Research on Matching of Power Transmission System of Electro-Hydraulic Hybrid Electric Vehicle

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Abstract. Considering the high power density and high recovery efficiency of the hydraulic energy storage system, the power system combined with the hydraulic pump is adopted. The matching of automobile power transmission system includes the matching of hydraulic pump parameters, hydraulic accumulator parameters, motor parameters and battery parameters. AMESim and Simulink were used to carry out simulation modeling to analyze its performance. The simulation results showed that the adaptive combination of hydraulic system and battery system in electro-hydraulic hybrid vehicle could effectively improve the economic performance of the vehicle while ensuring the dynamic performance of the vehicle. It puts forward more efficient technology concept for the future development of hybrid electric vehicle.

Keywords: Parameter matching, hydraulic accumulator, electric-hydraulic hybrid vehicle, power transmission system.

1. Introduction

In the development of automobile, new energy vehicles thought that the trend of The Times, but at this stage the limitations of pure electric vehicles is larger, the most prominent problem for life, if only to increase the number of battery and increase the range of pure electric vehicles, not only will increase the equipment of automobile quality, but also for the car space available for further compression. In this case, hybrid electric vehicles become an important part of the development of new energy vehicles at the present stage. Relevant studies have shown that according to the different characteristics of different motors, the range of battery life can be increased by 20%-50% through the development and optimization of energy recovery technology [1~3]. At present, new energy vehicles mainly refer to pure electric vehicles, hybrid electric vehicles and fuel cell vehicles [4]. At present, hybrid electric vehicles mainly include electric hybrid electric vehicles and hydraulic hybrid electric vehicles, and their driving modes are divided into series type, parallel type, mixed type and wheel-side type [5, 6]. Electro-hydraulic hybrid electric vehicle, after long-term research has further deepened this concept. The research on electro-hydraulic hybrid electric vehicle is very early abroad, which has accumulated a lot of experience in theoretical research and practical application [7, 8]. The working mode of electro-hydraulic hybrid vehicle is divided by analyzing different working conditions and...
working pressure of hydraulic accumulator. When the vehicle starts to accelerate, the hydraulic energy in the hydraulic accumulator can be converted into mechanical energy through the hydraulic pump. It can also assist the power provided by the motor to meet the requirement of instantaneous high power of the vehicle. When the vehicle travels at a constant speed, the battery pack will start to provide electric energy to the motor and turn it into mechanical energy to meet the vehicle's power demand. When the vehicle is accelerating up a hill, the vehicle needs a large torque to maintain the drive of the vehicle. After receiving the controller signal, the hydraulic accumulator releases its hydraulic energy to make up the power required by the vehicle; When deceleration braking, braking energy storage hydraulic accumulator, the motor stop working, the inertia force of the vehicle, through the half shaft, differential sun, the planet wheel and other components to drive hydraulic pump work, the mechanical energy into hydraulic energy, stored in the high pressure accumulator, when, after the expiration of the hydraulic accumulator of hydraulic energy storage generator will start to work the rest of the mechanical energy into electrical energy stored in the battery pack. According to the research results, electro-hydraulic hybrid electric vehicles can use hydraulic pump skillfully to effectively avoid damage of battery pack due to frequent charging and discharging, and at the same time, it can also supplement the power demand required by vehicle climbing acceleration and improve the energy conversion rate. In the future development of hybrid electric vehicle provided certain technical support.

2. Working principle of electro-hydraulic coupled dynamic system

![Figure. 1 Schematic diagram of electro-hydraulic coupled dynamic system](image)

The electro-hydraulic hybrid electric vehicle is mainly studied with the electro-hydraulic coupling system as the center. The electro-hydraulic coupling dynamic system is shown in Figure 1. All the solenoid valves in the system are two-position two-way solenoid valves, which are normally open or closed with power. Both high pressure and low pressure accumulators are hydraulic accumulators.

Acceleration signals, pressure sensor, brake, and battery, power converter control signal to the controller to control the battery pack, power converters, motor control and high pressure solenoid valve, low pressure solenoid valve, acceleration signals, brake and pressure sensor signal through the controller to control the displacement of the control motor adjusting hydraulic pump/motor and the electromagnetic valve and solenoid valve open and close.

