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A New Type of Low Speed High Torque Hydraulic Motor with Continuously Variable Displacement

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ABSTRACT

A new type of camshaft connecting-rod low speed high torque (LSHT) hydraulic motor providing continuously variable displacement is presented in this paper. On the base of traditional LSHT hydraulic motor with dual displacement, a continuously variable displacement mechanism, which is composed of a hydraulic control valve with mechanical-positional feedback to camshaft, is designed for the traditional LSHT hydraulic motor. So the cam ring on camshaft of the traditional LSHT hydraulic motor can stop at any position between minimum and maximum eccentricity, according to an input fluid pressure signal or an input electric control signal, and can stay anywhere stabilized through self-adjusting. The new type of continuously variable displacement mechanism is simple, stable and easy to be made. Firstly, the structure and principle of the continuously variable displacement mechanism is introduced in this paper. Secondly, the mathematic model is set up.

KEY WORDS

low speed high torque hydraulic motor, camshaft connecting-shaft type, continuously variable displacement, mechanical-positional feedback

NOMENCLATURE

A_1 : cross section area of the small varying displacement piston

A_2 : cross section area of the large varying displacement piston

A_c : cross section area of the valve collar

B_c : viscous damping coefficient

C_d : flow coefficient

e : eccentricity

F : loading force acting on the cam ring

k_1 : spring coefficient of the restoring spring

k_2 : spring coefficient of the one in the small varying displacement piston chamber

K : eccentric rate

m : mass of the cam ring and two varying displacement pistons

P : hydraulic force of the intake port fluid acting on one radial piston

p_0 : draining pressure, $p_0 \approx 0$, here

p_1 : pressure in the small varying displacement piston chamber

p_2 : pressure in the large varying displacement piston chamber

p_c : control pressure

p_s : supply pressure

Q_1 : flow into the small varying displacement piston chamber

Q_2 : flow into the large varying displacement piston chamber

V_{01} : initial volume of the small varying displacement piston chamber

V_{02} : initial volume of the large varying displacement piston chamber

V_1 : instantaneous volume of the small varying displacement piston chamber

V_2 : instantaneous volume of the large varying displacement piston chamber

w : area gradient

x : valve collar displacement

x_0 : pre-compression distance of the restoring spring

x_v : displacement of spool from a initial position

y : displacement of the cam ring

y_0 : pre-compression distance of the spring in the small varying displacement piston chamber

β : structure angle, $\frac{\pi}{5}$, here

β_e : fluid bulk modulus

ρ : fluid density

φ_1 : geometric rotating angle of the cam ring from the axis of a piston chamber in the motor

INTRODUCTION

Camshaft connecting- rod type low speed high torque hydraulic motors are widely used in many industrial fields. They are typically of fixed or single displacement. If the camshaft connecting- rod type low speed high torque hydraulic motors work in two discrete positions through the fluid pressure control in the two varying displacement piston chambers on the camshaft, the working mode is of dual placement. Unlike axial piston pumps or motors, there is still no mechanical structure or circuit that could accomplish the task of continuously varying displacement in radial piston pump or motor yet. People just added hydraulic and electronic valves or circuits to fixed or dual placement motors to continuously control the angular velocity of the camshaft[1]. Thus camshaft connecting-rod type motors could work in a status of constant power output to improve overall efficiency.

Based on the traditional LSHT hydraulic motor with dual displacement, a continuously variable displacement mechanism is designed for the traditional LSHT hydraulic motor in this paper. The patented mechanism is mainly composed of a hydraulic control valve with mechanical-positional feedback to camshaft. So the cam ring on camshaft can stop at any position between minimum and maximum eccentricity, according to an input fluid pressure signal or an input electric control signal, and can stay anywhere stabilized through self-adjusting. Firstly, the structure and principle of the continuously variable displacement mechanism is introduced in this paper. Secondly, the mathematic model is set up.

