



High Energy Efficiency Driving of the Hydraulic Excavator Boom with an Asymmetric Pump

Lei Ge, Long Quan*, Xiaogang Zhang, Jiahai Huang and Bin Zhao

Taiyuan University of Technology, Key Lab of Advanced Transducers and Intelligent Control System of
Ministry of Education, Yingze street 75, Taiyuan, China*
E-Mail: quanlong@tyut.edu.cn

Hydraulic excavator is widely used in the construction field, due to their small size to power ratio and big actuation forces. However, due to large throttling loss and gravitational potential wasting, its energy efficiency is very low, which is even lower than 10%. This paper aims to improve the energy efficiency of the hydraulic excavator by reducing throttling loss and regenerating potential energy directly based on a novel pump controlled system. The system under consideration utilizes a newly designed asymmetric pump which has three ports, the two are connected to the hydraulic cylinder, the other is connected to an accumulator. Thus, this system can regenerate the potential energy directly and can match the unequal flow rates of the single rod cylinder basically. Furthermore, working performances of the excavator boom system with the asymmetric pump and independent metering circuit are studied comparatively. Results show that, compared with an independent metering circuit, the electric power consumption during the boom going up can be reduced by 56%.

Keywords: Hydraulic excavator, high energy efficiency, asymmetric pump controlled, energy recovery

Target audience: Mobile Hydraulics, Mining Industry, Design Process

1 Introduction

Nowadays, hydraulic excavator is widely used in the construction field, and there are millions in use in the world. However, the energy efficiency of the whole excavator is poor, which mainly caused by the low thermal efficiency of the fuel engine^[1-2], large throttling loss^[3-4] and kinetic energy and potential energy loss of the working device^[3]. Hence, increasing the energy efficiency of excavators has become a hot topic for the manufacturers and researchers.

In terms of engine energy efficiency increasing, a conventional approach is to adjust the engine speed according to the load condition^[5]. The other is the diesel engine cylinder deactivation technology^[6]. However, these two approaches can only improve the economy of the diesel engine in light load. An approach to comprehensively improve the engine efficiency is to add an auxiliary power unit to the system, called the hybrid technology^[7-10]. Furthermore, a relatively thorough approach is to use some accumulators to separate the engine from the actuators, allowing optimal engine operation independent of the current power demand^[11-15]. And also, the engine can be replaced with an electric motor to eliminate emissions completely^[16].

Conventional valve controlled systems usually feature low energy efficiency due to the inherent throttling losses and the simultaneous actuation of the valves' meter-in and meter-out control edges. Therefore, some theses attempt to use an independent metering system to replace the four-side valves to deal with this problem. And this is also one of the research hotspots in valve controlled systems^[17-18]. And also, to the mobile machine, a single pump was often used to drive more than one actuators which work under different pressure level, thus large throttling loss was needed to control the cylinders velocities. Thus, the throttling loss cannot be avoided in the valve controlled system. Therefore, there are many years' efforts to develop hydraulic systems without throttling losses. Pump controlled systems also called displacement controlled system, can eliminate throttling loss completely and have proven themselves in practice for a long time^[19-20]. However, once the linear drives are to

be used in the form of differential cylinders, it becomes difficult to connect the asymmetric flow rates of the consumer with the balanced volume flow of the pump.

For hydraulic excavator, usually its boom weight is heavier than the load. When the boom moves downwards, it does not need to supply power to drive the boom cylinder down, and it needs to balance the gravity force of the working device by controlling the pressure in the cylinder rodless chamber. During this process, the potential energy of the working device is consumed on the control valve and converted into heat. Therefore, it is necessary to recover the potential energy to reduce the fuel consumption. As a result, much research has been conducted in the field of energy saving mobile hydraulics. And current research can be divided into electrical recovery and hydraulic recovery according to their storage style. For the electrical recovery solutions, an electric generator/motor is used to recover the potential energy and maybe an accumulator was used to decrease the installed power of the electric generator/motor by decoupling the boom lowering and power generation process. And then, the stored electric energy can be used to drive the main pump during another process^[21-24]. For the hydraulic recovery, a hydraulic motor/pump is used to control the cylinder velocity and an accumulator is used to store the energy. And then, during another process, the hydraulic motor can be used for auxiliary driving the main pump^[25-27]. And also, there is another way to control the cylinder with a hydraulic transformer^[28]. However, many energy conversion links will cut down the energy recuperation efficiency, and the installed power is large. That is to say, the energy recovery efficiency is not high enough and many devices need to be added to the hydraulic excavator, which makes it complicated and expensive.

