Proceedings of the 7th JFPS International
Symposium on Fluid Power, TOYAMA 2008
September 15-18, 2008

P1-12

A STUDY ON ENERGY SAVING POTENTIAL OF HYDRAULIC CONTROL SYSTEM USING SWITCHING TYPE CLOSED LOOP CONSTANT PRESSURE SYSTEM

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ABSTRACT

Up to now, several types of hybrid systems have been developed to deduce energy consumption. Switching type closed loop constant pressure system (SCL-CPS) was proposed as one of feasible hybrid systems. SCL-CPS also uses flywheel, hydraulic accumulator and hydraulic power transmission as a traditional CPS but it has two alternatively high pressure lines. At a same time, one is used as the high pressure line and the other is the low one. Switching between them to overcome large hydraulic shock and noise considered as serious problems in traditional CPS. In this paper, energy saving potential of system is evaluated by considering effect of component efficiencies in system. Recovery efficiency during deceleration the wheel is estimated by simulation. The results indicate that proper determination of recovery time and operating pressure improves significantly energy recovery potential of the system.

KEY WORDS

Constant Pressure System (CPS), Flywheel Switching, Energy saving, Secondary Control

NOMENCLATURE

C	: Viscous friction coefficient
D_{max}	: Wheel moment of inertia
J_1	: Flywheel moment of inertia
J_2	: Different pressure
p_{pre}	: Accumulator pre-charge pressure
$Q_{1,2}$	: Flow rate
$T_{ac,br}$	: Acceleration, braking torque
T_{in1}	: Torque at pump shaft
T_{out2}	: Torque at motor shaft
$u_{1,2}$	: Control signal
μ	: Oil viscosity
μ_V	: Volumetric loss
μ_M	: Mechanical loss

INTRODUCTION

Recently, hybrid systems equipped an energy recovery and a secondary energy store system have been attractive systems from the viewpoint of energy saving. Several hybrid systems have been developed in literature such as CVT-flywheel system, Flywheel battery system, Electro-chemical batteries system or hydraulic hybrid system. Among them, hybrid systems using flywheel have been considered to be advantageous for some applications because of their high specific power. They have not been applied widely due to some inherit disadvantages for instances CVT-flywheel systems have many problems about controlling the CVT (Continuously Variable Transmissions) or flywheel battery systems need flywheel to work at very high velocity. CPS has been proposed and considered as one of the feasible solutions of low flywheel velocity hybrid systems. In former researches [1], the effectiveness of the CPS hybrid vehicle was verified by simulation. However, the pressure peak generated by the abrupt change of the displacement of pump/motors to change their functions is one of the most obstacles that restrict applicability of this system.

Switching type closed loop CPS (SCL-CPS) is proposed as a good solution to overcome those drawbacks. Energy saving of SCL-CPS can be achieved by saving primary power source and recovering energy during deceleration time. The later is investigated here because it always contributes a considerable part in total saving potential of the system. Many studies on recovery strategies of SCL-CPS have been taken place by using relief valve [4] or changing two pump/motor displacements in a small range [2]. These researches indicate that about 50% energy of the wheel can be recovered but neither flywheel nor wheel is controlled. So they are not used in real applications where the wheel velocity or position must be controlled.

In this paper, influences of wheel deceleration methods, operating pressure of system and pump/motor operating situation are studied. Results of this analysis are use to determine a proper control strategy for the system. Recovery strategy based on constant pressure is chosen. High energy recovery efficiency and controllability of the wheel are dominations of the study when comparing with existences.

SWITCHING TYPE CLOSED LOOP CPS

Proposed Switching Type Closed Loop CPS

A schematic diagram of proposed SCL-CPS is shown in Figure 1. It is a hydrostatic transmission system which consists of a flywheel, two variable displacement pump/motors and three electric clutches. Two hydraulic accumulators and two controllable relief valves play an important role in this system. Especially, the drive pump/motor is only work from 0 to +100% of maximum displacement and there are two constant pressure lines for driving and energy recovery phase. Pressure in the driving line is high during the driving time, while pressure in the other line is high during recovery one. In mobile applications, system performance, refreshing oil and size of total system are issues need to be considered of a hydraulic circuit. The SCL-CPS using only two pump/motors in a closed loop circuit is a feasible solution of these issues.

