A Hydraulic Hybrid Architecture combining an Open Center with a Constant Pressure System for Excavators

REVIEWED

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Although energy efficiency of an Open Center System (OC-System), used widely for excavators, has been improved from the perspective of hydraulic efficiency, total efficiency including the engine has not been taken into account sufficiently. Meanwhile, a Constant Pressure System (CP-System) enabling the engine to be driven optimally is developed but is not accepted in the industry due to complexity of components. Thus in this research, a hybrid system combining an OC-System with a CP-System is proposed enhancing total efficiency. This system is designed for simulation based on the basic theory and the analysis of measurement data. The simulation shows it consumes 30 % less fuel than the conventional OC-System.

Keywords: Hydraulic Hybrid, Open Center, Constant Pressure, Energy Efficiency
Target audience: Mobile Hydraulics, Systems

1 Introduction

In recent years, a number of new hydraulic systems for hydraulic excavators have been proposed and developed in the world aiming to decrease the environmental awareness and operating costs /1//2//3//4//5/. Almost all of today's hydraulic excavators use valve controlled systems with the advantage that multiple actuators can be powered simultaneously by a common pressure supply. One of the most common valve controlled architectures is an OC-System.

In the conventional OC-System, throttling losses are unavoidable when a single pump supplies fluid to some actuators simultaneously due to the mismatch of required pressure levels. To eliminate these losses, a Three Pump Open Center System (TPOC-System) based on an OC-System was developed /6//7/. This system is shown in Figure 1.

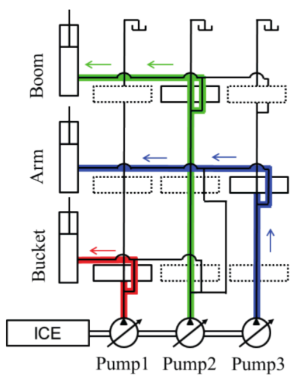

Figure 1: Outline of hydraulic system for TPOC-System

By using three pumps all three hydraulic actuators are powered by individual pumps, and therefore throttling losses are almost completely eliminated. On the other hand, the system features some shortcomings which are increased system costs and complexity and its higher drag losses caused by three large pumps in comparison to a two pump system. Moreover, the internal combustion engine (ICE) is not driven optimally resulting in poor total energy efficiency.

To improve the total efficiency of the hydraulic excavator, it is necessary to consider the ICE, because more than 60% of the fuel´s thermal energy is lost. IFAS at RWTH Aachen proposed a system, called STEAM aiming to increase the efficiency of the whole excavator, see Figure 2. This system basically consists of three pressure rails with high, medium and tank pressure (HP, MP and TP) /8//9//10/.

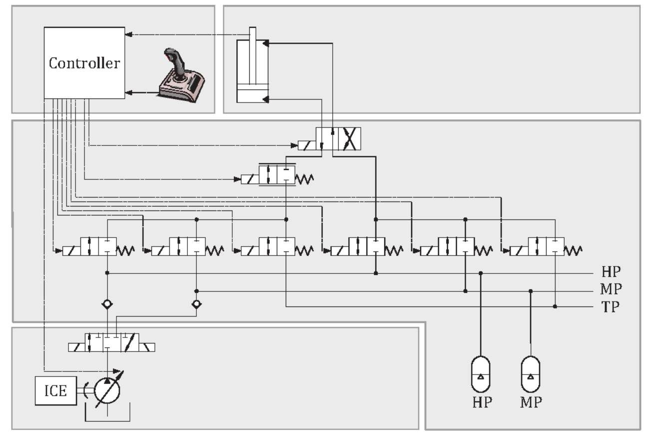

Figure 2: STEAM-System

The most important feature is that the ICE can always be driven at the most efficient operating point. Since the hydraulic actuators of this system are powered by constant pressure rails, a main pump which is mechanically connected to the ICE is only used to charge the accumulators. The pressure levels of the pump are automatically given by the accumulators, but the flow rate to charge the accumulators is able to be selected freely. Thus pump flow rate can be regulated to achieve an optional braking torque for the ICE, only at the most efficient spot in the engine efficiency map.

Moreover, in this system, six switching valves are installed for each linear actuator. Optimal combination of the pressure rails can, therefore, reduce throttling losses. This basic concept not only contributes to the hydraulic system efficiency but also the total system efficiency.

