Simulation Techniques for Improving the Fuel Efficiency of Hydraulic Excavators

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Simulation techniques to reduce the fuel consumption in hydraulic excavators are presented in three categories: first, a strongly non-linear dynamic simulation technique for a coupling system with a non-linear hydraulic system and a linkage system; second, a technique for evaluating fuel consumption in the engine when the engine powers the hydraulic pump in a digging operation performed by a hydraulic excavator in real time; and, finally, a dynamic simulation technique for evaluating the efficiency of a hybrid system consisting of power electronics equipment, electric-hydraulic equipment, and a linkage system.

Introduction

Due to global warming and a steep rise in the price of crude oil, lower fuel consumption is increasingly required even for hydraulic excavators. As shown in **Fig. 1**, a hydraulic excavator has a power train system, including an engine, a hydraulic pump driven by the engine, and hydraulic piping and valves to move an attachment. Various efforts have been made to reduce the fuel consumption of hydraulic excavators, including the control of pumps and the reduction of pressure loss in their pipes, but this still leaves room for further improvement. Now, all of the systems must be evaluated to further reduce their loss. A hybrid system[1), 2)] comprising an engine and battery is considered to be an effective solution.

This paper introduces system simulation techniques that are important in reducing the fuel consumption of hydraulic excavators. The techniques introduced first are a non-linear dynamic analysis technique for a system in which a strongly non-linear hydraulic system is coupled with a linkage system and a technique for evaluating the engine fuel consumption of a hydraulic excavator during a digging operation in which the power for the hydraulic pump is loaded on the engine in real time.

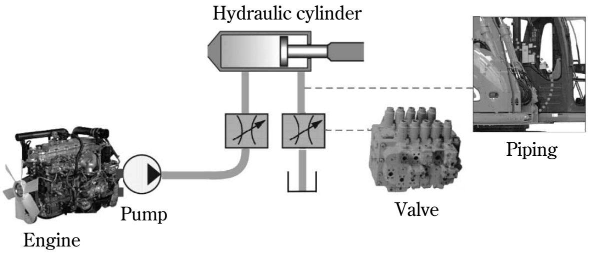

Fig. 1 Power train system of hydraulic excavator

This is followed by the introduction of a dynamic simulation technique for a hybrid system, based on the modeling of the total system consisting of electronics components, such as a generator, battery and converter, constituting a hybrid power source; electro-hydraulic components that constitute an actuator system; and a linkage system for attachments.

1. Power evaluation and reduction of fuel consumption of hydraulic excavators

1.1 Contribution analysis of power loss in hydraulic system

To conduct a coupled analysis of the hydraulic system and linkage system of a hydraulic excavator, the coupled system is described in an MCK type, non-linear equation of motion,[3)] using state variables of displacement for the linkage system and the integral of the flow rate for the hydraulic system. This has enabled numerical integration by an implicit method and has stabilized the analysis of the strongly non-linear system. In the linkage system, beam elements[4)] and truss elements are used, in consideration of the geometrical non-linearity caused by the large motion in a space. These elements are used for modeling the attachment of the hydraulic excavator (**Fig. 2**). The hydraulic system was modeled using piping elements, valve elements, cylinder elements[5)] and the like, as shown in **Fig. 3**. In each cylinder element, the flow of hydraulic oil in and out of the port either extends or

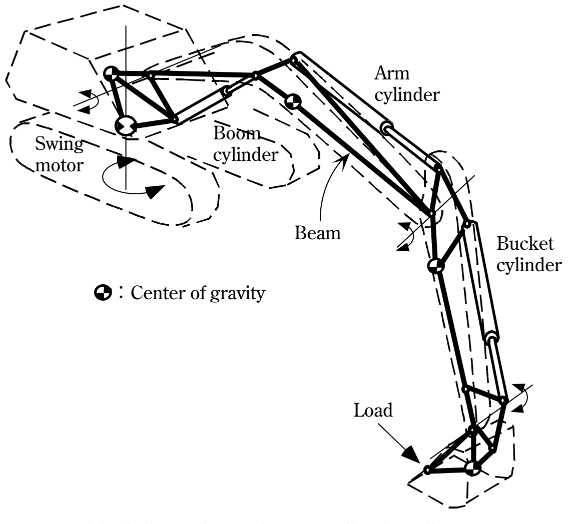

Fig. 2 Modeling of attachment of hydraulic excavator

contracts the cylinder, causing a pressure inside the cylinder, in accordance with the load applied at the end of the cylinder axis. In the cylinder elements, the integral of the flow rate of the hydraulic oil in the hydraulic system is coupled with the nodal displacement of the linkage system, enabling the coupled analysis.