Operation modes

The SCL-CPS works as a series hydraulic hybrid system with two different power sources that are the engine and the flywheel. Because of it configuration SCL-CPS is able to work in one of three modes that are on/off the engine, SCL-CPS and energy recovery mode at instantaneous time.

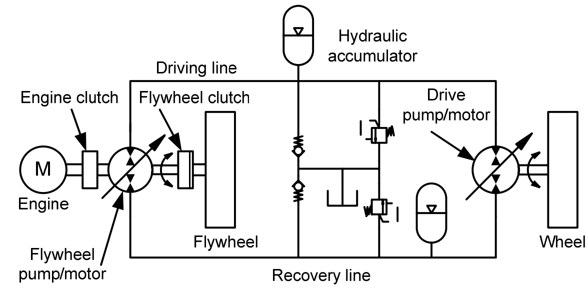

Figure 1 Schematic diagram of newly proposed CPS

On/off the engine mode

In this mode, the flywheel pump/motor functions as a hydraulic pump and the drive pump/motor functions as a hydraulic motor. The engine is turned on or off periodically and a cycle is described as follows. First, both clutches are engaged and the engine is turned on to drive the flywheel from the lower velocity to the upper velocity. Next, the engine clutch is disengaged and the engine is turned off. After that, only the flywheel functions as a power source to drive the wheel so its velocity begin decreasing. When the flywheel velocity gets value of the lower limit a cycle on/off is finished. Finally, the engine is turned on again and the engine clutch is engaged for next cycle.

SCL-CPS mode

The flywheel clutch is always disengaged and the engine is always turned on. Because two variable pump/motor displacements are used to control the wheel velocity so there is a redundant degree of freedom. Therefore, the operation of engine can be uncoupled from the speed and torque of drive wheels. It allows the engine to be operated in the optimum operation efficiency point. Generally, operation point of the engine is controlled to lie on the e-line of the engine at each calculated power of the system.

Energy recovery mode

This mode is depicted in Figure 2, the engine is turned off and the engine clutch is disengaged while the flywheel clutch is engaged during recovery period. The drive pump/motor functions as a pump while the flywheel pump/motor functions as a motor. The recovery line becomes high pressure line while the driving line becomes low one. Wheel kinetic transform into hydraulic energy via the pump then continuously transforms into flywheel kinetic energy via the motor.

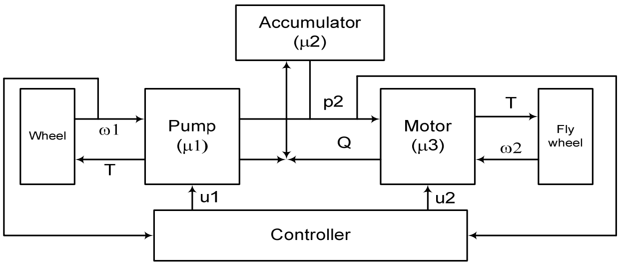

Figure 2 Energy recovery mode of SCL-CPS

Mathematical Model of SCL-CPS components

Hydraulic Pump

$$Q_{out1} = u_1.\omega_1.\mu_{pV}.D_{\max,p} \quad (1)$$

$$T_{in1} = u_1.D_{\max,p}.\frac{\Delta p}{\mu_{pM}} \quad (2)$$

$$\mu_{pV} = 1 - C_s.\frac{\Delta p.D_{\max}}{\mu.\omega_1 D} \quad (3)$$

$$\mu_{pM} = \frac{1}{1+\left(C_f + C_d.\frac{\mu.\omega_1}{\Delta p}\right).\frac{D_{\max}}{D}} \quad (4)$$

Hydraulic Motor

$$Q_{in2} = u_2.\omega_m.\frac{D_{\max,m}}{2.\pi\mu_{mV}} \quad (5)$$

$$T_{out2} = u_2.D_{\max,m}.\Delta p.\mu_{mM} \quad (6)$$

$$\mu_{mV} = \frac{1}{1+\left(C_S.\frac{\Delta p}{\mu.\omega_2}\right).\frac{D_{\max}}{D}} \quad (7)$$

$$\mu_{mM} = 1-\left(C_f + C_d.\frac{\mu.\omega_2}{\Delta p}\right)\frac{D_{\max}}{D} \quad (8)$$

