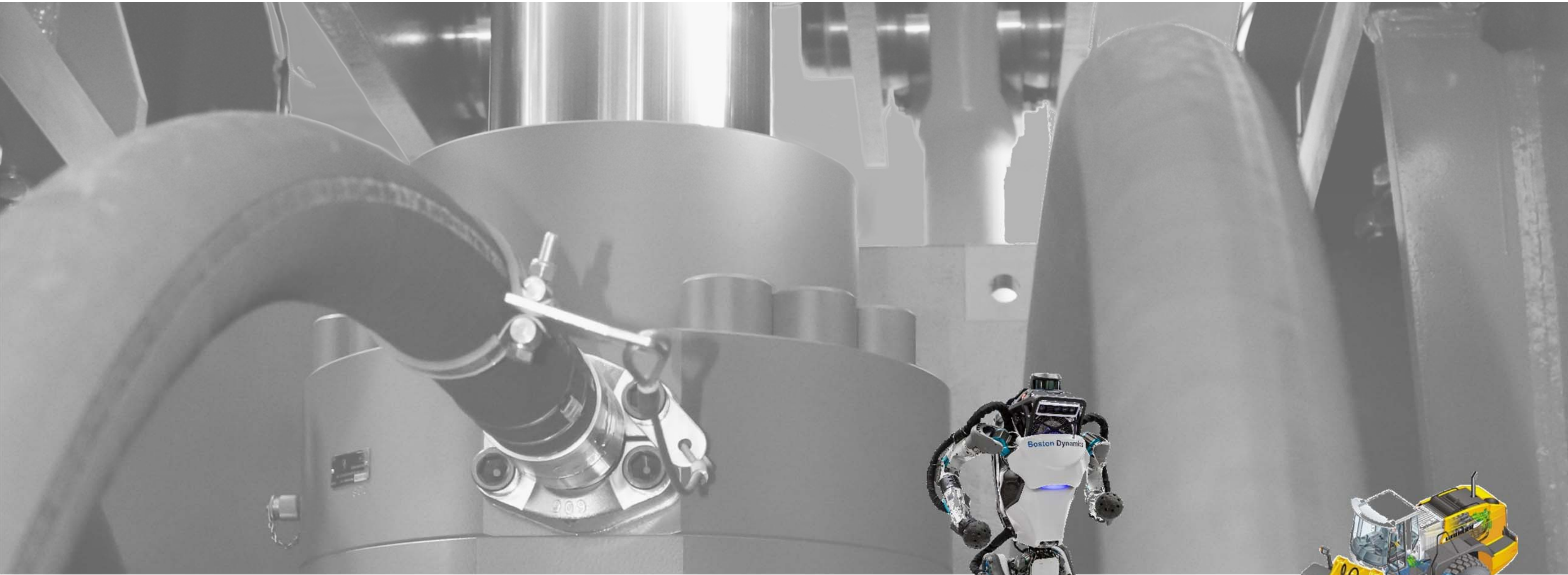
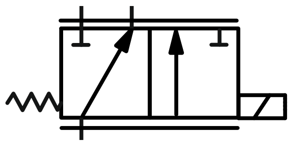
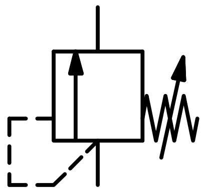
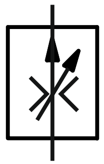


Fundamentals of Fluid Power

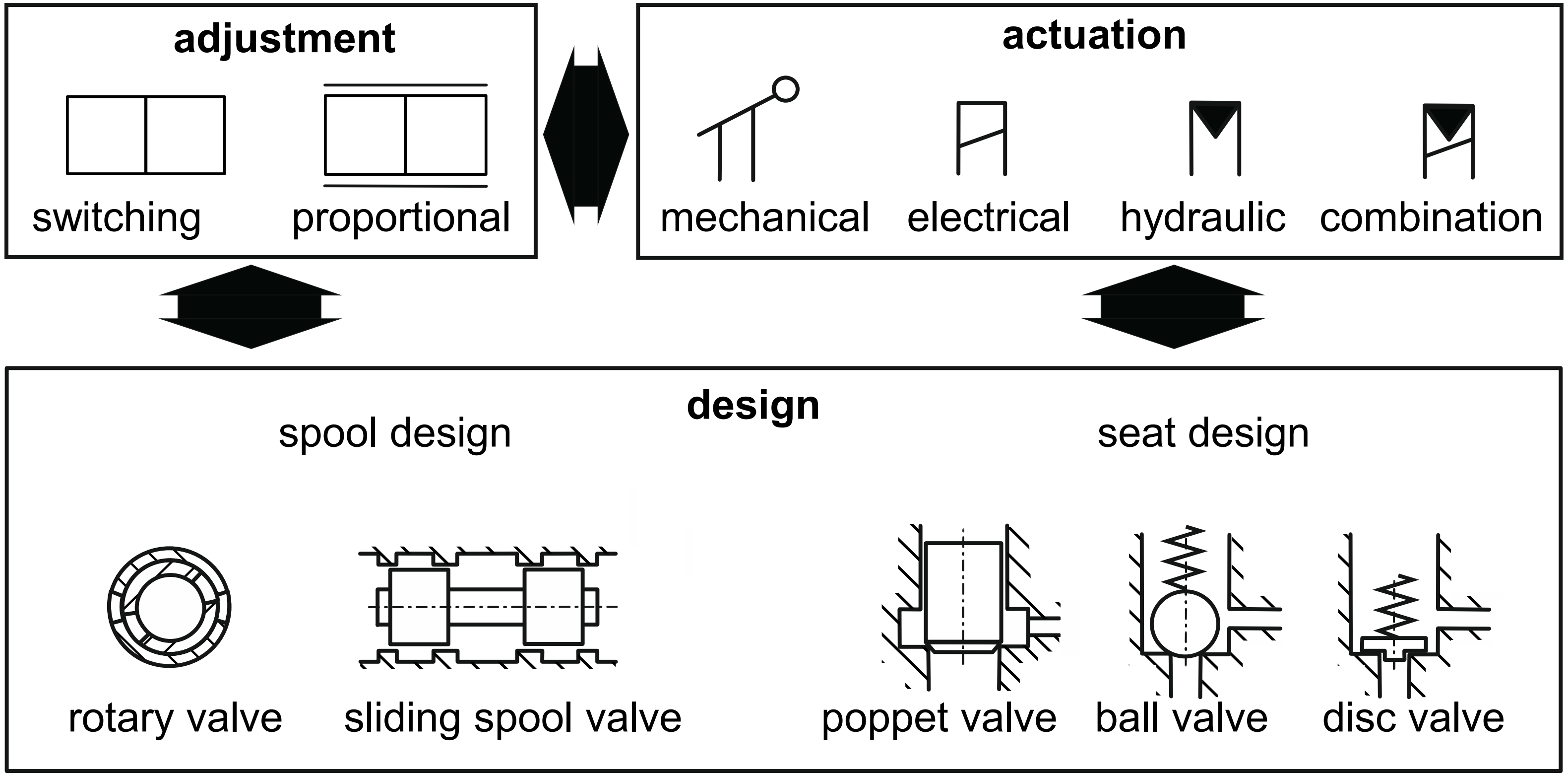
Lecture 6 – Valves

Valve types

valves

type	check valve	directional control valve	pressure control valve	flow control valve
function	Restriction of the flow in only one direction	Opening/ Partially Opening/ Closing of one or more flow paths	Control of the pressure	Control of the flowrate
example				

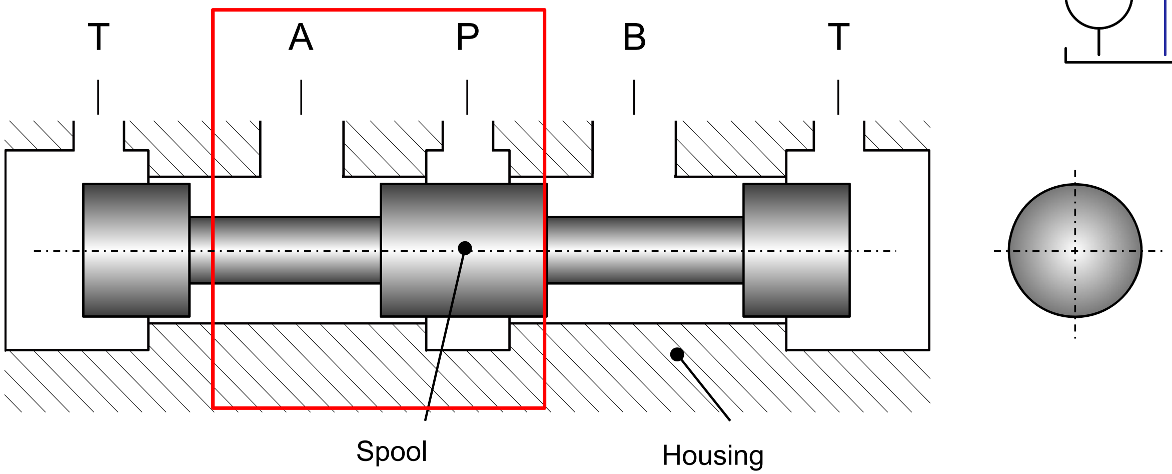
Distinctive features of hydraulic valves

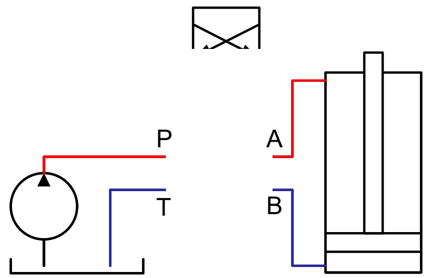


Outline of todays lecture

Design: sliding spool valve

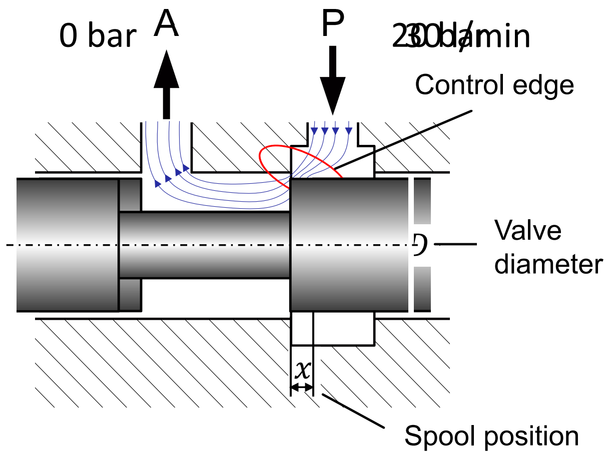
- Spool valve: Basis component in resistive controlled systems
- Design of a spool valve:

