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# ASPECTS RELATED TO AXIAL PISTON PUMP OPERATION WITHIN A HYDRAULIC CIRCUIT

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***Abstract:*** *An axial piston pump is a type of positive displacement pump that uses multiple pistons arranged axially in a circular array around a rotating shaft to displace fluid. This design allows for high-pressure operation, making it popular in hydraulic systems for applications such as construction machinery, aircraft hydraulics, and industrial equipment. Basic assembly components of an axial piston pump are represented by cylinder rotating block which contains the pistons and rotates with the drive shaft, a set of pistons that move inside the cylinder block's bores, swash-plate (angled plate) as a tilted plate that controls the stroke of the pistons by dictating their reciprocating motion, a drive shaft which transmits rotational motion to the cylinder block, valve stationary plate with ports for the inlet and outlet of the fluid and it controls the fluid flow into and out of the cylinder block. For variable displacement pumps, the swash-plate angle can be adjusted in order to control the pump's displacement. The efficient design makes axial piston pumps widely used in various industries where high-pressure and variable flow control is required. The basic parameters and the principle of operation are described in this work for axial piston pumps. The mathematical model describing the operation is also presented, as well as a numerical approach in order to highlight the operating characteristics.*

***Keywords:*** *Hydraulic actuation, axial piston pump, swash plate, bent-axis, fluid flow rate, operational parameters, numerical analysis*

## 1. Introduction

The axial pistons pump works based on the reciprocating motion of pistons as they move within the bores of the rotating cylinder block. The drive shaft (usually powered by an electric motor or engine) rotates the cylinder block, which contains multiple pistons axially positioned parallel to the shaft's axis. As the cylinder block rotates, each piston follows the angle of the swash-plate, which is fixed at a certain inclination. The swash-plate causes the pistons to move back and forth within the cylinder block. As the piston moves away from the valve plate (upstroke), the volume inside the piston chamber increases, creating suction that draws hydraulic fluid into the chamber through the inlet port of the valve plate. As the piston moves toward the valve plate (down stroke), the volume inside the piston chamber decreases, forcing the hydraulic fluid out through the outlet port of the valve plate. This cycle of suction (inlet) and discharge (outlet) happens continuously as the cylinder block rotates. In a variable displacement axial piston pump, the swash-plate's angle can be adjusted, so a greater swash-plate angle means a higher piston stroke, resulting in higher displacement (more fluid flow rate pumped per rotation), while a reduced swash-plate angle means a shorter piston stroke, resulting in lower displacement. Zero value of inclination angle means that the pistons do not reciprocate, and the pump essentially stops displacing fluid. This feature allows for control over the flow rate of the pump, making it highly versatile in hydraulic applications where the fluid flow needs to vary. The main constructive and functional axial piston types are as variable displacement which allows control over the flow rate by adjusting the swash-plate angle, providing flexibility and efficiency and as fixed displacement where the swash-plate angle is fixed, meaning the pump delivers a constant amount of fluid flow rate per revolution. In a fixed displacement axial piston pump, the swash-plate angle is fixed, meaning the pump has a constant displacement volume for every revolution of the cylinder block.

The flow rate in this type of pump is dependent on the rotational speed (RPM) of the drive shaft and cannot be adjusted without changing the pump's speed. In terms of efficiency and operation

considerations must be presented the high pressure capability as axial piston pumps can generate high-pressure output 40-45 MPa, making them ideal for demanding hydraulic systems.
Variable displacement versions allow precise control of flow, making them suitable for energy-efficient operations. These pumps are highly efficient due to their positive displacement mechanism and ability to maintain steady pressure. The main applications of axial piston pumps are related to construction equipment for hydraulic systems in excavators, bulldozers, and cranes, aircraft hydraulics for control surfaces, landing gear, and braking systems, industrial machinery like presses, injection moulding machines and hydraulic motors and also marine and offshore equipment for steering systems and deck machinery.

## 2. Constructive variants of fixed displacement axial piston pumps

Both constructive variants considered have different designs and operating principles, but they achieve similar outcomes in terms of converting mechanical energy into hydraulic energy.
In swash plate volumetric unit, the pistons are arranged in a circular pattern within a rotating cylinder block, while the pistons have a translational movement within the special bores.
The pistons are connected to the swash plate angled relative to the cylinder block.
As the cylinder block rotates, the angle of the swash plate causes the pistons to reciprocate. The angle of the swashplate determines the piston stroke. During half of the rotation, the pistons move outward (suction stroke), and during the other half, they move inward (discharge stroke), creating flow of hydraulic fluid.

