Development of New Hybrid Excavator

Masayuki KAGOSHIMA, Masayuki KOMIYAMA, KOBELCO CONSTRUCTION MACHINERY CO., LTD.
Takao NANJO, Mechanical Engineering Research Laboratory, Technical Development Group, KOBE STEEL, LTD.
Akira TSUTSUI, Production Systems Research Laboratory, Technical Development Group, KOBE STEEL, LTD.

In order to make construction processes more efficient, a 6 ton class hybrid excavator was developed through a collaborative effort between KOBELCO CONSTRUCTION MACHINERY, Kobe Steel, and NEDO. Reductions in fuel consumption were evaluated through simulations on a series-type hybrid system. Then a prototype demonstration machine was built to simulate practical operations. The experimental results proved that the proposed system can reduce fuel consumption by more than 60%. The remaining challenge is to develop a manufacturing process which reduces the cost of the components constituting this new hybrid system.

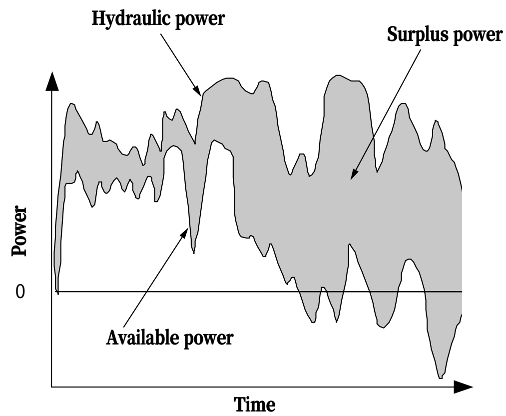

Fig. 1 Power of excavator

Introduction

The Kyoto protocol, which was adopted at the COP3 in December1997, to reduce Annex I countries' GHG (Greenhouse gas) emissions by an average of 5% below their 1990 levels, came into force on February 16 2005 following ratification by Russia on November 18 2004. Japan, required to reduce its emission by 6% from the 1990 level under the protocol, will now have to cut 13.6% from the 2002 level, an increase by 7.6%, and has enacted "the Law concerning the Promotion of the Measures to Cope with Global Warming" to enforce legal binding on quantitative targets and to accelerate measures to conserve energy.

It is believed that construction machinery generates 1% of the total GHG emissions of Japan, and hydraulic excavators are responsible for 59% of the portion. Hybrid systems[1), 2)] are now gaining attention as a means for reducing GHG emissions by improving fuel economy and energy efficiency.

Under such circumstances, KOBELCO CONSTRUCTION MACHINERY CO., LTD., in collaboration with the New Energy and Industrial Technology Development Organization (NEDO) and Kobe Steel, has developed a 6 ton class hybrid excavator to cut energy consumption by 40% or more. This paper reports the results of the verification test on the fuel economy of the hybrid excavator in actual operations.

1. The purposes of hybrid hydraulic excavators

Hydraulic excavators are subject to large variations in workloads while repeating high work load operations, such as excavation, and low work load operations, such as leveling and smoothing. Oil hydraulic systems are also required to supply high energies quickly to various actuators, including the ones for boom, arm, bucket, swinging and traveling, which are all separately and remotely disposed on excavators.

Figure 1 shows the workload profile of a conventional excavator. In a conventional excavator, hydraulic power, corresponding to the maximum workload, is always supplied from a pump and excessive power is dissipated as heat. It is difficult to reduce input power, even during low workload operations, because combined controls of actuators require distribution of flows and interflows, which increase loop loss and bleed loss. In addition, potential energies and kinetic energies at the time of lowering and slewing stoppage of attachments, are also dissipated as heat. As shown in **Figure 2**, only 20% of the engine output power is utilized in a conventional type excavator.

Taking those into consideration, a new hybrid hydraulic excavator was developed under the following concept.

- Reduction of energy loss due to hydraulic interflows and distributions by independently driven actuators.
- Reduction of control loss by using electrical/hydraulic hybrid actuators.
- Reutilization of regenerative energies, such as potential energy and kinetic energy.

The efficiency of the power supply engine was improved by the following.

