

Design and Control of Hybrid Electric Power System for a Hydraulically Actuated Excavator

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ABSTRACT

In this paper, a prototype hybrid excavator that incorporates two electric motors and an ultra-capacitor module in a commercial diesel engine powered hydraulic excavator is presented. The features of the developed hybrid excavator include (1) electric propulsion of the swing system, (2) electric power assistance for the diesel engine and (3) energy regeneration using an ultra-capacitor module. By designing a suitable swing control and power management algorithm, the developed hybrid electric power system can significantly improve the fuel economy of the diesel powered hydraulic excavator, without any performance degradation or drivability deterioration.

INTRODUCTION

During the last few decades, hybrid power system technologies have attracted their fair share of attention from automobile manufacturers worldwide, due to their potentiality for improving fuel efficiency and reducing pollution emissions.

In contrast to their great popularities in automobile industry, there have been only few reported applications of hybrid power system to heavy duty construction equipment like hydraulic excavators [2-8].

The fuel cost for running a heavy duty hydraulic excavator occupies the greater portion of the total cost of ownership than that of the automobiles, so that the fuel economy of a machine might be one of the most appealing factors to

customers. Furthermore, the social regulations on emission and fuel economy are expanding ever strictly from automobiles to off-road vehicles and construction equipment.

To meet these market demands and social trends, the hybrid power system technology will be a promising solution which can greatly improve the fuel and emission performance of hydraulic excavators.

As a plant for hybrid power system applications, hydraulic excavators have exclusive features compared with automobiles that make it better suited but, at the same time, more challenging.

- Multiple degrees of freedom of the hydraulic excavator mechanism implicate a greater number of possible hybrid drive train architectures each of which requires a hybrid power management algorithm of different complexities to meet the performance requirements.
- The drive train heavily depending on the fluid power systems leaves great potentiality to remove hydraulic energy loss via a suitable design of hybrid drive train architecture. In general, a number of hydraulic actuators are supplied with fluid power from the fewer pumps in hydraulic machines like excavators, so that the actuators are controlled in coupled with each other. As a consequence of these hydraulically coupled control mechanisms, without careful motion control strategies, the hybridization of hydraulic actuation systems would accompany unfamiliar driving characteristics.

- Load power of the diesel engine of hydraulic excavators varies over a wide range regularly and frequently, compared to that of automobiles. This leaves the greater fuel efficiency potential for hydraulic excavators if the proper power assisting control by an electric motor is successfully applied, so that the operating points of the engine are concentrated around the optimal fuel efficiency region.
- Large payload-carrying capability of a heavy duty hydraulic excavator makes it almost free from performance deteriorations originated from the increased vehicle weight when hybrid components are additionally equipped.

In this paper, a prototype hybrid excavator that incorporates a diesel engine, two electric motors and an ultra-capacitor module is presented. A hybrid architecture that best compromises the cost effectiveness and fuel efficiency is designed by examining the feasible hybrid drive trains. Based on the experimental data of a conventional hydraulic excavator, the component sizing of electric motors and ultra-capacitor module is carefully performed by considering the power requirement and duration of nominal performance. Also, the variable displacement hydraulic pumps are resized to operate the engine around its optimal fuel efficiency region. A swing motor control algorithm that simulates the driving characteristics of a hydraulic swing system is developed based on the test data. Moreover, a power management algorithm that stably and consistently manages the developed prototype hybrid excavator is presented.

OVERVIEW OF HYDRAULIC EXCAVATOR POWER TRAIN

Figure 1 depicts the configuration of the power train of the target hydraulic excavator. The major components are a diesel engine, variable displacement pumps, control valves and hydraulic actuators.

ENGINE - The speed of the engine is regulated at a constant speed according to a driver's set value. More precisely, the driver sets the high idle speed of the engine, and the engine speed is regulated along the prescribed droop curve which is slightly inclined toward the rated speed where the maximum power is achieved. The rated power of the engine and the resulting working power of the excavator are almost proportional to the engine set speed value.

PUMPS - Two variable displacement pumps are propelled by the engine and deliver the mechanical power of the engine to each hydraulic actuator in the form of fluid power. The displacement of each pump is controlled in several ways that limit the load power imposed on the engine in high-load operation mode while preventing the energy loss in case of low-load operation mode. Moreover, by observing the engine speed drop from the rated speed, the displacement of each pump is controlled to maximally

utilize the engine capability up to its rated power in high-load operation mode.

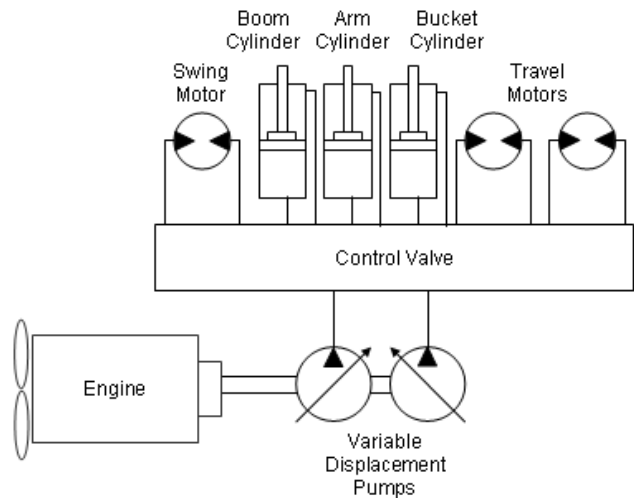


Figure 1. Power train of a conventional excavator

CONTROL VALVE - The control valve block is composed of a number of spools and on/off type valves each of which is controlled electronically or hydraulically. If a driver manipulates the joystick to control the mechanical linkages of an excavator, the discharged flow from the gear pump, which is omitted in Figure 1, is delivered to each end of the corresponding spool valve. Then the flow rate from the pump to each hydraulic actuator is determined from the pressure difference and the metering area that depends on the spool displacement. Although the fluid power media is extensively used in an excavator power train due to its favorable characteristics of compactness, accurate control performance and great power delivering capability, the main source of drive-train inefficiency is lying on its inherent control principles incurring energy dissipations during valve metering.

