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

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Design and Modeling of Fluid Power Systems

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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

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Literature


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

Hydrostatic System

- Energy Source
- Hydrostatic Pump
- Control Elements and Transm. Lines
- Hydrostatic Motor
- Mechanical Work

- High Pressures 50MPa
- Excellent Dynamic Behavior
- Easy Overload Protection
- Flexible Arrangement

- Energy Source
- Hyd. Energy
- Signal
- Mech. Energy
- Electrical Sensors and Electronic Devices
- Microprocessor

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System structure

ISO Symbols for Circuit Design

Control of energy transmission

Energy Source | Pump | Valves | Motor Part | Working Machine
---|---|---|---|---
EM | | | | mechanical
CE | | | | Work

ISO  International Organization for Standardization

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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
  - Pneumatically

- Valve with three positions
  - Hydraulically

2/2 directional control valve
  - Electrically

4/3 directional control valve
  - Manually

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 rod cylinder
- pressure relief valve
- reservoir

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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
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: \[ T = \Delta p \cdot A_K \cdot \Delta p \cdot r = \frac{\Delta p \cdot V}{2 \cdot \pi} \]

Piston work: \[ dA = T \cdot d\varphi = \frac{\Delta p \cdot V}{2 \cdot \pi} \cdot 2 \cdot \pi \cdot n \cdot dt = \Delta p \cdot n \cdot V \cdot dt \]

Volumetric flow: \[ Q = V \cdot n \]

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

input/output relationship

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Classification of pumps according to circuit configuration

Open circuit pumps
- \( p_2 > p_1 \)
- Fixed displacement

Closed circuit pumps
- \( p_2 > p_1 \)

Reversible pump
- \( Q \) or \( \overline{Q} \)

Overcenter pump
- \( p_2 \) or \( \overline{p_2} \)

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

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Industrial applications

Construction machines

Aerospace

Automotive

Offshore

Railway

Robotics

Manufacturing

Medical devices

Materials handling

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. Test
9. Manufacturing/Assembly

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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. The project should also 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.
System Specification

Design a new hydraulic actuation system for the boom and swing drive of a 5 t or 20 t excavator. Please note that the new system is required to work independent from the existing other actuators and drives installed in the excavator. The engine is sized to provide enough power for the boom and swing drive. The swing and boom are required to work simultaneously. The following system requirements are given:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>5 ton</th>
<th>20 ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boom Actuator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boom cylinder extension velocity</td>
<td>m/s</td>
<td>0.136</td>
<td>0.27</td>
</tr>
<tr>
<td>Boom cylinder retraction velocity</td>
<td>m/s</td>
<td>0.179</td>
<td>0.27</td>
</tr>
<tr>
<td>Boom Stroke</td>
<td>mm</td>
<td>678.6</td>
<td>1260</td>
</tr>
<tr>
<td>Boom cylinder extension force</td>
<td>kN</td>
<td>178</td>
<td>792</td>
</tr>
<tr>
<td>Boom cylinder retraction force</td>
<td>kN</td>
<td>127</td>
<td>395</td>
</tr>
<tr>
<td>Swing Drive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swing torque</td>
<td>kNm</td>
<td>175</td>
<td>1000</td>
</tr>
<tr>
<td>Swing rotational velocity</td>
<td>rpm</td>
<td>9.3</td>
<td>10</td>
</tr>
</tbody>
</table>

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Engineering project

The project includes a comparison with at least one alternative system solution. The comparison must include energy consumption, system complexity and an estimate of system costs.

The project includes 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 machine structure. Explain also the type of operation/ control of the boom and swing drive.

2. Size and select system components, include the order code in a summery table

3. Create models to predict system performance, the power loss and energy consumption (include line losses)

4. Create models to predict system dynamic behavior like actuator motion, velocity, system pressure as function of time.
5. Solve models using Matlab/Simulink and plot results for minimum one operating/working cycle of the machine.

6. Analyze system efficiency and power consumption for your defined operating cycle.

7. Define measurement methods and test procedure to compare your simulation results with measured data. Include a circuit diagram which shows also the required sensors for a selected component and your whole actuation system.

8. Document your proposed system, the system analysis and obtained results in form of an engineering report.
Experimental work project

Steady State Performance Measurement of a Variable Displacement Pump

Aim

To learn to plan, design and operate an experimental test set up for performance testing of a positive displacement machine. To become familiar with test set up according to ISO 4409, measurement equipment 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.
Experimental work project

Steady State Performance Measurement of a Variable Displacement Pump

1. Study the test rig structure according ISO standard 4409 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 Edat Kaya.

4. Evaluate the test results and complete a report.

Note: Performing the measurement and completing the report will be part of your homework of lecture 5 and will be graded (20% of your final grade)
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