There are, however, some disadvantages. Since a great number of switching valves electronic controls are needed, it is expected that it is difficult to be accepted by the industry and its customers. Another disadvantage is that the high efficiency of the hydraulic system is not expected for the TPOC-System, because relatively large throttling losses should occur due to the mismatch between the required pressure level and the actually provided pressure level. Therefore, the purpose of this study is set to design a new hybrid system which combines the advantages of OC-System with CP-System, while at the same time eliminating their disadvantages. In this research the TPOC-System is used as a reference system.

2 Basic Principles

In order to explain the principles of the new hybrid system, the excavator's actuator status is explained at first. Figure 3 describes the load situation for the actuators. The x-axis shows the flow required by each actuator (Q_L), the y-axis shows the force or load pressure (p_L) of the actuator.

Depending on the movement, each actuator experiences either a resistive force opposing its motion (Q I and Q III) or an assistive force aiding its motion (Q II and Q IV). Consequently, in quadrants I and III the actuator must be actively supplied with power, while in quadrants II and IV, the actuators can actually supply power to the system.

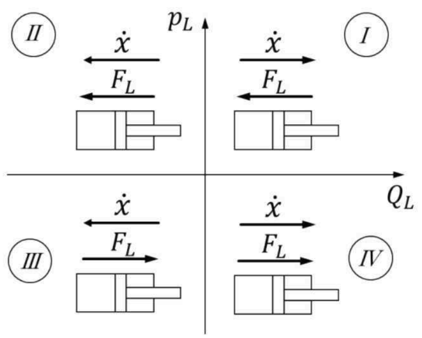

Figure 3: Load quadrants of hydraulic cylinder

2.1 Operating Modes of CP-System

STEAM has operating modes which have different ways of connecting an actuator to the three pressure rails, see Figure 4. The switching valves, which are installed at the piston and rod sides of the cylinders and connect to the three pressure rails, generate nine modes leading to nine different cylinder forces.

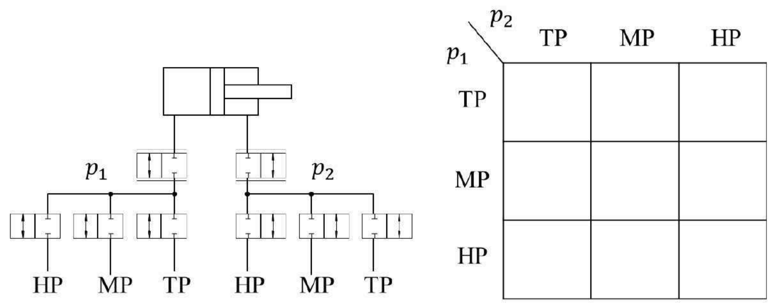

Figure 4: System operating modes

Figure 5 describes all nine modes labelled in load quadrants of the hydraulic cylinder. For example, the first label of MP/HP shows that the medium pressure is connected to the piston side and the second label of that indicates that the high pressure is connected to the rod side. The position of the modes depends on the HP, MP and TP pressure levels as well as the piston area ratio α. The lines passing through quadrants one and three can be used to actively supply an actuator with flow, while the lines passing through quadrants two and four allow energy to be recovered from the actuator and stored in one of the accumulators.

According to switching modes, when a resistive force occurs such as OP_1 in Figure 5, mode HP/HP lying directly above the current operating point is selected in order to minimize throttling losses. When an assistive force occurs such as OP_2, MP/MP lying directly below the current operating point is selected.

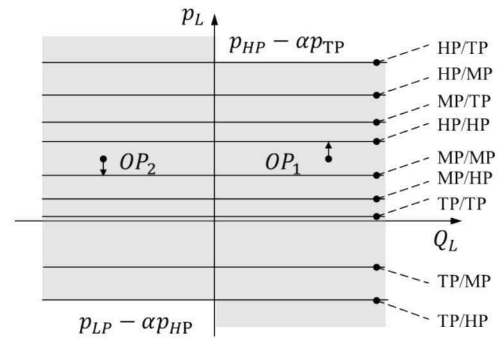

Figure 5: Region of operation of all nine modes

In this way, throttling losses of the CP-System can be reduced by using the three pressure rails, however the usage of the three pressure rails cannot promise sufficient total energy efficiency. Normally the higher pressure level of HP must be set to be equal to the maximum operating pressure of the conventional machines to keep the same performances. This results in large throttling losses due to expanding pressure differences between respective modes. Thus, high efficiency for the total system is not expected due to throttling losses.

