

# Driving Mechanism of Tapered Pistons in Bent-Axis Design Axial Piston Pumps

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In order to assure the quality of the bent axis design axial piston pumps driven by tapered pistons, it is necessary to know the characteristics of force applied to tapered pistons and the mechanism for driving the tapered pistons. Since they are able to perform both reciprocating and spinning motions in cylinder block, it is difficult to understand the driving mechanism and to measure the forces applied to tapered pistons experimentally. In the present study, the theoretical mechanism for driving the tapered pistons is studied by use of the geometric method. The driving area of the tapered pistons is measured by measuring the strain of a cylinder forced against a tapered piston using an electric strain gauge and a slip ring. The forces applied to tapered pistons is also investigated with the change of discharge pressure and the rotational speed. As a results of this investigation, it is concluded that the cylinder block is driven by one tapered piston in a limited area and the driving area is changed due to space angle of the tapered pistons and the swivel angle of the cylinder block. It is also observed that the force applied to tapered pistons increases as the discharge pressure and the rotational speed increase.

**Key Words :** Bent-Axis Design Axial Piston Pump, Tapered Piston, Driving Mechanism

## Nomenclature

$L$  : Length of tapered piston  
 $R_d$  : Pitch circle radius of disk  
 $R_c$  : Pitch circle radius of cylinder block  
 $R_{dc}$  : Distance between center of cylinder block and center of spherical bearing  
 $\alpha$  : Swivel angle of cylinder block  
 $\beta_0$  : Tilting angle of tapered piston  
 $\delta_0$  : Ahead · delay angle of spherical bearing in tapered piston  
 $\delta_0'$  : Ahead · delay angle in universal joint driving

$\delta_x$  : Clearance angle between tapered piston and cylinder  
 $\theta$  : Rotational angle from BDC  
 $\xi$  : Taper angle of tapered piston  
 $\varphi$  : Direction angle of tapered piston

## 1. Introduction

Oil hydraulic piston pumps can be classified according to an arrangement of a piston and the driving mechanism such as axial type, radial type, in-line type. Axial piston pumps are further divided into swash plate design or a bent-axis design. Bent-axis design axial piston pumps are able to control the power, pressure and the flow-rates by using a regulating system with high overall efficiency. Therefore, usage of the axial piston pumps is rapidly increasing due to their variable delivery characteristics, higher overall efficiency

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and higher working pressures despite the fact that axial piston pumps are more expensive than other type of pumps. As a result of this, axial piston pumps must be capable of meeting heavy demands.

Many researches have been carried out about axial piston pumps. Particularly, specialized design features to improve the action and the performance of the axial piston pumps were described by Franco (1961), Hibbert and Lindsay (1971). In addition to the extensive survey for various inventions related to these machines, an important study which is concerned with certain valve plate design techniques has been conducted by Shute and Turnbull (1963). Furthermore, many researches have been carried out for cylinder block/valve plate interface, swash plate/shoe interface of the major tribological parts in swash plate design axial piston pumps (Mckeown, et al., 1966; Tanaka, et al., 1994 and 1999). However, studies for the bent-axis design axial piston pumps have not received considerable attention in the recent years. Especially, the bent-axis design axial piston pump does not reveal in detail for driving mechanism.

Therefore, attempts have been made in this paper to study the driving mechanism of tapered pistons by using an experimental method and theoretical analysis in order to propose the design method of tapered pistons in bent-axis design axial piston pump driven by tapered pistons.

## 2. Theoretical Analysis

### 2.1 Driving mechanism of tapered pistons

Driving mechanism by a universal joint is based on a driving mechanism of the tapered pistons. Therefore, it is necessary to know a driving principle of the universal joint in bent-axis design axial piston pump before analyzing a mechanism for driving the tapered pistons. The universal joint type bent-axis design axial piston pump is connected by universal joint between a cylinder block and a shaft disk. The cylinder block of the bent-axis design axial piston pump driven by the universal joint is simultaneously rotated with the shaft disk. But, the cylinder block of the bent-axis

