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Simulation Study on Energy Recovery and Reuse of Hybrid Loader Actuator

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1. Introduction

In recent years, with the increasingly stringent international standards for engine emissions, the efficient use of energy has become a central issue in almost every field, whether in manufacturing, electricity, or construction machinery [1, 2]. Hybrid power systems (HPS) and energy recovery (ER) are widely used in the field of construction machinery to overcome an energy crisis caused by the accelerated use of energy resources in the industrial sector [3, 4]. Hybrid technology is currently one of the best internationally recognized energy-saving solutions. It can effectively improve the engine's working condition and increase the engine's fuel consumption rate by using the "peak-shaving" effect of the auxiliary motor, thus reducing the energy consumption and emissions of the engine [5, 6].

As one of the main types of construction machinery, loaders have the characteristics of a large mass, complex working conditions, and significant changes in power demand [7]. During the frequent loading and unloading of materials operations, the engine operating point is prone to instability, resulting in poor economy of the whole vehicle. At the same time, the severe energy loss of the boom arm leads to the rapid temperature rise of the hydraulic oil, which may cause equipment failure in severe cases and affect the regular operation of loaders [8]. Therefore, it is essential to carry out energy recovery and reuse loaders. The hydraulic system energy recovery can be divided into mechanical, hydraulic, and electrical according to energy recovery [9]. The mechanical type is subdivided into the flywheel, counterweight, and spring [10]. The flywheel type mainly uses the rotating flywheel as the energy storage element, which has the advantages of high efficiency, fast response, long life, and easy monitoring of energy storage status [11]. The hydraulic type uses an accumulator as the energy storage element, with fewer conversion links, low cost, and high reliability [12]. The electrical type uses an ultra-capacitor or battery as the energy storage element. The hydraulic motor drives the generator to generate electricity to convert the hydraulic energy to be recovered by the system into electrical energy and then realizes the storage and reuse of energy recovery through the electrical energy storage system, which has the characteristics of high energy recovery efficiency [13]. For the energy recovery of the hydraulic system, scholars have conducted much research [14, 15]. Baoyu Cao proposed a new dynamic arm energy recovery system by analysing the excess energy of three hydraulic cylinders in the conventional hydraulic excavator and modeled and simulated it with AMESim. The simulation results showed that the proposed cantilever potential energy recovery system has high energy-saving efficiency [16]. Jie Li proposed a purely electric drive excavator electro-hydraulic energy recovery and reuse system and conducted a modeling simulation in Simulation X. The simulation results show that the system energy recovery effect is remarkably reaching 72.11%, which can save 29.6% of energy [17].

This study proposes a hybrid loader arm energy recovery and reuse system for the conventional loader arm system, which uses an ultra-capacitor as the energy storage element. The system uses the high-pressure oil generated in the rodless chamber when the loader arm cylinder is dropped to drive the hydraulic motor to drive the DC generator to charge the ultra-capacitor to realize energy recovery. The ultra-capacitor supplies power to the DC motor. The DC motor drives the hydraulic pump through the actuator to realize energy reuse, which can effectively reduce the engine to provide energy for the system, fuel consumption, and pollutant emissions.

This paper is organized as follows. Section 2 introduces the principle of loader actuator energy recovery and reuse system. Section 3 introduces the mathematical model analysis. Section 4 introduces the system modeling and simulation. Section 5 introduces the simulation results analysis. Section 6 is the conclusions.

