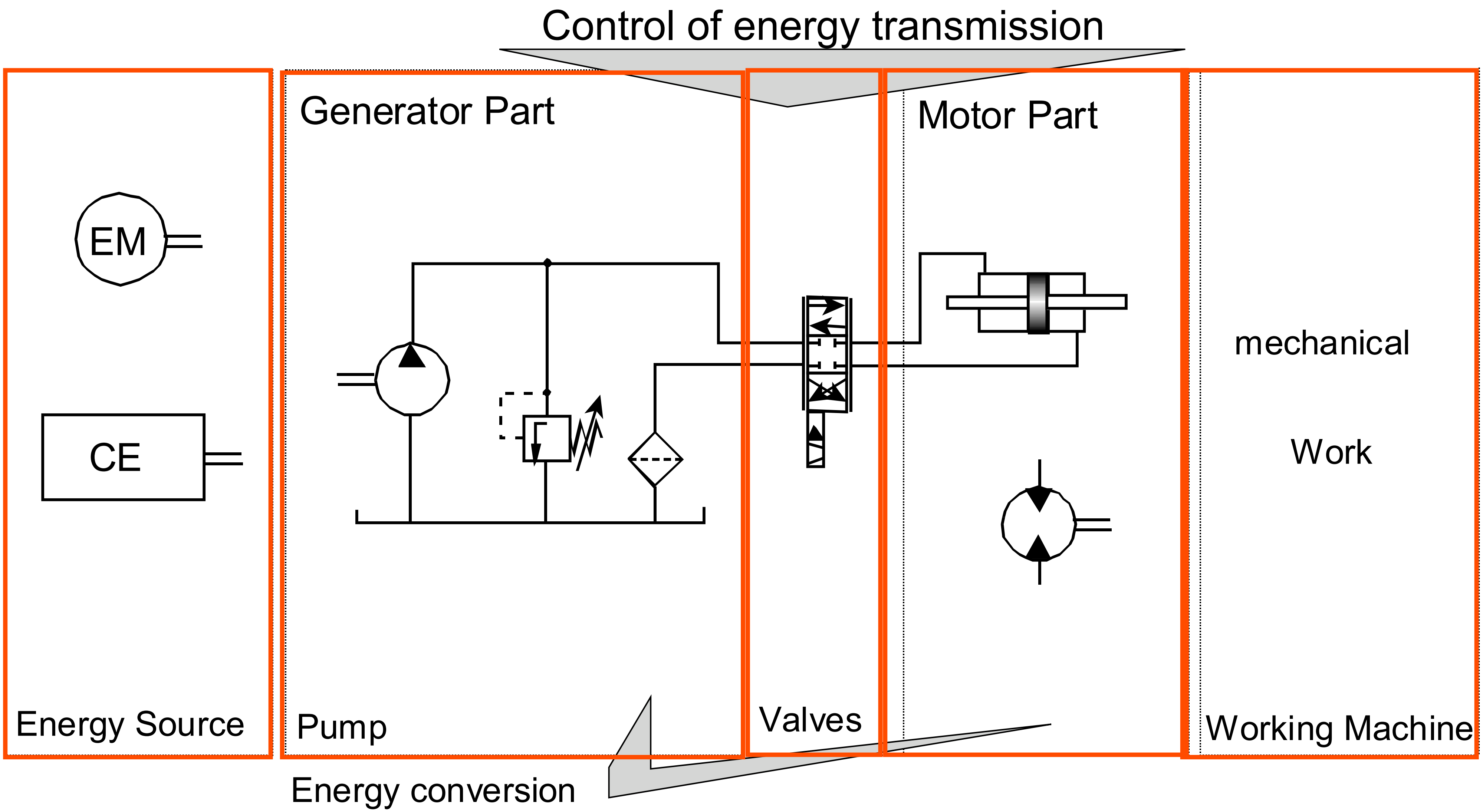
Basic system structure

Power Transmission in hydrostatic systems

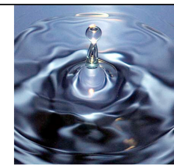


System structure

ISO Symbols for Circuit Design



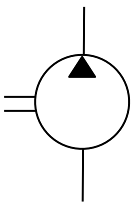
ISO International Organization for Standardization



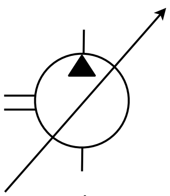
Circuit design

ISO Symbols for Circuit Design

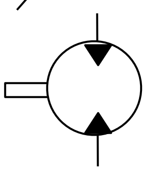
a basic selection of ISO 1219:1991



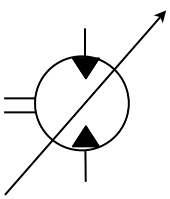
fixed displacement pump



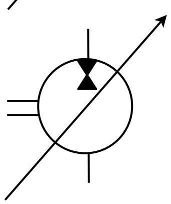
variable displacement pump



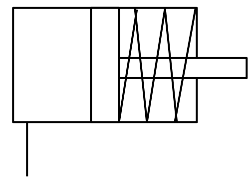
fixed displacement motor



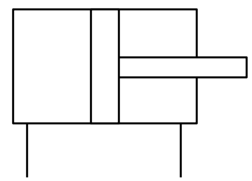
variable displacement motor



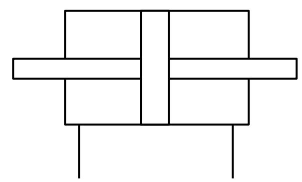
variable displacement machine



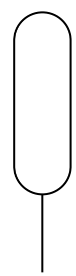
single rod cylinder



single rod cylinder-double acting



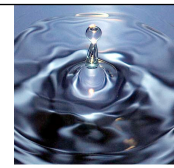
double rod cylinder



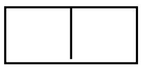
accumulator

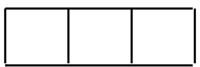
Circuit design

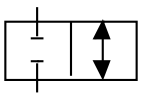
ISO Symbols for Circuit Design

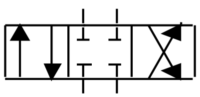


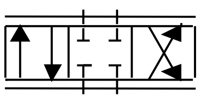
Directional control valves

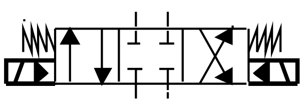
 **valve with two positions**

 **valve with three positions**

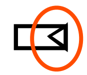
 **2/2 directional control valve**

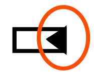
 **4/3 directional control valve**

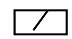
 **proportional valve – hydraulic resistance continuously changeable**

