Chapter 6

Axial Piston Units

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1 Introduction

1.1 Circuit types

There are three types of circuits in hydraulics:

– Open loop circuit

– Closed loop circuit

– Semi-closed loop circuit

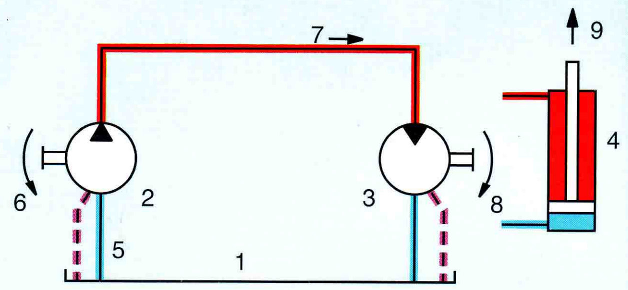
Open and closed loop circuits will be described in more detail below. The semi-closed loop circuit is a mixture of both types of control circuit and is used in applications where volumes are to be balanced e.g. via anti-cavitation check valves (e.g. when using a single rod cylinder block).

Typical features of open loop are:

- Suction lines
  Large diameters, small lengths
- Directional valves
  Sizes dependent on flow
- Filters/coolers
  Cross-sectional areas/sizes dependent on flow
- Tank size
  Multiple of max pump flow in litres
- Pump arrangement
  Next to or under the tank
- Drive speeds
  Limited by amount of suction
- Unloading in the return line via valves

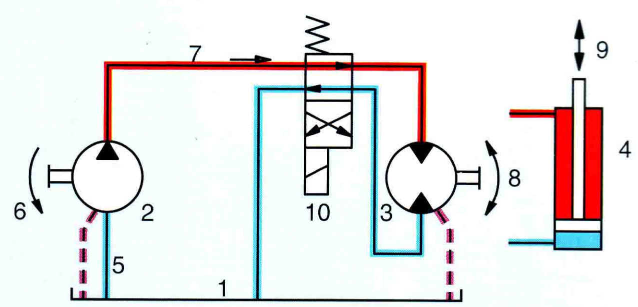
Typical feature of closed loop circuits are:

- Directional valves
  Small sizes for pilot operation
- Filters/coolers
  Small openings to flow/small sizes
- Tank size
  Small - determined only by flow of auxiliary pumps and system flow
- Speeds
  High limits due to anti-cavitation
- Arrangement/installation position
  Any
- Drive
  Completely reversible through zero position
- Support of loads
  Via drive motor
- Return of braking energy



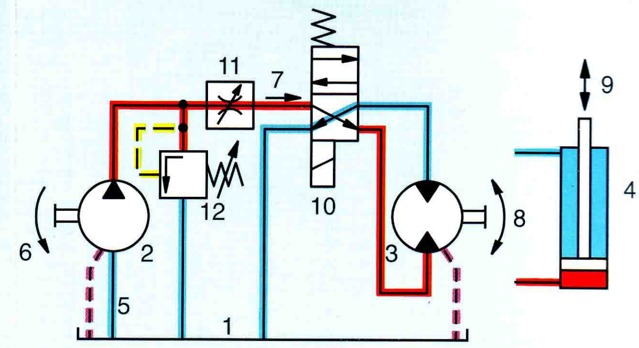
1 Tank
2 Fixed displacement pump
3 Fixed displacement motor
4 Hydraulic cylinder block
5 Suction line
6 Drive speed
   n= constant
7 Flow
   Q= constant
8 Output speed
   n= constant
9 Stroke velocity
   v= constant

Basic design with hydraulic pump and hydraulic motor/cylinder block, drive, output and direction of stroke are on one side.



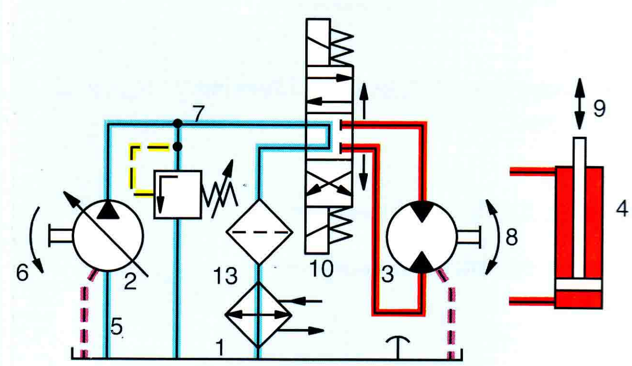
1 Tank
2 Constant displ. pump
3 Constant displ. motor
4 Hydraulic cylinder block
5 Suction line
6 Drive speed
   n= constant
7 Flow
   Q= constant
8 Output speed
   n= constant
9 Stroke velocity
   v= constant
10 Directional valve
   for control of direction

Due to the directional valve the direction of rotation or movement may be changed at the actuator.



1 Tank
2 Fixed displacement pump
3 Fixed displacement motor
4 Hydraulic cylinder block
5 Suction line
6 Drive speed
   n= constant
7 Flow
   Q= variable
8 Output speed
   n= variable
9 Stroke velocity
   v= variable
10 Directional valve
   for control of direction
11 Flow control valve
   for flow adjustment
12 Pressure relief valve
   for protection against overload

By using a flow control valve (11) the output speed (velocity) is made variable. Pressure relief valve (12) protects hydraulic system from overloading.



1 Tank
2 Variable displ. pump
3 Constant displ. motor
4 Hydraulic cylinder block
5 Suction line
6 Drive speed
   n= constant
7 Flow
   Q= variable
8 Output speed
   n= variable
9 Stroke velocity
   v= variable
10 Directional valve
   for control of direction
12 Pressure relief valve
   for protection against overload
13 Accessories
   such as filtration, cooling etc.

A variable displacement pump replaces the constant displacemnt pump and flow control valve. Further directional valve functions, e.g. free-wheeling circuit of actuator, use of accessories such as filters, coolers etc. complete the hydraulic system.

1.1.1 Open loop circuits

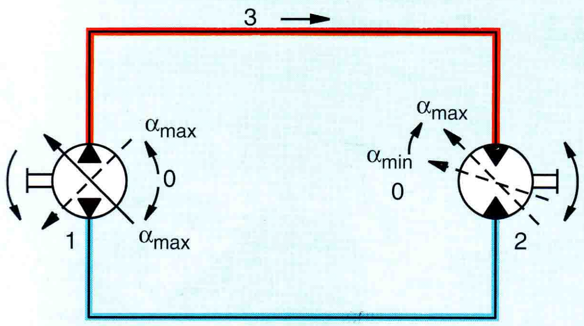
In general, open implies that the suction line of a pump is fed below the surface of the fluid in the tank and the surface of the fluid is in direct contact with the atmospheric pressure (i.e. the surface is not enclosed). The balance of pressures which is ensured between the air in the hydraulic tank and the ambient air, enables the pump to have an excellent suction characteristic. Resistances in the feed line must not cause the pressure to fall below the so-called suction height/suction limit.

Axial piston units are self-aspirating. However in certain individual cases low pressure is fed to the suction side.

In open loop circuits fluid is fed to the actuator via directional valves and returned via the same valves to tank.

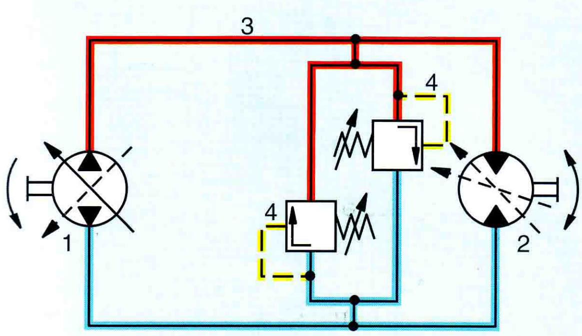
The open loop circuit is the standard circuit used in many industrial and mobile applications. Examples range from machine tools and press drives to winch and mobile drives.

Fig. 1: *Open loop circuit*



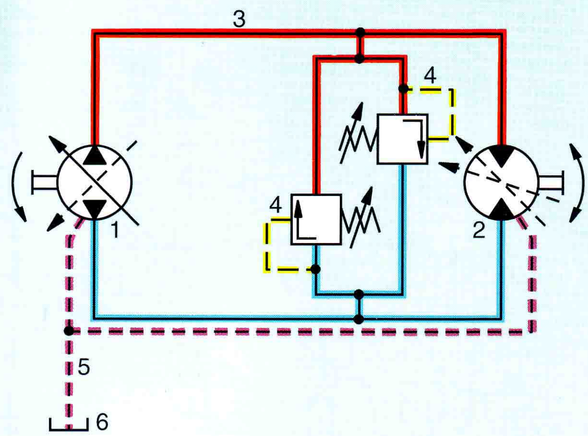
1 Hydraulic pumpe
2 Hydraulic motor
3 Flow
Q= variable

Basic design with variable displacement pump and motor. The pump rotates in one direction only, the motor rotates in both directions (is reversible) The pump swivel angle may be smoothly adjusted through zero, i.e. the direction of flow may be changed. Motor may swivel on one side of centre and is also smoothly adjustable.



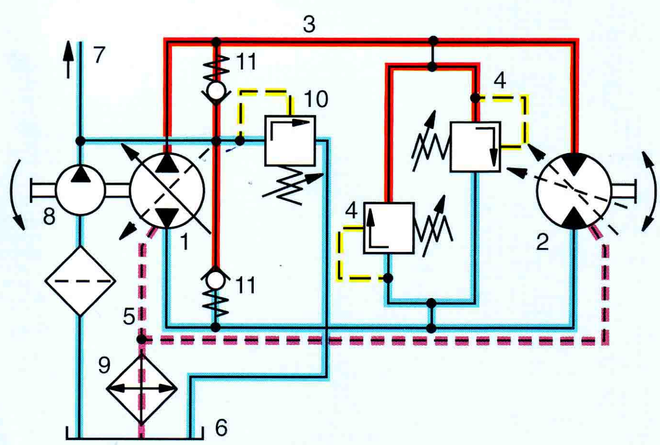
1 Hydraulic pump
2 Hydraulic motor
3 Flow
Q= variable
4 Pressure relief valve
for protection against overload
(a valve per pressure side)

By using pressure relief valves the maximum pressure is ensured. A pressure relief valve is inserted for each pressure side.



1 Hydraulic pump
2 Hydraulic motor
3 Flow
Q= variable
4 Pressure relief valve
for protection against overloading
(per pressure side of valve)
5 Drain case line
6 Fluid tank for leakage oil

Leakage from pump and motor is led back to a small tank and must be replaced!



1 Hydraulic pump
2 Hydraulic motor
3 Flow
Q= variable
4 Pressure relief valve for protection against overload (a valve per pressure side)
5 Drain case line
6 Fluid tank for leakage oil
7 For pump control
8 Aux. pump for anti-cavitation
9 Accessories
such as filtration, cooling etc.
10 Feed and pressure relief valve
11 Check valve

An auxiliary pump for the replacement of leakage oil and for the control of the pump, check valves for anti-cavitation, protection via a feed / pressure relief valve and use of accessories such as filters, coolers etc. complete the hydraulic system.

1.1.2 Closed loop circuit

A hydraulic system is a closed loop circuit when the fluid returning from the actuator is fed straight back to the hydraulic pump.

Pumps have high and low pressure sides and these change depending on the direction of the load.

The pressure is limited on the high pressure side via pressure relief valves, which unload to the low pressure side. The fluid remains in the circuit.

Only the internal leakages from the pumps and motors need to be replaced (depending on operating data).

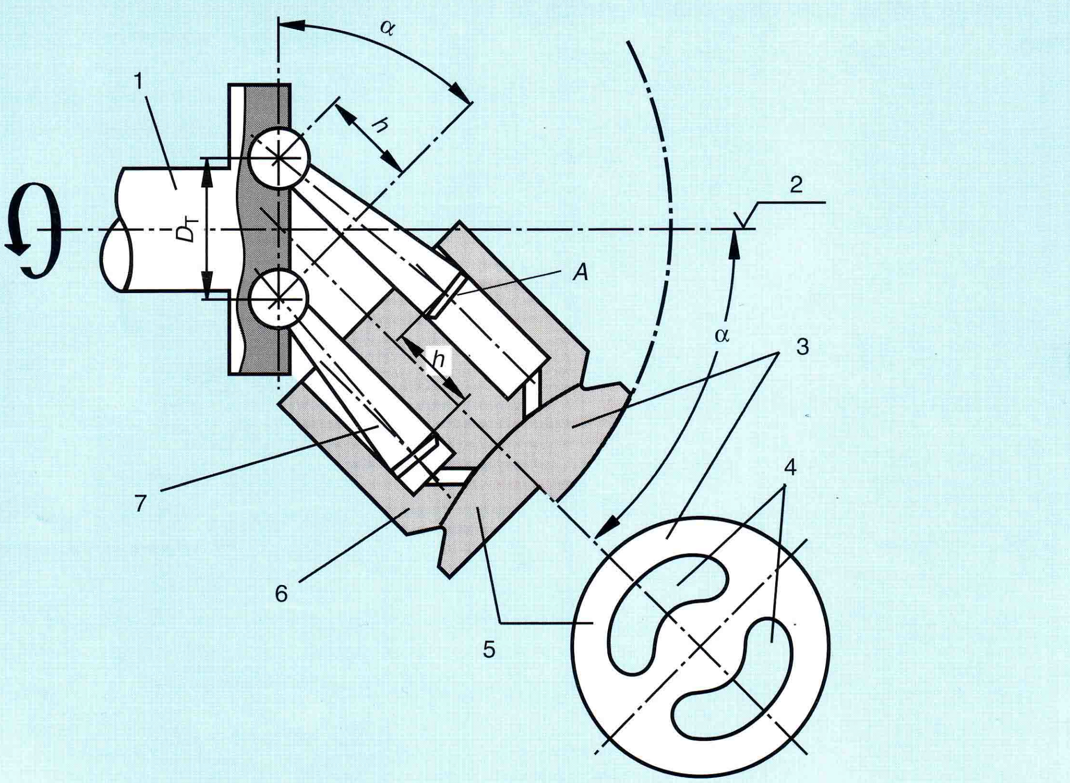
This occurs via (in general) an auxiliary pump connected directly by a flange to the pump. This auxiliary pump continually sucks fluid from a small tank and delivers sufficient fluid (boost fluid) via a check valve to the low pressure side of the closed loop circuit. The flow which is not required is returned by a boost pump operating in an open loop circuit via a boost pressure relief valve to tank. Due to the low pressure side being replenished, this pump enables higher operating characteristics to be attained.