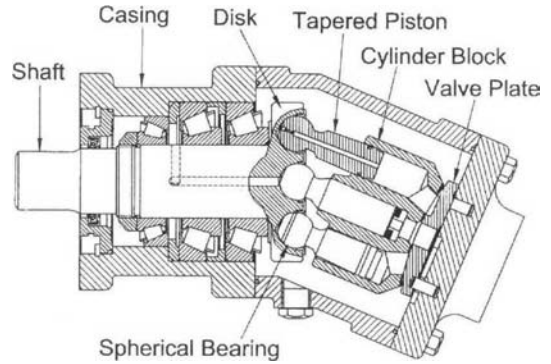


Fig. 1 Bent-axis design axial piston pump driven by tapered pistons

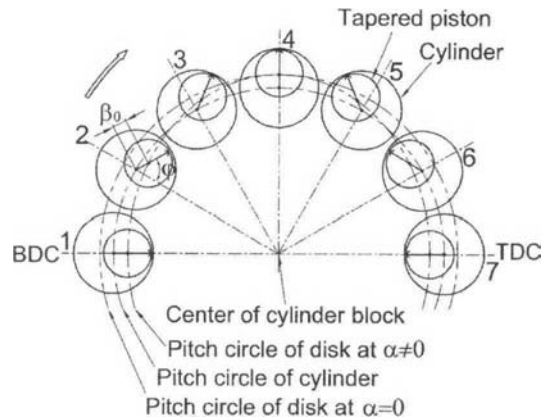
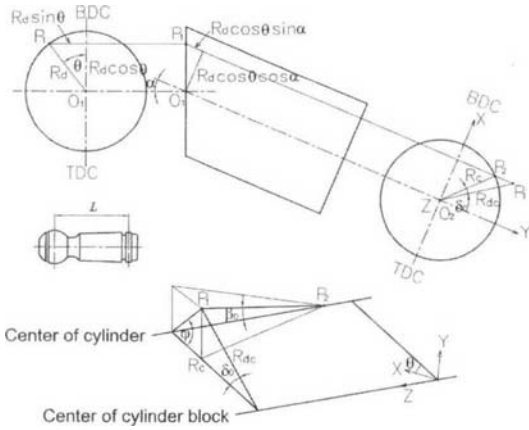


Fig. 2 Movement of tapered piston in a cylinder

design axial piston pump driven by tapered pistons is rotated differently from the rotating speed of the shaft disk.

Fig. 1 shows the bent-axis design axial piston pump driven by tapered pistons. If the swivel angle  $\alpha$  between the cylinder block and the shaft disk is not zero, the rotation of a shaft disk will display an elliptical motion as shown in Fig. 2. The direction angle of tapered pistons  $\varphi$  rotates in reverse direction to the shaft disk. When the shaft disk turns one rotation, the tapered pistons rotate two revolutions in the cylinder.

Fig. 3 shows the geometric relation to the shaft disk, tapered piston and the cylinder block when the cylinder block rotates simultaneously with the shaft disk in bent-axis design axial piston pump. Since a rotational motion of the shaft disk is elliptic, the shaft disk has a delay to cylinder



**Fig. 3** Geometric relations of the driving mechanism in bent-axis design axial piston pumps

block's motion (ahead · delay angle  $\delta_0$ ). If the shaft disk is rotated upto  $\theta$  at the swivel angle  $\alpha$ , the mathematical relation for  $\delta_0$ ,  $\varphi$ ,  $\beta_0$  will be given as follows :

$$R_{dc} = R_d \sqrt{\sin^2 \theta + (\cos \theta \cos \alpha)^2} \quad (1)$$

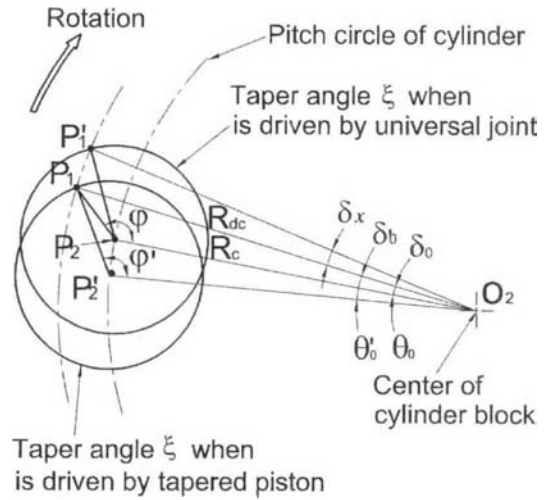
$$\delta_0 = \sin^{-1} \left( \frac{R_d \sin \theta}{R_{dc}} \right) - \theta \quad (2)$$

$$\varphi = \tan^{-1} \left( \frac{R_{dc} \sin \delta_0}{R_c - R_{dc} \cos \delta_0} \right) \quad (3)$$

$$\beta_0 = \sin^{-1} \frac{\sqrt{R_c^2 + R_{dc}^2 - 2R_c R_{dc} \cos \delta_0}}{L} \quad (4)$$

