EXPERIMENTAL EVALUATION OF SYSTEM EFFICIENCY FOR A HYDRAULIC HYBRID ARCHITECTURE OF EXCAVATORS

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DOI : 10.17973/MMSJ.2018_10_201836

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Development and research for an Open Center System (OC-System), which is typically used for excavators, has been conducted from the perspective of hydraulic efficiency. However, total system efficiency including the internal combustion engine (ICE) has not been considered thoroughly. On the other hand, a Constant Pressure System (CP-System) enabling the engine to be driven optimally is developed but is not accepted in the industry due to the complexity of the required components. Thus in this research, a hybrid system combining an OC-System with a CP-System is proposed enhancing the total system efficiency. The new system consists of an open center valve, an accumulator and a minimum of required components for the CP-System. In order to confirm the system efficiency, experiments are conducted with a test rig based on a 7t excavator. The test results lead to an estimated reduction in fuel consumption of 16 % compared to the conventional OC-System.

KEYWORDS

hydraulic hybrid, open center, constant pressure, system efficiency, mobile hydraulics, excavators

1 INTRODUCTION

During recent years, in an attempt to improve efficiency of hydraulic excavators, a number of new hydraulic systems have been proposed in the world [Busquets et al. 2016] [Dengler et al. 2012] [Egawa et al. 2011] [Siebert et al. 2016] [Pöttker 2006]. One of the most common valve controlled architectures is an OC-System [Nakamura et al. 2012]. Advantages of this system are simple configuration and high efficiency when a pump provides flow rate to only one actuator because of low throttling losses between the pump and the actuator. However, when the single pump supplies fluid to multiple actuators simultaneously throttling losses are unavoidable due to the mismatch between the pump's pressure level, low pressure level actuators and high pressure level actuators. Moreover, in this system, the ICE is not driven optimally resulting in poor total energy efficiency.

To improve the total efficiency ifas at RWTH Aachen University proposed a CP-System, called STEAM [Vukovic et al. 2013] [Vukovic et al. 2016], see Figure 1. This system consists of a large number of switching valves, two accumulators used for driving actuators and a pump for charging the accumulators. The most important feature is that the rotational speed of the ICE is fixed in a high efficiency region. Moreover, by using switching valves, installed at the piston and the rod side of a cylinder and connected to the accumulators, this system can create different cylinder forces which contribute to the reduction of throttling losses and recuperate actuator energy. There are, however, some disadvantages. Since a high number of switching valves is needed, acceptance of the system in the industry is difficult.

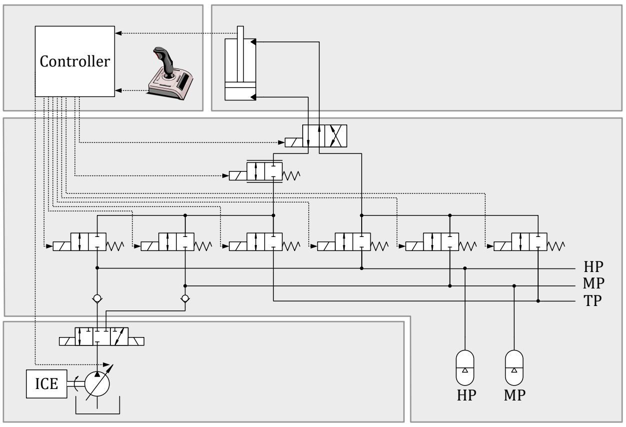

Figure 1. STEAM System

For improving this problem, the authors propose a new hybrid system combining an OC-System and a CP-System [Hijikata et al. 2018]. This paper begins to introduce basic principles of the new system, and then experimental results are shown in comparison to a conventional system. In this research the OC-System is used as a reference system.

2 NEW HYBRID ARCHITECTURE

In this research, a levelling cycle is used to design the new hybrid system. Figure 2 shows an outline of this cycle. This cycle consists of two motions. During the roll-in motion, the arm is pulled to the machine and the boom is lifted slightly. The next motion is roll-out and return to the initial position. These figures show the strokes of each actuator.

