Adoption of Electrification and Hybrid Drive for More Energy-efficient Construction Machinery

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OVERVIEW: As for automobiles, electric and hybrid drives are effective technologies for improving the energy efficiency of construction machinery. In July 2011, Hitachi Construction Machinery Co., Ltd. released the 20-metric-ton ZH200 hybrid hydraulic excavator. Having overcome the cost, reliability, durability, and safety challenges associated with the adoption of hybrid drive, the number of ZH200 machines in service is steadily growing thanks to the strong reputation it has earned for ease of use and work performance as well as for energy efficiency. In the future, Hitachi Construction Machinery intends to continue incorporating its device and electronic control technologies for electric drives into construction machinery to deliver products that match customer needs while also providing excellent energy-efficient performance.

INTRODUCTION

FACTORS such as rapid rises in the price of oil and moves to reduce carbon dioxide (CO_2) emissions to help prevent global warming in recent years are behind growing demand for construction machinery to be made more energy efficient. A number of government policies have been introduced in response to this, including giving points for use of energy-efficient construction machinery in bidding for public works projects, and subsidies for purchases of hybrid models.

As in the automotive sector, electric and hybrid drives are effective technologies for improving the energy efficiency of construction machinery. Hitachi Construction Machinery Co., Ltd. has been engaged in the development of electrically driven construction machinery for some time, and has already released an electric-hydraulic excavator that operates using commercial electric power supplied by electric companies via transmission lines, an electric powered excavator fitted with lithium-ion batteries, and a large wheel loader with a series hybrid drive. Hitachi Construction Machinery also released the 20-metric-ton ZH200 hybrid hydraulic excavator in July 2011.

This article describes key aspects of energy efficiency improvement for hydraulic excavators and the issues associated with adopting hybrid drive, and also gives an overview of the ZH200 hybrid hydraulic excavator.

ENERGY EFFICIENCY IMPROVEMENT FOR HYDRAULIC EXCAVATORS

Whereas the motive force for an automobile is achieved by transmitting the torque produced by the engine to the wheels, a hydraulic excavator uses

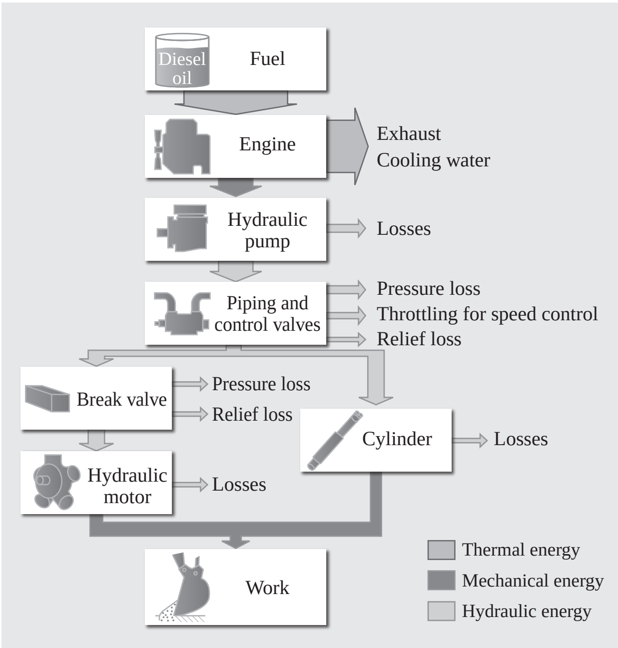

Fig. 1—Energy Losses in Hydraulic Excavators.
Because of the various losses that occur in the engine and hydraulic system, less than 10% of the energy contained in the fuel ends up being converted into work.

its engine to turn a hydraulic pump, which in turn drives the hydraulic actuators that perform the work. Accordingly, the operation and concept behind the use of hybrid systems to save energy is different to that for automobiles, even though both use electric motors and electrical storage devices. Similarly, while it is possible to assess automobile fuel consumption based on the fuel consumed per unit of distance traveled, the diverse range of tasks and uses to which hydraulic excavators are put makes defining fuel consumption difficult.

