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Study on the Effect of Hydraulic Energy Storage on the Performance of Electro-Mechanical-Hydraulic Power-Coupled Electric Vehicles

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Abstract: In order to address the problems of low energy storage capacity and short battery life in electric vehicles, in this paper, a new electromechanical-hydraulic power coupling drive system is proposed, and an electromechanical-hydraulic power coupling electric vehicle is proposed based on this system. The system realizes the mutual conversion between mechanical energy, hydraulic energy, and electric energy through the electromechanical–hydraulic coupler. This paper describes the structural characteristics and working principles of the system and analyzes the different working modes during the driving of the vehicle. We established a mathematical model of the hydraulic accumulator and the hydraulic pump and motor. Based on the vehicle dynamics model, an AME Sim vehicle model was built and the vehicle, and the relevant hydraulic parameters were set in combination with the actual situation. The braking energy recovery and release process was jointly simulated by AME Sim and Simulink. The simulation results show that the hydraulic accumulator size of the accumulator volume can influence the maximum working pressure of the accumulator and the SOC of the vehicle battery, and it is verified that 35 L is the best capacity. This study has an important reference value for matching electromechanical–hydraulic coupling parameters of electric vehicles.

Keywords: electromechanical-hydraulic dynamic coupling system; hydraulic accumulator; joint simulation

1. Background and Significance

1.1. Introduction

In response to the energy crisis and environmental degradation, as well as people’s pursuit of driving experience and transportation efficiency, the use of electric vehicles is becoming increasingly common [1]. Electric vehicles are becoming the core focus of future development and competition in the world automotive industry [2]. Constrained by battery technology and other issues [3], pure electric vehicles have low driving efficiency in urban conditions, short range, and short battery life due to severe load shock [4]. If the number of batteries is increased in order to increase the range of pure electric vehicles, this will not only increase the equipment mass of the vehicle but also further compress the available space inside the vehicle, which does not meet the practical application requirements [5]. A hydraulic power storage system is used for vehicle start-up acceleration or regenerative braking because of advantages such as high-power density and fast energy conversion [6]. This is undoubtedly a good choice, but an increase in hydraulic energy storage, hydraulic power conversion, and other devices will again make the powertrain structure lose.
Therefore, Qingdao University proposed the structure principle of an electromechanical-hydraulic coupler and applied it to electric vehicles to form a new electromechanical-hydraulic power-coupled electric vehicle (EMHCEV). Such a structure has hydraulic power involved and only one energy conversion device in the power transmission, i.e., an electromechanical-hydraulic power coupling device. The electromechanical-hydraulic power coupling device synthesizes the traditional electric motor and hydraulic pump/motor into one and performs the synergistic coupling of mechanical, electrical, and hydraulic power in order to realize the interconversion of electrical, mechanical, and hydraulic energy. Hong et al. introduced the electro-hydraulic power coupling drive system and suggested the method of distributing the electro-hydraulic ratio under different working conditions. The research results show that the system can reduce the phenomenon of motor torque shock when the electro-hydraulic ratio is at a suitable ratio [7]. Based on theoretical analysis of the electro-hydraulic power-coupled drive system, Yang et al. established an optimal energy management strategy, submitted a fuzzy controller, and optimized the control strategy in order to improve the overall vehicle performance further [8]. Yang, Meng, et al. conducted parameter matching design for the transmission system in the electromechanical hydraulic coupling electric vehicle. Simulations show that the electro-hydraulic hybrid vehicle effectively improves the vehicle economy while ensuring vehicle dynamics [9]. Sun Yue et al. introduced the application of electromechanical-hydraulic power coupling in pure electric vehicles, using AME Sim software to build a simulation model of the whole vehicle and MATLAB/Simulink software to build a model of the control strategy using a joint simulation method to verify the dynamic performance of the electromechanical–hydraulic power coupling. The reasonableness and validity of the model was verified by analysis [10].