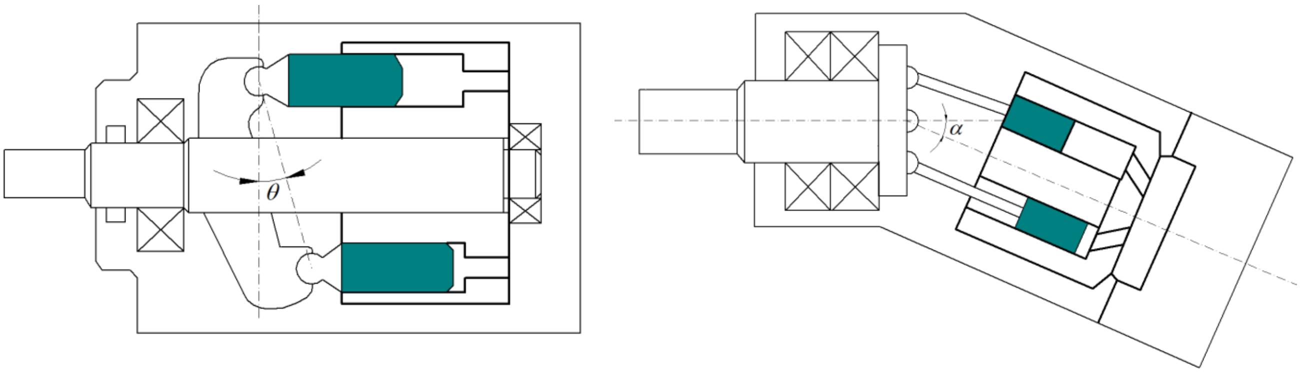


**Fig. 1.** Fixed displacement axial piston pump variants (swash plate and bent axis)

In a bent axis pump, the pistons are also arranged in a circular pattern, but the cylinder block is oriented at an angle to the drive shaft (bent axis).
The pistons are directly connected to the drive shaft via piston rods. As the shaft rotates, the angle between the drive shaft and the cylinder block causes the pistons to reciprocate within the bores.
The reciprocating action of the pistons results in the suction and discharge of hydraulic fluid.

## 3. Mathematical model for axial piston pump constructive variants

For a swash plate axial piston pump, the pistons move linearly in and out of the cylinders as the rotating cylinder block is driven by the drive shaft. The swash plate angle value determines the pistons stroke, which in turn controls the pump's displacement and flow rate values.
At a bent-axis axial piston pump, the cylinder block is positioned at an angle relative to the drive shaft axis, so the pistons are connected to the drive shaft by means of a universal joint and during operation, as the block rotates, the pistons are pushed in and out of the cylinder. [1-7]

Both models share some similarities, as they both depend on parameters such as the number of pistons$(n)$, piston diameter$(d_p)$, angular velocity$(\omega)$, and displacement$(V_r)$. However, the swash plate pump uses a swash plate angle *θ*, while the bent-axis pump uses the bent angle *α*.

The key parameters can be calculated using the following equations for piston stroke $(l_c)$, displacement per revolution $(V_r)$, flow rate $(Q_p)$ and torque $(T_p)$:

$$l_c = 2r\sin(\theta) \tag{1}$$

$$V_r = n \cdot A_p \cdot l_c \tag{2}$$

$$Q_p = \frac{\omega}{2\pi} \cdot V_r = \frac{\omega}{2\pi} \cdot \frac{\pi \cdot n \cdot d_p^2}{4} \cdot 2r\sin(\theta) = \frac{n \cdot d_p^2 \cdot r \cdot \omega \cdot \sin(\theta)}{4} \tag{3}$$

$$T_c = \frac{n \cdot d_p^2 \cdot p \cdot r \cdot \sin(\theta)}{8} \tag{4}$$

The flow rate will be directly proportional to the swash plate angle *θ*, the pump shaft angular velocity *ω* and the piston diameter. For the torque value it is considered the pressure force acting on the piston head and also the moment with the distance *r* between the pistons position.
For the bent axis constructive variants the parameter equations are as follows:

$$l_c = 2r\sin(\alpha) \tag{5}$$

$$V_r = n \cdot A_p \cdot l_c = \frac{n \cdot \pi \cdot d_p^2}{4} \cdot 2r \cdot \sin(\alpha) \tag{6}$$

$$Q_p = \frac{\omega}{2\pi} \cdot V_r = \frac{\omega}{2\pi} \cdot \frac{\pi \cdot n \cdot d_p^2}{4} \cdot 2r\sin(\alpha) = \frac{n \cdot d_p^2 \cdot r \cdot \omega \cdot \sin(\alpha)}{4} \tag{7}$$

$$T_c = \frac{n \cdot d_p^2 \cdot p \cdot r \cdot \sin(\alpha)}{8} \tag{8}$$

## 4. A numerical analysis for axial piston pump constructive variant

In order to model the axial piston pump operation, the time-varying dynamics of key physical parameters are considered, with focus on fluid flow rate, pressure, and displacement. The models are derived from the physical principles governing fluid mechanics, pressure-volume relations and the mechanicals of pistons movement (table 1).

