Development of 20-tonne Class Hybrid Excavator, SK200H-10

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Power electronics technology continues to evolve, particularly in the automobile industry, with the aim of reducing fuel consumption and the environmental burden. This technology was adapted for a hybrid hydraulic excavator, the SK200H-10, equipped with a lithium-ion battery, as introduced in this paper. A continuous engine assist has been realized for the hydraulic excavator by effectively using the regenerative energy generated during slewing deceleration, due to the large inertia of its slewing body, and by adopting a lithium-ion battery with high output and large capacity. As a result, the fuel consumption of the excavator has been reduced significantly. The scrap handling machine (with magnet), the SK210DLC-10, has the same generator motor as SK200H-10 and applies a hydraulic excavator with a totally new power generation system, which was formerly based on a hydraulic pump. This machine enjoys a remarkably increased magnetic attraction and considerably reduced fuel consumption, thanks to the reduced energy loss during power conversion.

Introduction

The reductions of greenhouse gases that cause global warming, including CO_2, as well as the reduction of nitrogen oxides (NOx) causing air pollution and health damage, are major issues for the international community as a whole. These issues are characterized by the slogans of "ecology" and "sustainable society."

The greatest number of construction machinery units in operation are hydraulic excavators, and energy conservation and reduction of the environmental burden are their major challenges. In response, hybrid hydraulic excavators exploiting power electronics technology have recently been commercialized.

This paper summarizes the hybrid hydraulic excavator, the SK200H-10,[1)] which is equipped with a lithium-ion battery that is being used for hybrid electric vehicles (HV) and electric vehicles (EV) to further reduce fuel consumption and the environmental burden. This paper also introduces the SK210DLC-10, a scrap-handling machine with a magnet (hereinafter referred to as a "lifting magnet excavator"), which adopts the same generator motor as the SK200H-10 and has a renewed power generation system, which has conventionally been driven by a hydraulic pump.

1. Efforts to reduce fuel consumption of hydraulic excavators

A hydraulic excavator repeats high-load tasks such as digging and low-load tasks such as leveling in a short time and thus is subjected to a great fluctuation of the load. The flow of energy in a hydraulic excavator is shown in **Fig. 1**. This figure shows the energy loss at each part of the hydraulic excavator, assuming the combustion energy to be 100%. A hydraulic excavator supplies power that can handle the maximum load from its engine. However, the energy loss in each part is approximately 55% for the engine, approximately 15% for the hydraulic pump, approximately 20% for the hydraulic control system and approximately 1% for the mechanical transmission elements. As a result, the final effective output is only approximately 9% of the combustion energy.

On the basis of the above, various improvements have been made for hydraulic excavators to reduce these energy losses. For the fuel combustion of the engine, where the loss is the greatest, the combustion efficiency has been improved by increasing the fuel injection pressure through, among other means, the common-rail system. Furthermore, the combustion efficiency is improved by, for example, adopting the variable nozzle VG turbo (**Fig. 2**) so that the amount of intake air can be adjusted by the opening of the exhaust side nozzle. For the hydraulic control system, where the loss is the second greatest after

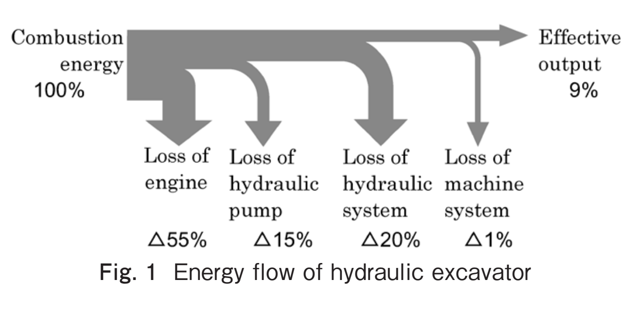


Fig. 1 Energy flow of hydraulic excavator

the engine, the efficiency has been improved by such means as reducing the pressure loss in hydraulic devices and hydraulic piping, and by hydraulic regeneration circuits that utilize the mass of the attachment on the hydraulic excavator (**Fig. 3**).

These efficiency improvement technologies have been adopted to conventional hydraulic excavators. The following section introduces the hybrid technology applied to SK200H-10 (**Fig. 4**).