In this paper, an innovative pump controlled architecture with a newly designed asymmetric pump which can efficiently recover the potential energy of the working device is put forward. Innovative research and major contribution of this article are that the high energy efficiency and simple reusing can be achieved with only the newly designed asymmetric pump without long energy conversion links and complex recovery circuit.

This paper is organized as follows. Firstly, the system structure and working principle of the single rod cylinder controlled by asymmetric pumps is given in Section II. In Section III, experiments are carried out to prove the performances of the system, and the energy efficiency of the new system is compared with a separate metering in and separate metering out system. A conclusion is given in Section V.

2 Asymmetric pump controlled single rod cylinder system

Recently, a single pump controlled single rod cylinder in the study region is one of the hot topics in pump controlled systems due to its simple structure, low costs, and big output force. In these systems, there exist unequal flow rates at two ports of the cylinder due to its asymmetric structure. And when a conventional pump is used to control this type cylinder, either a deficient or excess flow rate is always formed in the closed circuit. Hence researches have been focused on the compensation method of the unequal flow rates and on improving the stability of the system. This paper proposes a novel compensation solution based on a new designed asymmetric pump and the system energy efficiency can be improved without much control efforts and additional element.

2.1 System structure

Our team has introduced the principle of asymmetric valve controlled asymmetric cylinder system to the pump controlled single rod cylinder system based on a new designed asymmetric pump. The principle of asymmetric pump controlled single rod cylinder is given in Fig.1. A servo motor is used to regulate the drive speed of the newly designed asymmetric fixed displacement pump. The ports A₁ and B₁ of the pump are directly connected to the single rod cylinder, and port C₁ is connected to an accumulator directly and to a tank through a check valve. Two pressure relief valves are utilized to limit the operating pressure, respectively.