To verify the validity of the present analysis, the evaluation of a hydraulic excavator during two cycles of digging work was compared with the experimental results. A digging task roughly consists of digging, boom raising, dumping, boom lowering and swinging. It involves all the actuators except for the one used for traveling. **Fig. 4** compares the experimental and analysis results for the actuator behavior, pump power and fuel consumption. The analysis fairly reproduces the actual performance with an error in fuel consumption of no greater than 0.4%. The power losses occurring in various parts of the hydraulic system are obtained from the results of the analysis (**Fig. 5**). **Fig. 6** shows the losses classified by the elements of the hydraulic system, such as piping, valve opening and valve passage. This diagram indicates the contributions of the losses occurring in the hydraulic system during a digging task, an important result used for determining a quantitative energy-saving guideline. Based on the result shown in Fig.6, a specific target was set to halve the power losses for the portions where they are significant.

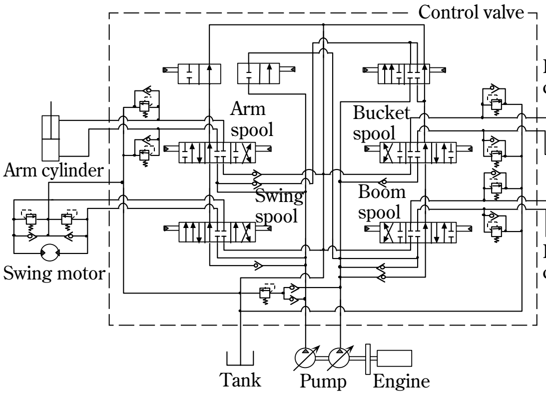

Fig. 3 Hydraulic system of hydraulic excavator

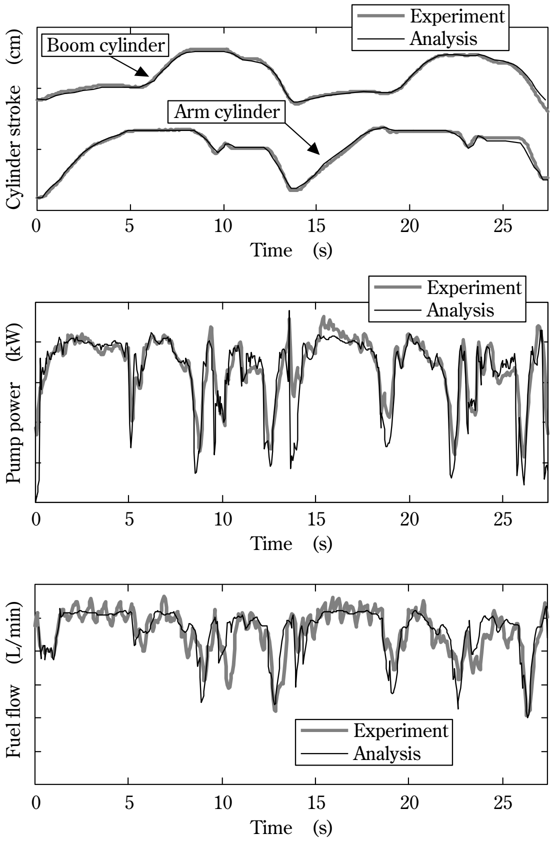

Fig. 4 Comparison with experimental and analytical results in digging operation

This technique has enabled us to analyze the complex motions of a hydraulic excavator during a digging operation in a detailed and accurate manner. The clear definition of the contribution to energy-saving has enabled an effective reduction of the power loss caused, for example, by the pressure loss at a valve, and has realized a hydraulic system for