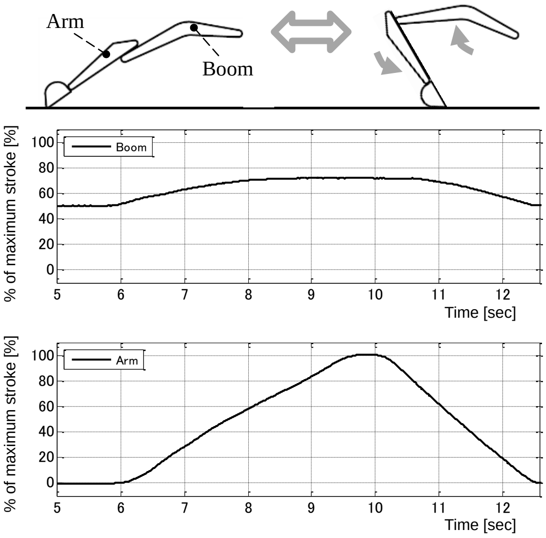

Figure 2. Leveling cycle

Figure 3 shows the hydraulic circuit of the new hybrid system. The new system consists of open center valves used as a basic hydraulic system, the accumulator and a minimum of required components which are two valves with proportional solenoids and a pressure sensor measuring pressure level of the accumulator. Moreover in order to charge the accumulator with a pump, electrical actuation applies to a proportional valve 5 in the open center valves. All valves with the proportional solenoids are controlled by a controller based on joystick signals and value of the pressure sensor. Proportional directional valves from 1 to 4 in the open center valves are operated with hydraulic actuation depending joystick signals. Compared to conventional OC-Systems, the accumulator, the additional valves which are the two valves with proportional solenoids, the pressure sensor for the accumulator, the electrical actuation for one proportional valve of the open center valves and the controller are added to the new system. By using the open center valves, this architecture results in a simple configuration.

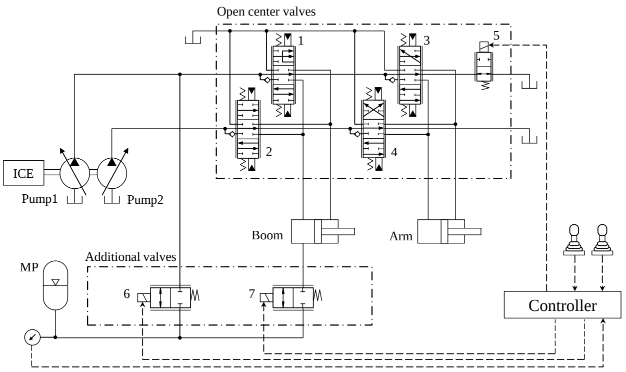

Figure 3. Hydraulic circuit of new hybrid system

This system is designed based on three basic principles from the perspective of energy efficiency.

First, boom energy can be recuperated using the accumulator and stored energy can be provided to actuators. Thus, the pump's power for this system can be reduced by using recuperated energy. Second, the flow rate to the actuators with quite lower or higher pressure level than the accumulator pressure level is provided directly from the pumps. For example, if the actuator with a low pressure level is powered by the accumulator, a large differential pressure between the accumulator and the actuator occurs. Moreover, if the accumulator pressure level is set to the highest actuator pressure, large throttling losses will occur between the accumulator and other actuators which have a lower pressure level. In the levelling cycle during roll-in, the arm cylinder operates in the low pressure region and during roll-out the highest pressure region. Thus the flow rate of the arm is provided by the pump directly, and the accumulator pressure level set to the lower pressure level compared to the highest pressure level of the actuator. Third, the ICE can be operated in the high efficiency region like the STEAM-System. For explanation, a simple relative efficiency map of the ICE is shown in Figure 4. Generally the high efficiency region extensively appears at lower rotation speeds than are used in today's conventional excavators. Moreover, the ICE's friction depending on rotation speeds can be reduced at lower rotation speeds than higher rotation speeds. Therefore, the ICE is set to a low rotation speed. The reduction of the ICE's power resulting from altering the high rotation speed into the low rotation speed is compensated by the accumulators.