2. Principle of loader actuator energy recovery and reuse system

2.1. Principle of the loader boom arm system

In Fig. 1, the system is an open system consisting of a conventional loader boom arm hydraulic system and an electrical energy recovery and reuse system. Engine *1* and motor *2* drive hydraulic pump *4* through torque coupler *3* to produce high-pressure oil, and high-pressure oil enters boom arm cylinders *13.2* and *13.3* through check valve *5.2* and multi-way valve *7.2* in turn. The oil from the boom arm cylinder flows back to tank *12* directly through solenoid reversing valve *8.3* or flows back to the tank through solenoid reversing valve *8.3* and hydraulic motor *9* in turn. The hydraulic motor *9* drives the DC generator *10* to charge the ultra-capacitor *11* for energy recovery. Ultra-capacitor 11 supplies power to DC motor *2* for energy reuse. The hydraulic source *14* outputs high-pressure oil through check valve *5.1* and multi-way valve *7.1* in turn into the bucket cylinder *13.1*, and the oil coming back from the bucket cylinder flows directly back to the tank. Accumulator *6.1* and *6.2* has the function of buffer and shock absorption, and safety valve *15* has the function of overload protection.

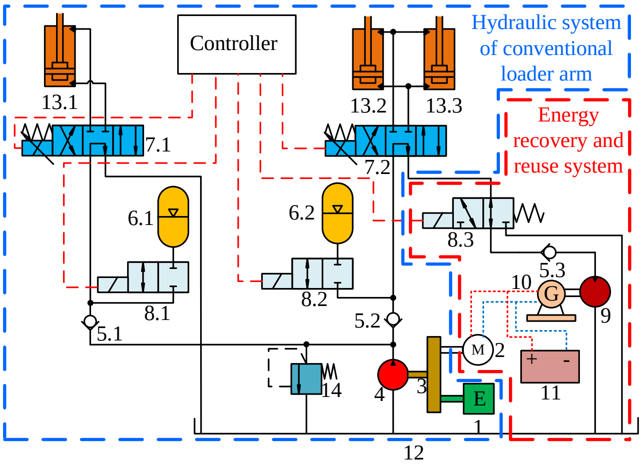

Fig. 1 Loader boom arm system: *1* - engine, *2* - DC motor, *3* - torque coupler, *4* - hydraulic pump, *5* - check valve, *6* - accumulator, *7* - multi-way valve, *8* - solenoid-operated reversing valve, *9* - hydraulic motor, *10* - DC generator, *11* - ultra-capacitor, *12* - tank, *13* - cylinder, *14* - safety valve

2.2. Energy recovery control strategy

In Fig. 2, the energy recovery strategy is based on the control signal of the boom arm cylinder. When the boom arm cylinder drops, the right position of the solenoid-operated reversing valve *8.3* works, and the torque of DC generator *10* is calculated by the external load. The system stops energy recovery when the ultra-capacitor SOC is greater than or equal to 90%, the left position of the solenoid-operated reversing valve *8.3* works, and the system stops energy recovery. Otherwise, the system continues with energy recovery. When the boom arm cylinder is not dropped, the left position of solenoid-operated reversing valve *8.3* works, and the system stops energy recovery.

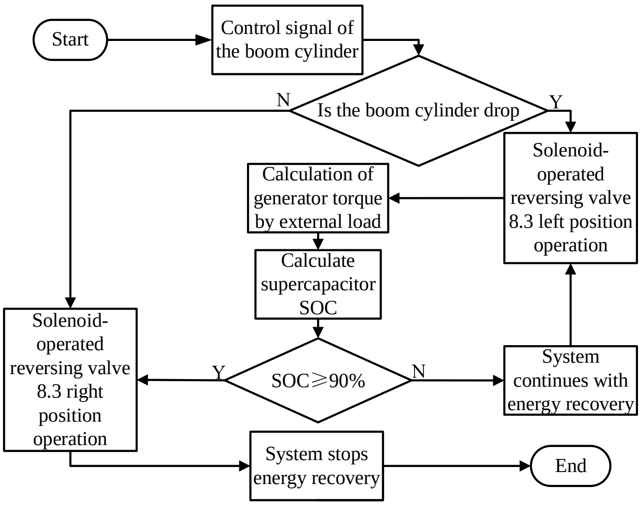

Fig. 2 Energy recovery strategy

2.3. Energy recovery control strategy

In Fig. 3, the energy reuse strategy is based on the ultra-capacitor SOC. When the ultra-capacitor SOC is less than or equal to 40%, the system enters the pure engine drive mode and is driven by the engine only. When the ultra-capacitor SOC is greater than or equal to 80%, the system enters the pure motor drive mode and is driven by the motor only. The external load calculates the motor drive torque. The system enters a hybrid mode when the ultra-capacitor SOC is greater than 40% and less than 80%. When the boom arm cylinder is at zero point or dropped, the motor drives the system, and the external load calculates the motor driving torque. When the boom arm cylinder is raised or held, it is driven by the engine motor together, and the external load calculates the motor driving torque.

