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Development of supervisory control algorithm for compound hybrid excavator

Hakgu Kim[1], Seungjin Yoo[2] and Kyongsu Yi
[1]*Mechanical and aerospace engineering, Seoul National University, Gwanak 599, Gwanak-ro, Seoul, Korea, 151-744*
iku3333@snu.ac.kr
[2]*Doosan Infracore Co., 39-3, Sungbok-Dong, Suji-Gu, Yongin-Si, Gyeonggi-Do, 448-795, Korea*
Seungjin. Yoo@doosan.com

Abstract

This paper presents a supervisory control strategy for a compound type hybrid excavator. The compound type hybrid drive train means that the parts of the hydraulic actuators are replaced by electric motors. Therefore, the required power of the replaced actuator should be provided by the electric energy storage device. This structure makes it difficult to design the supervisory control strategy, since the consumed energy by the electric motor causes the charge sustaining problem. To that end, hybrid supervisory control algorithm has been proposed in this paper. The algorithm composed of two parts: the optimal power distribution controller and engine set speed controller. The optimal power distribution controller determines engine assist motor power by considering the charge sustaining and fuel economy. The engine set speed control strategy determines engine set speed based on the pump load to shift engine operating points to the optimal operating line. The performance of the proposed supervisory controller has been compared with the thermostat controller using simulation. The simulation results indicate that the proposed controller improves 2-3% of fuel efficiency compared the thermostat controller and show excellent charge sustaining performance.

Keywords: compound hybrid excavator, fuel economy, supervisory control

1 Introduction

The successfully marketed hybrid vehicle in recent years stimulates the development of hybridization of the construction vehicle. Especially, the hybridization of conventional hydraulic excavator which is one of the representative construction machinery is being developed by major manufacturers. However, since the power demand of the hydraulic excavator is often highly transient, the application of the hybrid drive train on these systems should be cautiously analysed [1]. Additionally, the compound type hybrid excavator whose hydraulic swing motor is replaced by the electric motor and it makes the power management problem more difficult because the demanded power of the electric motor should be considered when the power management algorithm is designed. To that end, the supervisory control strategy has been proposed to improve fuel economy and guarantee charge sustaining.

A few papers were published in the modelling and control of hybrid excavator. Yoo describes the configuration of compound type hybrid excavator and swing motion control algorithm [2]. Kwon compared expected performance of various type of hybrid excavator using dynamic programming technique as a preliminary study for hybrid excavator [3]. Heuristically designed rule based control algorithm also has been proposed in many reports to control the power distribution of hybrid excavator [4]-[6]. In the earlier work, an optimal control strategy has been proposed in [7]. A parameter optimization technique also has been introduced in [8].

In this paper, optimal power management algorithm and engine set speed control strategy have been proposed as a solution for the fuel optimization and charge sustaining problem of the compound type hybrid excavator. The optimum based control strategy in [7] could be a best solution, but in the case the production cost of super capacitor is the problem, the equivalent fuel minimization strategy could be a proper solution as a near optimum solution and its excellent charge sustaining performance [9]. An engine set speed control strategy taking into account load condition and engine dynamics also presented in order to improve fuel economy.

Remainder of this paper is organized as follows: The simulation model for evaluating the performance of the proposed controller is presented in chapter 2. The supervisory control strategy including power management algorithm and engine set speed algorithm has been briefly depicted in chapter 3. Finally, the simulation results and conclusions are presented in chapter 4 and chapter 5.

2 Hybrid Excavator Model

The simulation model for target excavator is depicted in fig. 1. The compound type hybrid excavator composed of the diesel engine, engine assist motor, dc/dc converter, super capacitor, hydraulic pumps and swings motor. The diesel engine is a primary energy source of the hybrid excavator. It is automatically controlled based on

