Research on Distribution Method With Check Valve of Axial Piston Pump

Zhang Junhui

Professor. Yang Huayong

Professor. Xu Bing

State Key Laboratory of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027,China.

Abstract

The development of axial piston pump more and more focuses on efficiency and noise emission. Noise reduction in axial piston pumps has been attempted by many researchers with different design approaches and techniques. But most traditional structures on valve plate for noise reduction is at the cost of efficiency to different extent. In this paper, a new distribution method with pressure equalization mechanism is proposed, and analyzed in details. The analysis shows that the natural frequency of check valve and the size of PRC are vital for the pressure equalization mechanism. Compared with present commercial axial piston pump, the results indicate that with the pressure equalization mechanism composed of check valve and pressure recuperation chamber the flow ripple and the torque pulsation is sharply reduced. Moreover, the volumetric and mechanical efficiency of axial piston pump is improved, and because the mean value of torque on swash plate is reduced by more than 60%, the power of variable-displacement control mechanism will be reduced and the control accuracy can be improved easily. Therefore, the pressure equalization mechanism is quite promising in the design of high-performance axial piston pump with low noise level.

KEYWORDS: axial piston pump, flow ripple, noise reduction

1. Introduction

Axial piston pump is widely used in hydraulic driving system for its advantages such as high power-mass ratio, high limit load pressure and excellent controllability. However, it also has obvious disadvantages such as low efficiency and high noise level, especially with the increase of operating parameters. Pump is the main noise source in hydraulic systems. On one hand, the force pulsation inside the pump causes vibrations of the pump shell. On the other hand, the flow ripple of the delivery flow interacts with the hydraulic system and creates pressure pulsations that cause the vibration of hydraulic components and pipelines /1/. The magnitude and frequency of both vibrations can be large, resulting in not only high noise level, but also loose of fixing components, leakage and fatigue.

The goals of all the researches on noise reduction of axial piston pump are to reduce flow ripple of the delivery flow and torque pulsation on swash plate /2/. Most researches focused on the optimization of transition region of valve plate, including orifices, notches or recesses /3/. These resistors increase the wrap angle of transition region and decrease the actual suction and delivery time in a cycle, consequently reducing the displacement of axial piston pump. What's more, in order to realize smooth pressure transition in piston chamber from high delivery to low suction pressure, a small part of the high-pressure oil in the piston chamber flows into the suction kidney slot through the groove during the transition region. This can be referred as a kind of leakage. Researchers also proposed some other methods, such as external pre-compression chamber /4/, check valve between piston chamber and delivery port /5/, and timing control of swash plate /6/. Some of these methods have satisfactory results in noise reduction by reducing flow ripple and torque pulsation, but all the methods have the same characteristic that the smooth pressure transition of piston chamber is at the cost of efficiency of axial piston pump.

During the transition region, the pressure variations in piston chamber at ODC (Outer Dead Center) and IDC (Inner Dead Center) are contrary, so pressure equalization between ODC and IDC is another principle for noise reduction. The hydraulic energy stored in the dead volume at IDC can be used to pressurize the piston chamber at ODC. Hereby recuperating hydraulic energy from IDC to ODC can not only reduce flow ripple but also improve efficiency /7/, /8/. This is beneficial especially for axial piston pump with high working pressure and large displacement.

This paper proposes a distribution method of axial piston pump with high frequency check valve based on pressure equalization principle. The effect of this method on flow ripple of out flow, torque pulsation on swash plate, displacement and efficiency of pump are investigated based on a simulation model of axial piston pump that is verified by experiment. The application of this method on axial piston pump with odd and even pistons are compared and discussed in details. Some encouraging results are obtained, which can be used in the design of low-noise and high-efficiency axial piston pump.

2. Simulation model

In order to analyze the noise source, a general simulation model of axial piston pump was developed with AMESim software. The schematic is shown in **Figure 1**. The number of piston chamber in the cylinder module could be odd or even as needed. The valve plate module calculates variation of the flow area for every piston chamber in a cycle. The external module is optional and could be different according to the investigated distribution method. In this research, it includes a mathematical model of check valve.