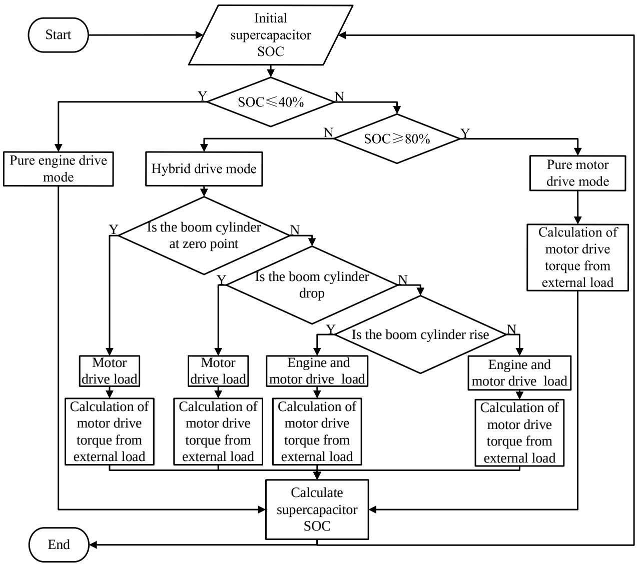

Fig. 3 Energy reuse strategy

3. Mathematical model analysis

3.1. Loader boom arm force analysis

In Fig. 4, the center of rotation of the loader arm is taken as the coordinate origin *O*. Coordinates are established, the hinge point of the boom arm cylinder with the frame is *A*, the hinge point with the boom arm is *B*, the boom arm with the linkage is *C*, the hinge point with the bucket is *D*, and the center of gravity point of the boom arm is *G*. The clockwise direction is positive. The dynamic equation of the boom arm is expressed as follows:

$$J_1 = \frac{d^2\gamma}{dt^2} F_1 L_{AB} \sin\alpha \cos\alpha - F_G L_{OG} \cos\beta - T_1\,, \qquad (1)$$

where: J_1 is the rotational inertia of the boom arm concerning *O*, γ is the angle of *OB* concerning the x-axis, F_1 is the combined force on the boom arm cylinder, α is the angle

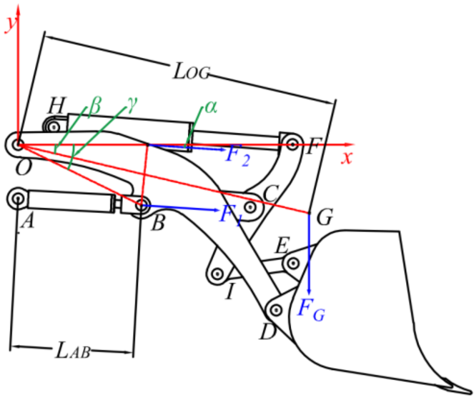

Fig. 4 Loader boom arm force analysis

with the x-axis, L_{AB} is the distance between A and point B, F_G is gravity, L_{OG} is the distance between point O and point G, β is the angle of the OG with the x-axis, T_1 is the resistive moment to the rotation of the boom arm.

The force equation of the boom arm cylinder is expressed as follows:

$$F_1 = m\frac{d^2 L_{AB}}{dt^2}, \tag{2}$$

where m is the total weight of the boom arm cylinder.

