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Two Motion of freedom Piston Pump Developed for High-speed vehicle

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Abstract

The two motion of freedom piston pump has been invented to enhance efficiency, compactness, integration and reduce weight, noise, vibration. This article presents recent developments on piston pumps, particularly on two motion of freedom piston pumps used for high-speed vehicle. In this study, the structures and key techniques of this pump are presented briefly. Spatial cam-roller driving mechanisms and a rotary reciprocating piston with 4 distributing grooves have been investigated. Simulation software are used to support the design process and analyze the characteristics of pumps. This article also emphasizes the experimental test results, compared with the simulation data of this pump. Both of the simulation analysis and experimental results show that the performance characteristics of the pump achieve the anticipated aim and suitable for high-speed vehicle.

Keywords: *two motion of freedom piston pump, design, prototype, characteristics analysis*

Nomenclature

a – Piston's axial acceleration
n – Motor speed
t – Pump's runtime
ω – Piston's angular velocity
h – Piston's stroke
S – Piston's position
v – Piston's axial velocity

1. Introduction

A pump is the heart of a high-speed vehicle's fluid power system, including fuel supply system and hydraulic control system[1]. Aircraft's pumps are becoming more intelligent, energy efficient and lightweight. Pump design techniques, efficiency, reliability, price, and operating conditions are researched by many groups and industries[2]. Current state-of-the-art piston pumps have been fairly well designed. But there are still many challenges and disadvantages in piston pump areas[3]. They have complex structures, lots of sliding friction pairs, expensive manufacture and maintaining costs. Due to the limitation of the structures, each piston only do once inhale and discharge in one reciprocation. The efficiency and compactness are limited. So it is of great importance to carry out the basic research on new axial piston pump.

In 2006, Navarro Thierry invented a volumetric pump with a rotatable and axially movable piston. The fluid is distributed by the piston. The drawback of this system results essentially from an additional sliding friction pair. And the speed may be limited by the swinging motion of the piston [4]. In 2007, Noah D. Manring combined two axial piston pumps into one tandem pump to reduce torque ripple and vibration of the conventional piston pump [5].In 2011, Xiaohui Luo presented an axial piston water-pump with piston valve, which drains and sucks water through the collaboration of each pistons. The pressure ripple and friction pairs of this pump can be reduced by using piston valves, but the leakage increases a lot [6]. Besides, in 2016, Ruilong Du introduced rotary valves into a axial piston pump for high-speed fluid distribution, replacing check valves [7].

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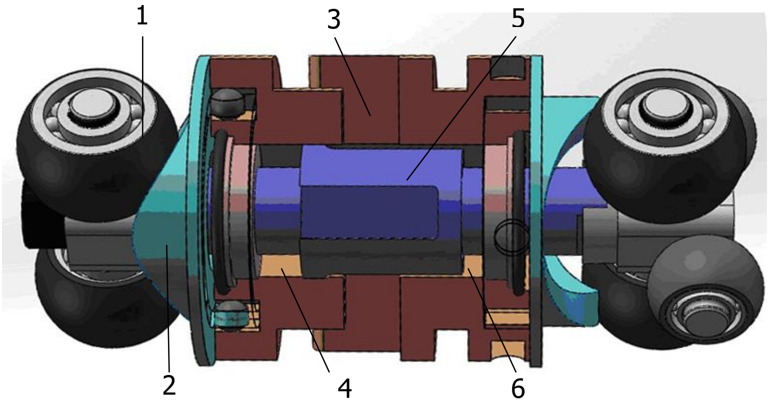
This study was conducted to develop a new type of two motion of freedom piston pump for high-speed vehicle. We build a 3D pump mode and analyzed its strength by ABAQUS software, particularly on the cam-roller mechanisms. A pump prototype was manufactured and a pump test bench was built to test it. The test results show that the two motion of freedom piston pump theory is correct, and the characteristics can fulfill the demands of high-speed vehicle.