Hydraulic Accumulator

$$\frac{V_{gas}}{V_{ac}} = \left(\frac{p_{pre}}{p_{gas}}\right)^{\frac{1}{\gamma}} \quad (9)$$

$$p_{gas}dt = \gamma.\left(\frac{p_{gas}+10^5}{V_{ac}}\right).q_{out} \quad (10)$$

The Wheel and Flywheel

$$T_{br} = J_1\frac{d\omega}{dt} + C.\omega \quad (11)$$

$$T_{ac} = J_2\frac{d\omega}{dt} + C.\omega \quad (12)$$

INFLUENCES ON ENERGY RECOVERY POTENTIAL OF SCL-CPS

Wheel deceleration and flywheel acceleration

To estimate this influence three types of decelerations are considered. Parabolic wheel velocity -1st, constant deceleration - 2nd and constant torque - 3rd method are chosen because of their natural characteristics. Parabolic wheel trajectory minimizing friction loss L in Eq. (13) during deceleration the wheel from initial velocity to zero in a given recovery time is chosen to estimate wheel efficiency. Wheel and flywheel trajectories are shown in table 1.

$$L = \int_0^{t_r} C.\omega(t)^2.dt \quad (13)$$

Wheel and flywheel efficiencies versus time and deceleration and acceleration methods are depicted in Figure 3 and 4. Generally, maximum wheel or flywheel efficiency is inversely proportional to deceleration or acceleration time. Maximum value is reached about 96.67% for first method within 2s deceleration time. Second method is less efficiency than the last, which is inverted during acceleration time. Recovery time more than 16s is not efficiency for energy saving purpose.

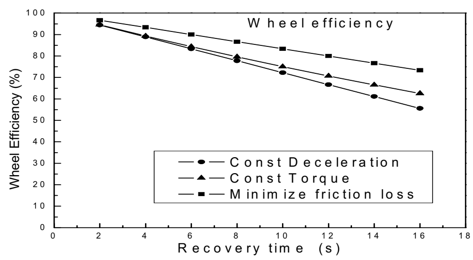

Figure 3 Wheel efficiency

Pump and motor efficiency

Overall CPS recovery efficiency is product of all component efficiencies. Figure 5 shows value of maximum system efficiency when that average value of pump/motor varies from 25-90% and wheel/flywheel efficiency come from previous section.

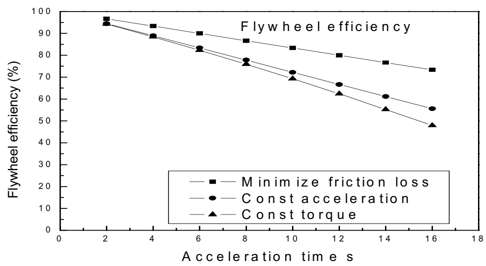

Figure 4 Flywheel efficiency

This value is proportional pump/motor efficiency. If maximum pump motor efficiency is 50% that value of system will be 22.6 % for 2s and 8% for 16s recovery time. It is smaller than 50% system efficiency is very small. It implies that finding out economical operating situation of pump and motor contributes to improvement saving potential of the system.

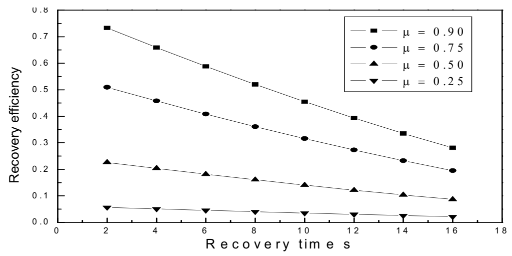

Fig 5 influence of pump/motor efficiency

Figure 6 and 7 describe pump/motor efficiency versus operating pressure, velocity and displacement. The results can be used to estimate pump/motor efficiency in operating situations. In the same working condition, the operating pressure and velocity, pump/motor operates in higher efficiency with higher displacement.