3.2. Analysis of recyclable energy of boom arm cylinder

When the boom arm cylinder piston drops, the boom arm's potential energy is converted into pressure energy. The formula for the recyclable energy E_1 of the boom arm cylinder is expressed as follows:

$$E_1 = \int p_1 v_1 A_1 dt, \tag{3}$$

where p_1 is the rodless chamber pressure of the boom arm cylinder, v_1 is the boom arm cylinder descent velocity. A_1 is the rodless cavity area of the boom arm cylinder.

3.3. Ultra-capacitor mathematical model analysis

The charging and discharging performance of the ultra-capacitor can be described by the change of voltage or power at both positive and negative terminals. If the ultra-capacitor is charged with a constant current I, after a time, the power changes from Q_1 to Q_2, and the voltage changes from U_1 to U_2. The ultra-capacitor stored energy E_2 is expressed as follows:

$$E_2 = \frac{Q_2^2 - Q_1^2}{2C} = \frac{C\left(U_2^2 - U_1^2\right)}{2}, \tag{4}$$

where C is the intrinsic capacity.

The ultra-capacitor SOC is expressed as follows:

$$SOC = \frac{U - U_{min}}{U_{max} - U_{min}}, \tag{5}$$

where U is the current voltage, U_{min} is the minimum allowable voltage, U_{max} is the maximum allowable voltage.

3.4. System efficiency analysis

The system energy recovery efficiency η_1 is expressed as follows:

$$\eta_1 = \frac{E_2}{E_1}, \tag{6}$$

The system energy reuse efficiency η_2 is expressed as follows:

$$\eta_2 = \frac{E_4}{E_3}, \tag{7}$$

where E_3 is the ultra-capacitor that releases energy, E_4 is the torque coupler that gains energy.

4. System modeling and simulation

4.1. System Modeling

According to the loader boom arm system in Fig. 1, energy recovery strategy in Fig. 2, and energy reuse strategy in Fig. 3, AMESim is used to build the models shown in Fig. 5, in which the hydraulic library is used to build the hydraulic system model of the boom arm, the 2 D mechanical library is used to build the boom arm mechanism model, and the running signal library is used to build the energy recovery and reuse strategy model.

4.2. System Simulation

A 5 t loader is used as the object of study, and the simulation is carried out under typical working conditions, i.e., the loader is unloaded, the boom cylinder rises and drops once, and the bucket cylinder drops and rises twice in one operating cycle.

The simulation time is set to 388 s, i.e., the boom arm system operates 12 times continuously with a step of 0.01 s. When the input value of the mode control signal is ‘1’, the system enters pure engine mode. The system enters the hybrid mode when the input value is ‘2’. The system enters the pure motor mode when the input value is ‘3’. The set mode control signal is shown in Fig. 6, and the system operates in hybrid mode, pure engine mode, and pure motor mode four times each in turn. Ignoring the system leakage, set the system simulation parameters as shown in Table 1.

Table 1

Simulation parameters

Components	Parameters	Values
Engine	Rotational speed /rev/min	2000
	Total engine volume /L	10
	The hot engine idle speed /rev/min	800
Hydraulic Pump	Displacement /mL/rev	120
Boom cylinder	Piston diameter /mm	150
	Rod diameter /mm	70
	Stroke length /mm	750
Hydraulic Motor	Displacement /mL/rev	100
DC Generator	Rated speed /rev/min	3500
	Efficiency /%	90
Ultra-capacitor	Open Circuit Voltage /V	375
	Intrinsic capacity /F	40
	Initial charge /C	15000
	Maximum charge /C	25000
The mass of the bucket	Mass/kg	2500
	Rotational inertia /kg·m^2	700