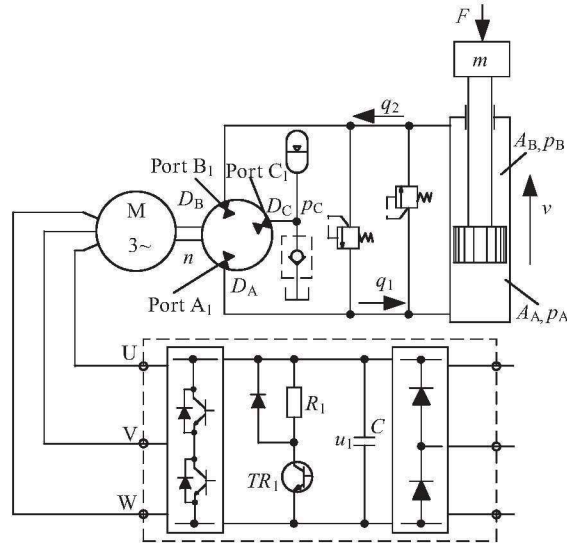


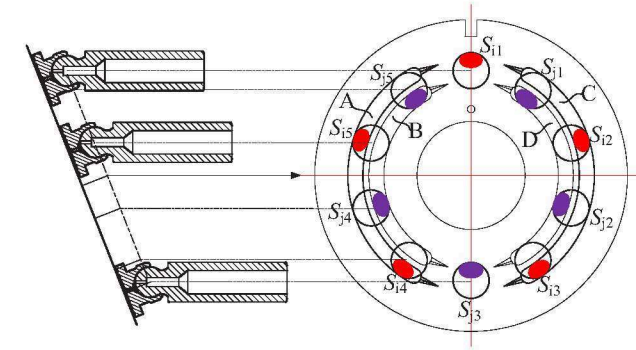
Fig.1 System structure and principle

During the cylinder extension process, the pump sucks oil from cylinder rod chamber through port B₁, and from tank or accumulator through port C₁. Then the pump discharge oil to cylinder rodless chamber. During the cylinder retraction process, the pump sucks oil from cylinder rodless chamber through port A₁. Then the pump discharge oil to the cylinder rod chamber and to the accumulator through port B₁ and C₁.

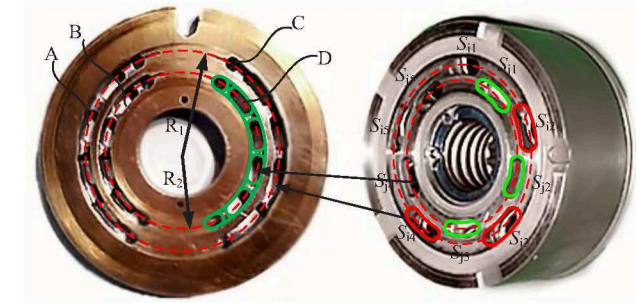
n is the rationing speed of the pump, v is the velocity of the cylinder, A_A and A_B represent the area of the rodless and rod chamber of the cylinder. D_A , D_B and D_C are the displacements of the pump ports A₁, B₁ and C₁. When the system is used to control the boom cylinder, the control cavity is the rodless chamber. The cylinder velocity can be written as $v = D_A \cdot n / A_A$. As the displacement ratio is designed to equal to the area ratio of the rodless and rod chamber of the cylinder, the flow rates in and out of the pump and cylinder can match to each other basically.

2.2 Asymmetric pump

Fig.2 gives the working principle and a photograph of valve plate and cylinder block of the new designed asymmetric pump. As shown in Fig.2, it can be seen that there are four assignment windows on the valve plate, named A, B, C and D, where A and C are in the same circle with a radius of R_1 and B and D on one with R_2 . Both windows A and B are connected to each other by the port A₁ on the pump end shell cover. Both windows C and D are one-to-one correspondence with the pump ports of B and C. There are 10 plunger chambers that are divided into two groups averagely. At the bottom of the cylinder block, there are an inner annular array and an outer annular array. The pitch radiuses of those two annular arrays match with the slots of A, B, C and D on the valve plate. As shown in Fig. 2(b), the plunger chambers are identified as S_i , corresponding to the outer annular array, and those five pistons suck and discharge the oil only from the outer annular array. Such benefits from the asymmetric structure of the flow distribution make the flow rates ratio of the three ports of the pump be 1:0.5:0.5. And an area ratio of the single rod cylinder can be matched to change the flow rate ratio by adjusting the piston diameters or R_1 and R_2 . Benefiting from such asymmetric structure of the pump, the flow rates of the cylinder and the pump can be balanced basically.



(a) Working principle



(b) Photograph of the valve plate and cylinder block

Fig.2: Asymmetric pump

2.3 Theoretical analysis

According to the flow continuity equation of hydraulic cylinder, the flow of the cylinder can be formulated as Eq.1 and Eq.2.

$$q_1 = A_A v + \frac{V_1}{\beta_e} \frac{dp_A}{dt} \quad (1)$$

$$A_B v = q_2 - \frac{V_2}{\beta_e} \frac{dp_B}{dt} \quad (2)$$

During the working period, the hydraulic cylinder is under the action of hydraulic pressure and load force, according to the force balance equation, the dynamic equation of the hydraulic cylinder can be shown in Eq.3.

$$p_A A_A - p_B A_B = m \ddot{x} + B_c \dot{x} + F \quad (3)$$

The pump is under the action of hydraulic load pressure, accumulator pressure and torque regulated by the electric motor, according to the torque balance equation, the dynamic equation of the hydraulic pump can be shown in Eq.4.

