The Development of an 8 tonne Class Hybrid Hydraulic Excavator SK80H

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There is an increasing demand for construction machines with lower fuel consumption to prevent global warming and to decrease the operational cost. In response to such demand, we have developed a hybrid system for an excavator of the 8 tonne class. The system employs advanced power electronic components, such as an electric motor, inverter and battery. These components are similar to the ones that have been used for hybrid cars, but are more sophisticated in that they are designed for an increased number of actions performed by an excavator. When installed in an SK80H model, the system has reduced its fuel consumption by 40% or more and also decreased the noise level significantly.

Introduction

With the growing concerns about global warming caused by greenhouse gas emissions, energy-saving technology is receiving increased attention. In the automotive industry, the improved performance of motors, advanced power electronics (e.g., inverters) and improved battery technologies (e.g., NiMH/Li ion batteries) have led to the commercialization of hybrid systems. Furthermore, all-electric vehicles are being put into use[1), 2)].

Since 1999, KOBELCO CONSTRUCTION MACHINERY CO., LTD. has collaborated with the New Energy and Industrial Technology Development Organization (NEDO) and Kobe Steel, Ltd. in R&D activities on a hydraulic excavator adapting a series hybrid system. The resulting technology was used to develop a system that is more practical and commercially feasible. This paper reports on a hybrid excavator, the SK80H, which was developed for mass production.

1. The purpose of hybrid excavators

1.1 The construction of a hydraulic excavator and the use of power

A hydraulic excavator comprises several actuators, such as the cylinders that actuate the boom, arm and bucket, and motors that are used for swinging and traveling. These actuators are driven by a hydraulic pump to perform tasks such as digging (**Fig. 1**). **Fig. 2** shows the change in the input power of the hydraulic pump and the change in the power consumed by the actuators during the cycle of an excavation task performed by a conventional hydraulic excavator of the 8 tonne class. As shown in this figure, the hydraulic pump in a conventional hydraulic excavator supplies the power required for the maximum load all the time, even when the power consumed by the actuators is low. The surplus power is dissipated as heat. The dissipated heat also includes heat caused by operational loss that is intentionally incorporated to improve the maneuvering feel of each operation. Also included in the dissipated heat are potential / kinetic energies consumed by lowering, swinging and stopping the working apparatuses. **Fig. 3** shows the flow of power

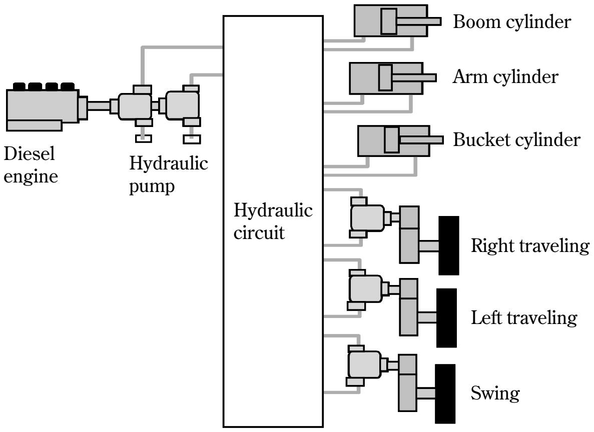

Fig. 1 Block diagram of hydraulic excavator

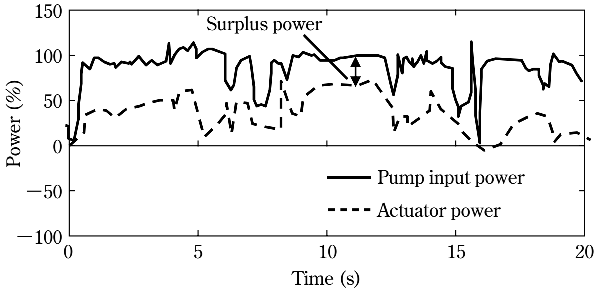

Fig. 2 Excavator power

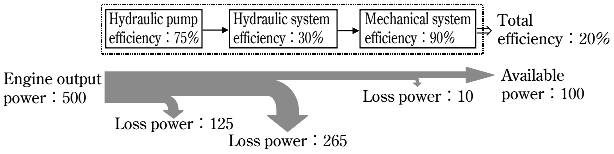

Fig. 3 Power flow

in the hydraulic excavator. The figure also shows the efficiency of each subsystem and a power flow diagram assuming the engine power to be 500. On the average, only 20% of engine output power is exploited in a conventional hydraulic excavator.