MECHANISM AND PRINCIPLE

Mechanical structure

A typical radial piston camshaft connecting- rod LSHT hydraulic motor with dual displacement is shown in Fig.1. Two fluid channels connect two varying displacement piston chambers on the camshaft respectively. If one channel is supplied with high pressure oil from the intake port of the motor or from an isolated power unit, the corresponding varying displacement piston chamber is full of high pressure oil

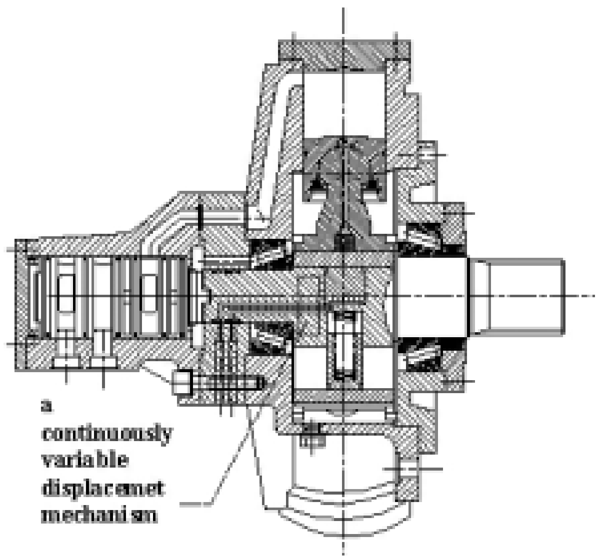

Figure 1 Schematic diagram of a radial piston LSHT hydraulic motor with dual displacement

and the corresponding large or small varying displacement piston will push the cam ring on the camshaft to a limited position. Thus, the motor works at its maxi or mini eccentric position and has its maxi or mini fluid discharging volume. As shown in Fig.1, when the small varying displacement piston pushes out, the motor is at its maxi eccentric position. While the large piston pushing out, it is vice versa.

As shown in Fig.1, the author improves the camshaft connecting- rod LSHT hydraulic motor with dual displacement by adding a spool valve structure to the camshaft and cam ring to realize the continuously displacement function. Fig.2 is a schematic diagram of the continuously variable displacement mechanism. As shown in Fig.2, component 1 is a valve collar that has five pairs of round or quadrate orifices on it. Component 2 is a 3-land valve spool and has a long draining orifice to prevent dead cavity. Component 3 is a restoring spring acting on the open side of the valve collar and precision tempered. Component 4 is a screw-worm structure making the valve spool and component 5, the cam ring, hard-connected to send out a mechanical-positional feedback signal. Component 6-9 is the small varying displacement piston, the restoring spring in the small varying displacement piston chamber, the camshaft and the large varying displacement piston respectively. Component 6, 7 and 9 are unchanged compared with the typical radial piston camshaft connecting- rod LSHT hydraulic motor with dual displacement.

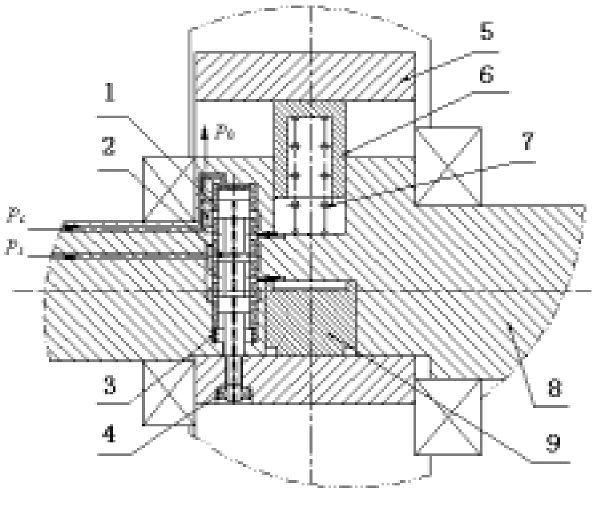

Figure 2 Schematic diagram of a continuously variable displacement mechanism

Fig.3 is a schematic diagram of the working principle of a continuously variable displacement mechanism. Seen from Fig.2 and Fig.3, there is a machined valve house in the camshaft. There are 5 grooves in the valve house named as e1-e5. e1 and e5 connect the draining channel, the fluid pressure is p_0, the pressure in the motor main-body house which can be assumed to be 0. e2 connects the small varying displacement piston chamber and e4 connects the large one. e3 connects the supply channel which fluid pressure is p_s. The supply fluid comes from the intake port of the motor or an isolated power unit. The top of the valve house connects the control channel which fluid pressure is p_c. The control fluid which pressure signal p_c is determined by a hydraulic circuit or adjusted by an electric control circuit, acts on the close side of the valve collar, moving the valve collar against the restoring spring. The five pairs of orifices on the valve collar are named as w1-w5, mapping e1-e5. The fit between the valve house, the valve collar and the valve spool is close-tolerance, forming five cavities named as z1-z5.

Fluid in cavity z2 and z5 drains into the motor main-body house through the orifice on the spool and clearance between spool and the open side of the valve house.

