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ENERGY SAVING SYSTEM FOR HYDRAULIC EXCAVATOR
(SIMULATION OF POWER ASSISTANT SYSTEM WITH ACCUMULATOR)

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ABSTRACT

In this study we investigate development of energy saving system for hydraulic excavator. In the system an accumulator storages power when energy exceeds and assists necessary power which is required by the actuators. As a first step of the study, simulation program of the system is developed. By using the simulation program it is expected that the static and dynamic performance is easily grasped. And it will contribute to the rationalization of the system design. In this paper, the validity of the energy saving system is evaluated.

KEY WORDS

Key words, Energy saving , Hydraulic excavator, Simulation, Accumulator

NOMENCLATURE

C_d : Flow coefficient
C_p,C_v : Constant-pressure molar heat and constant-volume molar heat [j/mol-k]
d_a : Diameter of pipeline [m]
d_{pr} : Displacement volume per revolution [m^3]
$G(x)$: Transfer function of a rack system
j : Moment of inertia around a crankshaft [kg-m^2]
k_{pr1} : Proportional gain
k_{ir1} : Integral gain
k_p : Pump efficiency [%]
K : Bulk modulus [Pa]
p_1, p_2 : Inlet pressure and outlet pressure for each element [Pa]
P_g : Pressure in accumulator [Pa]
P_{PR} : Minimum gas pressure [Pa]
p_{wr} : Work performed by pump [kW]
q_1, q_2 : Flow rate at pipe inlet and outlet [m^3/s]
q_{ag} : Flow rate into an accumulator [m^3/s]
r_1 : Pump revolution [rpm]
r_2 : Target pump revolution [rpm]
Δr : Difference between the target revolution and actual revolution [rpm]
s : Laplace operator
t_q : Motor torque [kgf-m]
t_l : Load [kgf-m]
t_e : Engine torque [kgf-m]
u : Control input into a rack system

v_G : Accumulator capacity [m^3]
v_{AC} : Maximum gas volume [m^3]
v_{LQ} : Liquid volume in accumulator [m^3]
x_r : Target rack position [m]
x_{ra} : Actual rack position [m]
ρ : mass density of fluid [kg/m^3]

INTRODUCTION

In recent years, environmental consciousness has risen in various fields and "energy saving" for hydraulic equipment (construction machinery) has become an important keyword [1]. In the present hydraulic driving system, the constant capacity pump is driven with a constant velocity by the engine, and the hydraulic pressure and flow rate are regulated by the control valve in order to supply necessary power for the actuator. In such system, rate of fuel consumption increases under the condition such as too much load on the actuator or small load while idling, because engine runs at constant rotational speed and it makes combustion efficiency low. Thus, it is considered that energy saving may be attained by storing excess energy by using an energy storage device, such as an accumulator, and utilize the stored energy when it is needed. This study was to prepare a basic simulation program of an actual equipment system as a preliminary step to conduct comparative verification experiments for the energy saving of a small-sized hydraulic shovel using the method mentioned above.

Once the simulation program is prepared, it would be easy to understand the dynamic characteristics of the actual equipment system. Even if the parameters and structures of the equipment system are changed, the change of the performance and behavior may be easily understood and the program would be a very effective means to promote the rationalization and efficiency of the system design [2].

In view of the above background, this study intended to prepare the simulation program of a power assist system for the purpose of energy storage and recovery using an accumulator and verify the effectiveness of the power assist system using the analysis result.

SYSTEM CONSTRUCTION

The power assist system is a type of system to store and recover energy using an accumulator as if it were a storage battery. It is a system to store energy into an accumulator during equipment idling periods and utilize the stored energy during loaded periods for energy saving purpose. Fig. 1 shows the schematic diagram of the power assist system.