Fig. 2: *Closed loop circuit*

2 Basic function

2.1 Bent axis

Fig. 3: *Fixed displacement unit with tapered piston rotary group*



1 Drive shaft
2 Zero position
3 Control lens for variable displacement
4 Control slots (kidney slots)
5 Control plate for constant displacement
6 cylinder block block
7 Tapered piston

$h = D_T \bullet \sin\alpha$
$V_g = x \bullet A \bullet h$
$V_g = x \bullet A \bullet D_T \bullet \sin\alpha$

h = piston stroke
A = piston area
D_T = pitch circle diameter on drive shaft
α = swivel angle (e.g. 25°)
V_g = geometric stroke volume in cm^3
x = number of pistons (e.g. 7)

Fig. 4: *Bent axis design with fixed or variable swivel angle*

2.1.1 Bent axis principle

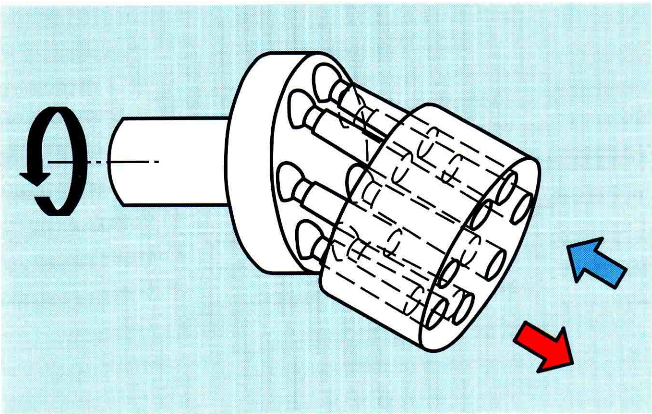


Fig. 5

The bent axis mechanism is a displacement machine, the displacement pistons of which are arranged at an angle to the drive shaft axis.

2.1.1.1 Pump function

As the drive shaft rotates, the cylinder block is caused to rotate by the pivoted pistons. The pistons move up and down within the cylinder block bores. The length of stroke is dependent on the angle of the bent axis. Fluid is fed to the low pressure side (inlet) and then delivered via the pistons on the high pressure side (outlet) to the system.

2.1.1.2 Motor function

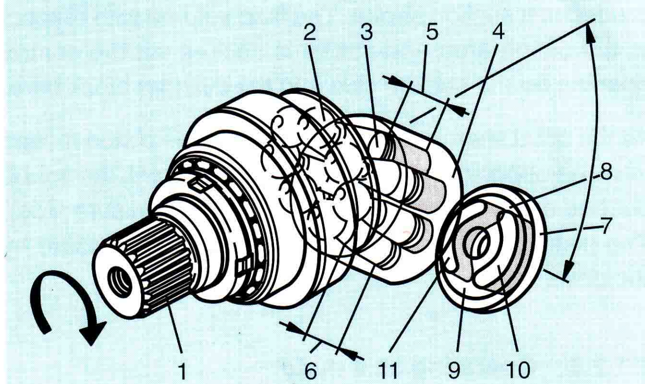
In contrast to the pump function, pressurised oil is fed into the inlet. The pistons move up and down within the cylinder block bores. This movement is converted into a rotary movement via the piston ball joint at the drive flange. The cylinder block is caused to rotate by the pistons and an output torque is created at the drive shaft. The fluid emerging from the motor is then returned to the system.

2.1.1.3 Swivel angle

The swivel angle of the fixed displacement unit is set by the housing and hence it is fixed. In a variable displacement unit this angle may be smoothly adjusted between certain limits.

By changing the swivel angle a different piston stroke is obtained and hence an adjustable displacement volume may be produced.

2.1.2 Description of the function by means of an example of a constant displacement unit



1	Drive shaft	**8**	Upper idle point
2	Piston	**9**	Lower idle point
3	Piston area	**10**	Control opening on pressure side (in dir. of rotation shown)
4	cylinder block	**11**	Control opening on suction side (in dir. of rotation shown)
5	Pressure stroke		
6	Suction stroke		
7	Control plate		

Fig. 6

2.1.2.1 Description

The axial piston units in bent axis design with fixed or variable stroke volumes may operate as hydraulic pumps or as hydraulic motors.

When used as a pump, the flow is proportional to the drive speed and the swivel angle. If the unit is used as a motor, the drive speed is proportional to the flow fed to the unit. The torque received (pump) or produced (motor) increases as the pressure drop increases between the high and low pressure sides. When operating as a pump, the unit converts mechanical energy into hydro-static energy. In contrast, when operating as a motor, the unit converts hydrostatic energy into mechanical energy. In variable displacement pumps or motors the displacement volume, i.e. the pump flow or the suction flow in motors may be varied by adjusting the swivel angle.

2.1.2.2 Operating as a pump in an open loop circuit

As the drive shaft is rotated the cylinder block is made to rotate via seven pistons which are mounted via ball joints in a circle on the drive flange. The cylinder block slides on the spherical control plate, in which there are two kidney shaped control openings. On rotation, each of the seven pistons moves in the cylinder block bores from the upper idle point to the lower idle point and vice versa. They thereby carry out a stroke which is dependent on the swivel angle. The piston movement in the cylinder block bore from the lower idle point to the upper idle point produces a suction stroke. The fluid volume with respect to the piston area and stroke is sucked via the control opening on the suction side into the cylinder block bore.

As the drive shaft is further rotated and the piston moves from the upper idle point to the lower idle point, the fluid is pushed out of the other control opening (pressure side). The pistons are supported under hydraulic pressure by the drive shaft.

2.1.2.3 Operating as a motor

The motor function is the reverse of the pump function. Here fluid is fed through a control opening into the cylinder block bores via the port plate. Three or four cylinder block bores are situated above the control opening on the pressure side and four or three bores above the opening in the return side. One bore may be directly connected to the idle point via the control plate. The force (resulting from the pressure and piston area) which acts on the drive shaft
causes an output torque to be produced.

2.1.2.4 Adjustment (in variable displacement unit)

The swivel angle of the bent axis may be adjusted e.g. mechanically via a positioning screw or hydraulically via a positioning piston. The hydraulic part of the drive cylinder block is moved via a control lens (control plate) and depending on the circuit and whether the operation is mechanical or hydraulic, held in either the zero position or output position. As the angle increases, the displacement volume and torque increase. As the angle decreases these values decrease accordingly. If the angle is zero, the displacement volume is zero. It is usual to have mechanically or hydraulically acting adjustment devices which may be controlled either mechanically, hydraulically or electrically. Well-known examples of these types of control are: handwheel, electronic proportional control, pressure control and power control.

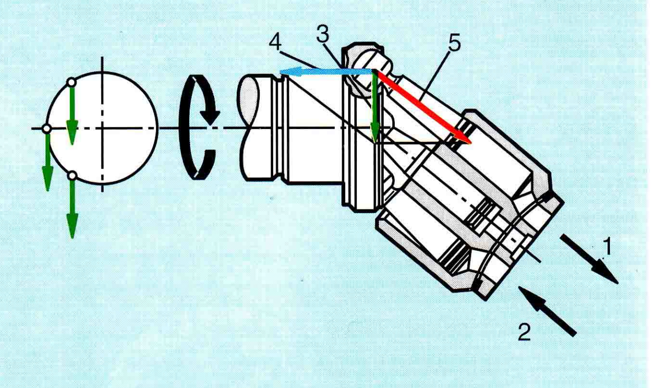
2.1.2.5 General

In both cases of pump and motor operation the torque is created directly on the drive shaft due to the bent axis design. The pistons only produce very small side forces in the cylinder block. This is advantageous for the wear behaviour, efficiency and starting torque. Due to the spherical control plate, the cylinder block is situated on a torque-free bearing. This is because all the forces acting on the cylinder block act on one point. Sideways movements due to elastic deformations do not cause leakage losses to be increased between the cylinder block and control plate. During idle operation and when operation is started, the cylinder block is pushed onto the control plate by the Belleville washers. As the pressure increases, the increasing hydraulic forces are hydraulically balanced so that the resultant forces are maintained within acceptable limits while maintaining a minimum clearance between the cylinder block and contral plate, thus keeping leakage losses to a minimum. A set of bearings is situated on the drive shaft to absorb the forces which occur in axial and radial directions. A radial seal ring and O-rings are used to seal the rotary group from the outside. The complete rotary group is held in the housing via a retaining ring.

2.1.3 Rotary group forces

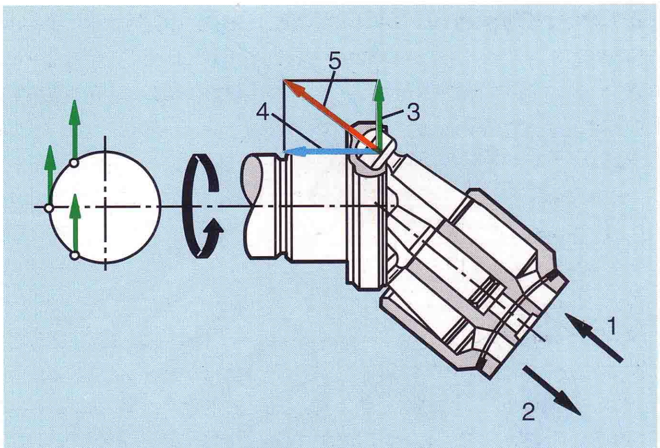
Representation in force parallelogram of a fixed displacement unit

Forces are resolved at the drive flange, i.e. directly at the drive shaft. The conversion of torque into piston force in pumps or vice versa in motors ensures that the best efficiencies are obtained. Wherever forces must be resolved (e.g. angular displacement) a loss of efficiency occurs.



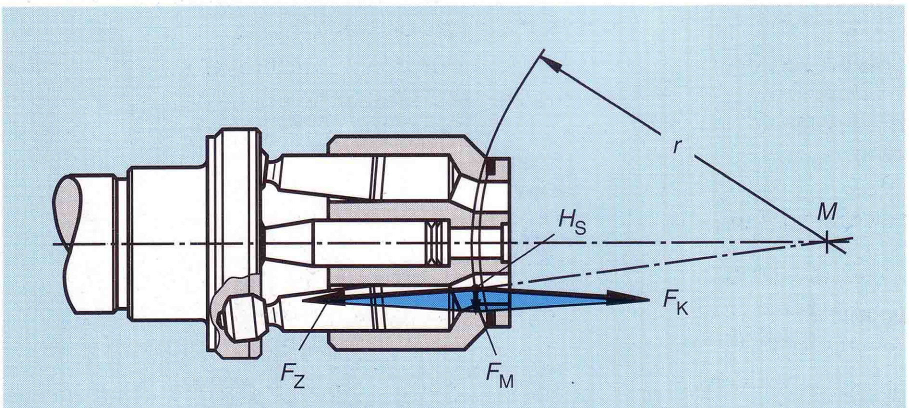
1 High pressure
2 Low pressure (suction pressure)
3 Torque (drive force)
4 Bearing force (support force)
5 Piston force (high pressure force)

Fig. 7: *Resolution of forces at drive flange of pump*



1 High pressure
2 Low pressure (return pressure)
3 Torque (output force)
4 Bearing force (support force)
5 Piston force (high pressure force)

Fig. 8: *Resolution of forces at motor drive flange*

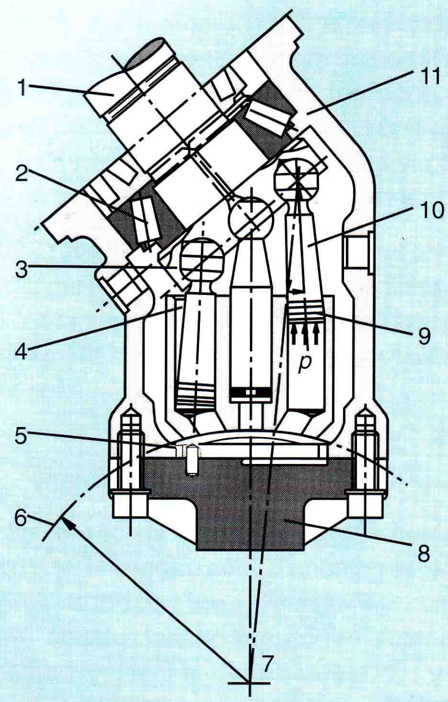


M = Virtual centre of spherical face
r = Radius of this face
H_S = Centre of gravity of hydrostatic bearing force field
F_K = Sum of forces of 3 or 4 pistons
F_Z = Force of hydrostatic pressure field of cylinder block
F_M = Resultant force on mid-pivot

Fig. 9: *Resolution of forces at the control plate with its spherical surface*

In considering torque, a segment of the hydraulic rotary group is removed and simplified until it is illustrated as a pure static example at a swivel angle of 0°.

In practice, dynamic loading processes are present in rotary groups where the swivel angle is greater than zero, as three or four piston surfaces are being continually pressurised with high pressure.