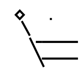
 **4/3 directional control valve, electro hydraulically operated and centered by springs**

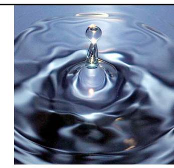
type of valve operation

 **pneumatically**

 **hydraulically**

 **electrically**

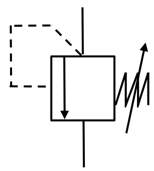
 **manually**



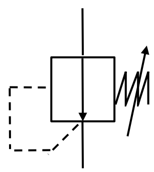
PURDUE UNIVERSITY

Circuit design

ISO Symbols for Circuit Design

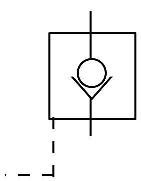


pressure relief valve

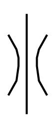


pressure reduction valve

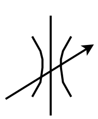
check valve



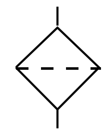
pilot operated check valve



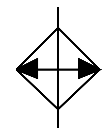
throttling valve



adjustable throttling valve

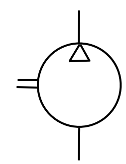


filter

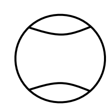


cooler

reservoir



compressor

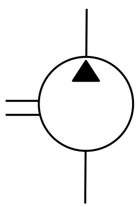


flow meter

Circuit design

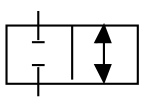
Design of a circuit diagram

A fixed displacement pump driven by an electric motor operates a single rod cylinder. The circuit is protected against overload by a pressure relief valve. The lifting function is realized using an easy 2/2 directional control valve, which is operated by an solenoid. Draw the circuit!

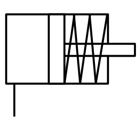


fixed displacement pump

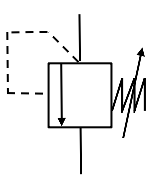
electric motor



2/2 directional control valve

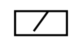


single road cylinder

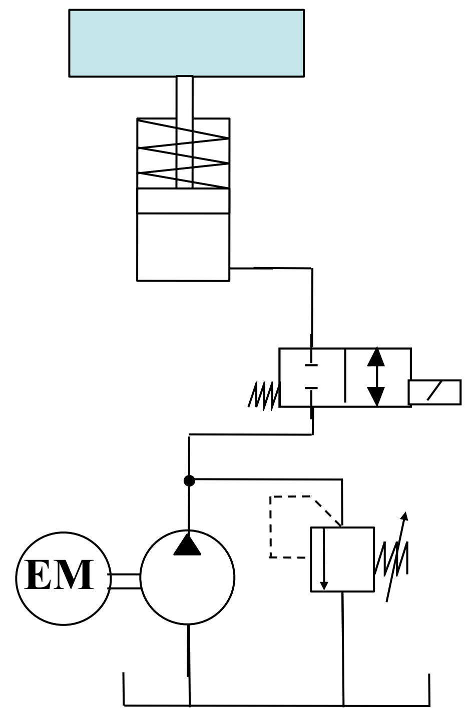


pressure relief valve

reservoir



electrically

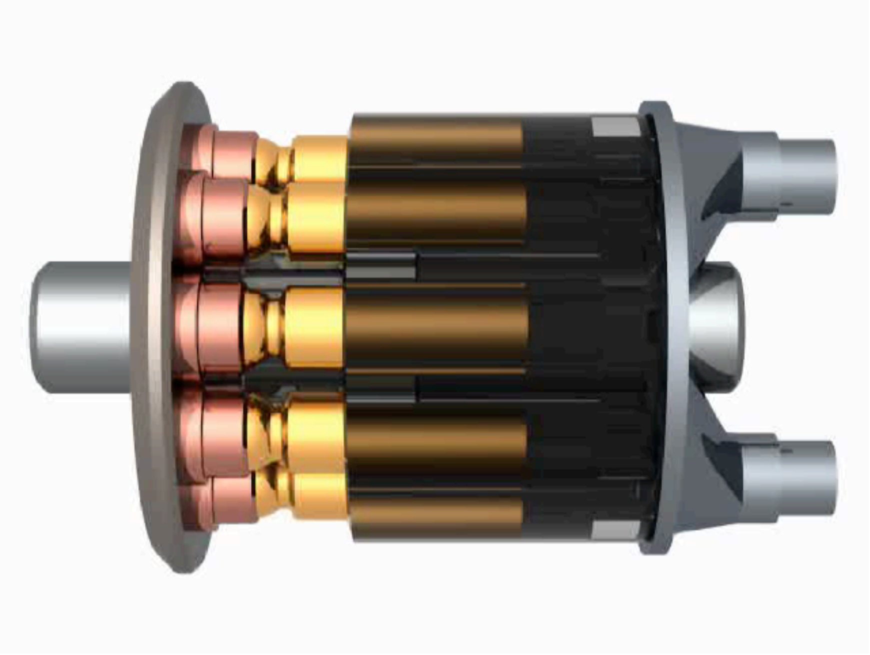


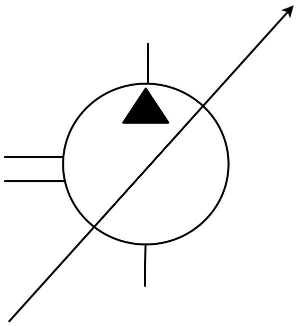
Displacement machine

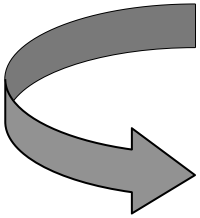
Axial piston pump & motor

Power source in fluid power systems

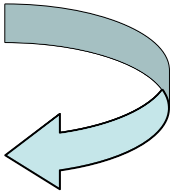
Transfers mechanical power into fluid power