Fig. 4 shows a mechanism for driving the tapered pistons when the cylinder block is differently rotated with the rotational speed of the shaft disk in bent-axis design axial piston pump. The motion area of the tapered pistons is determined by  $L$ ,  $R_c$ ,  $R_d$  and  $\alpha$ . When the shaft disk is rotated upto  $\theta$  by tapered pistons, cylinder block is delayed equal to  $\delta_0$ . The distance between  $P_1$  and  $P_2$  becomes  $\overline{P_1 P_2} = L \sin \beta_0$ . The tapered piston will be the first contact at the location of  $P'_2$  in  $\overline{P_1 P'_2} = L \sin \xi$ . Therefore, the clearance angle between tapered piston and cylinder,  $\delta_x$ , is expressed as follows by geometric relations.

$$\begin{aligned} \delta_x &= \delta'_0 - \delta_0 \\ &= \cos^{-1} \frac{R_{dc}^2 + R_c^2 - (L \sin \xi)^2}{2R_c R_{dc}} - \delta_0 \end{aligned} \quad (5)$$



**Fig. 4** Driving mechanism of tapered pistons

## 2.2 Results of theoretical analysis

A variation of the clearance angle  $\delta_x$  with the swivel angle  $\alpha$  at  $\xi = 1.7^\circ$  are shown in Fig. 5 and Fig. 6. It is observed that the variation width of  $\delta_x$  is increased as the swivel angle  $\alpha$  increases. This reflects that the motion area of the tapered pistons grows larger as the swivel angle increases. The numbers (1~7) in Fig. 5 indicate the tapered pistons following the rotational direction from BDC. It is recognized that a shape of the  $\delta_x$  variation shows a regular trace like a sine function. The cylinder block is driven by the tapered pistons at the areas of the  $\delta_x$  minimum value. The tapered pistons of the driving area are changed to the next tapered piston step by step.

A variation of the clearance angle  $\delta_x$  with taper angle  $\xi$  at  $\alpha = 23^\circ$  is shown in Fig. 7. The minimum value of clearance angle is increased by the increase of the taper angle, because the cylinder block rotation is delayed more as the taper angle increases. The effect of the taper angle can be understood in more detail from Fig. 8. In this Fig. 8, the minimum value of  $\delta_x$  is increased as the taper angle increases and the start point of the driving area is also changed. The taper angle largely affects the driving mechanism of the cylinder block in bent-axis design axial piston pump driven by the tapered pistons. Therefore, it is concluded that the cylinder block is driven by one tapered piston in a limited area and the driving