1 Drive shaft
2 Tapered roller bearing
3 Drive flange
4 cylinder block
5 Fixed control plate
6 Spherical sliding surface with hydrostatic compression springs
7 Mid-point
8 Port plate
9 Piston rings
10 Tapered piston
11 Housing

Fig. 10: *Bent axis tapered piston rotary group with 40° fixed swivel angle*

Features:

- Automatic centring
- Cardanless cylinder block drive
- Torque free cylinder block bearings
- Self-centering rotary group
- Spherical control plate
- Taper roller bearings
- Single tapered piston with two piston rings
- Automatic lubrication of bearings
- Force resolution direct at drive flange

2.1.4 Types

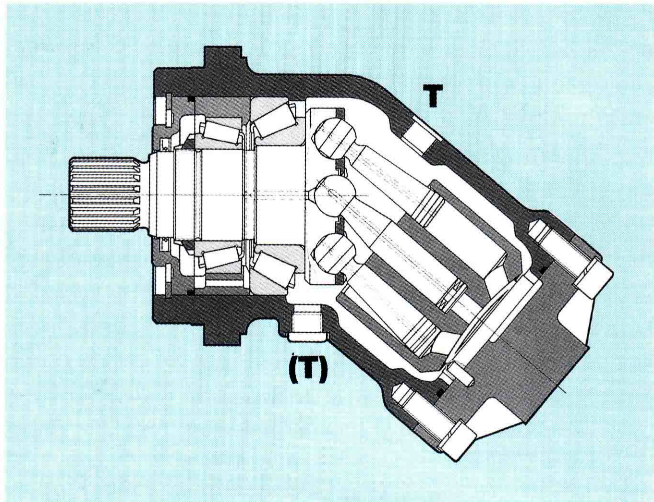


Fig. 11: *Fixed displacement unit, type A2F (fixed swivel angle), as a pump or motor for open and closed loop circuits*

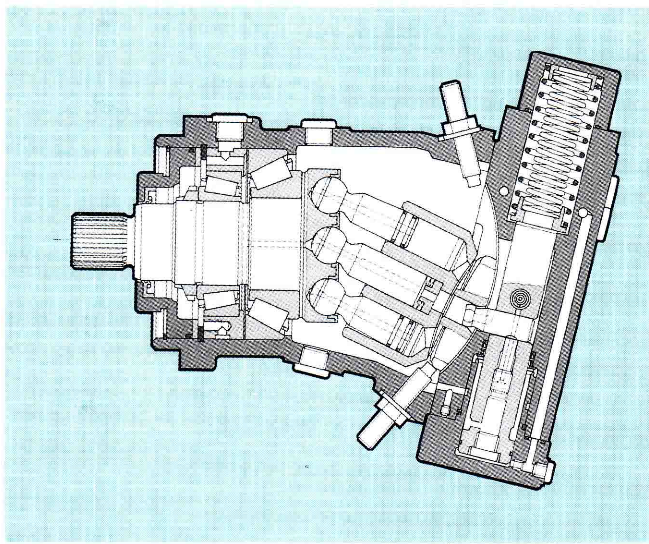


Fig. 12: *Resolution of forces at drive flange of pump*

2.1.5 Symbols

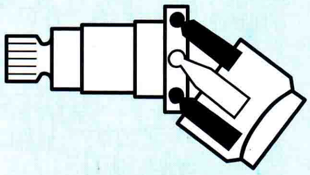
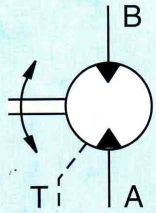
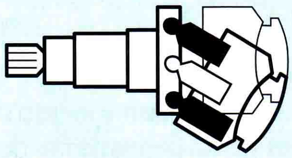
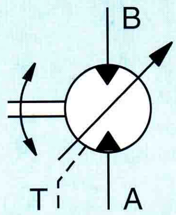
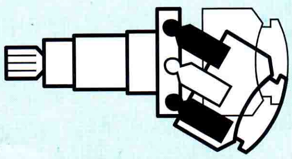
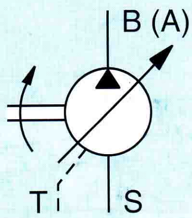
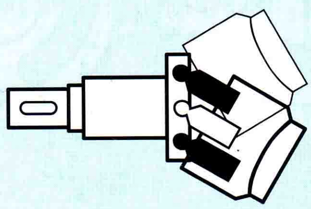
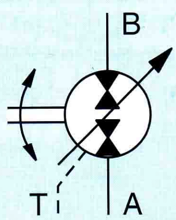
Type	Schematic diagram	Symbol	Description
Fixed displacement motor, type A2FM			Fixed displacement motor for open and closed loop circuits, fixed swivel angle, both output directions of rotation possible.
Variable displacement motor, type A6VM			Variable displacement motor for open and closed loop circuits, swivel angle smoothly adjustable (single sided), both output directions of rotation possible.
Variable displacement motor, type A7VO			Variable displacement pump for open loop circuit, swivel angle smoothly adjustable (single sided), single output direction of rotation possible.
Variable displacement motor, type A2V			Variable displacement pump, angles may be changed on both sides, swivel angle smoothly adjusted through zero position, both output directions of rotation possible.

Fig. 13

2.2 Swashplate

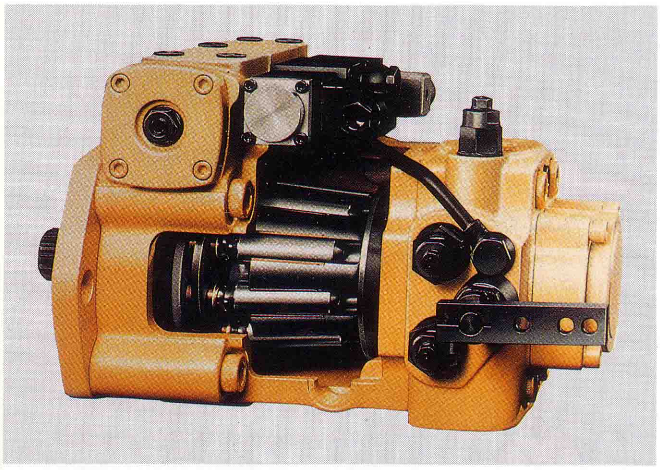
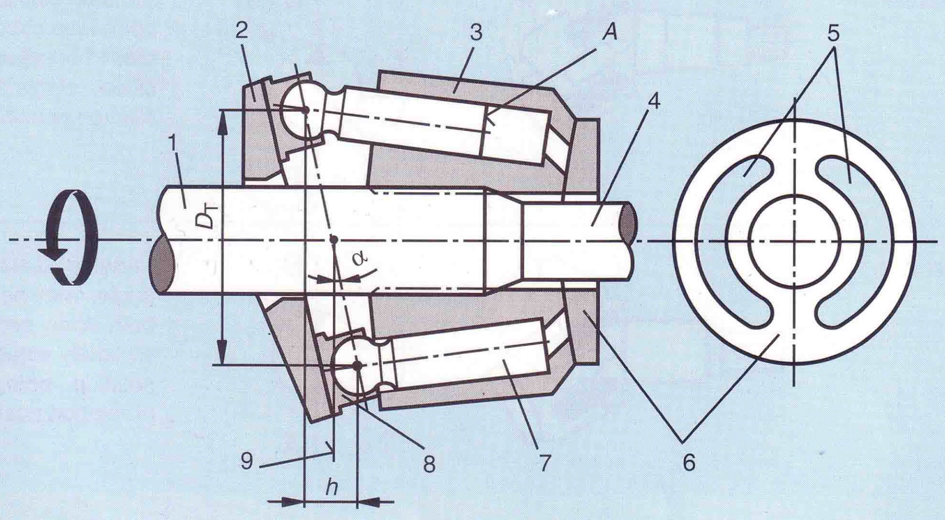


Fig. 14: *Variable displacement pump with electronic-hydraulic adjustment, speed dependent control and mounted auxilliary pump*



1 Drive shaft
2 Swashplate
3 Cylinder block
4 Through drive
5 Control kidneys
6 Control plate
7 Piston
8 Slipper pad
9 Zero position

$h = D_T \cdot \tan \alpha$

$V_g = x \cdot A \cdot h$

$V_g = x \cdot A \cdot D_T \cdot \tan \alpha$

h = piston stroke
A = piston area
D_T = pitch circle diameter at $\alpha = 0°$
α = swivel angle (e.g. 15°)
V_g = geometric stroke volume in cm^3
x = number of pistons (e.g. 9)

Fig. 15: *Swashplate design with fixed or variable swivel angle*

2.2.1 Swashplate principle

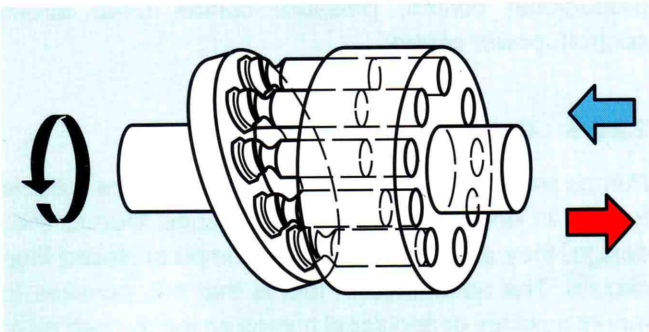


Fig. 16

The swashplate mechanism is a displacement machine, the displacement pistons of which are arranged axially to the drive shaft. The reaction force of the pistons is carried by the swashplate.

2.2.1.1 Pump function

As the drive shaft rotates, the cylinder block is driven by means of splines. The pistons move up and down within the cylinder block bores. This movement is dependent on the angle to the swashplate. Fluid is fed to the pump via the low pressure side (inlet) and then delivered via the pistons on the high pressure side (outlet) into the system.

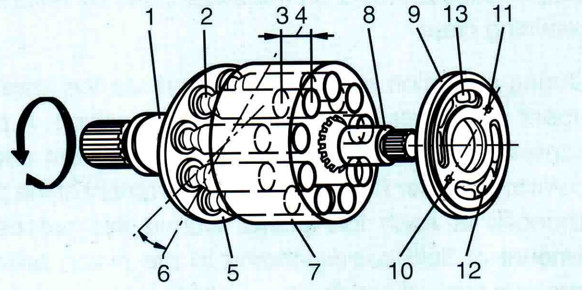
2.2.1.2 Motor function

In contrast to the pump function, fluid is fed into the inlet. The pistons carry move up and down within the cylinder block bores and turn the cylinder block, which then turns the drive shaft via the connected splines. The fluid is pushed out of the low pressure side (outlet) and fed back into the system.

2.2.1.3 Swivel angle

The swivel angle of the swashplate in the housing in the fixed displacement unit is fixed. In a variable displacement unit the angle of the swashplate may be smoothly adjusted between specific limits. By changing the angle of the swashplate it is possible to change the piston stroke and hence the displacement volume.

2.2.2 Description of the function by means of an example of a variable displacement pump



1	Drive shaft	8	Through shaft
2	Piston	9	Control plate
3	Piston area	10	Upper idle point
4	Piston stroke	11	Lower idle point
5	Swashplate	12	Control opening on pressure side (in direction shown)
6	Swivel angle	13	Control opening on suction side (in direction shown)
7	Cylinder block		

Fig. 17

2.2.2.1 Description

The axial piston units in swashplate design with constant or variable stroke volumes may operate as hydraulic pumps or hydraulic motors.

When operating as a pump the flow being delivered is proportional to the drive speed and swivel angle. If the unit is used as a motor the output speed is proportional to the flow it receives.

The torque received (pump) or produced (motor) increases as the pressure difference between the high and low pressure sides increases.

In pump operation the mechanical energy is converted into hydrostatic energy and in motor operation the hydrostatic energy is converted into mechanical energy.

In variable displacement pumps and variable displacement motors the displacement volume, i.e. the pump or motor flow may be changed by adjusting the swivel angle.

2.2.2.2 Operating as a pump

The drive shaft driven by a drive motor (e.g. diesel engine or electric motor) rotates and drives the cylinder block via splines.

The cylinder block together with its 9 pistons rotates with the drive shaft. The ends of the pistons are held by slipper pads which slide on the face of the swashplate, causing the pistons to move up and down the cylinder bores. The slipper pads are held on the swashplate by means of a retaining plate.

During a rotation each piston moves via the lower and upper idle points back to its starting position. A piston carries out a complete stroke in moving from one idle point to the other (the direction of movement of the piston changes at each idle point). During this process an amount of fluid corresponding to the piston area and stroke is sucked or delivered via both control openings in the control plate.

In a suction stroke, fluid is sucked into the increasing piston chamber, i.e. in effect the fluid is pressurised by atmospheric pressure in open loop circuits or by the boost pressure in closed loop circuits. On the other hand in a pump stroke the fluid is pushed from the piston bores into the hydraulic system.

2.2.2.3 Operating as a motor

The motor function is the opposite of the pump function. In this case, fluid is fed from the hydraulic system to the hydraulic motor. The fluid reaches the cylinder block bores via the control openings in the control plate. Four or five cylinder block bores are situated opposite the kidney shaped control opening on the pressure side. The rest of the cylinder block bores are over the other control opening. These latter bores are connected with the return side or they are partly closed via the connection pin between the control kidneys. By loading the piston, the piston slides down the swashplate. In so doing, it takes the cylinder block which is driving with it. The cylinder block with the nine pistons rotates with the drive shaft and the pistons carry out a stroke movement. The hydraulic pressure creates the torque at the cylinder block and hence the rotation of the drive shaft. The amount of flow being fed to the motor determines the output speed.

2.2.2.4 Adjustment (in variable displacement units)

The angle of the swashplate may be changed e.g. mechanically via a stub shaft or hydraulically via positioning pistons. The swashplate is held lightly in position by roller or friction bearings and its zero position is spring centred. As the swivel angle is increased the displacement volume and torque increase. As this angle is decreased these values decrease accordingly. If the swivel angle is zero, then the displacement volume is zero. It is usual to have mechanically or hydraulically acting adjustment devices, which may be controlled either mechanically, hydraulically or electrically. Well-known examples of these types of control are: electronic proportional control, pressure control (zero stroke control), power control.