HYDRAULIC ACTUATORS - The mechanical linkages of an excavator are controlled by the multiple hydraulic cylinders and hydraulic motors as shown in Figure 1. Because there are more hydraulic actuators than the fluid power sources, they are controlled in coupled with each other. For example, if a driver manipulates a specific hydraulic actuator, the resulting speed of the hydraulic actuator would be different depending on the condition of the other actuators, i.e., whether they are fixed or controlled.

Figure 2 shows the load power of the engine and the gross power output of hydraulic actuators during a cycle of typical excavation tasks.

The auxiliary load power for the cooling fan, the alternator charging the battery and the gear pump discharging pilot flow is negligible, and consequently is not considered here.

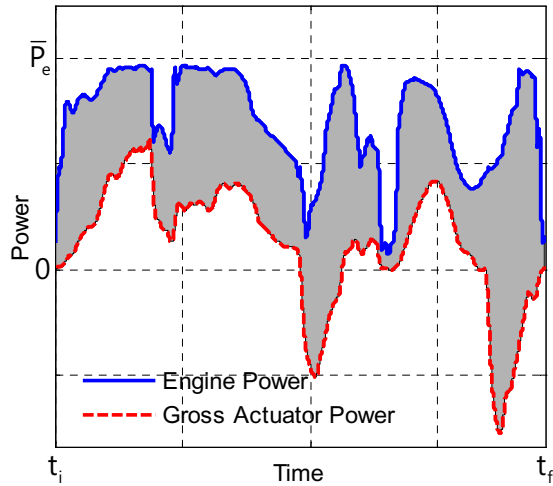


Figure 2. Power loss of a conventional excavator

Therefore, the load power of the engine is solved from Equation (1) considering the efficiency of the pump, while the gross actuator power is obtained from the sum of each actuator power output in Equation (2).

$$P_e = \tau_e \omega_e \quad (1a)$$

$$\tau_e = \sum_{i=1}^2 \eta_{p,i} D_{p,i} p_{p,i} \quad (1b)$$

$$P_{c,i} = (a_{ch,i} p_{ch,i} - a_{cr,i} p_{cr,i}) v_{c,i} \quad (2a)$$

$$P_{sm} = D_{sm} \Delta p_{sm} \omega_{sm} \quad (2b)$$

The actuator power outputs in Equation (2) are containing the working power to excavate the ground and deliver it to the dumping location, and also the power required to move the excavator's mechanical linkages. It is observed that the significant amount of power is consumed by the power train compared to the relatively small effective power output at the hydraulic actuators. The difference between the engine power and the gross actuator power, shaded area in Figure 2, reflects the power train efficiency of the conventional excavator. The major sources of inefficiency are fluid power loss in the control valves and dissipation of the regenerable power of the excavator's mechanical linkages.

The above power dissipation in drive-train together with the ineffective operation of the engine, which will be explained in the later section, motivates our development of a more efficient hybrid power train with energy regeneration capability.

DESIGN OF HYBRID DRIVE TRAIN

In [2-8], various kinds of hybrid drive train architectures are proposed. According to their topological structure, the hybrid drive train architecture can be classified into three categories such as parallel, series and compound type.

PARALLEL TYPE - As can be found in various automobile applications of hybrid power system, the parallel type is characterized by its mechanically interconnected electric propulsion system with the engine [1]. Of the major benefits from the application of a parallel type hybrid power system is its cost effectiveness from relatively minor effort in the system modification or integration. The fuel efficiency can be improved by the power assisting control of the electric propulsion system, which enables the engine to be operated in the optimum fuel efficiency region [2,5-6]. However, the regeneration capability of this type of hybrid system is only limited to automobile applications. In a hydraulic excavator, the re-generable power is wasted into heat energy in the hydraulic system, whereby the load power on the engine is always positive as in Equation (1).

SERIES TYPE - In a series type hybrid system, all the hydraulic actuators are replaced by electric or electro-hydraulic actuators that enable the kinetic or potential energy regeneration of mechanical linkages [7-8]. Because the engine merely plays the role of the prime mover that generates the electric power, it is always possible to operate the engine in optimal fuel efficiency region independent of the load imposed on each actuator. Obviously, the series hybrid system is the most fuel economic solution among the possible hybrid drive train architectures. But it is cost-expensive and a significant modification of the existing drive train is required. Furthermore, without a sophisticated motion control logic that matches the control characteristics of the hybrid excavator to that of the conventional one, the problems due to the unfamiliar driving characteristics would result, that give rise to deteriorated working efficiency of the excavator driver.

COMPOUND TYPE - The trade-off between the cost effectiveness and fuel efficiency brought the various types of compound hybrid power system into the excavator applications. One of the most popular designs is depicted in Figure 3, where the electric swing motor and the engine assist motor are incorporated into the conventional drive train [3-4]. In this architecture, the primary function of the engine assist motor is to supply the additional propelling power to drive the pumps in case of high-load operation mode. The other function is to generate the electrical power to charge the energy storage device or to supply the driving power for the electric swing motor.

By replacing the hydraulic swing motor with an electric motor, it is possible to regenerate the kinetic energy of the excavator's turning body as well as to remove the energy loss during the valve metering.