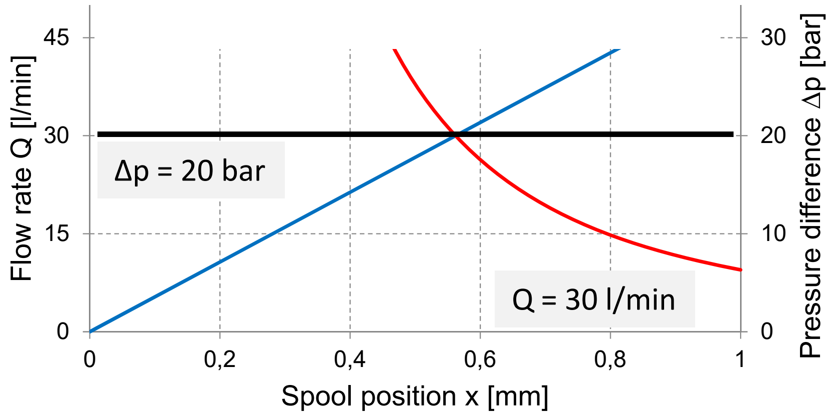




Working principle of a spool valve

- Control of flow rate rsp. Pressure difference via resistor



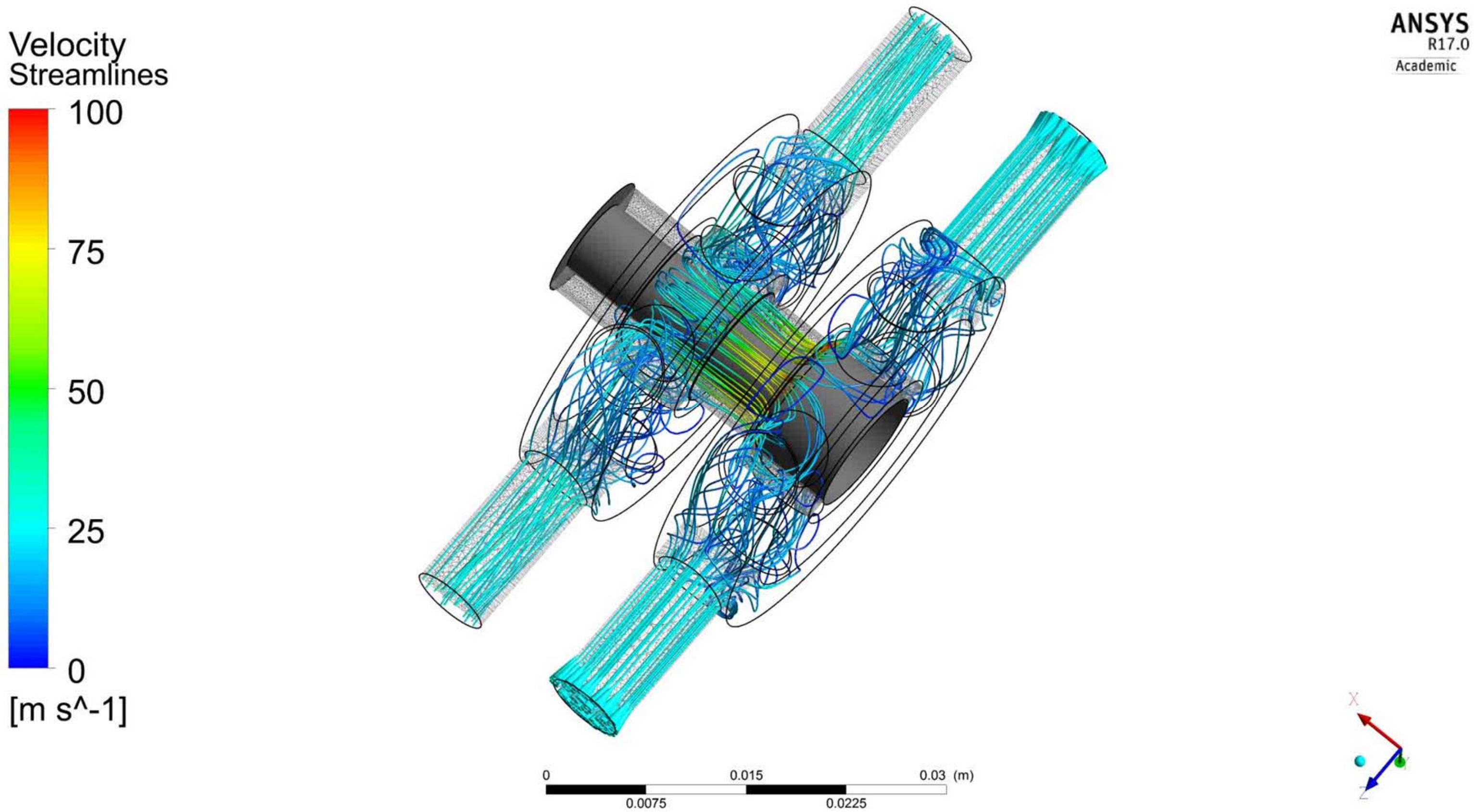


- Calculation of flow with orifice equation

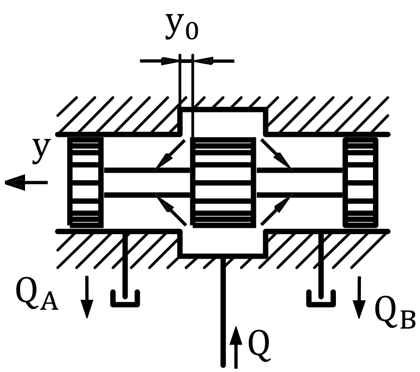
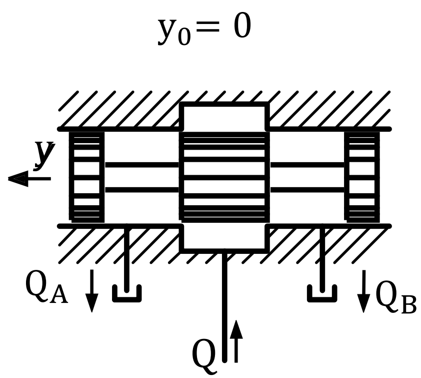
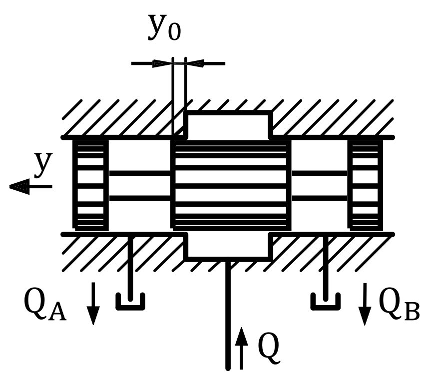
$$Q = \alpha_D \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}}$$

$$A = D \cdot \pi \cdot x$$

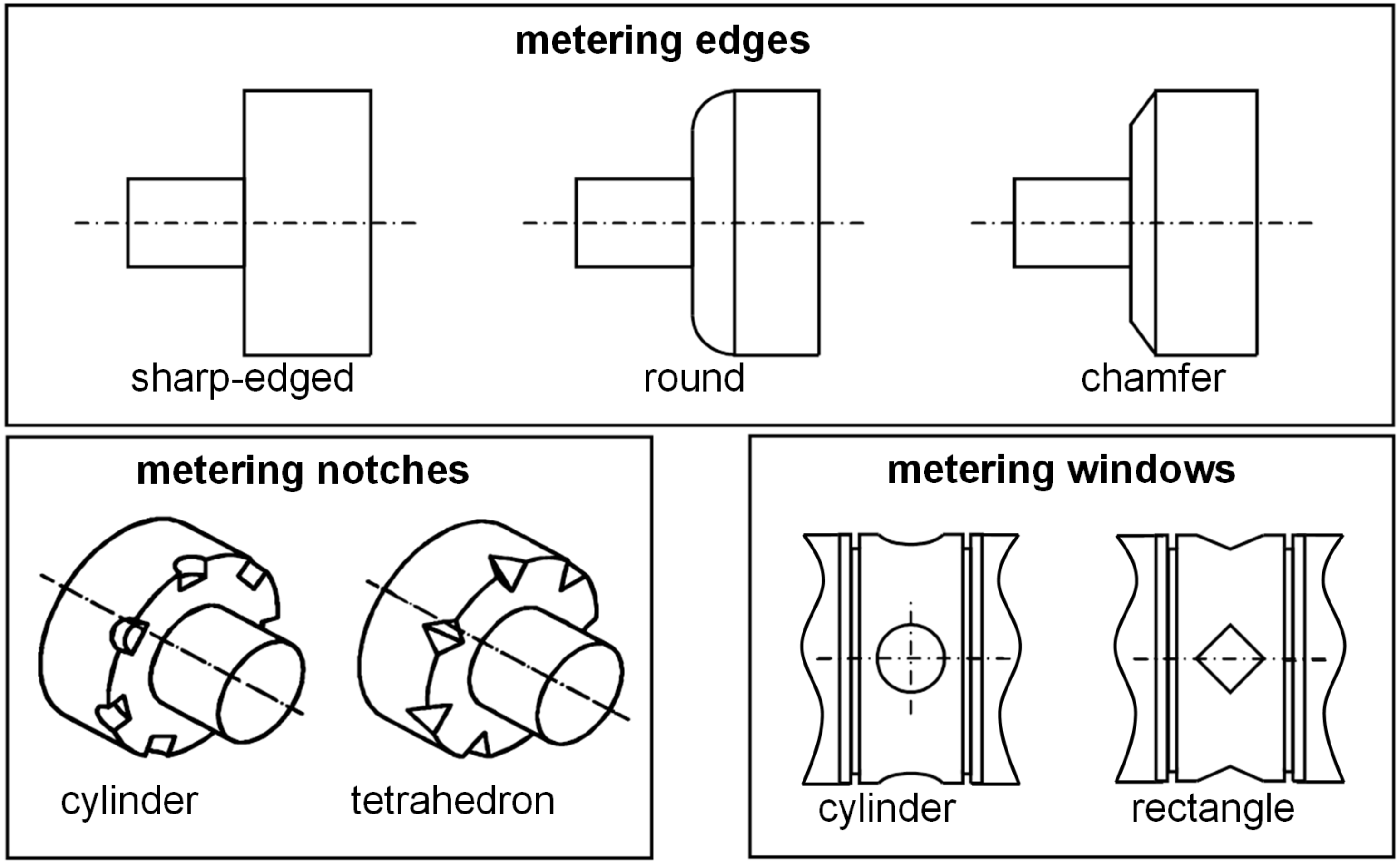
Simulation and representation of flow in valves



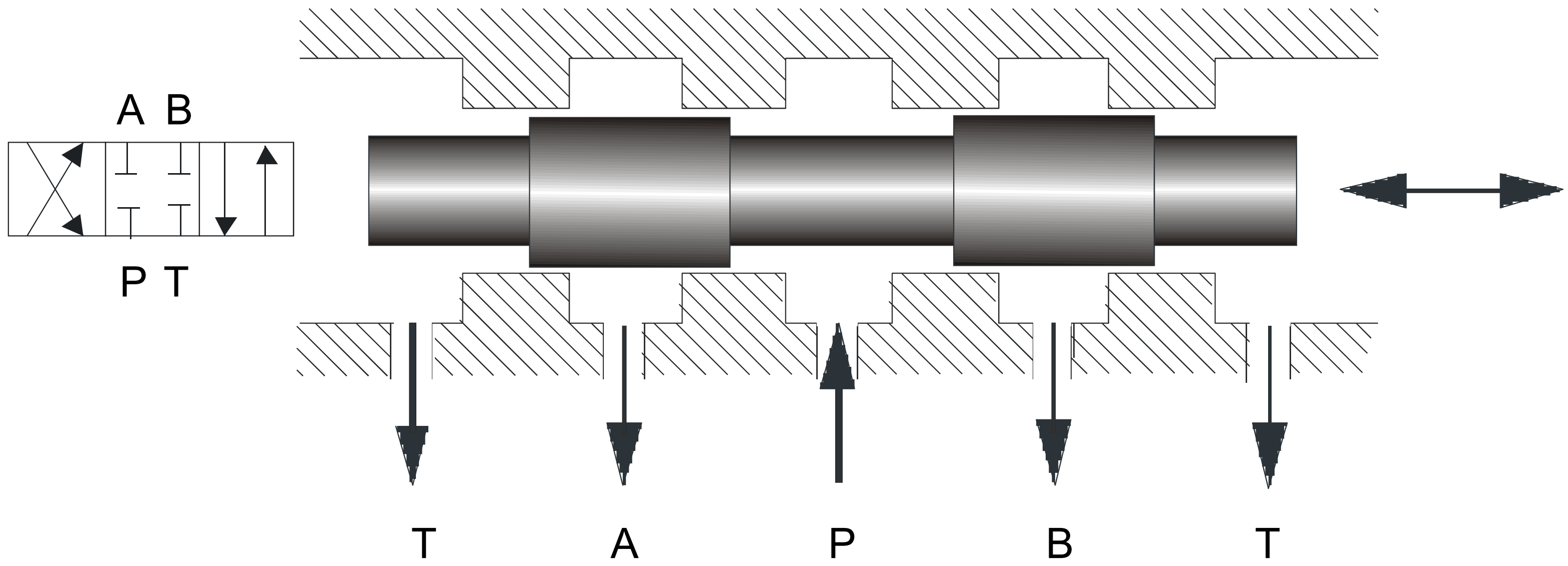
Overlap conditions of valves

negative overlap	zero overlap	positive overlap
		
$Q_A(y) = 0$ at $y \geq y_0$	$Q_A(y) = 0$ at $y \geq 0$	$Q_A(y) = 0$ at $y \geq -y_0$