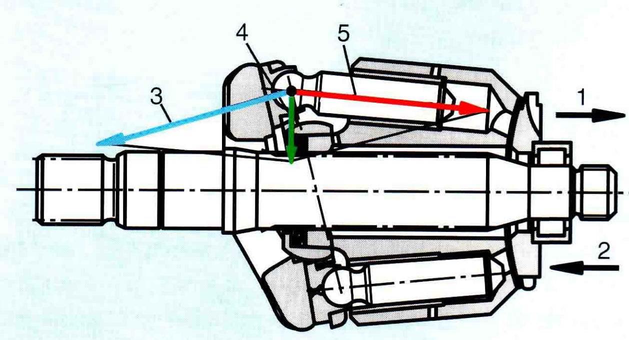
2.2.2.5 General

Pumps and motors in the swashplate design are suitable for use in open and closed loop circuits. Due to their design, they are mainly used as pumps in closed loop circuits. The advantage in this is that it is possible to mount auxiliary or additional pumps on the through drive and to make use of the integrated design of adjustment device and valves. In addition, this compact, space and weight saving unit is capable of having a long life, as the slipper pads are on hydrostatic bearings (plain bearings). The force resolution (piston forces/torque) is via the slipper pad on the swashplate. The hydraulic part of the rotary group, i.e. the cylinder block with piston and control plate forms part of a balanced force system. The drive shaft bearings are able to absorb external forces. The principle of the spherical control surface, its lubrication, the pre-tensioning of the cylinder block via plate springs, etc. is comparable to the function of the bent axis rotary group.

2.2.3 Rotary group forces

Representation in force parallelogram of a variable displacement unit

The resolution of the forces takes place at the swashplate in the slipper pads and cylinder block. The piston slipper pads have hydrostatic bearings and hence ensure that the rotary groups have a long service life.



1	High pressure	**4**	Torque (drive force)
2	Low pressure (suction pressure)	**5**	Piston force (high pressure force)
3	Bearing force (support force)		

Fig. 15: *Swashplate design with fixed or variable swivel angle*

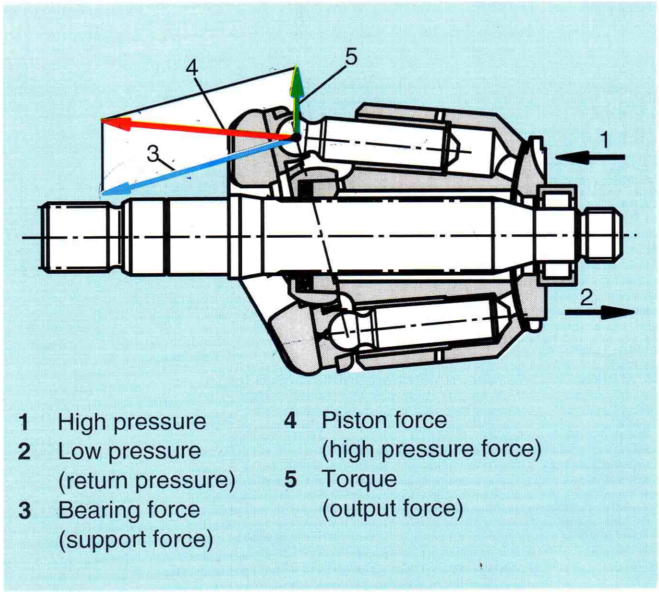


Fig. 19: *Resolution of forces at the swashplate of a motor*

2.2.4 Swashplate rotary group
(simplified representation)

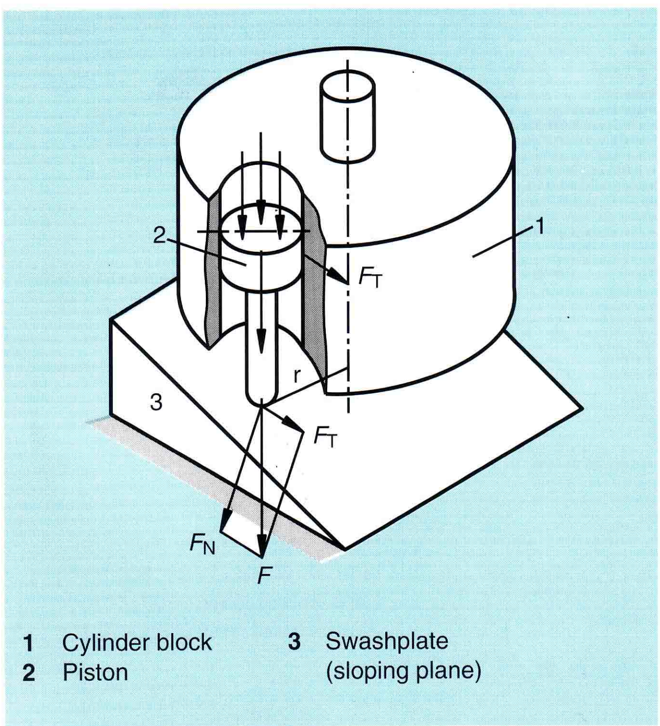


Fig. 20: *Basic components of swashplate rotary group*

2.2.4.1 Swashplate rotary group operating as a motor

As explained in the functional description, the piston is fed fluid from the pump and hence pushed against the sloping surface.

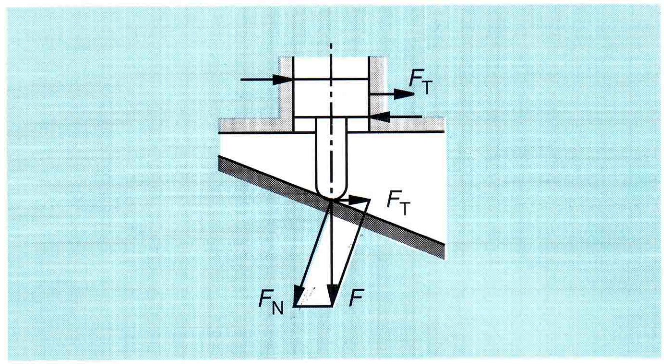


Fig. 21: *Resolution of forces*

Resolving the forces at the point of contact (friction bearing) with the sloping surface, a bearing force and a torque force component (F_N and F_T) are obtained. The piston slides down the sloping surface, carries out a stroke movement and in so doing takes the cylinder block and drive shaft along with it. However, as the piston can tilt (as far as the clearance allows) in the cylinder block bore, a greater frictional resistance occurs at the moment the unit is started than during a normal stroke movement (stick/slip). This double resolution of forces is the reason for the slightly lower initial efficiency of the swashplate as compared with the simple resolution of forces of the bent axis. In practice, this initial efficiency may be important in motor operation, but not in pump operation.

2.2.5 Types

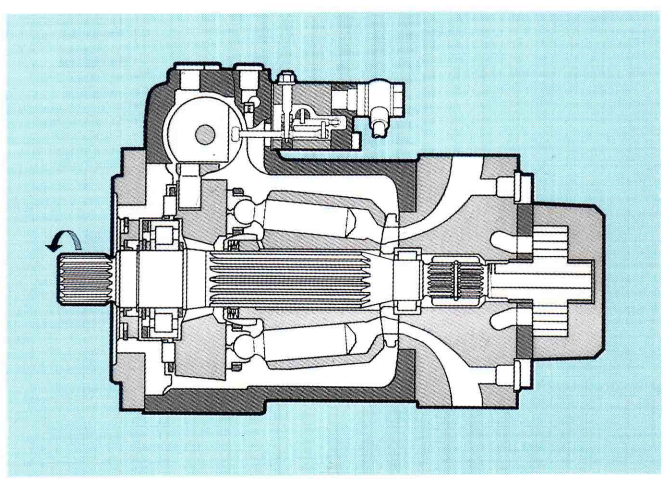


Fig. 22: *Variable displacement pump for closed loop circuit, type A4VG*

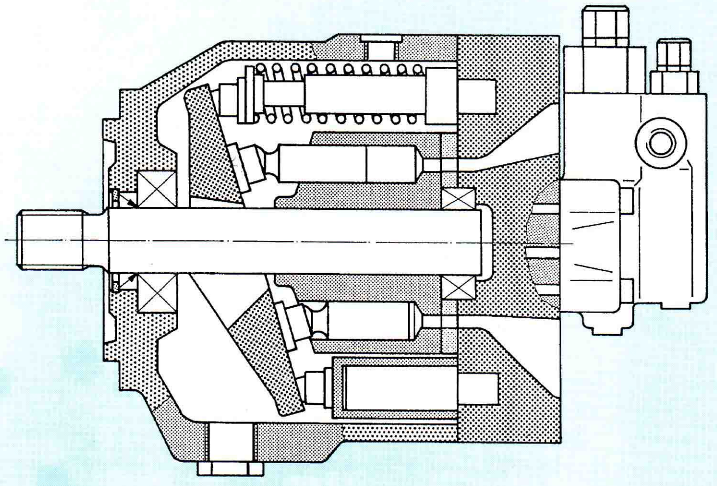


Fig. 23: *Variable displacement pump for open loop circuit, type A10VO*

2.2.6 Symbols

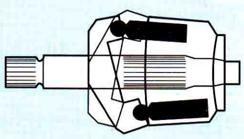
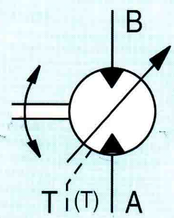
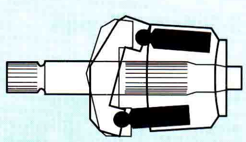
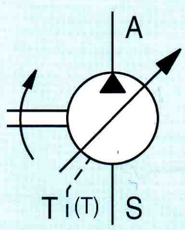
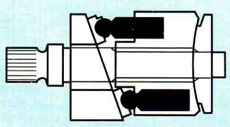
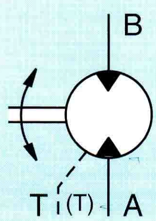
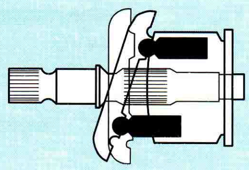
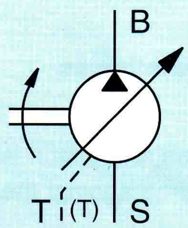
Type	Schematic diagram	Symbol	Description
Variable displacement pump, type A4VG			Variable displacement pump for closed loop circuit, angles may be changed on both sides, swivel angle smoothly adjusted through zero position, both output directions of rotation possible.
Variable displacement pump, type A4VO			Variable displacement pump for open loop circuit, angle may be changed on one side, swivel angle smoothly adjusted, single output direction of rotation possible.
Fixed displacement motor, type A4FM			Fixed displacement motor for open or closed loop circuit, fixed swivel angle, both output directions of rotation possible.
Variable displacement pump, type A10V			Variable displacement pump for open loop circuit, angle may be changed on one side, swivel angle smoothly adjusted, single output direction of rotation possible.

Fig. 24

2.2.7 Basic calculations for axial piston units in swashplate design

Determination of pump size	Fixed displacement pump	Variable displacement pump
Flow in L/min	$Q = \frac{V_g \cdot n \cdot \eta_{vol}}{1000}$	$Q = \frac{V_{g\,max} \cdot n \cdot \tan\alpha \cdot \eta_{vol}}{1000 \cdot \tan\alpha_{max}}$
Speed in rpm	$n = \frac{Q \cdot 1000}{V_g \cdot \eta_{vol}}$	$n = \frac{Q \cdot 1000 \cdot \tan\alpha_{max}}{V_{g\,max} \cdot \eta_{vol} \cdot \tan\alpha}$
Drive torque in Nm	$M = \frac{V_g \cdot \Delta p}{20 \cdot \pi \cdot \eta_{mh}} = \frac{1{,}59 \cdot V_g \cdot \Delta p}{100 \cdot \eta_{mh}}$	$M = \frac{V_{g\,max} \cdot \Delta p \cdot \tan\alpha}{20 \cdot \pi \cdot \eta_{mh} \cdot \tan\alpha_{max}}$ $= \frac{1{,}59 \cdot V_{g\,max} \cdot \Delta p \cdot \tan\alpha}{100 \cdot \eta_{mh} \cdot \tan\alpha_{max}}$
Drive power in kW	$P = \frac{2 \cdot \pi \cdot M \cdot n}{60000} = \frac{M \cdot n}{9549}$ $P = \frac{Q \cdot \Delta p}{600 \cdot \eta_{vol} \cdot \eta_{mh}} = \frac{Q \cdot \Delta p}{600 \cdot \eta_t}$	$P = \frac{2 \cdot \pi \cdot M \cdot n}{60000} = \frac{M \cdot n}{9549}$ $P = \frac{Q \cdot \Delta p}{600 \cdot \eta_{vol} \cdot \eta_{mh}} = \frac{Q \cdot \Delta p}{600 \cdot \eta_t}$
Determination of motor size	Fixed displacement motor	Variable displacement motor
Flow in L/min	$Q = \frac{V_g \cdot n}{1000 \cdot \eta_{vol}}$	$Q = \frac{V_{g\,max} \cdot n \cdot \tan\alpha}{1000 \cdot \eta_{vol} \cdot \tan\alpha_{max}}$
Speed in rpm	$n = \frac{Q \cdot 1000 \cdot \eta_{vol}}{V_g}$	$n = \frac{Q \cdot 1000 \cdot \eta_{vol} \cdot \tan\alpha_{max}}{V_{g\,max} \cdot \tan\alpha}$
Drive torque in Nm	$M = \frac{V_g \cdot \Delta p \cdot \eta_{mh}}{20 \cdot \pi} = \frac{1{,}59 \cdot V_g \cdot \Delta p \cdot \eta_{mh}}{100}$	$M = \frac{V_{g\,max} \cdot \Delta p \cdot \eta_{mh} \cdot \tan\alpha}{20 \cdot \pi \cdot \tan\alpha_{max}}$ $= \frac{1{,}59 \cdot V_{g\,max} \cdot \Delta p \cdot \eta_{mh} \cdot \tan\alpha}{100 \cdot \tan\alpha_{max}}$
Drive power in kW	$P = \frac{2 \cdot \pi \cdot M \cdot n}{60000} = \frac{M \cdot n}{9549}$ $P = \frac{Q \cdot \Delta p}{600} \cdot \eta_{vol} \cdot \eta_{mh} = \frac{Q \cdot \Delta p \cdot \eta_t}{600}$	$P = \frac{2 \cdot \pi \cdot M \cdot n}{60000} = \frac{M \cdot n}{9549}$ $P = \frac{Q \cdot \Delta p}{600} \cdot \eta_{vol} \cdot \eta_{mh} = \frac{Q \cdot \Delta p \cdot \eta_t}{600}$

Table 1

Where:

Q	= flow	in L/min
M	= drive torque (pump) output torque (motor)	in Nm in Nm
P	= drive power (pump) output power (motor)	in kW in kW
V_g	= geometric stroke volume	in cm³
$V_{g\,max}$	= max. geometric stroke volume	in cm³
n	= speed	in rpm
α_{max}	= max. swivel angle (various depending on type)	in °
α	= set swivel angle (may be between 0° and α_{max})	in °
η_{vol}	= volumetric efficiency	
η_{mh}	= mechanical-hydraulic efficiency	
η_t	= total efficiency ($\eta_t = \eta_{vol} \cdot \eta_{mh}$)	
Δp	= pressure drop	in bar

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2.2.8 Basic calculations for axial piston units in bent axis design

Determination of pump size	Fixed displacement pump	Variable displacement pump
Flow in L/min	$Q = \frac{V_g \cdot n \cdot \eta_{vol}}{1000}$	$Q = \frac{V_{g\,max} \cdot n \cdot \sin\alpha \cdot \eta_{vol}}{1000 \cdot \sin\alpha_{max}}$
Drive speed in rpm	$n = \frac{Q \cdot 1000}{V_g \cdot \eta_{vol}}$	$n = \frac{Q \cdot 1000 \cdot \sin\alpha_{max}}{V_{g\,max} \cdot \eta_{vol} \cdot \sin\alpha}$
Drive torque in Nm	$M = \frac{V_g \cdot \Delta p}{20 \cdot \pi \cdot \eta_{mh}} = \frac{1{,}59 \cdot V_g \cdot \Delta p}{100 \cdot \eta_{mh}}$	$M = \frac{V_{g\,max} \cdot \Delta p \cdot \sin\alpha}{20 \cdot \pi \cdot \eta_{mh} \cdot \sin\alpha_{max}}$ $= \frac{1{,}59 \cdot V_{g\,max} \cdot \Delta p \cdot \sin\alpha}{100 \cdot \eta_{mh} \cdot \sin\alpha_{max}}$
Drive power in kW	$P = \frac{2 \cdot \pi \cdot M \cdot n}{60000} = \frac{M \cdot n}{9549}$ $P = \frac{Q \cdot \Delta p}{600 \cdot \eta_{vol} \cdot \eta_{mh}} = \frac{Q \cdot \Delta p}{600 \cdot \eta_t}$	$P = \frac{2 \cdot \pi \cdot M \cdot n}{60000} = \frac{M \cdot n}{9549}$ $P = \frac{Q \cdot \Delta p}{600 \cdot \eta_{vol} \cdot \eta_{mh}} = \frac{Q \cdot \Delta p}{600 \cdot \eta_t}$
Determination of motor size	Fixed displacement motor	Variable displacement motor
Flow in L/min	$Q = \frac{V_g \cdot n}{1000 \cdot \eta_{vol}}$	$Q = \frac{V_{g\,max} \cdot n \cdot \sin\alpha}{1000 \cdot \eta_{vol} \cdot \sin\alpha_{max}}$
Output speed in rpm	$n = \frac{Q \cdot 1000 \cdot \eta_{vol}}{V_g}$	$n = \frac{Q \cdot 1000 \cdot \eta_{vol} \cdot \sin\alpha_{max}}{V_{g\,max} \cdot \sin\alpha}$
Output torque in Nm	$M = \frac{V_g \cdot \Delta p \cdot \eta_{mh}}{20 \cdot \pi} = \frac{1{,}59 \cdot V_g \cdot \Delta p \cdot \eta_{mh}}{100}$	$M = \frac{V_{g\,max} \cdot \Delta p \cdot \eta_{mh} \cdot \sin\alpha}{20 \cdot \pi \cdot \sin\alpha_{max}}$ $= \frac{1{,}59 \cdot V_{g\,max} \cdot \Delta p \cdot \eta_{mh} \cdot \sin\alpha}{100 \cdot \sin\alpha_{max}}$
Output torque in kW	$P = \frac{2 \cdot \pi \cdot M \cdot n}{60000} = \frac{M \cdot n}{9549}$ $P = \frac{Q \cdot \Delta p}{600} \cdot \eta_{vol} \cdot \eta_{mh} = \frac{Q \cdot \Delta p \cdot \eta_t}{600}$	$P = \frac{2 \cdot \pi \cdot M \cdot n}{60000} = \frac{M \cdot n}{9549}$ $P = \frac{Q \cdot \Delta p}{600} \cdot \eta_{vol} \cdot \eta_{mh} = \frac{Q \cdot \Delta p \cdot \eta_t}{600}$

Table 2

Where:

Q	= flow	in L/min
M	= drive torque (pump) output torque (motor)	in Nm in Nm
P	= drive power (pump) output power (motor)	in kW in kW
V_g	= geometric stroke volume	in cm^3
$V_{g\,max}$	= max. geometric stroke volume	in cm^3
n	= speed	in rpm
α_{max}	= max. swivel angle (varies depending on model)	in °
α	= set swivel angle (may be between 0° and α_{max})	in °
η_{vol}	= volumetric efficiency	
η_{mh}	= mechanical-hydraulic efficiency	
η_t	= total efficiency ($\eta_t = \eta_{vol} \cdot \eta_{mh}$)	
Δp	= pressure drop	in bar

3 Components

3.1 Fixed displacement motors and pumps - bent axis design

Features:

- Direct drive of cylinder block block via tapered pistons
- Tapered pistons with piston rings for sealing
- Robust tapered roller bearings with long lives
- Flange and shaft ends to ISO or SAE standard
- Two drain case ports as standard
- Direct mounting of deceleration valve possible
- Model variations for special applications
- Nominal pressure of up to 400 bar
- Peak pressure of up to 450 bar

3.1.1 Fixed displacement motor

This unit may be used as a motor in both open and closed loop circuits. It is used in mobile and stationary industrial applications, that is, wherever a constant displacement is required for hydrostatic power transfer.

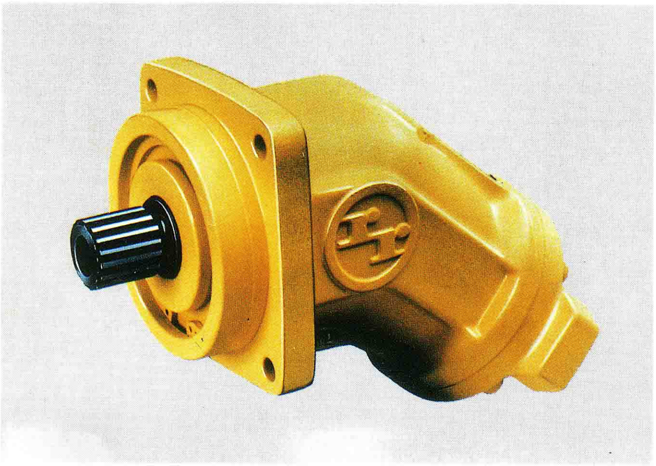


Fig. 25: *Fixed displacement motor, type A2FM*

3.1.2 Fixed displacement pump

The A2FM pump may be converted into an A2FO pump via a suitable port plate. This is suitable for the open loop circuit and its main features are: robust, reliable, long life and low noise (not illustrated).

3.1.3 Fixed displacement pumps for lorries

This pump has special characteristics and connection dimensions suitable for use in trucks. It is designed for a pressure range of 250 to 350 bar. If a change in the direction of rotation is required (e.g. with a different gear box), the direction of rotation of the drive may be changed for the pump in open loop by simply rotating the port plate.

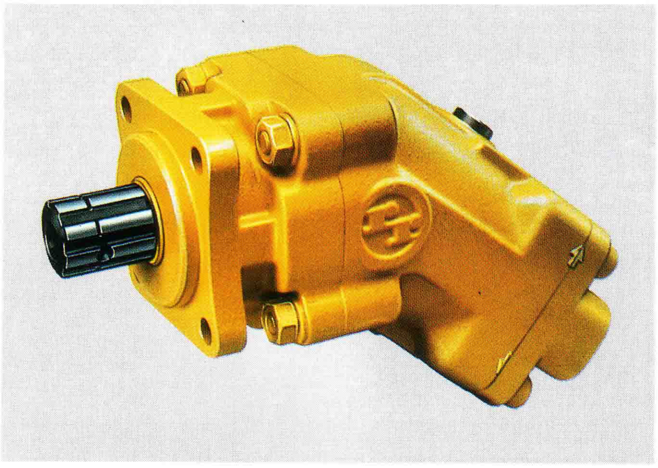


Fig. 26: *Fixed displacement pump for trucks, type KFA2FO*

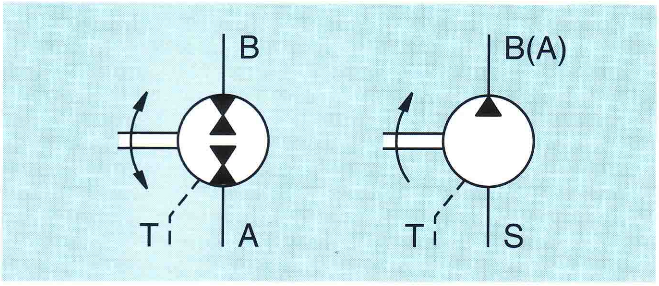


Fig. 27: *Left: Fixed displacement motor/pump for two directions of flow; Right: fixed displacement pump for one direction of flow*

3.2 Variable displacement motors in bent axis design for open and closed loop circuits

Features:

- A larger control range in hydrostatic drives due to the variable displacement motors
- Fulfilment of the requirement of higher speed and high torque
- Reduction of cost by saving on multi-ratio gear boxes or by possibly using smaller pumps
- Low power weight
- Good starting characteristic
- Various control and adjustment devices
- Single sided swivel action
- Nominal pressure is 400 bar
- Peak pressure is 450 bar

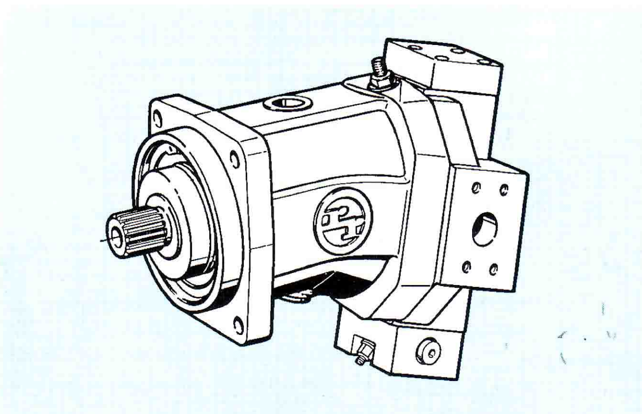


Fig. 28: Variable displacement motor, type A6VM...HA

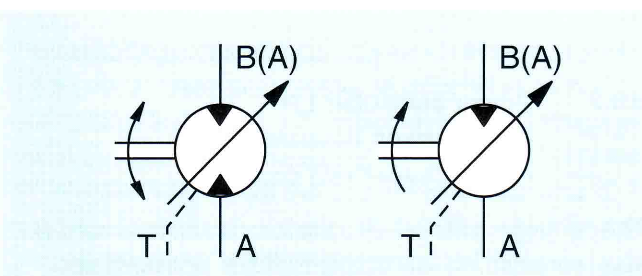


Fig. 29: *Left: Variable displacement motor for two directions of flow; Right: For one direction of flow*

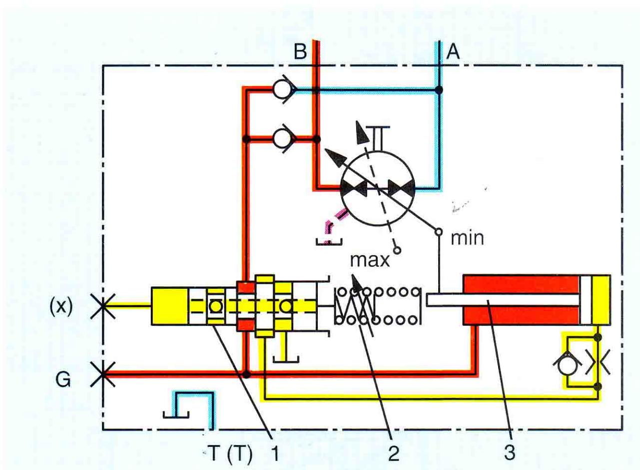
3.2.1 Automatic adjustment device, dependent on high pressure

The A6VM variable displacement motor has a rotary group which operates to the bent axis principle. Torque is produced direct at the drive shaft. The cylinder block is directly driven by the tapered pistons. The rotary group swivel angle is changed by moving the control lens along a circular track via a positioning piston.

Given the condition that pump flow and high pressure must remain unchanged, the following is valid:

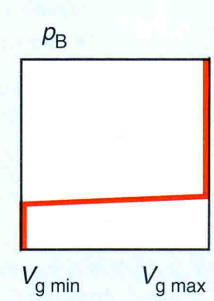
- As the angle is decreased, the speed increases and the possible torque decreases.
- As the angle is increased, the torque increases and the possible speed decreases.

The designation "HA" indicates that the adjustment of the motor is dependent on high pressure. The displacement is automatically set, dependent on the operating pressure. Once the operating pressure set at the control valve has been reached (measured internally at A or B), the motor switches over from V_{gmin} to V_{gmax}. The motor remains at the minimum swivel angle below the set value.