3. Matching analysis

Hydraulic Pump

When the vehicle starts to accelerate or climbs a hill, the vehicle needs a large instantaneous power to support its work. Therefore, the hydraulic pump should first meet the needs of the vehicle in different running state of the maximum instantaneous power, at the same time, the vehicle braking energy generated in a timely manner after recovery and storage in the hydraulic accumulator. Therefore,
when selecting the hydraulic pump, the maximum power required under different driving conditions of
the vehicle should be calculated first, and then select the hydraulic pump meeting the requirements for
matching.

3.1. Maximum Power of Hydraulic Pump
The power consumed by the vehicle under the condition of accelerating on a good, flat road is:

\[ P_{\text{max}, a} = \frac{1}{\eta} \left( \frac{Gf_{\text{max}, a} + C_D A u_{\text{max}, a}^2}{3600} + \frac{\delta m_{\text{a}} u_{\text{max}, a}}{3600} \frac{du}{dt} \right) \]  

\[ P_{\text{acc}} = \frac{\delta m_{\text{a}} u_{\text{a}}}{3600} \frac{du}{dt} \]  

Where, \( u_{\text{max}, a} \) is the maximum speed of hydraulic pump driving mode; \( \eta \) is the mechanical
transmission efficiency of the hydraulic system to the wheel, which is 0.85. \( C_D \) is the air resistance
coefficient; \( G = m_0 \times g \), where \( m_0 \) is the full load mass and \( g \) is the gravitational acceleration (9.8m/s²); \( A \) is the windward area; \( P_{\text{max}, a} \) is the maximum power required when hydraulic pump is driven
separately; \( P_{\text{acc}} \) is set as the total power consumed by vehicle accessories. \( P_{\text{acc}} = 5\text{kW} \); \( f \) is the rolling
resistance coefficient.

3.2. Maximum Hydraulic Torque
The maximum torque \( T \) of hydraulic power is:

\[ T = 9549 \times \frac{\alpha \times P_{\text{max}, a}}{n_{\text{max}, a}} \]  

Where, \( \alpha \) is torque adaptability coefficient, \( \alpha = (1.1 \sim 1.3) \), \( \alpha = 1.2 \); \( n_{\text{max}, a} \) is the maximum power
rotation speed, select \( n_{\text{max}, a} = 5350 \text{r/min} \).

4. Hydraulic Accumulator
Hydraulic accumulator is an important part of electro-hydraulic hybrid electric vehicle, which can
store the hydraulic energy generated by hydraulic pump when the vehicle is braking, and release the
stored hydraulic energy into mechanical energy at the stage of vehicle starting and vehicle climbing.

4.1. Determination of Working Pressure of Pressure Accumulator
The calculation formula of the accumulator's minimum working pressure \( P_1 \) is:

\[ P_1 = \frac{2\pi \left( Gf + \frac{C_D A u_{\text{max}, a}^2}{21.15} \right)}{V_a i_0} \]  

Where, \( V_a \) is the displacement of hydraulic pump/motor; \( u_{\text{max}, a} \) for hydraulic pump/motor drive mode
alone maximum speed. The charging pressure \( P_0 \) should first consider the minimum capacity of the
hydraulic accumulator, so take:

\[ P_0 = P_1 \]
4.2. Determination of Pressure Accumulator Volume

According to the energy balance equation:

\[
\frac{1}{2} \delta m (\dot{u}_2^2 - \dot{u}_1^2) = E_1 + E_2 + E_3
\]  

Where, \(\dot{u}_2\) and \(\dot{u}_1\) are the vehicle speeds at time \(t_2\) and \(t_1\); \(E_1\) is the energy lost due to rolling resistance of the vehicle; \(E_2\) is the energy recovered during braking; \(E_3\) is the energy lost by vehicle due to air resistance. The energies are calculated as follows, \(\delta\) is the rotation mass conversion factor of the car, \(\delta=1.01\) in general.

\[
E_1 = GfS
\]  

\[
E_3 = \frac{C_D A}{21.15} (u_2^2 - at)^2
\]  

\[
E_2 = \frac{PV_0}{n-1} \left[ \left( \frac{P_1}{P_2} \right)^{\frac{n}{n-1}} - 1 \right]
\]  

Where, \(S\) is the vehicle braking displacement, \(m\); \(u_0\) is the initial speed of vehicle braking; \(a\) is the deceleration of vehicle braking; \(n\) is the gas polytropic index, adiabatic change process \(n=1.4\).