The hydraulic system necessary for electromechanical-hydraulic power coupling electric vehicles is an important piece of mechanical equipment and control systems. With a large power-to-weight ratio, fast response, and good stability, hydraulic systems are widely used in aerospace, manufacturing, and daily life. Currently, hydraulic simulation technology is also becoming increasingly mature and is a powerful tool for hydraulic system designers. Among them, the DSH software of RWTH Aachen University in Germany and Bath/FP of Bath University in the UK was launched the earliest and has the greatest influence in the industry. With the developments in the past few years, dozens of hydraulic simulation software and general system simulation software have come into being. Dong Han et al. used AME Sim to build a vehicle model and simulate it and then conducted experiments on the experimental bench for the corresponding typical operating conditions. The correctness of the AME Sim model and the energy-saving characteristics of the hydraulic hybrid system were verified by simulation curves and experimental results. Jin Ying Ji established a simulated experimental environment of YT4543 combined machine tool power slide by Fluid SIM software and realized the simulation of the actual working process of the machine tool power slide feeding system [11]. Li Rong Wan et al. Wang et al. used EASY5 graphical modeling method to establish the model of the hydraulic circuit of the excavator arm. Through the simulation and analysis of the results, it can be seen that the simulation results can accurately simulate the dynamic characteristics of actual hydraulic circuit, and show the variation of the pressure in the hydraulic cylinder chambers [12]. Fang Jian et al. used DSH plus to build a hydraulic system model of a hydraulic breaker, and the results obtained through simulation were within 10% error of the parameters obtained from the real vehicle test, which proved that the simulation model built by DSH plus was correct [13]. Lei Xiao used HyPneu to build a hydraulic system schematic diagram of the boom in order to simulate and analyze the hydraulic system, verifying the realizability of the hydraulic simulation software HyPneu and the rationality of the test bench design [14]. In this paper, the simulation technology of AME Sim and Simulink is used to build a model of the whole vehicle, which can better set the internal parameters of the vehicle to be closer to the various driving conditions of the whole vehicle.

Energy storage is used to assist electric vehicles and can improve the short battery life of pure electric vehicles. The energy recovery efficiency of electric vehicles with the
addition of energy storage is improved and the driving range of the vehicle is significantly increased. In recent years, many people have also chosen different energy storage systems to assist electric vehicles. Song et al. proposed a flywheel energy storage system and verified that it has better acceleration characteristics [15]. Kouchachvili et al. combined batteries with supercapacitors and found that supercapacitors can provide excess energy for electric vehicles with higher multiplier capacity and better cycling capability [5]. However, in comparison, hydraulic accumulators have the advantages of high energy density and low cost, which are more suitable for energy storage systems [16,17]. In addition, hydraulic accumulators have the following advantages.

A sudden change in direction, a sudden stop of the actuating element, etc., will produce a shock pressure in the hydraulic system so that the system pressure increases instantly. At this time, the accumulator can be a good buffer and absorb this part of the energy to ensure the stability of the entire system pressure. When the vehicle starts to accelerate, climbs hills, or other needs for high power work, the accumulator can be stored energy into hydraulic energy release, and re-supply the hydraulic system auxiliary motor to drive work. Due to the complexity of the hydraulic system itself, researchers have to choose an accumulator with a simpler and lighter structure, responsive and functional to meet the required working pressure and flow rate, etc. Therefore, we have to choose the right accumulator, carry out the optimal capacity matching [18], and study the problems of the hydraulic system on the vehicle performance, etc.

1.2. Contribution of This Paper

The following work was conducted in this paper:
1. Analysis of the structure and operating principle of the EMHCEV;
2. Establishing the mathematical modeling of the hydraulic accumulator;
3. Completion of the simulation of the whole vehicle and the hydraulic accumulator based on AME Sim;
4. Analysis of the hydraulic energy accumulator dynamic whole-vehicle performance and hydraulic power participation behavior.

2. Structure and Working Principle of an Electro-Hydraulic Coupling Electric Vehicle
2.1. The Structure of Electro-Hydraulic Coupling Electric Vehicle

The principle of an electromechanical-hydraulic power coupling electric vehicle power transmission system is shown in Figure 1, primarily composed of a power battery pack, power converter, high and low voltage accumulator, electromechanical-hydraulic coupling, main reducer/differential, controller, etc. [19]. The controller receives acceleration signals, braking signals, and signals from pressure sensors. The control motor regulates the displacement of the hydraulic pump/motor and the opening and closing of the high-pressure and low-pressure solenoid valves. There are different fits between the hydraulic accumulator, motor, and battery in different operating modes, as described in Section 2.2. The electromechanical-hydraulic coupler can realize any mutual transformation between mechanical, hydraulic, and electric power, and is the core component of the whole power transmission system. The system, through the synergy and coupling of mechanical, electrical, and hydraulic power, can drive the vehicle to travel and at the same time meet the hydraulic energy demand of the hydraulic working device. It can also efficiently recover and utilize the braking energy and the inertial energy of the hydraulic working device, which improves the power, economy, and reliability of the vehicle-carrying electricity.

