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INNOVATIONS IN PUMP DESIGN – WHAT ARE FUTURE DIRECTIONS?

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ABSTRACT

Displacement-controlled actuators, advanced continuously variable transmissions and hydraulic hybrid power trains represent new technologies for mobile hydraulic machines, off road and on road vehicles. These new technologies allow major fuel savings and reduced emissions, but they change the performance requirements of positive displacement pumps and motors. Additionally, the market demand for positive displacement machines will increase. This paper briefly discusses these technology trends and the impact on existing pump and motor designs. The three major challenges are efficiency improvements, noise reduction and advancements in pump and motor control. Examples from the author's research team documenting the progress in computer modeling of piston pumps and motors will be given.

KEY WORDS

Displacement controlled actuators, pump design, pump efficiency, pump model

NOMENCLATURE

A : piston area
R : pitch radius
Δp: differential pressure
V_0 : volume of displacement chamber at ODC
V_D : dead volume
β : swash plate angle
ΔV : volume to be compressed

INTRODUCTION

High power density is one of the greatest strengths of fluid power technology. This makes fluid power especially advantageous for mobile applications where part of the consumed energy is required to move the installed actuators and transmissions. Fluid power is the best choice for actuators and drives in agricultural, mining and construction machinery as well as other automotive and aerospace applications. However, the efficiency of fluid power systems is relatively low compared to electromechanical actuators and transmissions. This fact is becoming distressing due to rising fuel prices and stringent emissions requirements. The current use of metering valves (hydraulic resistances) in nearly all hydraulically powered actuation systems is one of the main reasons for low overall system efficiency. Another problem is the relatively low efficiency of most of the currently used pumps and motors. This paper will briefly discuss the potential of displacement controlled systems and other major trends in mobile machines like power split drive and hydraulic hybrids. These new technologies allow major fuel savings and reduced emissions, but they change the performance requirements of positive displacement pumps and motors. Furthermore, the market demand for positive displacement machines will increase.

TRENDS IN MOBILE HYDRAULICS

Displacement control for working hydraulics

Displacement controlled actuators avoid throttling losses and allow energy recovery. Berbuer [1] studied the performance of displacement controlled actuation introducing a hydraulic transformer 20 years ago. Since then many others have contributed to new circuit solutions for displacement controlled actuators. An overview of early pump controlled actuation concepts can be found in Ivantysynova [2]. Figure 1 shows the circuit solution proposed by Rahmfeld and Ivantysynova [3] for displacement controlled linear actuators with single road cylinder. Several advantages make this concept attractive:

- Throttling losses are eliminated
- Relief and check valves can be integrated into the pump case, thereby reducing the number of discrete components and fluid connectors
- Multiple cylinders can share a single low pressure line
- Recovery of potential and kinetic energy is possible since the pump automatically runs in motoring mode when the cylinder is driven by an aiding load

A similar solution has been studied by Lawrence et al [4]. An open circuit solution for displacement controlled actuators has been introduced by Haybroek, Larsen and Palmberg [5].

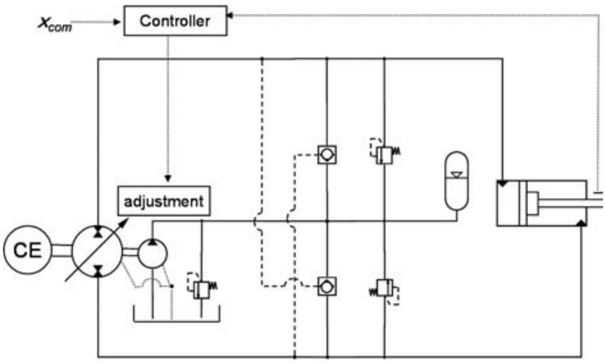

Figure 1 Displacement controlled actuator with single rod cylinder

Although much research effort has been spent over the last 20 years and impressive fuel savings have been reported displacement controlled actuators are still not on the market[10]. The author's research group continues its effort on introducing displacement controlled actuators to mobile machinery. Figure 2 shows a simplified circuit for an excavator with displacement controlled actuators for all functions. Detailed dynamic models of the standard LS excavator system and the proposed displacement controlled system were constructed, and a trench digging cycle was simulated for both. The displacement controlled excavator consumed 29% less total energy than the LS excavator for the simulated operation, more details can be found in [6]. In displacement controlled actuators the pump becomes the main source of losses. In addition, more pumps need to be installed in each machine. Therefore the pump efficiency will determine the achievable energy savings. The impact of pump efficiency on total power consumption has been studied by the author's research group [7].