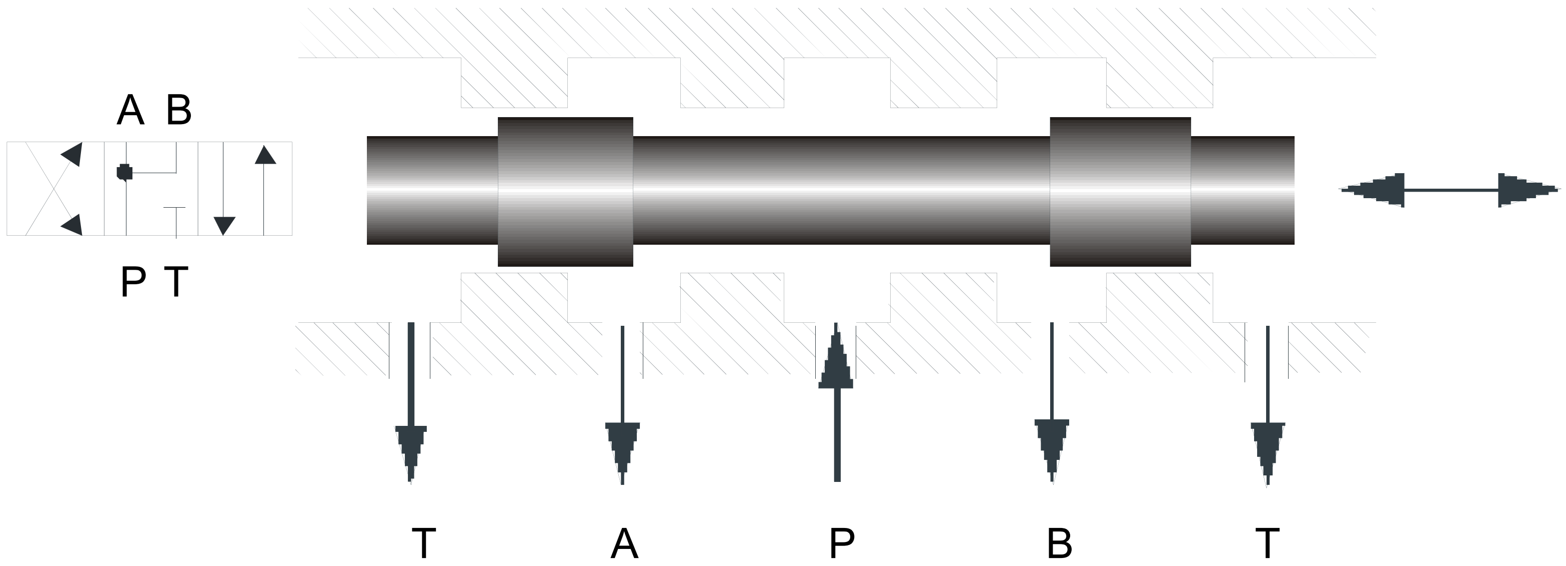
Variation of the metering geometry (examples)



4/3-way valve with blocked connections in centre position



4/3-way valve with open connection to the pump in centre position



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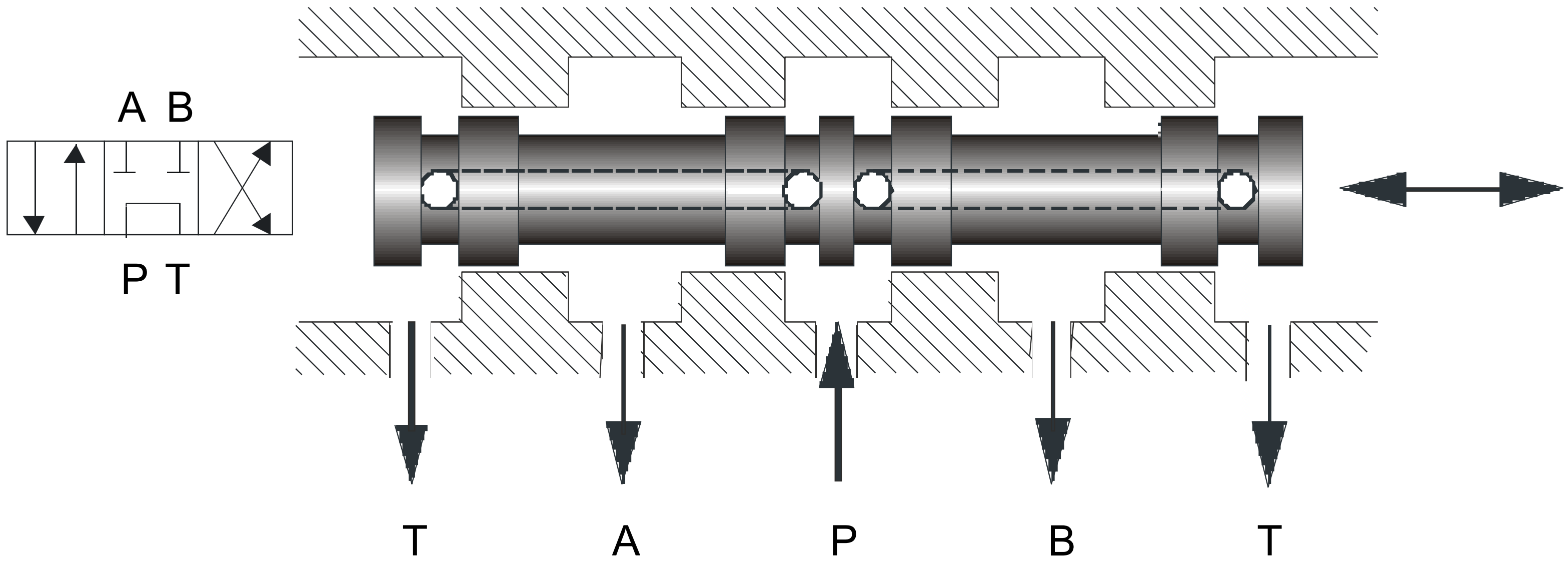
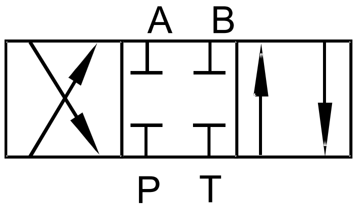
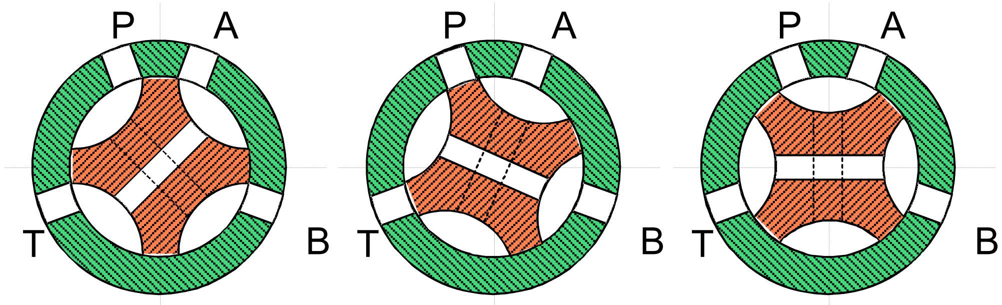
4/3-way valve with circulation in centre position