The power battery is the only power source of the entire vehicle, and the hydraulic energy of the high-pressure accumulator comes from brake regeneration or is converted by electric energy. At low speed and heavy load, the hydraulic power is utilized independently or assisted by electric power to drive the vehicle to travel, and at high speed, the electric power is mainly used. When braking, the electric power is used when the speed is high and the inertial energy is recovered to the power battery in the form of electric energy; when the speed is low, hydraulic power is used, and the inertial energy is recovered to
the high-pressure accumulator in the form of hydraulic energy; if the braking intensity is large, the electric power and hydraulic power are used to brake at the same time, and the inertial energy is converted into electric energy and hydraulic energy to be stored separately [20]. The switching of the whole process is also affected by the pressure of the hydraulic accumulator and the SOC of the power cell.

![Figure 1. Schematic diagram of electromechanical-hydraulic power coupling transmission system.](image)

The powertrain in the electromechanical-hydraulic coupling is a complete, independent energy and power conversion unit, and the corresponding vehicle is no longer a hybrid vehicle in the traditional sense. Hybrid vehicles are vehicles whose drive systems are composed of two or more individual drive systems that can operate simultaneously, and the vehicle’s driving power is provided by the individual drive systems individually or jointly according to the actual vehicle driving state. The driving power of the vehicle is provided by a single drive system alone or together according to the actual vehicle driving status; there are more than two energy/power conversion devices. Second, mechanical energy, hydraulic energy, and electric energy are coupled and transformed in the electromechanical-hydraulic coupler, and the braking energy can be recovered and stored in the form of hydraulic energy and electric energy to the hydraulic accumulator and battery for reuse [21]. Third, hydraulic power is only auxiliary power, and electric power is the main power. Therefore, a vehicle utilizing this transmission system is called an electromechanical-hydraulic power coupled electric vehicle.

### 2.2. The Working Principle of Electro-Hydraulic Coupling Electric Vehicle

The electromechanical-hydraulic coupled electric vehicle has different requirements for the power and minimum working pressure of hydraulic accumulators under different working conditions, etc. Therefore, we can divide the working modes into parking accumulation mode, starting acceleration hydraulic drive mode, pure electric drive mode, hybrid drive mode, and regenerative braking mode, as shown in Figure 2.

1. **Parking energy storage**: hydraulic power drives the vehicle to start. When the pressure in the hydraulic accumulator is higher than the minimum working pressure of the hydraulic accumulator, then the high-pressure oil in the high-pressure accumulator flows to the low-pressure accumulator through the hydraulic pump/motor, converting the hydraulic energy stored in the hydraulic accumulator into mechanical energy.

2. **Vehicle acceleration**: electric power and hydraulic power coupling output energy together to drive the vehicle. The mechanical energy generated when the vehicle is going downhill or braking is first converted into hydraulic energy by the electromechanical-hydraulic coupler and then recovered and stored in the high-pressure accumulator.
When the energy is rich, then the electric motor will convert it into electric energy and recover and store it in the battery pack, thereby improving the efficiency of energy recovery.

3. When the vehicle is running at a constant speed: The vehicle is judged according to the actual situation of the working pressure in the hydraulic accumulator. When using hydraulic energy to start the vehicle, the high-pressure fluid in the high-pressure accumulator pushes the hydraulic pump/motor to rotate, converting the hydraulic energy stored in the hydraulic accumulator into mechanical energy and driving the vehicle to start. When uniform speed is reached, the battery pack starts to provide electric energy to the electric motor, and the vehicle is driven by electric power to drive.

4. When the vehicle climbs/accelerates: After the vehicle starts, the electric power drives the vehicle into acceleration mode. At this time, the electric energy is converted into mechanical energy through the electric motor, which works simultaneously with the hydraulic power. The two are superimposed in the electromechanical-hydraulic coupling for torque to drive the vehicle at a higher speed.

5. When decelerating and braking: The vehicle’s electric motor is used as a generator and the vehicle coasts forward under the action of inertia force. The braking energy is converted into hydraulic energy in the electromechanical-hydraulic coupler and stored in the high-pressure accumulator. At the same time, the electric motor starts to work, converting mechanical energy into electrical energy, which is stored in the battery pack through the power converter.

![Figure 2. Typical work cycle model.](image)

The new electromechanical-hydraulic power transmission system proposed in this paper effectively combines the characteristics of zero-emission and no pollution in pure electric vehicles [22] with the high energy recovery rate and high power density of the hydraulic systems in hydraulic hybrid vehicles [23], and as a result, it better meets the needs of the economy, reliability, and safety of vehicles [24].

