Development of a Parallel Hydraulic Hybrid Loader Through Modelling

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Abstract. With the aggravation of the energy crisis, people pay more and more attention to the rational utilization of energy. Thus the construction machinery field has started to take hybrid technology into consideration to save the energy. This paper analyses the working condition of a 5 tons loader and develops the hydraulic parallel hybrid scheme which has little research in the loader field. The system adopts a dynamic rule-based control strategy, which takes the required torque and the SOC value of the accumulator as the input to realize the output torque of the engine and the pump/motor. A power-train model is also developed in the paper. The results show the scheme can reduce the fuel consumption by 13.5% compared to the conventional loaders.

1. Introduction
With the aggravation of the global energy crisis [1, 2], hybrid, which is a new fuel-saving technology, has gained more attention in recent years [3-5]. Loader, as a typical construction machines, has the characteristics of frequent starts/stops, low energy utilization, high energy consumption and poor emissions. Numerous construction machinery manufacturers at home and abroad have started to study the hybrid power technology of construction machinery. The first hybrid loader was proposed by Hitachi Construction in 2003 [6], Volvo introduced L220F Hybrid wheel loader, an energy-efficient parallel hybrid electric drive system batteries for storage in 2008 and a LXI prototype hybrid wheel loader using a series hybrid system made a first appearance In Switzerland which showed that it could improve fuel efficiency by 50% in 2016 [7]. The CLG862-HYBRID, China's First Hybrid Loader, proposed by Liugong in 2010, is a series-parallel hybrid wheel loader with super capacitor [8]. XCMG launched a parallel hydraulic hybrid system with engine, variable pump, hydraulic accumulator, hydraulic pump/motor devices which can reduce 15% fuel consumption by recovering of braking kinetic energy in the same year [9]. There is few literature on hybrid loader due to technical confidentiality and other reasons.

This paper reports the development of parallel hybrid versions of a loader through modelling. The models were made using two different software packages, LMS Imagine.Lab AMESim and AMESet based on a 5 tons loader. The energy-saving effect and performance of the system are studied which can prepare for parameter matching and subsequent test validation.

2. Parallel hydraulic hybrid loader

2.1. Working condition of loader
A typical working cycle of a 5 tons loader consists of six steps [10]. The first step is that the empty
loader drives to the gravel bank from initial position, the second step is that the empty loader scoops and loads gravel which means the empty loader becomes to the full-load loader, the third step is that the full-load loader returns to the initial position, the fourth step is that the full-load loader drives to the unloading position, the fifth step is that the loader unloads the gravel and the full-load loader becomes to the empty loader, the final step is that the empty loader returns to the initial position. Generally speaking, for a loader with two forward gears and one backward gear, the first, second and fourth steps are carried out in the first forward gear, the third and final steps are carried out in the backward gear.

2.2. Structure of parallel hydraulic hybrid loader
As shown in figure 1, the structure of parallel hydraulic hybrid loader is illustrated. The brake energy is regenerated by pump/motor and stored in the accumulator and a coupler works as a transmission which can match the speed of pump/motor in order to prevent over-speed. The energy of the engine is divided into two parts. One is transmitted to drive the working device and control the steering of the loader and the other is converted by the torque converter, the gearbox and the transaxle to drive loader.

![Figure 1. Structure of parallel hydraulic hybrid loader.](image)

3. Hybrid propulsion system design

3.1. Modelling subsystems
Most key components of hybrid loader can be found in AMESim and the object-oriented modelling means more convenient modelling process. The characteristic map of engine and primary characteristics of a torque converter should be taken to ensure the correctness of the model. Part of the key components is similar to the ordinary loader and parameters can be reference to the ordinary loader, and the other components need continuous matching to find the best configuration. And the transmission ratio of coupler has a limit, it should guarantee that the pump/motor will not get over-speed [11], as shown in equation (1), among it $n_{\text{max}}$ is the max speed of pump/motor, $v_{\text{max}}$ is the max velocity of loader, the transmission ratio $i_\alpha$ is from coupler to the wheel, the transmission ratio of coupler is $i_c$.

