Development of the independent swing system for a fuel efficient hydraulic excavator

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Abstract

This paper presents an improvement of fuel efficiency and power control for independent swing system. The swing pump and swing motor comprise a closed hydraulic circuit. Not only does this system remove pressure loss, but it can also regenerate swing kinetic energy. The developed independent swing system is installed into the Doosan Infracore 48ton class excavator and evaluated with 12.3% improvement of the pump power compared to current system in the excavating test mode. Through the feed forward logic, engine speed is controlled to stay within 4% from the reference RPM.

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KEYWORDS: swing drive, independent swing system, power control

1. Introduction

The enforced environmental regulations and the soaring price of oil are forcing the manufacturers of mobile construction equipment to make their product more fuel efficient than ever. In the field of mobile hydraulics for fuel saving performance of equipment, lots of systems are under study and have been researched for a long time. Especially by adopting electro-hydraulic system, most of the construction vehicle makers and component makers are trying to find the efficient way to realize the best fuel efficiency. However, there are good opportunities to increase fuel efficiency by only

changing the configuration of hydraulic system. Independent swing system is a kind of such system that can save energy by only changing the configuration of the hydraulic system with one more pump.

The conventional hydraulic system in most excavators from mid to heavy class generally adopts two pumps. The one pump which provides flow to a swing motor also works for other actuators, which means swing system is not independent from other actuators. For this configuration, output pressure of the pump is always higher than the highest pressure among all actuators that the pump is assigned to. Due to the pressure difference between actuators pressure losses of pumps is not inevitable. The independent swing system can remove this loss by adopting another pump wholly dedicated to the swing motor. The swing pump and swing motor comprise a closed hydraulic circuit. Not only does this system remove pressure loss, but it can also regenerate swing kinetic energy when the machine decelerates its swing motion. The braking torque generated from the pressure at the hydraulic lines is delivered to the engine shaft or to the other main pumps resulting in the recovery recuperation of energy.

In this paper, we will introduce methods used and efforts made during the development of the swing independent system. Bosch-Rexroth's independent swing system was adopted for a Doosan Infracore's 48 ton excavator. After that, the independent swing system proved to be fuel efficient while it was not easy to tune it to be same as current conventional machine in the point of operational controllability. To make the machine have same operational performance, lots of work has been done from modification of a suction pipe connection to rearrangement of swash plate of swing pump. To meet the acceleration, deceleration and maximum velocity specification of swing motion, such factors as size of the pump, relief pressure and swash plate's returning speed were studied to find the best value. Also, some methods to prevent critical engine speed drop during the combination motion of boom up and swing acceleration were derived and tested. After that, the swing independent system proved that it can be one of the most promising systems for fuel efficient hydraulic mobile equipment with reasonable cost increase.

2. Development of the Swing Independent System

2.1. Introduction of independent swing System

As the introduction mentioned, several companies and schools have researched the electro controlled system to improve the fuel efficiency. Based on the LUDV system, the EFM research is performed at the Dresden University/01/. VBO (Virtual Bleed Off) based on the closed centre type control valve, which has load-dependant characteristics is studied by Rexroth/02/. Doosan Infracore is also developing an EPFC (Electro Positive Flow Control) system based on NFC (Negative Flow Control) to upgrade the energy efficiency and to improve the driver comfort/03/. Especially, while Doosan Infracore was developing the EPC system, we discovered how to improve the fuel efficiency through the pressure control of the starting point of the swing operation. During the swing operation, acceleration of upper body of the excavator requires high pressure due to its big inertia resulting in a huge amount of pressure loss. In common digging work, the excavator swings to dump after digging and to go back to the digging position after dumping. It means swing operation takes a big portion of the common digging work. Therefore, the fuel efficiency can be improved by optimizing the swing mechanism.