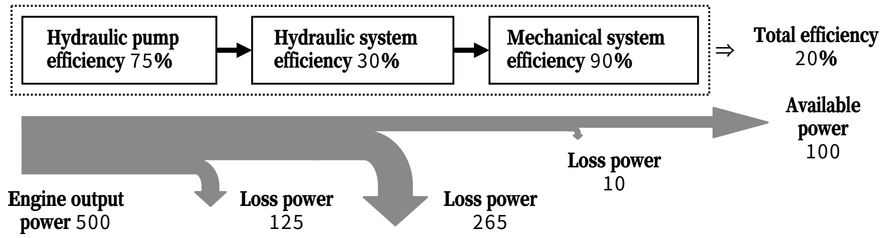

Fig. 2 Power flow

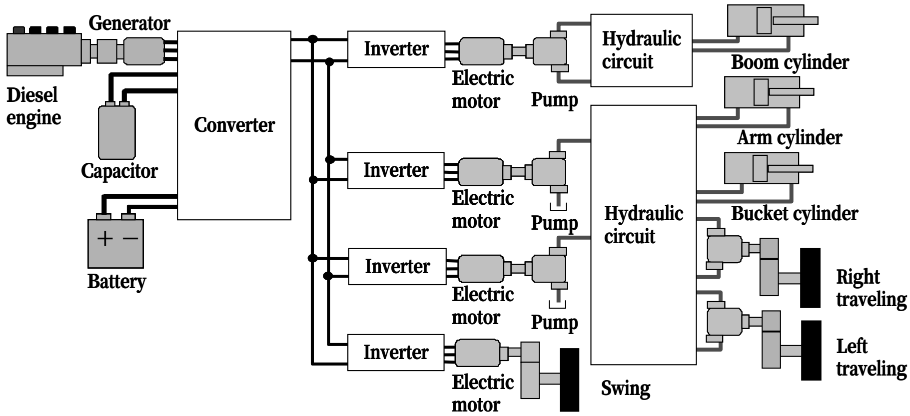

Fig. 3 Hybrid system configuration

- Equalization of engine loads using batteries and capacitors and engine operations in high efficiency regions.
- Reduction in fuel consumption by intermittent engine operations.

2. The system configuration of a hydraulic excavator

The system configuration of the developed hybrid excavator is shown in **Figure 3**. The excavator is a 6 ton class, having a series-type hybrid system as shown in the figure.

The actuator system comprises six quasi-independent actuators driven by electric motors and pumps. The quasi-independent configuration minimizes hydraulic interferences among actuators and the losses occurring in conventional hydraulic systems. The boom is driven by a closed system comprising an electric motor and hydraulic pump rotatable in both the directions, so that potential energy accumulated at "up" positions is regenerated as electric energy via the hydraulic pump when the boom goes down. The slewing motions are driven by an electric motor, instead of a hydraulic actuator, and the kinetic energy of the upper body is regenerated as electric energy when the slewing stops. The travel system, which involves rotational motion suitable for electric drive, employs an electric/hydraulic drive which shares a hydraulic source with the arm and bucket.

The power source is a series-type hybrid source comprising an engine, battery and capacitor. The use of the battery and capacitor compensates for the excess and deficiency of the engine power even in the large workload variation, smoothes the engine load, allows the use of a smaller-than-conventional engine and improves fuel efficiency.

In addition, the system converts the engine power into electrical energy once, and the engine can be stopped even during excavation operations, if there is spare energy in the battery and capacitor. This intermittent engine operation further improves the fuel economy.

The specifications of the hybrid system are summarized in **Table 1**. The upper rows of the table represent the specifications of the actuator driving motors and the lower rows represent those of the power source devices. The actuator driving motors are selected to have capacities higher than the maximum outputs of respective actuators, and the

Table 1 Hybrid system specifications

Boom	Rated output	20 kW (3,000min^{-1})
Arm (Left traveling)	Rated output	11 kW (3,000min^{-1})
Bucket (Left traveling)	Rated output	11 kW (3,000min^{-1})
Swing	Rated output	6 kW (3,000min^{-1})
Engine	Rated output	22 kW (1,600min^{-1})
Generator	Rated output	20 kW (6,600min^{-1})
Battery	Rated voltage	288 V
	Capacity	6.5 Ah
Capacitor	Max voltage	304 V
	Capacity	11.3 F

power source devices are selected based on the power balance among the engine, generator and battery, during continuous heavy load operations. The engine output is only about a half of that of the conventional excavators.

3. Fuel economy simulation during actual operation

3.1 Simulation modeling

A kinetic simulation model was made, using the non-linear kinetic analysis code SINDYS[3] developed by Kobe Steel, to represent the kinetic responses of the whole system. The model includes modeling of all the structural elements of the hybrid excavator, such as the driving system of the power source, electrical system, hydraulic systems for the actuators and link mechanisms of the bucket and attachments.

The main object of the simulation is to evaluate the fuel consumption characteristics and fuel economy based on the model. In order to reflect the actual efficiency and loss characteristics of each component, simulation parameters were identified by testing performance of individual component.

The following are the efficiency and loss characteristics taken into considerations for the simulation modeling.

- The charge / discharge characteristics of the battery and capacitor.
- The efficiencies of the generator and motor.
- The fuel efficiency of the engine.
- The efficiency characteristics of the electrical control system.
- The pressure loss characteristics of the piping and control valves.
- The volume efficiencies and mechanical efficiencies of the hydraulic pumps and motors
- The power consumptions by auxiliary machines

3.2 Fuel economy in the standard mode

Fuel economy was evaluated for a sewer pipe laying work, a typical work for a 6 ton class excavator. The evaluation was carried out on a work pattern comprising the standard work modes[4], which were based on our own data obtained from actual operations in work fields. **Table 2** summarizes the time ratio of each work in the standard work mode. The mode reflects actual operations, in that it covers seven operations, excluding the engine stop, ranging from light to heavy load operations. Actual data for the actuator speed and load were measured on a conventional machine and were used in a virtual continuous operation for about one hour in total. The virtual operation was evaluated by simulation.

