Design and Modeling of Fluid Power Systems
ME 597/ABE 591    Lecture 5

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Displacement Machines

Study different design principles and learn about the following topics:

Axial piston pump design solutions (swash plate and bent axis)

Radial piston pumps and motors – piston support

Gear Pumps – internal and external – axial and radial gap compensation

Vane pumps – advantage and disadvantage of this design

Please study the appropriate chapters in


**Aim:**
- To be able to select the right design for your system application!
- Knowledge about limitations of each basic design
- To apply models on system level for each design
Displacement Machines

- Axial Piston Machines
- In-line Piston Machines
- Radial Piston Machines
- Gear Machines
- Vane Machines

Fixed displacement machines ↔ Variable displacement machines

- Swash Plate Machines
- Bent Axis machines

- with external piston support
- with internal piston support

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Bent axis axial piston pumps

Synchronization of cylinder block

Using a universal joint

Using a bevel gear

Cylinder block

Driving flange
Bent axis axial piston pumps

- Synchronization of cylinder block
- Cardan joint
- Connecting rod
- Piston
- Piston rod
- Synchronization by piston rod
- Synchronization by pistons
Kinematics of bent axis pumps

Assuming a fixed connection between link 2 and link 4, achieved by synchronization, the mechanism has finally two degrees of freedom.

Piston can rotate about $z_3$-axis and piston rod can rotate about $z_5$-axis.
Piston Design

Short piston with piston rod

Long piston with piston rod

Synchronization by universal joint or bevel gear

Synchronization by pistons or piston rods

Spherical piston with piston ring

Conical piston with piston rings
Design Examples

Driving flange bearings

Spherical valve plate

Pump control device
Design Examples

- Driving flange bearings
- Conical piston
- Spherical valve plate

Fixed displacement pump
Radial Piston Pumps

with external piston support

Rotating cylinder body

Suction

Stroke ring

Delivery

eccentricity

with internal piston support

Stationary cylinder body

Suction

Rotating cam or crankshaft

Delivery

Displacement volume adjustable by changing eccentricity e
Radial Piston Pumps

Multiple stroke radial piston pumps

with external piston support
Rotating cylinder body
Stationary stroke ring

with internal piston support
Stationary cylinder body
Rotating cam

Only fixed displacement pumps realizable!
Piston support on outer stroke ring

- Plane valve plate
- Stroke ring
- Rotating cylinder body
- Piston

Piston rotation enforced by friction force $F_f$
Piston support on outer stroke ring

Stroke ring borne in roller bearings

Piston roller guide

Piston sliding bearing
Piston support on outer stroke ring

- Slipper support
- Stroke ring
- Hydrostatically balanced slipper
- Slipper pocket
- Hydrodynamically balanced slipper
- Ball joint inside the piston
Stroke ring support

Using a sliding carriage supported using line contact

Stroke ring mounted on a pivot

Change of eccentricity by pivoting the stroke ring about pivot axis
Design Example

- Pump control system
- Slipper
- Piston
- Control journal
- Stroke ring
External gear pump

Basic principle

Radial gaps between teeth addendum circle and housing

Axial gaps between housing and the gear pair must be very small to seal the displacement chamber

\[ Q_e = V \cdot n - Q_s \]
Two stage gear pump

\[ \Delta p_1 = p_2 - p_1 \]

Driving gear

[Diagram of a two-stage gear pump]

Outlet 1 and inlet 2 can be connected

\[ p_2 = p_3 \]

or the pump can have two separate outlets

\[ p_1 = p_3 \]

\[ \Delta p_1 \approx \Delta p_2 \]

the driving gear is pressure balanced!
Using teeth of standard involute design requires a combination where the pinion has two or more fewer teeth than the ring gear! Pinion and ring gear are then separated by a crescent shaped divider.

Advantages:
- Better suction ability
- Higher efficiency
- More compact design
- Less noise emission

Longer duration of teeth meshing leads to better sealing function.
Internal gear pump

Crescent shaped divider

Many different tooth profiles have been applied in the recent past.
Annular gear pumps

Applying specially generated tooth curves it can be achieved, that the inner rotor (the pinion) has only one tooth less than the ring gear, thus eliminating the crescent-shaped divider.

Each tooth of the pinion maintains continuous sliding contact with a tooth of the ring gear, providing fluid tight engagement.

Relative sliding velocity between pinion and ring gear is very small, quiet operation and long service life.

\[ n_2 = n_1 \cdot \frac{z_1}{z_2} = n_1 \cdot \left(1 - \frac{1}{z_2}\right) = n_1 \cdot \left(1 + \frac{1}{z_1}\right)^{-1} \]

\[ z_2 = z_1 + 1 \]
Annular gear pump – Orbit principle

Ring gear \( z_2 \) fixed

Rotating pinion \( z_1 \)

Displacement volume is given by \( z_1 \) times \( z_2 \) tooth spaces

Multiple delivery of each tooth space

1 Suction port

2 Pressure port

Outlet

Inlet

\[ z_2 = z_1 + 1 \]
Pressure compensated axial gaps

\[ A = (1.1 \div 1.3) \frac{F_z}{p_2} \]

- Sealing ring
- Gear pair
- Shaft seal
- Sliding bearing
- Pressurized area A
- Axial gap
- End cap
- Bearing bushings
- Housing
- Front cover

Only one direction of shaft rotation possible!
Pressure compensated axial gaps

\[ A = (1.1 \div 1.3) \cdot \frac{2 \cdot F_z}{p_2} \]

- Driving gear
- Axial gap – pressure compensated
- Pressurized area
- Sliding bearings
- Driven gear
- Sealing
- Improved volumetric efficiency
Pressure compensated radial gaps

Radial gap compensation

Bearing bushing

Small pressure zone achievable

Axial gap compensation

Pressurized area
Gear pump – design example

Bearing bushing performing a radial and axial gap compensation

Driving gear

Driven gear

Shaft seal

inlet

outlet
Internal gear pump- design example

Internal gear pump with axial and radial gap compensation

Ring gear
Pinion
special shaped divider

inlet
Moveable bearing shell
Radial gap compensation

Pressurized area
outlet
Screw Pumps

With two meshing screws

inlet

outlet
Screw Pumps

With three meshing screws

t...thread pitch
Vane Pumps

Classification of vane pumps

Unbalanced vane pump

Balanced vane pump

Fixed and variable pump design

Only fixed displacement pump
Vane pumps- basic working principle

Single stroke vane pump – variable displacement volume

Overcenter pump – the direction of flow can be reversed by change of eccentricity, i.e. without changing the direction of rotation of the drive shaft

Relatively high friction between axial moveable vanes and rotor & between vanes and stator

Large radial forces exerted on the rotor

Limitation of max. operating pressure (20 MPa)
Vane pumps - classification

Multiple stroke vane pump

Rigid vane pump

Rotor
Fluid distribution

External fluid distribution

Internal fluid distribution

Outlet

Inlet

Distributor - fixed control journal

Rotor

Stator
Rigid vane pump

Displacement volume:

$$V_g = 2 \cdot \frac{\pi \cdot (D^2 - d^2)}{4} \cdot \frac{180 - \alpha}{180} \cdot b - 2 \cdot \left( \frac{D}{2} - \frac{d}{2} \right) \cdot c \cdot b$$

Pulsation free flow