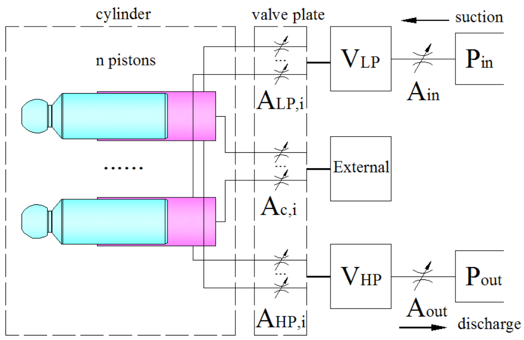

Figure 1: Schematic Diagram of the Simulation Model

The actual pressure in piston chamber is calculated by integrating (1) that defines the pressure-rise-rate. The accurate bulk modulus is important for the calculation of pressure overshoots during the transition region. In this simulation model, the fluid bulk modulus is defined with a table of bulk modulus values against pressure from experimental results. Because of the presence of air, with the variation of pressure, the air can be dissolved in the liquid or can be free as bubbles, which is related to cavitations on valve plate /9/.

$$\frac{dP}{dt} = \frac{K_{\mathrm{e}}}{V_{\mathrm{pc}}}\left(Q_{suc} - Q_{\mathrm{del}} - Q_L - \frac{dV_{\mathrm{pc}}}{dt}\right) \tag{1}$$

The general simulation model of axial piston pump is shown in **Figure 2**. Some extra modules can be added if new distribution method is investigated. This simulation model can analyze the instantaneous pressure in piston chamber, the flow ripple of out flow, the torque pulsation applied on swash plate and the leakages of every friction pairs in a cycle. In order to verify the general simulation model, a test rig for flow ripple measurement was designed. The flow ripple of pump is a kind of signal with high frequency, and cannot be tested directly by the present commercial flow transducer, so a test rig of the flow ripple testing was built based on the ISO 10767-1-1996 (Hydraulic fluid power- Determination of pressure pulsation levels generated in systems and components— Part 1: Precision method for pumps). The comparison of simulation and experimental results shows that the error of the simulation model of axial piston pump in flow ripple prediction is only 2.0% /10/. Therefore, the simulation model has a satisfying accuracy, and can be applied in the design and analysis of distribution method of axial piston pump.

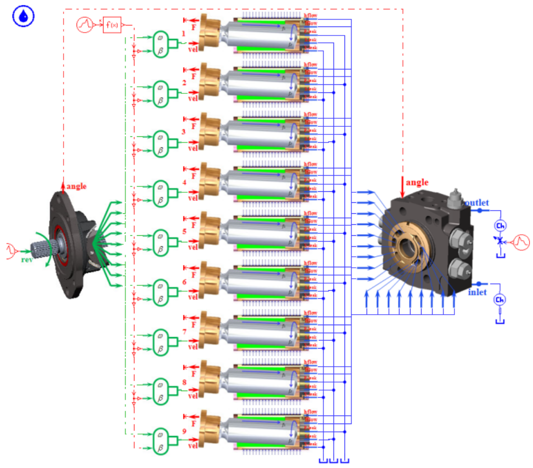

Figure 2: General Simulation Model of Axial Piston Pump

3. Design of pressure equalization pump with even pistons

Using the hydraulic energy stored in the dead volume at IDC to pressurize the piston chamber at ODC directly, it requires the number of piston is even. For axial piston pump with odd pistons, there has to be a PRC (Pressure Recuperation Chamber) as an intermediate station. Because the ideal geometrical flow ripple and torque pulsation on swash plate of axial piston pump with even pistons are much larger than pump with odd pistons, the practical commercial axial piston pump products almost all have odd pistons, especially nine. Wang Y investigated even piston pump through simulation and experiment, and pointed out that the flow ripple of piston pump was much larger than ideal geometrical value due to fluid bulk modulus, and the flow ripple of piston pump with eight pistons is close to the one with nine pistons /11/. However, another important factor in the analysis of noise reduction of axial piston pump, the torque pulsation applied on swash plate wasn't analyzed in his researches.

