Review

Development of hybrid powered hydraulic construction machinery

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Abstract

Facing the environment problems, the improvement on the efficiency of the construction machinery such as the excavator and wheel loader is highly demanded. The hybrid power systems used in automobiles have been adapted into the construction machinery. This paper first analyzes the difference between the hybrid powered automobile vehicle and the hybrid powered construction machinery. The research and development of the hybrid power systems and energy regeneration systems of construction machinery are reviewed, and the applications of hybrid systems in construction machinery are presented. Finally, the challenges facing the researchers and the construction machinery manufacturers are discussed.

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Keywords:
Hybrid system
Excavator
Wheel loader
Energy regeneration
Energy saving
Construction machinery

Contents

1. Introduction ............................................................... 1
2. Difference between the hybrid driving of automobiles and hybrid power of construction machineries ............................................................... 12
  2.1. Working style ........................................................... 12
  2.2. Key components ......................................................... 12
  2.3. Actuators ............................................................. 12
  2.4. Reliability ............................................................. 13
3. Research on hybrid power system .................................................... 13
  3.1. Structures of hybrid hydraulic excavator .............................................. 13
  3.2. Control strategy .......................................................... 13
4. Research on energy regeneration system ................................................. 13
  4.1. Hydraulic accumulator energy recovery system ........................................... 14
  4.2. Electric accumulator energy recovery system ............................................ 14
5. Prototype hybrid hydraulic construction machinery ............................................ 14
  5.1. Komatsu ............................................................. 14
  5.2. Hitachi .............................................................. 15
  5.3. Kobe Steel, and NEDO ....................................................... 16
  5.4. New Holland ........................................................... 16
  5.5. Volvo ............................................................... 16
6. Challenges ............................................................... 18
  6.1. Acceptable cost .......................................................... 18
  6.2. The control property of the system ................................................ 18
  6.3. The new energy recovery system ................................................. 18
7. Conclusion ............................................................... 18
Acknowledgements .............................................................. 18
References .................................................................. 18

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1. Introduction

In order to prevent global warming, conserve natural resources and adjust to the even more stringent emission regulations that will become effective in 2011, manufacturers of earthmoving equipment are more than ever aware of the importance of producing environmentally friendly machines with significant improvement of fuel economy. Though traditional methods have played an important role in energy saving of hydraulic construction machinery, they are still working with low fuel efficiency and bad exhaust. New technologies are needed to further reduce fuel consumption and pollutant emissions. Since advanced hybrid propulsion technology is the key to achieve fuel economy construction machinery makers have put much effort in the research on applying hybrid propulsion techniques.

This paper is organized as follows: Section 2 discusses the difference between hybrid automobile and hybrid construction machinery. And we provided historical overview of technology in Sections 3–5. Section 6 contributes to the challenges facing the hybrid power of construction machinery.

2. Difference between the hybrid driving of automobiles and hybrid power of construction machineries

2.1. Working style

Applying the hybrid power concept, the system has to be considered to fit its special working style [1]. Fig. 1 illustrates the output of the power system of a 20-ton class hydraulic excavator that works in a typical working period of 20 s. It can be seen from Fig. 1 that the output power changes quickly and periodically [2]. Compared with automobiles, the load change rate and amplitude are much larger. Its total load power can be changed twice or thrice between 0 kW and 60 kW. Also the regenerated energy of the boom is illustrated in Fig. 2. It indicates that the regenerated energy is rather large and changes quickly.

2.2. Key components

A hybrid powered car requires a large amount of electric energy when it starts moving and accelerating, then it can run with relatively stable engine revolution. By comparison, construction equipments have to accommodate dynamic and frequent fluctuations of the engine revolution. As the electric accumulator charging/ discharged is a matter of second rather than minutes in a hybrid excavator, it should work with faster charge–discharge speed, much more charge–discharge cycles and lower specific energy, Hence, it is suitable to choose capacitor as the accumulator of the power system.

The drive system of the hybrid hydraulic construction machinery requires an electric motor to be installed together with the engine in a very limited space, the demand for the electric motor is small size, lightweight, but providing high output efficiency. In hybrid powered cars, the rotational speed of electric motor can reach more than 5000 rpm, but for the hybrid excavator, the rotational speed of the electric motor is about 2000 rpm without reduction gear box at the same rating power, hence, the specific power of the electric motor in a hybrid excavator is hard to reach to more than 1 kW/kg, which is easily exceeded in a hybrid powered car. Also as the electric motor used in hybrid excavator is compensating for the excess or the deficiency of the engine power, the max output torque of electric motor cannot diminish at high speed area which is shown in Fig. 3, or else, it cannot show the hybrid system’s greatest advantage at its working area.