4/3-way rotary spool valve





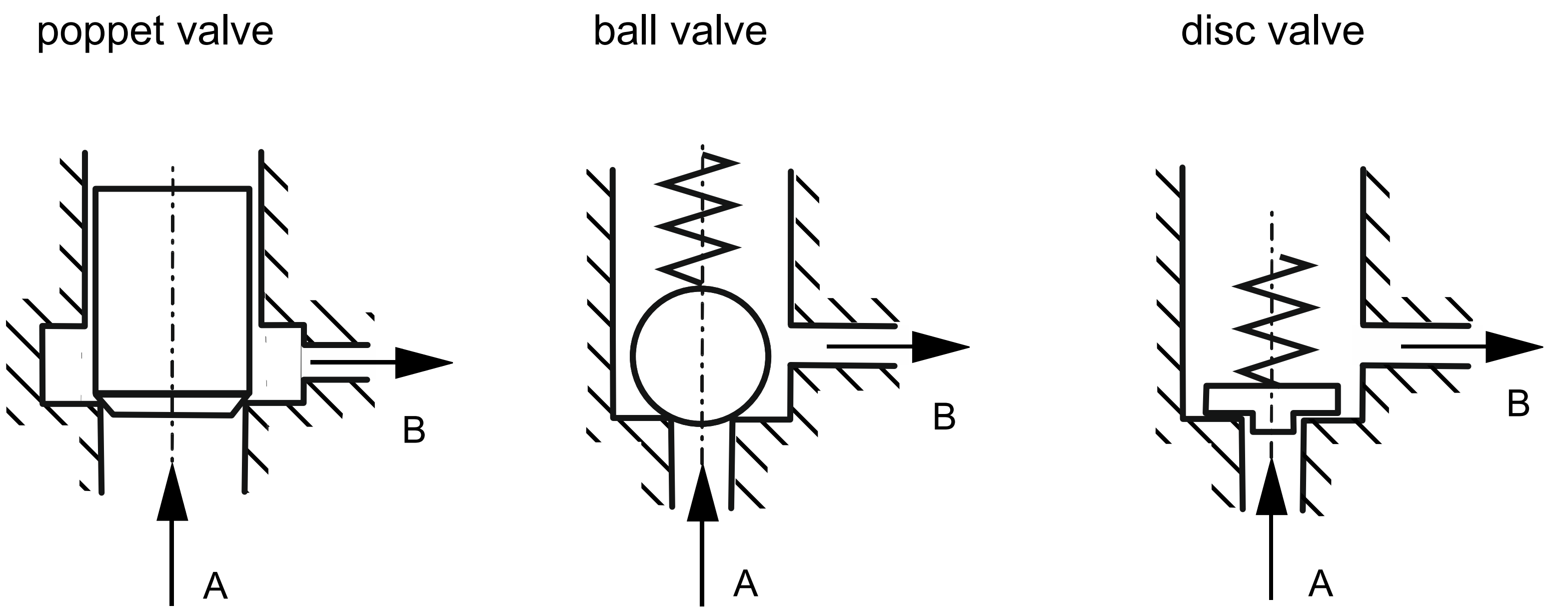
P → B
A → T

ports
closed

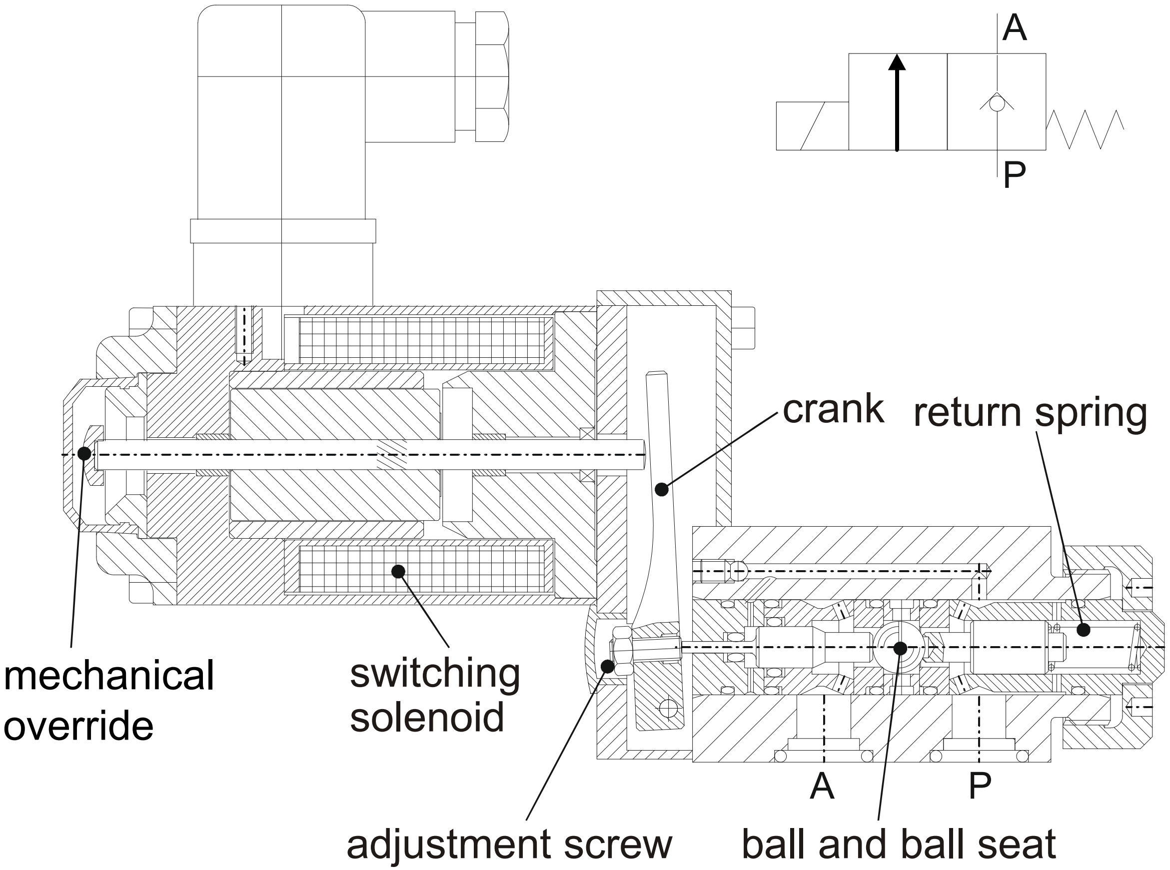
P → A
B → T

Outline of todays lecture

Functional principle of seat valves

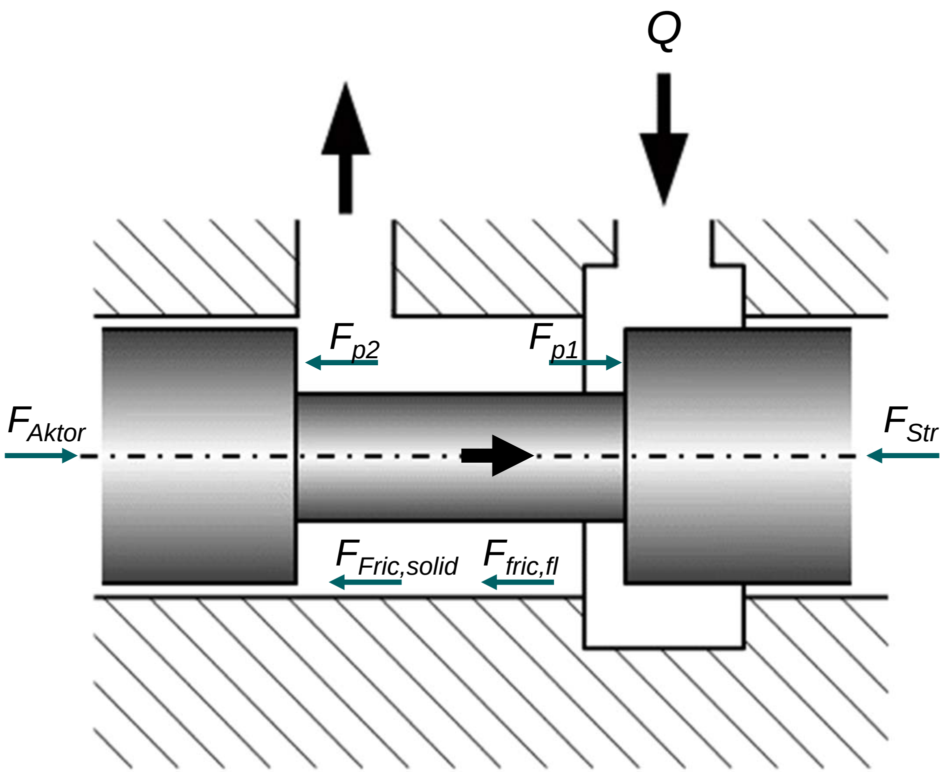


Ball valve with switching solenoid (Dr. Breit GmbH)



Outline of todays lecture

Forces acting on a valve spool

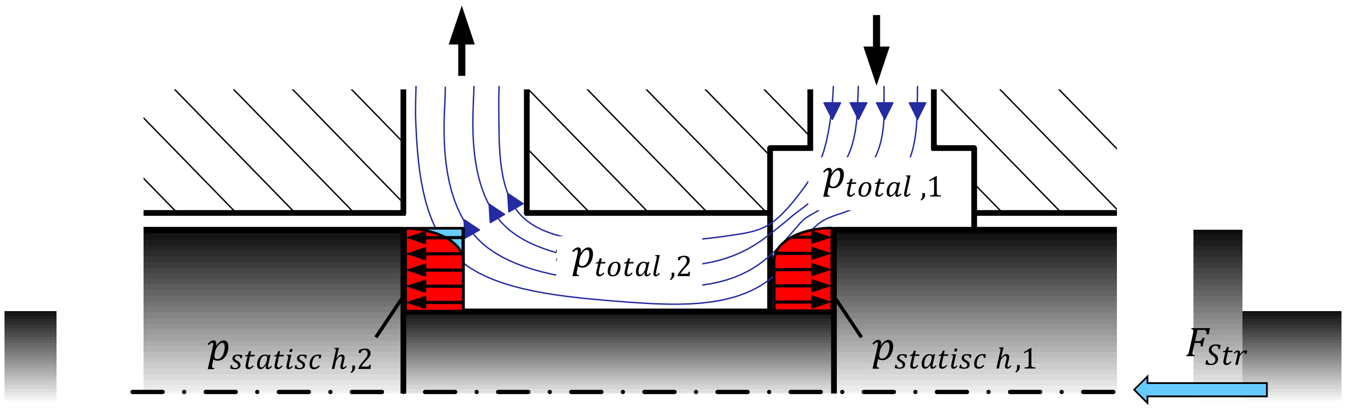


Simplified analysis of flow forces

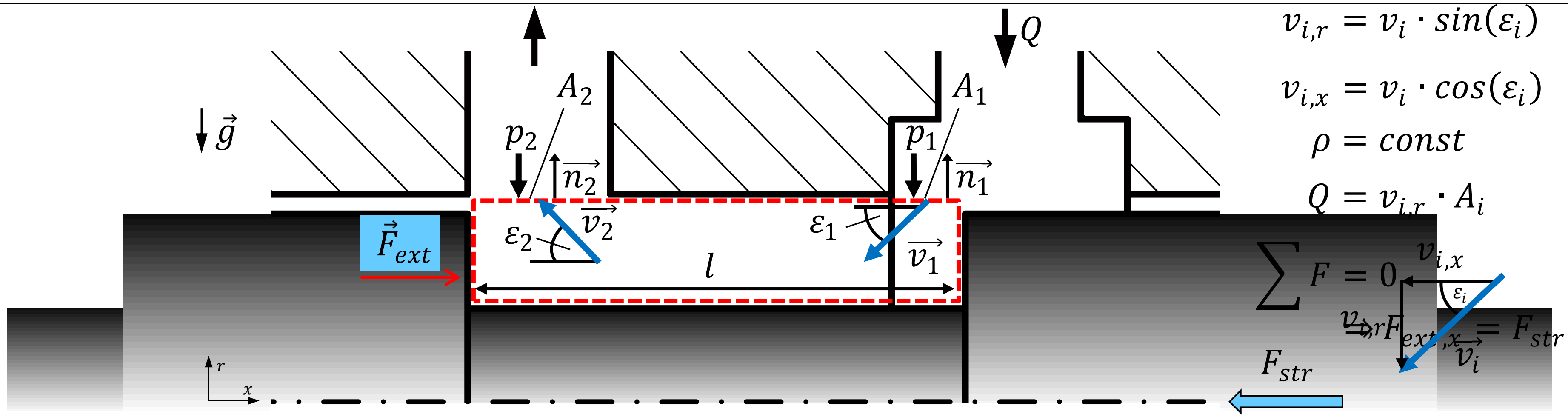
- Restistance flow:
  Total pressure constant (Bernoulli for lossfree, idealised flow)

$$p_{statisc\ h} + \underbrace{\rho \cdot \frac{v^2}{2}}_{p_{dyn}} = p_{total} = const$$

- High velocities at control edge
  → local high dynamic pressure
  → local low static pressure
  → force in valve closing direction



Conservation of momentum in a spool valve



$$v_{i,r} = v_i \cdot sin(\varepsilon_i)$$

$$v_{i,x} = v_i \cdot cos(\varepsilon_i)$$

$$\rho = const$$

$$Q = v_{i,r} \cdot A_i$$

$$\sum F = 0 \Rightarrow F_{ext,x} = F_{str}$$

- Conservation of momentum:

$$\cancel{\vec{F}_{Druck}} + \cancel{\vec{F}_{Reib}} + \cancel{\vec{F}_{Gew}} + \vec{F}_{ext} = \frac{\partial}{\partial t}\int_{KV} \vec{v} \cdot \rho \cdot dV + \int_{KF} \vec{v} \cdot \rho \cdot (\vec{v} \cdot \vec{n}) dA$$

- Application on control volume spool valve:

$$F_{str} = \rho \cdot \frac{\partial}{\partial t}((\vec{v})_x \cdot V_{KV}) + (\vec{v_1})_x \cdot \rho \cdot (\vec{v_1} \cdot \vec{n_1}) \cdot A_1 + (\vec{v_2})_x \cdot \rho \cdot (\vec{v_2} \cdot \vec{n_2}) \cdot A_2$$

$$F_{str} = -\rho \cdot l \cdot \frac{\partial Q}{\partial t} + (-v_{1,x}) \cdot \rho \cdot (-v_{1,r}) \cdot A_1 + (-v_{2,x}) \cdot \rho \cdot (v_{2,r}) \cdot A_2$$

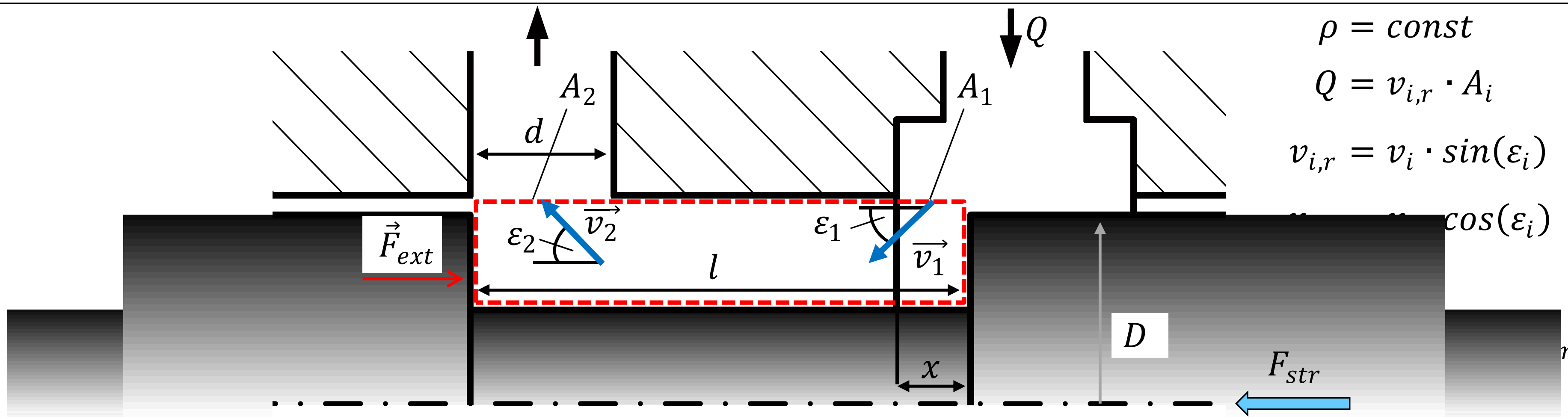
Conservation of momentum in a spool valve

$$\rho = const$$

$$Q = v_{i,r} \cdot A_i$$

$$v_{i,r} = v_i \cdot sin(\varepsilon_i)$$

$$cos(\varepsilon_i)$$



$$F_{str} = -\rho \cdot l \cdot \frac{\partial Q}{\partial t} + v_{1,x} \cdot \rho \cdot v_{1,r} \cdot A_1 - v_{2,x} \cdot \rho \cdot v_{2,r} \cdot A_2$$

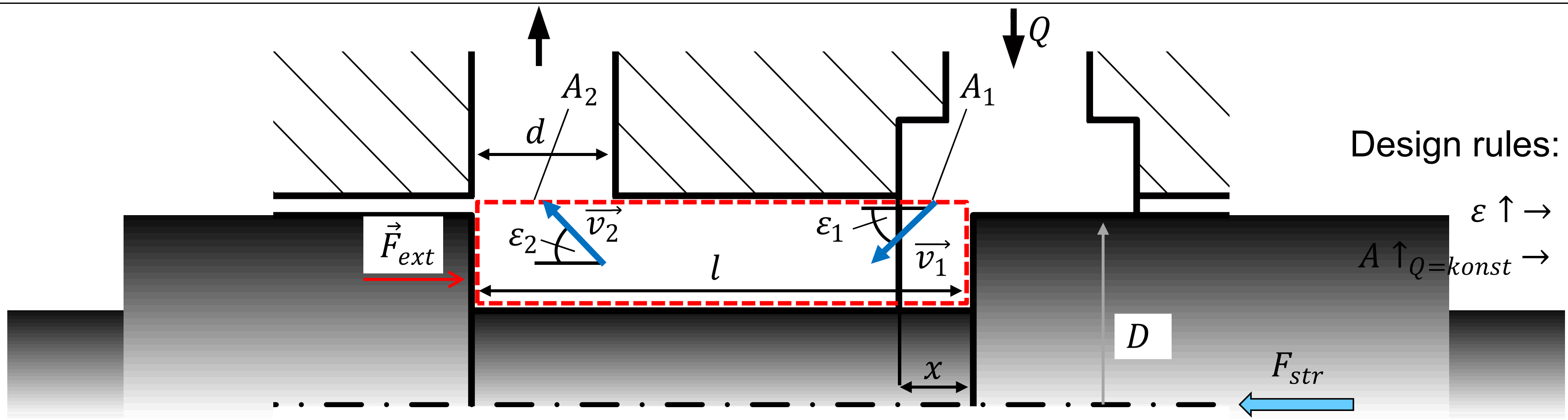
- Replacing velocity by flow rate:

$$F_{str} = -\rho \cdot l \cdot \cancel{\frac{\partial Q}{\partial t}} + \frac{\cos(\varepsilon_1)}{\sin(\varepsilon_1) \cdot A_1} \cdot \rho \cdot Q^2 - \frac{\cos(\varepsilon_2)}{\sin(\varepsilon_2) \cdot A_2} \cdot \rho \cdot Q^2$$