2. Theory of two motion of freedom Piston Pump

This pump is used for high power density applications, especially for high-speed vehicle. It is composed of a cam-piston group, a cylinder, a shell and others. The cylinder has four evenly distributed nozzles around, replacing the traditional fuel distribution plate, which are two suction nozzles and two discharge nozzles. And the piston, which has four channels correspondingly, can be rotated by drive shaft in the cylinder. Two spatial cams are set on both sides of the cylinder to make the piston to do reciprocating motion. So the piston can rotate and reciprocate in the same time. That's why it's called a two motion of freedom piston pump. The geometric locus of the curved surface on two spatial cams in a circle is shown in Fig.1.



1- Rollers assemble 2-Spatial cam 3- Cylinder 4- Working volume (left) 5-Piston 6- Working volume (right)

Fig.1 Cutaway view of a two motion of freedom piston pump core

By referring to Fig. 2 (a), (b) and (c), the detailed functioning process of the pump is illustrated as below. There are four windows distributed uniformly around the cylinder which are labeled A, B, C and D in sequence. The window A and C are connected to circular groove of the outlet or high pressure port of the pump, whereas the window B and D which are connected with circular groove of the inlet or low pressure port of the pump. Correspondingly, there are four grooves distributed uniformly around the piston which are labeled E, G, H and F in sequence. The grooves E, H are linked to the left chamber and the grooves G, F are linked to the right chamber. The roller-cam mechanism is composed of spatial cams mounted at the two ends of cylinder and rollers fixed to the piston rods through a crossed pin axes. When the piston is driven by the motor or engine with the fork-roller coupler and rotates in the direction shown in Fig.2, it also makes reciprocating motion due to the constraint of the cams. When the motion phase of the piston is changing gradually from 4a to 4b, the volume of left chamber is decreasing and the fuel inside is pumped out through the distributing grooves E and H to high pressure windows A and C. At the meantime, the volume of right chamber is increasing and the fuel is sucked in through the low pressure windows B and D to the distributing grooves F and G. In the progress from Fig.2 (a) to Fig.2(b), the overlapping areas between windows and distributing grooves are increasing until arriving at peak. While in the progress of state changing from Fig.3(b) to Fig.2(c), the overlapping areas between windows and distributing grooves are decreasing until fully closed. Compared to the Fig.2(a), the piston in Fig.2 (c) has rotated for 90° and reached the far left of its working position. Meanwhile, the left chamber finishes its function of pumping and the right one finishes its function of sucking. As the piston keep on rotating, it will reverse its linear motion. In the next piston rotating angle from 90° to 180°, the volume of right chamber is decreasing and the fuel inside is pumped out through the distributing grooves F and G to high pressure windows A and C. Meanwhile, the volume of left chamber is increasing and the fuel is sucked in through the distributing grooves E and H from low pressure windows B and D. As the piston continues to rotate, the process above is repeated for every 180°, i.e., the cycle of the pump is corresponding to 180°. More specifically, every working chamber sucks and delivers twice in rotating angle of 360° , which means the pump with two working chambers sucks and delivers four times per round of the piston.