2.3. Actuators

In an automobile, only a motor drives the tires, and a large part of its engine power is prepared for its acceleration. A hybrid powered car can regenerate driving energy in braking process, and reuse it for acceleration, so the engine size can be easily cut down, and the fuel consumption reduced. But for a hydraulic excavator, there are 6 actuators. According to its working content, sometimes the machine will share the total engine power with several actuators simultaneously, and sometimes it needs to concentrate the full power onto one actuator. The analysis of which actuator consumes more power, which actuator has more potential power to regenerate and how to downsize the engine power is a quite difficult problem in hybridization of these machines [3].
2.4. Reliability

Construction machinery has to be applicable to all kind of environmental condition. So its components need to have the same, even higher performances than automobiles. For example, automobiles need only to resist vibration about 5–7 g, but the construction machinery need to resist more than 10 g.

3. Research on hybrid power system

3.1. Structures of hybrid hydraulic excavator

Zhang et al. [4] presented a simulation study concerning hybrid construction machinery. They compared different hybrid systems (series, parallel and series-parallel systems) and other possible energy saving methods based on a 20-ton excavator. Results show the best energy saving possibilities on a system that combines the hybrid system, motor regeneration system, separate driving system and meter-out control. The system can save energy up to 58%. Anyway the realization of motor regeneration is considered difficult at present, hence the future prospects are in combination of the parallel hybrid system, the separate driving, the meter-out controlling and an electrical motor driving the rotary actuator.

In a study by Wang et al. [5], a small 5-ton excavator was the subject of a computer-based investigation aimed to find the optimum power train hybridization. This research analyzed the performance of the power train hybridization of a hydraulic excavator and compared the performances among the parallel, the series and the conventional configurations. It was concluded from Table 1 that the parallel hydraulic power train one has better fuel economy than the other two configurations in the heavy and light modes, whereas both the series and parallel hybrid power trains show better fuel economy in the medium mode. Considering the performance and cost synthetically, the parallel power train is the best configuration for hybrid excavators at present.

Yoshiyuki et al. [6] studies at the Japan Waseda University were focused on a series type hybrid system to improve fuel economy, exhaust emissions and noise. Pump/motor systems were used to independently actuate the boom, arm and bucket and to regenerate their moving energy during deceleration or descending. The test results showed that the system can reduce fuel consumption by 35% compared to the conventional system. Numerical simulations can predict energy efficiency, the control of the arm and boom fluctuations and the decrease in battery capacity.

Etsujiro et al. [7] developed a simulation model of a hybrid excavator for the estimation of fuel consumption and the optimum design of the hybrid system's dynamics in practical operation of the hybrid excavator. The hybrid excavator consists of a hybrid power train system with power electronics devices such as converter, an actuator system driven by electro-hydraulic system, and linkage system of a front attachment with the boom, the arm, and bucket, which is explained in Section 5.3 and Fig. 7. In this paper, the total system equations are established by considering the coupling of the power electronic system, the hydraulic system, and linkage system. The boom system was picked up for the operability design for the residual vibration, and the energy saving effect was estimated for the boom system.

Takao et al. [8, 9] developed a simulation model of a hybrid excavator for the estimation of the fuel consumption in the practical operations of the hybrid excavator. The whole hybrid excavator consists of a series hybrid power system, a boom driven by a closed system comprising an electric motor and a hydraulic pump-motor, and the other actuators systems driven by electric motors and pumps. It is shown that the energy saving effect of the proposed hybrid excavator can be over 40%.

Kwon et al. [10] presented several structures of hybrid excavators with the super capacitor and compared them with each other in terms of the fuel economy, additional cost due to the hybridization, and the expected payback time. According to the comparison, the compound hybrid structure is a better solution than the parallel type and the series type because of its short expected payback time and higher reliability. Also they proposed a power control algorithm for the engine and the super capacitor. The simulation results show that by hybridization, the fuel consumption can be reduced by about 24% compared to the conventional hydraulic excavator.