In the field of automobiles, hybrid systems have been developed and brought into practical use for hybrid cars. These automobiles focus on the reuse of regenerative energy and on the improvement of system efficiency during the partial load operation of their engines. A hydraulic excavator, on the other hand, has a greater number of actuators to be controlled than an automobile has, and the actuators are subject to large resistance such as the reactive force of digging. In addition, the actuators are subject to large load variation, because they are repeatedly, and in a short period of time, used for high-load tasks, such as heavy digging, and low-load tasks, such as horizontal towing and leveling. **Table 1** compares a hybrid system for a hydraulic excavator with that of an automobile. A hybrid system for an automobile cannot be adopted as-is to a hydraulic excavator that is subject to large load variation. There is a need for a newly-developed system for hydraulic excavators.

Table 1 Comparison of automobile and hydraulic excavator

	Automobile	Hydraulic excavator
Application	Running	Digging, Leveling, Loading
Operation	Handle, Pedal	Lever (multiaxial)
Number of actuator	1	6
Type of Load	Running resistance	Excavation reaction force
	Inertial force	Inertial force
Load fluctuation	small	big
Velocity fluctuation	small	big

1.2 Points for fuel saving

Having in mind the facts mentioned in the above discussion, we focused on the following three points in the development of a hybrid system for a hydraulic excavator.

1) Electrically-driven swing

Making the swing motion electrically driven has made regenerative power available for reuse, significantly reducing the loss caused by the hydraulic drive. The electrical drive permits the swing motion to be driven independently from other actuators such as the boom. This has decreased the distribution loss that would otherwise have been generated during compound control actions, such as the simultaneous operation of boom raising and swinging.

2) Loss reduction in hydraulic system

The hybrid system alone cannot sufficiently improve the fuel efficiency. The efficiency of the hydraulic system must also be improved. We have significantly reduced the hydraulic loss by performing a thorough review of flow resistances in hydraulic devices, such as pumps and valves, and piping. The review included design revisions and the replacement of parts.

3) Leveling of engine load

Fig. 4 shows the changes in the engine power of a hybrid excavator during its major operations (i.e., digging, boom raising/swinging, dumping and boom lowering/swinging). Also included for comparison in this figure are the power changes of a conventional excavator. As shown in this figure, the hybrid excavator converts the surplus energy from low-load operations into electricity and stores it in a battery. The power stored in the battery is used to drive an electric motor during high-load operations to positively assist the engine. This arrangement allows

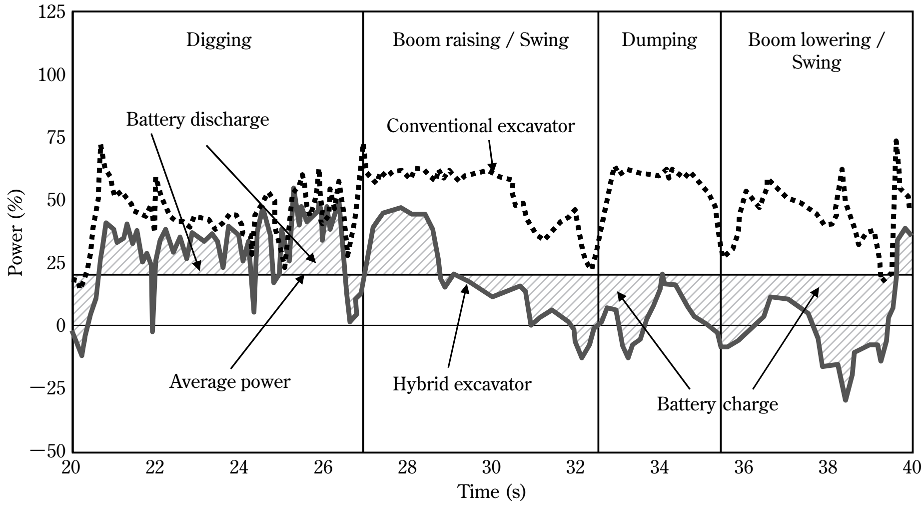

Fig. 4 Leveling of engine load

the leveling out of the engine load, enabling the downsizing of the engine and operation at high-efficiency.