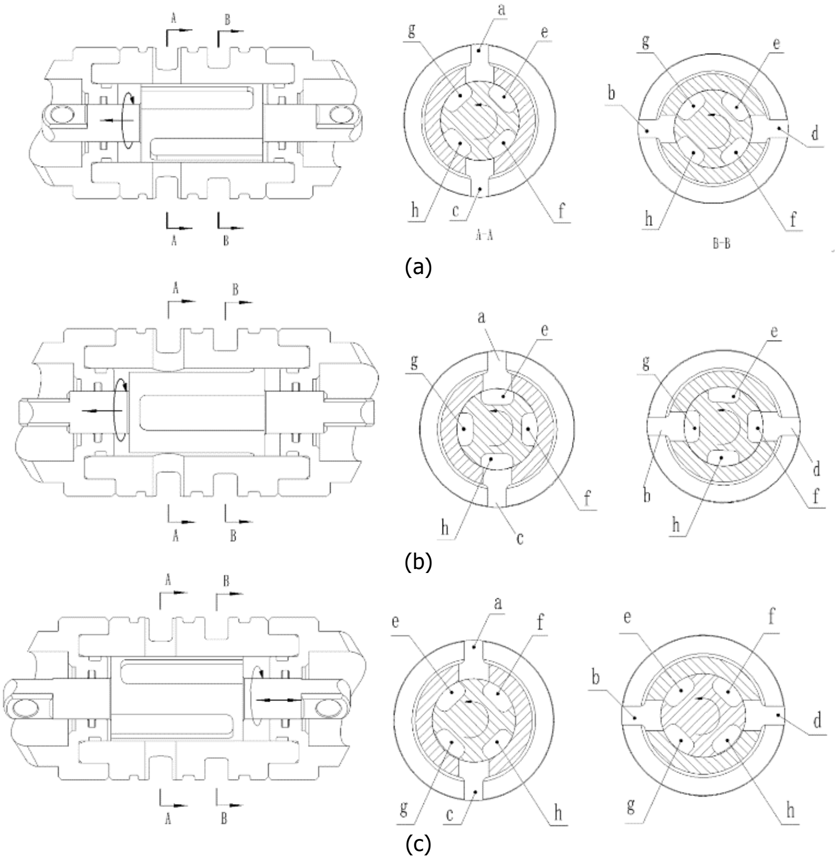


Fig. 2 Functioning process of two motion of freedom piston pump

3. Cam-roller Mechanisms

This pump's piston is connected with two groups of rollers, and the rollers run along two spatial cams at both sides (Fig.3). So the motion of piston is determined by the shape of the cams. Based on the comprehensive consideration of pressure, flow pulse and torque ripple, we design the shape of the cam to make sure the piston's axial motion is uniformly accelerated and decelerated, shown in Fig.3. When the piston's revolving speed is constant, driven by a motor, the piston's axial movement follows the law of equal-acceleration and equal-deceleration. So there is no rigid impact and infinite acceleration in this pump.

Fig.3 Image of a spatial cam

In one round, the piston with two pairs of rollers reciprocates twice, so the rotation angle of a reciprocating movement of the pump is a half turn (π). The piston's reciprocating movement stroke is h and rotation speed is ω, shown in Fig.4.

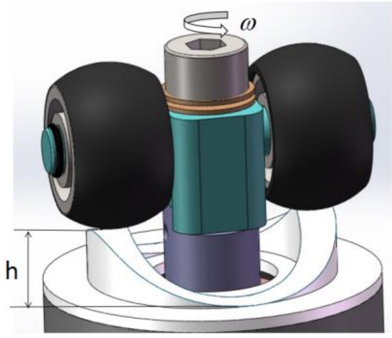


Fig.4 A cam-roller mechanism

In one cycle, it can be divided into 3 stages according to the acceleration. From 0 to $\pi/4$, the piston does equal-acceleration axial movement. From $\pi/4$ to $3\pi/4$, the piston does equal-deceleration axial movement. From $3\pi/4$ to π, the piston does equal-acceleration axial movement. In this way, three quadratic functions, describing the position (S) of the piston relative to the lower dead point, can be obtained; that is:

$$S=\begin{cases}\dfrac{8h}{\pi^2}(\omega t)^2 & \omega t\in(0,\dfrac{\pi}{4}),\\ -\dfrac{8h}{\pi^2}(\omega t)^2+\dfrac{8h}{\pi}\omega t-h & \omega t\in(\dfrac{\pi}{4},\dfrac{3\pi}{4}),\\ \dfrac{8h}{\pi^2}(\omega t)^2-\dfrac{16h}{\pi}\omega t+8h & \omega t\in(\dfrac{3\pi}{4},\pi),\end{cases} \tag{1}$$

where t is the runtime of this pump. When t is equal to 0, the piston is at the right end position.

The function of the axial motion velocity v can be acquired by taking derivative of t in Eq. (1) ; that is:

$$v=\begin{cases}\dfrac{16h}{\pi^2}\omega^2 t & \omega t\in(0,\dfrac{\pi}{4}),\\ -\dfrac{16h}{\pi^2}\omega^2 t+\dfrac{8h}{\pi}\omega & \omega t\in(\dfrac{\pi}{4},\dfrac{3\pi}{4}),\\ \dfrac{16h}{\pi^2}\omega^2 t-\dfrac{16h}{\pi}\omega & \omega t\in(\dfrac{3\pi}{4},\pi).\end{cases} \tag{2}$$