- For stationary conditions:

$$\boxed{F_{str,stat} = \frac{\cos(\varepsilon_1)}{\sin(\varepsilon_1) \cdot A_1} \cdot \rho \cdot Q^2 - \frac{\cos(\varepsilon_2)}{\sin(\varepsilon_2) \cdot A_2} \cdot \rho \cdot Q^2}$$

Stationary flow force acting on spool valve



Design rules:

$\varepsilon \uparrow \rightarrow \; F_{str} \downarrow$

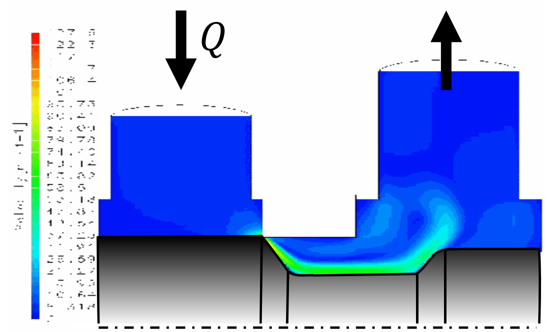
$A \uparrow_{Q=konst} \rightarrow \; F_{str} \downarrow$

Determination of areas:

$$A_1 = \pi \cdot D \cdot x \qquad\qquad A_2 = \frac{\pi \cdot d^2}{4}$$

Determination of angles:

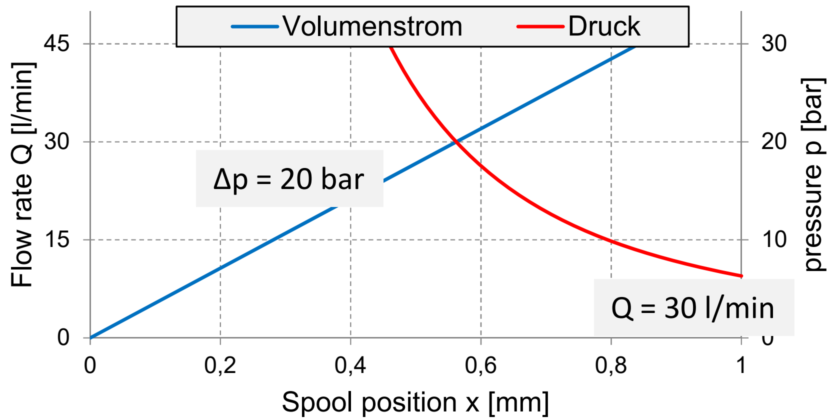
$\varepsilon_1 \sim 69°$ $\qquad \varepsilon_2 \sim 90°$

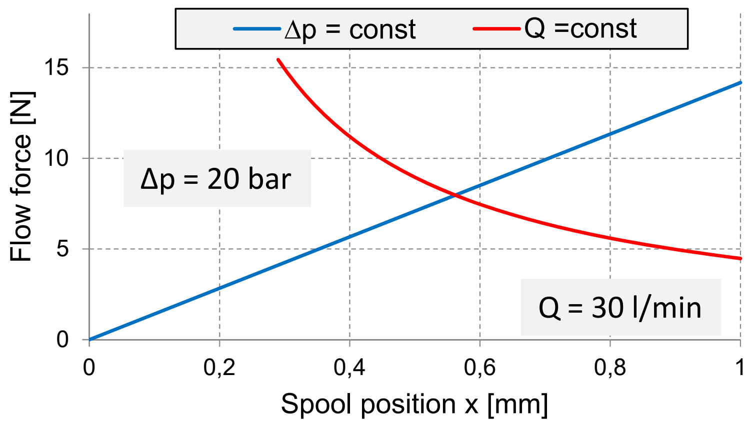


$$\boxed{F_{str,stat} = \frac{\cos(\varepsilon_1)}{\sin(\varepsilon_1) \cdot A_1} \cdot \rho \cdot Q^2 - \frac{\cos(\varepsilon_2)}{\sin(\varepsilon_2) \cdot A_2} \cdot \rho \cdot Q^2}$$

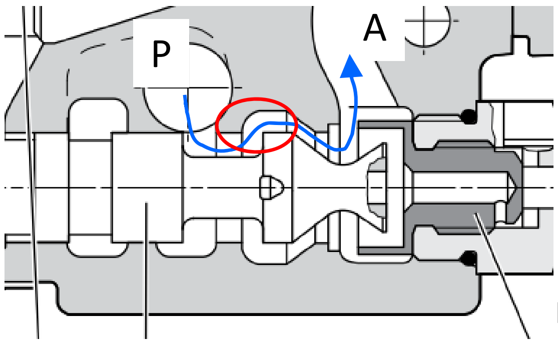
Stationary flow force acting on spool valve

- Flow force over spool position

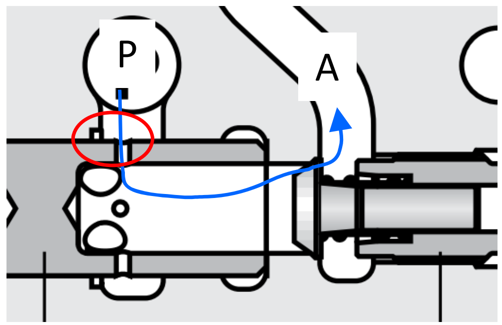




- Ways to reduce flow forces via compensation

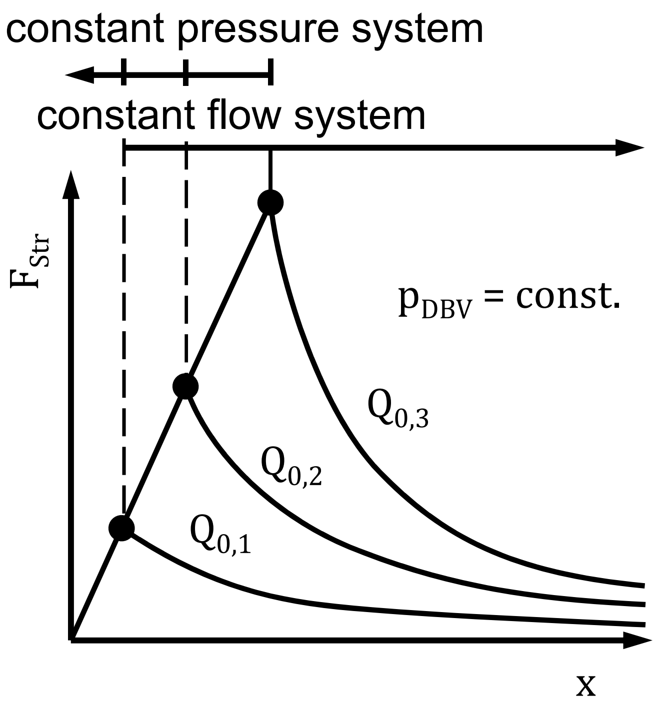


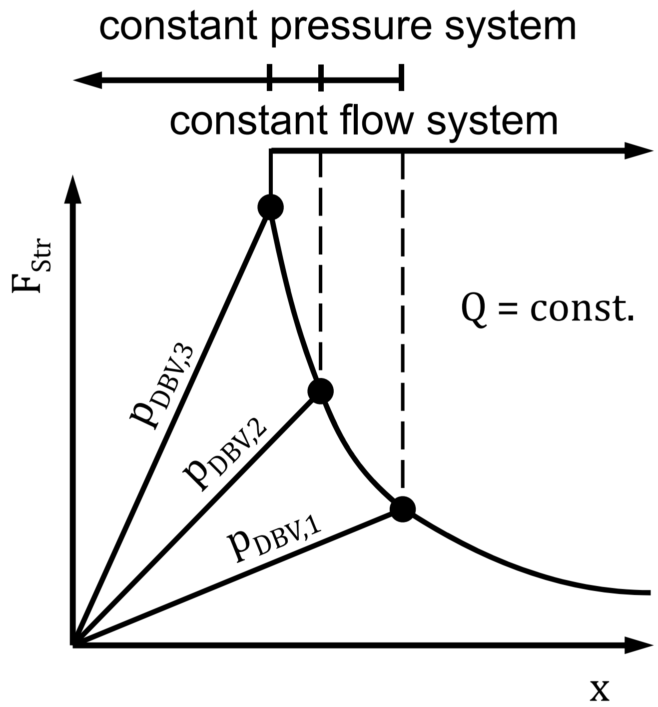
[Rexroth]



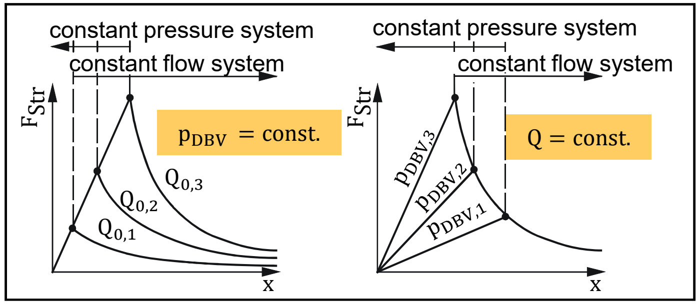
[Rexroth]

Schematic curve of the flow force as function of spool stroke





Flow force as a function of the spool stroke



1. Constant pressure system (small spool stroke)

$$F_{Str} = \rho \cdot v \cdot Q \cdot \cos(\varepsilon)$$

$$\downarrow$$

$$\frac{Q}{A} = \alpha_D \sqrt{\frac{2\Delta p}{\rho}}$$

$$Q = \alpha_D \cdot \underbrace{A}_{\pi \cdot d \cdot x} \cdot \sqrt{\frac{2\Delta p}{\rho}}$$

$$F_{Str} = 2 \cdot \alpha_D^2 \cdot \pi \cdot d \cdot \Delta p \cdot \cos(\varepsilon) \cdot x$$

$$=> F_{Str} \sim x$$

2. Constant flow system (large control stroke)

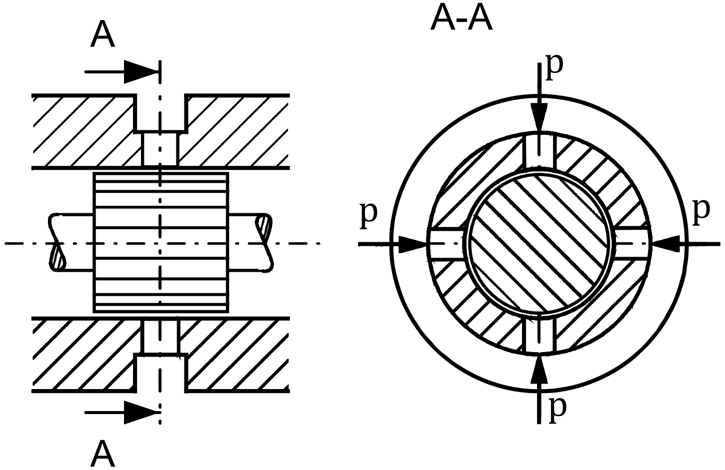
$$F_{Str} = \rho \cdot \frac{Q^2}{A} \cdot \cos(\varepsilon)$$

$$= \rho \cdot Q^2 \cdot \frac{\cos(\varepsilon)}{\pi \cdot d} \cdot \frac{1}{x}$$