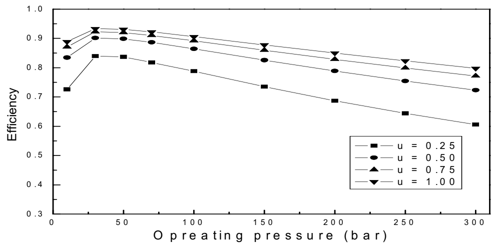

Figure 6 Pump/motor efficiency versus pressure

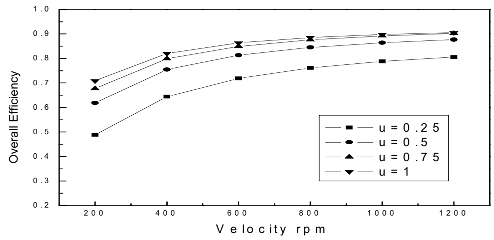

Figure 7 Pump/motor efficiency versus velocity

Operating pressure

In CPS operating pressure and desired torque is directly relative via Eq. (2). System is said to be controlled when it can generate any desired torque depending on deceleration method. The max/min torque depends not only recovery time but also deceleration method. In general that value is inversely proportional to deceleration time. Torque value changes significantly from maximum value to zero in the first method, which differs from the others. Desired torque increases lightly from beginning to the end for 2nd method and be constant for the last. Value of this torque is described in Table 2. Eq. (2) implies that operating pressure is inversely proportional to pump displacement and product of control input and pressure depends on deceleration method. So it should be chosen properly to force pump operate with large displacement, otherwise pump efficiency is small. Range of operating pressure is limited by volume and pre-charge pressure of the hydraulic accumulator. Operating pressure versus recovery time and deceleration methods is described in Figure 8. Figure shows that system pressure in 1st method must be reached 262 or 534bar with maximum u(t) = 1 and u(t) = 0.5 respectively for 2s recovery time. However, maximum value of pressure for 3rth method needs only 132bar when using maximum displacement and 264 for 50% of that value. The figure also shows that maximum pressure changes significantly when recovery time changes from 2 to 4s. Moreover, maximum operating pressure in 1st method is always considerably higher than that of other methods.

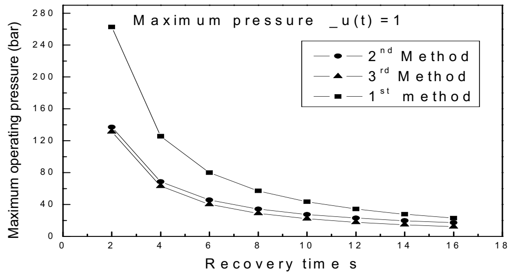

Figure 8 Operating pressure

Control strategies

Eq. (2) implies that the wheel is controlled by changing pressure or pump displacement. In other word, there are three possible strategies as follows.

i. Pressure is controlled as constant and pump displacement is controlled to mach desired torque

ii. Pump displacement is kept as constant and pressure is controlled to mach desired torque

iii. Pressure and pump displacement are variable

In order to estimate effect of control strategy on system saving energy potential a feed-forward controller is used. Secondary control, which includes two sub-controllers one for wheel control the other for pressure control, is used for simulation. Obviously, high working pressure forces pump/motor work in low efficiency but too low value is not able to control the wheel. Beside, efficiency of wheel and flywheel only depend on deceleration or acceleration method. Therefore, pressure is chosen at the possible lowest value for each method. Variable displacement and pressure control strategy is not necessary. Results of two control strategies with 2s recovery time are shown in Figure 9 and 10. Figure 10 and 11 indicate that if wheel is decelerated rapidly then flywheel is fast accelerated without influence of control strategy. If friction loss of the wheel is reduced by using parabolic trajectory that loss of the flywheel is increased during acceleration. Therefore, efficiency of CPS depends strongly on pump/motor one.

In constant pressure control displacement of pump and motor vary to mach desired torque and pressure. Pump and motor displacement vary little and get high value in 2nd and 3rd deceleration method. Motor displacement changes a lot and has lower value in the first method. From the figures, it is also realized that 2nd and 3rth deceleration method are quite similar.

