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

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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

8. Flow and pressure pulsation, model of displacement chamber pressure

9. Resistance control, modeling of steady state and dynamic performance, pressure and flow control valves

10. Servo- and proportional valves, nonlinear and linear system models

11. Modeling of valve controlled systems, linear and rotary actuators
Contents

12. Modeling of displacement controlled actuators, pump control systems

13. Secondary controlled actuator, modeling and application

14. Special system design aspects, load sensing systems

15. Hydrostatic transmissions
Literature


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

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.

\[ p = \frac{F_1}{A_1} = \frac{F_2}{A_2} \]

we can build machines to multiply forces!
Basic system structure

Power Transmission in hydrostatic systems

Hydrostatic System

Energy Source

High Pressures 50MPa

Excellent Dynamic Behavior

Easy Overload Protection

Flexible Arrangement

Hydrostatic Pump

Control Elements and Transm. Lines

Hydrostatic Motor

Mechanical Work

Electrical Sensors and Electronic Devices

Microprocessor

Mech. Energy

Hyd. Energy

Signal
System structure

ISO Symbols for Circuit Design

Control of energy transmission

Energy Source

Generator Part

Motor Part

Working Machine

Pump

Valves

Energy conversion

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

<table>
<thead>
<tr>
<th>Valve Type</th>
<th>Number of Positions</th>
<th>Operation Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve with two positions</td>
<td>2</td>
<td>Pneumatically</td>
</tr>
<tr>
<td>Valve with three positions</td>
<td>3</td>
<td>Hydraulically</td>
</tr>
<tr>
<td>2/2 directional control valve</td>
<td></td>
<td>Electrically</td>
</tr>
<tr>
<td>4/3 directional control valve</td>
<td></td>
<td>Manually</td>
</tr>
<tr>
<td>Proportional valve</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Proportional valve – hydraulic resistance continuously changeable
- 4/3 directional control valve, electro hydraulically operated and centered by springs
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
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
```
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
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: \( P = \frac{W}{dt} = \Delta p \cdot Q \)
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: \( T = \Delta p \cdot A_K \cdot r = \frac{\Delta p \cdot V}{2 \cdot \pi} \)

Piston work: \( dA = T \cdot d\phi = \frac{\Delta p \cdot V}{2 \cdot \pi} \cdot 2 \cdot \pi \cdot n \cdot dt = \Delta p \cdot n \cdot V \cdot dt \)

Volumetric flow: \( Q = V \cdot n \) \( \text{with } \omega = 2 \cdot \pi \cdot n \)

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

\[ n \rightarrow V \rightarrow Q \rightarrow T \rightarrow \frac{2 \cdot \pi}{V} \rightarrow \Delta p \]
Classification of pumps according to circuit configuration

Open circuit pumps

- $p_2 > p_1$
- Fixed displacement

Variable displacement

Closed circuit pumps

- $p_2 > p_1$
- Reversible pump
  - or $Q$
- Overcenter pump
  - or $Q$

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

Construction machines
Aerospace
Automotive
Offshore
Medical devices
Materials handling
Manufacturing
Robotics
Railway

Fluid Power Systems

Agricultural and forestry machinery
FP system design steps

Specification  ➔ System structure  ➔ Performance Prediction  ➔ Product

Example: Steering System (Servotronic made by ZF)
FP system design steps

1. Specification
2. Circuit design
3. Selection & Sizing of components
4. Modeling
5. System simulation
6. Controller Design
7. Performance Prediction
8. Manufacturing/Assembly
9. Test

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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 hydraulic 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.
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

Controller

Pump control

Engine

Pump module

Motor Module
Engineering project

The project includes measurements 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 prove 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.
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.
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