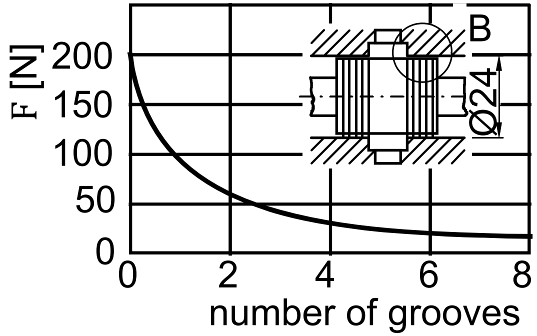
$$=> F_{Str} \sim \frac{1}{x}$$

Reduction of radial load on a control spool

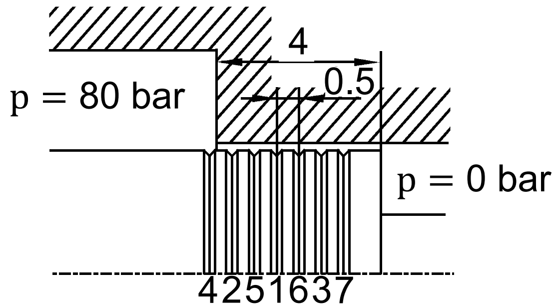
symmetric bores



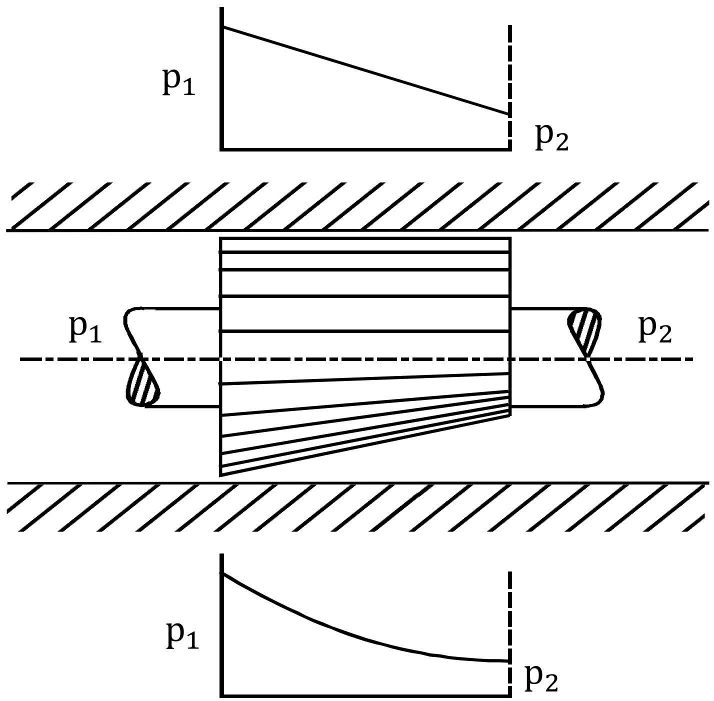
pressure compensation grooves

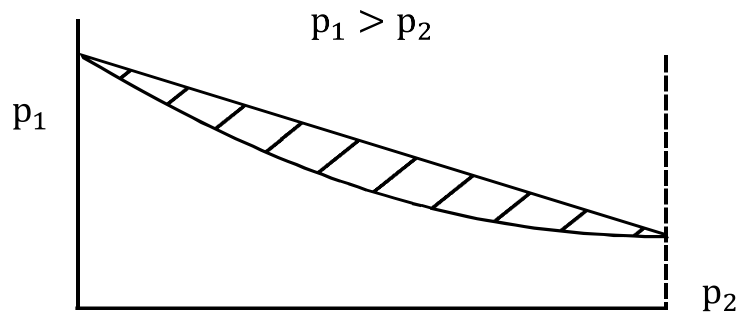


detail B



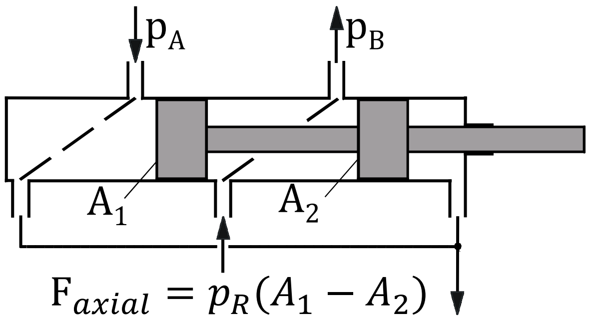
Shape deviations of a control spool



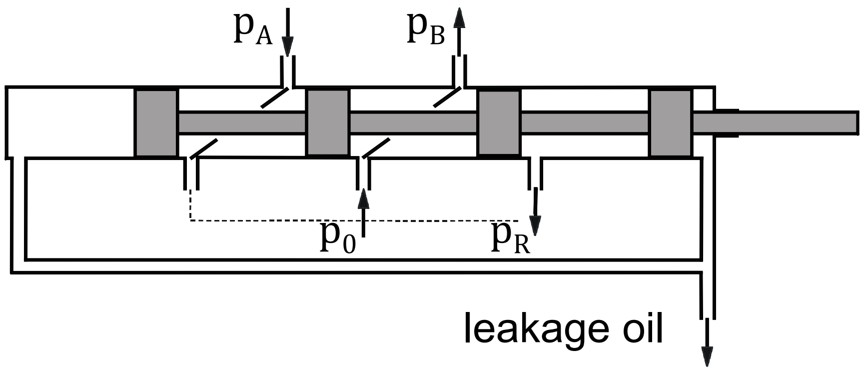


Axial unloading of a spool

3-chamber valve

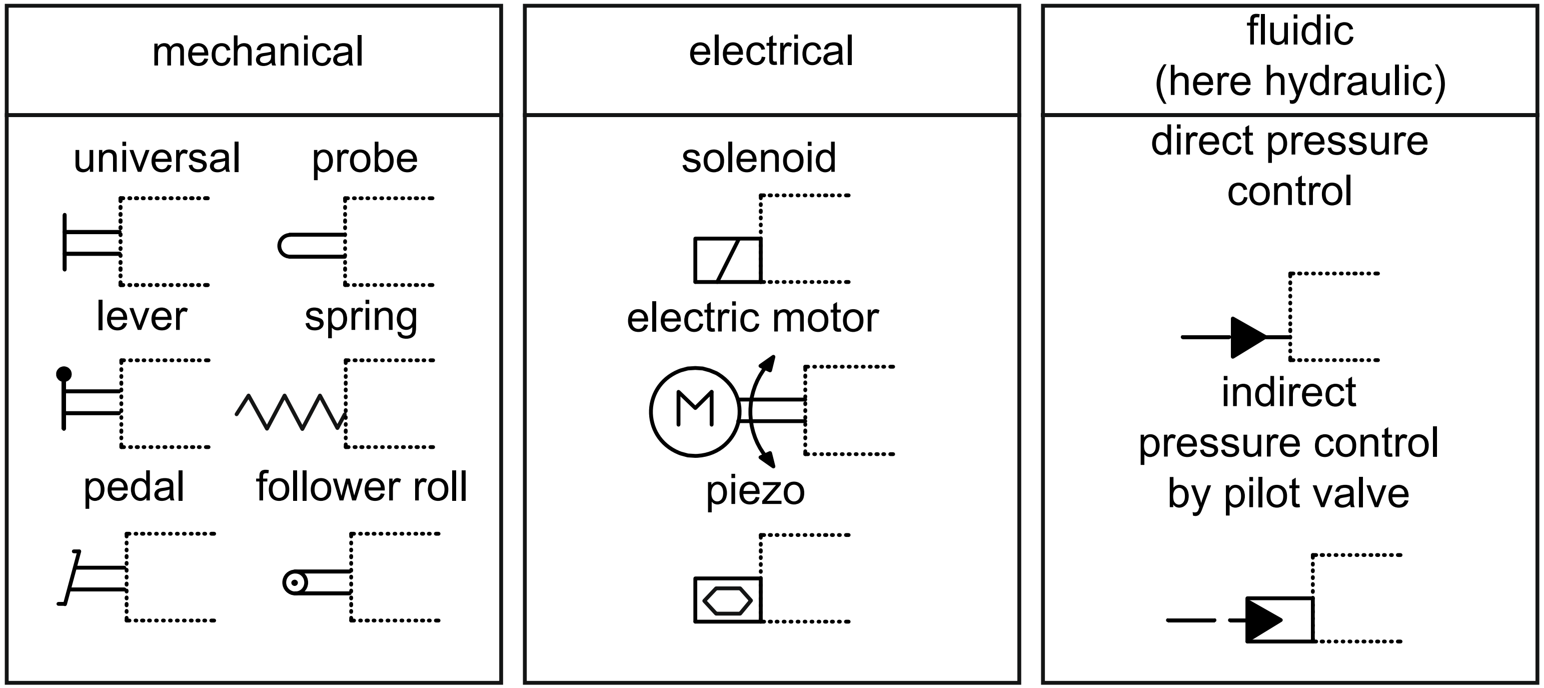


5-chamber valve

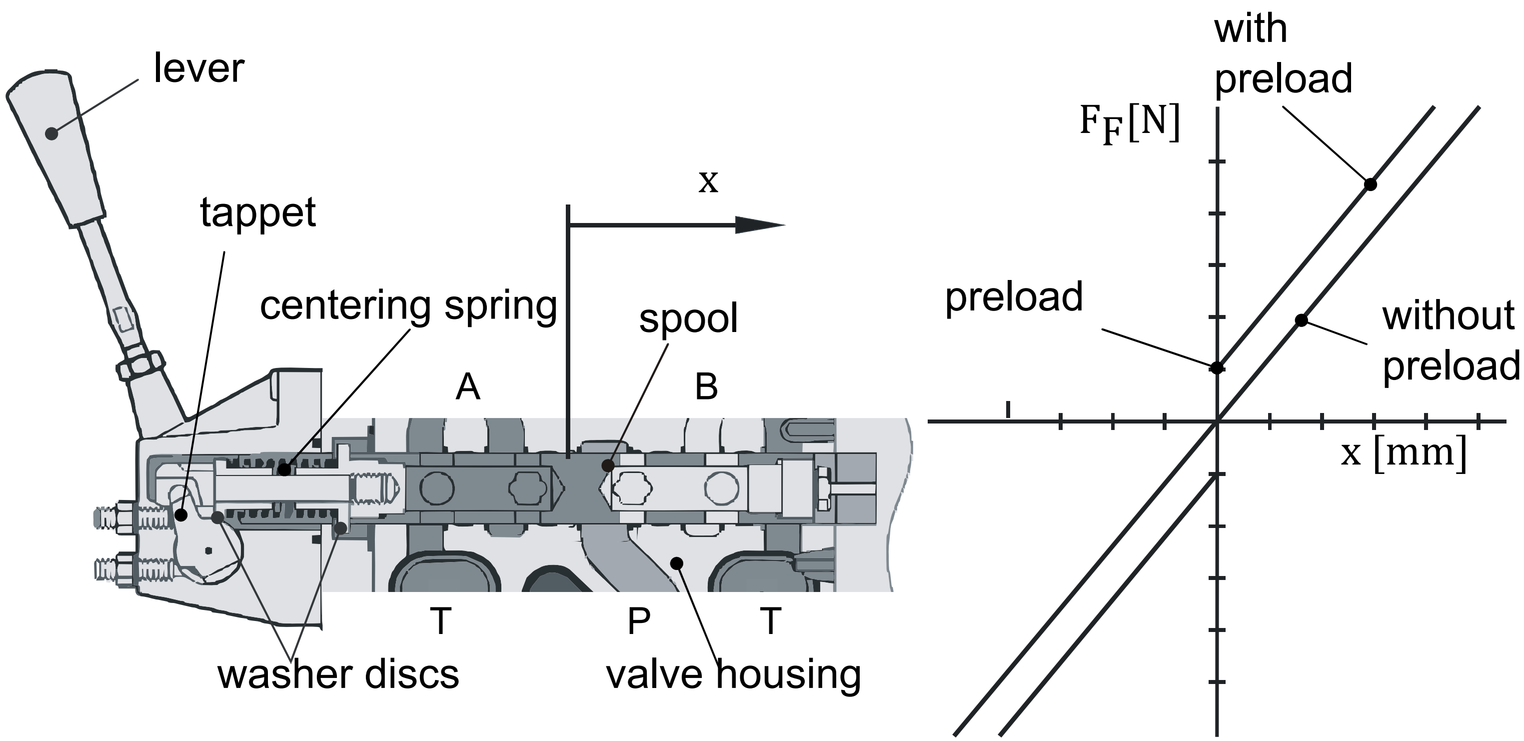


Outline of todays lecture

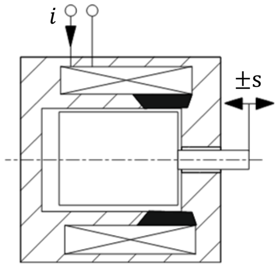
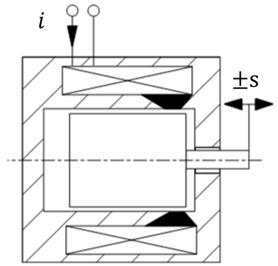
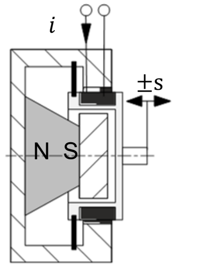
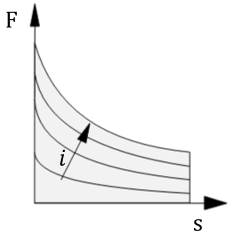
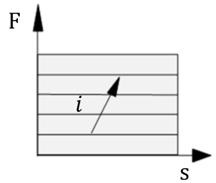
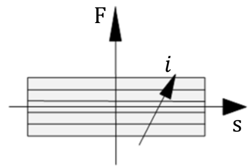
Symbols for different actuation principles