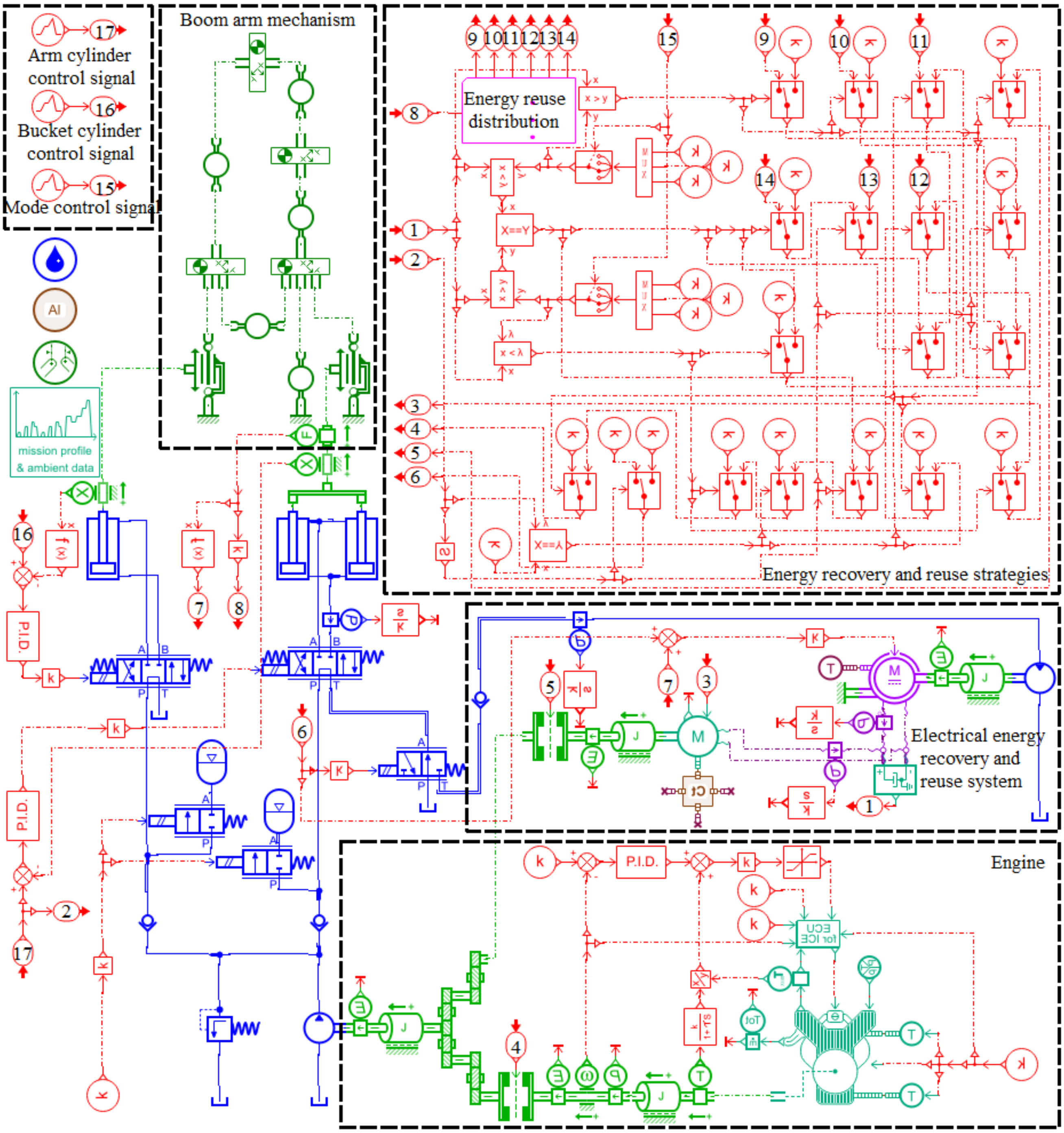

Fig. 5 AMESim model

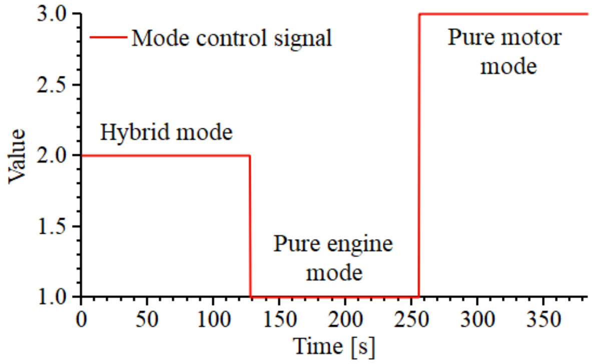

Fig. 6 Mode control signal

5. Simulation results analysis

5.1. Dynamic arm motion characteristics analysis

In Fig. 7, during the first operating cycle, the hybrid power system tracks the boom arm cylinder displacement and velocity well compared to the conventional system. Furthermore, the velocity fluctuation is less for both when the speed changes. The hybrid power system does not affect the regular motion characteristics of the boom arm cylinders.