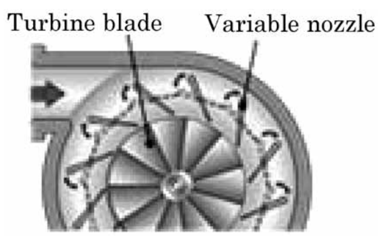
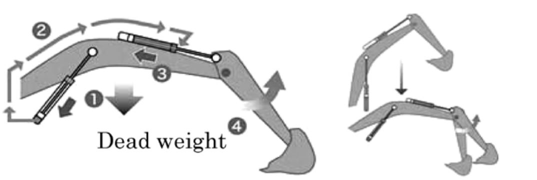


Fig. 2 Variable nozzle VG turbo



①Boom cylinders are contracted by its dead weight.
②High-pressure oil supplied to arm cylinder.
③Arm cylinders are contracted.
④Arm moves forward.

Fig. 3 Hydraulic regenerative circuit

Fig. 4 Overview of SK200H-10

2. Outline of hybrid system

Fig. 5 shows the constitution of the hybrid system for the SK200H-10. In this system, the hydraulic pump is driven by both the engine and the generator motor directly connected to it. In addition, the actuator for slewing the machine body is electrically driven and separated from the hydraulic circuit. Furthermore, the regenerative energy of slewing deceleration is converted into electrical energy.

Kobelco Construction Machinery Co., Ltd. (hereinafter referred to as "the Company") has released hybrid hydraulic excavators, including the SK80H, in 2009 and the SK200H-9 in 2012. The SK200H-10 has adopted a generator motor to continuously support the engine and, at the same time, utilized for the first time a large-capacity lithium-ion battery with high output in order to accelerate and decelerate the excavator's slewing body with a large inertial mass. The hybridization has significantly improved its environmental performance.

3. Outline of hybrid devices

We developed the main devices mounted on the SK200H-10 (**Fig. 6**) with the aim of making the vehicle size and layout common with those of the standard hydraulic excavators, pursuing energy saving performance, and maximizing the work capacity. To this end, we decided to start development from scratch and to manufacture the generator motor, slewing electric motor, and lithium-ion battery unit in-house.

In particular, all the devices adopt liquid cooling systems in order to achieve compactness and high output. For the lithium-ion battery, a heating system and protection system compliant with the standards for electrically-powered automobiles were adopted to cope with harsh working conditions and a natural

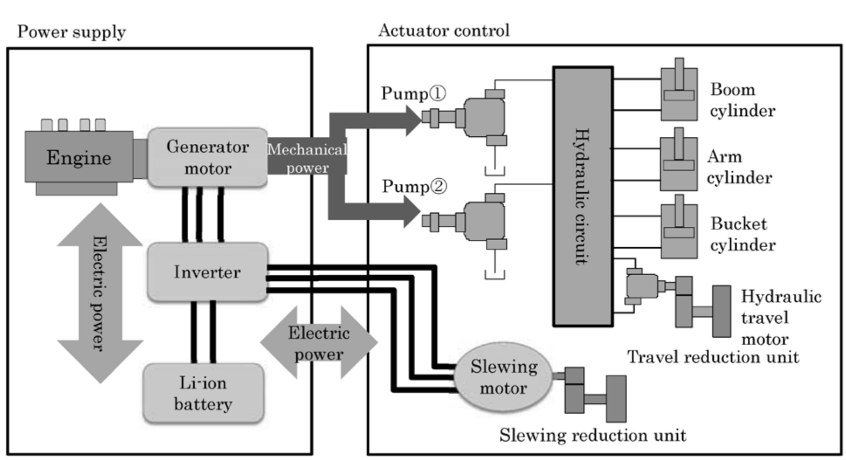


Fig. 5 Constitution of hybrid system

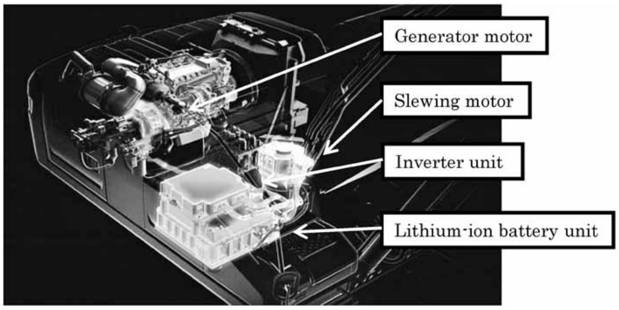


Fig. 6 Overview of main hybrid device

environment. An outline follows.