2.2. System specification and configuration

Doosan Infracore's 48 ton excavator was selected in order to prove the improvement of the fuel efficiency by adopting the independent swing system. The swing pump and swing motor were designed to have the same operational performance compared to the current swing system. **Table 1** shows the pump and motor's specification of current and independent swing system. We selected the A4VG125 pump by Bosch Rexroth. The theoretical swing speed calculated from the design parameters of the newly designed independent swing system is almost same with the theoretical swing speed from the design parameters of the current swing system. (* : Gear ratio : N_{input}/N_{PTO} = 0.804)

Items	Unit	Current System	Independent Swing System
Pump Volume	cc/rev	200	125
Pump Input Speed	RPM	1800	2238*
Motor Volume	cc/rev	140.5	107
Swing Speed (theoretical)	RPM	8.817	9.000

Table 1: Specification of swing pump and motor

A4VG125 pump is selected and installed between main pump and fan drive pump. The swing pump is connected directly to the twin swing motors without any valve. The pilot pressure from the joystick is used as the control signal of the swing pump. The schematic diagram of the independent swing system is shown in **Figure 1**. And **Figure 2** shows a installed swing pump at 48ton excavator.

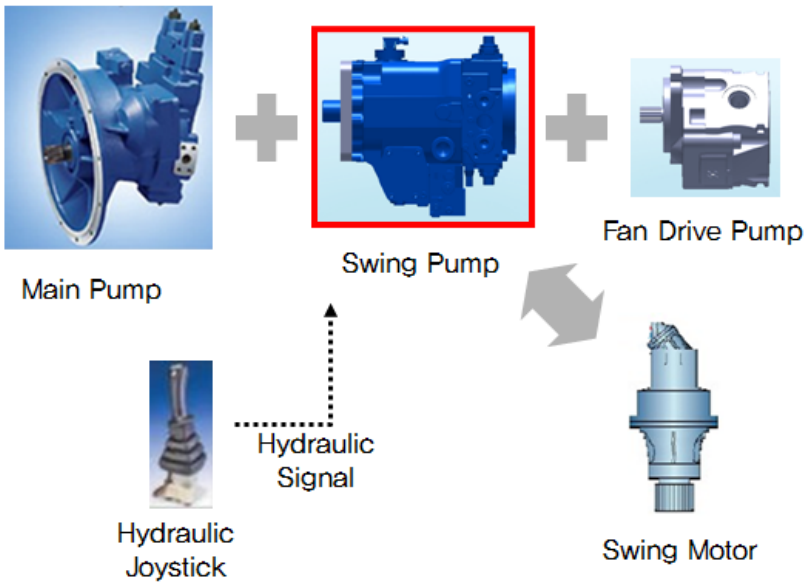

Figure 1: Schematic diagram of independent swing system

Figure 2: Photograph of swing pump installation at 48ton excavator

Figure 3 shows the swing operation characteristic for the fast movement test of the current system and the independent swing system. As the graph shows, the time spent to reach the maximum speed at reference engine RPM and the time spent to stop are similar. The difference in time to reach reference swing speed which means 1.0 in the y axis of the graph between current system and ISS (Independent Swing System) is less than 0.1 sec. The value in the Figure 3 labelled as “Swing Speed” is over 1.0 because normally actual engine speed is higher than the reference RPM.