**Table 1:** Axial pump modeling parameters

| Axial Piston Pump | | |
|---|---|---|
| | Swash Plate | Bent-Axis |
| State variables | $x(t) = \begin{bmatrix} p(t) \\ \theta(t) \\ \omega(t) \end{bmatrix}$ | $x(t) = \begin{bmatrix} p(t) \\ \alpha(t) \\ \omega(t) \end{bmatrix}$ |
| Hydraulic pressure dynamics | $\frac{dp(t)}{dt} = \frac{Q(t)}{C_t} - \frac{p(t)}{R_h}$ | |

| | | |
|---|---|---|
| Angle dynamics | $\frac{d\theta(t)}{dt} = -k_1 \cdot \theta(t) + k_2 \cdot u(t)$ | $\frac{d\alpha(t)}{dt} = -k_1 \cdot \alpha(t) + k_2 \cdot u(t)$ |
| Angular velocity dynamics | $\frac{d\omega(t)}{dt} = \frac{T_m(t) - T_h(t)}{J}$ | |

The derived state-space models for both the swash plate and bent-axis axial piston pumps can be solved numerically to simulate their behavior over time.
Initial conditions are based on the initial values for *p(0), θ(0)* or *α(0),* and *ω(0).*
The analysis model used a direct numerical simulation based on analytical expressions for sinusoidal motion, with a transient response factor.
The piston positions were calculated using a sinusoidal function corresponding to their periodic movement. This analytically method is using trigonometric functions to directly compute the displacement over time.
The transient behavior was modeled using an exponential term which was multiplied by the sinusoidal function to simulate a gradual increase in piston displacement.
The flow rate and pressure were computed directly from the piston displacement using arithmetic relations, assuming linear dependencies.
The simulation results would be the time-varying operation behaviour from pressure, fluid flow rate and position over time for each piston.
This numerical approach allows analyzing how the pump will respond under varying loads, control inputs, and operating conditions. The models can also be used for designing controllers or optimizing pump performance [8-10].
The obtained results are presented in figure 2, highlighting the swash plate constructive variant in 5 piston configuration design.