The size of dead volume of piston chamber is an important parameter in analysis of flow ripple, so the piston diameter of even piston pump should keep the same in the simulation. Therefore, in this paper, the piston pump with eight pistons is compared with that of nine pistons. This will simplify the design of model pump in future experimental research, because most components of the original commercial pump will remain unchanged. If manufacturing ten cylinder bores, the minimum distance of the adjacent cylinder bores will become smaller, and this will affect structural strength of the cylinder. For piston pump with even pistons, it just needs a check valve to realize pressure equalization between piston chambers near IDC and ODC, as shown in **Figure 3**. The pressure equalization process starts at the moment when the piston chamber is disconnected from kidney slots. The high-frequency check valve guarantees that the oil can only flow from IDC to ODC, permitting the pressure transition in the two piston chamber simultaneously. In the simulation model, the grooves of valve plate are reserved, and an ideal model of check valve is employed that neglects the dynamic characteristics of opening and closing processes.

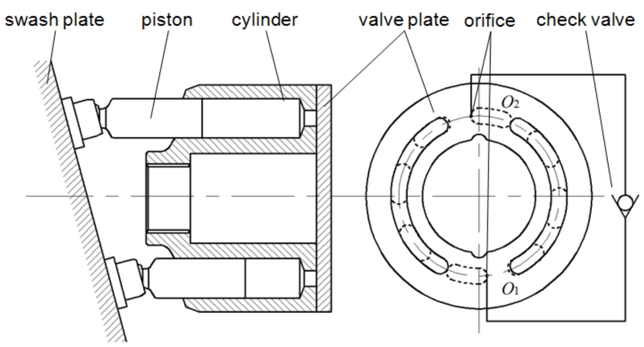

Figure 3: Schematic Diagram of Pressure Equalization Pump with Even Pistons

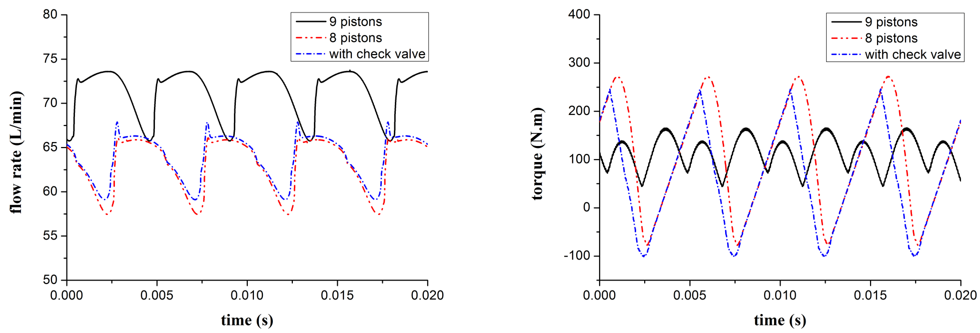

Figure 4: Comparison of Flow Ripple and Torque Pulsation

The theoretical flow ripple of piston pump with eight pistons is 7.80%, five times the value of piston pump with nine pistons that is 1.53%. The simulation results in **Figure 4** show that the flow ripple of piston pump with eight pistons is 14.00%, a little larger than the value of pump with nine pistons that is 13.01%, both quite larger than theoretical value. The flow ripple of pump employing pressure equalization with check valve is reduced to 13.80%. The fluctuant torque applied on swash plate is the source causing vibration of pump shell. What's more, it is the input for variable-displacement control mechanism. Therefore, smaller torque not only means lower noise, but also is beneficial for variable-displacement control of pump. Although the pressure equalization mechanism with check valve helps to reduce the torque, the torque fluctuation region of piston pump with eight pistons is still almost two-fold larger than that of pump with nine pistons. Therefore, although the pressure equalization mechanism with check valve of piston pump with even pistons is simpler and helps to reduce the flow ripple to some extent, its torque is still quite larger than that of traditional piston pump with odd pistons, which should also be the main reason why almost all the commercial axial piston pumps have odd pistons. Therefore, the pressure equalization mechanism does not help to overcome the shortcomings of axial piston pump with even pistons.