Energy Losses in Hydraulic Excavators

A hydraulic excavator can be thought of as a machine that converts the energy in fuel (typically diesel oil) into useful work by driving various hydraulic actuators.

Fig. 1 shows the energy losses in a hydraulic excavator.

When the thermal energy in the fuel is converted to the output from the engine’s driveshaft, approximately 60% escapes as heat. The driveshaft energy of the engine is then used to turn a hydraulic pump, converting it into hydraulic energy that is distributed via pipes and control valves to the various hydraulic actuators. In addition to the direct pressure losses, each of the actuators has different characteristics and a considerable amount of energy is also lost in the hydraulic system to provide the controllability needed to operate them as required. Similarly, positional and inertial energy generated during operation is also lost in the hydraulic system through conversion to heat. While it varies depending on operating conditions, the proportion of useful energy available for performing work is less than 10% of the energy in the fuel[1].

Operation of Hybrid Systems

Over time, numerous enhancements have been made to different parts of hydraulic excavators to reduce the different losses that affect them, including the hydraulic equipment and systems, engine, structure, and mechanical components.

Hybrid excavators seek to achieve even better energy efficiency by combining the excellent characteristics of electrical drive components to boost overall system efficiency.

The most important of these characteristics are listed below.

(1) High level of control responsiveness (compared to engines and hydraulics)

(2) High level of drive and transmission efficiency (compared to hydraulics)

(3) Potential for use of regenerative energy (compared to hydraulics)

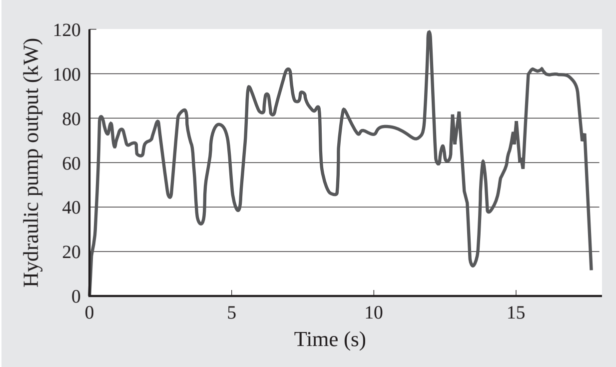

Fig. 2—Example of Variation in Pump Output during Excavation by 20-metric-ton Hydraulic Excavator.
The pump output varies from near zero to close to maximum engine output.

Fig. 2 shows data on the variation in hydraulic pump output on a hydraulic excavator during excavation work[2]. The engine load is roughly equivalent to this output. This shows one of the characteristics of hydraulic excavators, namely that their output varies from near zero to close to maximum engine output.

Being subject to this sort of variation in load means that the engine and pump are not necessarily working at an efficient operating point. While it makes sense to operate the engine at a speed that provides high efficiency, the slow control response of the engine represents a bottleneck. When hybrid drive is used, it is possible to take advantage of the control responsiveness [characteristic (1) above] to use the electric motor to assist when changing the engine speed, thereby keeping the engine and hydraulic pump at more efficient operating points (see Fig. 3). Similarly, characteristics (2) and (3) can also be used to save energy by converting some of the hydraulic actuators, such as the swing device, to electric operation, thereby increasing overall system efficiency and allowing regeneration to be used during deceleration. Scope for reducing other energy losses, particularly in the hydraulics system, also lies in making skillful use of these three characteristics.

Issues Associated with Adopting Hybrid Drive

While the adoption of hybrid drive clearly represents an effective means for making hydraulic excavators more energy efficient, the key problems are cost, reliability, and durability.