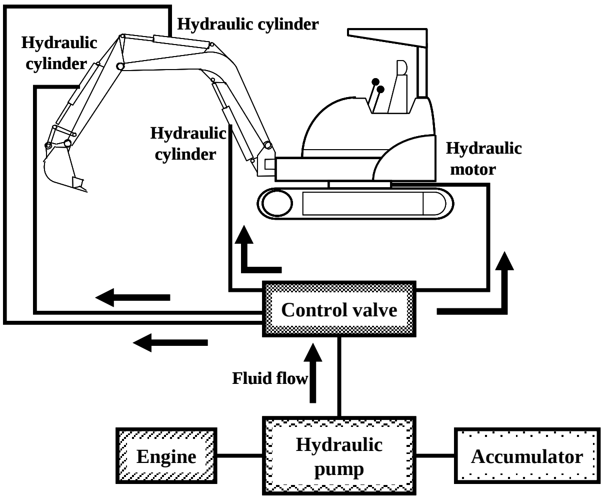
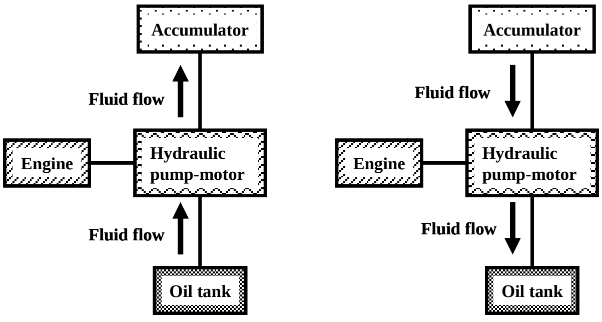


Fig. 1 Schematic diagram of the power assist system

The power assist system consists of an engine, accumulator, hydraulic pump /motor unit. The sensor of the power assist system measures the pump load and accumulator pressure then the computer begins to calculate a control input and gives it to the hydraulic pump/motor unit. By this signal, the system, as shown in Fig. 2, makes the hydraulic pump/motor unit operate as a hydraulic pump during no-load idling periods in order to pump hydraulic fluid into the accumulator to store it. When load is applied to the system, the system recovers the energy of the hydraulic fluid stored in the accumulator to drive the hydraulic pump/motor unit as a motor in order to assist the engine. The engine can maintain a constant and most efficient load and revolution with this method and, as result, fuel efficiency can be improved.



No – load Condition **Loaded Condition**

Fig. 2 Operating procedures of power assist system

An actual equipment system to verify the effectiveness of the power assist system is assumed to consist of an engine, two hydraulic pump/motor units, piplines, an accumulator and a control system as its main elements.

The schematic outline of the hydraulic circuit diagram is shown in Fig. 3. The two hydraulic pump/motor units are connected directly to the crankshaft. The hydraulic pump/motor unit 2 that is connected to the accumulator compresses the accumulator and assists to drive the engine. The hydraulic pump/motor unit 1 functions as a variable-displacement pump and it may be considered as a load-producing device because it produces a load torque. It is considered that the unit 1 can produce almost the same workload of an actual working condition by changing the discharge amount. The controller determines the control input into the hydraulic pump/motor unit 2 from the load torque and accumulator pressure that are detected by the sensor.

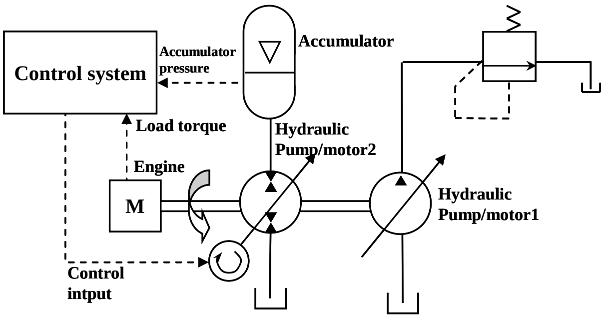


Fig. 3 Hydraulic circuit diagram of the power assist system

MATHEMATICAL MODEL FOR SIMULATION

This section explains the mathematical model of the accumulator, hydraulic pump/motor units and engine that are the main constituting elements of the power assist system. Fig. 4 shows the schematic model of the accumulator.