2. Hybrid excavator

2.1 The system configuration

Fig. 5 is a block diagram of a hybrid system developed by KOBELCO CONSTRUCTION MACHINERY CO., LTD. This system, designed for an 8 tonne class excavator, is a series-parallel hybrid system in which the hydraulic circuits for the boom and the like are driven in parallel and the swing motion is driven in series. This system configuration was selected from among various hybrid systems that were considered. The selection was based on the desire to obtain the highest rate of efficiency at a lower cost, i.e., considering the rate of the fuel-saving effect vs. the calculated cost increase incurred by hybrid apparatuses such as motors. A conventional excavator has an engine that drives a pump to distribute hydraulic pressure to its actuators. The present system drives its pump using power from both the engine and generator-motor.

The control system includes several controllers, such as a hybrid controller, generator-motor controller, engine controller and battery monitor, for cooperative control (Fig. 5). Compared with conventional excavators, hybrid excavators are exposed to an environment with more severe noise, including, in particular, inverter noise. Therefore, wiring must be kept as short as possible, especially for the sensors. Because of this, the controllers are built into units along with other devices, and the controller units are connected by high-speed serial lines to achieve the high reliability of the system.

The following explains the function of each controller. Each component (i.e., engine, generator-motor, swing motor and battery) is assigned its own controller. The hybrid controller transmits commands to the component controllers. Component failures are detected. Stopping control is executed at the time of any component failure. The hybrid controller receives and manages information (e.g., the status of components, sensing data and errors) from the component controllers and executes the power management control for the entire system. The proper function arrangement for the controllers has enabled the cooperative control of the entire system.

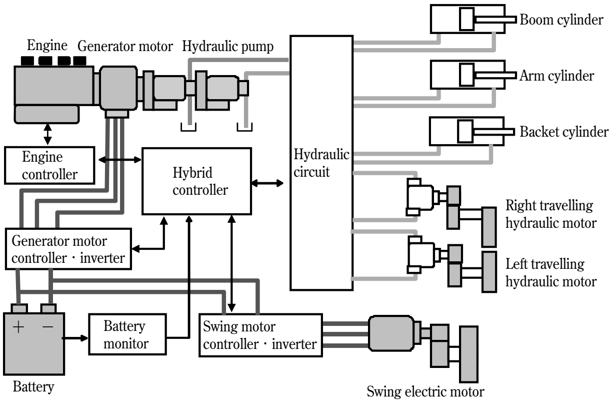

Fig. 5 Block diagram of hybrid excavator

2.2 Hybrid components

The performance of a hybrid system (i.e., system efficiency and power performance) is determined by the way that the power is shared by each component. Thus, the determination of the output power is most important in the component specifications. In the present development, the power required for each component is determined by calculation, as well as simulation based on the results of the power actually measured on conventional excavators. The following outlines the major components listed in **Table 2**.

1) Engine

The downsizing of engines is effective in improving fuel efficiency. Conventional machines require engines of about 40kW, while the present system employs a smaller engine of 27kW. With power assistance from the generator-motor, the system has achieved a working speed and power just as high as those of the conventional systems.

2) Battery

A hybrid system requires a battery with high power density. A nickel hydrogen battery has been adapted for use in this system; it is the same type as that used for automobiles. Its capacity was determined such that its discharge power meets the output requirement for an 8 tonne class excavator with engine assist. The charging capacity is determined on the basis of the maximum regenerative power of the electric swing motor.

3) Generator-motor

Being coupled with the engine, the generator-motor must be small and possess high efficiency; hence, a permanent magnet motor has been adapted for use. This motor is flat in shape and is built in between the engine and pump. Its output was determined such that its power, including assist

Table 2 Equipment specifications

Engine	Rated power 27(kW)/1,800(min^{-1})
Generator motor	Rated power 10(kW)/1,800(min^{-1})
Swing electric motor	Rated power 8(kW)/1,890(min^{-1})
Battery	Rated voltage (288V)

power, would be at the same level as that of a conventional excavator.

4) Electric swing motor

A permanent magnet motor with high efficiency was adapted for the electric swing motor. The motor, combined with the inverter control, enables the regeneration of energy during the deceleration of swing motion. The output is determined such that the swing motion acceleration is achieved at the same level as that of conventional excavators.

5) Inverter

The inverter adopted was one integrated for both the generator-motor and electric swing motor. The inverter output was determined from the capacity required for driving all the electric motors, considering their maximum loads.

