Contents

- Classification of power supply systems
- Pump control systems
- Modeling of pump control
- Load sensing systems
Classification of hydraulic actuators

1. Constant Pressure Net
2. Displacement Controlled Actuator
3. EHA - VP
4. EHA - VSM
Overview pressure supply systems

- Fixed displacement pumps
  - Flow source
  - Pressure source
- Variable displacement pumps
- Pressure controlled systems
Classification pump control systems

Open and closed loop control

Manual actuation

Hydraulic control

Electro-hydraulic actuation

Electro-mechanical actuation

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

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Pump control

Pressure compensated pump – direct hydraulically operated & controlled

Volumetric losses $f(p)$
Axial piston pump – force analysis

\[ F_{SK} \ldots \text{reaction force of swash plate} \]

Pressure force:
\[ F_{DK} = A_K \cdot (p - p_e) = \frac{\pi \cdot d_k^2}{4} \cdot (p - p_e) \]

Inertia force:
\[ F_{aK} = -m_K \cdot a_K = m_K \cdot \omega^2 \cdot R \cdot \tan \beta \cdot \cos \varphi \]

Centrifugal force:
\[ F_{\omega K} = m_K \cdot a_u = m_K \cdot R \cdot \omega^2 \]

Piston friction force:
\[ F_{TK} = f_K \cdot F_{RK} \cdot \text{sign}(-v_K) \]

with \( f_K \) friction coefficient

\[ F_{TG} = \int_{r_G}^{R_G} \tau \cdot 2 \cdot \pi \cdot r \cdot dr \]
Forces applied on the piston

\( F_{SK} \ldots \) reaction force of swash plate

Resultant axial piston force:

\[
F_{AK} = F_{DK} + F_{aK} + F_{TK}
\]

Reaction force of swash plate:

\[
F_{SK} = -\frac{F_{AK}}{\cos \beta}
\]

Resultant radial force:

\[
F_{RK} = \sqrt{\left( F_{SKy} + F'_{\omega Ky} + F_{TGy} \right)^2 + \left( F'_{\omega Kx} + F_{TGx} \right)^2}
\]
Forces exerted on swash plate

\[ F_{AKi} = F_{DKi} + F_{aKi} + F_{TKi} \]

\[ F_N = \sum_{i=1}^{z} F_{NSi} \]

\[ F_{Sx} = 0 \quad F_{Syi} = -F_{NSi} \cdot \sin \beta = -F_{AKi} \cdot \tan \beta \]

Trajectory of origin of \( F_N \)

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Pressure forces dependent on cylinder pressure

Normal force $F_N$ changes its origin during one shaft rotation

$$F_{AKi} = F_{DKi} + F_{aKi} + F_{TKi}$$

Pressure force $F_{DKi}$ depends on instantaneous cylinder pressure $p_i$

$$F_{Sy} = \sum_{i=1}^{z} F_{Syi} = -\tan \beta \cdot \sum_{i=1}^{z} F_{AKi}$$

$$F_{Sz} = \sum_{i=1}^{z} F_{AKi}$$

$F_{Sx} = 0$
Moments acting on swash plate

\[ F_{Sx} = 0 \quad F_{Sy} = \sum_{i=1}^{z} F_{Syi} = -\tan \beta \cdot \sum_{i=1}^{z} F_{AKi} \]

\[ F_{Sz} = \sum_{i=1}^{z} F_{AKi} \]

\[ M_{Sx} = \sum_{i=1}^{z} \left( F_{Szi} \cdot y_{Si} - F_{Syi} \cdot z_{Si} \right) \]

\[ M_{Sx} = \sum_{i=1}^{z} R \cdot F_{AKi} \cdot \cos \varphi_i \cdot \left( 1 + \tan^2 \beta \right) \]

\[ M_{Sx} = \frac{R}{\cos^2 \beta} \cdot \sum_{i=1}^{z} F_{AKi} \cdot \cos \varphi_i \]

\[ M_{Sy} = -\sum_{i=1}^{z} F_{Szi} \cdot x_{Si} = -R \cdot \sum_{i=1}^{z} F_{AKi} \cdot \sin \varphi_i \]

\[ M_{Sz} = \sum_{i=1}^{z} F_{Syi} \cdot x_{Si} + M_{TSz} = -R \cdot \tan \beta \cdot \sum_{i=1}^{z} F_{AKi} \cdot \sin \varphi_i + M_{TSz} \]

\[ x_{Si} = R \cdot \sin \varphi_i \]

\[ y_{Si} = R \cdot \cos \varphi_i \]

\[ z_{Si} = y_{Si} \cdot \tan \beta = R \cdot \tan \beta \cdot \cos \varphi_i \]