$$T_m = J \frac{dn}{dt} + B_m n + \frac{1}{2\pi\eta} (p_A D_A - p_B D_B - p_C D_C) \quad (4)$$

With the asymmetric pump controlled boom cylinder system, the pressure in the rod chamber, p_B can be assumed as zero. And for the hydraulic cylinder with an area ratio of 1:2, the displacement ratio of the three port of the

asymmetric pump can be designed as $D_A=2D_B=2D_C$. When the pressure in the accumulator is double that of the pressure in the cylinder rodless chamber, the electric motor only needs to overcome the frictional torque and to compensate the nonlinearity of accumulator during the working process. Thus, the installed power of boom system can be reduced to the minimum and the energy efficiency of the system can be further increased.

3 Experimental system

In order to provide compared data about working performance and energy efficiency, the test of boom cylinder with the independent metering system driven by an inverter motor is implemented first. Fig.3 gives the principle of the experimental system controlled by independent metering valves.

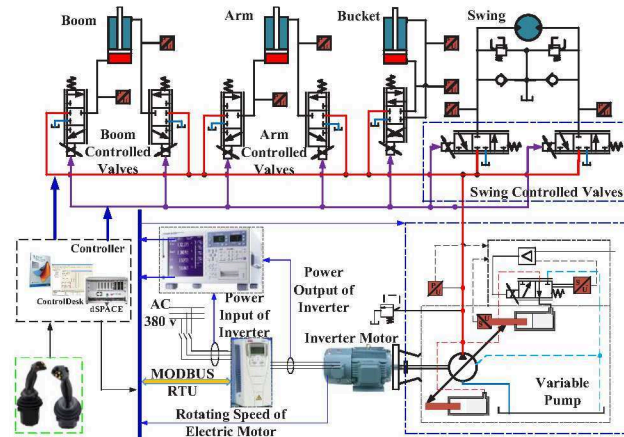


Fig.3 Boom cylinder controlled by separate metering system

In Fig.3, the system in which boom cylinder, arm cylinder and swing motor are controlled by independent metering system driven by an inverter motor. An electro hydraulic axial piston variable displacement pump which the pressure and flow are continuously tunable is used in this system. There are additional instruments such as displacement sensors in the actuators, pressure sensors installed to detect the pressure inside the actuators and pump ports, the power sensors and rotational speed sensor on the motor to detect the electric power and rotational speed. The control concepts are being realized by the hardware in the loop computer control system ds1103.

The proposed system works as below: the controller takes in the inputs of the joystick and the measured quantities such as pressures, powers, displacements, flow and speed of the motor. And then the controller analysis the demand automatically and output the voltage signals directly applied to the converter motor, pump and valves according to the set strategy [4].

After the test of the boom cylinder controlled by independent metering system, the asymmetric pump controlled arm cylinder test rig is constructed, as shown in Fig.4.

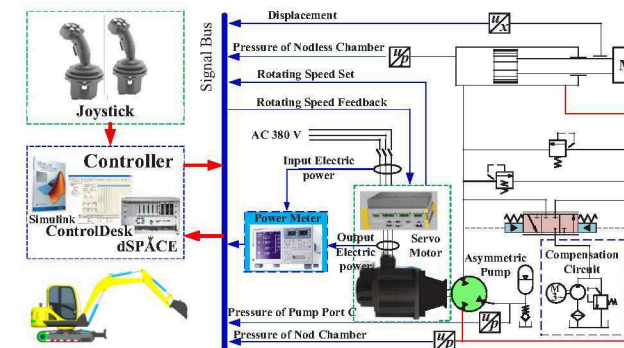


Fig.4 Experiment platform

As shown in Fig.4, the boom cylinder is controlled by an asymmetric pump driven by a servo motor. A small gear pump is introduced to compensate the unbalanced flow caused by leakage. And also, there are additional instruments such as displacement sensor in the actuator, pressure sensors on the pump and cylinder, power sensor and rotational speed sensor on the motor which are employed to detect the corresponding variables. The circuit control concepts are being realized by ds1103. The test rig and instruments are shown in Fig.5.