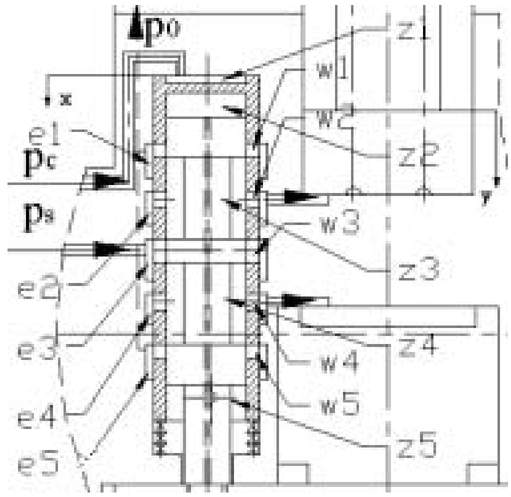

Figure 3 Schematic diagram of the working principle of a continuously variable displacement mechanism

Principle

Seen from Fig.3, the motor works at its maxi eccentric position and has its maxi fluid discharging volume. The working principle is explained through 4 cases: case 1-case2 on how to reduce or improve the eccentric rate, case 3-case4 on returning to its stable working status from a smaller or larger discharging volume.

Case 1

If a smaller discharging volume is needed, the control fluid with an adjusted pressure signal p_c enters cavity z1 and pushes the valve collar down overcoming resistance of the restoring spring until the force formed by p_c equals the one formed by the restoring spring. Then the valve collar stops at a new balance position. Assuming the friction between the valve collar and the spool could be neglected, movement of the spool is independent from the valve collar. When the collar shifts down, the orifices w3 on the valve collar open, supply fluid which pressure is p_s enters the large varying displacement piston chamber through the access of groove e3, orifices w3, cavity z4, orifices w4 and groove e4, pushes large varying displacement piston out. Thus the cam ring goes down and the eccentricity decreases. The spool moves together with the cam ring because of the mechanical linkage between them. When the cam ring and the spool move to the place where the valve collar is, orifices w3 is closed and the access is shut down. Motor is at its new eccentric position. This is a typical mechanical-positional negative feedback. When the supply fluid which pressure is p_s enters the large varying displacement piston chamber, the fluid in the small varying displacement piston chamber drains into the motor main-body house through the access of groove e2, orifices w2, cavity z3, orifices w1 and groove e1. The two accesses open up and shut off at the same time. Because the control fluid pressure signal p_c could be adjusted continuously, the eccentricity could also change continuously. The function of continuously variable displacement is realized.

Case 2

When the motor works at a middle eccentricity and a larger discharging volume is needed, the pressure signal p_c comes down, the restoring spring pushes the valve collar up overcoming resistance of the control fluid until the force formed by p_c equals the one formed by the restoring spring. Then the valve collar stops at a new balance position. When the collar shifts up, the orifices w3 open, supply fluid which pressure is p_s enters the small varying displacement piston chamber through the access of groove e3, orifices w3, cavity z3, orifices w2 and groove e2, pushes small varying displacement piston out. Thus the cam ring goes up and the eccentricity increases. When the cam ring and the spool move to the place where the valve collar is, orifices w3 is closed and the access is shut down. Motor is at its new eccentric position. At the same time, the fluid in the large varying displacement piston chamber drains into the motor main-body house through the access of groove e4, orifices w4, cavity z4, orifices w5 and groove e5. The eccentricity could change continuously.

When p_c equals 0, the motor has a maxi fluid discharging volume. When the restoring spring is compressed to the bottom, the motor has a mini fluid discharging volume. Theoretically, the eccentricity could decrease to 0.

Case 3

While the spool valve structure working at a stable position, all the fluid accesses are blocked. If the eccentricity decreases because of load impact or leakage, the spool shifts down because of the mechanical linkage with the cam ring. The fluid accesses are the same as case 2. Supply fluid enters the small varying displacement piston chamber and the eccentricity increases again until the fluid accesses are blocked. The motor returns to its stable status.

Case 4

If the eccentricity increases because of load impact or leakage, the spool shifts up. The fluid accesses are the same as case 1. Supply fluid enters the large varying displacement piston chamber and the eccentricity decreases again until the fluid accesses are blocked. The motor returns to its stable status.

MATHEMATICAL MODEL

The movement law of the cam ring and the spool valve structure on the camshaft is a composite linear and rotating motion. The rotating speed of LPHT motors is always quite low and the system pressure is usually rather high. So the effect of rotating motion on linear motion could be neglected.