4. Design of pressure equalization pump with odd pistons

For axial piston pump with odd pistons, there is no another piston chamber near ODC when a piston chamber is near IDC, and vice versa. Therefore, the hydraulic energy stored in piston chamber near IDC has to be transferred into an intermediate chamber firstly. When the next piston chamber finishes oil suction and enters into the transition region near ODC, the high-pressure oil in the intermediate chamber flows into this low-pressure piston chamber. Thus, the pressure transition process from high delivery to low suction pressure in piston chamber near IDC is a little ahead of the inverse pressure transition process in piston chamber near ODC. The schematic diagram is shown in **Figure 5**. The high-frequency check valve guarantees that the oil can only flow from high-pressure piston chambers to low-pressure ones. The positions of the orifices ensure that the piston chamber connects with PRC as soon as it disconnects from kidney slots. The volume of PRC is set three-fold the size of the dead volume of piston chamber at first.

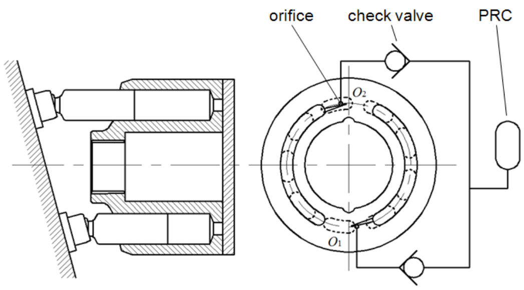

Figure 5: Schematic Diagram of Pressure Equalization Pump with Odd Pistons

The comparisons of simulation results demonstrate the pressure equalization mechanism with check valve and PRC is quite effective in noise reduction, and the dynamic characteristics of check valve have an evident influence on the flow ripple and torque pulsation reduction, as shown in **Figure 6**.

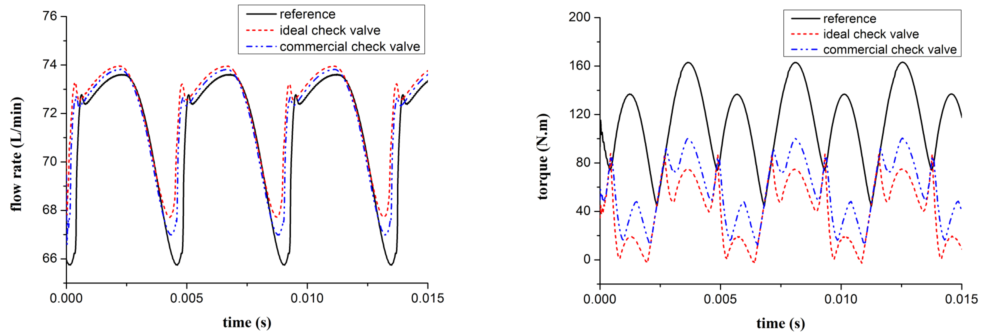

Figure 6: Comparison of Flow Ripple and Torque with Different Check Valve

With the pressure equalization mechanism, the flow ripple of piston pump decreases from 13.01% to 9.58%, reduced by 26.4%, meanwhile the simulation result of model with high-frequency commercial check valve is 10.32%, a little larger than that of model employing ideal check valve. The compressed volume due to the axial movement of piston and backflow from delivery kidney slot to piston chamber are the two reasons for the pressure transition in piston chamber near ODC from suction to delivery pressure. Moreover, the value of the backflow is crucial in determining the minimum value of flow ripple. For the axial piston pump with pressure equalization mechanism, the high-pressure oil from piston chamber at IDC contributes to the pressurization of the piston chamber at ODC, so the backflow from delivery kidney slot to piston chamber at ODC will decrease. This is also why the mean value of out-flow increases from 71.25 to 72.13 L/min in Figure 6. We can say that in some sense the volumetric efficiency of axial piston pump increases by 1.24%. Because this part of hydraulic energy stored in piston chamber at IDC that is transformed from mechanical energy of motor is used in pressurizing piston chamber at ODC, other than leaking into suction kidney slot, the pressure equalization mechanism will improve the overall efficiency of axial piston pump apparently. With the pressure equalization mechanism, the mean value of torque applied on swash plate decreases from 113.71 to 40.23 N.m, reduced by 64.6%. The fluctuation region decreases from 118.94 to 90.57 N.m, reduced by 23.8%. Therefore, the oscillating magnitude of the source for vibration of pump shell decreases apparently. What's more, the smaller average value means smaller input power for the variable-displacement control mechanism of axial piston pump, and the smaller oscillating magnitude means higher accuracy of displacement control.