3.2. Control strategy

Qing Xiao et al. [11] investigated the dynamic-work-point control strategy of a hybrid system used in hydraulic excavators. First, the research considered two different control strategies: an engine constant-work-point strategy and a double-work-point, each with their associated advantages and disadvantages. Then a dynamic-work-point control strategy, which regulates the engine's working point dynamically, was developed to make the system work better. Experimental results showed that the dynamic-work-point control strategy can improve the distribution of engine's working points, restrain the capacitor's SOC and has little influence on the performance of the system.

The control strategy applied by Lin Xiao et al. in simulation of the parallel hydraulic hybrid excavator uses a so-called multi-work-point dynamic control strategy [12]. The control strategy has both closed-loop speed PI (proportion integral) control and direct torque control. Although simulation results indicated that the hybrid system with this strategy can meet the power demand and achieve better system stability and higher fuel efficiency, this would not be applicable to an actual hybrid excavator.

Masa i yu et al. focused on a hybrid system on hydraulic excavators for energy saving in construction machinery [13, 14]. Based on a serial hybrid excavator, the control system consists of DC voltage control, power distribution control, engine control, capacitor voltage control and battery voltage control. A Bench test equipment of the power train system was set up, and the evaluation of the energy saving performance was carried out.

4. Research on energy regeneration system

Due to large mass associated with the boom of construction machinery, when the actuators of a construction machine go down, the heavy arm of hydraulic excavators requires large energy to balance the gravity force. There is a possibility to utilize the gravitational potential energy, for example, using energy storage components to store the potential energy when the boom goes down and releasing the energy when the boom goes up again.

A lot of researches have been reported during the last two decades in the field of energy regeneration systems of vehicles. USA, Europe, and Japan have spent a huge amount of capital on related projects and many valuable results are now available, some of the results can be used to provide solutions for construction machinery. In the field of hydraulic excavators, there are normally two kinds of energy recovery

<table>
<thead>
<tr>
<th>Table 1</th>
<th>The comparison of fuel cost involving three configurations and load level.</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>Load level</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>The conventional</td>
<td>100%</td>
</tr>
<tr>
<td>The parallel</td>
<td>70.5%</td>
</tr>
<tr>
<td>The series</td>
<td>71.7%</td>
</tr>
</tbody>
</table>
systems: the battery/capacitor energy recovery system, and the hydraulic accumulator energy recovery system.

4.1. Hydraulic accumulator energy recovery system

The hydraulic accumulator energy recovery system stores a volume of hydraulic oil under high pressures so that it is immediately available as a source of energy. The key advantage of using hydraulic accumulators in hydraulic construction machinery is the seamless interface, they can be easily integrated into a hydraulic circuit by hydraulic pumps/motors.

Liang and Virvalo [15,16] studied the energy recovery system with a balance cylinder connected to the hydraulic accumulator that can save and restore the hydraulic energy in cranes hydraulic system. The balance cylinder is a separate cylinder that moves with the actual working cylinder; when the crane comes down with load the accumulator is charged, the potential energy of the crane and load is saved in the form of hydraulic energy; when the crane arm goes up the saved energy can be reutilized. A similar system was studied by Nyman and Rydberg [17].

One way to improve system’s efficiency is to utilize the degree of freedoms of the boom [18]. The idea is to store the potential energy in downward movement of the lift cylinder in a hydraulic accumulator, or use it simultaneously to drive other actuators. Here the objective is that the telescope cylinder could be controlled with the saved energy. If energy in the accumulator is not adequate to drive the telescope cylinder, the principle must be changed to ensure that it is possible to take necessary energy from the supply unit. When the lift cylinder is moving downward the fluid can be driven into a tank, or an accumulator or the telescope cylinder. If the telescope cylinder need to be driven, the flow is controlled to fill it and the extra fluid goes into the accumulator; if the pressure in the lift cylinder is not adequate for the accumulator, the fluid is directed to the tank.