The character of the spool valve structure is the same as that of a 4-way spool valve. It is had better zero-lapped. The character of the spool valve structure and two varying displacement piston chambers is the same as that of a valve-controlled hydraulic cylinder except that the two varying displacement piston chambers are unsymmetrical.

Assuming there is no leakage and supply fluid enters the small varying displacement piston chamber, the flow equations of the spool valve structure are given by

$$Q_1 = C_d w x_v \sqrt{\frac{2}{\rho}(p_s - p_1)} \quad (1)$$

$$Q_2 = C_d w x_v \sqrt{\frac{2}{\rho} p_2} \quad (2)$$

The flow equations of the two varying displacement piston chambers are given by

$$Q_1 = \frac{dV_1}{dt} + \frac{V_1}{\beta_e}\frac{dp_1}{dt} \tag{3}$$

$$Q_2 = \frac{dV_2}{dt} + \frac{V_2}{\beta_e}\frac{dp_2}{dt} \tag{4}$$

where V_1 and V_2 are given by

$$V_1 = V_{01} + A_1 x_v \tag{5}$$

$$V_2 = V_{02} - A_2 x_v \tag{6}$$

The force balance equation of the valve collar and the restoring spring is expressed as

$$A_c p_c = k_1 (x_0 + x) \tag{7}$$

The force balance equation of the system is expressed as

$$A_1 p_1 - A_2 p_2 = m\frac{d^2 y}{dt^2} + B_c \frac{dy}{dt} - k_2 (y_0 - y) + F \tag{8}$$

When the camshaft rotates the force F changes from time to time. The varying law[2] is determined by structures of LSHT motors:

While $0 \le \varphi_1 \le \beta$

$$F = P\left[\frac{\sin\left(\frac{\beta}{2} - \varphi_1\right)}{2\sin\frac{\beta}{2}} + \frac{K}{2}\frac{\cos(2\varphi_1 - \beta)}{2\cos\beta} - \sum\frac{K}{2}\right] \tag{9}$$

While $\beta \le \varphi_1 \le 2\beta$

$$F = P\left[\frac{\sin\left(\frac{3\beta}{2} - \varphi_1\right)}{2\sin\frac{\beta}{2}} - \frac{K}{2}\frac{\cos(2\varphi_1 - 3\beta)}{2\cos\beta} - \sum\frac{K}{2}\right] \tag{10}$$

When supply fluid enters the large varying displacement piston chamber, the force balance equation of the system is expressed as

$$A_2 p_2 - A_1 p_1 = m\frac{d^2 y}{dt^2} + B_c \frac{dy}{dt} + k_2 (y_0 + y) + F \tag{11}$$

where

$$y = x \pm x_v \tag{12}$$

When the spool valve structure works at a stable position, $y = x$.

Getting y by solving equation (8) or (11), the relationship between control pressure and eccentricity (seen from Fig. 4):

$$e = e_{\max} - y \tag{13}$$

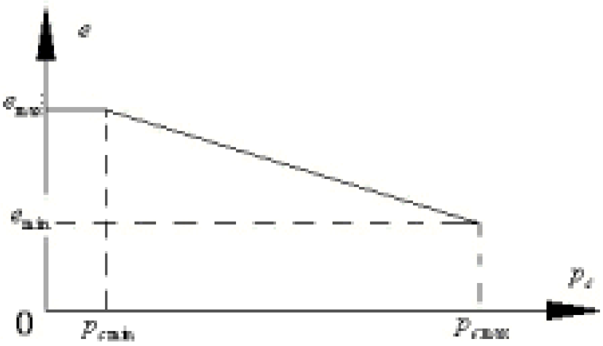

Figure 4 relationship between p_c and e

CONCLUSIONS

By adding a spool valve structure to a traditional radial piston crankshaft connecting- rod LSHT hydraulic motor with dual displacement, the task of continuously varying displacement is realized. Through mechanical-positional feedback and self-adjusting of the continuously variable displacement mechanism, the cam ring on camshaft of the traditional LSHT hydraulic motor can stop at any position between minimum and maximum eccentricity. The new type of continuously variable displacement mechanism is simple, stable and easy to be realized.

The character of the spool valve structure is the same as that of a 4-way spool valve. The character of the spool valve structure and two varying displacement piston chambers is the same as that of a valve-controlled hydraulic cylinder. These characters are very typical and there have been many literatures about them.

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