2.3 Hybrid excavator motions

Compared with an automobile, an excavator has a greater number of actuators and performs more motions. Thus, it is important to select the power sources, such as the engine and battery, according to these motions. **Fig. 6** shows the operation of the major components according to the motions of the hybrid excavator.

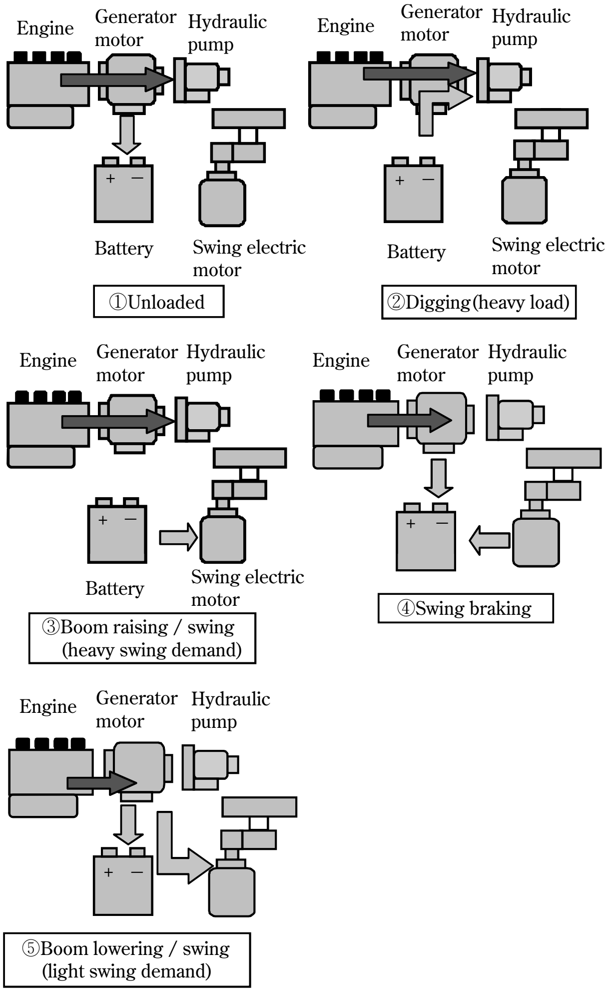

Fig. 6 Operation of hybrid excavator

1) Unloaded (Fig. 6, ①)

When the excavator is unloaded and the battery charge is below a predetermined level, the engine drives the generator to charge the battery. Thus, the battery charge is maintained at the level required for power assist, making the excavator ready for high-load operation.

2) Heavy digging (without swing motion; Fig. 6, ②)

During heavy digging, the engine drives the pump with assistance from the generator-motor driven by battery power. The use of the battery power allows the small engine to achieve the same level of power performance as that achieved by conventional machines.

3) Boom raising/swing (heavy digging and swinging; Fig. 6, ③)

During heavy digging involving swing motions, the engine drives the hydraulic pump, while the battery powers the electric swing motor. The coordinated action of the engine and motor provides the power required for the compound motions of the hydraulic system and the swinging.

4) Swing braking (Fig. 6, ④)

When the swing motion is decelerated, the regenerative power of the swing motion is charged into the battery. At the same time, the power generated by the generator-motor that is driven by the engine is also charged into the battery. This enables the reuse of the regenerative energy of the swing motion, energy that is conventionally dissipated as heat.

5) Boom lowering and swinging (light load swinging; Fig. 6, ⑤)

During hydraulic driving, the surplus power from the engine is used to generate electricity; that power is used to drive the electric swing motor and is also charged into the battery. This enables the leveling of the engine load and improves the system efficiency.

3. Effect of hybridization

3.1 Hybrid power source control

A hybrid system comprises various components such as an engine, battery and electric motor. Thus, it is important to control the power supplied to each of these components according to the load imposed on each actuator. **Fig. 7** shows the result of a test conducted on the power source control of an actual machine. In the figure, numbers ② to ⑤ correspond, respectively, to the motions ② to ⑤ depicted in Fig. 6. Numbers ② and ③ are cases with a relatively