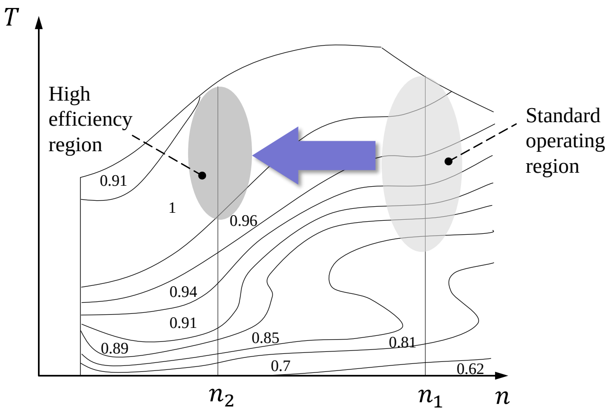

Figure 4. Schematic relative efficiency map of ICE

Table 1 shows which actuator is powered by the pumps or the accumulator and is decided based on three basic principles which were explained. In levelling roll-in motion, flow rate of the pump 1 and the pump 2 goes to an arm bottom side through the valve 3 and the valve 4 due to the low pressure level of the arm cylinder. For the boom, flow rate is provided by the accumulator with valve 7, and a boom rod side connects to a tank through valve 1 and valve 2 in the open center valves. Therefore an additional valve for connecting the boom rod side to the tank is not necessary. According the levelling roll-out motion, the pump 2 sends flow rate to the arm rod side with the valve 4, and the pump 1 charges the accumulator. For that, the valve 5 should be closed and the valve 6 should be opened.

The pressure level of the accumulator is basically higher than pressure level of the boom bottom side because of providing flow rate to the boom from the accumulator. This means that it is impossible to recuperate the boom energy with the accumulator during a boom down motion. In order to resolve this problem, the bottom side and the rod side of the boom are connected with the valve 1 in the open center valves. This results in approx. double of the pressure of the bottom side for the cylinder of the boom. Namely, the pressure level of the boom becomes higher than the pressure level of the accumulator during the boom down motion. Thus, the accumulator recuperates boom potential energy.

Motions	Pump1	Pump2	MP
Levelling Roll-in	- Arm	- Arm	- Boom
Levelling Roll-out	- Accumulator charge	- Arm	- Boom recuperation

Table 1. Flow distribution matrix in levelling motion

3 TEST RIG FOR EXPERIMENTAL EVALUATION OF SYSTEM EFFICIENCY

In order to confirm the system efficiency of the new hybrid system, experiments are conducted with a test rig based on the 7t excavator. In this research, only a levelling cycle is used. A digging cycle with soil is not conducted. The test rig consists of a front-end attachment of a 7t excavator, its main control valves, an accumulator (32 L), and additional valves for the CP-System. An electric motor (55 kW) is installed to drive pumps instead of an ICE. The system efficiency is compared by measuring torque and speed of the shaft of the pumps and calculating fuel consumption with this measurement data and the efficiency map of the ICE. Moreover, the actuator's energy is calculated by measurement data of cylinder strokes and pressure levels in order to compare the system efficiency. In figure 5, the setup of the test rig is shown.