or when working as motor

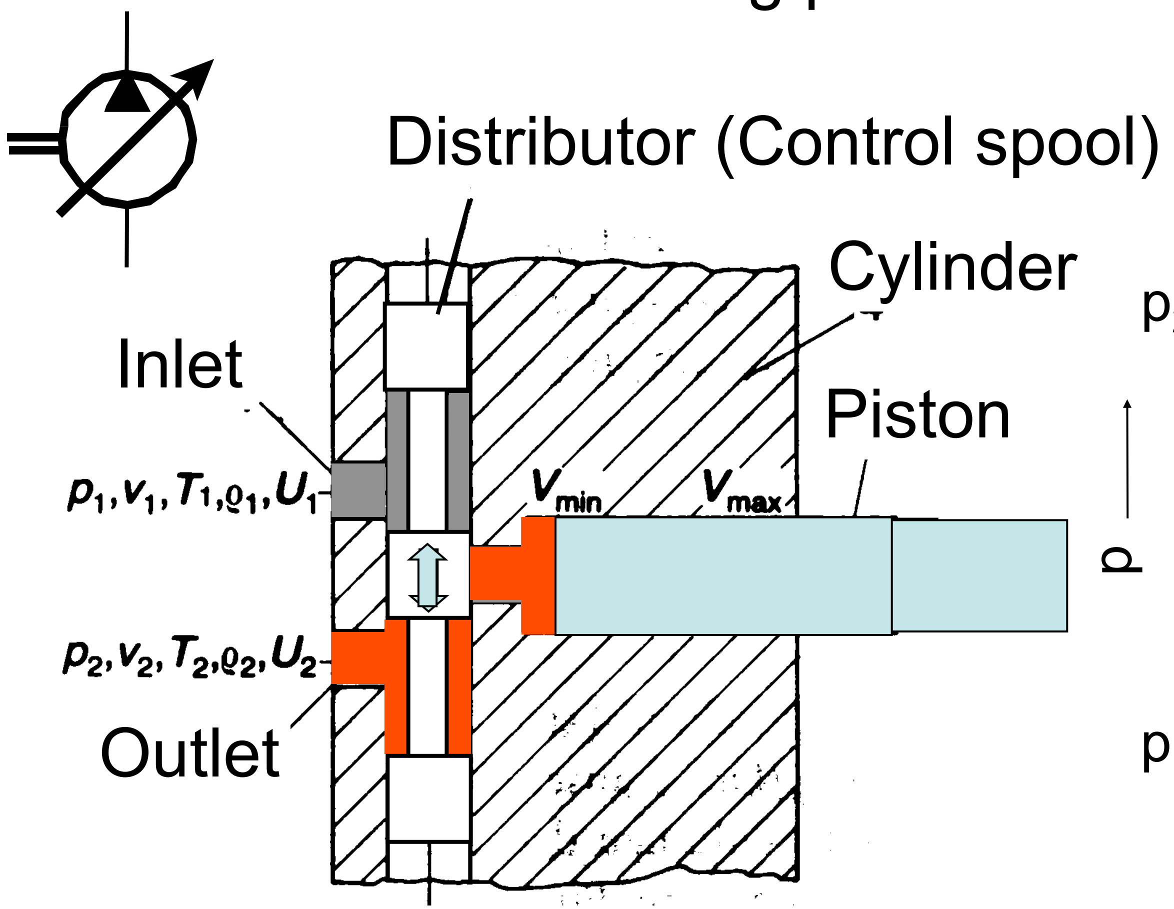


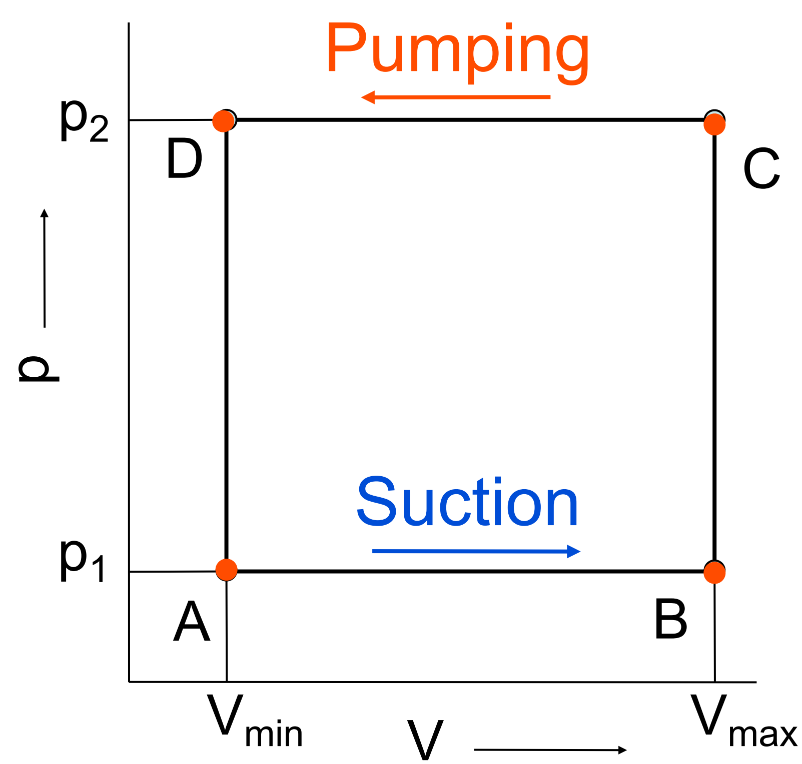
Transfers fluid power into mechanical power

Displacement machine

How it works?