3. Accumulator Selection

A hydraulic accumulator is a kind of auxiliary component in the hydraulic pneumatic system and is also the emergency power source in the hydraulic system. During vehicle operations with high power needs, such as vehicle start, vehicle climbing, and other working conditions, the accumulator can release the pressure oil supply hydraulic pump/motor hydraulic energy, and re-supply the hydraulic system auxiliary motor to drive the vehicle together. When the system pressure increases instantly, the accumulator can absorb this part of the energy to ensure the stability of the whole system pressure and can moderate the hydraulic system during a sharp hydraulic shock [25]. Accumulators are divided into spring type, weight type, and gas type according to the loading method [26]. The gas type accumulator is further divided into gas–hydraulic direct contact, piston type,
diaphragm type, and skin type according to the structural characteristics. A comparison of the characteristics of several commonly used accumulators is shown in Table 1.

Table 1. Characteristics of the accumulator.

| Categories      | Features                                                                                                                                 |
|-----------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Spring Type     | The spring-type accumulator converts the oil compression spring into elastic potential energy for energy storage. Its structure is simple and low-cost. However, the spring has limited expansion and contraction, and the spring reacts slowly to the pressure action. This kind of accumulator is only suitable for low-pressure systems with small capacity and is mostly used as a buffer device. |
| Weighted        | The weighted accumulator uses a mass block on a piston to convert pressure energy into gravitational potential energy. It has a simple structure and stable pressure but has a large installation limitation and can only be installed vertically. It uses a mass block with high inertia. This accumulator has low sensitivity. It is difficult to seal and is only used for temporary energy storage. |
| Contact         | A contact-type accumulator has direct contact between oil and gas. This kind of accumulator is responsive, but the oil and gas are mixed, and the oil utilization rate is low. |
| Piston type     | The piston accumulator separates the oil from the gas utilizing a piston. This ensures that the oil is not oxidized. The accumulator has a long service life, but the friction that exists between the piston and the inner wall makes it less sensitive. This type of accumulator can be used to adjust the system pressure. |
| Diaphragm type  | The diaphragm-type accumulator separates the oil from the inert gas by means of a rubber diaphragm. The elasticity of rubber effectively increases the sensitivity of this type of accumulator. This type of accumulator has a limited filling pressure because of its small capacity and can be used to absorb shock pulsations. |
| Bladder type    | The bladder type accumulator uses a bladder to separate the oil from the gas. The capsule is filled with an inert gas (e.g., nitrogen) and the oil is filled outside the capsule. The bladder-type accumulator achieves the discharge of oil through the compressibility of the inert gas. This kind of accumulator has the advantages of small inertia, responsiveness, and good sealing, and its overall structure has various sizes and specifications and is easy to install and maintain. This is also the most widely used accumulator. |

According to Table 1, it is known that the spring-type accumulator has limited spring expansion and contraction, which is not suitable for high-frequency occasions; the weight-type accumulator is large and bulky, the piston-type accumulator is not sensitive, and the diaphragm-type’s capacity is small. The characteristics of various accumulators and the requirements of the hybrid transmission system are integrated [27], so this paper selects the responsive and lightweight skin-type accumulator as the energy storage element of the electromechanical-hydraulic hybrid transmission system, as shown in Figure 3.

![Skin type accumulator](image-url)
4. Mathematical Modeling

4.1. Hydraulic Accumulator

The hydraulic accumulator is the main component of the electromechanical-hydraulic power transmission system. As an auxiliary power, it provides hydraulic power to drive the vehicle, and is also a component for braking energy storage [28]. Therefore, mathematical modeling of the hydraulic accumulator is performed [29]. The high-pressure accumulator (HPA) and low-pressure accumulator (LPA) in the pulse discharge process have a relationship between pressure (MPa) and volume (L) according to Boyle’s law as

\[ P_0 v_0^n = P_1 v_1^n = P_2 v_2^n = P v^n, \]  

(1)

where \( P_0 \) is the initial inflation pressure of the gas in the accumulator, MPa; \( v_0 \) is the inflation volume when the accumulator pressure is \( P_0 \), L, at which time the skin is filled with the inner cavity of the shell, i.e., the capacity of the accumulator; \( P_1 \) is the minimum working pressure of the accumulator, MPa; \( v_1 \) is the gas volume when the accumulator pressure is \( P_1 \), L; \( P_2 \) is the maximum working pressure of the accumulator, MPa; \( v_2 \) is the gas volume when the accumulator pressure is \( P_2 \), L; \( n \) is the gas multivariable index.