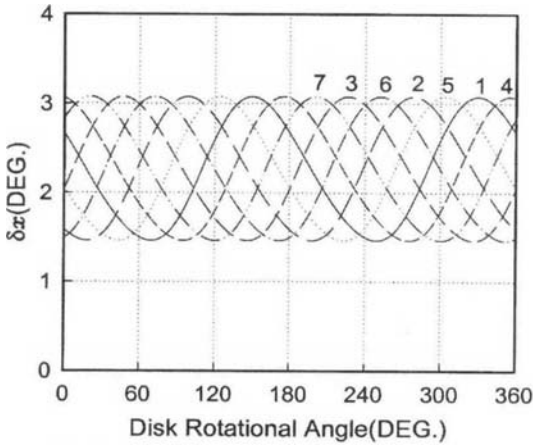


Fig. 5 Variations of  $\delta_x$  at  $\xi=1.7^\circ$ ,  $\alpha=12^\circ$

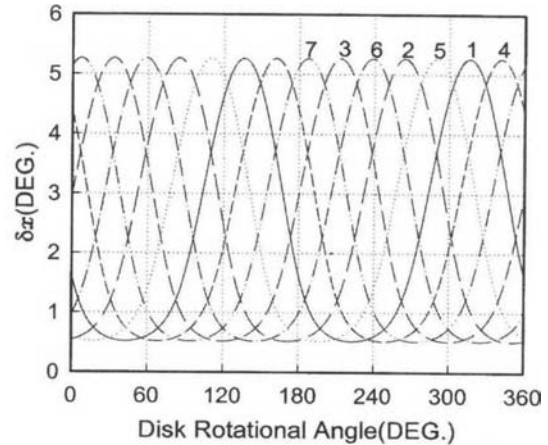


Fig. 6 Variations of  $\delta_x$  at  $\xi=1.7^\circ$ ,  $\alpha=23^\circ$

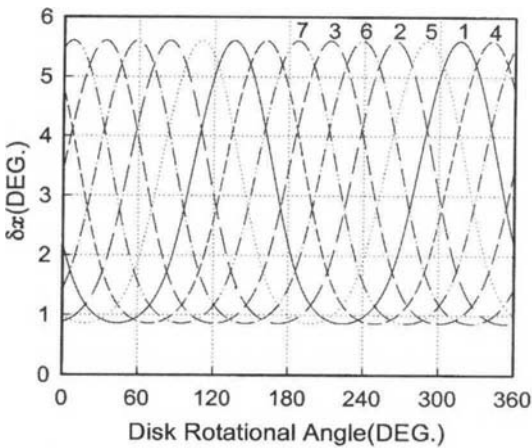


Fig. 7 Variations of  $\delta_x$  at  $\xi=1.9^\circ$ ,  $\alpha=23^\circ$

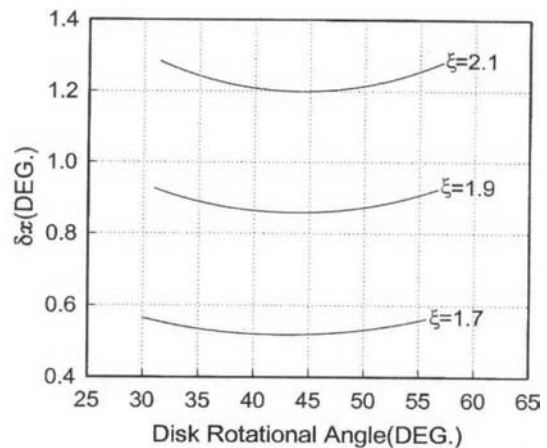


Fig. 8 Variations of  $\delta_x$  according to  $\xi$  at  $\alpha=23^\circ$

area is changed by the taper angle of the tapered pistons and the swivel angle of the cylinder block.

### 3. Experiments

#### 3.1 Experimental apparatus and test method

The schematic diagram of the test cylinder block is shown in Fig. 9. A hole is made around the cylinder to measure the variation of the strain value. A strain gauge is mounted in the hole around cylinder. The wires of strain gauge are led through the center of a center piston in the cylinder block and taken out through a center of a valve plate and a rear housing. A slip ring unit is used to carry the strain gauge signal from the rotating cylinder block. A digital storage scope

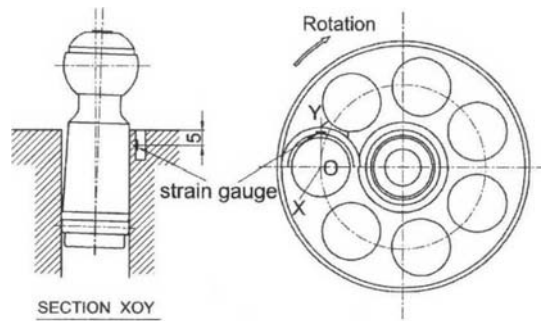


Fig. 9 Schematic diagram of test cylinder block

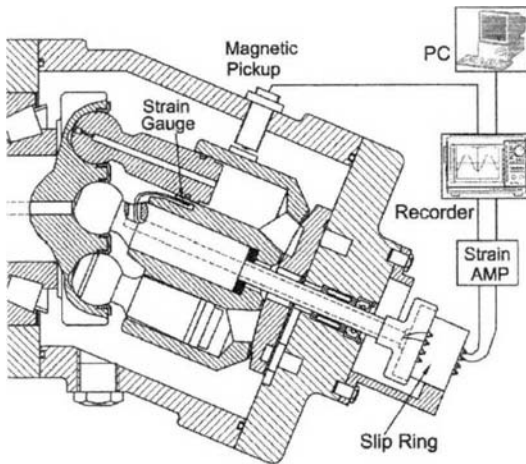
is used in order to display the strain gauge signals.

A schematic diagram of the test piston pump is shown in Fig. 10. Also, a specification of the test

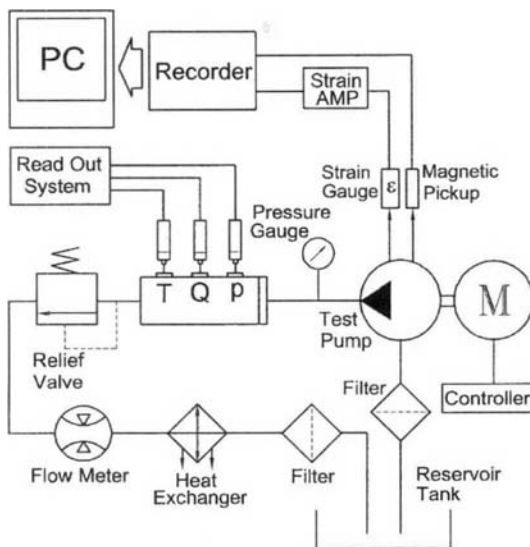
piston pump is shown in Table 1. The cylinder slides on the spherical valve plate having two