The ideal working process assuming an ideal fluid



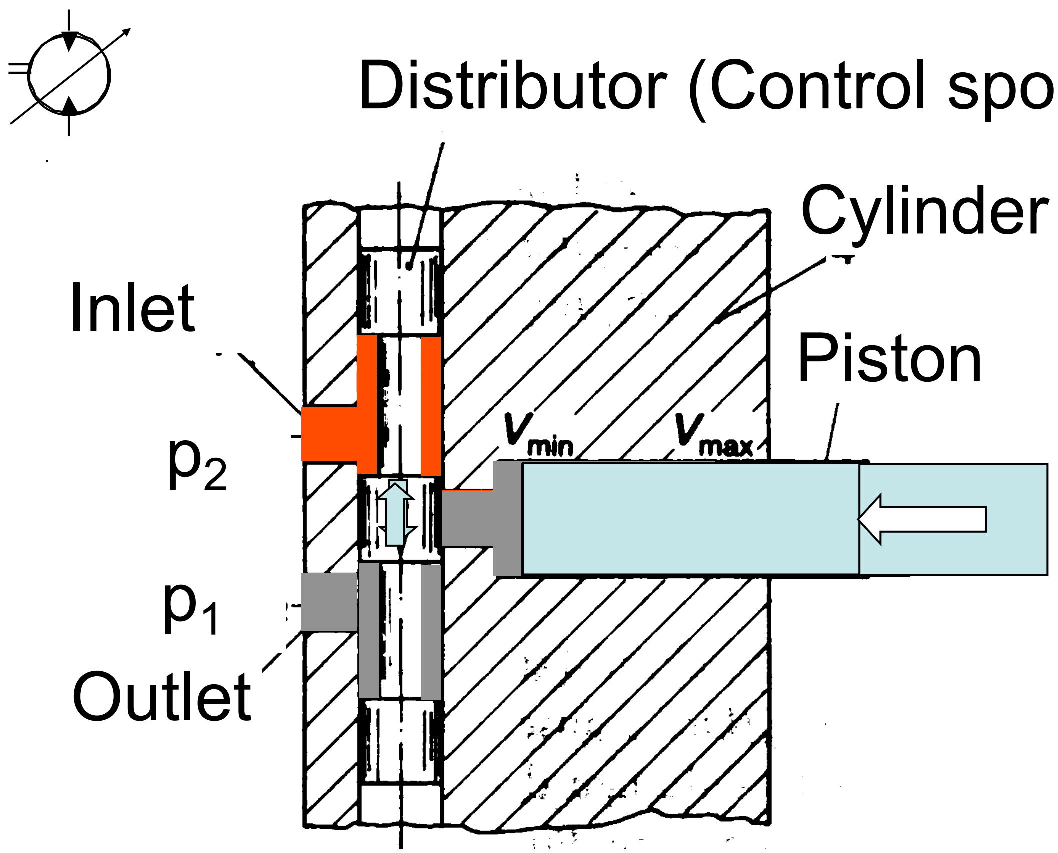


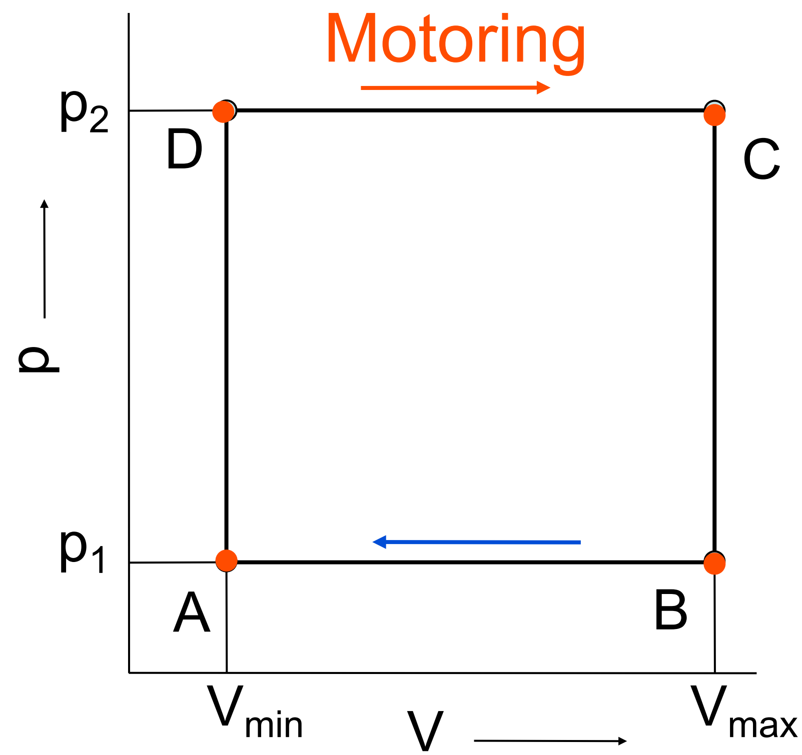
The displacement machine works as pump

Displacement machine

When changing ports – the machine works as motor

The ideal working process assuming an ideal fluid

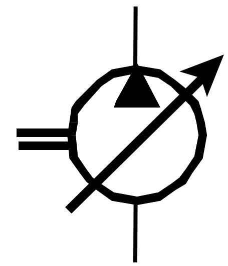




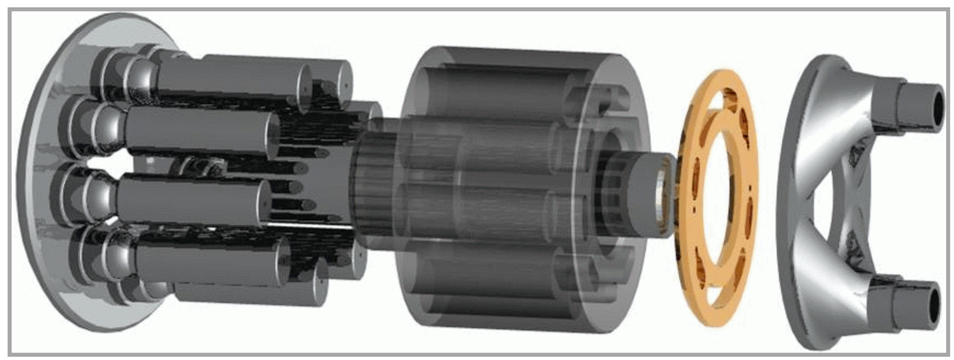
The displacement machine works as motor

Displacement machine

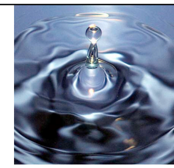
Assumptions for ideal working process of displacement machines



- Ideal machine means:
- - rigid parts
- - no clearance between moveable parts
- - ideal switching between port connection