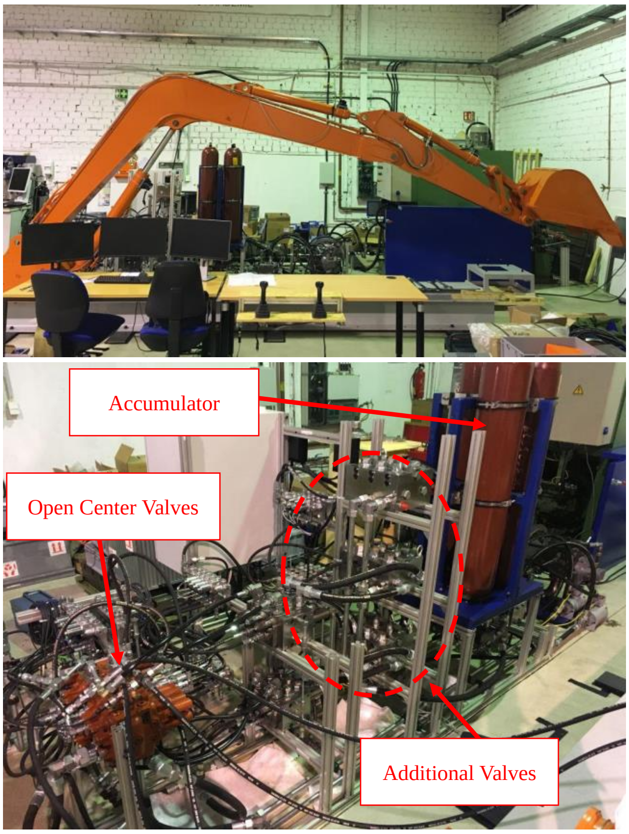

Figure 5. Test rig based on 7t excavator

Figure 6 indicates a hydraulic circuit of the test rig. To measure value needed for calculation of the system efficiency, a torque sensor and a speed sensor are installed on the shaft of the pumps, and also pressure sensors for the pumps and the cylinders, flow rate sensors for the pumps and stroke sensors for the cylinders are added.

The test rig can be operated with two modes. One is the standard mode, where only pumps and open center valves are used to drive actuators, and another mode is the hybrid mode in which the accumulator and the additional valves are used. Therefore, by using this test rig, the system efficiency of the standard and the hybrid mode can be compared. To use two modes, actuation of valves in the open center valves is changed to electrical actuation. Moreover, since the open center valves are used for the standard mode, valve 1 and valve2 can not be used for the hybrid mode. Therefore valve 8 and valve 9 are added for the hybrid mode in the test rig.

Pump speed of the hybrid mode is reduced by 30% against the standard mode based on the basic principle. The accumulator is set to about 40 % of maximum pressure, corresponding to the pressure level of the boom to provide flow rate to the boom with low throttling losses.

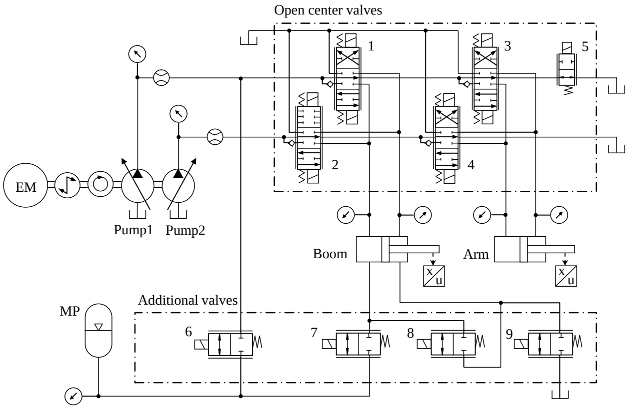

Figure 6. Hydraulic circuit of test rig

In figure 7 hybrid mode operations are shown in the levelling roll-in motion. Both pumps provide flow rate to the arm, and the accumulator is used to supply flow rate to the boom.

In the standard mode, the pumps and the open center valves are only used. Namely in the levelling roll-in motion for the standard mode, the pump 1 sends flow rate to the boom bottom side through the valve 1, and the pump 2 provides flow rate to the arm bottom side through the valve 4. The valve 2 and the valve 3 are not used in this motion for the standard mode.