3.1 Generator motor

In order to give the body the same width as that of the standard hydraulic excavator, a flat-type water-cooled generator motor with an axial direction dimension (total length) of approximately 140 mm was newly developed so as to fit between the engine and hydraulic pump. A permanent-magnet three-phase synchronous AC motor was adapted to enable engine assist, which is effective in reducing fuel consumption. This motor has the further capability of generating power high enough to charge the large-capacity lithium-ion battery and to accelerate the slewing electric motor.

3.2 Slewing electric motor

A water-cooled slewing electric motor was newly developed to ensure a mountability comparable to that of the conventional hydraulic motor, and to realize a machine-body slewing performance equivalent to that of the standard hydraulic excavator. A permanent-magnet three-phase synchronous AC motor was adopted as a vertical high-speed motor to allow its direct connection to the slewing reduction gears. This has enabled the energy generated during slewing deceleration to be efficiently regenerated, while realizing smooth and powerful slewing acceleration characteristics.

3.3 Inverter unit

In order to secure mountability to the machine body, the slewing motor inverter and generator motor inverter were integrated into a newly developed, small water-cooled inverter unit. This inverter unit was linked with the controllers for the hydraulic devices and engine in order to control the entire hybrid system, including the control for generator-motor/slewing-motor and the charge-discharge control of the lithium-ion battery, to realize a remarkable reduction in fuel consumption.

3.4 Lithium-ion battery unit

Since the operating temperature range of a lithium-ion battery is limited, it is housed in a protective casing having a cooling function and warming function. The unit comprises a function that detects leaks and automatically shuts off power, as well as a manual shut-off switch, to prevent any direct/indirect electric shock caused by the lithium-ion battery, not to mention its compliance with the United Nations Recommendations on the Transport of Dangerous Goods.

4. Features of SK200H-10

4.1 Energy saving effect and work volume

The SK200H-10 adopts a high-output, large-capacity, lithium-ion battery. This has enabled the engine assist of the generator motor and effective use of regenerative energy of slewing deceleration while greatly reducing the fuel consumption and increasing the work volume. **Fig. 7** shows the measurement results for fuel consumption (fuel consumption per hour) during the digging/loading operation. The SK200H-10 exhibits a fuel consumption that is 17% less than that of the conventional hydraulic excavator and 12% lower than that of the SK200H-9. **Fig. 8** compares the work volume (the amount of material carried per hour) with that of the conventional hybrid machine. This figure indicates the difference for each working

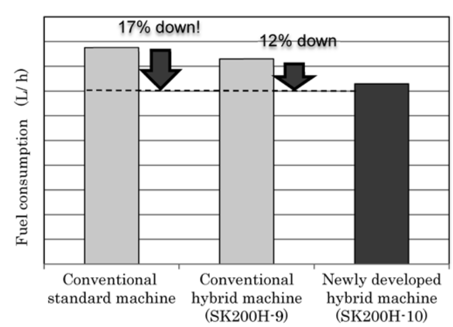


Fig. 7 Comparison of fuel consumption under same workload

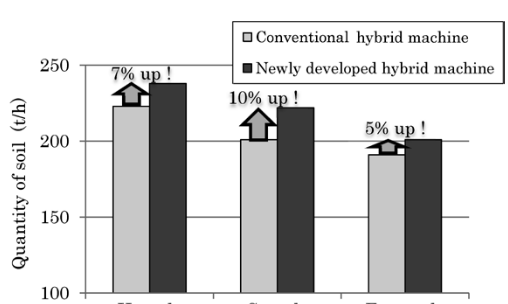


Fig. 8 Comparison of work volume between conventional and newly developed hybrid machines

mode, showing a 7% to 10% increase in work volume for all the modes. The increase in work volume is attributable to the improvement of work performance described below. It should be noted that this measurement was carried out on the basis of the Company's own standards and the work modes are a heavy work mode (H-mode), a normal work mode (S-mode), and an energy-saving mode (Eco-mode).