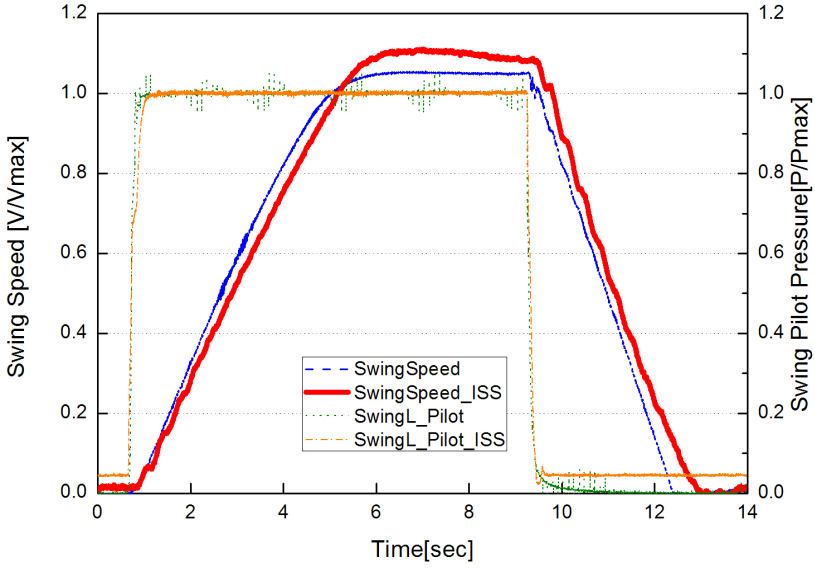

Figure 3: Comparison of performance in a fast movement test

2.3. Ideas to improve fuel efficiency

In case of the Bosch Rexroth Company’s A4VG125 pump, there is the pressure cut-off function as shown in the hydraulic diagram at **Figure 4** /4/. Generally the angle of the swash-plate angle is controlled by the swing pilot pressure but it can also be influenced by the pump pressure when the swing pump pressure is higher than the set pressure. It means the fuel efficiency can be improved by adjusting the swash-plate angle through the pressure cut-off function when the high pressure is occurred at the starting point of swing during the acceleration. It is one of the ideas we can increase the fuel efficiency.

As I mentioned, the pressure cut-off corresponds to a pressure regulation which, after reaching the set pressure, adjusts the pump angle of the pump to minimum value. This

valve prevents the operation of the high pressure relief valves when accelerating or decelerating. The pressure peaks occurring when the swashplate is swivelled rapidly and the maximum pressure in the system are limited by the high pressure limit valves