For example, while the Toyota Motor Corporation sold about 300,000 of its Prius hybrids in Japan alone

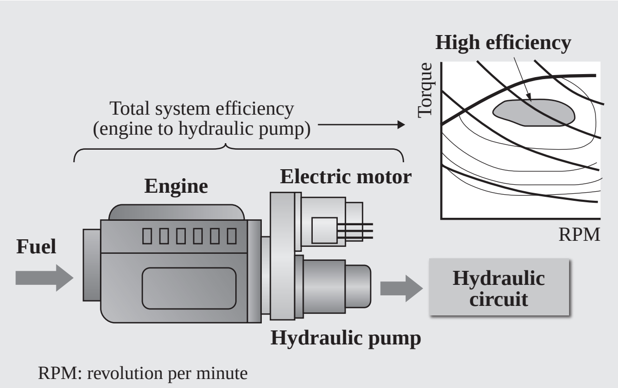

Fig. 3—Example of High Efficiency Operation of System Comprising Engine, Electric Motor, and Hydraulic Pump.
Energy savings are achieved by controlling overall operation to remain within an operating range with high total system efficiency.

Fig. 4—ZH200 Hybrid Hydraulic Excavator.
The ZH200 was awarded a Good Design Award 2011 from the Japan Institute of Design Promotion.

during 2010 (source: Japan Automobile Dealers Association), total international demand for hydraulic excavators of all classes does not exceed 150,000 machines a year (excluding very large excavators and mini excavators)(3). Because the cost savings of mass production are considerable for electrical components, reducing the cost of hybrid systems requires not only the wider adoption of hybrid excavators but also other cost cutting measures such as standardization of parts across different models and the use of automotive parts(4).

Furthermore, because it is not uncommon for hydraulic excavators to remain in use for 20 years or more in harsh environments, the reliability and durability of electrical drive components, particularly energy storage devices, is a major issue. There is no advantage for customers in machines that fail due to faulty electrical drive components or that cannot be repaired due to obsolescence.

Adequate account also needs to be taken of safety. Hybrid excavators need not only to be kept safe from high voltages, they must also be able to be operated safely even if electronic control becomes unavailable.

ZH200 HYBRID HYDRAULIC EXCAVATOR

Hitachi Construction Machinery's technology and many years of experience with electric construction machinery have culminated in the release of the ZH200 20-metric-ton hybrid hydraulic excavator. It was developed based on extensive market research into customer needs and achieves a high degree of balance between its initial cost and excellent fuel consumption performance, as well as the practicality to be able to be used for any sort of work or at any site (see Fig. 4).

ZH200 Hybrid System

The ZH200 features a newly developed system that combines hybrid technology with the newly developed fuel-efficient, three-pump hydraulics system. Fig. 5 shows an overview of the system.

In contrast to previous two-pump/two-valve hydraulics systems, it has a three-pump/three-valve configuration that includes an additional heavy-duty pump and valve. The availability of three hydraulic power sources improves system efficiency by limiting throttling losses when performing complex operations.

The ZH200 is also equipped with an electric-hydraulic swing mechanism with an electric motor that can produce regenerative energy during swing deceleration and assist with swing acceleration.

In addition to using the hybrid system, features such as advanced engine control, an idling stop function, and reduced pressure losses in the hydraulic piping also help the ZH200 deliver 20% better fuel consumption than the standard model (ZX200-3).

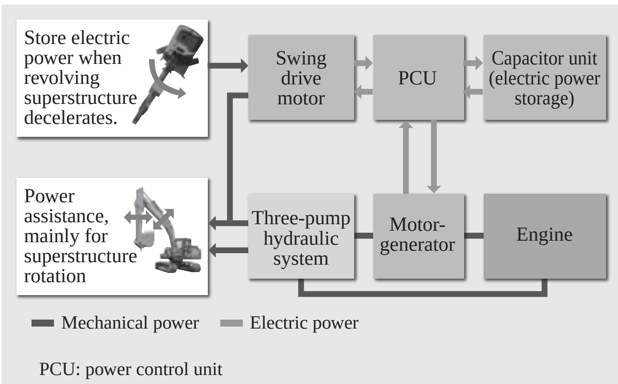

Fig. 5—ZH200 Hybrid System.
The ZH200 combines a newly developed three-pump/three-valve hydraulic system with a hybrid system to achieve excellent basic performance together with energy efficiency.