1 Control valve **2** Setting spring
3 Positioning cylinder (positioning piston)

Fig. 30: *High pressure dependent adjustment device*



p_B = operating pressure V_g = geom.stroke volume

Diagram 1: *Automatic adjustment dependent on high pressure*

3.3 Variable displacement pump in bent axis design for open loop circuits

Features:

- Axial tapered piston rotary group
- Direct drive of cylinder block block via tapered pistons
- Robust long life bearings
- Flow setting from V_{g0} to V_{gmax}
- Power control with exact hyperbolic operating curve
- Pressure control, hydraulic and electrical adjustment units, load sensing operation possible
- High pressure range up to 350/400 bar
- Used in mobile and industrial applications

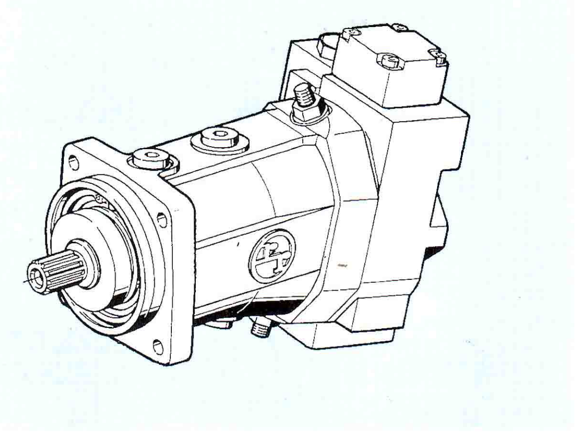


Fig. 31: *Variable displacement pump, type A7VOLR, with power controller built into the port plate*

3.3.1 Application in high pressure range

The A7VO variable displacement pump is a pump with internal leakage oil return for open loop circuits. The rotary group operating to the bent axis principle combines robustness and good self-aspiration. The drive shaft bearings are used to support external forces. If high requirements are made on the input of forces and on the running time, a rotary group is available with extra bearings (A7VTO).

The rotary group swivel angle may be changed by moving the control lens along a circular track via a positioning piston.

If the swivel angle is increased, the pump flow and the required drive torque increase.

If the swivel angle is decreased, the pump flow and the required drive torque decrease. The maximum swivel angle is, for example, 25 or 26.5°; the minimum is 0°. The pump is controlled dependent on the operating pressure or adjusted via external control signals. The required positioning energy is taken from the pressure side.

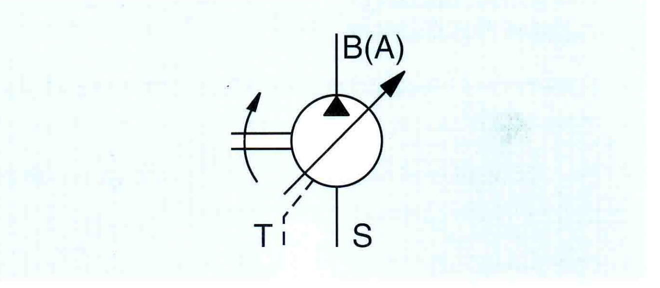
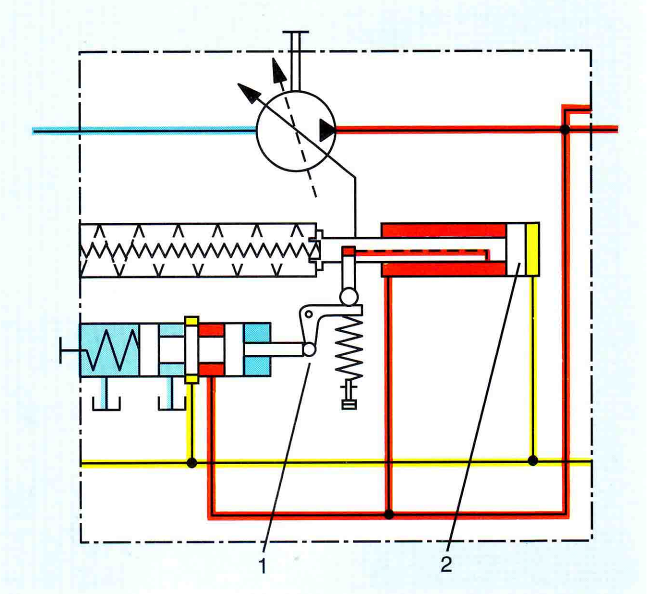


Fig. 32: *Variable displacement pump for 1 direction of flow*



1 Power controller **2** Positioning cylinder (piston)

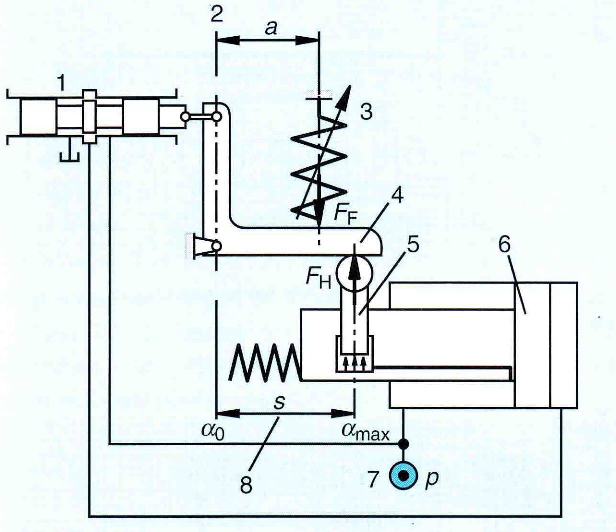
Fig. 33: *Variable displacement pump with power controller*

3.3.2 Power controller LR (Comparison between spring control/hyperbola control)

The controller ensures that the torque *M* (Nm) received is kept constant. In connection with a constant speed *n* (rpm), the function power control is obtained. The mechanical drive power $P = M \bullet n$ (kW) is opposed by the hydraulic output power $P = Q \bullet p$ (kW). Whilst the operating pressure *p* (bar) is dependent on the load, the flow *Q* (L/min) may be changed by the swivel angle.

Similarly to a computer, the controller continually multiplies pressure and flow and compares the result with the set value. If a positive deviation occurs the swivel angle is decreased and if a negative deviation occurs this angle is increased. The controller may be set (srewing in of the setting screw = rising set value).

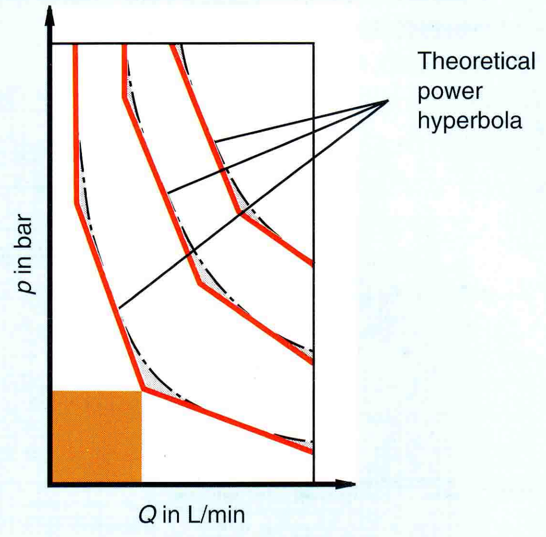
Control is started at the max. swivel angle. The position when control is finished is given by the maximum pressure. In addition, deviating from this, both end values may be limited by strop screws. Be careful: if the maximum set angle is increased there is danger of cavitation in the pump and danger of overspeeding in the motor! If the minimum set angle is increased the drive motor may be overloaded in the high pressure range.



1 Control valve
2 Lever arm (fixed)
3 Spring force (adjustable)
4 Rocker
5 Measuring piston
6 Positioning cylinder with positioning piston
7 Operating pressure
8 Swivel angle
Lever arm (variable)

Fig. 34: *Power controller*

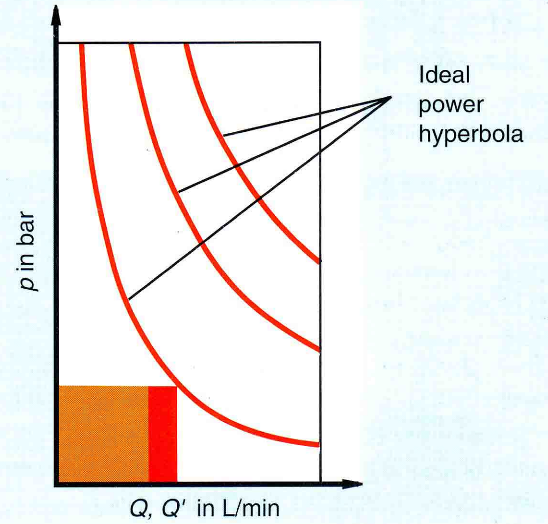
The operating pressure acts on a rocker in the positioning piston via a measuring piston. In opposition to this is a spring force (externally set), which determines the power set. If the operating pressure p exceeds the calculated permissible value from the power calculation $P = Q \cdot p$ (kW), the control valve is operated via the rocker and the pump is returned. The flow is reduced until the product of $Q \cdot p$ corresponds to the power available again. The ideal hyperbola has been reached and the drive is not overloaded due to the "power control". Conversely, the pump flow, depending on the operating pressure, may be increased to its max. value via a return spring.



Hydraulic power: $P = Q \cdot p$ in kW = constant

Diagram 2: *p-Q operating curve for a spring controller with aproximate operating curve*

Features:
- Power matching via exchange of spring package
- Slight power losses in shaded regions
- No zero stroke position, i.e. residual flow at high pressure produces heat



Hydraulic power: $P = Q' \cdot p$ in kW = constant

Diagram 3: *p-Q operating curve for a hyperbolic controller with ideal hyperbolic operating curve*

Features:
- Optimum power matching via external smooth adjustable spring force
- Zero stroke position, i.e. no residual flow

3.3.3 Double variable displacement pump with 2 parallel bent axis rotary groups

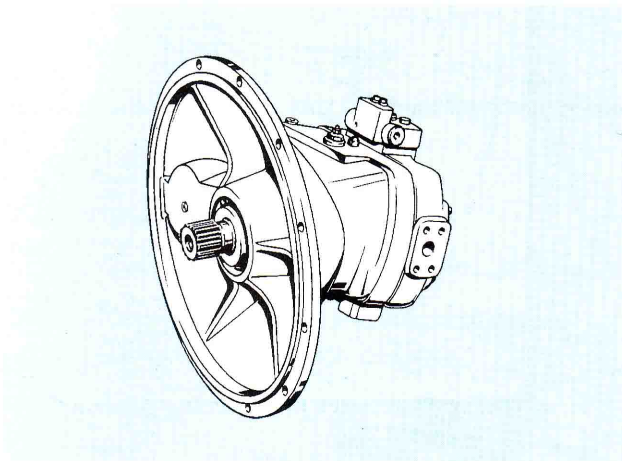


Fig. 35: *Variable displacement pump A8VO...SR with summation power controller*

Two variable displacement pumps - one drive.
This is an advantageous combination of two individual pumps with integral splitter box.

At present, models with an auxiliary drive and/or auxiliary pump for the supply of additional hydraulic circuits are the standard ones used, especially in mobile applications.

To complement the power control of an individual pump (see A7VLR, *fig. 34*), in two parallel circuits the A8VSR pump with summation power control (for example) is installed. This means that the complete drive power is distributed to both circuits in the ratio of their pressures.

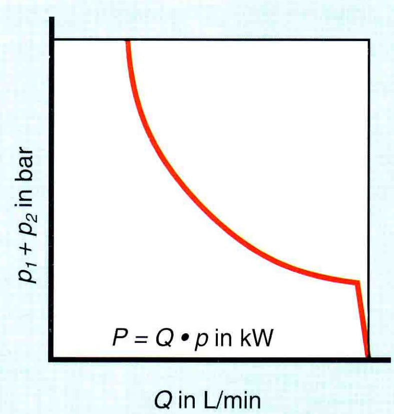
The high pressure signal produced in the summator valve is used as a measurement value.

The ideal hyperbolic power operating curve is attained, once the torque forces acting on the rocker of the power controller are balanced.

The hydraulic torque, formed from the high pressure force F_H and the angular displacement s, is only allowed to be as large as the mechanical torque obtained from the set spring force F_F and the fixed lever arm *a*.

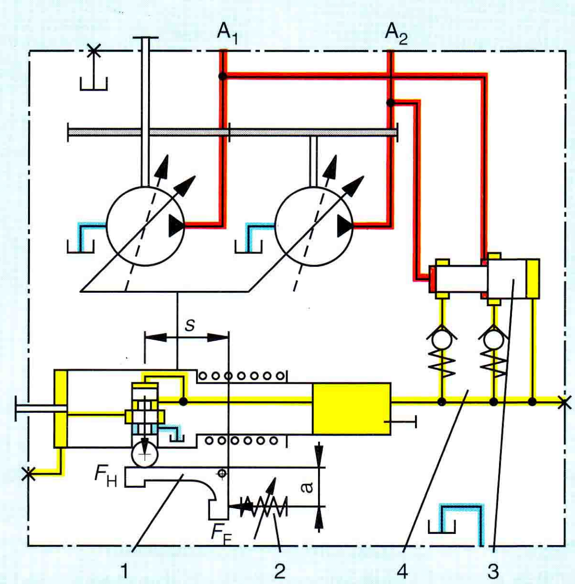
As the hydraulic system sets the operating pressure p and the pump can only change its flow Q, this means that when the power is exceeded the pump swivel angle is automatically reduced. The angular displacement is decreased until the hydraulic torque obtained from it is the same as the given mechanical torque.

In practice, individual or combined controls are used. Common variations are e.g. load limiting control, 3 point control, load sensing, etc.



Q = flow
p_1 = operating pressure of 1st pump at A1
p_2 = operating pressure of 2nd pump at A2

Diagram 4: *p-Q operating curve for summation power controller, hyperbolic controller*



1 Power controller, hyperbolic controller
2 Spring force (adjustable)
3 Summation valve $p_1 + p_2$
4 Measured high pressure signal

Fig. 36: *Double variable displacement pump with summation power controller*

3.4 Variable displacement pump in bent axis design for universal applications

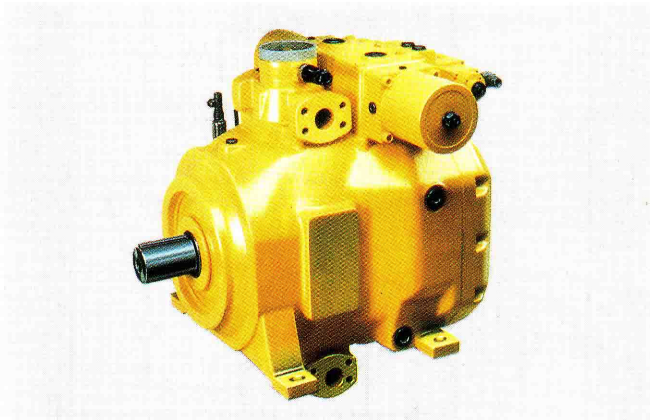


Fig. 37: *Variable adjustment pump, type A2V*

The A2V variable displacement pump is universally suitable for use in open, closed and semi-closed loop circuits. A variety of controls for varying the displacement are available. The variations with tandem roller bearings or slipper pad bearings (for extremely long bearing lives) are especially preferred for industrial applications. By fitting the A2V with valves and auxiliary pumps, it is turned into the primary power unit A2P.