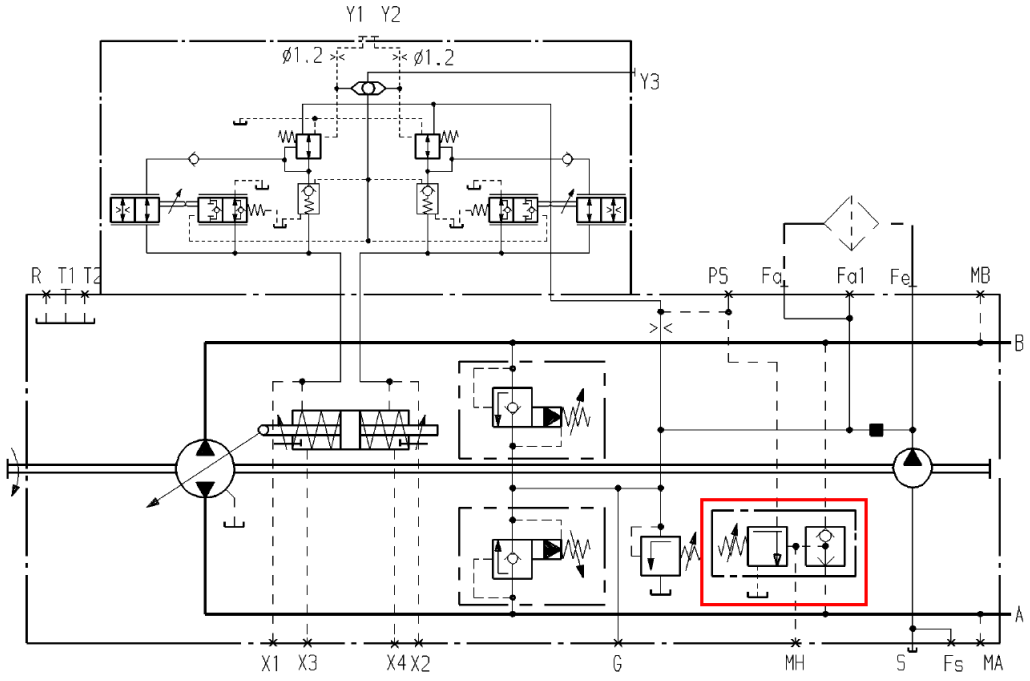

Figure 4: Hydraulic diagram of A4VG125 pump

Figure 5 shows the pressure change at the X2 port in the Figure 4 when it receives a step input by manipulating the swing joystick. As explained previously, when the pump pressure is high, the pilot pressure from the gear pump becomes lower because of the pressure cut-off function. So the angle of swash plate will be restricted by the lowered pilot pressure and therefore, the flow output from the pump will be decreased. So the pressure loss will be decreased. In the current NFC system, the pressure loss caused by the relief valve is quite big because the pump's swash-plate angle is maintained at the maximum angle, because the pressure for swing is controlled by only the relief valve. According to Figure 5, the main reason for the high oscillation at X2 is the pressure feedback characteristics of the control unit.

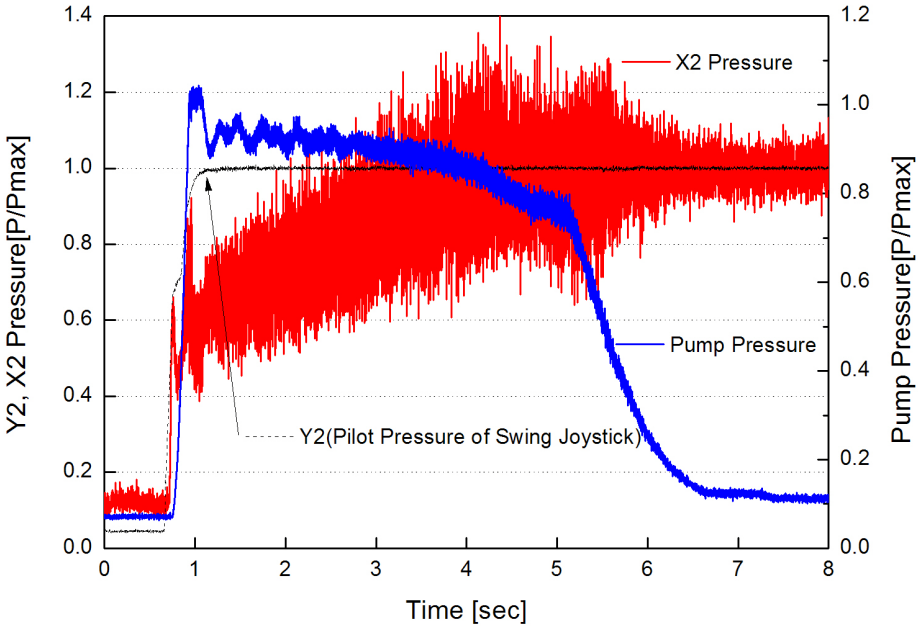

Figure 5: Test result of swing fast movement

Because there are no valves between swing pump and swing motors, the meter-in and meter-out losses do not exit. In case of NFC system, swing operation generally uses the same pump with other functions such as arm operation, so the pressure losses caused by the pressure differences among actuators are inevitable. The independent swing system can remove these losses by adopting another pump wholly dedicated to the swing motor. Independent swing system is closed loop system, so it can also regenerate swing kinetic energy when the machine decelerates its swing motion. The braking torque generated from the pressure at the hydraulic lines is delivered to the engine shaft or to the other main pumps resulting in the recovery recuperation of energy.

3. Power control of independent swing system

For the excavators, there is a maximum power setting value at each engine speed depending on the engine power curve. When the main pumps use more than the maximum power, the engine speed drops. To prevent this, the current excavator has a controller which controls the swash-plate angle of the main pumps depending on the engine speed. This logic is called power control. It generates pressure which controls

the swash-plate angle of the main pump by the changing the current command of the EPPR valve included in the regulator of the main pump. For example, in the case of the current 48 ton NFC excavator, if the excavator works under high load such as boom up with swing operation, the engine will undergoes speed drop.