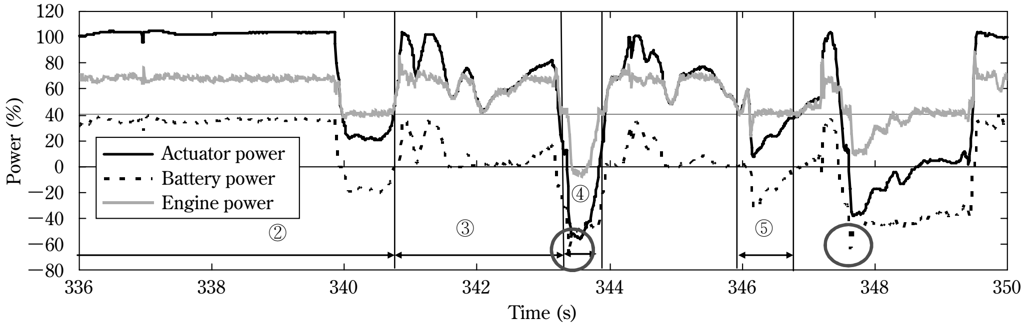

Fig. 7 Results of power control test

heavy load, in which the battery-driven generator-motor provides power assist when the total power consumed by the actuators exceeds the power supplied by the engine. Number ④ represents a case in which the swing motion is decelerated, during which action the regenerative power from the electric swing motor is stored in the battery. Number ⑤ represents a case in which the boom is lowered with a swing motion; engine power is being used to drive the swing motion and, at the same time, is being stored in the battery. As shown, almost all the motions depicted in Fig. 6 are realized. In the battery control, the maximum powers for the battery charging and discharging are determined by the battery SOC (State of Charge) and battery temperature. For the motions shown in Fig. 7, the maximum charging power and maximum discharging power are set at 46% and 48%, respectively. The battery power varies greatly, and, in a transient state, may exceed the maximum power of charging and discharging (as shown by circles in Fig. 7). Except for these portions, the power is controlled so as to remain within the maximum amount of power for charging and discharging, showing that the hybrid power source control is functioning as intended.

3.2 Fuel consumption reduction effect

The fuel efficiency evaluation of hybrid hydraulic excavators has been newly established in the Japan Construction Machinery and Construction Association Standard (JCMAS)[3]. The test method covers a comprehensive evaluation of motions, including digging & loading, leveling, traveling and idling. The fuel efficiency of the SK80H was evaluated on the basis of this standard.

Fig. 8 shows the results of the fuel efficiency measurement based on the new JCMAS. The fuel consumption for each task is compared to that of the conventional machine produced by KOBELCO CONSTRUCTION MACHINERY CO., LTD. In this figure, the data for the conventional machine is assumed to be 100 percent. For digging and loading tasks, an almost 40% reduction in fuel consumption has been achieved. The data also confirms that a maximum reduction of 40% has been realized for CO_2 emissions.

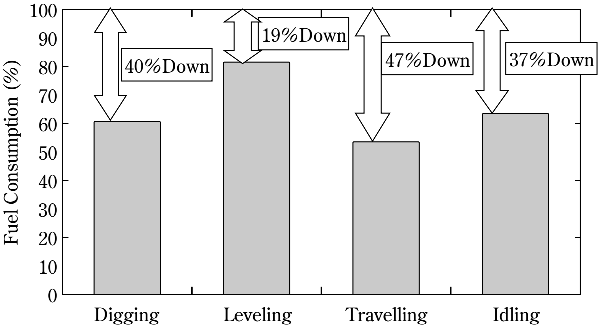

Fig. 8 Improving of fuel consumption

3.3 Noise reduction effect

Silence is another important feature for excavators of the 8 tonne class, since they are used for construction work in urban areas. A hybrid excavator, the SK80H, was measured for its noise reduction effect. When compared to a conventional excavator of the same class, the hybrid excavator emits less noise, thanks mainly to the noise reduction effect of its downsized engine. Although, in comparison with conventional machines, it lacks any special noise reduction measures, the SK80H emits 90 dB(A), a significant noise reduction about 3 dB(A) lower than the standard value. The machine is officially designated as ultra-low-noise construction equipment under Japanese Ministry of Land, Infrastructure, and Transport noise regulations. The hybrid system has been proven to provide an effective means for noise reduction.

Conclusions

The SK80H, developed as an 8 tonne class hydraulic excavator, has been introduced as an example of volume production machinery designed as energy-saving construction equipment. The hybrid system has enabled the downsizing of the engine, improved the fuel efficiency by 40% and achieved a significant noise reduction. We will continue to strive to further improve our product on the basis of field information, such as actual operational data, and also to reduce the cost and increase productivity, while maintaining the above-described fuel efficiency performance.

References

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