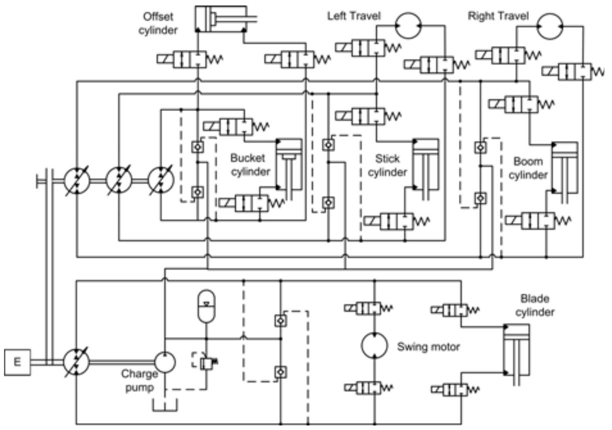

Figure 2 Simplified hydraulic circuit of a displacement controlled excavator

Figure 3 shows a simulated working cycle for a skeed-steer loader with displacement controlled boom and bucket functions, where two different pumps were used. Pump A had a maximum efficiency of 87% and pump B 90%. Although the difference in maximum efficiency is just 3% the system using type B pumps consumed 16% less energy for the same cycle. Thus improving efficiency in the entire range of operating parameters is very important for displacement controlled actuation.

Power Split & Hybrid Power Trains

The power train technology will also undergo major changes. Among the continuously variable transmission concepts (CVT) the power split transmission principle is the most efficient. It allows very effective engine management and can be used for a wide range of applications. Besides the current tractor applications power split and hydraulic hybrids will be introduced in different off road and on road vehicles [8],[9]. The transmission efficiency and ratio are strongly dependent on the efficiency of the pump and motor.

Closed loop control & Automation

A third clear trend is the introduction of more automatic functions and the development of small and large heavy-duty mobile robots or robot like machines. The replacement of human control by closed loop control will allow faster operation. The installation of necessary sensors to measure cylinder and pump displacement, system pressure, speed and machine acceleration will allow the use of the installed actuator power for additional functions like active vibration damping [10].

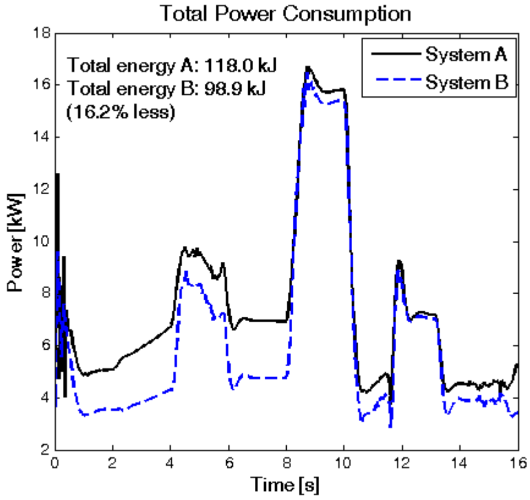

Figure 3 Total power consumption of displacement controlled skid steer loader

PUMP AND MOTOR REQUIREMENTS

The described new system technologies require major changes in pump and motor design. Highly efficient electrohydraulically controllable overcenter pumps are requested for the realization of displacement controlled linear and rotary actuators. The power split and hydraulic hybrid technology requires overcenter pumps and variable motors of the highest efficiency. The closed loop control of actuators and drives will require variable displacement pumps with installed sensors to measure the pump displacement. The integration of microcontrollers into the pump or motor will allow implementing many different control concepts and customer features by software, i.e. the design of smart pumps. Pumps for displacement controlled actuators usually require higher bandwidth of the pump controlled system. In addition pump noise will become a major challenge for mobile equipment when installing multiple pumps and motors in machines with quieter engines. The replacement of valve controlled systems by displacement control will increase the demand for smaller pumps. The future direction for pump and motor design need to address the following objectives:

- reduction of pump and motor power losses in the entire range of operating parameters
- increase of bandwidth of pump control
- reduction of pump and motor noise
- high operating pressures
- compact design and high power density