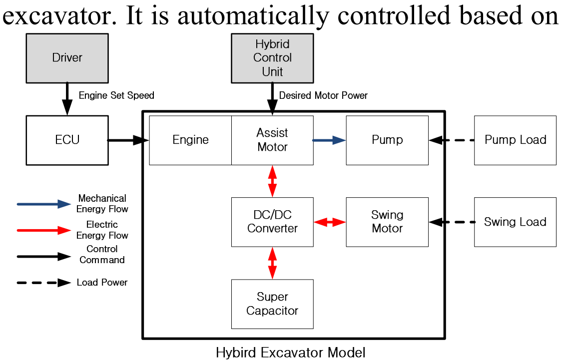


Figure1: Simulation model of hybrid excavator

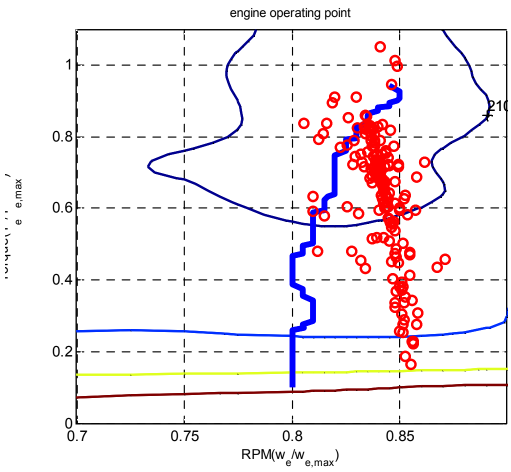


Figure2: Engine operating points

the user pre-set engine speed to maintain engine speed. The engine operating points are controlled to follow the engine droop curve as depicted in fig. 2. The super capacitor which provides the demanded power of swing motor is the secondary energy source of the target excavator. The dc/dc converter manages the electric energy flow between the super capacitor, assist motor and swing motor. The engine assist motor is the key component because it converts the mechanical energy to electric energy or vice versa. Since the engine is automatically operating during excavation process, the output power of the engine and super capacitor can be regulated only through the engine assist motor. If the engine assist motor power determined, the output power of other components of hybrid drive train are also automatically determined from power balance equation.

The demanded powers of the hydraulic pumps and swing motor have been replaced to the experiment in simulation, since the dynamic responses of the pumps and swing motor is much faster than that of the diesel engine. The simulation model is developed based on Matlab Simulink and validated using experiment data.

3 Hybrid Supervisory Control

The charge sustaining problem of the compound hybrid excavator should be considered in the power management problem because the demanded power of the swing motor could easily cause depletion of the super capacitor. Therefore, the power management strategy should manipulate the super capacitor voltage above a threshold value before the swing action. The strategy also minimizes energy loss of the electric system and improves the fuel economy of the diesel engine by adjusting the engine operating points. The control objectives have been achieved by applying equivalent fuel consumption minimization strategy(ECMS) [9]. The ECMS is near optimal and it can manipulate the state of charge of the super capacitor to desired value. The ECMS controller has been modified and applied to the power management of the compound hybrid excavator.

The ECMS considers the output power of the secondary energy source of the hybrid drive train as the equivalent fuel. Then it determines the desired engine assist motor power to minimize the summation of the equivalent fuel and consumed fuel of the diesel engine. The concept of ECMS is depicted in fig. 3.

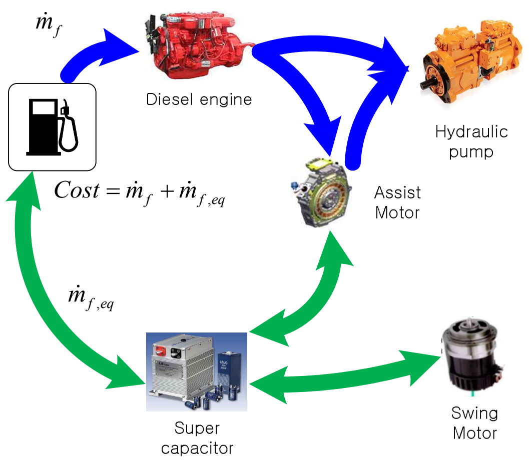


Figure 3: Schematic diagram of ECMS

The cost function of ECMS is defined as follows:

$$J = \dot{m}_f + \dot{m}_{f,eq} \qquad (1)$$

where $\dot{m}_f$ is the consumed fuel at diesel engine and $\dot{m}_{f,eq}$ is the equivalent fuel consumption at super capacitor. $\dot{m}_f$ is computed using engine map and it is a function of engine power.

$$\dot{m}_f = f\left(P_{eng}\right) \qquad (2)$$

where P_{eng} is the engine output power. Since the engine operating points is on the droop curve in fig. 2, the fuel consumption rate can be represented as a function of engine power approximately. $\dot{m}_{f,eq}$ contains a penalty function to guarantee the charge sustaining as follows:

$$\dot{m}_{f,eq} = f_{pen} \frac{P_{sc}}{H_{LHV}} \qquad (3)$$

where f_{pen} is penalty function, P_{sc} is super capacitor power and H_{LHV} is low heating value of diesel. If the value of penalty function is large number, it is desirable to charge the super capacitor using engine assist motor. When the penalty function is relatively small, the cost function is minimized when the super capacitor uses its charged energy. Therefore the penalty function is the key of ECMS which determines the fuel efficiency and charge sustaining performance. The penalty function is defined as a function of state of charge(SOC).