5.2. System energy recovery analysis

In Fig. 8, after four operating cycles, the total recyclable energy of the boom arm cylinder is 286600.4 J, the total recyclable energy of the hydraulic motor is 206611.2 J, and the total recyclable energy of the motor is 199122.2 J. The total stored energy of the ultra-capacitor is 168720.5 J. The energy recovery efficiency of the system reaches 58.9%, and the hybrid power system has a good energy recovery. The hybrid power system has good energy recovery performance.

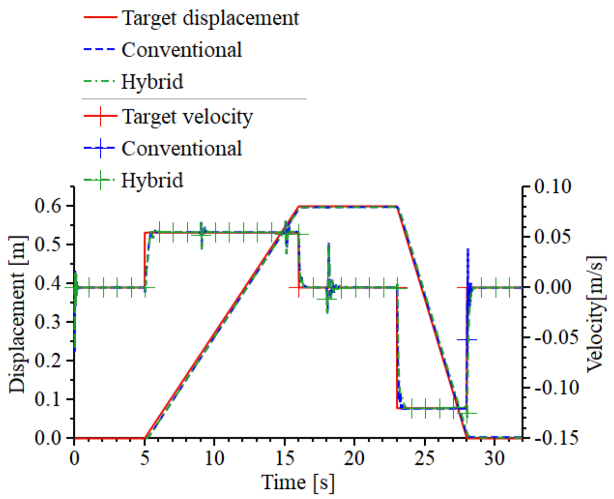

Fig. 7 Displacement and velocity curves of the boom arm cylinder

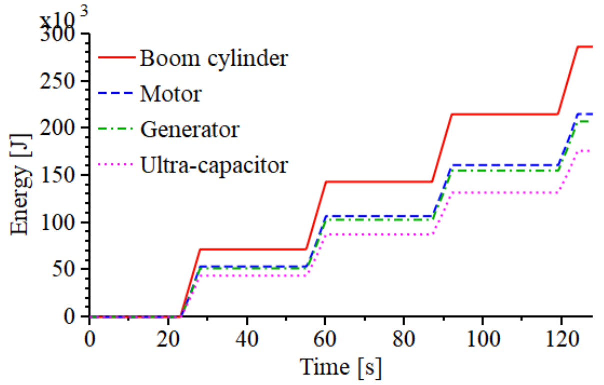

Fig. 8 System energy recovery curves

5.3. System energy reuse analysis

In Fig. 9, after four operating cycles, the total energy released by the ultra-capacitor is 164,415.4 J, and the energy gained by the torque coupler is 142,863.1 J. The energy reuse efficiency of the system is 86.9%, and the hybrid power system has good energy reuse performance.

5.4. Ultra-capacitor SOC analysis

As shown in Fig. 10, the SOC decreased from 60% to 59.6% and then increased to 60.02% during the first operation cycle in the hybrid model. The ultra-capacitor SOC increased by 0.05% after four operating cycles, and the ultra-capacitor SOC maintained an increasing trend with minor changes.

As shown in Fig. 11, the ultra-capacitor SOC increased from 60.05% to 60.51% after one operating cycle in the pure engine mode. After four operating cycles, the ultra-capacitor SOC increased by 1.84%.