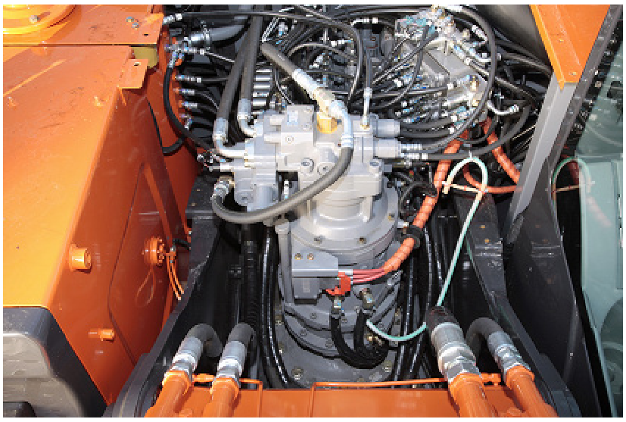

Fig. 6—ZH200 Swing Device.
The swing hydraulic motor is visible at the top while the swing electric motor has three-phase cable connections.

ZH200 Electrical Drive Components

The electrical drive components used in the ZH200 include two motors, a power control unit (PCU), and a capacitor unit.

The swing electric motor is located between the swing device's hydraulic motor and the swing reduction gear (see Fig. 6). The swing electric motor is a water-cooled, permanent magnet synchronous motor, and its torque is controlled by commands from the PCU. This includes producing regenerative electric power when the revolving superstructure of the excavator is decelerating and assisting the swing hydraulic motor during acceleration.

The motor-generator is a permanent magnet synchronous motor connected to the driveshaft that runs from the engine to the hydraulic pump and its primary role is to control charging of the capacitor unit.

The PCU incorporates the electrical circuit for the power system comprising the motor drive inverter and chopper, and drives the two motors at the specified torques based on commands from the supervisory controller.

The capacitor unit includes large-capacity, electric double-layer capacitors, control circuits, and a main relay. It stores regenerative electric power from the swing drive motor and generated electric power from the motor-generator.

ZH200 Objectives and Features

Before the ZH200 could be released, it needed to overcome the aforementioned challenges of cost, reliability, and durability.

To reduce the cost of the hybrid system, the ZH200 uses automotive products for its power system electric components, and the maximum current and output requirements have been reduced by sharing energy delivery with the hydraulic system. The electric drive components, including the capacitor unit, have a design life that exceeds the life of the excavator chassis. Furthermore, the system is designed so that, even if these components were to fail, the machine can continue to operate as far as possible by switching over to hydraulics-only mode.

For safety, the electrical design follows those for hybrid or electric vehicles, while the mechanical design is such that the hydraulics system keeps the excavator in a safe condition even if an electrical fault occurs.

Hitachi Construction Machinery hydraulic excavators need to combine appropriate levels of both basic performance and ease-of-use. The energy efficiency of vehicles can be measured in terms of how much fuel they consume for each unit of distance traveled. In the case of hydraulic excavators, on the other hand, while fuel consumption relative to work done might be more suitable, measuring fuel consumption relative to operating time is more practical. Some caution is required, however, because an excavator that does not operate the way its operator wants it to is not necessarily very energy efficient, even if its hourly fuel consumption is low. For example, a task that can be done in a single operation by an easy-to-use machine might take two or even more inefficient operations to complete on a less useful machine. In the case of the ZH200, the control algorithms were developed using a model-based design method(5) with a seamless transition between simulation and live testing to ensure that, despite its being a hybrid, its operation would feel no different to that of a conventional excavator.

CONCLUSIONS

This article has described key aspects of energy efficiency improvement for hydraulic excavators and the issues associated with adopting hybrid drive, and also given an overview of the ZH200 hybrid hydraulic excavator.

Making a major contribution to minimizing global warming will require widespread market adoption of energy-efficient construction machinery like the ZH200. In addition to incorporating Hitachi Construction Machinery's electric drive device technology and electronic control technology into its construction machinery products, Hitachi Construction Machinery Co., Ltd. also intends to continue developing the core technologies for construction machinery, specifically engines, hydraulics systems, structures, and mechanical components, so that it can continue to satisfy customer needs and supply construction machinery products with even greater energy efficiency.

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