When the gas in the accumulator is fully exchanged with the external heat, the process can be considered as an isothermal state, when \( n = 1 \); when the gas in the accumulator expands rapidly and the heat exchange is not sufficient, the process can be considered as an adiabatic state, when \( n = 1.4 \).

Regarding the performance of the accumulator, the main parameters involved are filling pressure, minimum working pressure, maximum working pressure, and accumulator volume [30].

1. Determination of the minimum working pressure \( P_1 \)

\[ P_1 = \frac{2\pi \left( m g f + \frac{C_D A u_0^2}{21.15} \right)}{V_a i_b i_0}, \]  

(2)

where \( m \) is the mass of the vehicle; \( f \) is the rolling friction coefficient of the wheels; \( C_D \) is the air resistance coefficient; \( A \) is the windward area; \( u_0 \) is the vehicle speed when braking; \( V_a \) is the displacement of the hydraulic pump/motor; \( i_b \) is the torque synthesizer speed ratio; \( i_0 \) is the transmission ratio of the main drive.

2. Determination of the maximum working pressure \( P_2 \)

The maximum working pressure \( P_2 \) of the bladder accumulator is determined according to the requirements of the system and the compression ratio of the bladder (\( b = P_0 / P_2 \)). From experience, the maximum working pressure \( P_2 \) cannot exceed three times the minimum working pressure \( P_1 \). That is, \( P_2 \leq 3P_1 \). Otherwise, the gas inside the airbag will lead to the deformation of the skin bag due to rapid compression, which will shorten the life of the skin bag.

3. Determination of inflation pressure \( P_0 \)

Theoretically, the energy that can be stored and released by the hydraulic accumulator is

\[ E_1 = -\int_{v_0}^{v_2} P dv, \]  

(3)

From Equation (1), we have

\[ P = P_0 \left( \frac{v_0}{v} \right)^n, \]  

(4)

by substituting into Equation (3)

\[ E_1 = \frac{P_0 v_0}{n-1} \left[ \left( \frac{v_0}{v_2} \right)^{n-1} - 1 \right], \]  

(5)
From Equation (1), we have
\[ \frac{v_0}{v_2} = \left( \frac{P_2}{P_0} \right)^{\frac{1}{n}}, \] (6)
by substituting into Equation (3)
\[ E_1 = \frac{P_0 v_0}{n - 1} \left[ \left( \frac{P_2}{P_0} \right)^{\frac{n-1}{n}} - 1 \right], \] (7)

From Equation (5), it can be seen that increasing the volume of the accumulator \( v_0 \) and increasing the maximum working pressure of the accumulator \( P_2 \) can increase the energy stored in the accumulator. However, due to space constraints, the volume of the accumulator cannot be too large; the maximum working pressure of the accumulator cannot be too high due to the constraints of sealing and safety factors.

As a rule of thumb, the accumulator filling pressure should be set between 90% of the minimum operating pressure of the system and 25% of the maximum operating pressure of the system, that is
\[ P_0 = 0.25P_2 \sim 0.9P_1, \] (8)

If \( P_1 = P_0 \), \( v_0 \) and \( P_2 \) are taken as constants. Set \( \frac{dE}{dP_0} = 0 \) to obtain the maximum value of energy absorbed by the accumulator.
\[ \frac{dE}{dP_0} = \frac{v_0}{n-1} \left[ \frac{1}{n} \left( \frac{P_0}{P_2} \right)^{\frac{1}{n}} - 1 \right] = 0 \] (9)
Yielding
\[ \frac{1}{n} \left( \frac{P_0}{P_2} \right)^{\frac{1}{n}} - 1 = 0, \] (10)
\[ P_0 = n^{\frac{n}{n-1}}P_2, \] (11)

Let \( P_1 = P_0 \); substituting Equation (11) into Equation (7) yields the maximum stored energy \( E_{\text{max}} \) as
\[ E_{\text{max}} = n^{\frac{n}{n-1}}P_2v_0, \] (12)

4. Determination of accumulator volume \( v_0 \)

The energy balance equation for the vehicle braking in the ideal state is
\[ \frac{1}{2} \delta m \left( u^2 - u_0^2 \right) = E_1 + E_2 + E_3, \] (13)
where \( \delta \) is the vehicle’s rotating mass conversion factor and generally takes \( \delta = 1.01 \); \( m \) is the vehicle’s mass, kg; \( u_0 \) is the vehicle’s initial velocity at the beginning of braking, m/s; \( u \) is the vehicle’s speed after \( t \) moments of braking, m/s; \( E_1 \) is the energy recovered by the hydraulic accumulator, J; \( E_2 \) is the energy lost by the vehicle to overcome rolling friction, J; \( E_3 \) is the energy lost by the vehicle to overcome air resistance.