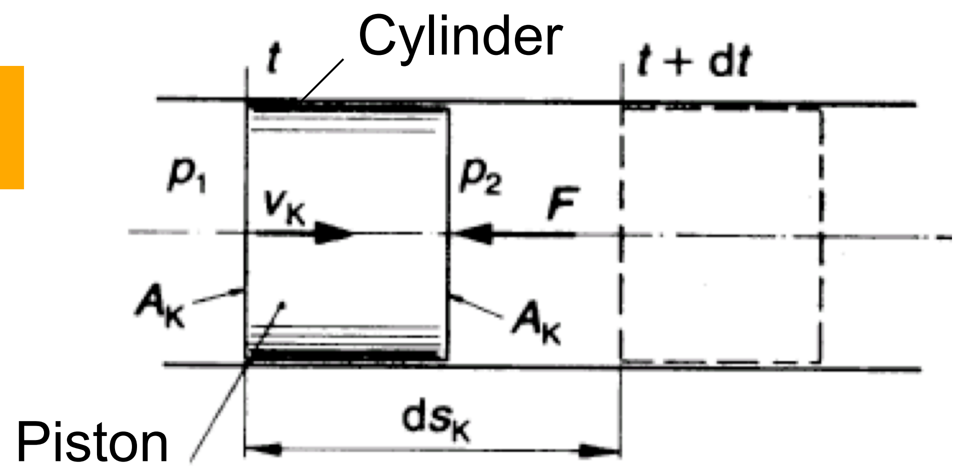
- Ideal fluid means:
- - incompressible
- - non-viscous



Displacement machine

With linear motion

Pressure difference: $\Delta p = p_1 - p_2$



Force acting on piston: $F = \Delta p \cdot A_K$

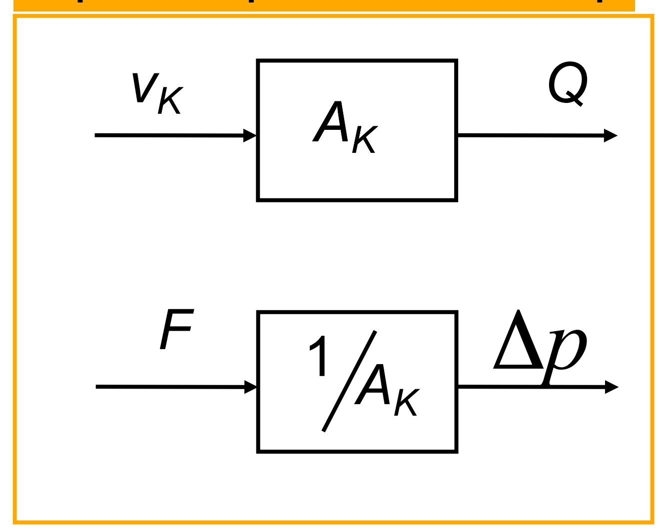
Piston displacement: $ds_K = v_K \cdot dt$

Volumetric flow: $Q = v_K \cdot A_K$

Piston work: $W = F \cdot ds_K = \Delta p \cdot Q \cdot dt$

Power: $P = \frac{W}{dt} = \Delta p \cdot Q$

input/output relationship



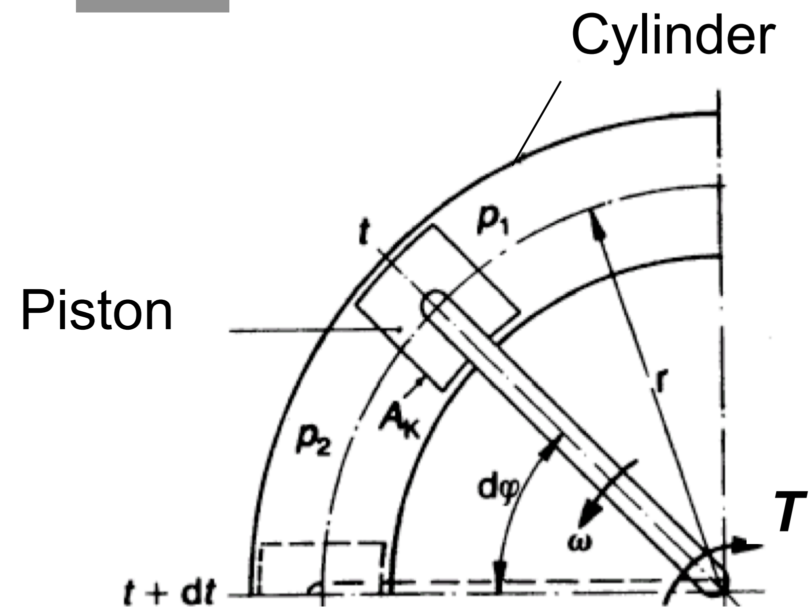
Displacement machine

With rotary motion

Pressure difference: $\Delta p = p_1 - p_2$

Displacement volume: $V = 2 \cdot \pi \cdot r \cdot A_K$

Torque: $T = \Delta p \cdot A_K \cdot r = \dfrac{\Delta p \cdot V}{2 \cdot \pi}$



Piston work: $dA = T \cdot d\varphi = \dfrac{\Delta p \cdot V}{2 \cdot \pi} \cdot 2 \cdot \pi \cdot n \cdot dt = \Delta p \cdot n \cdot V \cdot dt$

Volumetric flow: $Q = V \cdot n$ with $\omega = 2 \cdot \pi \cdot n$

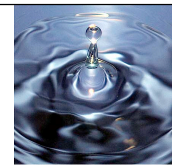
Power: $P = \dfrac{W}{dt} = \Delta p \cdot Q$

input/output relationship

$$n \longrightarrow \boxed{V} \xrightarrow{Q} \qquad T \longrightarrow \boxed{\frac{2 \cdot \pi}{V}} \xrightarrow{\Delta p}$$

Classification of pumps

according to circuit configuration

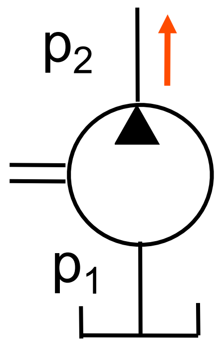


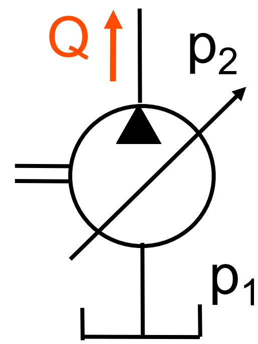
Volume displaced per revolution can be varied. This allows to vary the flow rate at pump outlet.