\[
i_c \leq \frac{2\pi n_{\text{max}}}{60v_{\text{max}} i_\alpha}\tag{1}\]

3.2. Control Strategy
Control strategy is the core issue of energy management allocation in hybrid power system [12-14]. In this paper, two control strategies are adopted and their fuel-saving effects are compared to each other.
One is the static logic threshold control strategy (SLTCS)—as shown in Figure 2—and the other is dynamic rule-based control strategy (DRCS)—as shown in Figure 3.

![Figure 2. Static logic threshold control strategy.](image1)

![Figure 3. Dynamic rule-based control strategy.](image2)

The SLTCS first determines whether the loader is in braking state or not. In braking state, the braking strength $z<z_{min}$ then the torque of hydraulic system $T_H$ will be provided by torque of engine $T_E$ and the torque of drive system $T_{re}$ will be provided by that of pump/motor $T_{P/M}$ otherwise the torque of drive system $T_{re}$ will be provided by the torque of pump/motor $T_{P/M}$ and the torque of mechanical brake system $T_{MC}$. When the loader is out of braking state, if the velocity $v<v_{min}$ and the accumulator charging state $SOC>SOC_{min}$, $T_H$ will be supplied by $T_E$ and $T_{re}$ will be supplied by $T_E$ and $T_{P/M}$; if the velocity $v_{min}<v<v_{max}$ and the $SOC>SOC_{min}$, $T_H$ will be supplied by $T_E$ and $T_{re}$ will be supplied by $T_{P/M}$; if the velocity $v_{max}<v$ or the $SOC<SOC_{min}$, $T_H$ and $T_{re}$ will all be supplied by $T_E$.

The DRCS first determines whether the loader is in braking state or not, and the braking state means acceleration of loader $a<0$. In the braking state, if the braking strength $z<z_{min}$ then the torque of hydraulic system $T_H$ will be provided by torque of engine $T_E$ and the torque of drive system $T_{re}$ will be provided by the torque of pump/motor $T_{P/M}$ and the torque of mechanical brake system $T_{MC}$. When the loader is out of braking state, if the velocity $v<v_{min}$ and the accumulator charging state $SOC>SOC_{min}$, $T_H$ will be supplied by $T_E$ and $T_{re}$ will be supplied by $T_E$ and $T_{P/M}$; if the velocity $v_{min}<v<v_{max}$ and the $SOC>SOC_{min}$, $T_H$ will be supplied by $T_E$ and $T_{re}$ will be supplied by $T_{P/M}$; if the velocity $v_{max}<v$ or the $SOC<SOC_{min}$, $T_H$ and $T_{re}$ will all be supplied by $T_E$.

**4. Simulation model**

As shown in Figure 4, the models were created by LMS Imagine.Lab AMESim and AMESET. The objective of the study was the preliminary sizing of the hybrid configurations for the loader. The hydraulic parallel hybrid loader is shown in Figure 1, and some parameters are shown in Table 1.

### Table 1. Parameters of hydraulic parallel hybrid loader.

| Specifications                        | Value | Specifications                        | Value |
|---------------------------------------|-------|---------------------------------------|-------|
| Displacement of pump/motor(ml r$^{-1}$)| 180   | Maximum speed in first gear (km h$^{-1}$) | 11.8  |
| Volume of accumulator(L)              | 30    | Maximum speed in second gear (km h$^{-1}$) | 15.6  |
| Ratio of coupler                       | 2.73  | Maximum reverse speed (km h$^{-1}$)     | 37.4  |
| Ratio of gearbox                       | 2.547/0.683/1.864 | Working pump (ml r$^{-1}$)               | 100   |
| Main drive ratio                       | 4.928 | Steering pump (ml r$^{-1}$)             | 83.6  |
| Wheel reducer ratio                   | 4.625 | Maximum speed in first gear (km h$^{-1}$) | 11.8  |
5. Results