Therefore, the pressure equalization mechanism with check valve and PRC has three advantages. Firstly, it can reduce the noise level of pump because of its smaller magnitude of flow ripple and torque pulsation. Secondly, it can improve the volumetric and mechanical efficiency of axial piston pump. Thirdly, it can reduce the power needed for variable-displacement control mechanism and improve the control accuracy.

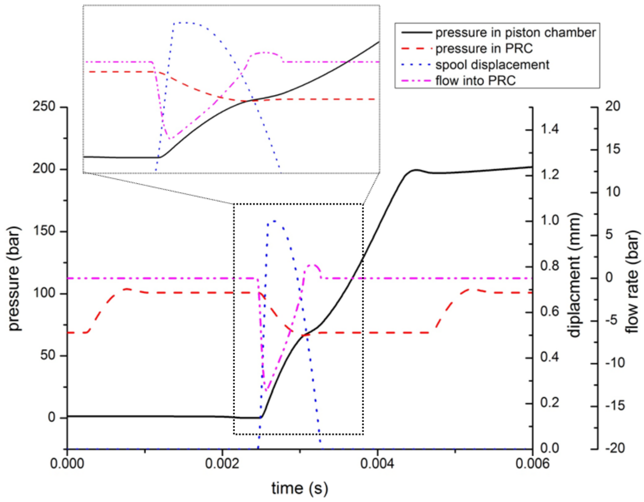

Figure 7: Pressure Transition from Suction to Delivery

The pressure transition process of piston chamber at ODC from low suction pressure to high delivery pressure is employed to analyze the principle of pressure equalization. As shown in **Figure 7**, the pressure in PRC is approximately the mean value of the suction and delivery pressure, fluctuating during one certain region. When the piston chamber finishes the suction process and connects with the orifice, because the pressure in PRC is larger than pressure in this piston chamber, the check valve opens under the pressure difference, and the spool displacement increases gradually. The fluid oil flows into piston chamber from PRC. Thus, the pressure in PRC decreases, meanwhile the piston chamber is pressurized. Then the pressure difference between piston chamber and PRC decreases. The spool begins to move backwards when the thrust force due to pressure difference is smaller than the spring force of check valve. Therefore, the flow rate from PRC to piston chamber decreases with the reduction of pressure difference and spool opening. The flow decreases to zero when the pressures in PRC and piston chamber are equal. However, the check valve is still open, and the pressure in piston chamber is still increasing after that through other structures during transition region of valve plate, so a small amount of fluid oil flows back into PRC due to the new pressure difference until the check valve totally closes. By now, the pressure equalization between PRC and piston chamber at ODC terminates. The pressure equalization process between PRC and piston chamber at IDC is similar.

For the model of ideal check valve, the closing and opening of check valve take no time, so the period of this process of pressure equalization is shorter, and the small part of backflow does not exist, as shown in **Figure 8**. This also explains why the dynamic characteristics of check valve have an influence on the noise reduction effect of pressure equalization mechanism. Hence, the frequency of the check valve should be as high as possible to reduce the amount of backflow. A tiny high-frequency check valve is chosen for the experimental research in the next step whose dynamic characteristics of this check valve is employed in the simulation model. The moving parts of the check valve weights only 0.2g. Because the size of the check valve is so small that the extra noise caused by its opening and closing will also be small.