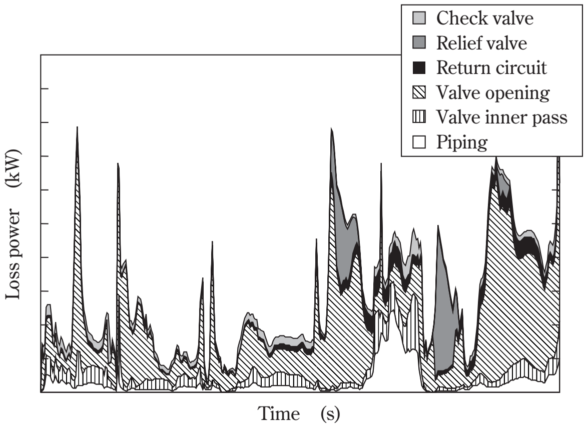

Fig. 5 Simulation results of hydraulic loss power in digging operation

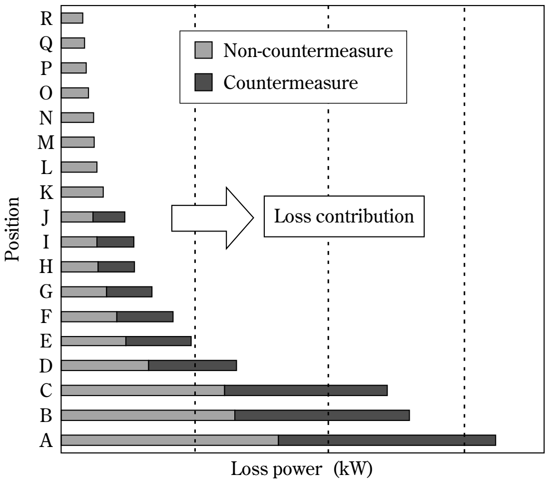

Fig. 6 Simulation results of power loss contribution generated in hydraulic system

hydraulic excavators with high energy savings.

1.2 Technique for reducing power loss in hydraulic system

The results of the loss contribution analysis indicate that the pressure losses inside the valves account for the major portion of the power loss in the hydraulic system. Expanding all the internal passages enlarges the valves, making it difficult to mount them on a hydraulic excavator; so we focused on the most effective passages, as indicated by the loss contribution analysis, and expanded them.

The loss contribution analysis also identifies the relief valves of the hydraulic system, which are used in swinging, as major parts causing power loss in the hydraulic system. Therefore, we devised a swinging relief control, combined with a pump flow control. In the hydraulic system for the swinging motion of a conventional hydraulic excavator, the oil from the hydraulic pump is supplied to the hydraulic motor during acceleration, but a portion of the flow is unused and discharged from the relief valve. Hence, we focused on the characteristics of the relief valves and devised a control method in which the pump pressure signal is used to control the supply flow from the pump, such that the flow that had been unused and discharged from the relief valve is minimized, while securing the pressure required for the swinging motion. Other improvements made on the hydraulic system include a control method in which the pump control and valve control are optimally combined to optimize the pump supply flow, which has led to a significant reduction of loss in the hydraulic system.

1.3 Evaluation and improvement of engine fuel consumption

Fig. 7 is a conceptual diagram showing a "hardware in the loop simulation" (HILS) system. This particular system includes an engine (engine HILS), in which the hydraulic pump power, in response to the operating lever during actual operation, is determined by simulation and loaded on the engine in real time. This system has an animation display capability which allows lever operations in response to the actual movement of the attachment. The engine HILS system for engines integrates the system analysis and engine bench evaluation technique, thereby enabling the evaluation of the fuel consumption performance of the engine during various operations without a load pattern. This new technique has enabled the highly accurate test-bench evaluation of the fuel consumption of the engine installed on a hydraulic excavator. Efforts have been made to improve the fuel consumption of, not just the engine alone, but the entire system. As a result, the newly developed engine-pump control technique has optimized the fuel consumption performance of the engines of hydraulic excavators.

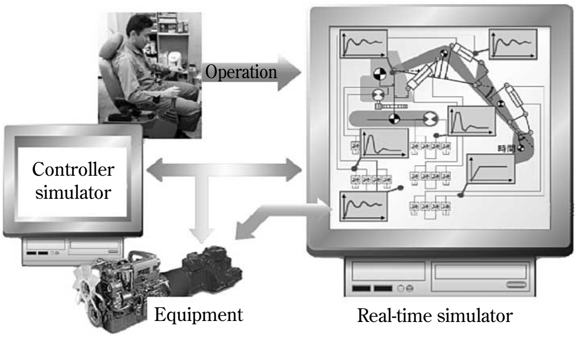

Fig. 7 Configuration diagram of engine HILS system

An engine purchased from a truck manufacturer is tuned for trucks; therefore, it must be adapted for the load imposed by a hydraulic excavator. A truck engine is tuned to exhibit high fuel consumption at a low rotational speed, which deteriorates fuel consumption in the region suitable for a hydraulic excavator. For this reason, the engine HILS system was used to optimize the fuel consumption characteristics of the excavator engine. As a result, a significant improvement has been achieved in fuel consumption in the high torque region.

As for engine-pump control, a conventional machine, which prioritizes productivity, aims at maximizing the horse power at the maximum rotational speed. However, the problem with this approach is that engine combustion efficiency is sacrificed at high rotational speeds at which the torque is low. An isochronous control was adapted for controlling the rotational speed so that it would be as low as possible and kept at a constant level, with the aim of optimizing the pump control and engine revolution. As a result, the fuel consumption has been reduced significantly.