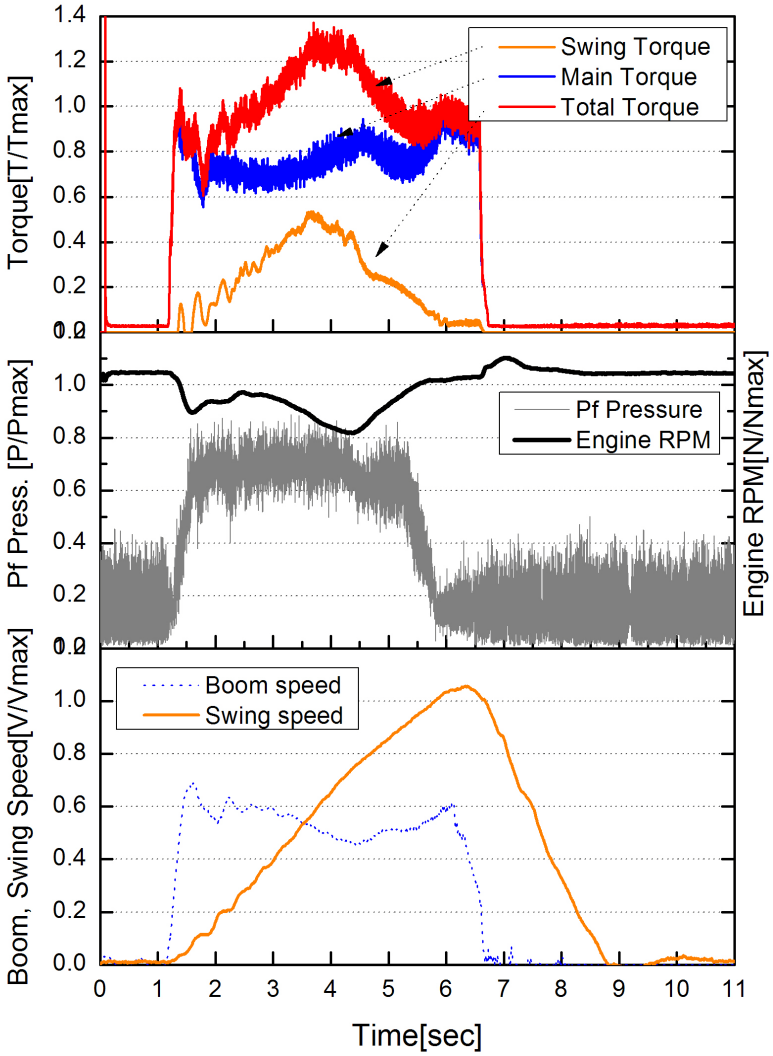

Figure 6: Simultaneous operation of Boom up and swing

At this point, the controller senses the engine speed and then reduces the main pump's swash-plate angle through the EPPR valve which controls the engine speed to maintain the set value.

In the independent swing system, the main pump controls the engine speed through the power control, but in the case of the A4VG125DWDMT1/32R pump, there is no way to control the swash-plate angle of the pump from the outside. This means, the engine speed drop is inevitable in the high load work like boom-up and swing. **Figure 6** shows that the engine speed drops because of the dynamic characteristic caused by

the load suddenly increased. Then engine speed drops because the pumps use more than the maximum torque. When boom-up and swing are operated at the same time, the main pump controls the swash-plate angle so that the engine speed should recover to its target speed by reducing the flow output. However, engine speed continually drops caused by increase of the swash-plate angle of the swing pump. After the excavator finishes the swing acceleration, the engine speed recovers its nominal target speed. According to the calculation of the torque of the main pumps and the swing pump respectively, they used more than the engine's maximum torque after 3sec, so the engine speed drops.

3.1. Power control concept of independent swing system

In order to prevent the engine speed drop, the total power should be limited by controlling the swing pump's swash-plate angle. However, this logic could be applied to the A4VG125. The result of Figure 6 shows that the engine speed drops for a very short instant, because the engine torque is insufficient. Therefore, an idea that controlling the power consumption in the main pumps rather than that of swing pump might be helpful to prevent engine speed drop cause its one big issue in the customer's voice. This idea can result in some imbalance in simultaneous operations but the imbalance has proved to be acceptable because it continues for only a short period of time.