Fig.5 Photograph of mini-excavator with the proposed system

3.1 Working performance and energy efficiency

3.1.1 With independent metering system

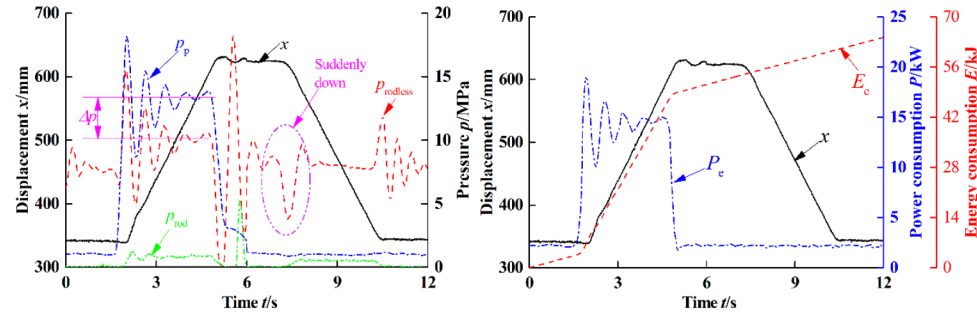
The main task of the boom cylinder is to lift the working mechanism and load to the specified position. Its operational characteristics are that the load condition during the extension process is resistance mainly, and which is overrunning mainly during the retraction process.

In the process of frequent retraction, the gravitational potential energy of the working mechanism is dissipated into heat in the control valves, and the pump still outputs the flow to the cylinder during the overrunning retraction process. A simple way to reduce the energy consumption is using the flow regeneration technology. In this paper, when the boom cylinder extends, the inlet and outlet oil valves open fully to reduce throttling loss. And then the regeneration technology is used when the boom cylinder retracts.

The pressures of the system and position of the boom cylinder with respect to time are presented in Fig.6 (a). It can be seen that the pressure of the pump, p_p , is about 13.0 MPa and the pressure in the cylinder rodless cavity, $p_{problems}$, is about 10.1 MPa and which is 0.8 MPa in the rod cavity. Thus, the pressure loss of the system, Δp , is

about 2.9 MPa. By referring to the results, during boom cylinder extension process, the pump pressure tends to oscillate which is similar to the load sensing system. And, there is a sudden decrease pressure during the startup stage of the cylinder retraction.

Fig.6 (b) gives the electric power and energy input to the inverter, when the boom cylinder velocity is about 100 mm/s. It can be seen that the electric power input to the inverter, P_e , is about 14.5 kW during the boom cylinder extending the process, and which is 2.3 kW during the cylinder retraction and non-working process. During a complete extension and retraction process, the energy input to the inverter, E_e , is about 64.2 kJ.

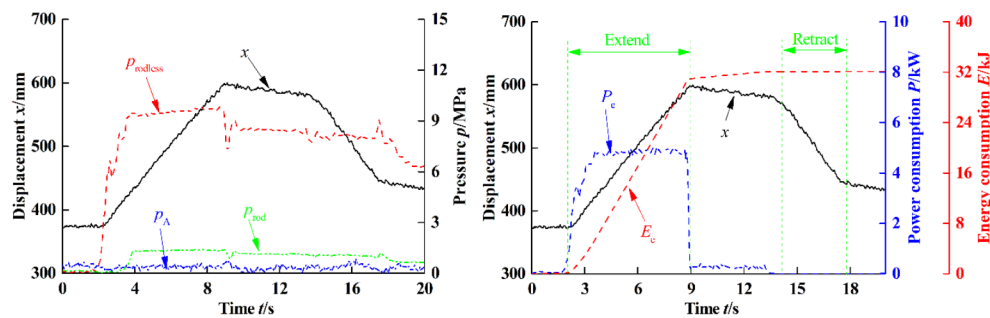


(a) System pressure (b) Energy consumption

Fig.6 Pressure and energy consumption when boom working with independent metering system