$$f_{pen} = f_{pen,zero} - \left(f_{pen,zero} - 1\right)\frac{SOC}{SOC_{des}} \qquad (5)$$

where $f_{pen,zero}$ is the penalty when the super capacitor is completely discharged and SOC_{des} is the desired state of charge. Both values have been determined by evaluating the fuel efficiency and charge sustaining performance. The resulting penalty function is depicted in fig. 4.

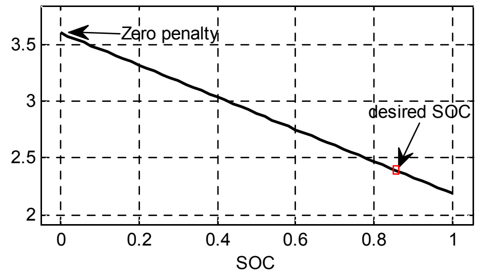


Figure 4: Penalty function of ECMS

The engine power and super capacitor power are determined from the power balance equation of mechanical linkage and electric system.

$$P_{eng} + P_{mot} + P_{pump} = 0 \qquad (6)$$

$$P_{sc} - P_{mot} + P_{swing} = 0 \qquad (7)$$

where P_{mot} is the engine assist motor power, P_{pump} is pump power and P_{swing} is swing power. Given load condition, if the engine assist motor power is determined, the engine power and super capacitor power are also determined. For given required pump and swing power, the cost function can be calculated as a function of engine assist motor power as follows:

$$J\left(P_{mot}\right) = f\left(P_{eng}\right) + f_{pen}\frac{P_{sc}}{H_{LHV}} \qquad (8)$$

where $P_{eng} = -P_{mot} - P_{pump}$ and $P_{sc} = P_{mot} - P_{swing}$. Then, the cost function is the function of P_{pump}, P_{swing} and SOC. Besides, there is no dynamics in the cost function. Therefore, the optimal motor power for given pump power, swing power and SOC is uniquely determined and it can be expressed as a three dimensional map. The two dimensional ECMS control maps for SOC = 0.2,