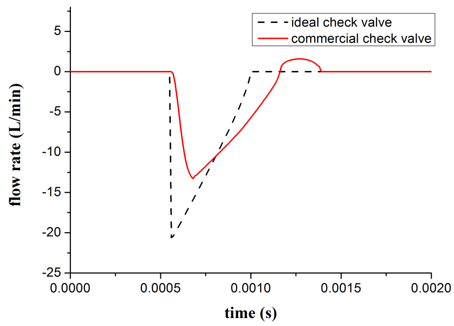

Figure 8: Comparison of Flow into PRC with Different Check Valve Model

5. Parameters optimization

The size of the PRC determines the terminal pressure during the two processes of pressure equalization between PRC and piston chambers, sequentially having an influence on the noise reduction effect. To have an optimal value for the size of PRC, simulations are carried out for the sizes of PRC ranging from 20 to 60 cm^3.

Size (cm^3)	Flow ripple	Mean flow rate (L/min)	Torque magnitude (N.m)	Mean torque (N.m)
20	10.65%	71.89	85.22	54.27
30	10.32%	71.97	88.11	50.97
40	10.11%	72.01	90.22	49.24
50	9.96%	72.03	91.54	48.17
60	9.86%	72.05	92.47	47.45
20	10.65%	71.89	85.22	54.27
30	10.32%	71.97	88.11	50.97

Table 1: Comparisons of Out Flow and Torque

The simulation results are shown in **Table 1**. The flow ripple and mean torque on swash plate decrease gradually as the volume of PRC increases, meanwhile the mean flow rate and magnitude of torque pulsation increase. As shown in **Figure 9**, the varying range of pressure in PRC is larger for the smaller PRC. Therefore, the pressure differences during the two pressure-equalization processes are larger sequentially, and then the opening and closing speeds of the check valve increase. However, the total flows between piston chambers and PRC increase with larger size of PRC, which contributes to the reduction of flow ripple and increment of mean value of out-flow rate.

Low noise level requires both small flow ripple and small torque pulsation. Lager mean out-flow rate is beneficial for efficiency improvement and smaller mean torque on swash plate is beneficial for variable-displacement control of axial piston pump. Moreover, the variation is much small when the size of PRC is larger than 30 cm^3. And lager volume of PRC will increase the total mass of axial piston pump. Therefore, taking all factors into account, 30cm^3 is the best choice for the size of PRC, which is about 3 times the size of dead volume of piston chamber. More accurate value calls for smaller steps in the simulations.