3.1.2 Simple asymmetric pump controlled without energy recovery

Fig.7 gives the measured cylinder displacement, pump pressure, electric power, and energy input to the inverter, and the hydraulic energy output of the pump, when the pump port T is connected to the oil tank. During 0 ~ 2 s, 9 ~ 14 s and 17.8 ~ 20 s, the control signal is zero, the speed of the motor is set to zero and the hydraulic cylinder does not move. It can be seen that when the speed of the servo motor is zero, the cylinder displacement goes down gradually due to the leakage.



(a) System pressure (b) Energy consumption

Fig.7 Pressure and energy consumption when boom working with asymmetric pump controlled system

As shown in Fig.7 (a), it can be seen that, during the extension process, the pressure of pump port A and cylinder rodless cavity, $p_{rodless}$, is about 9.6 MPa and which is 1.4 MPa in the rod cavity. And during the working process, the pressure in the cylinder is respectively stability.

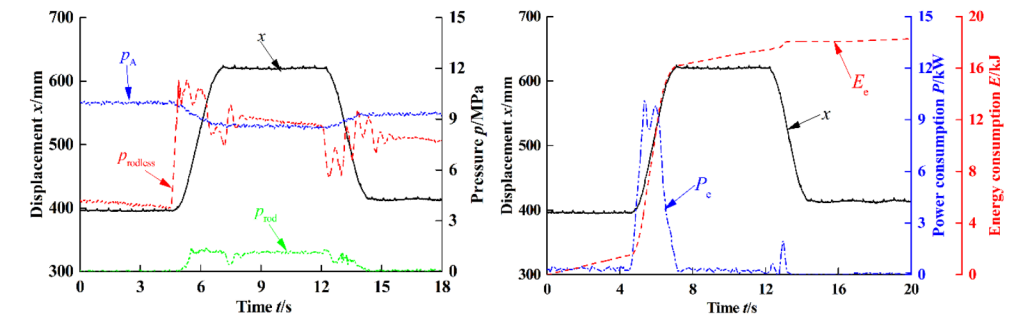
Fig.7 (b) gives the electric power and energy input to the inverter, when the boom cylinder velocity is about 40 mm/s. It can be seen that the electric power input to the inverter, P_e , is about 4.9 kW during the boom cylinder extending the process, and which is 3 W during the cylinder retraction and non-working process. Compared to

the independent metering system, the power consumption can be reduced about 2.0 kW during cylinder retraction with the asymmetric pump controlled system.

During an extension process, the energy input to the inverter, E_e , is about 31.0 kJ, and which is 32.1 kJ during a complete extension and retraction process. The energy consumption per stroke during the extension process can be calculated as $\Delta E_e / \Delta x$, which is about 0.14 kJ/mm. And it is about 0.20 kJ/mm with the independent metering system. Thus, it can be concluded that the energy saving ratio is about 30%.

3.1.3 Asymmetric pump controlled with energy recovery

Fig.8 gives the measured cylinder displacement, pump pressure, electric power, and energy input to the inverter, and the hydraulic energy output of the pump, when the pump port T is connected with an accumulator, in which the oil pressure is the same with the pressure in the cylinder rodless. In order to decrease the leakage impact on the cylinder displacement, we designed an position closed loop method when the control signal is zero and it works well. In addition, we can add two valves to cut the connection between the pump and cylinder.



(a) System pressure (b) Energy consumption

Fig.8 Pressure and energy consumption when boom working with asymmetric pump controlled system

As shown in Fig.8 (a), it can be seen that, during the extension process, the pressure of pump port A and cylinder rodless cavity, $p_{rodless}$, is about 10.4 MPa and which is 1.2 MPa in the rod cavity. And during the working process, the pressure in the cylinder is respectively stability.