4.2 Improvement of work performance

In the Company's hybrid system, the actuator driving the slewing body with a large inertial mass is fully motorized and separated from the hydraulic circuit, which has eliminated hydraulic interference during combined operations of attachment and travelling. Furthermore, in the SK200H-10, the combination of a large capacity lithium-ion battery and a slewing electric motor has greatly increased the acceleration energy of slewing, achieving operability that is smoother and more powerful than that of the conventional machines.

The work performance of the SK200H-10 is suitable not only for civil engineering works in Japan, but also supports various work types and area characteristics, including Europe, where rotary tilt buckets (**Fig. 9**) are heavily used, and North America, where work volume with large buckets is emphasized. Thanks to this, it has a successful reputation among customers around the world.

5. Development of SK210DLC-10

5.1 New lifting magnet excavator

The SK210DLC-10 scrap handling machine with magnet (lifting magnet excavator), which is developed based on a hydraulic excavator, adopts the same generator motor as that of the SK200H-10 to renew its power generation system which had been driven by a hydraulic pump. **Fig.10** shows the system configuration diagram of the new lifting magnet excavator and **Fig.11** shows its appearance.

5.2 Increased magnetic attraction and energy saving effect

Reducing the energy loss at the time of power conversion has greatly increased the magnetic attraction and significantly reduced the fuel consumption. As shown in **Fig.12**, the power conversion loss has been improved, going from 57% to 14%. This is an effect of changing the power generation, which was accomplished with a hydraulic pump in a system using a generator