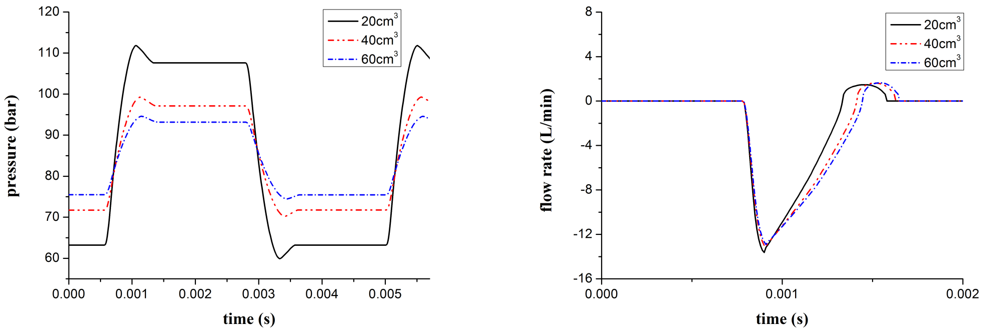

Figure 9: Comparison of Pressure in PRC and Flow into PRC

6. Conclusions

In this paper, a new distribution method of axial piston pump based on pressure equalization principle is proposed and analyzed in details. Because the torque on swash plate of axial piston pump with eight pistons is almost two-fold larger than that of pump with nine pistons, pressure equalization mechanism is not suitable for axial piston pump with even pistons. With the pressure equalization mechanism with check valve and PRC applied on the traditional commercial axial piston pump, the noise level of axial piston pump can be reduced apparently, because the flow ripple is reduced by more than 25%, meanwhile the torque pulsation is reduced by more than 20%. Moreover, the volumetric and mechanical efficiency of axial piston pump are improved obviously. The power of variable-displacement-control mechanism will decreases and the control accuracy can be improved easily, because the mean value of torque on swash plate is reduced by more than 60%. Therefore, the pressure equalization mechanism is promising in the design of high-performance axial piston pump with low noise level. The dynamic characteristic of check valve is vital for the pressure equalization mechanism, so the natural frequency should be as high as possible. The optimal size of PRC is about 3 times the size of the dead volume of piston chamber. A model pump for experimental research in next step de-signed according to the analysis and optimization in this paper is being manufactured based on a commercial axial piston pump.

7. Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant No. 51075360), the National Key Technology R&D Program of the twelfth Five-year Plan of China (Grant No. 2011BAF09B03) and the Doctoral Foundation of Ministry of Education of China (Grant No. 20090101110041).

8. Bibliographical References

/1/ Seeniraj G K, Ivantysynova M. Noise Reduction in Axial Piston Pump Machines Based on Multi-parameter Optimization. In: Proc. of 4th FPNI-PhD Symp. Sarasota, 2006. 235-246.

/2/ Ivantysynova M, Seeniraj G, Huang C. Comparison of Different Valve Plate Designs Focusing on Oscillating Forces and Flow Pulsation. In: Proceeding of the 9th Scandinavian International Conference on Fluid Power. Linköping, 2005.

/3/ Ma J, Fang Y, Xu B, et al. The Optimization of Valve Plate Cross Angle Based on the Pumping Dynamics Model. Journal of Zhejiang University SCIENCE A, 2010, 11(3):181-190.

/4/ Pettersson M, Weddfelt K, Palmberg J. Methods of Reducing Flow Ripple From Fluid Power Piston Pumps-A Theoretical Approach. SAE transactions, 1991.100(2):158-167.

/5/ Harrison A, Edge K. Reduction of Axial Piston Pump Pressure Ripple. In: Proc Instn Mech Engrs Vol 214 Part I. 2000. 53-63.

/6/ Johansson A, Ölvander J, Palmberg J. Experimental Verification of Cross Angle for Noise Reduction in Hydraulic Piston Pumps. In: Proc. IMechE Vol. 221 Part I: J. Systems and Control Engineering. 2007. 321-330.

/7/ Nafz T, Murrenhoff H, Rudik R. Active Systems for Noise Reduction and Efficiency Improvement of Axial Piston Pumps. In: Proceeding of Fluid Power and Motion Control. Bath, 2008. 327-340.

/8/ Lemmen R, Schmitt J. Axialkolbenmaschine mit Mitteldrucköffnung. DE 19804374A1.

/9/ Vacca A, Klop R, Ivantysynova M. A Numerical Approach for the Evaluation of the Effects of Air Release and Vapour Cavitation on Effective Flow Rate of Axial Piston Machines. International Journal of Fluid Power. 2010, 11(1): 33-45.

/10/ Ma J. Study on Flow Ripple and Valve Plate Optimization Of Axial Piston Pump (in Chinese). PhD dissertation. Hangzhou: Zhejiang University, 2009. 105-106.

/11/ Zou J, Wang Y. Research for Pressure and Flow Pulsating Characteristic of Swash Plate Axial Piston Pump with Even Pistons. In: Proceedings of the second International Conference on Fluid Power Transmission and Control. 1989.325-327.

9. Nomenclature

n	number of pistons	
P	pressure in piston chamber	Pa
P_{in}	suction pressure	Pa
P_{out}	delivery pressure	Pa
$A_{x,i}$	flow area of ith piston	mm^2
K_e	bulk modulus of fluid oil	Pa
Q_{suc}	suction flow rates of a piston chamber	L/min
Q_{del}	delivery flow rate of a piston chamber	L/min
Q_L	leakage flow rate of a piston chamber	L/min
V_{pc}	instantaneous volume of piston chamber	cm^3
t	time	s