In order to overcome this problem, STEAM has also proposed to reduce the pressure level of HP. As shown in Figure 6, by changing HP from p_{HP1} to p_{HP2}, it is possible to reduce throttling losses occurring in regions of respective modes. A problem of the system is that the HP cannot supply to loads requiring higher pressure levels than p_{HP2}. In such a case the main pump can supply the fluid to the loads directly.

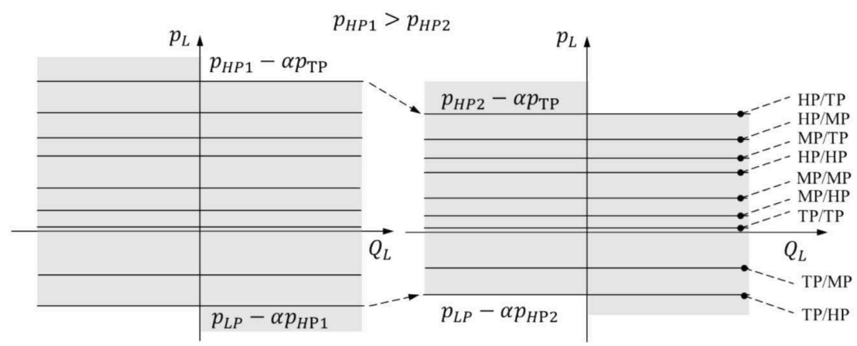

Figure 6: Comparison of regions of operation against HP

Nevertheless, when the cylinder is operated in a low resistive force, throttling losses between the cylinder and the accumulators increase relatively against the pressure levels of the cylinder. For example, a maximum operating pressure level of an excavator is set to 300 bar, and if throttling losses between the cylinder and the accumulators are 20 bar, those losses do not seem to be large against the maximum operating pressure. However, if the load pressure of the cylinder is 30 bar, and moreover throttling losses occurring between the cylinder and the accumulators are 20 bar, those losses are quite large against the load pressure of that. Thus, total system efficiency in the regions of the low resistive force is not high due to large throttling losses.

There is, moreover, a possibility that energy efficiency becomes worse for a low assistive load. In quadrants IV of Figure 5, mode TP/TP is used while the assistive load is lower than TP/MP against the negative direction. In this case, both sides of the cylinder are connected to the tank, and thus, there is a risk for cavitation occurring on the meter-in side of the cylinder. This causes that the braking performance of the cylinder becomes worse and results in poor controllability in a machine for an operator. Therefore, it is difficult to use this mode in real machines. MP/HP mode, which is able to provide flow rate to the meter-in side of the cylinder, can be used as other solution to prevent cavitation. Nevertheless, if a cycle with a low assistive load and a low resistive load such as levelling cycle continues for a long time, a lot of fluid is sent to HP due to connecting the rod side of the cylinder to HP in quadrants I. In this situation, HP cannot efficiently provide flow rate to cylinders with a low assistive load and a low resistive load due to quite large throttling losses.

In conclusion, while the assistive load and the resistive load see low levels, throttling losses become quite large and the benefit generated by the efficient operation of the ICE is lost.

2.2 New hybrid architecture

To reduce throttling losses and complexity of valves, the authors propose a new hybrid system. The hybrid system combines a Two Pump Open Center System with two constant pressure rails. The reason of using Two Pump Open Center System is that the system is most commonly used in current mobile applications. Thus easy installation and low cost are expected in real machines. An important characteristic of this system is that the pumps directly provide flow rate to the cylinders not only for the high resistive force but also low resistive and assistive force, see Figure 7.

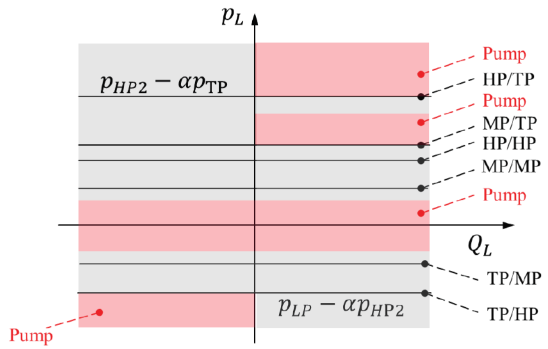

Figure 7: Regions of operation with direct supply by pumps

Since in the case of a high resistive force the cylinder is driven by the main pump, the pressure level of HP can be reduced. Thus, throttling losses occurring in regions of respective modes are reduced. This system can also decrease throttling losses between the cylinder with the low pressure level and the accumulators because the cylinder with the low pressure level is driven by the main pumps as well. Furthermore, by driving the cylinder in a part of medium resistive force with the main pump, several switching valves can be reduced. The outline of the new system is shown in Figure 8. Because it is possible to use the OC-System valves, the simple configuration can be realized by adding a minimum of required components.