By combining the above formulas 6), 7), 8) and 9), we can get:

\[
V_0 = \frac{(n-1) \left[ \frac{1}{2} \delta m (\dot{u}_2^2 - \dot{u}_1^2) - \frac{C_D A}{21.15} (u_2^2 - at)^2 - GfS \right]}{P_1 \left( \frac{P_1}{P_2} \right)^{\frac{n}{n-1}} - 1}
\]  

The initial speed of the car in the urban road \(u_0=60\text{km/h}\), and the speed at the end of braking \(u_1=0\). In the case of emergency braking, the maximum deceleration is generally \(7.5\text{~}8\text{m/s}^2\). In general, the average deceleration should be \(3\text{~}4\text{m/s}^2\). In the actual use of braking, except in emergencies, the deceleration should not be greater than \(1.5\text{~}2.5\text{m/s}^2\).

4.3. Determination of Effective Working Volume \(V_x\) of Pressure Accumulator

The accumulator volume corresponding to the initial charging pressure of the accumulator is:

\[
V_0 = \frac{V_x (P_1/P_0)^{\frac{1}{n}}}{\left( 1 - P_1/P_2 \right)^{\frac{1}{n}}}
\]  

The above formula can be obtained as follows:

\[
V_x = V_1 - \left( \frac{P_1}{P_2} \right)^{\frac{1}{n}} \cdot V_1
\]
Where, $P_0$ is the initial charging pressure of the accumulator; $V_0$ is the accumulator volume corresponding to the initial charging pressure of the accumulator; $V_x$ is the effective volume of the accumulator.

Motor

When the parameters of automobile motor are matched, the dynamic performance of automobile should be satisfied first. The rated power of the motor can be determined by the maximum speed of the vehicle in pure electric mode and its ability to overcome a small slope at low speed [9].

4.4. Determine the Rated Power and Peak Power

According to the actual driving condition and transmission efficiency of the vehicle, the maximum value of $P_c$ and $P_e$ of the vehicle full load is taken as the peak power of the electric power when selecting power parameters:

$$ P_{\text{max}} \geq \max(p_c, p_e) $$

Where, $P_c$ is the required power of the vehicle when it climbs the hill with the maximum speed in the pure electric driving mode; $P_e$ is the power required when driving at the maximum uniform speed in pure electric mode.

The air resistance and acceleration resistance can be ignored when the car is climbing a slope at a steady speed:

$$ P_x = \frac{1}{\eta_T} \left( \frac{GF \cos \theta u_{\text{max}}}{3600} + \frac{G \sin \theta u_{\text{max}}}{3600} + \frac{C_D A u_{\text{max}}^3}{76140} \right) + P_{\text{acc}} $$

Where, $u_{\text{max}}$ is the maximum speed in the pure electric mode when climbing the hill, and $u_{\text{max}}=50\text{km/h};G$ is the gravity of the car; $\eta_T$ is the mechanical transmission efficiency between the output shaft of the motor and the driving wheel, set $\eta_T=0.85; f$ is the rolling resistance coefficient, $f=0.0135; \alpha$ is the slope; $P_{\text{acc}}$ is the total power consumed by vehicle accessories.

When the vehicle speed is in the pure electric mode with the maximum speed, the corresponding demand power is:

$$ P_e = \frac{1}{\eta_T} \left( \frac{GF u_{\text{max}}}{3600} + \frac{C_D A u_{\text{max}}^3}{76140} \right) + P_{\text{acc}} $$

Where, $C_D$ is the air resistance coefficient, and the air resistance coefficient $C_D$ is 0.32. $A$ is the windward area; $f$ is the rolling resistance coefficient.