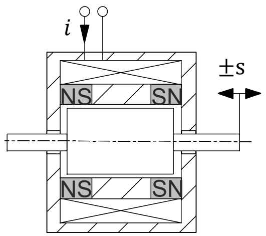
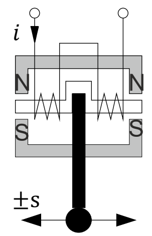
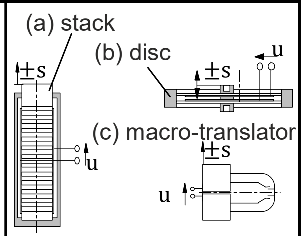
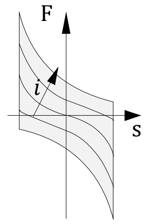
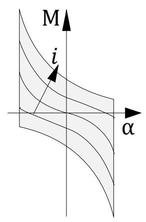
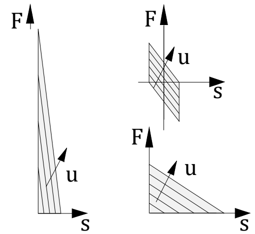
Centering by spring and actuation by lever (Sauer-Danfoss)



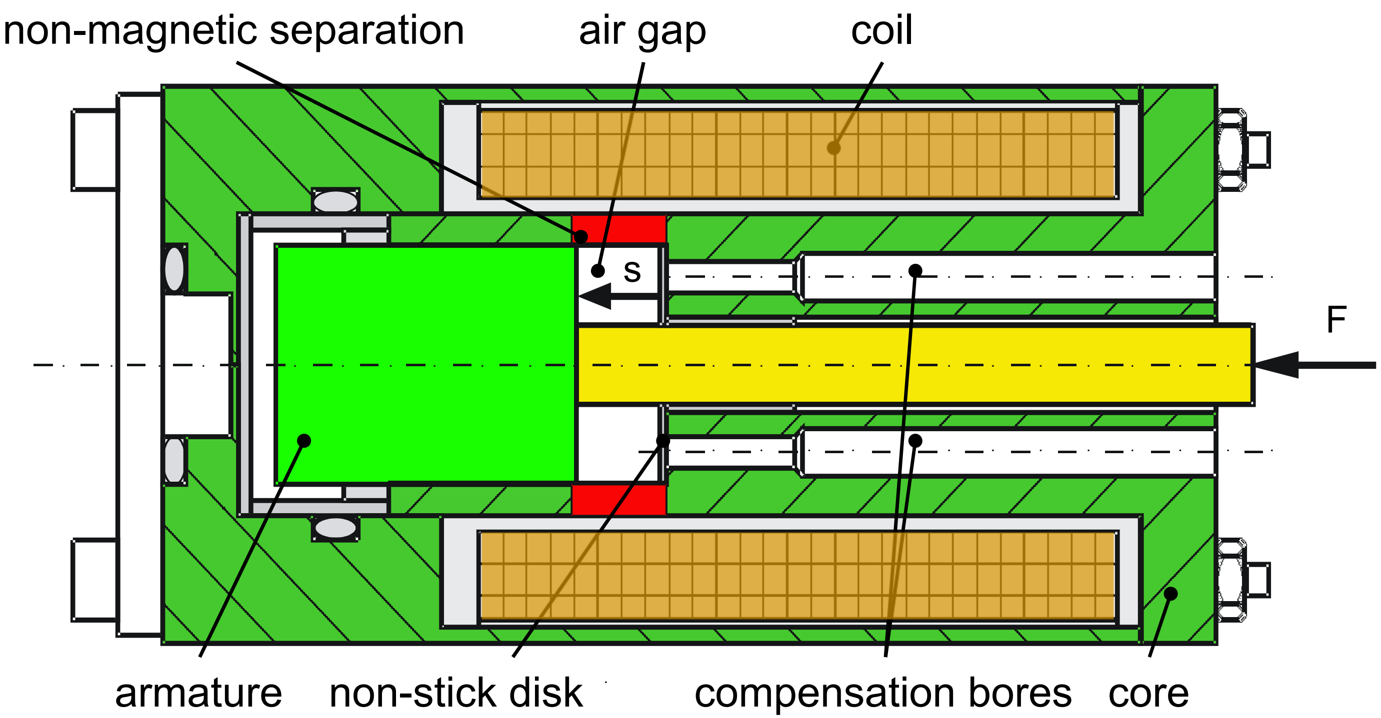
Electro-mechanical converters, part 1

electro-mech. converter	switching solenoid	proportional solenoid	voice coil
exemplary design			
characteristic curves			
stroke range maximum forces energy of stroke energy of stroke/ space hysteresis linearity dynamic range input power complexity pressure restistance comments	3 - 8.5 mm 55 - 220 N 75 - 850 Nmm 2.1 - 3.8 Nmm/cm³ n. s. correction control required n. s. 16 - 42 W low (without control) standard unusual for control valves	2 – 4.5 mm 45 - 200 N 70 - 800 Nmm 1.3 - 3.5 Nmm / cm³ controlled < 4 % good < 200 Hz 15 - 40 W moderate (control cone) standard no fail-safe	> 2 mm > ± 100 N > 300 Nmm ca. 1.2 Nmm/cm³ good very good typ. 350 Hz < 100 W expensive perm. magnets special connector required low load density

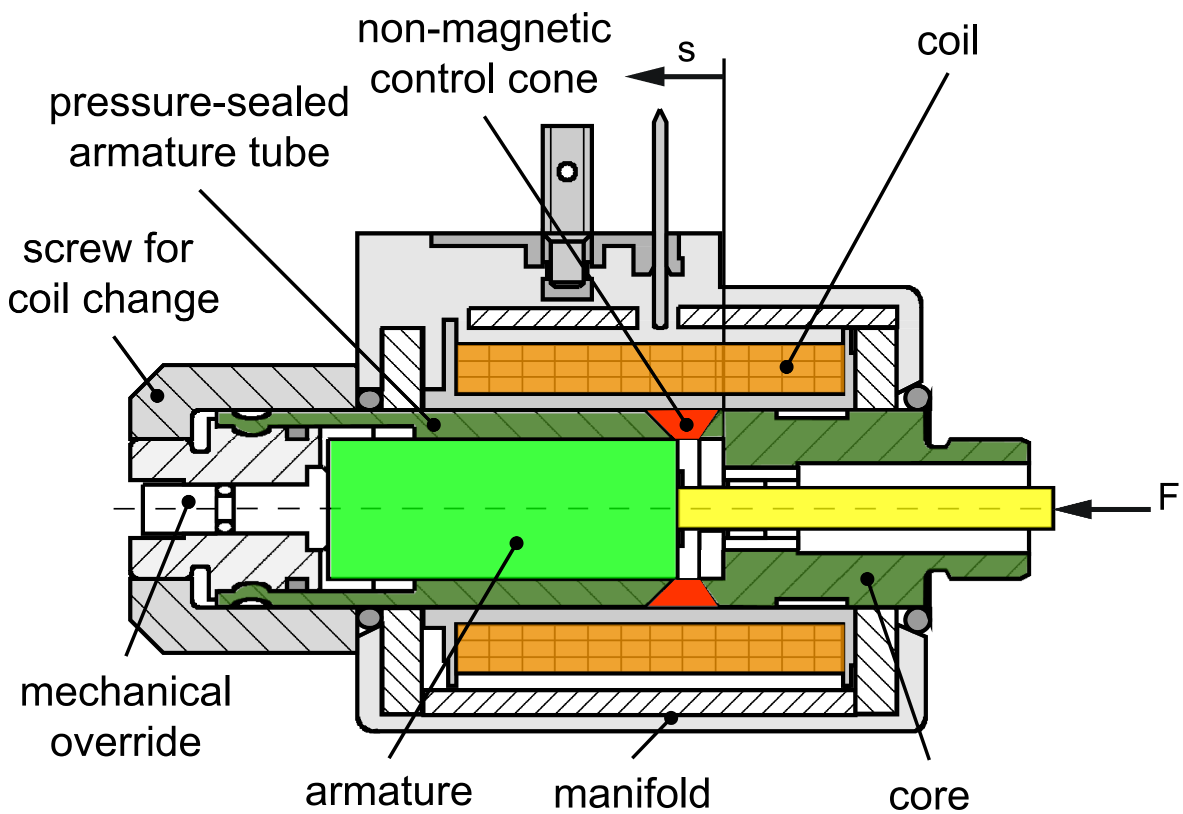
Electro-mechanical converters, part 2

electro-mech. converter	linear motor	torque motor	piezo-el. converter
exemplary design			
characteristic curves			
stroke range	0.7 - 2 mm	Lever: ±0.25 - 0,8 mm Deflector.: ± 0.035 mm	< 0.18 | < 0.2 | <1 mm
maximum forces	± 100 - ± 300 N	< 70 N	3500 | 35 | 50 N
energy of stroke	140 - 780 Nmm	2 - 40 Nmm	> 400 | 7 | 50 Nmm
energy of stroke / space	1.5 - 2.5 Nmm/cm³	n. s.	ca. 5 | 0.25 | 1 Nmm/cm³
hysteresis	n. s.	controlled < 3%	low in control mode
linearity	moderate if uncontrolled	controlled < 5%	high in control mode
dynamic range	ca. 260 Hz	100 - 1000 Hz	> 2000 | 1100 | 100 Hz
input power	7.2 - 65 W	0.02 - 7.5 W	typ. 50 W
complexity	expensive perm. magnet	expensive perm. magnet	high (accurate parts req.)
pressure restistance	yes	yes	n. s.
comments			expensive,(a) long design

Switching solenoid (Magnet-Schultz)

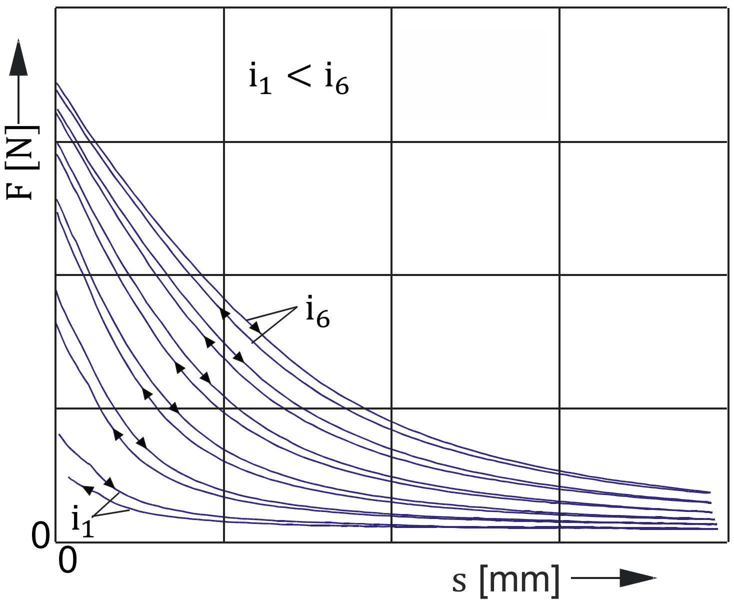


Proportional solenoid (Magnet-Schultz)

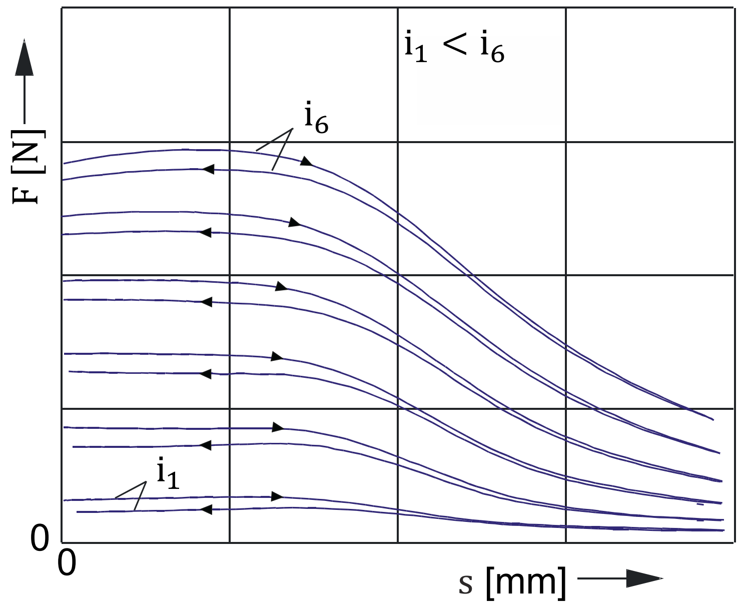


Solenoid force – stroke characteristic curve (static)