Sun and Virvalo [19] studied an energy saving system of the boom hydraulic system. The main parts of the system consist of one hydraulic accumulator and two hydraulic pump/motors. When the boom is moving down, the other pump/motor acts to charge the accumulator, the energy saved in the accumulator can be utilized later in moving up the boom. If the pressure in the accumulator is not enough for lifting the load, additional pressure is taken from the supply unit, meanwhile the accumulator still supplies part of the pressure, thus the power consumption of the supply unit is much smaller than that without the accumulator-pump-motor system (APM-system). The APM-system can be used to drive not only the lift cylinder but also other cylinders of the boom. They described the system’s working principle, and the control strategy, gave the simulations on energy saving, showing that the APM-system can raise the efficiency of the boom hydraulic system up to 34%.

A similar system was presented in [20] where it was called the hydraulic accumulator balancing (HAB) system. Sun and Virvalo also simulated variations in the connections and analyzed the energy utilization in the concerned system.

Although energy recovery applications are widely used in industry and many developments geared to energy saving have been achieved on the mobile machines, only a few energy recovery systems have been developed for the hydraulic excavator. Bruun [21] presented an application called “Eco Mate” based on a hydraulic accumulator ER system and installed it onto a 50 ton hydraulic excavator. The “Eco Mate” system is said to be one of the most successful inventions to recover energy on the hydraulic boom-control system in recent years [22,23].

4.2. Electric accumulator energy recovery system

Battery is the only commercially available method of storing electrical energy suitable for mobile machines. Familiar applications include the vehicle starting, industrial lift trucks and the backup or uninterruptible power supplies. The main problem in electrical battery systems is that they cannot be charged with large power which is always required in the off-highway vehicles and the hybrid powered construction machines, especially the hydraulic excavators.

Nyman et al. [24] described a way to enable the energy recuperation in electrically powered warehouse truck. They combined the use of a hydraulic pump as a motor with a counter balance technique. When lowering the load the hydraulic pump drives the electric motor, which acts as a generator and charges the electric batteries. The counter balance technique is implemented with the hydraulic support cylinder and the accumulator. The counter balance system is such dimensioned that it can compensate the weight of the lifting mast. Simulation results show that combining the counter balance and battery recharging techniques can save 40–60% of the lifting energy.

Andersen et al. [25] studied a similar system. They concentrated on energy recovery in the main lift system with electric motor and batteries. The idea is the same as that of Nyman et al. When lowering the load the batteries are charged and the saved energy can be afterwards used in either driving the truck or lifting. Andersen et al. compared different systems and control strategies. The best scheme considered was built up and the energy calculations were made, the results show improved energy efficiency but with shorter life time of the components because of the system’s oscillatory response.

For hydraulic excavators, Zhang et al. [26] put forward a simulation study on the energy saving scheme with hydraulic motor regeneration for hydraulic actuators. The proportion of the regenerated energy for each actuator and the energy saving effects were calculated. The simulation shows that the boom and bucket energy recovery is much more important than the other actuators. Lin et al. [27] also conducted a computer-based research focused on the performance of the energy recovery system. The hydraulic motor–generator regeneration equipment can also have high control performance by restricting the pipe length, the time constant of the induction motor and the displacement controller and the torque signal delay.

5. Prototype hybrid hydraulic construction machinery

Over the last five years there have been several projects undertaken by various research institutions and major manufactures worldwide in developing hydraulic hybrid construction machinery. The majority of projects were aimed at hybrid excavator and hybrid wheel loader. The major hybrid construction machinery have the specifications outlined in Table 2.

5.1. Komatsu

In May 2007, Komatsu launched the world's first hybrid electric forklift trucks on the market, and the world's first hybrid excavator was also manufactured by Komatsu in May, 2008 [28–30]. Fuel savings were recorded at around 25% to 41% in comparison to the standard PC200-8 hydraulic excavator.

<table>
<thead>
<tr>
<th>Manufacture</th>
<th>Structure</th>
<th>Energy accumulator</th>
<th>Energy saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Komatsu</td>
<td>20-ton parallel hybrid excavator</td>
<td>Super capacitor</td>
<td>25%–41%</td>
</tr>
<tr>
<td>Hitachi</td>
<td>20-ton parallel hybrid excavator</td>
<td>Super capacitor</td>
<td>25%</td>
</tr>
<tr>
<td>Kobelco and NEDO</td>
<td>6-ton serial hybrid excavator</td>
<td>Battery</td>
<td>25%–30%</td>
</tr>
<tr>
<td>New Holland</td>
<td>7-ton parallel hybrid excavator</td>
<td>Super capacitor and battery</td>
<td>More than 40%</td>
</tr>
<tr>
<td>Volvo</td>
<td>Parallel hybrid wheel loader</td>
<td>Battery</td>
<td>40%</td>
</tr>
</tbody>
</table>