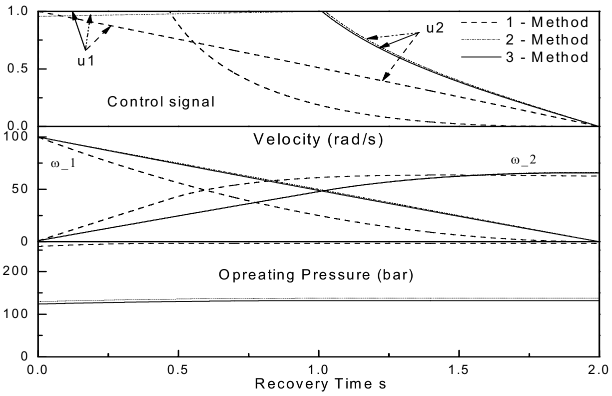

Figure 9 Constant pressure control

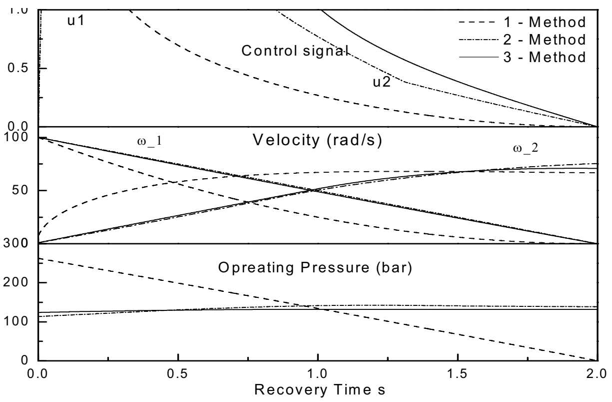

Figure 10 Variable pressure control

For variable pressure control, pump displacement is kept at maximum value. Pressure decreases from maximum to zeros in first method but increases from minimum to maximum value in second method.

Finally, simulation results show that pump or motor efficiency is always low in parabolic deceleration for both control strategies. Control strategy has an insignificant effect on recovery efficiency of the system.

SIMULATION

Simulation is verified by using AMESim software for recovery time changing from 2 to 16s. The value of pressure is minimum for each method corresponding to a given recovery time. Figure 12 and 13 depict overall recovery efficiency of the system in two control strategies and three deceleration methods. The efficiency is calculated in Eq. (14).

$$\mu_{CPS} = \frac{J_2\left(\omega_{2,tr}^2 - \omega_{2,0}^2\right)}{J_1\left(\omega_{1,0}^2 - \omega_{1,tr}^2\right)} \quad (14)$$

A particular situation of 4s recovery time, constant torque deceleration method, operating pressure of 63 bar with constant pressure control is investigated. Overall recovery efficiency of system is about 61%. Figure 13 indicates component efficiency in CPS. To evaluate pump/motor efficiency during deceleration and acceleration some parameters are defined as follows.

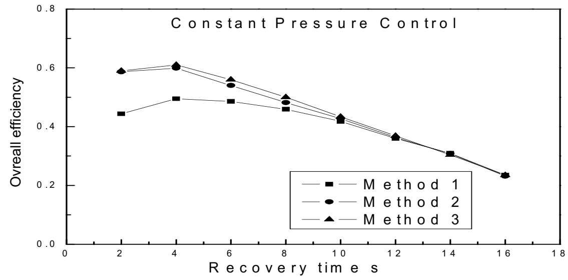

Figure 11 CPS efficiency in constant pressure control

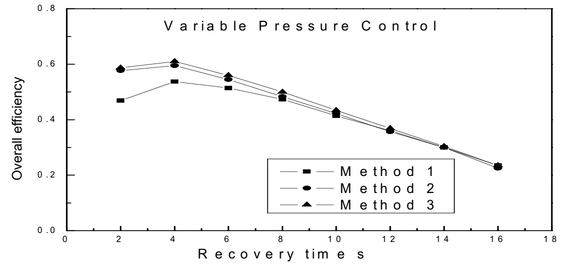

Figure 12 CPS efficiency in variable pressure control

Fig 14 describes relation between overall efficiency and operating pressure. It implies that the efficiency decreases when operating pressure over needed value.