1.4 Low fuel consumption effect

The energy-saving technology of the hydraulic system and technique for improving engine fuel consumption have achieved fuel consumption reductions of 20% for S-mode digging accomplishing the same amount of work, and an improvement of 8% in the amount of work for H-mode digging using the same amount of fuel, when compared with a conventional 20 tonne class hydraulic excavator. The fuel consumption was measured according to the Japan Construction Mechanization Association

Standards (JCMAS). The results confirmed a 17% reduction in fuel consumption, compared with the conventional machine.

2. Development of hybrid hydraulic excavator

2.1 Hybrid system outline

An exterior view and system configuration of a hybrid excavator are shown respectively in **Fig. 8** and **Fig. 9**. The system consists of independent actuators. This reduces the hydraulic distribution loss that occurs in conventional hydraulic excavators. The hybrid power source is a series system consisting of an engine, battery and capacitor for leveling the engine power.

2.2 Power source system

Because the power source is a series system, the power is supplied from the hybrid power source to each actuator via a direct current bus. Therefore, the power is supplied and distributed to each actuator in accordance with the actuator's power consumption. For a stable supply of power from the power source to the actuators in accordance with their power consumption, the control keeps the voltage in the direct current bus constant (direct current bus voltage control).

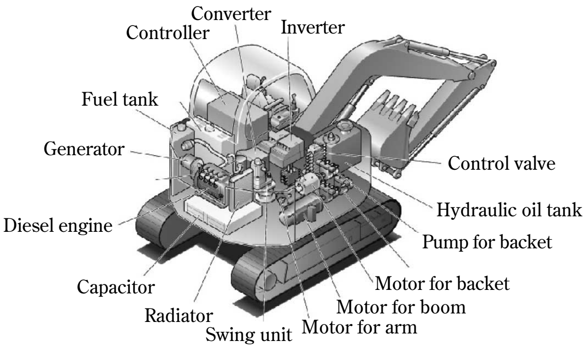

Fig. 8 Conceptual scheme of hybrid excavator

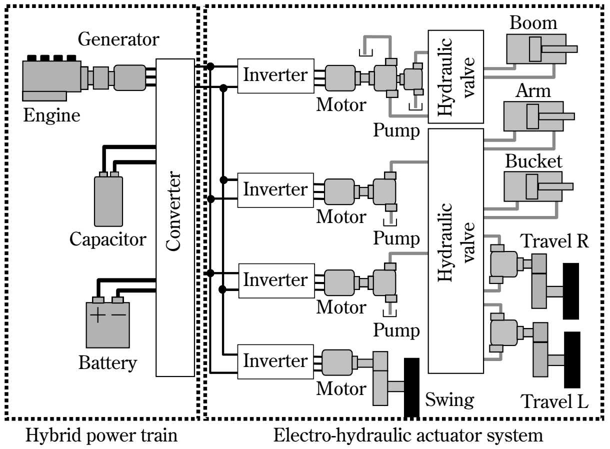

Fig. 9 System diagram of hybrid excavator

2.3 Actuator system

The actuator system consists of a boom system, arm-bucket system, traveling system and swing system. The boom system, holding the weight of the attachment, is an electro-hydraulic system that is closed and comprises an electric motor, bi-directional hydraulic pump and control valve, designed to regenerate the potential energy accumulated while the boom is raised. The hydraulic power generated by the boom head when the boom descends is exerted on the bi-directional hydraulic pump, which generates regenerative electric power in the electric motor. This regenerative electric power is charged into the capacitor and battery. The arm-bucket system is an open system comprising an electric motor, mono-directional pump and direction control valve. The swinging system is a system driven by an electric motor and does not employ hydraulic devices because of its rotational motion. The traveling system is a system driven electro-hydraulically, using the hydraulic source for the arm and bucket.

2.4 System equations

The mathematical model of a hybrid excavator consists of system equations, in which the equations, formulated for the elements of the linkage system, hydraulic system, power electronics system, and engine system, are combined according to the formulation of the finite element method[6)]. **Fig.10** depicts the configuration of the mathematical model for a hybrid system. The characteristics matrix generated for each element and the system command for the power source system and actuator system are incorporated into the matrix and external force terms of the system equations. Subsequently, the system equations of motion are solved for each time step to conduct a simulation. This technique employs the Newmark β method for time integration and Newton's method for convergent calculation, which secures the stability of the numerical analyses.