Table 2: The outline of the prototype hybrid hydraulic construction machinery.
Fig. 4 shows that the PC200-8 hybrid is powered by a parallel hybrid system. While the standard equipment normally uses a hydraulic motor to turn the upper structure, Komatsu has developed an electric motor to turn the upper structure. The electric motor collects energy generated when the upper structure of the excavator slows down with turning. The energy collected is converted into electric energy to be stored in the capacitor. The stored electricity is utilized via an electric motor to assist the engine when it is accelerating. As a result, the engine can be used in a low-rotation zone with high-efficiency combustion. In addition, the rotation can be maintained at 700 rpm when the engine runs idle.

5.2. Hitachi

Looking at the development of hybrid technology in Hitachi, they launched the world’s first hybrid wheel loader in 2003 [31] and its 20-ton hybrid excavator in May, 2008 [32,33]. Fig. 5 shows the system outline of the hybrid hydraulic excavator developed in Hitachi Construction Machinery [34]. The ZAXIS 200 hybrid hydraulic excavator is powered by a parallel hybrid system, and the new hybrid model uses an electric motor to drive the swing. When the swing is braking and the boom is going down, the energy could be converted into electric energy to be stored in the capacitor [3], and a fuel saving of 25% was recorded. In this machine, the engine rating power was not downsized to keep the total operation performance at the same level as the standard machine.

Fig. 6 shows the system outline of the hybrid wheel loader. Engine drives the hydraulic pump and electric generator in parallel and the pump drives the hydraulic system of the working front that consist of the boom, the arm and so on, and the generator drives electric motor and then the wheel movement. The working front driving employs the conventional hydraulic system, the wheel driving employs a serial hybrid system. Since the ratio of traveling in total working process of the wheel loader is quite large, it has preferred effect on the power saving. In practice, the hybrid system regenerates the braking energy into electric power and saves it in battery as the wheel loader is decelerating and use the power to assist the engine as it is in acceleration. Compared with the conventional wheel loader, the fuel consumption can be cut down by 30–40%.

![Fig. 4. System outline of PC200-8 hybrid excavator.](image)

![Fig. 5. System outline of ZX200 hybrid excavator.](image)
5.3. Kobe Steel, and NEDO

The Kobelco Construction Machinery, in collaboration with the New Energy and Industrial Technology Development Organization and Kobe Steel, has developed a 6-ton class prototype series hybrid excavator in July, 2008. The experimental results proved that it can reduce fuel consumption by more than 40%[35].

The system configuration of the developed hybrid excavator is shown in Fig. 7. The actuator system comprises six independent actuators driven by electric motors and pumps. The independent configuration minimizes the hydraulic interferences among actuators and the losses occurring in conventional hydraulic systems. The boom is driven by a closed system comprising an electric motor and a hydraulic pump that can rotate in both the directions, so that the potential energy accumulated at “up” positions is regenerated into electric energy via the hydraulic pump when the boom goes down.

The power source is a series type hybrid source with a downsize engine from 39 kW to 22 kW. The slewing motions are driven by an electric motor, instead of a hydraulic actuator, and the kinetic energy of the upper body is regenerated into electric energy when the swing stops. The use of the battery and capacitor compensates for the excess and deficiency of the engine power even in the large workload variation, smooths the engine load, allows the use of a smaller-than-conventional engine and improves fuel efficiency. In addition, the system converts the engine power into electrical energy once, and the engine can be stopped even during excavation operations, if there is spared energy in the battery and capacitor. This intermittent engine operation further improves the fuel economy.

5.4. New Holland

While still in its prototype stage, New Holland Construction previewed its hybrid 7-ton parallel hydraulic excavator at the 2006 Internet show. According to New Holland, both fuel consumption and CO2 emission are reduced by 40% versus a 7-ton conventional excavator.

Fig. 8 shows the driveline layout for the parallel hybrid excavator.

Unlike the 705R excavator that is powered by a diesel engine rated 40.5 kW, the parallel hybrid system uses a diesel engine rated 27.5 kW and a 20 kW battery-powered motor. New Holland uses a 288 V lithium battery to store energy produced by the engine and generator. The hybrid excavator is able to produce as much power as a conventional 7-ton excavator without sacrificing any digging performance. The hybrid excavator achieves regenerative charging through an electric swing motor, which produce additional electrical power through the regenerative braking.