Fig. 9 Overview of SK200H-10 equipped with tilt bucket

Fig.11 Overview of scrap handling machine with new-type magnet

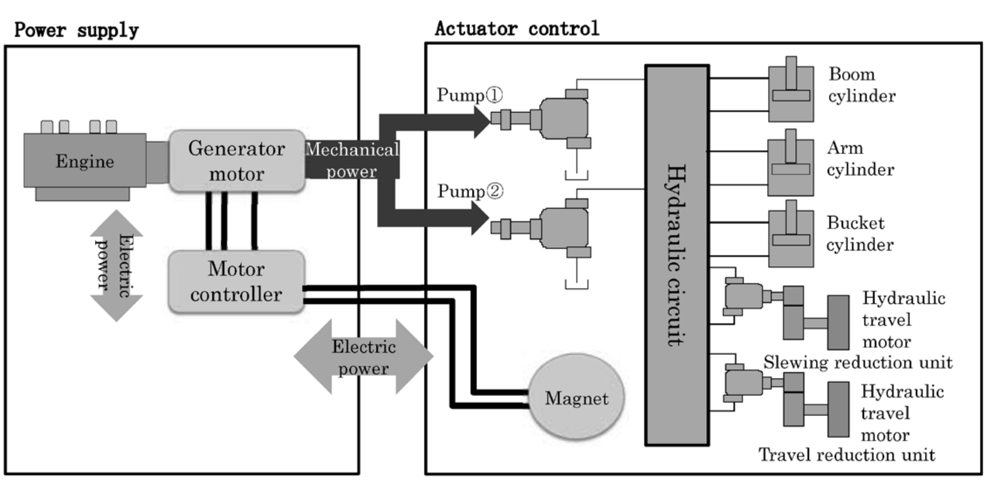


Fig.10 System constitution of scrap handling machine with new-type magnet

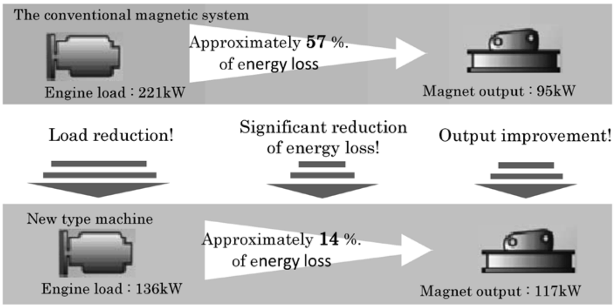


Fig.12 Power conversion efficiency

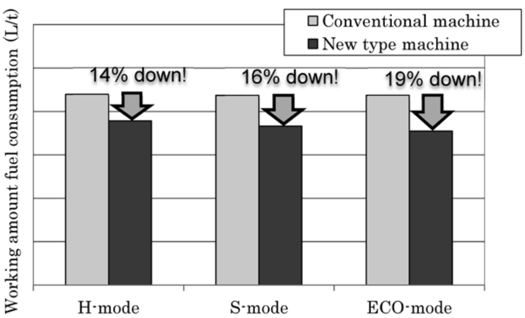


Fig.13 Comparison of work volume fuel consumption

motor that is disposed in series between the engine and hydraulic pump. **Fig.13** compares the work volume fuel consumption (fuel consumption per tonne of transported sediment) of the various working modes, measured in accordance with our own standard. Here, the differences among the working modes are shown, and the work volume fuel economy has been improved by 14% to 19% in all the modes. This is attributable not only to the improved power conversion efficiency, but also to the increased attraction of the magnet.

5.3 Improvement of visibility and maintainability

In parallel with the simplification of the system, the control panel, which was placed on the right front of the conventional machine body, was housed in a guard, thereby simplifying that side of the machine body. As a result, the visibility for the operator and accessibility to the upper surface of the machine body during maintenance has been greatly improved (**Fig.14**).

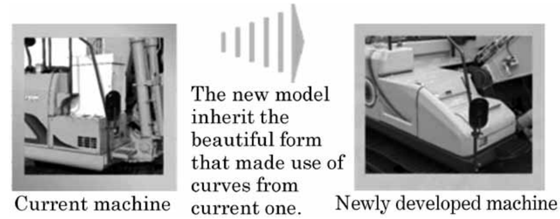


Fig.14 Comparison of appearance of right front spaces in conventional and newly developed machines

6. Utilization of IT data

In recent construction machinery, including hydraulic excavators, there has been an upsurge in the installation of communication devices and utilization of IT data. The SK200H-10 and SK210DLC-10 are also equipped with functions to closely monitor the operating state of their electric motors, inverters, lithium-ion batteries, including the electric motor output, system voltage, and temperature of the main devices for the hybrid system and the magnet power generation control system, in addition to the operating status of the hydraulic system and engine. Furthermore, the monitoring data on the machine side is statistically processed by a cloud server to detect any signs of abnormality, thus enhancing the preventive maintenance and maintenance services (**Fig.15**).

Moreover, operational information such as the daily fuel economy and work volume is offered to customers to be utilized in their machine operation management and operation planning.

Conclusions

This paper has introduced the SK200H-10 equipped with a lithium-ion battery and the SH210DLC-10 with a renewed power generation system as examples of efforts to reduce the CO_2 footprint and fuel consumption of hydraulic excavators.

The hybrid excavator has realized the effective use of the regenerative energy generated when the large inertial mass of the slewing body decelerates. In addition, a high output/large capacity lithium-ion battery has been adopted, enabling a sustainable

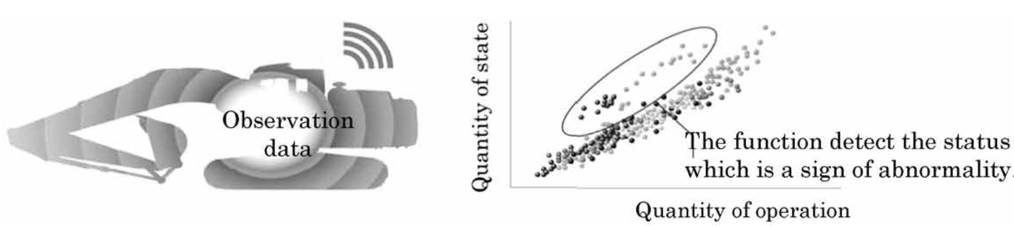


Fig.15 State observation function using IT measurement data

engine assist, and achieving a significant reduction in fuel consumption.

In the lifting magnet excavator, reducing the energy loss during power conversion has greatly increased the magnet attraction while greatly reducing the fuel consumption.

It is envisaged that the development of new technology for zero emissions will be accelerated, led by the automobile industry. We will strive to introduce these technologies in the construction machinery represented by hydraulic excavators to further decrease fuel consumption and reduce the environmental burden.

References

1) S. Saeki. *Journal of JCMA. 2017*, Vol.69, No.1, pp.35-38.