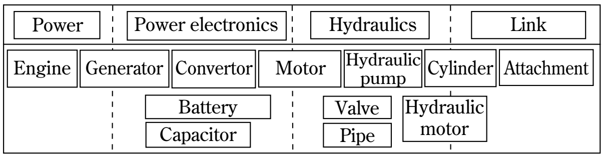

Fig.10 Configuration of mathematical model of hybrid system

2.5 Performance evaluation analysis and accuracy verification

Various performance evaluation analyses were conducted using the total simulation model for the hybrid system. A hybrid excavator was built for performance demonstration so that it could be compared with that of a conventional machine.

As an example of power evaluation during actual operation is shown in **Fig.11**, in which performance evaluations were conducted on the power of the actuators during excavating and dumping tasks, typical tasks for hydraulic excavators. The action is a combined action of the four actuators for the boom, arm, bucket and swing. The comparison was made between the sum total of the input power supplied to the electric motor for driving the actuators of the hybrid system and the output power from the hydraulic drive pump of the conventional machine, this output power being regarded as the power input to the actuators. In the hybrid system, a significant reduction of input power is observed in the later stage of the operation, the stage where the actuator output becomes low, which verifies the reduction of hydraulic distribution loss during low hydraulic output, as intended. **Fig.12** shows the energy balance of the actuator system during this operation. During the operation, a power reduction of approximately 45% was achieved, as compared with the conventional hydraulic system.

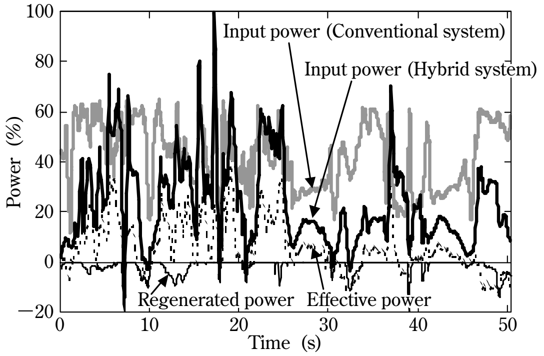

Fig.11 Actuator power on excavating and loading

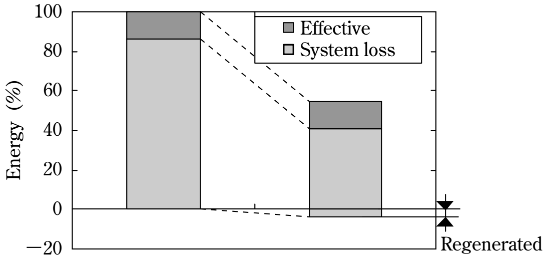

Fig.12 Energy consumption of actuator in excavating and loading

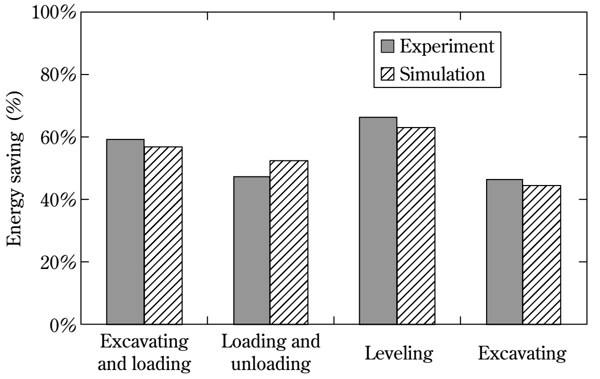

Fig.13 Experimental and simulation results of fuel energy saving effect on each operation mode

The total simulation model was used to evaluate the fuel consumption performance during typical work patterns, including the aforementioned excavating and dumping tasks. The result was compared with the performance of the actual machine for verification. **Fig.13** shows the energy-saving effect of the hybrid system, as compared with the conventional system. Also shown in the figure are a comparison of results for the actual machine and the simulation model. Overall, energy-saving effects of no less than 40%, compared with a conventional machine, have been achieved for all the types of operation, although the effects vary according to the type of operation. The simulation results and the results actually measured on the demonstration machine yield the same energy-saving effects within a 5% margin of error. The target performance has been achieved as intended. This verifies that the simulation technique according to the present method is a practical technique for accurately predicting the fuel consumption performance of hybrid excavators.

Conclusions

The technology used for the development of an energy-saving type of hydraulic excavator has been outlined in this paper. The need for energy-saving-type hydraulic excavators will continue to increase; however, it is difficult to achieve any significant improvement solely by improving the current power system losses, which requires the development of new systems. To carry out this purpose, a system evaluation technique covering power electronics is indispensable. We will continue to strive for further energy saving and contribute to the protection of the global environment.

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