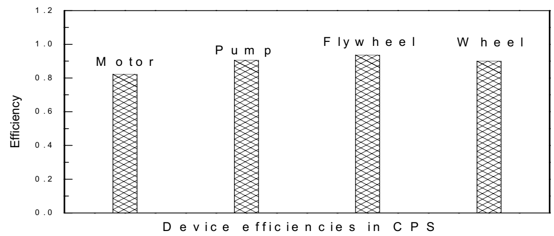

Fig 13 Component efficiency in CPS

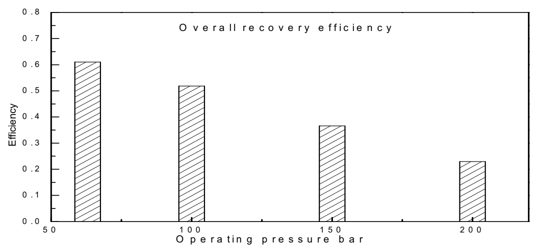

Fig 14 overall efficiency versus operating pressure

CONCLUSIONS

CPS recovery efficiency is analyzed from view point of investigation on operating condition of devices in the system. Pump/motor efficiency influences considerably on overall recovery one. Recovery time and operating pressure must be determined properly to get high energy saving potential. Good conditions for this system are recover time from 2 to 6s, constant pressure control and constant torque deceleration. The study also indicates that CPS is able to recover about 61% energy of the wheel.

Table 1 Wheel and flywheel velocity trajectory

Deceleration methods	Parameters	Wheel – Deceleration	Flywheel –Acceleration
Minimize friction loss	Velocity	$\omega(t)=\frac{\omega_0}{t_r^2}.t^2-2.\frac{\omega_0}{t_r}.t+\omega_0$	$\omega(t)=\frac{\omega_{max}}{t_a^2}.t^2$
	Friction Loss	$L=\int_0^{t_a} C.\omega(t)^2.dt \quad L_{min}=\frac{1}{5}.\omega_0^2.C.t_r$	$L=\int_0^{t_a} C.\omega(t)^2.dt \quad L_{min}=\frac{1}{5}.\omega_0^2.C.t_r$
	Valuated Efficiency	$\mu_{reco}=\frac{\frac{1}{2}J.\omega_0^2-E_{loss}}{\frac{1}{2}J.\omega_0^2}.100$	$\mu_{reco}\frac{\frac{1}{2}J.\omega_{max}^2-E_{loss}}{\frac{1}{2}J.\omega_{max}^2}.100$
Constant Deceleration/ Acceleration	Velocity	$\omega(t)=\omega_0\left(1-\frac{1}{t_r}t\right)$	$\omega(t)=\frac{1}{t_r}t$
Constant torque	Velocity	$\omega(t)=-10T+K.e^{-0.04166t}$ $K=\frac{\omega_0}{1-e^{-0.041.t_r}}$ $T=\frac{K-\omega_0}{10}$	$\omega(t)=T+K.e^{-0.04166t}$ $K=-\frac{\omega_0}{1-e^{-0.041.t_r}}$ $T=-K$

Table 2 Desired torque

Deceleration methods	Desired torque	Max value	Min value
Minimized Friction Loss	$T_d(t)=-\omega_0\left[\left(\frac{C}{t_r^2}\right).t^2+\frac{2}{t_r^2}(J-Ct_r)t+\left(\frac{Ct_r-2J}{t_r}\right)\right]$ $0\le t\le t_r$	$T_{max}=-\omega_0\left(\frac{Ct_r-2J}{t_r}\right)$ $t=0$	$T_{min}=0\ ,\quad t=t_r$
Constant Deceleration	$T_d(t)=-\frac{\omega_0}{t_r}(C(t_r-t)-J)$ $0\le t\le t_r$	$T_{max}=\frac{\omega_0 J}{t_r}\ ,\quad t=t_r$	$T_{min}=-\frac{\omega_0(Ct_r-J)}{t_r}$ $t=0$
Constant Torque	$T_d(t)=\omega_0\left(\frac{e^{-0.04166t_r}}{\left(1-e^{-0.04166t_r}\right)}C\right)$ $0\le t\le t_r$	$T_{const}=\omega_0\left(\frac{e^{-0.04166t_r}}{\left(1-e^{-0.04166t_r}\right)}C\right) \quad 0\le t\le t_r$	

ACKNOWLEDGEMENTS

This work was supported by grant No. (R01-2006-000-11390-0) from the basic research program of the Korea Science and Engineering Foundation.

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