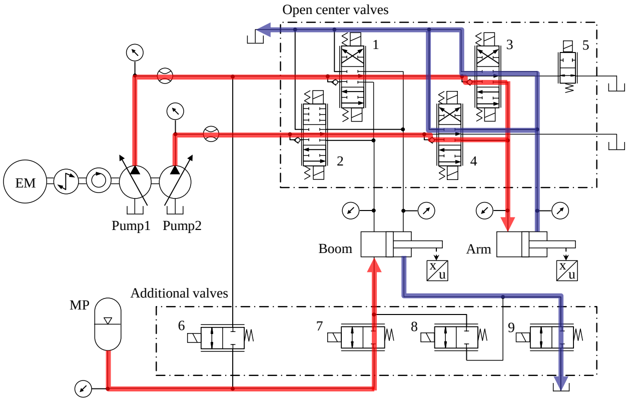

Figure 7. Levelling roll-in motion

In figure 8 hybrid mode operations in the levelling roll-in motion are shown. In this motion, the flow rate for the arm cylinder is provided by pumps. The boom energy can be recuperated by the accumulator, and at the same time, the bottom side and the rod side of the boom are connected with the valve 8 to increase the pressure level of the boom bottom side. During levelling roll-out motion, the accumulator can be charged with the pump.

In the levelling roll-out motion for the standard mode, the pump 1 sends flow rate to the boom rod side through the valve 1, and the pump 2 provides flow rate to the arm rod side through the valve 4.

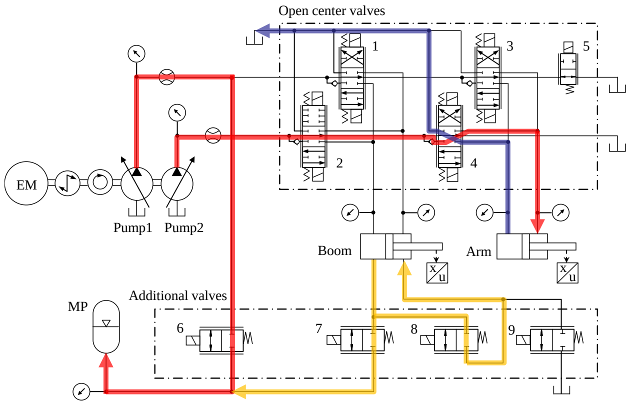

Figure 8. Levelling roll-out motion

4 TEST RESULTS

The experiments were conducted with three levelling cycles. In figure 8, experimental results of three strokes are shown. The upper figure is the boom and the lower figure indicates the arm. The black line is the standard mode and the red dash line shows the hybrid mode. In the experiments, the three levelling cycles for the hybrid mode are a little slower than the standard mode since there are time-gaps for the arm strokes of the hybrid mode between the end of the first cycle and the start of the second cycle (around 15 sec) and between the end of the second cycle and the start of the third cycle (around 26 sec). The reason for this is that the levelling cycles are operated manually. The system efficiency is calculated based on used energy of diesel fuel from the start of the first cycle and the end of the third cycle for each mode. Therefore, it is expected that hybrid mode energy increases a little due to the small time-gaps. This results in a slightly reduced system efficiency for the hybrid mode. Using these measurement data, the system efficiency can be estimated.