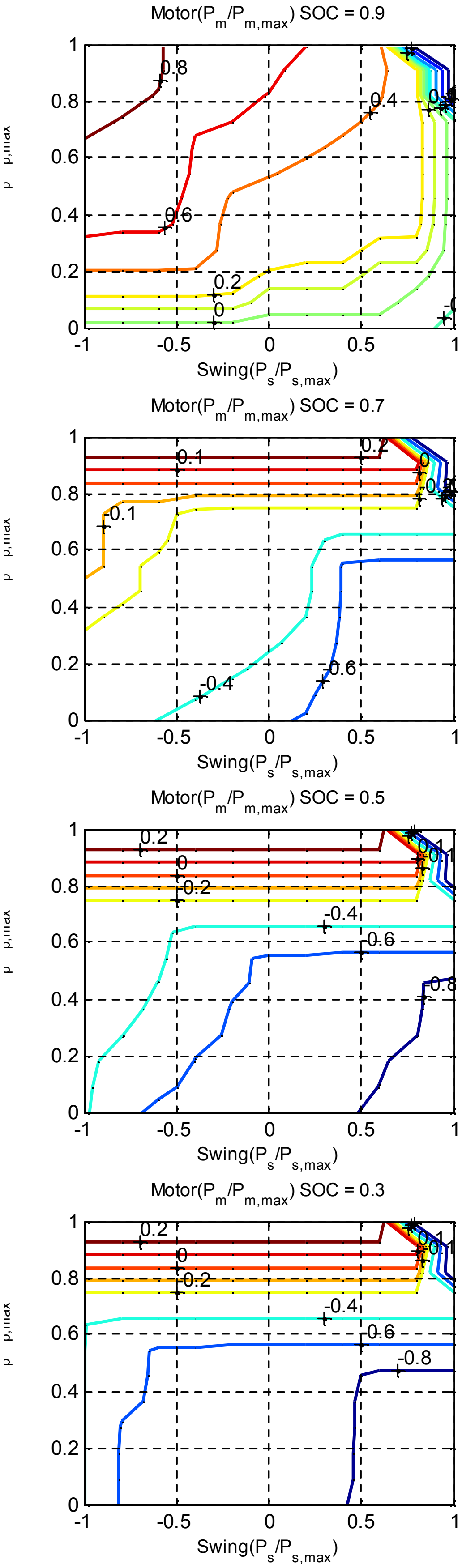


Figure 5: ECMS control map

0.5, 0.9 are depicted in fig. 5. SOC is lower, the charging area in the control map is larger. Note that the slope of penalty function relates to the fuel economy and charge sustaining performance. The large negative slope means excellent charge sustaining performance and degraded fuel economy. Adversely, small negative slope imply the degraded charge sustaining performance and improved fuel economy. Therefore, the design parameters of zero penalty and desired SOC in penalty function should be determined by considering the dynamic characteristics of hybrid drive train.

While the ECMS controls the power flow of the hybrid drive train, the engine set speed controller helps to shift the engine operating points to efficient region. The controller has been heuristically designed by considering the operating characteristics of the diesel engine. When the pump load is high, the diesel engine operates the best efficient region of the engine map. Therefore, there is no need to change engine set speed. However, in the case the pump load is low, the high engine set speed can cause large engine damping loss and the engine operating point is far from the optimal operating line. Therefore, it is desirable to shift the engine set speed to low set value when the pump load is low.

$$\begin{aligned} &if\ P_{pump} > P_{pump,thr} \\ &\quad \omega_{\mathrm{eng,set}} = \omega_{\mathrm{eng,set,high}} \\ &else \\ &\quad \omega_{\mathrm{eng,set}} = \omega_{\mathrm{eng,set,low}} \end{aligned} \tag{9}$$

The frequent engine set speed change during excavation can decrease transient response of the hydraulic pump. Therefore, engine speed compensation algorithm using engine assist motor is included to increase dynamic performance of the hydraulic pump.

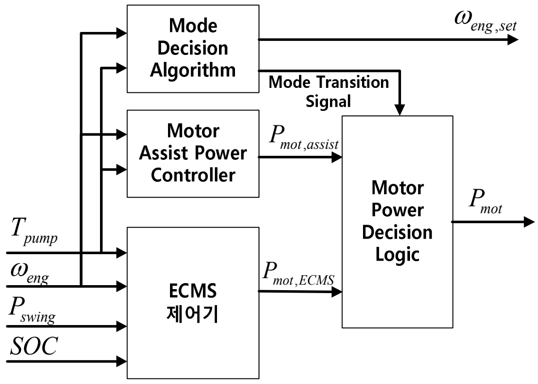


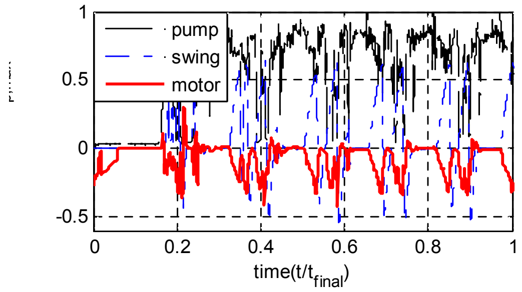
Figure 6: Hybrid Supervisory Controller

The schematic diagram of the hybrid supervisory controller is depicted in fig. 6. It includes the

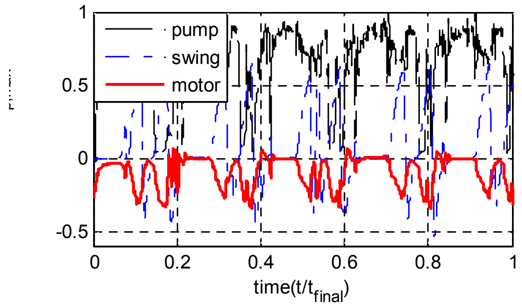
ECMS power management controller, engine set speed controller and mode transition algorithm to compensate engine speed error when the engine set speed switching occurs.

4 Simulation Results

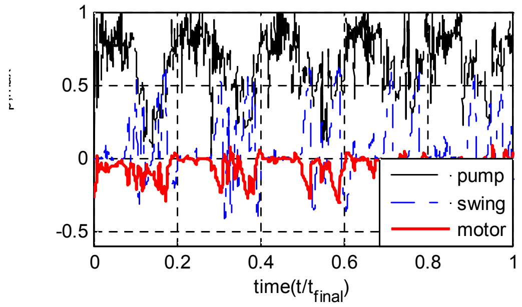
The fuel effectiveness and charge sustaining performance of the proposed algorithm have been evaluated using simulations. It has been applied to three representative excavation cycles in fig. 7. The control results of engine assist motor power are also depicted in the same figure. The results are normalized to the engine max power. The charge sustaining performance for several initial SOC is depicted in fig. 8. The simulation results show that the engine assist motor power smoothly controlled and by the ECMS and it guarantees the charge sustaining performance during excavation.