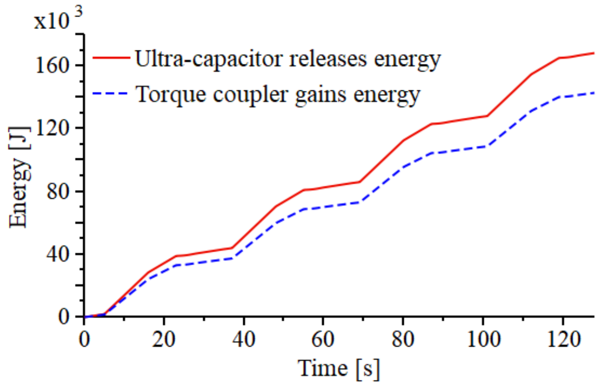

Fig. 9 System energy reuse curves

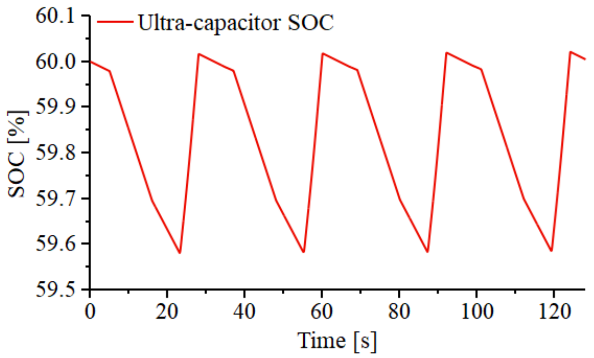

Fig. 10 Ultra-capacitor SOC curve in hybrid mode

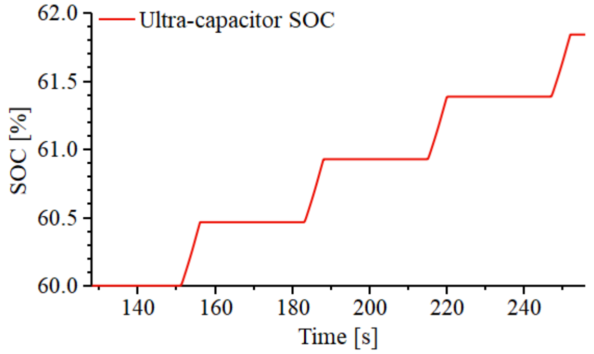

Fig. 11. Ultra-capacitor SOC curve in pure engine mode

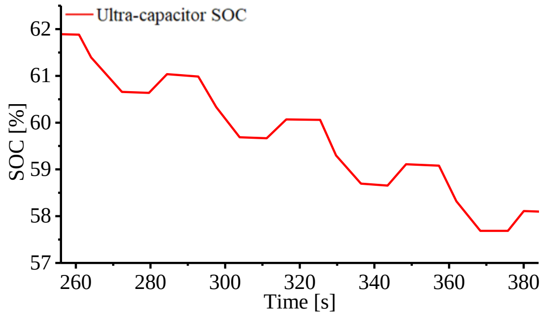

Fig. 12 Ultra-capacitor SOC curve in pure motor mode

As shown in Fig. 12, the ultra-capacitor SOC decreased from 61.84% to 61.03% after one operating cycle in the pure motor mode. After four operating cycles, the ultra-capacitor SOC decreased by 3.81%. The ultra-capacitor SOC increased significantly when the boom arm cylinder was dropped. The hybrid power system does not affect the regular energy recovery of the system in the pure engine mode and the pure motor mode.

5.5. System energy saving and emissions reduction analysis

As shown in Fig. 13, after four operating cycles, the total fuel consumption of the conventional system is 166.7 g, the total fuel consumption of the hybrid power system is 125.2 g, and the engine fuel consumption is reduced by 24.9%. The hybrid power system can effectively reduce engine fuel consumption.