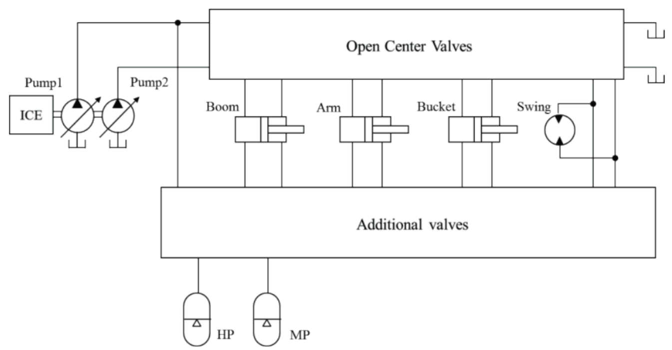

Figure 8: Outline of new hybrid system

It's quite important to use the ICE in high efficiency operation to improve the total system efficiency. For considering that, a sample relative efficiency map of the ICE is shown in Figure 9. Generally the high efficiency region appears at lower rotation speeds than high rotation speeds which are used in today's conventional excavators. 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.

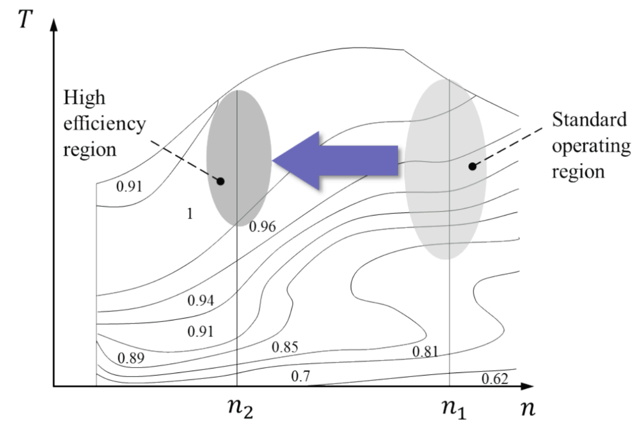

Figure 9: Sample relative efficiency map of ICE

3 Design of new system

At first, the data analysis of the typical cycle of the excavator was conducted in order to design the hydraulic circuit of the new system for a simulation model. In this research, measurement data of the levelling cycle which was measured using a 20-ton excavator. Figure 10 shows an outline of this cycle. This cycle consists of two motions. In the roll-in motion, the arm is pulled to the machine side 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. The cycle time is about 7 seconds.

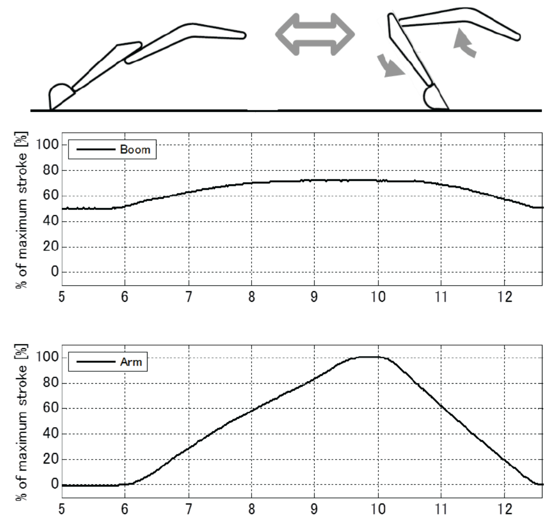

Figure 10: Levelling cycle

Figure 11 shows a histogram of load pressure levels and flow rate for each actuator. The left side of this figure shows the boom, and the right side indicates the arm. The load pressure levels of the boom during boom up and down motion appear frequently in about 25% of maximum pressure. The load pressure levels of the arm extending the piston in roll-in motion are shown mainly at about 5 % of the maximum pressure. On the other hand, the load pressure levels of the arm contracting the piston in roll-out motion appear mainly at about 10 % of the maximum pressure. They show that both boom motions and the arm contracting motion are operated in the medium load pressure levels, and the arm extending motion is operated in the low load pressure levels. In the levelling cycle, the load pressure levels are not high, and thus, in this research MP is only used as the constant pressure rail and the hydraulic circuit including HP will be considered in the next phase.