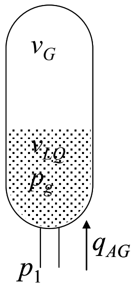


Fig. 4 Accumulator model for simulation

This element is composed of a bladder-type gas compression-method accumulator. The inflow into the accumulator should be obtained next. As an orifice is installed at the connection point of the pipe and the accumulator, the following equation can be made by assuming the orifice flow as being a laminar flow:

$$q_{AG} = \frac{\pi d_a^3 C_d^{\,2}}{2\mu R_{ET}}(p_1 - p_g) \tag{1}$$

The following equation can be derived:

$$p_1 = p_g + \frac{2\mu R_{ET}}{\pi d_a^3 C_d^{\,2}} q_{AG} \tag{2}$$

p_g, the hydraulic fluid pressure in the accumulator can be obtained as follows:

$$p_G v_G^{\ \gamma} = \text{constant} = p_{PR} v_{AC}^{\ \gamma} \tag{3}$$

where, γ is the ratio of the specific heat of gas c_p to c_v as follow:

$$\gamma = c_p / c_v$$

Thus, the pressure of the hydraulic fluid in the accumulator can be obtained as follow:

$$\dot{p}_g = \frac{K}{\rho}\left[\frac{\rho(q_1 - q_2)}{v_{LQ}} \Bigg/ \left(1 + \frac{K}{\rho} \cdot \frac{\rho v_G}{\gamma p_g v_{LQ}}\right)\right] \tag{4}$$

The volume of the hydraulic fluid, v_{LQ}, and the volume of gas, v_g, in the accumulator can be given by the following equations:

$$v_{LQ} = v_{AC} - v_g \tag{5}$$

$$v_g = v_{AC}\left(\frac{p_{pr}}{p_g}\right)^{\frac{1}{\gamma}} \tag{6}$$

Fig. 5 shows the schematic diagram of a variable displacement type axial piston pump/motor unit. The pump is made of the main elements of a swash plate, pistons, cylinders, a cylinder block and a valve plate. The inlet and outlet ports are separated by the valve plate.

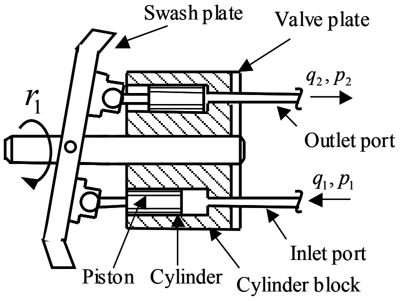


Fig. 5 Model of an axial piston pump for simulation

The outlet discharge of the hydraulic pump shown in the figure can be expressed by the following equation:

$$q_2 = d_{pr} \times r_1 \tag{7}$$

The work, p_{wr}, performed by the pump can be expressed by the following equation:

$$p_{wr} = \frac{q_2 \times (p_2 - p_1)}{k_p} \tag{8}$$

The relationship between the torque t_q that occurs when the pump/motor unit is used as a motor can be expressed as follow:

$$t_q = \frac{p_{wr}}{2\pi r_1} \tag{9}$$

Fig. 6 shows the schematic view of the engine element. This element consists of an electronic governor and an engine. The engine should be a simple one to produce torque by revolution and injected fuel without taking into consideration the combustion.

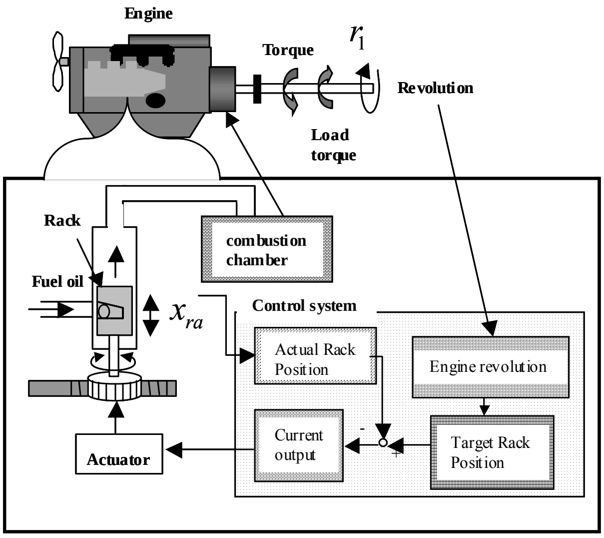


Fig. 6 Engine element model for simulation

The electronic governor is a device to detect engine revolution by the revolution sensor, calculates the target rack position that attains the target revolution of the engine and controls the rack position by the actuator. The simulation process is shown in Fig. 7.