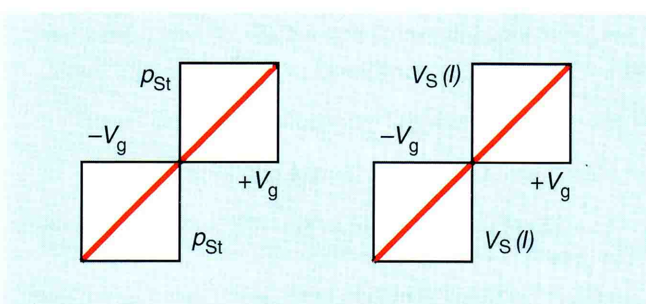


Diagram 5: *Characteristic curves of hydraulic adjustments, left: dependent on pilot pressure, right: dependent on flow (pilot flow)*

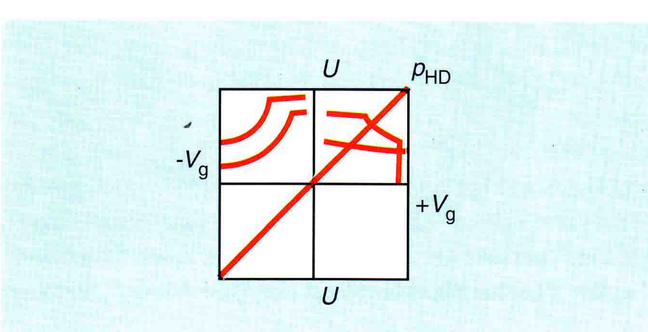


Diagram 6: *Characteristic curve of an electronic adjustment*

3.5 Variable displacement pump in swashplate design suitable for use in medium pressure range in open loop systems

The A10V axial piston pump is used in mobile and industrial fields for pressures of 250/315 bar. The variable displacement pump has the advantage over the fixed displacement pump of saving energy, e.g. by the automatic matching to force (pressure) and velocity (flow) via a combined pressure and feed flow controller.

The advantage of the swahplate design lies not only in the compact design, but also in the low power weight, long life and low noise level. The possibility of mounting further pumps on the through drive must not be neglected as an important feature.

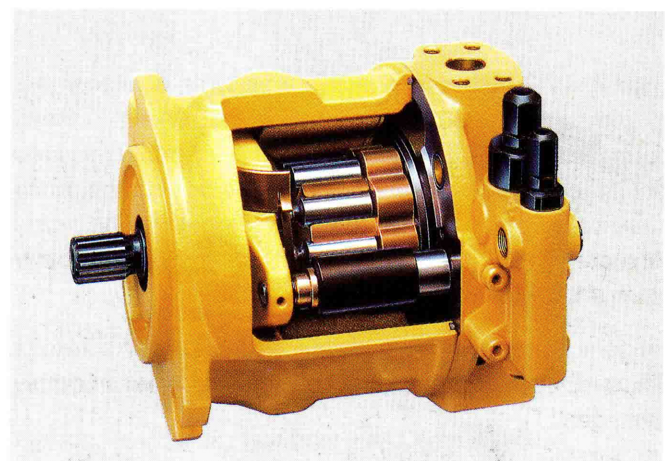


Fig. 38: *Variable displacement pump, type A10VO...DFR*

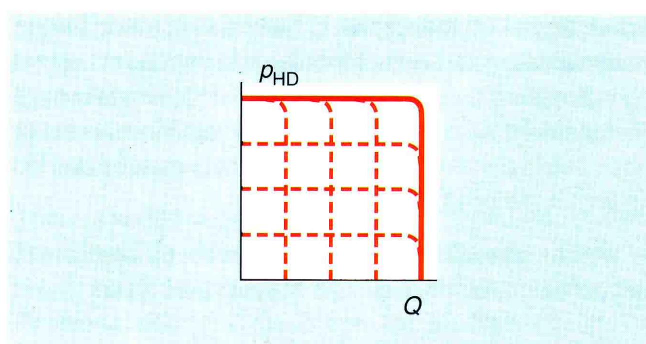


Diagram 7: *Characteristic curve of pressure/feed flow controller*

Legend to diagrams 5, 6 and 7

V_g = stroke volume
p_{HD} = operating pressure
p_{St} = pilot pressure
I = pilot current
U = pilot voltage
V_s = positioning volume
Q = flow

3.6 Variable displacement pump in swashplate design suitable for use in simple mobile applications in closed loop systems

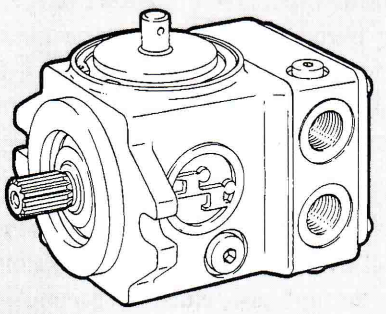


Fig. 39: *Variable displacement pump, type A11VG*

The A11VG hydraulic pump is a variable displacement pump in swahplate design for hydrostatic drives in closed loop circuits. All the valves and auxiliary pump required for it are integrated. Depending on the design, the pump may easily be converted to a multiple pump. The rotary group swivel angle may be directly changed by a rotary stub shaft without power amplification.

In zero position the pump flow is also zero. As zero is passed through, the direction of flow is smoothly changed.

If the rotary stub shaft is manually adjusted, it is directly connected to the bent axis of the rotary group. The angle of rotation of the rotary stub shaft corresponds to the swivel angle of the pump. The displacement torque produced either by hand or foot force is dependent on the high pressure and swivel angle. The limitation of displacement or angle in the positioning mechanism or the possible centring of the zero position must be carried out within the positioning mechanism.

As well as manual adjustment of the rotary stub shaft, hydraulic control mechanisms may also be used.

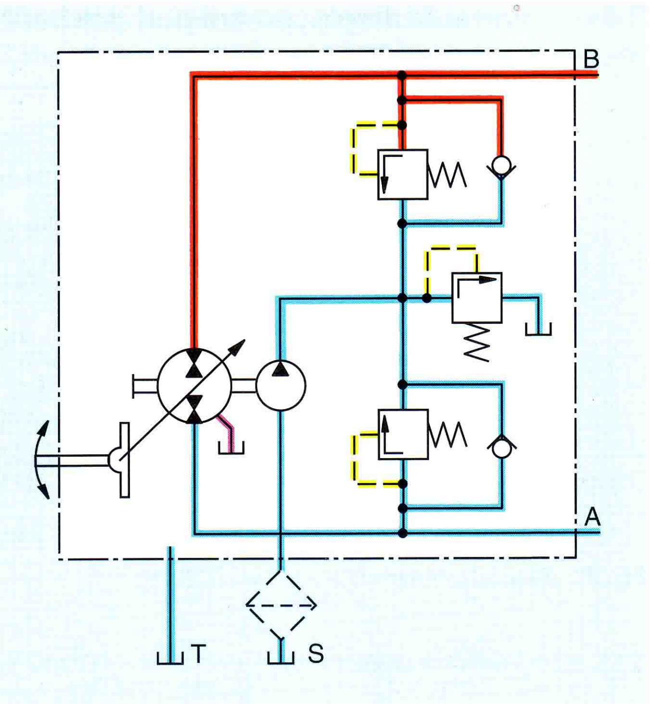


Fig. 40: *Variable displacement pump with adjustment, auxiliary pump and valves*

3.7 Variable displacement pump in swashplate design suitable for use in mobile applications in open loop systems

The control functions of the A4VO shown here may be either operated as combined or individual functions:

- Power control with hyperbolic operating curve
- Pressure control by means of isolating valve
- Load sensing control as Δp control of load pressure signal

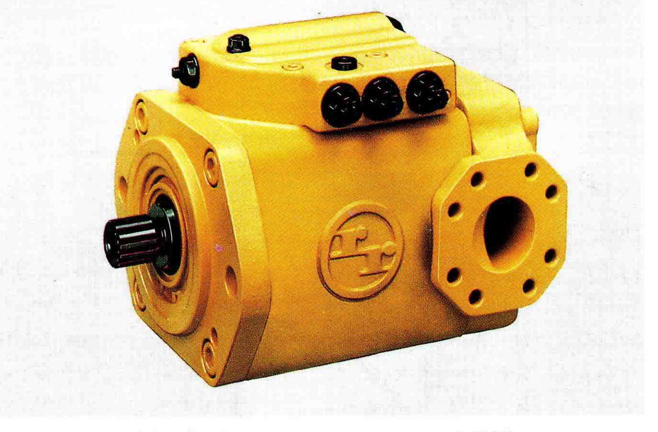


Fig. 41: *Variable displacement pump, type A4VO*

3.7.1 Power controller

The power controller controls the flow of the pump dependent on the operating pressure, so that a set drive power at constant drive speed is not exceeded.

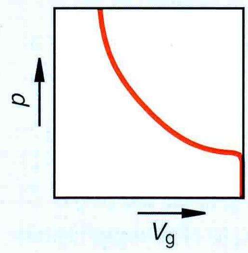


Diagram 8: *Characteristic curve of a power controller*

3.7.2 Pressure controller

The effect of pressure control is to return the pump towards $V_g = 0$ on reaching the max. operating pressure. This function is superimposed on power control.

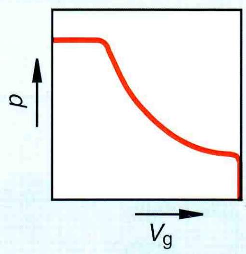


Diagram 9: *Characteristic curve of a power controller with superimposed pressure contol*

3.7.3 Load sensing controller

The load sensing controller operates as a load pressure driven flow consumption controller and matches the pump flow to the flow required from the user. The pump flow is dependent on the opening area of the directional valves, but is not effected by the load pressure in the region below the power operating curve. The power and pressure control are super-imposed on the load sensing function.

Legend to diagrams 8,9 and 10:
p = operating pressure
V_g= geom. stroke volume

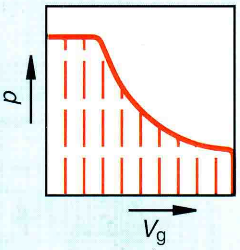


Diagram 10: *Characteristic curve of load-sensing controller*

3.8 Variable displacement pump in swashplate design suitable for use in high pressure mobile gears in closed loop systems

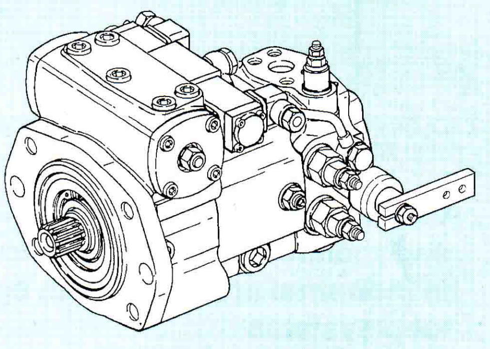


Fig. 42: *Variable displacement pump, type A4VGDA*

Similarly to that described under section 3.6, the pump A4VG is a complete power unit comprising all the components for a closed loop circuit. The unit with hydraulic adjustment with various control devices forms the typical "mobile pump". If this pump is connected to a fixed or variable displacement motor, an automatic vehicle transmission is produced.

This is a speed dependent automatic closed loop system. The pump is effected by the drive speed, operating pressure and electrically by the 2 switching solenoids. Positional energy is taken from the auxiliary circuit. The positional velocity of the pump is damped by throttles.

The speed dependent automatic control system is designed for transmission drives with internal combustion engines. It was taken into account that in internal combustion engines as the speed increases the torque increases and if the engine is loaded a speed pull-down occurs at the torque limit. The power consumption of an internal combustion engine is sufficiently accurately determined by its current speed. If the hydraulic side is suitably adapted, an optimum controlled vehicle transmission is produced.

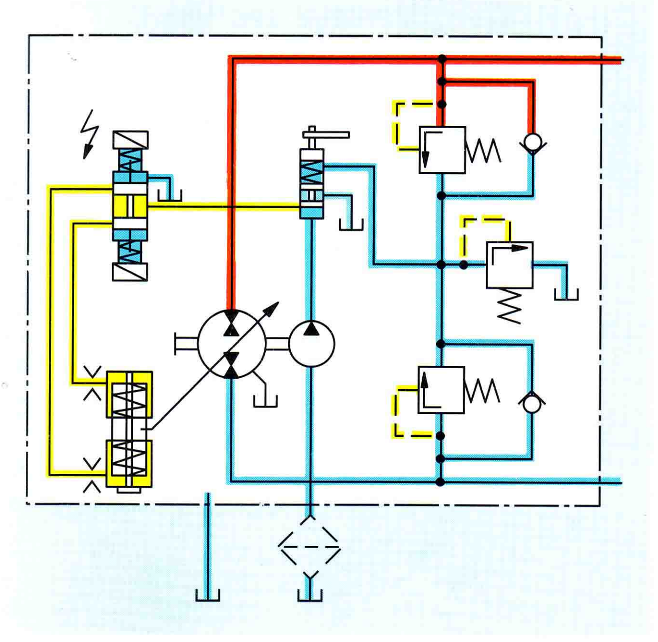


Fig. 43: *Variable displacement pump with adjustment, auxilliary pump and valves*

3.9 Variable displacement pump in swashplate design suitable for use in industrial applications in open loop systems

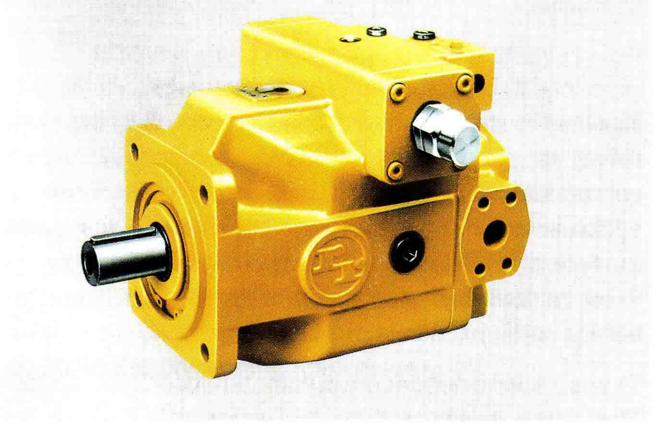


Fig. 44: *Variable displacement pump, type A4VSO*

This A4VSO pump especially designed for industrial applications has, in addition to the well-known advantages of swashplate design, also the advantage of long service life. Load sensing control and mooring control as well as secondary control may be used with this pump. In connection with a pressure controlled pump and its secondary controlled motor the system of secondary speed control has a high dynamic control response, exact speed control, low losses and energy recovery.