4.5. Determine Motor Speed

The rated speed of the motor affects the size of the transmission system and the rated torque of the motor. For electro-hydraulic hybrid vehicles, the motor must be able to provide a large enough torque to drive the vehicle under pure electric driving conditions.

5. Matching Examples and Analysis

Electric-hydraulic Hybrid Vehicle Powertrain Matching

Before studying the powertrain system of electro-hydraulic hybrid electric vehicle, the main parameters of the sample vehicle are firstly determined. In this paper, a certain hybrid electric vehicle is selected as the research object. The main parameters are shown in Table 1. The parameters of
relevant components are calculated and selected according to the dynamic performance requirements of the whole vehicle. In the process of parameter matching and component selection, the electro-hydraulic hybrid electric vehicle should have the same dynamic performance as the traditional vehicle. According to the requirements for the correlation of hybrid electric vehicles, the dynamic performance index parameter based on in this paper is: 100km acceleration time \( t_{\text{hybrid drive mode}} \) \( \leq 15 \) (s); Hydraulic pump/motor drive alone mode with maximum speed \( u_{\text{max}} \) of 160 (km/h); The maximum speed \( u_{\text{max}} \) in pure electric mode is 50 (km/h); Maximum climbing gradient \( \alpha_{\text{max}} \geq 30 \) (%).

| Table 1: Main parameters of electro-hydraulic hybrid electric vehicle |
|---------------------------------------------------------------|
| **Complete vehicle equipment quality /kg** | **Full quality \( m_0 \)/kg** | **Windward area \( A/m^2 \)** | **Rolling resistance coefficient \( f \)** | **Air resistance coefficient \( C_D \)** | **Tire width \( R/mm \)** | **Tire height \( H/cm \)** | **Maximum braking torque of front axle /Nm** | **Mechanical transmission efficiency \( \eta_h \)** |
|---------------------------------------------------------------|
| 1206 | 1850 | 2.28 | 0.0135 | 0.32 | 185 | 60 | 1000 | 0.85 |

### 5.1. Hydraulic Pump Parameters Matching
The relevant parameters are substituted into formula 1) and formula 3) for calculation. When the hydraulic pump is driven separately, the maximum power required is \( P_{\text{max}} = 64 \) kW. Considering that the hydraulic pump needs to leave about 10% surplus power for battery pack charging, \( P_{\text{max}} = 70 \) kW. Maximum torque \( T = 140 \) Nm. The hydraulic pump parameters were preliminarily selected as V1.6L displacement, 70kW maximum power and 140Nm maximum torque. And the axial piston pump hydraulic pump has a swash plate Angle affecting the motor torque, speed and steering, high efficiency, can output high pressure, so you can choose the axial piston pump hydraulic pump.

### 5.2. Hydraulic Accumulator Parameter Matching
According to formula 4), the minimum working pressure of the accumulator \( P_1 = 8.5 \) mpa. Considering the actual situation and other energy consumption, \( P_1 = 10 \) Mpa was selected. Where the maximum working pressure \( P_2 \) needs to be controlled at \( P_2 \leq 3P_1 \), and \( P_2 = 30 \) Mpa is selected based on data and modeling optimization [10]. Inflation pressure \( P_0 = 10 \) Mpa.

The initial speed of the car in the urban road \( u_2 = 50 \) km/h, and the speed at the end of the braking \( U_1 = 0 \). In the case of emergency braking, the maximum deceleration is generally 7.5−8m/s\(^2\). In general, the average deceleration should be 3−4m/s\(^2\). In the actual use of braking, except in emergencies, the deceleration should not be greater than 1.5−2.5m/s\(^2\). According to formula 10), the accumulator volume corresponding to the initial charging pressure of the accumulator can be calculated as \( V_0 = 30 \) L, and the accumulator volume \( V_0 = 35 \) L should be selected according to the total transmission efficiency. According to formula 12), the effective volume \( V_e \) of the accumulator is 30L.