The energy lost by the vehicle to overcome rolling friction is
\[ E_2 = mgfs, \] (14)
where \( m \) is the mass of the vehicle, kg; \( g \) is the acceleration of gravity (taken as 9.8 m/s\(^2\)); \( f \) is the rolling friction coefficient of the wheels; \( S \) is the braking distance of the vehicle, m.

The energy lost by the vehicle to overcome air resistance is
\[ E_3 = \frac{C_D A}{21.15} (u - at)^2, \] (15)
where \( C_D \) is the air resistance coefficient; \( A \) is the windward area; \( u \) is the velocity of the vehicle after braking moment \( t \); \( a \) is the deceleration of the vehicle braking.

Substituting Equations (3), (14), and (10) into Equation (13), we get

\[
v_0 = \frac{(n - 1) \left[ \frac{1}{2} \delta m (u^2 - u_0^2) - mg S - \frac{C_D A}{21.15} (u - at)^2 \right]}{P_0 \left[ \left( \frac{P_0}{P_1} \right)^{\frac{1}{n_m}} - \left( \frac{P_0}{P_1} \right)^{\frac{1}{n_l}} \right]}, \tag{16}
\]

### 4.2. Hydraulic Pump/Motor Matching

The hydraulic system is an important part of the electromechanical-hydraulic coupling, and hydraulic power as auxiliary power is also an important part of the energy conversion process. When the vehicle is starting, the hydraulic pump/motor drives the vehicle. When the vehicle is braking, the hydraulic pump can store the excess braking energy in the form of hydraulic energy into the accumulator.

1. **Maximum power of hydraulic pump/motor**

   The maximum power consumed by the hydraulic pump/motor while the vehicle is accelerating is calculated by the formula

   \[
P_{\text{max}} = \frac{1}{3600 \eta_h} \left( mg f u_{\text{max}} a + \frac{C_D A u_{\text{max}}^3}{21.15} + \delta m u_{\text{max}} \frac{du}{dt} \right), \tag{17}
\]

   where \( P_{\text{max}} \) is the maximum power required in the hydraulic pump/motor-alone drive mode; \( \eta_h \) is the mechanical transmission efficiency from the hydraulic system to the wheels, which is 0.85; \( m \) is the mass of the vehicle; \( g \) is the acceleration of gravity (taken as 9.8 m/s\(^2\)); \( f \) is the rolling friction coefficient of the wheels; \( u_{\text{max}} \) is the maximum vehicle speed in the hydraulic pump/motor-alone drive mode; \( C_D \) is the air resistance coefficient; \( A \) is the windward area; \( \delta \) is the rotating mass conversion factor of the vehicle, generally taken as \( \delta = 1.01 \).

2. **Maximum torque of hydraulic power**

   The formula for calculating the maximum torque of hydraulic power is

   \[
   T = \frac{9549 \alpha P_{\text{max}}}{n_{\text{max}}}, \tag{18}
   \]

   where \( \alpha \) is the torque adaptability coefficient, \( \alpha = (1.1 - 1.3), \alpha = 1.2 \) is selected; \( n_{\text{max}} \) is the maximum power speed, and \( n_{\text{max}} = 5350 \text{ r/min} \) is selected.

### 4.3. Electric Motors

The electric drive system is the core of the electromechanical-hydraulic power-coupled vehicle, in which the electric motor can recover the braking energy during the braking process and convert it into electrical and hydraulic energy. We choose a permanent magnet synchronous motor, which has the advantages of good speed regulation characteristics, high efficiency, and compact structure.

1. **The equations for the mechanical power** \( P_{\text{mec}} \) **and power loss** \( P_{\text{lost}} \) **of the motor are**

   \[
P_{\text{mec}} = \frac{T_m n_e}{9549}, \tag{19}
   \]

   \[
P_{\text{lost}} = (1 - \eta_e)|P_{\text{mec}}|, \tag{20}
   \]

   where, \( P_{\text{mec}} \) is the mechanical power of the motor; \( T_m \) is the output torque of the motor; \( n_e \) is the speed of the motor’s rotating shaft; \( P_{\text{lost}} \) is the power loss of the motor; \( \eta_e \) is the thermal efficiency of the motor.
The relationship between the mechanical power $P_{mec}$ and the electrical power $P_{elec}$ is

$$P_{elec} = P_{mec} - P_{lost},$$  \hspace{1cm} (21)

where, $P_{elec}$ is the electrical power.