Fig.8 (b) gives the electric power and energy input to the inverter when the boom cylinder velocity is about 40 mm/s. It can be seen that the electric power input to the inverter, P_e , is about 9.24 kW during the boom cylinder extending the process, and which is 3 W during the cylinder retraction and non-working process. During a complete extension, the energy input to the inverter, E_e , is about 16.2 kJ, and which is 18.3 kJ during the extension and retraction process. The energy consumption per stroke during the extension process is about 0.07 kJ/mm. And it is about 0.16 kJ/mm with the independent metering system. Thus, it can be concluded that the energy saving ratio is about 56%.

3.2 Energy consumption compared under different velocity

The experiments were conducted on an excavator and the cylinder displacement relies on person operation, which is often difficult to guarantee the same for each test. Thus, the energy consumption can be compared with energy consumption per stroke, which is calculated as $\Delta E_e / \Delta x$.

Fig.9 gives the comparison of energy consumption per stroke under different velocities with pump and valve controlled system. The results show that the energy consumption of the two system decreases as the velocity increases. The energy efficiency increasing of the electric motor is the main cause of this phenomenon. Compared to the independent metering system, the asymmetric pump controlled system was 50% more efficient

during the extension process. With the Figs.7-9, the estimated 41% of the potential energy could be regenerated and the utilization efficiency reaches to 90%.

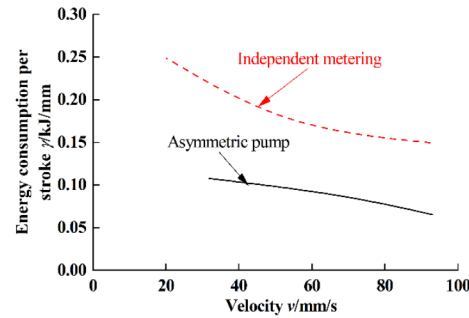


Fig.9 Energy consumption under different velocities

4 Conclusion

Due to large throttling loss and gravitational potential wasting, the energy efficiency of the hydraulic excavator is low, which is even lower than 10%. This paper aims to improve the energy efficiency of the hydraulic excavator by reducing throttling loss and regenerating potential energy directly. The system under consideration utilizes a newly designed asymmetric pump which has three ports, the two are connected to the hydraulic cylinder, the other is connected to an accumulator. Thus, this system can regenerate the potential energy directly without throttling loss and the utilization efficiency reaches to 90% which is very high than an existed project.

And compared with an independent metering circuit driven by a convert motor, the working performance of the excavator boom system with the asymmetric pump is stable. Compared with the independent metering circuit, the electric power consumption during the boom going up can be reduced by more than 40%. And if the energy efficiency of the power source is considered, during the whole process of the boom cylinder working, the energy consumption can be reduced by 50%.

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Nomenclature

Variable	Description	Unit
A_A	Area of the Cylinder Rodless	[m ²]
A_B	Area of the Cylinder Rod	[m ²]
B_c	Viscous Damping Coefficient	[Ns/m]
B_m	Rotional Viscous Damping Coefficient	[Nms/rad]
D_A	Displacements of the Pump Ports A ₁	[m ³]
D_B	Displacements of the Pump Ports B ₁	[m ³]
D_C	Displacements of the Pump Ports C ₁	[m ³]

F	Load Force of the Cylinder	[N]
J	Moment of Inertia	[kgm ²]
m	Inertia Mass Load	[kg]
n	Rational Speed of the Servo Motor	[rev/s]
p_A	Pressure in Cylinder Rodless Chamber	[MPa]
p_B	Pressure in Cylinder Rod Chamber	[MPa]
p_C	Pressure in Accumulator	[MPa]
q_1	Flow Rate into Cylinder Rodless Chamber	[L/min]
q_2	Flow Rate out Cylinder Rod Chamber	[L/min]
T_m	Torque of Pump	[Nm]
v	Cylinder Velocity	[m/s]
V_1	Volumes of the Rodless Chamber	[m ³]
V_2	Volumes of the Rod Chamber	[m ³]
β_e	Bulk modulus	[N/m ²]
η	Energy Efficiency of Pump	[-]

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