The current system feedbacks engine speed to control the power output of the hydraulic system resulting constant engine speed. If the control gain of this feedback system is tuned with the independent swing system, it can't get the maximum performance when there is no swing operation. When the swing pump is not operating, the system will hunt by the excessive output signal. So, we adopt feed forward control logic which reduces the torque needed for the swing operation when there is a swing pilot signal and the engine speed drops. Or, by using the variable control constant when swing is operated, we can get the better performance to maintain the engine speed. **Figure 7** shows block diagram of feed forward control.

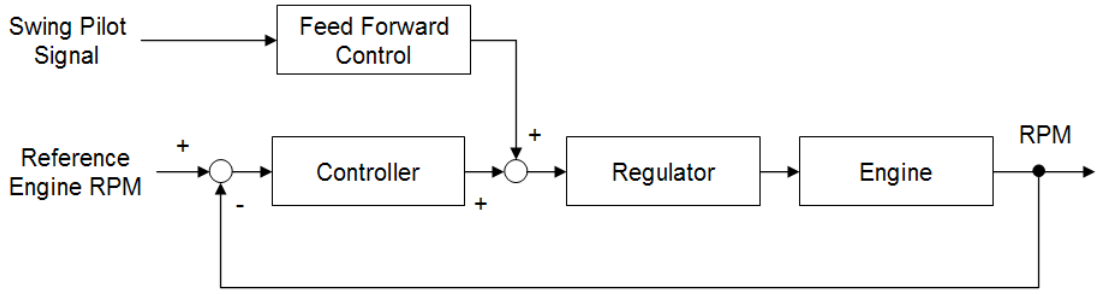

Figure 7: Block diagram of feed forward control

4. Test Results of the Independent Swing System

4.1. Results of the fuel consumption test

The fuel consumption test was performed in accordance with the company's standard. The work cycle is as follows; Digging → Swing & Boom up →Dump →Swing & Boom down. The operator keeps his maximum working speed and the amount of soil in the bucket is kept full. After a digging, the excavator rotates by 180◦, followed by dumping.

Pump power was decreased about 12.3% compared to current NFC system during the 26 cycles. The cycle time was decreased by 3.4%, maintaining the productivity almost same. Fuel efficiency was increased by the pressure cut-off function, elimination of the meter in-out loss at the valve and the loss caused by pressure difference between actuators using the same pump. According to **Figure 8**, pump power of independent swing system is smaller than that of current system when swing is operated, so independent swing system can decrease the pump power and increase the fuel efficiency.