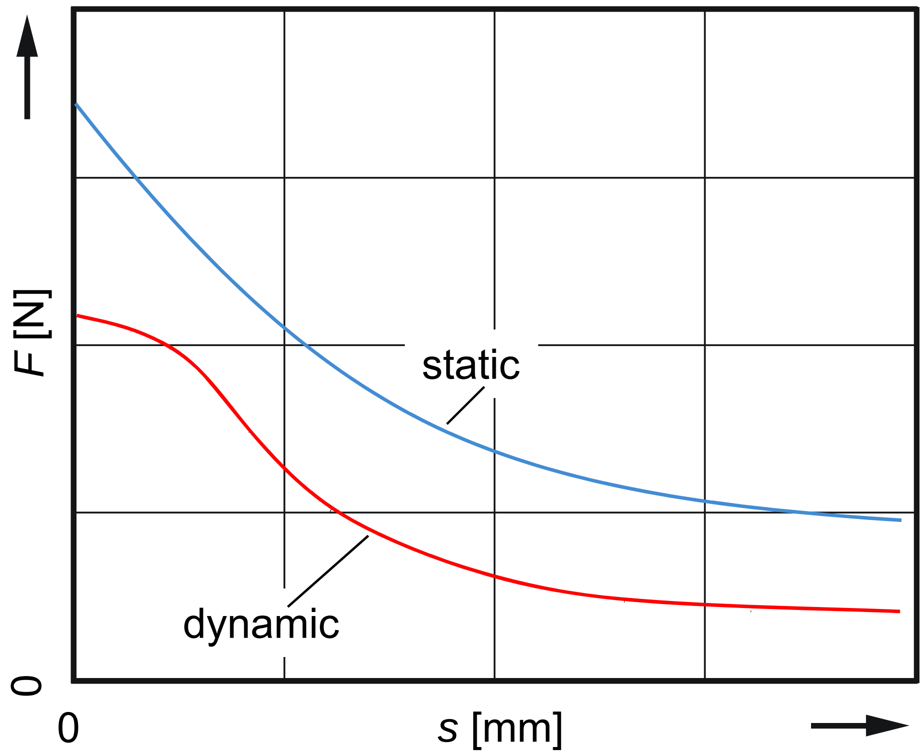
switching solenoid



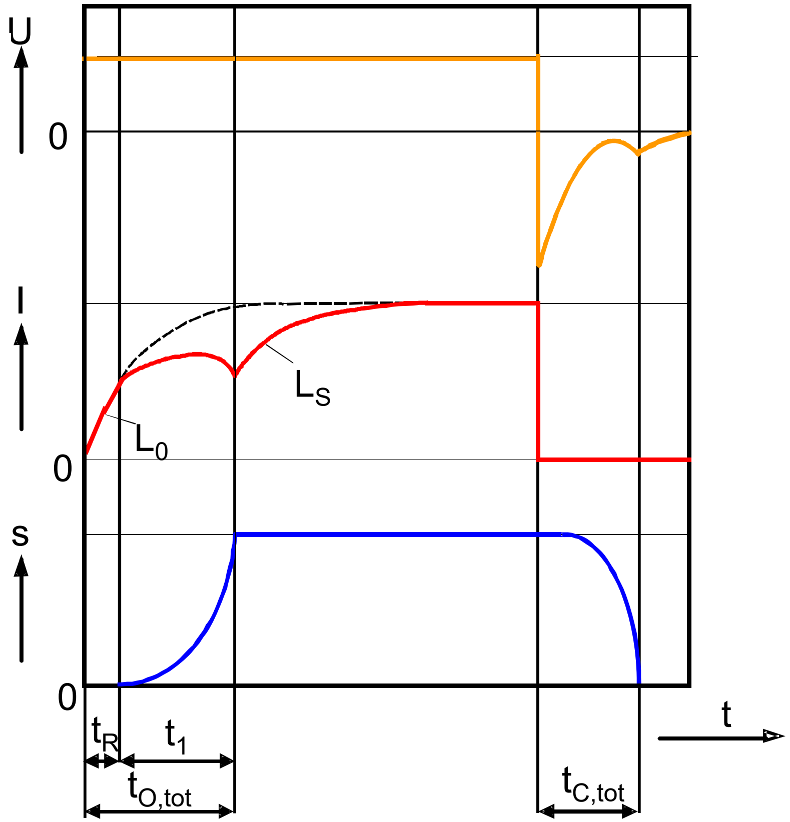
proportional solenoid



Static and dynamic characteristic curve of a DC solenoid



Switching cycle of a DC solenoid



Legend

t_R = reaction time

t_1 = switching time

$t_{O,tot}$ = opening time

$t_{C,tot}$ = closing time

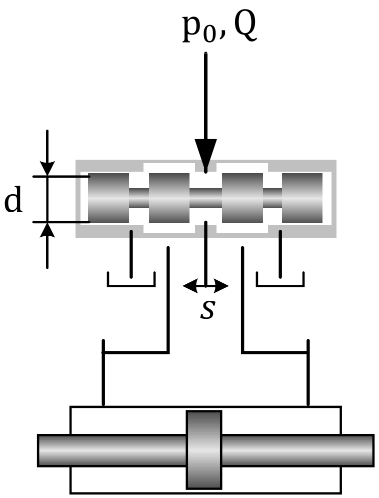
L_0 = inductivity: open

L_S = inductivity: closed

Outline of todays lecture

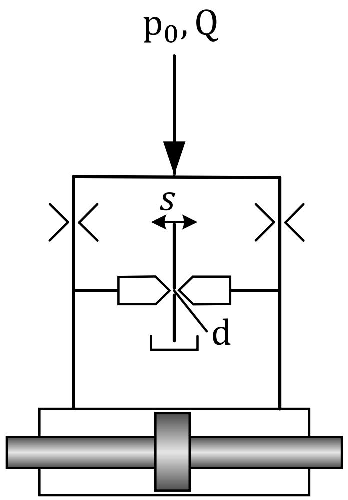
Mechanical-hydraulic converter

sliding spool



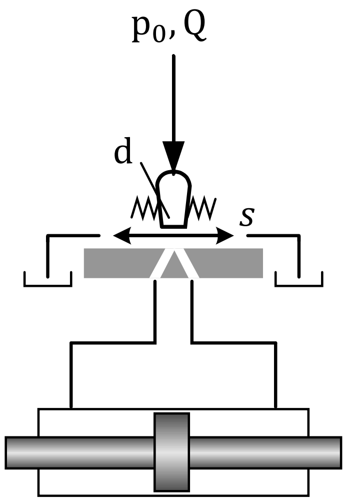
d = 4 - 12 mm
s_0 = 1 - 4 mm
p_0 = 0 - 350 bar
Q_{max} = 5 - 200 l/min

flapper-nozzle



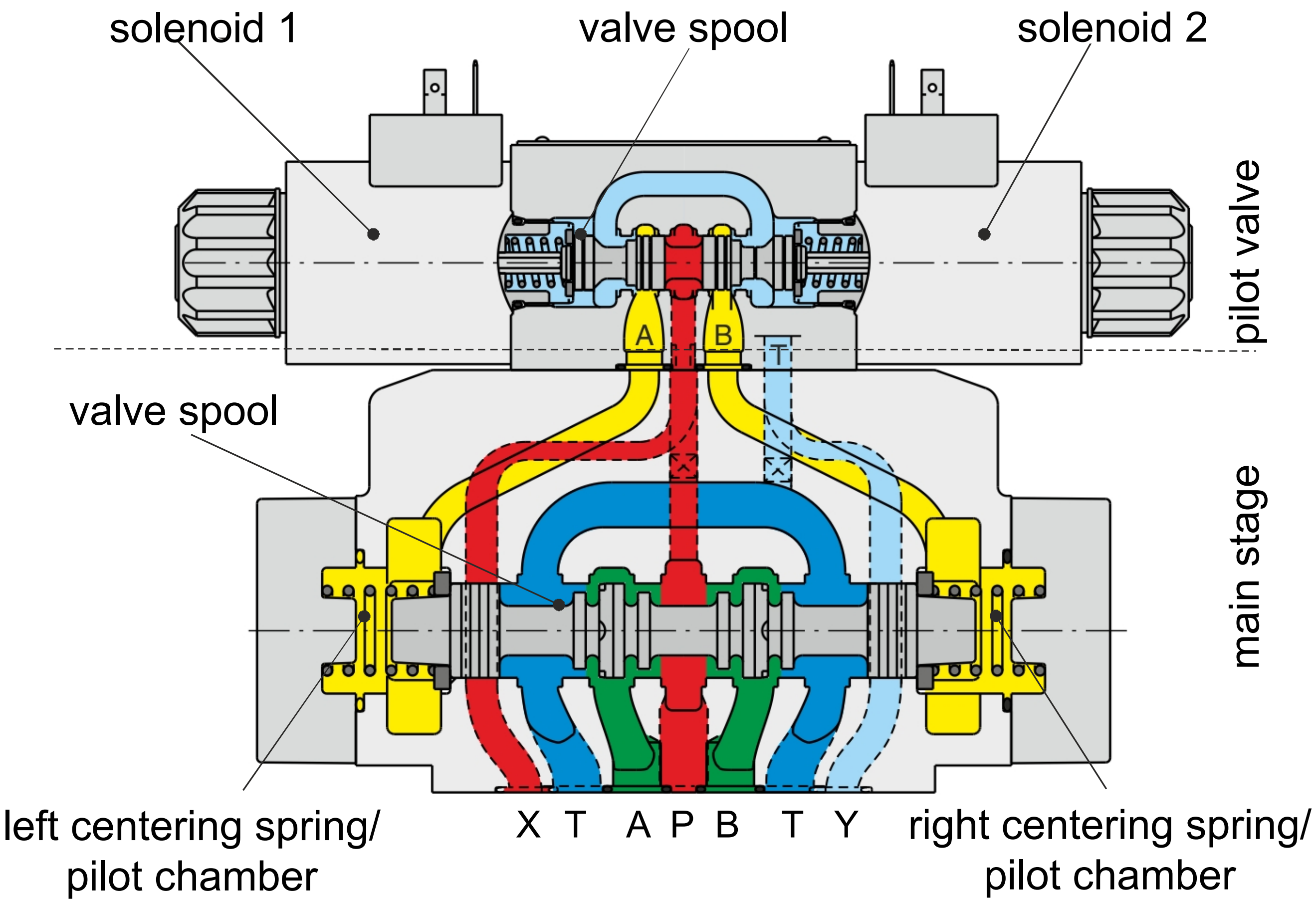
d = 0.25 - 0.5 mm
s_0 = 60 - 75 mm
p_0 = 0 - 350 bar
Q_{max} = 0.3 - 2.5 l/min

jet pipe



d = 0.12 - 0.2 mm
s_0 = 0 - 0.47 mm
p_0 = 0 - 210 bar
Q_{max} = 0.1 - 2.5 l/min

Two stage 4/3-way switching valve (Parker)



Outline of todays lecture

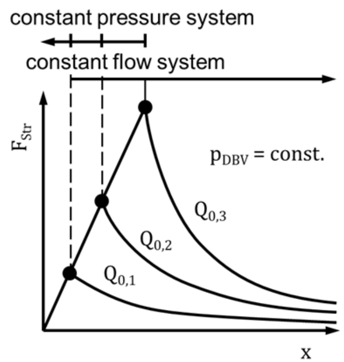
Summary

- For which functions are valves used?
  - Check valves, directional control valves, pressure control valves, flow control valves

- Which types of valves are available?
  - Spool design, seat design

- Which forces occur with translatory spool valves?
  - Friction forces (Coulomb, Newtonian), acceleration forces, pressure forces, flow forces

- How does the flow force change over the valve stroke?
  - Constant pressure system: $F_{Str} \backsim x$
  - Constant flow system: $F_{Str} \backsim \frac{1}{x}$



- How are valves operated?
  - Mechanical, electro-mechanical, mechanical-hydraulic

Thank you for your attention.