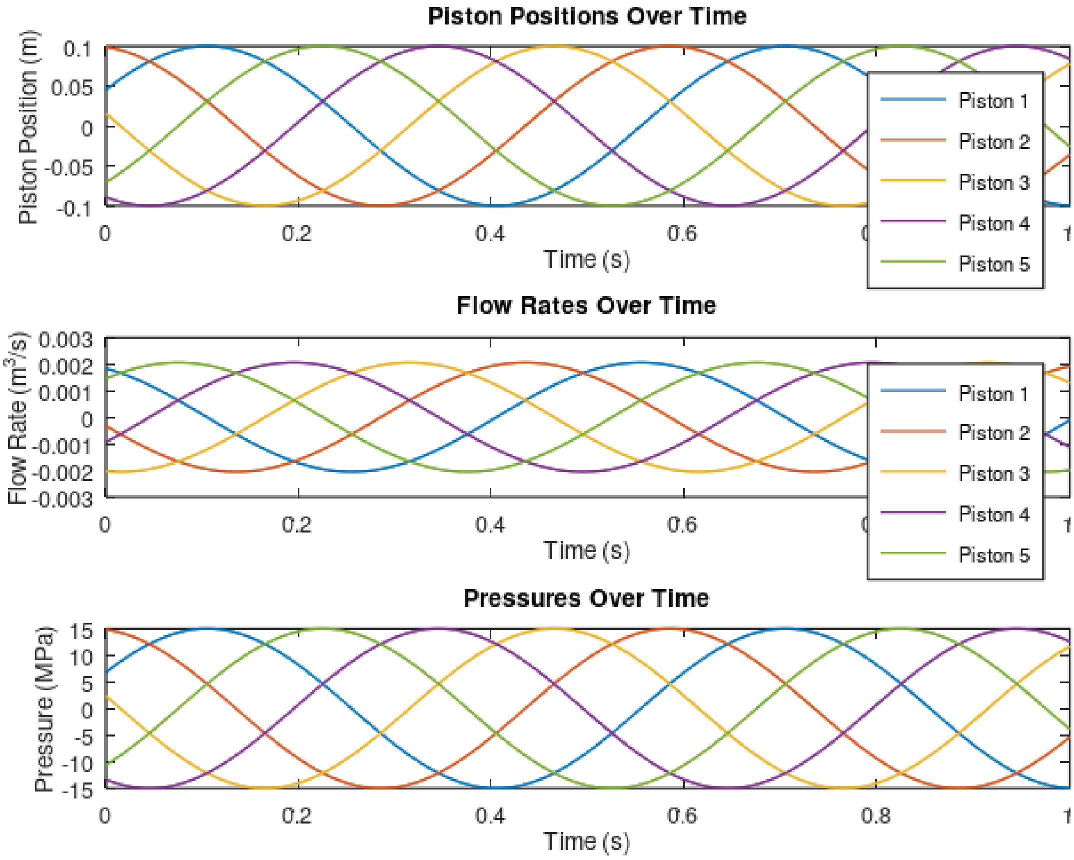


**Fig. 2.** The analysis results for the axial 5 piston pump

The numerical analysis method is providing solution especially when handling nonlinear dynamics such as those seen in the axial piston pump operation. The swash-plate angle is directly controlled by the time-varying control input, which in turn affects the pressure and angular velocity. The time-varying nature of the control input simulates real-world scenarios where the pump's swash-plate angle is adjusted in order to control the flow rate dynamically.
The bent-axis model behaves similarly to the swash plate model, but there are subtle differences regarding the pistons interaction with the shaft. The response of the pressure, angle and angular velocity encounter slight modification based on this geometry type.

## 5. Conclusions

The axial piston volumetric units are vital components in hydraulic systems due to their unique design and performance characteristics. These constructive variants are known for their high volumetric efficiency, which means they can transfer high amounts of hydraulic fluid with less energy loss and this efficiency is crucial for applications where power and energy conservation are important. They are commonly used in industrial machinery, construction equipment, aerospace, automotive applications, and other hydraulic systems. The pumps can handle high pressure levels, typically up to 450 bar (6,500 psi) and beyond, making them suitable for heavy-duty applications where substantial force is required, while this ability allows for compact and powerful system designs.
Many axial piston pumps come with variable displacement capabilities, allowing the user to adjust the output flow rate as needed and this adaptability provides better control over the hydraulic system, enhancing system responsiveness and efficiency.
The design of axial piston pumps is compact compared to other pump types, such as gear or vane pumps, making them suitable for applications where space and weight are critical factors.
Axial piston pumps offer smoother fluid flow and can be designed for low noise operation. This characteristic is especially beneficial in industrial settings where noise reduction is essential.
With proper maintenance, axial piston pumps can have a long service life. Their design enables high durability even under harsh operating conditions, making them cost-effective over time.
For the swash plate design, the pistons move linearly back and forth along a cylinder block due to the angled swash plate and the displacement is directly proportional to the swash plate angle.
The piston position follows a more regular sinusoidal pattern as it is driven directly by the rotation and the swash plate's fixed angle.
The flow rate will typically show a smoother sinusoidal pattern with less fluctuation between pistons.
In a bent-axis pump, the pistons are connected at an angle between the drive shaft and the cylinder block; the piston displacement depends of the bent axis angle and is driven by the rotation of the shaft. This can result in slightly different sinusoidal patterns for piston positions and flow rates due to the combined effect of the axis angle and rotational motion.
Variations in flow rate might be more pronounced due to the changing effective stroke over the pump cycle.
A constructive design axial volumetric unit swash plate with 5 pistons had been analyzed in this paper, highlighting the piston position, flow rate and pressure values corresponding to operation. The transient response was introduced in the models using an exponential term. This simulates the gradual stabilization of the pump's performance after starting up. The value of the time constant can significantly affect the initial behavior.
In both swash plate and bent-axis configurations, this transient effect shows a rise in flow rate, pressure, and piston positions, but the patterns of stabilization might slightly be different.
Swash plate pump tend to stabilize more uniformly due to the consistent motion induced by the swash plate, while the bent-axis variant may exhibit slight variations in transient behavior due to the varying effective stroke length at different piston positions over the cycle.

For swash plate volumetric units, the flow rate for each piston follows a consistent pattern because of the uniform driving mechanism.
Swash plate design offer more uniform sinusoidal behavior across piston positions, flow rates, and pressures.
The practical implications are that swash plate pumps are generally preferred for applications requiring smooth, consistent flow and pressure characteristics.
These values are related to the mechanical design of the pumps and become evident in simulations that account for transient behavior, displacement, and flow characteristics.

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