5.1. Fuel Consumption

Parts of the simulation results shown in figure 5 demonstrate that the hybrid loader can reduce fuel consumption. After five typical working cycles, ordinary loader consumes 1.01kg diesel oil. And hybrid loader with DRCS can reduce fuel consumption by 13.5%, while the reduction rate of hybrid loader with SLTCS is 9.6%. The pump/motor works in the pump mode which can convert the kinetic energy of the loader into hydraulic energy and store it in the accumulator during the deboost phase (speed of loader drops and the loader is not at shovelling stage) of loader, then the hydraulic energy is applied to drive the loader when the loader is moving or shovelling and the pump/motor works in the motor mode at this time. The relationship between pressure of accumulator and speed of loader is shown in figure 6.

However, hybrid loader with DRCS can recover more energy which means more fuel consumption decline as shown in figure 7. The pressure of accumulator for hybrid loader with DRCS increases from 18 Mpa to 24.3 Mpa in first recycling and the pressure of hybrid loader with SLTCS raises from 18 Mpa to 23.5 Mpa. And high pressure means more hydraulic energy is stored when other factors are the same ones. The stored hydraulic energy can be calculated. In a typical working cycle, hybrid loader with DRCS can reclaim 231 KJ of energy, while that of hybrid loader with SLTCS is 212.5 KJ. Because hybrid loader with DRCS can reduce the use of mechanical brake which means more kinetic energy is converted into hydraulic energy and stored instead of being consumed as thermal energy. As
shown in figure 8, if the pressure of accumulator is increasing, the pump/motor will recover energy. At this time, lower mechanical brake strength means more energy will be recovered. This value in hybrid loader with DRCS is closed to 0 and is much lower than that of hybrid loader with STLCS which is around 0.01. The brake moment at the wheel is 2000 Nm when the mechanical brake strength is 0.01 and the brake moment generated by pump/motor ranges from 20000Nm to 28000Nm.

Figure 7. Pressure of accumulator.  
Figure 8. Mechanical brake strength.

5.2. Speed control
The general trend of the speed of hybrid loader is the same as that of ordinary loaders as shown in figure 9. But there is a problem that the hybrid loader has greater fluctuation than ordinary loader.

Figure 9. Speed of loader.  
Figure 10. Jerk of loader.

This phenomenon is mainly reflected in the acceleration stage, especially when loader is full-load. As shown in figure 10, the jerk (derivative of acceleration) of the loaders are displayed. The jerk of the ordinary loader is close to 0 and is much lower than hybrid loader at about 19.2s, while that of the hybrid loader is -110.55 m/s\(^3\). The reason for this abnormal jerk of hybrid loader is that the pump/motor stops driving the loader and the engine can’t provide enough power in time. As shown in figure 11, the pressure of accumulator dropped to its lowest level which means pump/motor will stop. This problem can be solved by changing the control strategy. For example, to ensure the energy stored in accumulator is sufficient to drive the vehicle to the stage of uniform speed by changing the hydraulic energy release conditions or add a buffer stage before the accumulator runs out of stored energy. However, this is not within the scope of this paper.

Figure 11. Reason for the abnormal jerk.
6. Conclusions
This paper discussed the process of modelling and sizing of a parallel hydraulic hybrid 5 tons loader in order to save energy. The simulation results indicate the purpose was practicable with a fuel consumption reduction for about 13.5% with DRCS, while that of hybrid loader with STLCS is 9.6%. On the other hand, the reason for the problem of abnormal jerk is illustrated and the solutions of the problem are briefly introduced. The optimization of system parameters and control strategies are absence and require further refinements and the development of the activity. However, the purpose of this paper is to provide a basic parameter matching and control strategy simulation which can show how the hybrid loader is working and avoid unreasonable component parameters and control strategies before formal design testing by the performance of the hybrid loader in the simulation results.

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