2. Motor/generator efficiency

$$\eta_m = 2 - \frac{P_{elec}}{P_{mec}},$$  \hspace{1cm} (22)

$$\eta_g = \frac{P_{elec}}{P_{mec}},$$  \hspace{1cm} (23)

where, $\eta_m$ is the efficiency of the motor; $\eta_g$ is the efficiency of the generator.

4.4. Battery

The battery selected in this paper is lithium iron phosphate. A lithium iron phosphate battery has the advantages of high specific energy, high specific power, long cycle life, and good safety. The capacity of the battery pack must meet the requirements of the range of the vehicle. This paper adopts the equal speed method for calculation.

1. The power required to drive the vehicle at a constant speed in purely electric mode is

$$P_{ele} = \frac{1}{3600\eta} (mgfu_{ele} + \frac{C_D u_{ele}^3}{21.15}),$$  \hspace{1cm} (24)

where $P_{ele}$ for the car is equal to the form of power required, kw; $\eta$ for the motor and mechanical system total efficiency, take $\eta = 0.71$; $u_{ele}$ for the car is equal to the speed of travel, km/h.

2. The energy required to travel a certain distance $S$ over an equal distance is

$$W_{road} = P_{ele} \cdot t = P_{ele} \cdot \frac{S}{u_{ele}},$$  \hspace{1cm} (25)

where $W_{road}$ is the energy required to drive the vehicle mileage $S$, KWh; $S$ is the mileage of the electric vehicle in pure electric mode in the design requirements, km.

3. The stored energy of the battery required for electric vehicles is

$$W_B = \frac{U_B C_B \eta DOD}{1000},$$  \hspace{1cm} (26)

where $W_B$ indicates the actual energy of the battery pack, KWh; $U_B$ indicates the average working voltage of the battery pack, V; $C_B$ indicates the capacity of the battery pack Ah; $\eta DOD$ indicates the depth of discharge of the battery, take $\eta DOD = 0.8$.

4. The power cell pack energy constraint is

$$W_B > W_{road},$$  \hspace{1cm} (27)

5. Simulation Analysis

5.1. Simulation Methodology

In this paper, AME Sim software is used to build the whole vehicle simulation parameters of the electro-hydraulic vehicle, as shown in Table 2.

The whole vehicle simulation model of the electromechanical-hydraulic vehicle is built with the help of AME Sim software [31], as shown in Figure 4. The model mainly consists of the whole vehicle module, driver module, hydraulic hybrid system module, hydraulic hybrid control module, engine module, clutch module, etc.
Table 2. Main parameters of the whole vehicle.

| Parameter (Unit)                  | Numerical Value |
|-----------------------------------|-----------------|
| Overall vehicle mass m (kg)       | 1206            |
| Rolling resistance coefficient f  | 0.0135          |
| Air resistance coefficient $C_D$  | 0.32            |
| Windward area $A$ (m$^2$)         | 2.28            |
| Rotating mass conversion factor $\delta$ | 1.05       |
| Mechanical drive efficiency $\eta$| 0.85            |
| Tire width $R$ (mm)               | 290             |
| Secondary Component Displacement $V_p$ (mL·r$^{-1}$) | 30             |
| Motor traction power $P_e$ (KW)   | 32              |

Figure 4. Full vehicle simulation model of electromechanical-hydraulic vehicle.

The control strategy for an electromechanical-hydraulic vehicle was built with the help of Simulink, as shown in Figure 5. The control strategy model mainly includes two parts: mode switching and energy management. Mode switching includes the start mode, drive mode, brake mode, and stop mode. Energy management is the different torque distribution corresponding to each mode.

Simulink is a forward simulation that can be used to develop control strategies for the vehicle, and AME Sim is a reverse simulation that can be used to select the components of the vehicle. In this paper, we built the whole vehicle model in AME Sim, imported various working conditions of vehicle driving into it, and then created an interface that could open Simulink software so that we could realize joint AME Sim and Simulink utilization. The joint simulation technique of AME Sim and Simulink can be closer to the natural state of the vehicle with an electromechanical-hydraulic power system [32].

The work of the accumulator can be regarded as an independent thermodynamic system, its work process is the system and the external energy transfer and transformation process; the volume of the accumulator affects the entire vehicle braking performance and energy recovery effect [33].