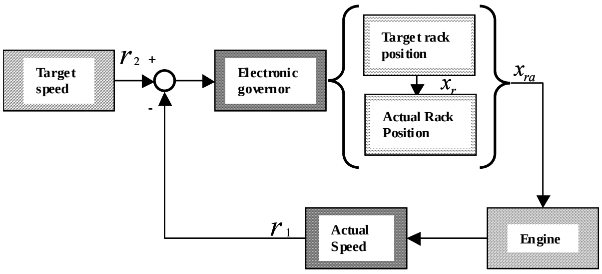


Fig. 7 Simulation process of engine model

The difference Δr between the target revolution r_2 and the actual revolution r_1 can be expressed by the following equation:

$$r_2 - r_1 = \Delta r \tag{10}$$

The target rack position x_r should be obtained at first. This is equivalent to the control system of the electronic governor and determines the target rack position x_r based on the control function.

$$x_r = g\ (\Delta r) \tag{11}$$

Input u to the rack system is to be obtained next. This is equivalent to the electric output of the control system and determines the input u by PI control. Thus, Input u can be obtained from x_r and x_{ra} by the following equation:

$$u = k_{pr1}(x_r - x_{ra}) + k_{ir1}\int (x_r - x_{ra})dt \tag{12}$$

The transfer function $G_{(r)}$ of the actuator from the input u of the rack system to x_{ra} can be derived from the system identification as follow:

$$G_{(r)} = \frac{0.0073}{0.04s + 1} \tag{13}$$

The engine torque t_e can be obtained by the following equation:

$$t_e = f(x_{ra}, r_1) \tag{14}$$

The function $f_{(x,r)}$ is based on Fig.8. This was obtained as a result of tests conducted by changing the revolution r_1 and the rack position x_{ra} of the actual equipment system. The abscissa indicates the engine speed and the ordinate indicates the torque. The shaded area indicates the rack position. If the rack position is at a constant position, the torque becomes greater when the revolution decreases. On the other hand, the torque becomes smaller when the revolution increases. Thus, the torque can be obtained from the engine revolution and rack position in Fig. 8.