The speed control DS1 controls the adjustment unit so that the required torque is available for the speed demanded.

This torque (under conditions of quasi-constant pressure) is proportional to the displacement volume and hence proportional to the swivel angle.

The swivel angle (position) is measured by an inductive positional transducer and the speed is measured by a tachogenerator.

3.10 Variable displacement pump in swashplate design suitable for use in industrial applications in closed loop systems

Another variable displacement pump in swashplate design is mounted on the unit described in section 3.9, but this unit operates in a closed loop circuit.

When used in industrial applications the A4VSG pump may be made into a complete hydraulic drive with suitable adaption via a valve subplate, auxiliary pump, tank and cooler. It is also possible to create a semi-closed loop circuit by including anti-cavitation check valves. By using these valves it is possible to compensate for the difference in volumes, e.g. in operations using single-rod cylinders.

Fig. 45: *Variable displacement pump, type A4VSG*

3.11 Summary of common adjustment methods in axial piston units

The electronic components (amplifiers) which are used as signal amplifiers are not mentioned in the following list:

The differences between the various types of adjustment are as follows:

- Type of control circuit
- Force transmission (hydraulic or mechanical)
- Operation (direct or pilot)
- Operating curve (position and setting)
- Open loop (without feedback)
  - mechanical: manual
  - mechanical: electrical
  - hydraulic: mechanical
  - hydraulic: electrical
  - hydraulic: hydraulic
- Closed loop (with feedback)
  - hydraulic: mechanical
  - hydraulic: electrical

3.11.1 Pump adjustments

Mechanical-manual,
Displacement volume proportional to displacement *s* at adjustment MA;
proportional to adjustment angle *β* at adjustment MD

Mechanical-electrical,
Displacement volume proportional to displacement *s* at adjustment EM

V_g = specific displacement volume
s = displacement
β = adjustable angle

Manual adjustment MA | Mechanical stub shaft adjustment MD | Electric motor adjustment EM

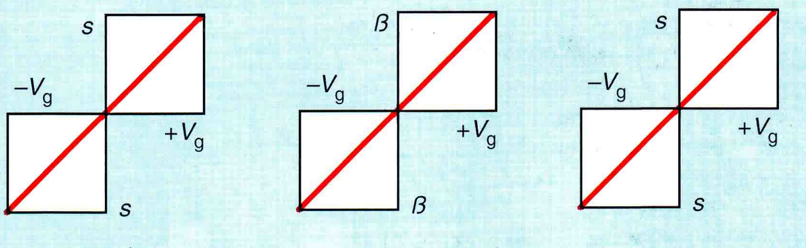


Diagram 11

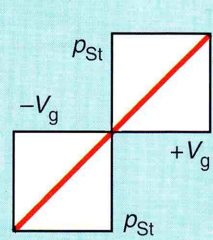
Hydraulic-mechanical,
Displacement volume
proportional to pilot pressure p_{St}
at adjustment DG;

proportional to swivel angle β
or displacement s
(in pumps with reversible operation)
at adjustment HW

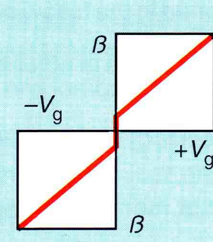
V_g = specific displacement volume
p_{St} = pilot pressure
β = swivel angle

1) = idle range at zero position

Direct operated
hydraulic adjustment
pressure dependent DG



Hydraulic
adjustment
stroke dependent HW [1]



Hydraulic
adjustment
stroke dependent HW

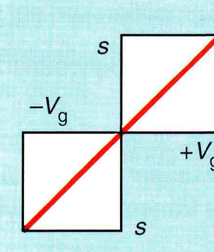


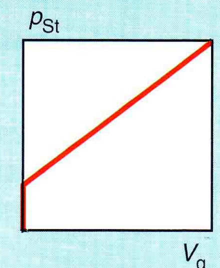
Diagram 12

Hydraulic-hydraulic,
Displacement volume
proportional to pilot pressure p_{St}
at adjustment HD
for pumps in open loop circuits or
reversible operation

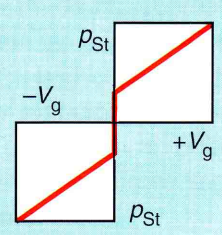
V_g = specific displacment volume
p_{St} = pilot pressure

1) = idle range at zero position

Hydraulic
adjustment
pressure dependent HD



Hydraulic
adjustment
pressure dependent HD [1]



Hydraulic
adjustment
pressure dependent HD

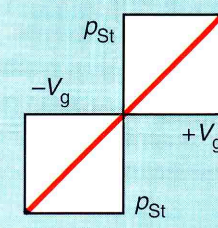
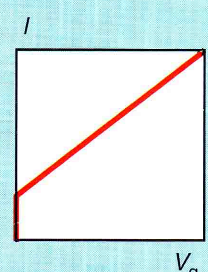


Diagram 13

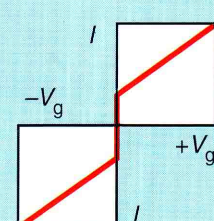
Hydraulic-electronic,
Displacement volume
proportional to pilot current I
at adjustment EP and ES in open loop circuits or reversible operation;
Adjustment EZ (with switching solenoid)
(no diagram)

V_g = specific displacment volume
I = pilot current

Electronic adjustment
with prop. solenoid
EP



Electronic adjustment
with prop. solenoid
EP



Electronic adjustment
with servo valve
ES

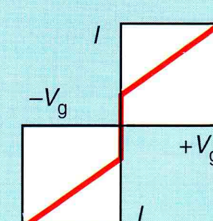


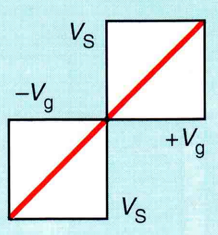
Diagram 14

Hydraulic-dependent on flow,
Displacement volume
proportional to
positioning oil flow V_S,
Reversible operation
at adjustment HM;

Electronic-hydraulic,
Displacement volume
proportional to pilot current I
at adjustment HS,
Reversible operation
with mounted servo valve

V_g = specific displacement volume
I = pilot current
V_S = positioning oil flow

Hydraulic adjustment
dependent on flow
HM



Hydraulic adjustment
with servo valve
HS

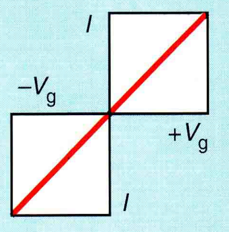


Diagram 15

Hydraulic-dependent on flow,
Displacement volume
proportional to pilot voltage U
with mounted proportional valve,
Reversible operation,
with electronic amplifier,
Control possible

V_g = specific displacement volume
U = pilot voltage
p_{HD} = high pressure

Electronic
adjustment EO

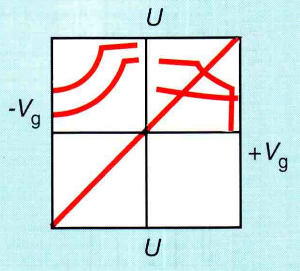


Diagram 16

3.11.2 Pump controls

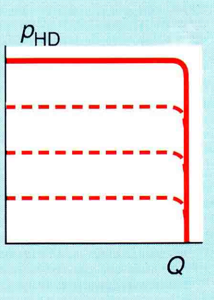
Hydraulic,
Pressure controller DR
System pressure is held constant, flow is matched.

Flow controller FR
Flow is held constant, even at varying system pressures.

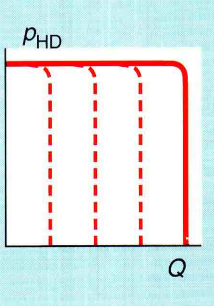
Pressure and flow controller DFR
Pressure and flow are held constant dependent on actuator.

Q = flow
p_{HD} = high pressure

Pressure controller
DR



Flow controller
FR



Pressure and
flow controller DFR

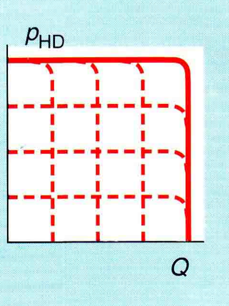


Diagram 17

Hydraulic,
Power regulator LR
Power consumption is held constant.
Power = torque x speed
$P = M \cdot n =$ constant

Summated power controller SR
In parallel operation of two pumps with a drive motor, power is automatically distributed according to the summated pressure.

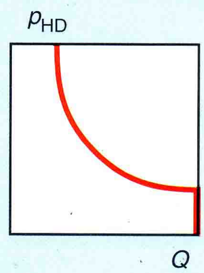
Pressure, flow and power controller DFLR
A power controller is superimposed on the combined pressure and flow controller.

Pressure controller with load sensing DRS
A pressure controller is superimposed on the load sensing controller. The set flow is held constant by the controller.

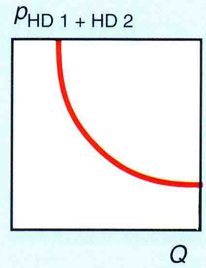
Power controller with pressure cut-off and load sensing LRDS
In connection with a power controller the max. drive torque is limited. Pump flow is changed dependent on the actuator.

Q = flow
p_{HD} = high pressure

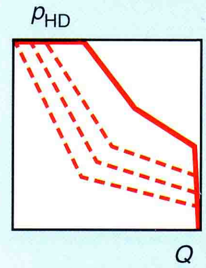
Power controller
LR



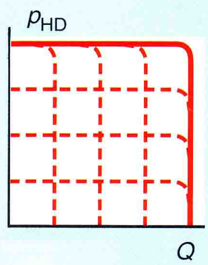
Total power controller
SR



Pressure, flow
and power controller
DFLR



Pressure controller with
load sensing DRS



Power controller with
pressure cut-off and
load sensing LRDS

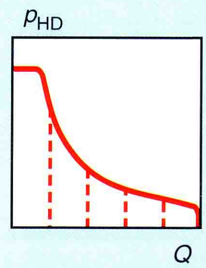


Diagram 18

Electronic
Pressure and flow controller DFE
Pressure and flow are held constant by electronic means dependent on the actuator.

Q = flow
p_{HD} = high pressure
↯ = electrical signal

Electronic pressure
flow controller
DFE

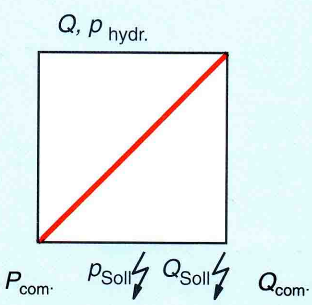


Diagram 19

3.11.3 Motor adjustments

Hydraulic-hydraulic,
Hydraulic adjustment dependent on pilot pressure HD
Displacement proportional to pilot pressure p_{St}

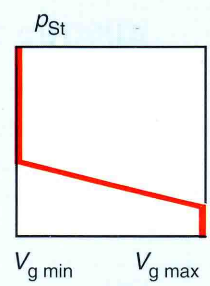
Hydraulic two point adjustment HZ

Hydraulic-electronic,
Electronic adjustment with proportional solenoid EP
Displacement proportional to the pilot current *I*

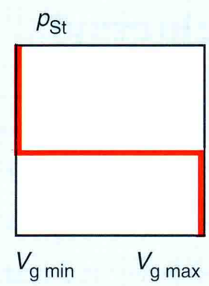
Displacement with switching solenoid EZ

V_g = specific displacement volume
p_{St} = pilot pressure
I = pilot current

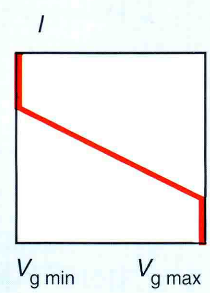
Hydraulic adjustment dependent on pilot press. HD



Hydraulic two point adjustment HZ



Electronic adjustment with prop. solenoid EP



Electronic adjustment with switching solenoid EZ

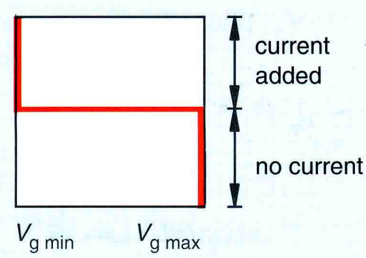


Diagram 20

3.11.4 Motor controls

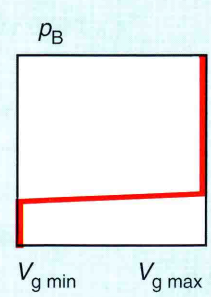
Hydraulic,
Automatic, dependent on high pressure Control HA
The motor automatically matches itself to the required torque.

Secondary controlled speed control DS
In secondary control, pumps with DS controller are used as motors.

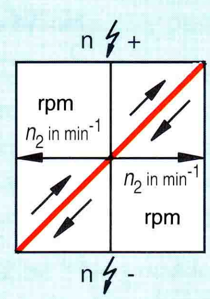
Hydraulic controller DA dependent on pressure
This type of control is the basis of an automotive controlled mobile drive

V_g = geometric stroke volume
p_B = operating pressure
n = speed

Automatic control dependent on high press. HA



Speed control, secondary control DS



Hydraulic control, dependent on speed DA

Diagram 21