For the effect of an energy storage volume on the working performance of the whole vehicle, in this paper, we use an AME Sim/Simulink co-simulation technique to run the simulation. The simulation input is the New European Driving Cycle (NEDC) condition, which contains four city cycle conditions and one suburban cycle condition, with a total duration of the 1180 s and a maximum speed of 120 km/h.
5.2. Determination of Energy Storage Capacity

The 20 L, 30 L, 35 L, 40 L, and 50 L hydraulic accumulators were replaced for simulation testing under the premise that the EMHCEV could follow the NEDC working speed normally. The comparison graphs of the SOC curves of the accumulator at different volumes of the vehicle battery (shown in Figure 6) and the pressure comparison graphs of the hydraulic accumulator (shown in Figure 7) were obtained through the simulation.

Figure 5. Full vehicle simulation model of an electromechanical-hydraulic vehicle.

Figure 6. Battery SOC variation curve with different volumes of the accumulator.

Figure 7. Pressure variation curve of accumulator with different volumes.
Figure 6 shows the comparison of the consumption of the vehicle battery when the volume of the accumulator is different. The initial battery SOC is set to 100%, and it is clear from the curve that the larger the volume of the accumulator, the smaller the consumption of the vehicle battery instead, i.e., the volume of the accumulator is proportional to the SOC of the battery. The accumulator with a volume of 20 L can make the vehicle’s SOC value reach 94.7099%, and the accumulator with a volume of 50 L can make the vehicle’s SOC value reach 94.7890%. Therefore, the difference in volume makes little difference to the vehicle battery consumption comparison.

The larger the volume, the more energy is stored in the accumulator, but it is important to match the optimal capacity to the vehicle due to the difference in weight, maximum speed, and usage of the vehicle itself. From Figure 7, we know that the 20 L, 30 L, and 35 L accumulators can reach the maximum operating pressure of 35 MPa throughout the braking recovery phase, which ensures energy recovery efficiency. In contrast, the 40 L and 50 L accumulators are always below the maximum operating pressure throughout the brake recovery phase. Therefore, a larger volume of the accumulator may have an impact on the braking time and braking distance of the vehicle, and the larger the volume of the accumulator, the more space it takes up in the vehicle, adding a larger load to the vehicle.

On balance, a 35 L accumulator is the best choice to ensure maximum operating pressure with minimum battery consumption. The 35 L volume accumulator is the best capacity match for this type of vehicle, as it can take into account both operating pressure and battery consumption.

5.3. Speed Following

The speed following is shown in Figure 8. The NEDC speed matches well with the simulated speed, and the EMHCEV has better power performance and braking performance.

![Figure 8. Speed simulation results.](image)

5.4. Hydraulic Power Involvement

The torque curve of the EMHCEV is shown in Figure 9, which shows the variation of the torque of the electric and hydraulic parts. The maximum total torque is up to 271 Nm. The first half of the torque phase represents the four city cycle driving conditions in NEDC operation, and the second half corresponds to the suburban operation.

The swashplate opening is the inclination angle of the swashplate of the hydraulic part of the electro-hydraulic coupler, ranging between (-1, 1), representing (-20°, +20°), whose opening and closing process is shown in Figure 10 and shows that the opening and closing of the cross plate can be done instantaneously. Negative numbers represent hydraulic regenerative braking, positive numbers represent the involvement of the start-up acceleration, and the high-speed phase is not involved in the work.
6. Conclusions

In this paper, an electromechanical-hydraulic coupled electric vehicle simulation model is established in AME Sim based on the vehicle dynamics model in order to better simulate the influence of each major parameter of the accumulator on the overall operating effectiveness of the vehicle. The vehicle and related parameters are set up in conjunction with the actual situation so that the vehicle is simulated and tested under the New European Driving Cycle (NEDC) operating conditions. Through simulation tests, the effect of different volumes of hydraulic accumulators in the hydraulic system on the operating pressure and the vehicle battery consumption is investigated. From the simulation results, it can be seen that the hydraulic accumulator in the electric vehicle with the electromechanical-hydraulic coupling system used in this paper, the difference of its volume on the vehicle battery consumption is not very different, but it will affect the highest working pressure of the vehicle work, so it may have an impact on the braking time and braking distance of the vehicle. Therefore, based on practical application considerations, a hydraulic accumulator with a volume of 35 L is the best capacity for electromechanical-hydraulic coupled electric vehicles. The research work in this paper provides a basis for subsequent research to improve the energy recovery efficiency of electromechanical-hydraulic coupled electric vehicles and has a certain reference value for the research and optimization of electromechanical-hydraulic coupled electric vehicles.

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