INNOVATIONS IN PUMP DESIGN

The first question to be answered is; do we need to invent new pump principles to fulfill the above listed requirements? With gear, vane, screw and piston pumps and many different existing designs for each type the number of designs to choose from seems to be large enough. The current designs are usually much simpler than those developed 50 years ago [11]. The market share of variable units has continuously increased over the last 30 years and this trend will continue. That's why this paper focuses on trends in the area of variable displacement machines and will not include gear and screw pumps. Among the variable positive displacement machines only piston machines are applicable for high pressures, i.e. vane pumps are not suitable for the discussed new technologies. In mobile hydraulics radial piston pumps have not been used very often, except radial piston motors for high torque and low speed applications. Radial piston pumps with outer piston support are very similar to swash plate type axial piston pumps, thus both design allow high pressures, high efficiencies and comparable power density. However due to the radial piston arrangement the radial piston pump with outer piston support is much shorter than the swash plate type axial piston pump. This could be an advantage for the displacement controlled systems requiring the installation of a larger number of pumps in a single machine like the excavator shown in Fig. 2. One of the disadvantages of variable radial piston pump with outer piston support is the higher movable mass compared to swash plate type, thus for applications with high bandwidth of the pump control system the swash plate type is clearly the best solution. There are only two types of axial piston machines - bent axis axial piston and swash plate axial piston machines. The main difference between these two different designs is the generation of torque. In swash plate axial piston machines the torque generation takes place at the cylinder block. Therefore the piston is heavy loaded by a large radial pressure dependent force. This large force does not allow using piston rings to seal the displacement chamber better. The piston-cylinder pair requires a very good design to fulfill its double function (sealing and bearing). In bent axis axial piston machines the torque is generated on the driving flange. The lateral piston force is very small and therefore piston rings can be used to seal the displacement chamber. Consequently this principle allows achieving higher efficiencies than all other known designs. High starting torque and higher speed limit due to lighter pistons and the possibility to have very large tilt angles (45°and more) are further advantages of the bent axis principle. The main disadvantages are higher production costs, lower bandwidth and more complex design, which does not allow a through shaft in case of larger tilt angles. The swash plate type axial piston machine represents the simplest design. Unfortunately swash plate machines have a higher number of sealing and bearing gaps, which create a real challenge in achieving comparable high efficiencies. Computer based design offers certain opportunities as will be discussed later in this paper. Another drawback of the swash plate unit is the limitation of maximum swash plate angle due to the high radial force exerted on the piston. This limits the power density of this design. Figure 4 shows a comparison of size of rotating group of different axial piston machines with different tilt angles, floating cup 10°, swash plate 18°, bent axis 45°. The dimensions shown are the main dimensions of the rotating group of a 125 cm^3 unit.

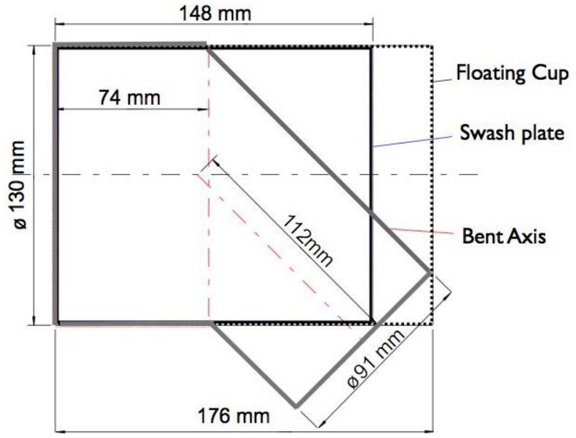

Figure 4 Comparison of main dimensions of rotating group of different piston machines

The floating cup design proposed by INNAS [12] is a bent axis machine with a limited tilting angle of 10°due to geometrical constraints [13]. The unit has 24 pistons and requires two valve plates and two cylinder blocks, i. e. the resulting number of parts of the rotating group is with 83 much higher compared to a 9 piston bent axis machine requiring 23 parts. Table 1 shows a comparison of power density of the three different designs. The swash plate unit and the bent axis have both 9 pistons. The high number of pistons (24) of the floating cup design allows reducing flow pulsation, but requires 50 gaps to be sealed. Compared to that, a bent axis with 9 pistons has only 19 gaps. Thus shows innovations in pump and motor design should rather focus on continuous improvement of well-known and well-understood principles, like bent axis, swash plate and radial piston units. Although decades of research many effects taking place in our current machines are not completely understood and models are still not accurate enough to reflect the complex nature of physical effects taking place in these machines. Sealing of the displacement chamber is the biggest challenge when designing a positives displacement machine for high pressure application. Therefore the design of the sealing and bearing gaps in the area of piston machines will offer many opportunities for innovations necessary to improve efficiency in the entire range of operating conditions. Surface shaping, surface texturing, the application of new materials and coatings together with new manufacturing technologies will form the basis for further innovations to meet the described challenges.