By taking derivative of t in Eq. (2), the function of the axial motion acceleration a can be obtained ; that is:

$$a=\begin{cases}\dfrac{16h}{\pi^2}\omega^2 & \omega t\in(0,\dfrac{\pi}{4}),\\ -\dfrac{16h}{\pi^2}\omega^2 & \omega t\in(\dfrac{\pi}{4},\dfrac{3\pi}{4}),\\ \dfrac{16h}{\pi^2}\omega^2 & \omega t\in(\dfrac{3\pi}{4},\pi).\end{cases} \tag{3}$$

From the Eq. (3), we can draw a conclusion that the acceleration a is independent of time *t*, only related to the angular velocity ω and the stroke *h*. When the stroke *h* and motor speed *n* are determined, the magnitude of axial acceleration a is a constant value, but the direction is changing periodically.

The piston's axial theoretical motion curves are showed in Fig.5. Figure (a) shows the curve of piston's position is composed of three parabolas in one cycle. It can be found from Figure (b) that there are no abrupt changes of the pistons' axial velocity. That means this pump has no rigid impact. From Figure (c), it can be found that there are several abrupt changes in axial acceleration, which means some flexible impact exist. But the abrupt changes of acceleration are finite, so their influence is limited.

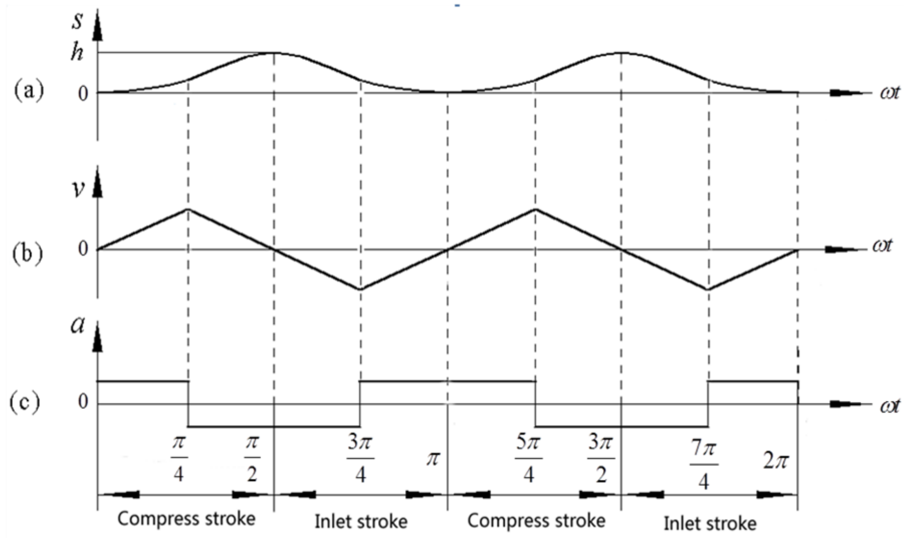


Fig.5 The piston's axial theoretical motion curves

5. Experimental

The elementary structures were determined, and the 3D model was established. We analyzed its strength by ABAQUS software, shown in Fig.6. After all structural analysis had been checked, a two motion of freedom piston pump prototype was manufactured, shown in Fig.7.