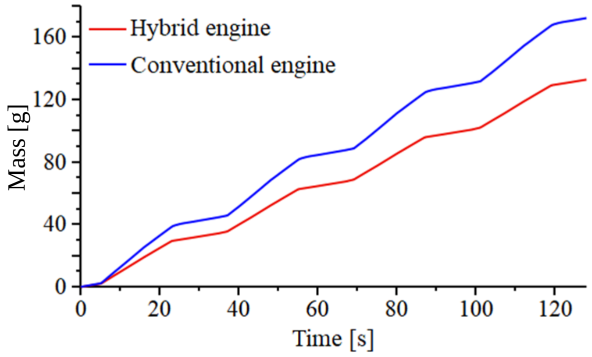

Fig. 13 Engine fuel consumption curves

As shown in Fig. 14, after four operating cycles, the conventional system's total CO, HC, and NOx emissions are 10300.3 mg, 9032 mg, and 1007 mg, respectively. In contrast, the total CO, HC, and NOx emissions of the hybrid power system are 8324.3 mg, 6694.8 mg, and 769.3 mg, respectively. Therefore CO, HC, and NOx emissions are reduced by CO, HC, and NOx emissions are reduced by 19.2%, 25.9%, and 23.6%, respectively. The hybrid power system can effectively reduce engine pollutant emissions.

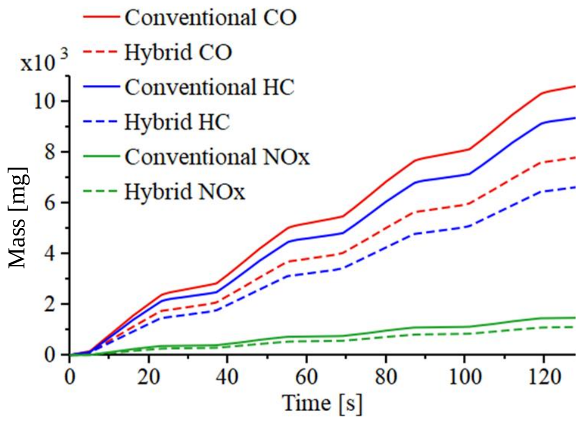

Fig. 14 Engine pollutant emissions curves

6. Conclusions

The following conclusions can be obtained by establishing the loader boom arm energy recovery and reuse system and analyzing the mathematical model of the components using AMESim for modeling and simulation.

1. The hybrid power system can track the displacement and speed of the boom arm cylinder well compared with the conventional system and does not affect the boom arm cylinder's regular motion characteristics.

2. The hybrid power system has good energy recovery and reuse performance. After four operating cycles, the energy recovery efficiency reaches 58.9%, and the energy reuse efficiency reaches 86.9%.

3. The hybrid power system can perform regular energy recovery in hybrid, pure engine, and motor modes.

4. The hybrid power system can effectively reduce the engine's energy system, fuel consumption, and pollutant emissions. The engine fuel consumption is reduced by 24.9%, and engine pollutant emissions CO, HC, and NOx are reduced by 19.2%, 25.9%, and 23.6%, respectively.

5. The hybrid power system provides a reference for energy-saving technology research for loaders.

Acknowledgments

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SIMULATION STUDY ON ENERGY RECOVERY AND REUSE OF HYBRID LOADER ACTUATOR

Summary

It is necessary to reduce engine fuel consumption for loaders to overcome the energy crisis faced by today's society. To this end, a hybrid loader arm energy recovery and reuse system is proposed, adding an electrical energy recovery and reuse system to the conventional loader arm system and effectively reducing the loader engine fuel consumption and emissions. The principle of the system is analyzed, the mathematical model of the system components is analyzed, and AMESim models the system. The simulation results show that the system does not affect the regular motion characteristics of the boom arm cylinders. The energy recovery efficiency of the system reaches 58.9%, and the energy reuse efficiency reaches 86.9% after four operation cycles. The system can recover energy in hybrid, pure engine, and motor modes. The system's engine provides 24.8% less energy, engine fuel consumption is reduced by 24.9%, and pollutant emissions CO, HC, and NOx are reduced by 19.2%, 25.9%, and 23.6%, respectively. The system provides a reference for the research of energy-saving technology for loaders.

Keywords: hybrid loader, boom arm, energy recovery, reuse, simulation, AMESim.

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