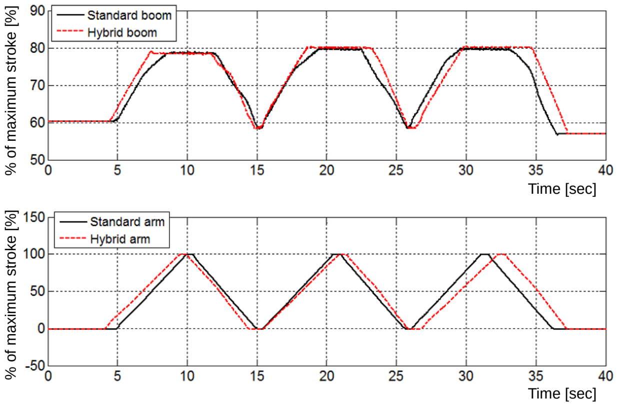

Figure 9. Experiment result for leveling cycle

In figure 9, a sankey diagram is shown in order to compare the system efficiency of the OC-System with the new hybrid system. The diagram indicates how much energy of diesel fuel was used for driving actuators and how much dissipated as heat losses in the machine. Energy of the blue area is estimated by measuring torque and speed of the shaft of the pumps and the efficiency map of the ICE. Energy of the gray area is calculated by only measurement data such as pump pressure levels, pump flow rate, cylinder strokes and cylinder pressure levels. According to the OC-System, 66.0 % of diesel fuel is dissipated as ICE losses, and also 9.5 % are auxiliary and pump losses. Moreover, 15.9 % are throttling losses in the valves and hoses. The OC-System can not recuperate actuator energy, and therefore recoverable energy is also dissipated as losses. Thus, only 6.7 % of diesel fuel energy is used for driving actuators. On the other hand, in the new system, 7.9 % of diesel fuel energy could be used in order to power cylinders. The reasons for the system efficiency improvement are the efficient operation of the ICE, the reduction of auxiliary and pump losses due to the ICE'S low rotation speed and recuperation of boom energy. Throttling losses in the valves in the new system increase due to charging the accumulator by the pumps. However, there is another reason for that. The ratio of throttling losses against diesel fuel energy goes up since diesel fuel energy of the new system as a denominator of the system efficiency is smaller than the OC-System.

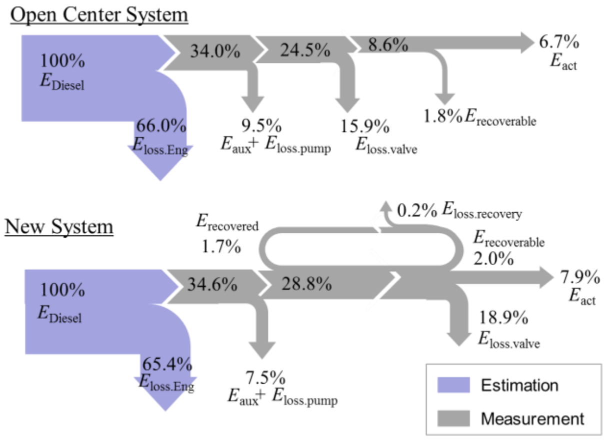

Figure 10. Sankey diagram for system efficiency

The fuel consumptions of both systems are shown in Figure 10. The result was calculated based on the ICE'S efficiency map and the pump's shaft power which was measured by the test rig. The new system consumes 16 % less fuel than the OC-System during the levelling cycle.

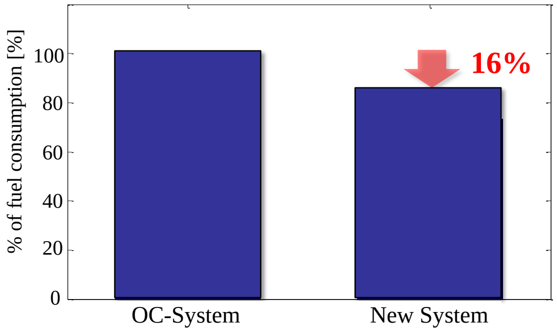

Figure 11. Comparison of fuel consumption for each system

5 CONCLUSIONS

A new system, which combines advantages of the OC-System and the CP-System, has been proposed. In particular, the new system is designed based on three basic principles, which are recuperating energy by an accumulator, providing flow rate from the pump directly and high efficient operation of ICE. In order to estimate the system efficiency and compare the fuel consumptions for the levelling cycle, the test rig was built based on a 7t excavator. Experiments with the test rig, show that the efficiency of the new system improves from 6.7 % to 7.9 % compared to the OC-System. Moreover, the experimental results show that the new system consumes 16 % less fuel than the OC-System for one sample levelling cycle. In the next phase, based on this test results a validated simulation model will be developed, and also other duty cycles will be considered with this model.

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