**Table 1** Specifications of the test piston pump

classifications	Specifications
Dia. of tapered piston	22.7 (mm)
Displacement	72 (cc/rev)
Max. swivel angle	23 (°)
Pitch dia. of shaft disk	33.3 (mm)
Pitch dia. of cylinder block	32 (mm)
Length of tapered piston	54.4 (mm)



**Fig. 10** Schematic diagram of test piston pump



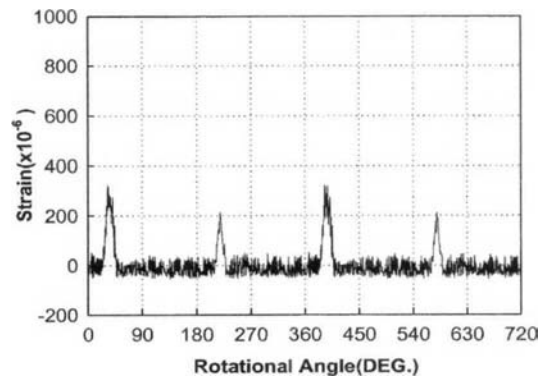
**Fig. 11** Hydraulic circuit for test system

kidney ports. The force on the pistons is generated directly by the torque on the drive shaft. Piston stroke is dependent upon the offset angle between the shaft and the center line of the cylinder block.

Fig. 11 shows a layout of a tested hydraulic circuit. The tested piston pump is driven by a variable speed electric motor (75 KW). The motor speed can be altered from 0 to 2,500 rpm by using a vector inverter motor controller. The test piston pump is connected with a driving motor by use of a chain coupling. The pressure, flow, and temperature sensors are mounted to a delivery line. The relief valve control the delivery pressure from 0 to 30 MPa in test pump. Heat exchanger was used to control oil temperature in test unit.

**3.2 Experimental results**

Fig. 12 and Fig. 13 show variations of the strain value with a rotational speed at an unload condition. In Fig. 12 and Fig. 13, it was observed that the strain value increases with the increase of the rotational speed. Fig. 14 shows a variation of the strain value with a load at 500 rpm. The strain value is remarkably increased due to load at the same rotational speed. Hence, the driving force by the tapered pistons seriously affects the speed and the load. The oil film thickness between the cylinder block and the valve plate will be change accordingly due to an increase of the rotation speed and load. Therefore, an increase of the resistance force in these sliding parts leads to an increase of the driving force.



**Fig. 12** Variation of strain value at 500 rpm, unload

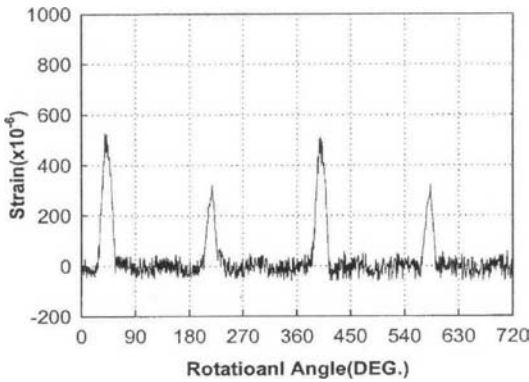


Fig. 13 Variation of strain value at 800 rpm, unload

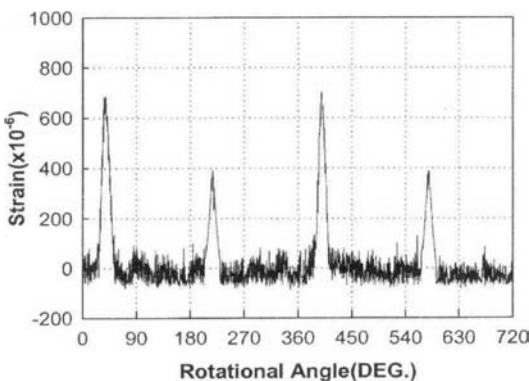


Fig. 14 Variation of strain value at 500 rpm, 5 MPa

#### 4. Conclusions

A mechanism for driving the bent-axis design axial piston pump driven by the tapered pistons was obtained by means of the theoretical analysis and the dynamic experiments.

As a result of this investigation, it is observed that the cylinder block is driven by one tapered piston in a limited area and the driving area is changed by a taper angle of the tapered piston and the swivel angle of cylinder block. It is also investigated that the forces applied to tapered pistons increase as the discharge pressure and the rotational speed increase.

Therefore, while designing the bent-axis design axial piston pump driven by tapered pistons, the taper angle of the tapered pistons should be chosen as adequate value with the swivel angle, the discharge pressure and the rotational speed.

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