### 5.3. Motor Parameters Matching
In the selection of motors, PMSM has the characteristics of high efficiency, good energy feedback, large starting torque and high operating reliability. Combined with the actual requirements of electro-hydraulic hybrid vehicles, PMSM meets the requirements of electric vehicles for high-power and high-density motors. Therefore, permanent magnet synchronous motor can be chosen as the power source. According to the aforementioned vehicle power performance indicators, the design maximum speed under pure electric mode is 50km/h; In addition, considering that the pure electric mode should have a certain climbing ability, the slope Angle is set as 5%, that is, the slope Angle is \( \theta = 2.78 \) (the general slope is set as 2%−5%).

When the car is climbing the slope at a steady and uniform speed, the demand power \( P_c \) of the car climbing the slope at the maximum speed in the pure electric driving mode is calculated by using
formula 14). Considering that about 10% of the power is left for battery charging and other losses, the demand power $P_c$ is set as 30kW.

When the vehicle speed is the maximum speed in pure electric mode, that is, $u_{\text{max}} = 50\text{km/h}$, $P_c = 16\text{kW}$ is calculated by substituting parameters into formula 15). Considering the need to leave about 10% residual power for battery charging and other losses, $P_c = 20\text{kW}$ is taken.

According to formula 4), the peak power of the motor $P_{\text{max}} = 30\text{kW}$ and the rated $P_m = 20\text{kW}$ are calculated and combined with practice. Can satisfy the vehicle under the condition of all the work requirement for power, at the same time, the motor can not only provide the current operation can also provide the remaining power through torque coupler to hydraulic pump/motor, hydraulic accumulator is stored in the rest of the energy, so that under various conditions can have enough energy to keep hydraulic power efficient work normally.

Determine the motor speed by referring to the existing design of ISG motor, and select the rated speed of the motor to be 2500 r/min. According to the actual situation, the speed is selected to be 2500r/min. As the ratio of the maximum motor speed to the rated speed is usually 2~3, in order to better match the motor speed with the motor speed, the maximum motor speed is 6000r/min[11].

5.4. Battery Parameter Matching

Battery is the main power source of electric-hydraulic hybrid electric vehicle, so the choice of battery is very important. Nickel metal hydride battery has the advantages of high energy, high specific power, high discharge rate and no pollution. This paper will use nickel metal hydride battery as the power battery. According to the actual situation, the maximum power of the battery pack should be higher than the maximum power of the motor $P_{\text{max}} = 30\text{kW}$, and the working efficiency is 0.95, so the maximum power of the battery pack $P_{\text{max}} = 35\text{kW}$.

6. Simulation Analysis of Electro-hydraulic Hybrid Power System

The electro-hydraulic hybrid vehicle model is established through AMESim, as shown in Figure 2.

![Figure 2 Simulation model](image)

Through the construction of control strategy in Simulink, the whole vehicle co-simulation co-simulation vehicle model running NEDC cycle. According to the following curve of vehicle speed, as shown in Figure 3, the co-simulation vehicle speed curve and the operating condition demand curve completely coincide to meet the vehicle dynamics; The SOC curve of the battery is shown in Figure 4. The initial SOC of the battery is 90%. When the vehicle performs braking deceleration every time, the battery SOC rises to a certain extent, which proves that it has good braking energy recovery performance and increases the range of the vehicle.
7. Conclusions
Based on the dynamic performance and range of the electro-hydraulic hybrid electric vehicle, this paper analyzes the working conditions of the electro-hydraulic hybrid electric vehicle in different driving stages. Firstly, the main structure of the electro-hydraulic hybrid electric vehicle is determined. The selection and parameter matching of hydraulic pump are determined based on vehicle parameters. The pressure, volume and effective working volume of hydraulic accumulator are determined according to the actual energy storage requirements of the electro-hydraulic hybrid electric vehicle. Motor parameters can be matched according to different driving power requirements of the electro-hydraulic hybrid electric vehicle. In order to meet the requirement of battery power for the electric-hydraulic hybrid electric vehicle, the parameter matching of battery is established. To form the theory and method of matching analysis. The co-simulation of AMESim and Simulink proves that this method is effective and improves the range of new energy vehicles. It provides the data foundation and structure foundation for the subsequent research of the electro-hydraulic hybrid electric vehicle.

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