(a) TosaA-profile



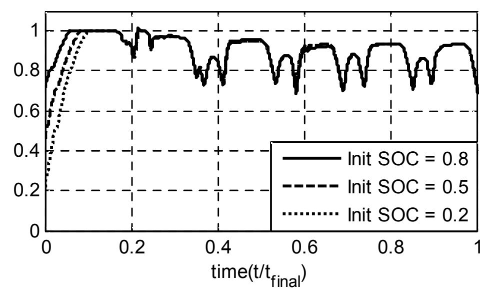
(b) TosaB- profile



(c) Rock profile

Figure 7: Excavation load profile and ECMS power management results

The consumed fuel during simulation is depicted in table 1. The results are compared to that of thermostat controller. The thermostat controller regulates the engine assist motor power using the SOC. It charges the super capacitor when the SOC is lower than a low threshold value until it reaches to high threshold value. The fuel economy also compared to that of dynamic programming technique. It gives off-line optimal solution for given load profile. Therefore, the results of dynamic programming can be used as a benchmark to evaluate the fuel economy of ECMS. The comparison results show that the ECMS is near optimum for various working cycles and it can improve fuel economy about 1-2% compared to simple thermostat controller. The results of hybrid controller are much better than the dynamic programming results because of the engine set speed controller. The results are normalized based on the results of thermostat controller.



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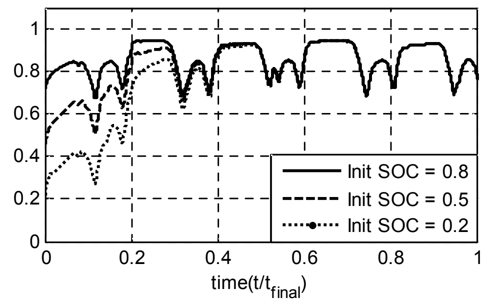
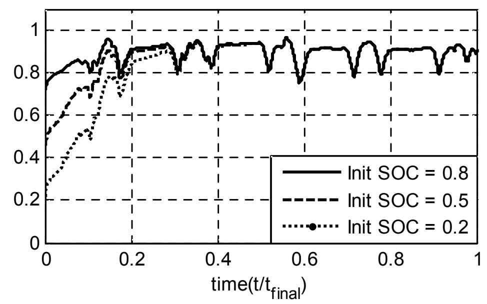


(b) TosaA-profile



(c) TosaA-profile

Figure 8: Super capacitor state of charge for different initial voltage

Table1: Fuel efficiency of hybrid supervisory controller

	TosaA	TosaB	Rock
Thermostat	100	100	100
Dynamic Programming	98.64	98.25	98.73
hybrid Controller	98.07	98.19	98.65

5 Conclusions

A hybrid supervisory control algorithm has been designed in this paper. It includes the equivalent fuel consumption minimization algorithm to manipulate power flow of hybrid drive train to maximize fuel economy and guarantee charge sustaining of super capacitor. The engine set speed controller is also developed so that the engine operating points can be near the optimal operating line. The simulation results shows that the proposed algorithm guarantees the charge sustaining of super capacitor and it can improve fuel economy about 1~2% more than the simple thermostat controller. Future work will focus on improving fuel economy using pattern recognition technique. The load profiles of the hybrid excavator are periodic and the optimum control parameters of hybrid supervisory controller can be different according to the load profiles. The hybrid supervisory controller integrated with pattern recognition algorithm will be developed in near future.

Acknowledgments

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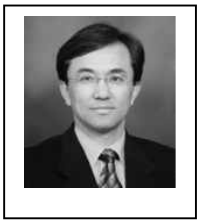
Authors

Ph.D. student. Hakgu Kim
School of Mechanical and Aerospace Engineering,
Seoul National University
iku3333@snu.ac.kr

Ph.D. Seungjin Yoo
Research Engineer
Institute of Technology of Doosan Infracore
Seungjin.yoo@doosan.com



Professor. Kyongsu Yi
School of Mechanical and Aerospace Engineering,
Seoul National University
kyi@snu.ac.kr