Based on the analysis of Figure 11, the cylinders with the medium load pressure levels are powered by the MP accumulator, and the arm extending motion with the low load pressure level is driven by the pumps directly, see Table1. Furthermore, during roll-out motion MP is charged by pump 1 and pump 2, and also the boom's potential energy can be recuperated by MP.

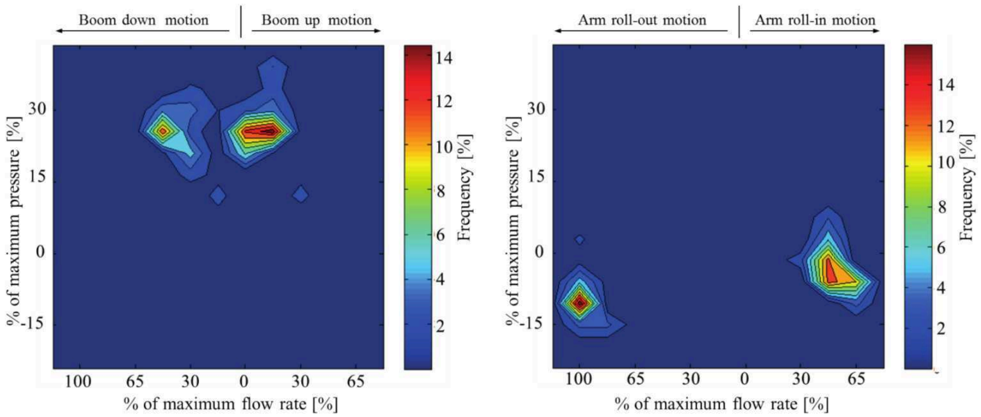

Figure 11: Analysis of levelling operation

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

Table 1: Flow distribution matrix

Figure 12 shows the hydraulic circuit of the new system in the simulation model. The upper area, framed with the dashed line, shows the open center valves, and the lower area, framed with the dashed line, shows the additional valves. Because the cylinders can be connected to the pumps and the tank by using the open center valves, the number of additional valves can be reduced. In order to drive the cylinder with the medium load pressure levels, MP is set to about 40 % of maximum pressure. However even if the bottom side of the boom during down motion is connected to MP, potential energy of the boom cannot be recuperated by MP due to the higher pressure level of the accumulator due to the pressure level of the boom. This means that the cylinder of the boom cannot be lowered by MP. In order to resolve this problem, the bottom side and the rod side of the boom are connected with 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 MP during boom down motion. Thus, MP which is set to about 40% of the maximum pressure can drive the cylinders in medium resistive force, recuperate boom potential energy and lower the cylinder of the boom.

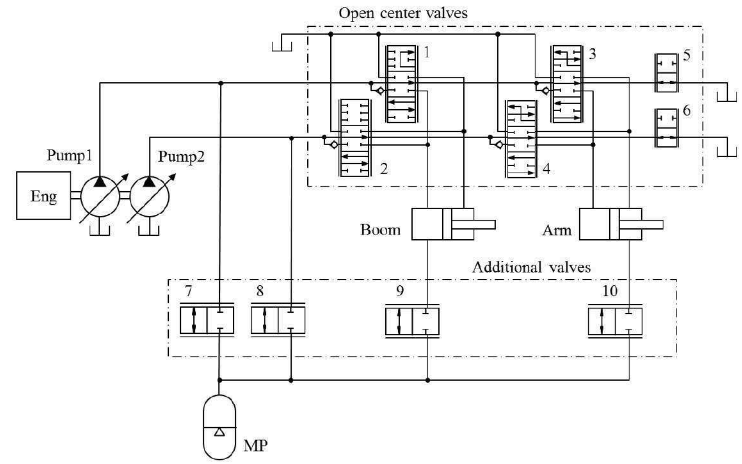

Figure 12: Hydraulic circuit of simulation model for new hybrid system

4 Simulation Model

Figure 13 shows the simulation model. The input signal and control logic are modelled using simulink, the hydraulic circuit is simulated by AMESim and multi-body dynamic model is made by Simulation X. All three programs are run in co-simulation. Measurement data was used as input signal.