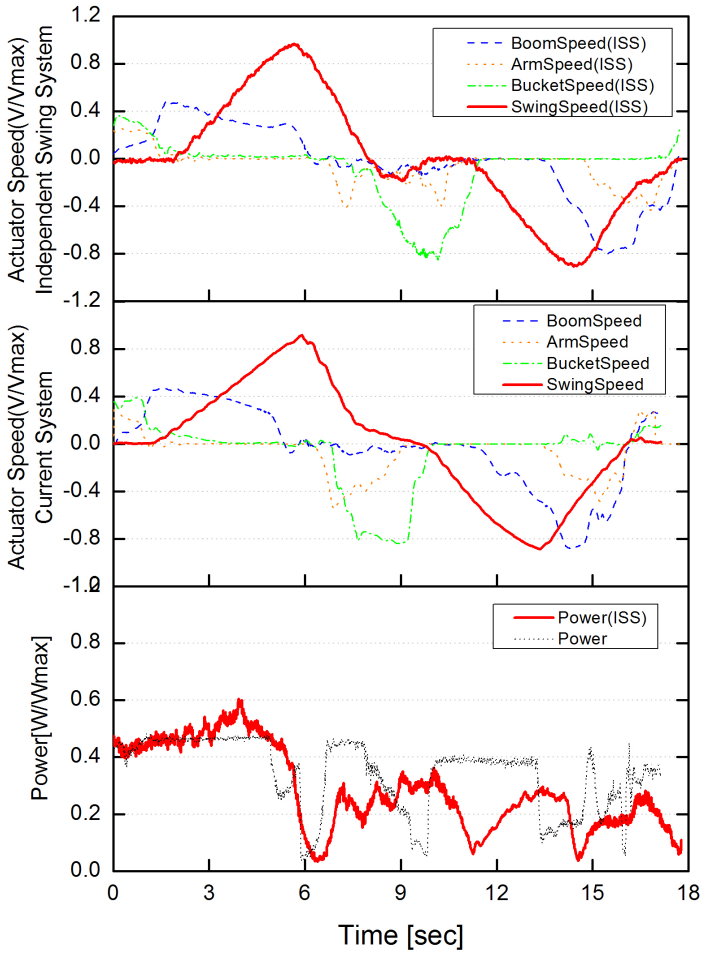

Figure 8: Result of fuel consumption test during the one cycle.

4.2. Results of the power control test

As I mentioned above, Figure 6 shows engine speed is dropped by 20% from reference speed, so operators can notice it. To solve this problem, we increase the Pf pressure up to 141% at the main pump. **Figure 9** shows the engine speed is kept to stay within 5% by increase of the Pf pressure.

From the test result, engine speed is dropped when workers operate simultaneous operation with swing. Therefore feed forward control is one of the ways to prevent the engine speed drop. Figure 9 shows result of simultaneous operation of boom up and swing. Feed forward control logic is to control the engine to stay speed within 4%. Especially at the first stage, engine speed does not drop below the reference RPM. Moreover we can decrease the range of the time with dropped engine speed. It means

the range of the decreased boom speed is shortened after application of the feed forward control logic. (FF : Feed Forward)

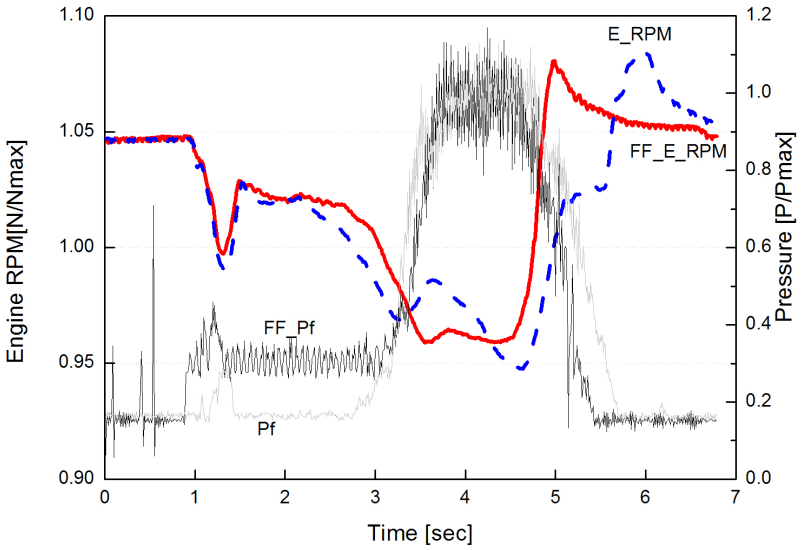

Figure 9: Simultaneous operation of boom up and swing whit feed forward control

5. Conclusion

Independent swing system is proposed to improve the fuel efficiency. The swing pump and swing motors are designed to have same swing operational performance as the current machine. By adopting closed loop system, independent swing system can eliminate many losses such as meter in-out loss, pressure loss due to pressure difference between actuators using the same pump. Through the fuel consumption test, pump power is reduced by 12.3% compared to current system. Especially, feed forward control is applied to reduce engine speed drop, so we can control the engine speed to stay within 4% from the reference RPM in the boom up and swing fast operation test. However, because we limit only main pump's swash-plate angle, boom speed becomes slower during the engine speed dropping. To solve this problem, we have to consider not only the power control of main pump but also the power control of swing pump to have good performance of simultaneous operation.

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Nomenclature

P	pressure	-
V	speed	-
T	torque	-
W	power	-
N	engine speed	-