Table 1: Rotating group power density comparison of 125 cm^3 positive displacement units

DePorP	P owe PPwwD PoPP r	P owe ΔP Poorr	P owe Po w wo Po w r	Powe PowPr	Power DePo Powe	
					Pow e owPr	Po r
PwoowPr PoP	Pooo	Poo	Poo	PPPe	oeww	woo
PwoPr Pwowe	Pooo	Poo	PPw	woeP	oewe	woe
PePw owP	Pooo	Poo	Peo	weww	oePP	Poo

Figure 5 shows measured power loss and overall efficiency of a 75 cm^3 variable swash plate unit for four different displacements and two operating pressures when running at 2000rpm. The power loss at lower swash plate angles is too high to keep the efficiency curve flat. In addition to that keeping the efficiency high also for lower pressures is very important for displacement controlled actuation and transmissions. Thus a further reduction of losses occurring at lower pressures is another challenge for the design of high pressure pumps and motors.

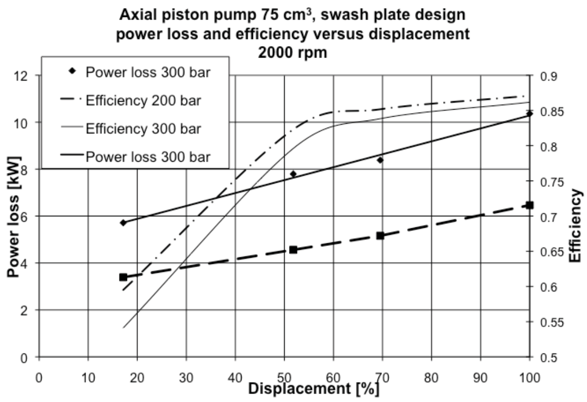

Figure 5 Measured power loss and overall efficiency of a 75 cm^3 unit for different swash plate angles

The program CASPAR allows supporting pump design and optimization based on modeling non-isothermal gap flow in all three connected gaps of swash plate axial piston machines [12]. The model has been extended to consider fluid structure interaction, i.e. the hydrodynamic effects due to elastic surface deformation [15]. The CASPAR model considers micro-motion of all movable parts of the rotating group to determine the varying gap heights between highly loaded sealing and bearing surfaces over one shaft revolution. Based on the final gap heights the load carrying ability of the gap and all other resulting parameters like viscous friction and leakage can be predicted. The program was used to optimize the piston shape for pumping and motoring conditions [16]. Recently the impact of a shaped valve plate has been studied [17]. Figure 6 shows the gap height between cylinder block and valve plate for the rotating angle ϕ=0°, i.e. the piston at the outer dead center. Changing external forces exerted on the cylinder block lead to a micro-motion of the cylinder block which causes varying gap height over one haft revolution while running the pump under steady state conditions. Figure 7 shows the impact of shaping on the fluid film thickness. The average maximum and minimum gap heights between valve plate and cylinder block are shown for different operating conditions (two speed settings, two different operating pressures and 100% and 20% swash plate angle). The gap heights for the standard design are shown in light gray and the gap heights obtained for the shaped surface in black. The investigated surface shape contributes to an increase of gap heights at lower operating pressures and lower displacements.

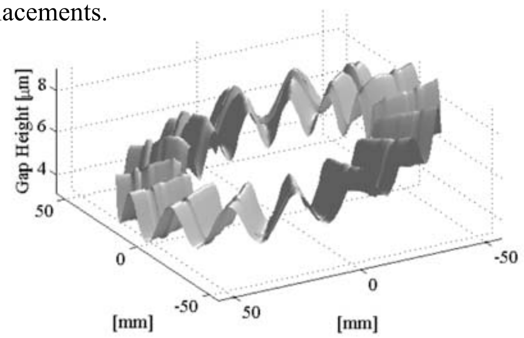

Figure 6 Gap height between valve plate and cylinder block using a shaped valve plate surface