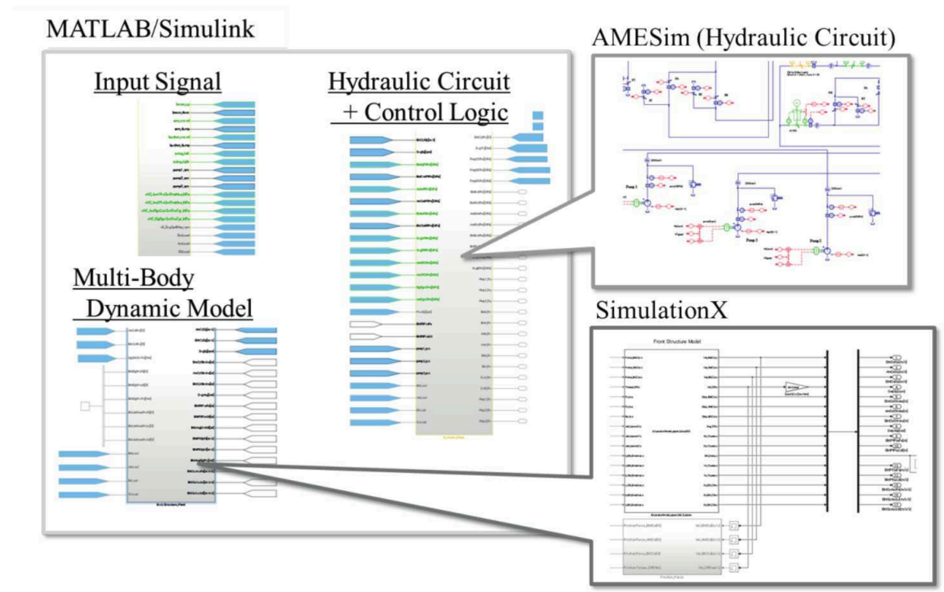

Figure 13: Simulation model

5 Simulation Results

The simulation is conducted with three levelling cycles. At first in Figure 14, simulation results of the boom are shown for only one cycle because of confirming behaviour of the new system. They show the stroke and the load pressure level of the cylinder. The pink lines indicate measurement data of the TPOC-System, and the black lines indicate the simulation results. Same behaviour for the simulation results of both systems is demanded against the stroke and the load pressure respectively because the boom, the arm and the motions of those should be same condition for each system to compare the fuel consumption fairly. The simulation results of the stroke are fairly accurate because the cylinder is driven in good accordance to the measurement. In the results of the load pressure level, nevertheless, the dynamic response of the simulation results do not correspond to the measurement data due to difference in stiffness of fluid between the simulation model and the real machine. In the phase of considering dynamic behaviour and a control logic, it is necessary to improve the hydraulic characteristics of the simulation model.

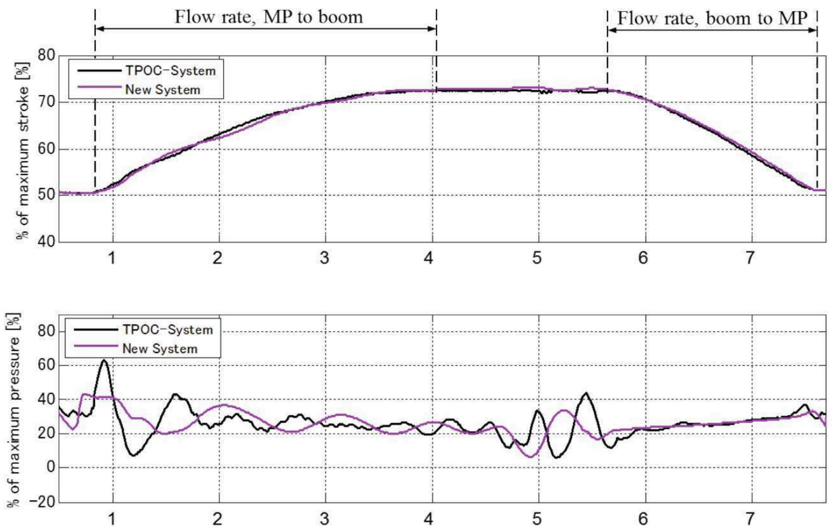

Figure 14: Simulation result of boom

Figure 15 displays the simulation results of the arm. As with the simulation results of the boom, they show stroke and load pressure levels. The simulation results correspond to the measurement data for the stroke very well. The load pressure levels also seem fairly good. According to from 4.6 s to 5 s there is a little pressure difference between the simulation results and the measurement data. However at this time, the cylinder of the arm reaches stroke end, and hardly moves. Thus, it does not relate to dynamic behaviour.