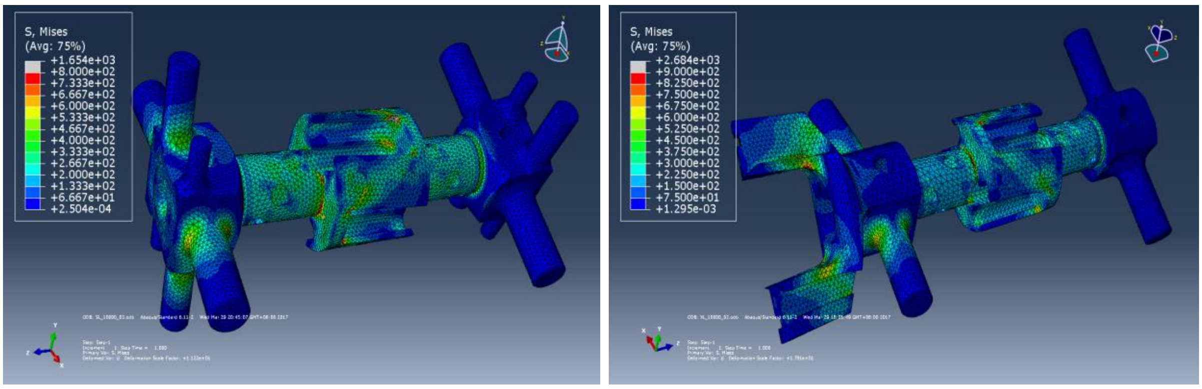


Fig.6 Stress calculation result of the two motion of freedom piston pump

Fig.7 Prototype of the two motion of freedom piston pump

Fig.8 shows a hydraulic system test bench built to test the pump. In the process of testing, we chose the speed sensor and flow meter to test the characteristics of this pump. No-load tests and load tests were conducted to obtain its flow characteristics and pressure-flow characteristics.

Fig.8 Test bench of the two motion of freedom piston pump

6. Results

A throttle valve was used to control the output load from 0MPa to 10MPa, and the piston was driven at the speed of 3000r/min, 9000r/min and 15000r/min. The Output flow rate characteristics are shown in Fig.9. As the load increases, the output flow rate decreases, mainly due to the system leakage. The experimental results are basically consistent with the theoretical analysis. It can concluded that the flow characteristic of this two motion of freedom piston pump is stable, and suitable for high-speed vehicle' fuel pumps.

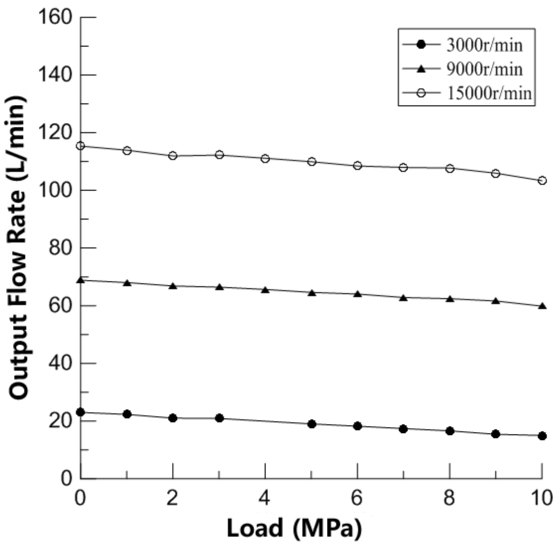


Fig.9 Output flow rate with load

Fig.10 presents the volume efficiency characteristics. The volume efficiency declines with the increase of load. Under the same load, the volume efficiency at high-speed is higher. Besides, at different speeds under certain pressure, the volumetric efficiency at higher speeds is relatively higher than these at lower speeds. Because the flow rate and leakage both increase when the speed goes up, but the leakage is not growing as fast as the flow rate.

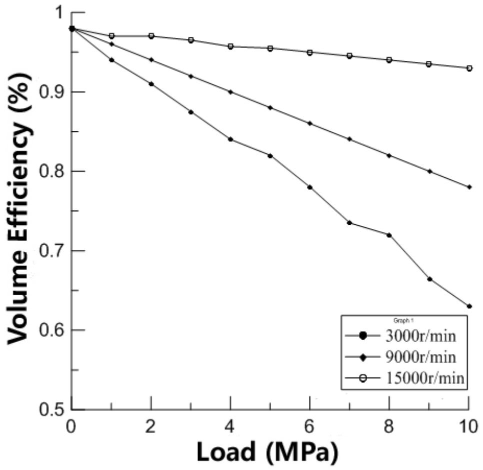


Fig.9 Volume efficiency with load

7. Conclusions

Modeling and testing of the two motion of freedom piston pump for high-speed vehicle has been carried out. The test results show the excellent performances of the pump and the rationality of the two motion of freedom piston pump theory. The two motion of freedom piston pump is an innovation particular in light quantification, with less rotation inertia and sliding friction pairs, high-speed response, compact structure, light weight, low costs and better anti-pollution capabilities. It will be applied widely in ships, aircrafts, vehicles and other fields.

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