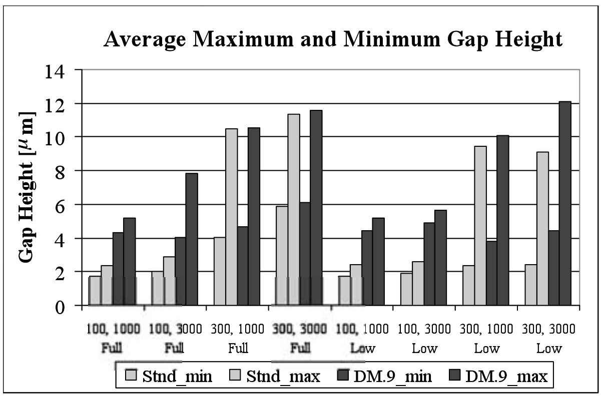

Figure 7 Maximum and minimum gap height between valve plate and cylinder block

The change in gap height leads to change in fluid flow conditions and consequently to a change of friction and leakage. Viscous friction and leakage determine the power losses generated in by the gap in case of full fluid film conditions. For all simulated eight operating conditions a sufficient thickness of the fluid film has been obtained. The shaped valve plate surface reduces the power loss by more than 60% for lower operating pressures and low displacement. In case of high operating pressures the impact of the investigated shape is negligible.

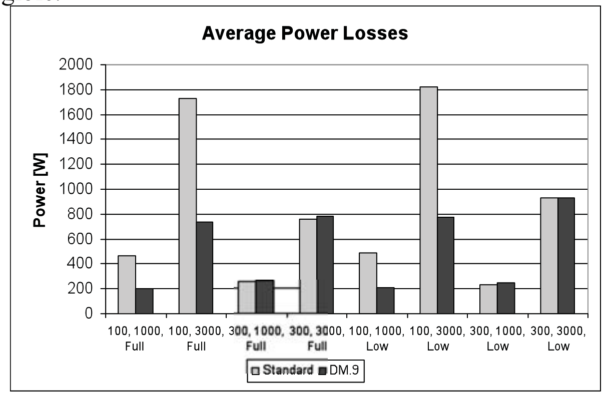

Figure 8 Average power loss of the gap between valve plate and cylinder block (standard & shaped valve plate)

Recently there has been an increasing trend of research on fast switching valves. The idea of creating a virtually variable displacement pump has been proposed and studied by different teams [18],[19]. Lumkes and Batdorff [19] investigated the losses associated with the use of fast switching valves, but did not consider that the fixed displacement pump will have in addition considerable losses. Fast electro-hydraulically operated switching valves could be used to reduce losses due to compressibility when integrating them in piston machines to connect each displacement chamber with the high pressure and low pressure port respectively. Figure 9 shows an example for a swash plate axial piston pump with rotating swash plate. By keeping the displacement chamber connected to suction during discharge for the required time the compression of the volume expressed by the second term in Eq. (1) will be avoided. Assuming that the switching valves are fast enough, for a 75 cm^3 pump running at 3000 rpm, 300 bar pressure and 20% displacement the theoretical increase in discharge flow rate is 1.34 l/min.

$$V_0 = V_D + R \cdot A\left(\tan\beta_{\max} + \tan\beta\right) \quad (1)$$

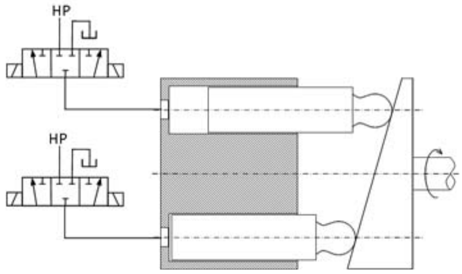

Figure 9 Swash plate axial piston pump with fast switching valves for individual chamber porting

CONCLUSION

Displacement controlled actuators, power trains based on power split transmission and hydraulic hybrids are the main emerging technologies, which can significantly reduce fuel consumption and emissions. These technologies require elctrohydraulically controllable variable displacement pumps with four-quadrant operation. Major challenges are high efficiency in the entire range of operating parameters; low noise and advancements in pump control. Surface shaping and texturing, the application of new materials and coatings together with new manufacturing technologies will form the basis for further innovations in pump and motor design. Due to the limited length of this paper only few examples for new directions in pump design are presented and the referenced work is very limited and does not reflect the amount of research accomplished in this field worldwide.