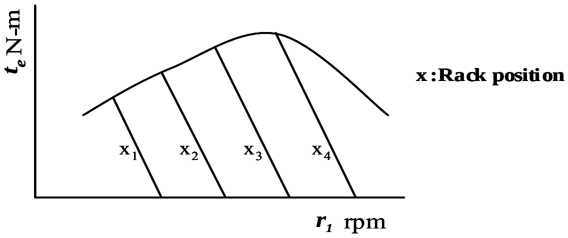


Fig. 8 Torque map

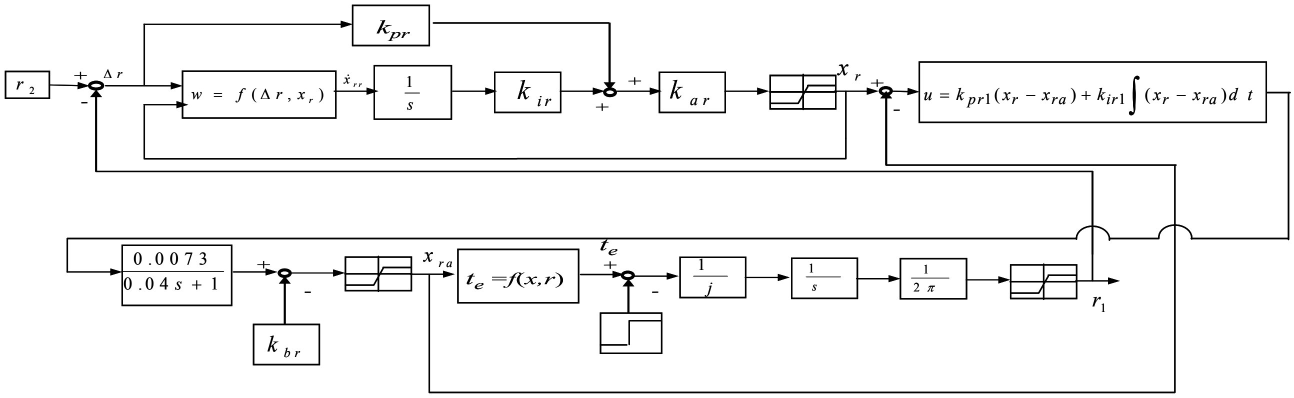


Fig. 9 Block diagram of engine

The equation of motion at the rotating shaft of the engine can be expressed by the following equation:

$$2\pi J\dot{r}_1 = t_e - t_l \qquad (15)$$

Based on the above equation, the block diagram becomes as shown in Fig. 9. The controller element changes the discharge amount per one turn of the hydraulic pump/motor unit and alternates the pump/motor operation. Input into the controller is the accumulator pressure and engine load torque values. The block diagram of the controller is shown in Fig. 10.

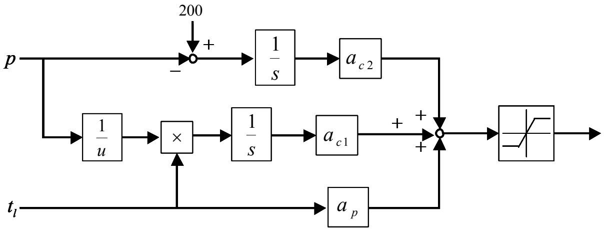


Fig. 10 Block diagram of controller

Based on the block diagram, the mathematical simulation of the power assist system can be made.

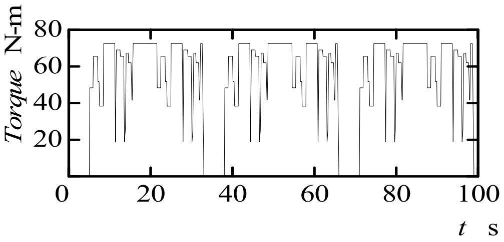
SIMULATION RESULTS

This section delineates the verification of the effectiveness of the power assist system by the simulation conducted based on the mathematical model described in the previous section. The simulation results of the two-types of load patterns (load-torque waveforms) are shown in Figs. 11 and 12 respectively. The given load torque waveforms are shown in the graphs (a), the torque of the hydraulic pump/motor unit in the graphs (b), the accumulator pressures in the graphs (c) and the engine speeds in the graphs (d) in both figures respectively. The fine lines in graphs (d) show the simulation results without power assist. The given load-torque waveforms were determined based on data obtained through actual equipment operation.

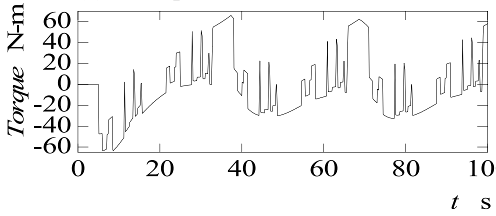
When looking into the results shown in Fig. 11 and paying attention to the torque of the hydraulic pump/motor unit shown in Fig. 11 (b), the graph indicates that the hydraulic pump/motor was functioning as a hydraulic motor under zero-load condition. It can be seen from the accumulator pressure shown in Fig. 11 (c) that the accumulator was pressurized during the zero-load periods. However, zero load is occurred between 0 to 5 second and at the period the accumulator pressure is constant. The reason is that the pressure in the accumulator is set at the maximum at the initial condition. When comparing the engine speed shown in the graph (d) of Fig. 11, it is clear that the engine speed greatly deviated in the simulation without power assisting. But, the deviation of the engine speed became smaller in the simulation when power assist was used. As for the relationship between the engine speed and fuel consumption, the smaller the deviation of engine speed, the more efficiently it is possible to operate the engine by maintaining a better engine speed. Thus, it is considered that the power assist system may be able to attain energy saving.