Open circuit pumps

$p_2 > p_1$

Fixed displacement

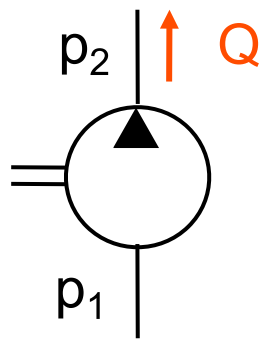


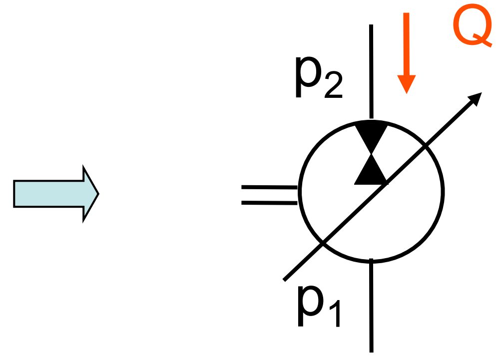


Variable displacement

Closed circuit pumps

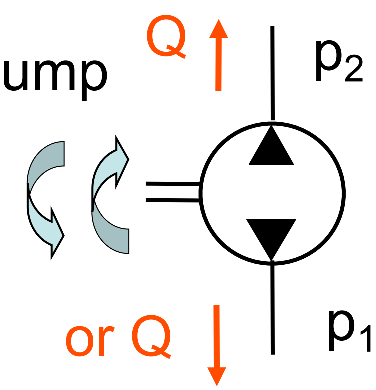
$p_2 > p_1$



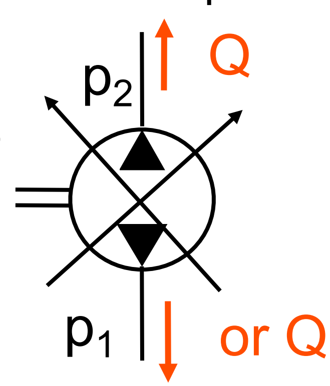


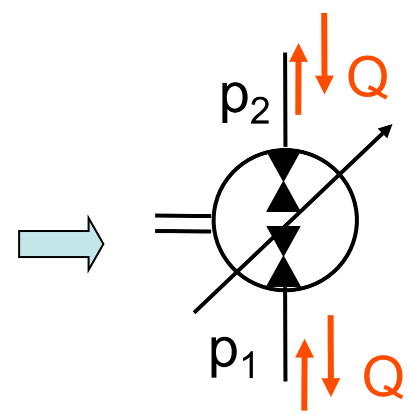
$p_2 > p_1$

Reversible pump

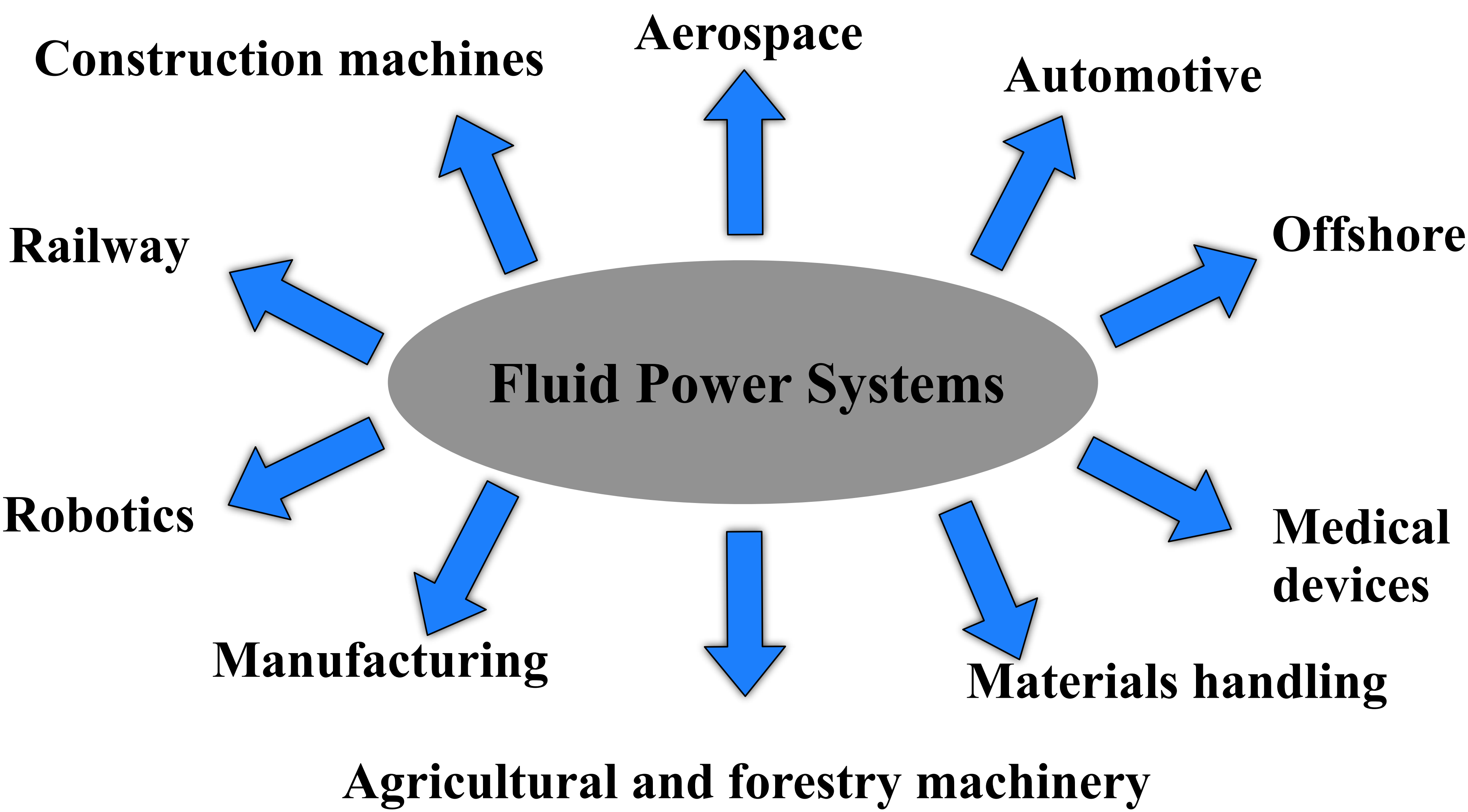


Overcenter pump



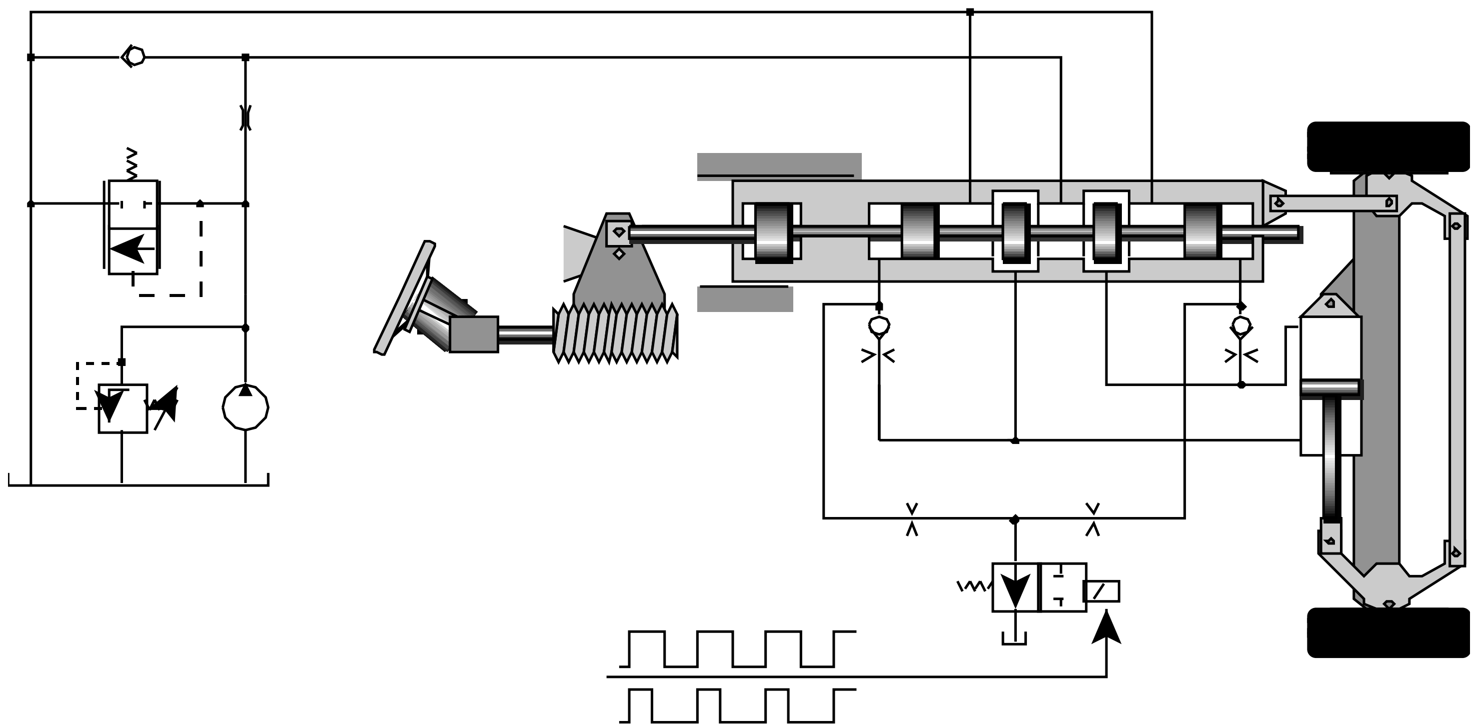


Industrial applications



FP system design steps

Specification ⇨ System structure ⇨ **Performance Prediction** ⇨ Product



Example: Steering System (Servotronic made by ZF)

FP system design steps

Specification

Circuit design

Selection & Sizing of components

Modeling

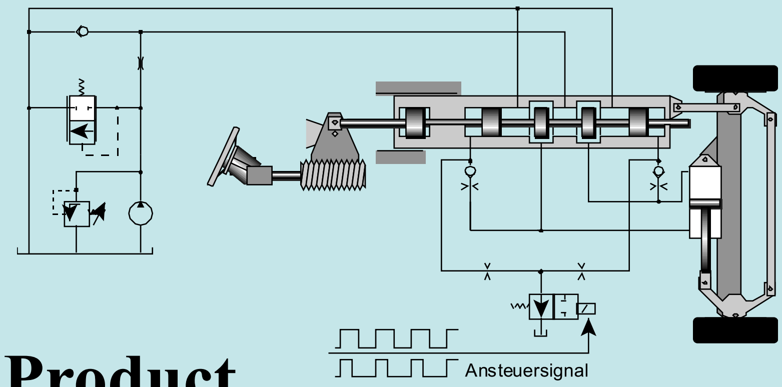
System simulation

Controller Design

Performance Prediction

Manufacturing/Assembly

Test



Product

Engineering project

Aim

To demonstrate in form of an engineering project the ability to design fluid power systems, to understand the function of components and how to model their steady state and dynamic behavior to predict the system performance and compare with measurements. The project should also train the ability to plan and conduct measurements on hydrauic actuation systems and finally proof the ability of writing an engineering report in an appropriate form.

Method

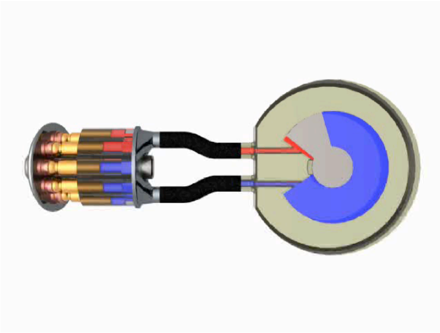
Students will solve several sub problems of the entire system design work as part of the regular course homework. The Lab 2 report will form one chapter of this engineering report.