Table 2 Standard work mode

Work	Cycle time (s)	Time ratio (%)
Loading	45	18
Unloading	35	8
Leveling	50	8
Hoisting	80	10
Sheet piling	75	7
Traveling	20	3
Idling	120	23
Engine stop	80	23
Total		100

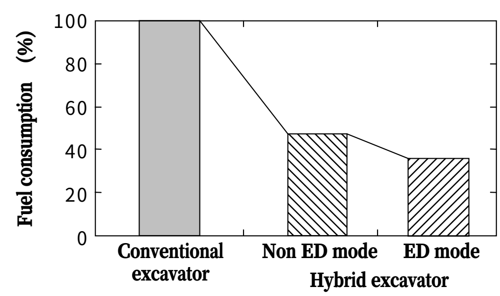

Fig. 4 Simulation results of standard work mode

Figure 4 shows fuel consumptions simulated under the standard work mode. The figure includes results from two conditions; with and without an Electric Drive (ED) mode. In the ED mode, actuators are driven electrically by the battery and capacitor, with the engine stopped during operations, depending on the actuator loads and charging conditions of the battery and capacitor. The engine runs intermittently in a high efficiency condition, improving fuel economy by 10% compared to the operation without ED. As a whole, the simulation results show that the hybrid excavator can reduce fuel consumptions by up to 64%, compared to conventional excavators.

4. Verification test

A prototype hybrid machine, simulating a 6 ton class hybrid excavator, was manufactured to verify the fuel economy. Comparisons were made, in various aspects, with a conventional excavator. Incidentally, it has been confirmed that the prototype hybrid machine has a comparable performance, in terms of actuator speed, response and ease of operation.

The following describes results of the verification test on the fuel economy and of the verification experiment on the prediction accuracy of the simulation.

4.1 Fuel performance evaluation in a sewer branch pipe laying work

Firstly, an asphalt pavement of 4 m wide and 30 m long was prepared to simulate actual work sites. The excavators were driven by an operator, specialized in

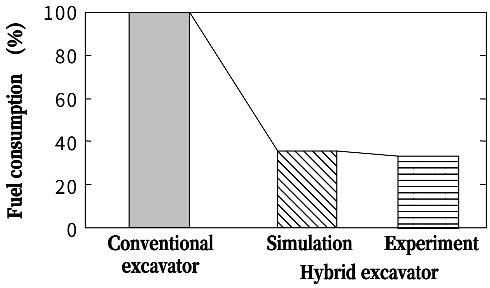

Fig. 5 Fuel consumption estimated result in sewer branch pipe laying work

Photo 1 Hybrid excavator (Monitor machine)

excavator operations, to simulate a sewer branch pipe laying work. A predetermined one day work, including pavement peeling, laying of sewer pipes and repaving, was repeated for three times to collect the fuel consumption data.

The fuel economies of the prototype hybrid machine and a conventional excavator are compared in **Figure 5**. As for the hybrid excavator, the figure includes both the prediction data simulated under the standard work mode and the actual experiment data. The actual experiment data matches well with the simulated data, verifying more than 60% reduction in fuel consumption. It is also verified that the simulation, based on a work pattern comprising standard work modes, predicts the fuel performance during actual operations.

5. Development of a monitor machine

Based on the achievement described above, KOBELCO CONSTRUCTION MACHINERY CO., LTD. has been developing commercial models and made presentations in INTERMAT2006 and CONET2006. **Photo 1** shows a monitor hybrid excavator.

Conclusions

Fuel performance of a 6 ton class hybrid excavator was simulated to evaluate how the hybrid reduces fuel consumptions.

A prototype hybrid machine was built for evaluations of fuel performance during operations simulating actual works. The results show that more than 60% reduction in fuel consumption, compared to conventional excavators of the class, can be achieved as in the case of automobiles.

KOBELCO CONSTRUCTION MACHINERY CO., LTD. will continue development works to commercialize hybrid excavators.

References

1) Sasaki, et al.: *Journal of the Society of Automotive Engineers of Japan*, Vol.32, No.4, p.181 (2001).
2) Ogata, et al.: *Journal of the Society of Automotive Engineers of Japan*, Vol.33, No.1, p.101 (2002).
3) Fujikawa, et al.: *R&D Kobe Steel Engineering Reports*, Vol.34, No.3, p.109 (1984).
4) Komiyama, et al.: "*KENSETSU-NO-KIKAIKA*" (Mechanization of construction), No.626, p.28 (2002).