When looking into the simulation results using a different load torque pattern shown in Fig. 12 and paying attention to the torque of the hydraulic pump/motor unit in graph (b) and the accumulator pressure in graph (c), it can be seen that the hydraulic pump/motor unit was functioning as a hydraulic motor and pressurizing the accumulator when the load became zero as the same as the case shown in Fig. 11. The accumulator pressurization was made not only during zero-load periods but also during a time when the load was small. Even there were no zero-load periods shown in Fig. 12 (a), the accumulator pressure did not drastically drop.

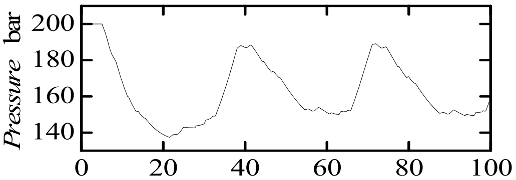
As for the engine speed shown in Fig. 12 (d), when the power assist system was used the deviation of the engine speed was small as the same as the case shown in Fig. 11. Thus, it is considered that energy saving was attained. As described above, the effectiveness of the power assist system was verified by this study.



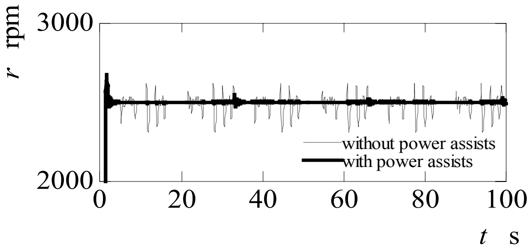
(a) Load pattern used for simulation



(b) Simulated torque of hydraulic pump/motor unit with power assist system

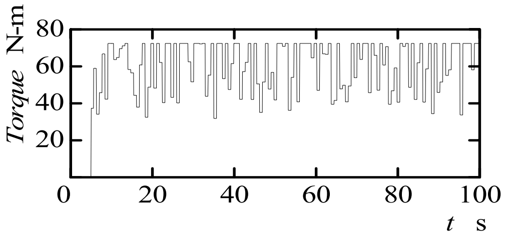


(c) Simulated accumulator pressure with power assist system

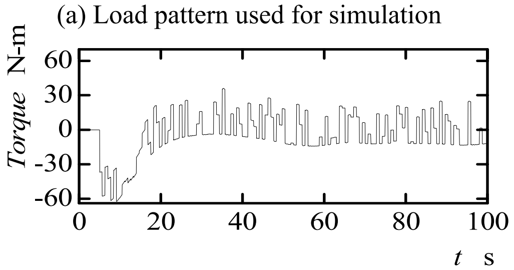


(d) Engine speed comparison

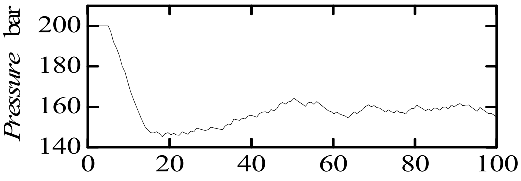
Fig. 11 Simulation result (load-pattern a)



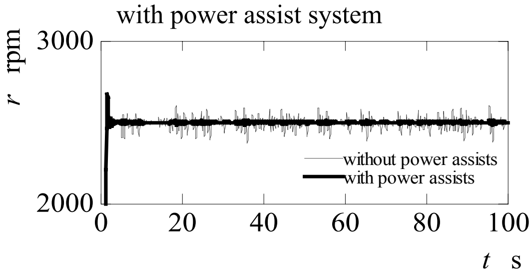
(a) Load pattern used for simulation



(b) Simulated torque of hydraulic pump/motor unit with power assist system



(c) Simulated accumulator pressure with power assist system



(d) Engine speed comparison

Fig. 12 Simulation result (load-pattern b)

CONCLUSION

In this study, a mathematical model of a power assist system was made for the purpose to prepare a simulation program of the power assist system to store and recover energy using an accumulator. Based on the mathematical model, the simulation of the dynamic characteristics of the power assist system was conducted. From the simulation analysis results, the effectiveness of the power assist system was verified.

As a future work we would like to build an actual experimental facility and would like to discuss how much the proposed system could save energy.

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