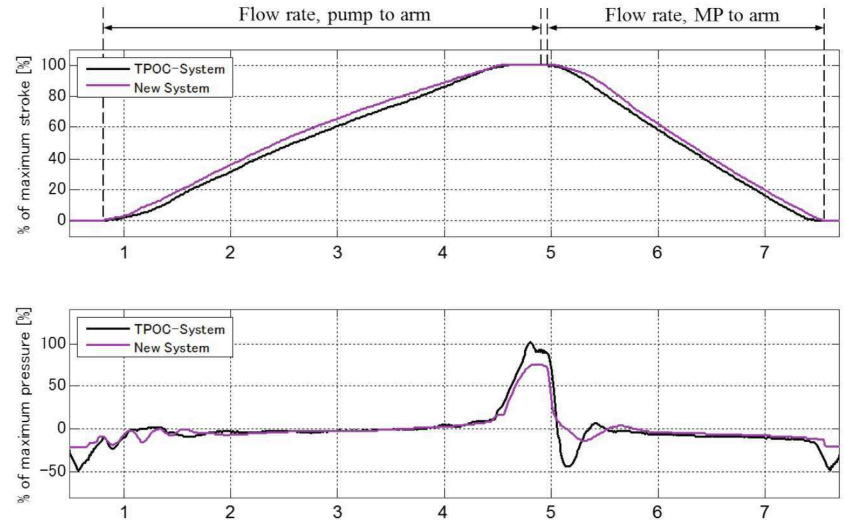

Figure 15: Simulation result of arm

Figure 16 shows power's distribution during the levelling cycle for simulation results only. The upper figure indicates the pump's power, and the lower figure is the accumulator's power. The power of the pump shows the total pump power for pump 1 and pump 2. During the roll-in motion, the arm is driven by the pumps, and the boom is powered by the MP accumulator respectively. During the roll-out motion, the MP accumulator provide flow rate to the arm, and moreover, the boom's potential power could be recuperated by the MP accumulator. Thus, the pump's power of this system can be reduced by using recuperated energy. From 4.7 s to 5.1 s for the upper figure, only pump 1 is used for charging the MP accumulator, and then both the pumps are used for that. It is recognized that the power of the pump and the accumulator are distributed to cylinders as shown in the flow distribution matrix of table 1.

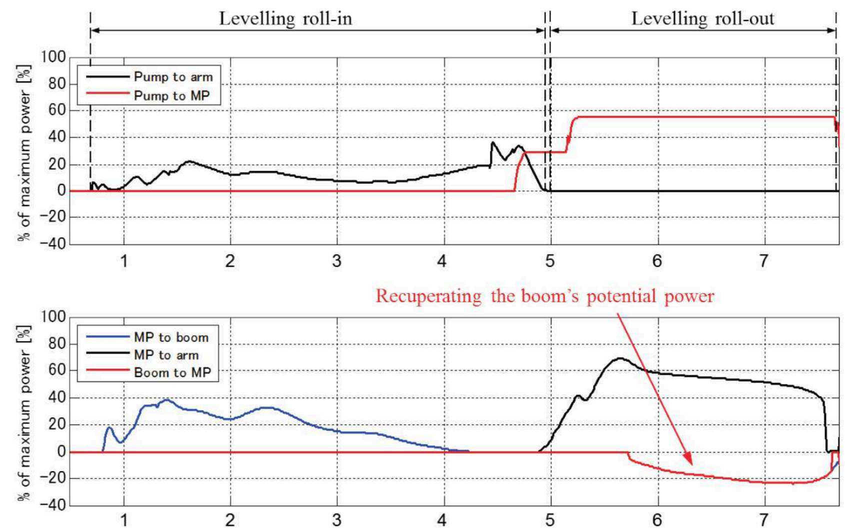

Figure 16: Simulation result for distribution of power

Figure 17 shows ICE operations for the TPOC-System and the new system during the levelling cycle with the efficiency map of the ICE. The left figure shows the TPOC-System, and the right side indicates the new system. The ICE of the TPOC-System cannot be operated in high efficiency regions mainly since the ICE is used at a high rotation speed and in a range of middle torque. Against TPOC-System, the ICE of the new system almost can be operated in the high efficiency regions by using the MP accumulator. Usage of the high efficiency regions of the ICE highly contributes saving fuel energy. Furthermore according to the new system, the ICE is slightly operated at a range of low torque. This means that an actuator, which has the low pressure level such as the arm during the roll-in motion, is powered by the pumps directly. If the actuator is driven by the MP accumulator, large throttling losses will occur between the MP accumulator and the actuator. Therefore, even if the ICE is not operated in the high efficiency regions, by providing flow rate to the actuator from the pumps directly, total system efficiency for the new system can be improved further.