The independent electric swing motor allows the energy produced through the swing circuit to be captured and stored in the battery for later use. This energy can also be used to drive the hydraulic pumps, which power the travel motors in the drive circuit, or to supply the excavator’s boom, arm and bucket cylinders.

5.5. Volvo

Volvo Construction Equipment officially unveiled its L220F hybrid wheel loader in the ConExpo-CON/AGG exhibition, US on March, 2008, offering fuel reductions of 10%. Up to 40% of a wheel loader’s time can be spent with the engine idling, this is a major benefit.

The Volvo L220F is powered by a parallel hybrid system. The heart of the hybrid system is an integrated starter generator. The electric motor rapidly starts the diesel engine. If needed, the electric motor gives the diesel engine a boost, enabling a faster take-off at lower revs. The diesel engine can be shut off when waiting for the next load carrier, during short breaks, etc. The batteries are charged by the electric motor/generator during normal operation without suppressing productivity. The integrated starter generator can also overcome...
Fig. 8. System outline of prototype hybrid excavator of New Holland.

Fig. 9. Schematic of the proposed energy regeneration system.
a diesel engine's traditional problem of low torque at low engine speeds by automatically offering a massive electric torque.

6. Challenges

6.1. Acceptable cost

Components used in a hybrid system can add significant amounts of cost to the excavator. This is much worse in the case of small size excavator than for large excavator. It is foreseen that a hybrid excavator will have an additional maintenance cost associated with it due to the complexity it adds to the power train. Certainly at the beginning, the price of hybrid excavators will be about 20% to 50% more expensive than a standard excavator. So the cost needs to come down to about the same level or just a little bit higher than the same class convention construction machinery.

6.2. The control property of the system

Adopting hybrid system has been a new way for hydraulic construction machinery to achieve energy saving. Hybrid system adds significantly to the power train complexity, through increased avenues for power flow, and the addition for complex computer control systems for energy management. Also, some hybrid systems have experienced excess noise and vibration. Hence, the problem in this development is how to keep the performance of the system to be close to the present hydraulic construction machinery.

6.3. The new energy recovery system

The major disadvantage of a hydraulic accumulator is that the energy storage density in hydraulic systems is severely limited relative to other competing technologies. Hydraulic energy storage is not attractive for storage of large amounts of energy. As an example, to capture the 282 116 J of the boom’s gravitational energy of a 20-ton hybrid hydraulic excavator would require currently about 501 volume. However, hydraulic accumulator systems have an order of magnitude advantage in terms of the power density over electric systems. Hence, hydraulic accumulator energy recovery systems are ideal for those confronted with frequent, short start–stop cycles in enough spaces.

For developing hybrid excavators, the key problem is to find storage space for the energy storage component. It can be seen from Fig. 2 that the time for the regenerative power of the hydraulic excavator is only 2–3 s. Therefore, both of the battery and hydraulic accumulator are not suitable to be used as the energy accumulator in the energy recovery system of the hydraulic excavator.

Advanced components such as the high specific power battery, low cost capacitor and high specific energy hydraulic accumulator, and so on, are available, but there is still much work to be done as being in the early stages of development of hybrid power systems. Here we propose a new energy recovery system that combines the advantages of the electric accumulator and hydraulic accumulator, which is illustrated in Fig. 9. When the boom goes down, the gravitational potential energy can be converted into both the electric energy and the hydraulic energy. The scale between the electric energy and the hydraulic energy depends on the recovery time. As the hydraulic accumulator can quickly store the energy, we can use a battery instead of a capacitor even if the recovery time is short. So it looks promising to be an ideal integral part of the future of earthmoving construction equipment.

7. Conclusion

This paper discussed the difference between the hybrid cars and the hybrid construction machineries. The developing hybrid prototype excavators or wheel loaders demonstrated the potential benefit of this technology. The present hybrid earthmoving equipment is not readily accepted until the cost comes down to the level of the conventional construction machinery with no sacrifice in performance. It can be anticipated that the earthmoving equipment manufacturers will continue concentrating their efforts on developing cheaper, more efficient hybrid power systems.

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