REFERENCES

1. Berbuer, J., NeuartigeServoantriebemitprimaer-erVerdraengersteuerung.PhD thesis RWTH Aachen, 1998.
2. Ivantysynova, M.,Pump Controlled Actuator - a Realistic Alternative for Heavy Duty Manipulators and Robots. Developments in Fluid Power Control of Machinery and Manipulators, Fluid Power Net Publication (2000), chapter 5, pp. 101 – 123.
3. Rahmfeld, R. and Ivantysynova, M. 1998. Energy saving hydraulic actuators for mobile machines. Proc.1st. Bratislavian Fluid Power Symposium, Casta-Pila, Slovakia, pp. 47 - 57.
4. Lawrence, P.D. ;Salcudean, S.E. ; Sepehri, N. ; Chan, D., Bachmann, S., Parker, N., Zhu, M. and Frenette, R., Coordinated and Force-Feedback Control of Hydraulic Excavators. 4th Intern. Symposium on Experimental Robotics, Stanford, USA, 1995.
5. Heybroek, K.; Larsson, J. and Palmberg, J.O., Open Circuit Solution for Pump Controlled Actuators. Proc. 4th FPNI PhD Symposium, pp. 27-40. Sarasota, Florida, USA, 2006.
6. Williamson, C., Zimmerman, J., Ivantysynova, M., Efficiency Study of an Excavator Hydraulic System Based on Displacement-Controlled Actuators. Bath/ASME Symposium on Fluid Power and Motion Control. Bath, UK, 2008.
7. Williamson, C. and Ivantysynova, M., The Effect of Pump Efficiency on Displacement Controlled Actuator Systems. Proceedings 10thSICFP '07, Tampere, Finland, Vol. 2, pp. 301-326, 2007.
8. Carl, B., Williams, K. and Ivantysynova, M., Comparison of Operational Characteristics in Power Split Continuously Variable Transmissions. SAE ComVec, Chicago, IL, USA, SAE Technical Paper 2006-01-3468.,2006.
9. Kumar, R.,Ivantysynova, M. and Williams, K.,Study of Energetic Characteristics in Power Split Drives for on Highway Trucks and Wheel Loaders. SAE ComVec, Chicago, IL, USA, SAE Technical Paper 2007-01-4193, 2007.
10. Eggers, B.,Rahmfeld, R. and Ivantysynova, M., An energetic comparison between valveless and valve controlled active vibration damping for off-road vehicles. 6th JFPS International Symposium on Fluid Power. Tsukuba, Japan. pp. 275-283, 2005.
11. Ivantysyn, J. and Ivantysynova, M., Hydrostatic pumps and motors, Akademia books international, New Delhi, 2001.
12. Achten, P. A. J., Power density of the floating cup axial piston principle. Proc. 2004 ASME ImechE Congress an Expo, IMECE 2004-59006 Anaheim, California, 2004.
13. Peter Aachten et al., Movement of the cups on the barrel plate of a floating cup axial piston machine. International Journal of Fluid Power 5 (2004) No. 2 pp. 25-33, 2004.
14. Wieczorek, U. and Ivantysynova, M., Computer Aided Optimization of Bearing and Sealing Gaps in Hydrostatic Machines - The Simulation Tool CASPAR. International Journal of Fluid Power, Vol. 3 (2002), No.1, pp. 7-20, 2002.
15. Huang, C. and Ivantysynova, M., A new approach to predict the load carrying ability of the gap between valve plate and cylinder block. PTMC 2003, Bath, UK, pp. 225 – 239, 2003.
16. Ivantysynova, M. and Lasaar, R., An investigation into Micro- and macro geometric design of piston/cylinder assembly of swash plate machines. International Journal of Fluid Power, Vol. 5 (2004), No.1, pp. 23- 36, 2004.
17. Baker, J. and Ivantysynova, M., Investigation of power losses in the lubricating gap between cylinder block and valve plate of axial piston machines. Proc.of 5thFPNI PhD Symposium, Cracow, Poland 2008.
18. Haink, C.T.,Rannow, M., Van de Van, J. Wang, M., Li, P., Chase, T., High speed rotary pulse width modulated on/off valve. Proc.of ASME-IMECE'07, Seattle, USA, IMECE 2007-42559, 2007.
19. Batdorff, M., Lumkes, J., Virtually variable displacement hydraulic pump including compressibility and switching losses. Proc.of ASME-IMECE'06, Chicago, USA, IMECE 2006-14838, 2006.