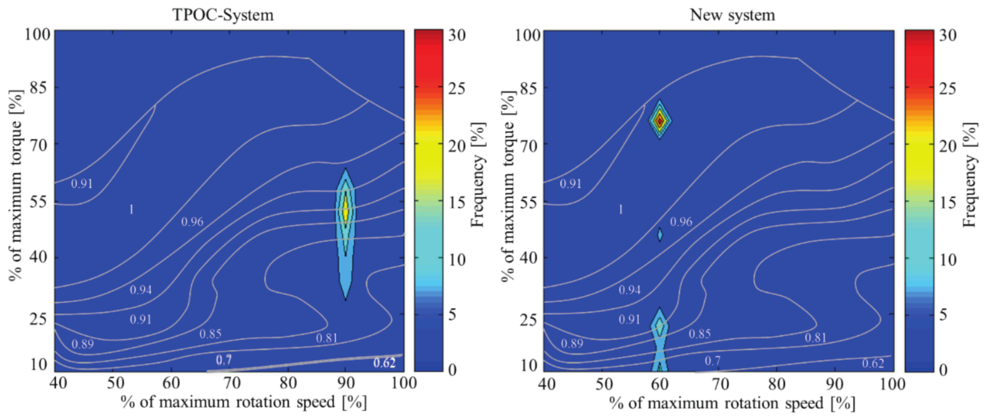

Figure 17: ICE operation during levelling cycle

The fuel consumptions of both systems are shown in Figure 18. The simulation result is calculated based on the efficiency map and the ICE's shaft power. Moreover for comparison with the measurement data fairly, this simulation result includes volumetric efficiency and hydraulic-mechanical efficiency of pumps, loads of auxiliary machines, hydrostatic resistance of hoses and friction of cylinders which are measured by a real machine. The fuel consumption of the TPOC-System is calculated by using the pump power from the measurement data with the same efficiency map against the simulation result. The new system consumes 30 % less fuel than the TPOC-System in simulation.

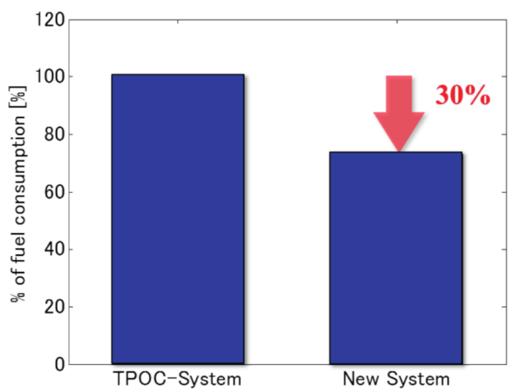

Figure 18: Comparison of fuel consumption for each system

6 Summary and Conclusion

The advantages and disadvantages of the TPOC-System and the STEAM are shown. A new system, which combines both advantages and at the same time eliminates their disadvantages, has been proposed. Based on the theory that the cylinder with the medium load pressure level is powered by the constant pressure rail and the cylinder with the low load pressure level is directly driven by the pump, the new system is designed for simulation against the real machine for a levelling cycle in order to compare the fuel consumptions. As a result, the simulation shows the new system consumes 30 % less fuel than the TPOC-System for one exemplary levelling cycle.

Nomenclature

Variable	*Description*	*Unit*
HP	High Pressure	[bar]
MP	Medium Pressure	[bar]
TP	Tank Pressure	[bar]
p_L	Actuator Load Pressure	[bar]
α	Actuator Area Ratio	[-]
Q_L	Actuator Load Flow	[l/min]
$\dot{x}$	Actuator Speed	[m/s]
F_L	Actuator Load Force	[N]
p_1	Accumulator Lower Pressure Threshold	[bar]
p_{12}	Accumulator Upper Pressure Threshold	[bar]
OP_1	Operating Pressure	[bar]
OP_2	Operating Pressure	[bar]
n	Engine Speed	[rpm]
n_1	Operating engine Speed	[rpm]
n_2	Operating engine Speed	[rpm]
T	Engine Torque	[Nm]

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