Project Description

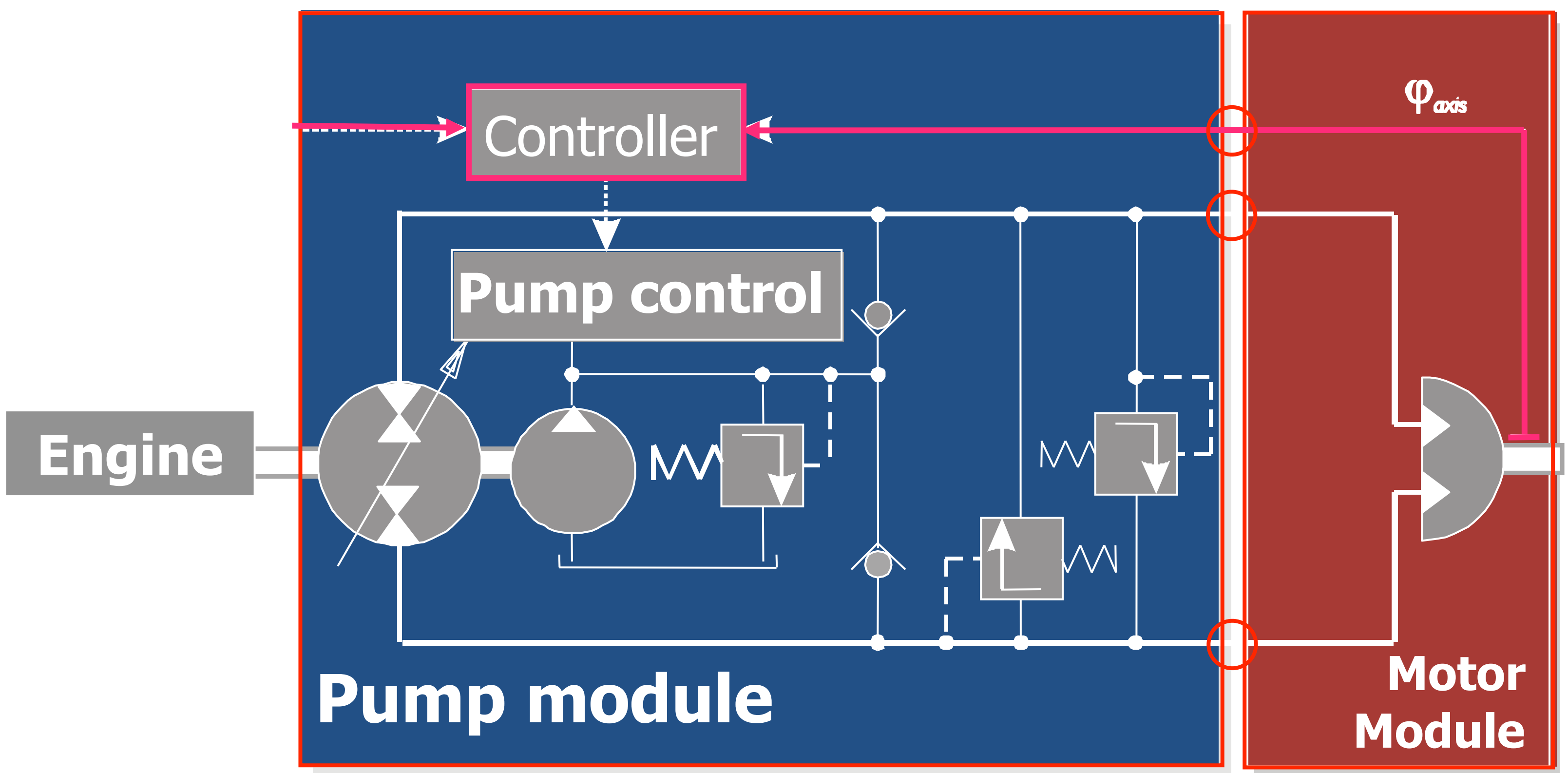
The goal of this engineering project is to design, model and predict the performance of the displacement controlled rotary actuator of the JIRA test rig. The JIRA test rig was built to test a novel displacement controlled rotary actuator under different load situations. The test rig can also be used to power the boom of the wheel loader L5 using displacement controlled actuation. The design, modeling and performance prediction of this linear actuator is also requested as part of this project.

System Performance

Maximum Actuator torque: 30 kNm
Maximum rotary actuator velocity: 0.628 rad/s



Displacement controlled rotary actuator



Engineering project

The project includes measurments on the JIRA test rig to proof your system model.

The project requires the following tasks:

1. **Define the system structure, draw the hydraulic circuit diagram and a scheme showing the interface between the fluid power system and the entire test rig structure. Explain also the type of operation/ control of both actuators.**

2. **Size and select system components, list the order code of each component in a summery table**

3. **Create models to predict system performance like actuator motion, velocity, system pressure as function of time for a defined operation cycle.**

Engineering project

4. Solve models using Matlab/Simulink and plot results for minimum one operating/ working cycle of the machine.

5. Conduct measurements on the Jira and compare measured system parameters with your simulation results

6. Document your design, system analysis (modeling, simulation) and measurements including all obtained results in form of an engineering report.

Experimental work project

Performance Measurement of displacement controlled rotary and linear actuators

Aim

To learn to plan, design and operate an experimental test set up for performance testing of displacement controlled machine. To become familiar with test set up, measurement equipment, system control and data acquisition system used on test rig.
The project should also proof the ability of performing a measurement, evaluation of test data and writing a measurement report in an appropriate form.

Method:

Students will have to form teams of three students. One lecture will be used for introduction into the problem and the existing test rig. Students will then have to learn to operate the test rig and to perform measurement. Each team has to write a measurement report. The report forms one chapter of the engineering report.

Experimental work project

Performance Measurement of displacement controlled rotary and linear actuators

1. **Study the test rig structure and describe it in the report accordingly.**
2. **Specify operating conditions and values to be measured, describe sensors and data acquisition system, including measurement accuracy.**
3. **Perform the measurement. Each group needs to make arrangements for performing their measurements with Rohit.**
4. **Evaluate the test results and complete a report.**

Homework

Circuit Design – aircraft system application

Draw the circuit of the flap and aileron actuation system of a small aircraft. The hydraulic system uses a variable engine driven pump as power supply. The pump takes flow from a reservoir. The circuit is protected against overload by a pressure relief valve.
The speed and the direction of rotation of the flap motor are controlled using an electrically operated proportional valve. The aileron actuator contains a double acting cylinder, which is also controlled by an electrically operated proportional valve. Draw the circuit using ISO standard!

Use the following symbol for the electrically operated proportional valve