Moment due to friction force of slipper \( F_{TG} \)
Moments acting on swash plate

Friction forces $F_{TSi}$ exerted on swash plate due to slipper movement:

$$\begin{align*}
F_{TSi} &= -F_{TGi} \\
F_{TSxi} &= F_{TSi} \cdot \cos \varphi_i \\
F_{TSyi} &= -F_{TSi} \cdot \sin \varphi_i \\
F_{TSzi} &= 0
\end{align*}$$

$$M_{TSz} = \sum_{i=1}^{z} \left( F_{TSyi} \cdot x_{TSi} - F_{TSxi} \cdot y_{TSi} \right)$$

$$M_{TSz} = -R \cdot \sum_{i=1}^{z} F_{TSi} \left( \sin^2 \varphi_i + \cos^2 \varphi_i \right) = -R \cdot \sum_{i=1}^{z} F_{TSi}$$

$$M_{Sz} = \sum_{i=1}^{z} F_{Syi} \cdot x_{Si} + M_{TSz} = -R \cdot \left( \sum_{i=1}^{z} F_{TSi} + \tan \beta \cdot \sum_{i=1}^{z} F_{AIi} \cdot \sin \varphi_i \right)$$

$x_{Si} = R \cdot \sin \varphi_i$

$y_{Si} = R \cdot \cos \varphi_i$

$z_{Si} = R \cdot \tan \beta \cdot \cos \varphi_i$
Forces exerted on swash plate

Resulting force $F_S$ exerted on swash plate:

$$F_S = \sqrt{F_{Sy}^2 + F_{Sz}^2}$$

and moments about $y$- and $z$-axis:

$$M_{Sy} = -R \sum_{i=1}^{z} F_{Szi} \cdot x_{Si} = -R \sum_{i=1}^{z} F_{AKi} \cdot \sin \varphi_i$$

$$M_{Sz} = -R \left( \sum_{i=1}^{z} F_{TSi} + \tan \beta \cdot \sum_{i=1}^{z} F_{AKi} \cdot \sin \varphi_i \right)$$

Moment $M_{Sx}$

$$M_{Sx} = \frac{R}{\cos^2 \beta} \sum_{i=1}^{z} F_{AKi} \cdot \cos \varphi_i$$

In case of variable displacement pumps $M_{Sx}$ must be overcome by the swash plate control system.
Swash plate control system

Electrohydraulic swash plate control system

\[ F = \frac{M_{Sx}}{r_c} \]

Servo valve

Adjustment cylinder

Controller
Pump control

Pressure compensated pump using one variable hydraulic resistance
Pump control

Pressure compensated pump using two variable hydraulic resistances
Load sensing

with variable displacement pump

with fixed displacement pump
Load sensing

Hydraulic-mechanical LS – pump control
Load Sensing Pump Control

Electric closed loop control & hydraulically operated

Hydraulically operated and controlled

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LS- Valve

LS port

Pressure Compensator

Anti cavitation valve

Secondary pressure relief valve

Shuttle valve

A

B

$p_0$

T
Classification power supply

Systems with fixed displacement pump

Only one actuator

Flow source

Pressure source

Load sensing

Actuator power

Pressure variable

Power loss

Simultaneous operation

Pressure variable

Q = const.

Q = const.

Q = const.
Classification power supply
Systems with variable pumps

Flow source
- Only one actuator

Pressure source
- Flow variable
- Pressure variable

Constant power
- Only one actuator

Load sensing
- Pressure variable
- Flow variable
Swash plate control system

charge pressure $p_0$

$Q_A, p_A$

$Q_B, p_B$

Controller
Pump control system design procedure

1. Valve plate optimization to reduce mean $M_{sx}$ as function speed, swash plate angle & pressure

2. Determine control cylinder arrangement (axial or transverse)

3. Determine pump control system supply pressure

4. Determine lever arm length/cylinder area & stroke
Pump control system design procedure

5. Determine swash plate centering mechanism

6. Determine maximum cylinder flow based on required system dynamics

7. Determine control valve type & size

8. Determine swash plate sensor & arrangement
## Swash Plate angle sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Range</th>
<th>Accuracy</th>
<th>Connection</th>
<th>Power supply</th>
<th>Protection</th>
<th>Price [euro]</th>
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<tbody>
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<td>ASM PRAS 20</td>
<td>0-360</td>
<td>+/- 1</td>
<td>Analog</td>
<td>8-36 V, 5V</td>
<td>IP 60</td>
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