MECHANICAL TRANSMISSION SYSTEM OF LOADER BASED ON HYDRAULIC HYBRID TECHNOLOGY

by

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In order to solve the problems of high energy consumption, high noise and pollution gas emission existing in the mechanical transmission system of loader, a research on the mechanical transmission system of loader based on hydraulic hybrid technology is proposed. The mechanical energy and heat energy are generated by the mechanical operation of the loader, which are converted into hydraulic energy and output to the drive system. According to the fast response characteristics and high power density characteristics of the hydraulic power system relative to the thermal engine, the dynamic model of the hydraulic hybrid drive system of the loader is established. The double fuzzy PID control method is used to identify and modify the unknown load and power parameters of the drive system. Through the experiment, it is concluded that the power parameter matching of the transmission system using the hydraulic hybrid technology is more optimized, the application effect is good, and the efficiency of the power transmission system can be maximized.

Keywords*: loader, hydraulic hybrid, mechanical power, power parameter matching*

Introduction

With the sustained, rapid and stable development of China's economy and the rapid development of construction machinery industry, more and more attention has been paid to the environment. Haze weather has become a symbol of China's winter environmental problems in 2014, especially in some northern big cities. Industrial exhaust and automobile exhaust are the main causes of air quality deterioration and urban haze. How to reduce the impact of industrial exhaust and automobile exhaust on urban environment is an urgent problem. China's loader enterprises have formulated and implemented the strategic objectives of international development, resulting in rapid growth of loader export. In view of the construction demand of large-scale infrastructure projects, loaders continue to develop to the trend of high power and high load. According to the characteristics of small-scale construction sites, the output of low power and low load loaders is also increasing, which can not avoid the problems of high energy consumption, noise interference, pollutant emission and so on [1]. Because the loader is a large internal combustion engine construction machinery, especially in

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high power, high load operation, the fuel consumption is significant. Loader operation not only consumes a lot of fuel, but also emits a lot of harmful gases, forming acid rain, causing greenhouse effect, aggravating environmental pollution and ecological balance damage. In addition, the loader will produce deafening noise under working conditions, which will affect the life and work of the surrounding residents. The loader works under heavy load, but it also needs to adapt to the working conditions of frequent starting and stopping. Therefore, the key components of loader are prone to failure. The high maintenance cost of construction machinery has become the burden of many users, and it is also one of the important problems and improvement factors in the design and development stage.

Structural scheme and characteristic analysis of mechanical hydraulic hybrid power transmission system of loader. The research results of loader energy-saving technology are quite fruitful, but there are some deficiencies and concerns, which need to be further improved. The traditional energy-saving technology or optimization method of loader can not solve the key problem of low efficiency and high emission from deep level, so it is difficult to improve the energy-saving effect of loader. Frequent starting and stopping, periodic operation, reciprocating movement and other characteristics of loaders in the normal operation process often cause the actual output of the engine to deviate from the rated index, thus causing such phenomena as high energy consumption of the whole vehicle or redundancy of the output energy of the internal combustion engine [2]. However, the reasonable parameter matching of the hybrid power system can not only ensure the dynamic performance of the vehicle, but also reduce the fuel consumption of one hundred kilometers and the emission of pollutants [3].

- It is necessary to reduce energy consumption and emissions. The energy saving and emission reduction characteristics of loaders will seriously restrict the domestic and export of domestic loaders, and restrict their competitiveness in the international market. The expected goal can be achieved by using hydraulic hybrid technology.
- Remarkable results have been achieved in energy conservation and emission reduction. The energy saving effect of traditional internal combustion engine technology optimization is limited, so it is difficult to have a significant room for improvement. Hydraulic accumulator has many advantages, such as large energy storage, strong energy storage capacity, fast response speed of energy storage and release process, *etc*. The key problem of energy storage and release can be effectively solved by applying it to hydraulic hybrid technology.
- The promotion and application of hydraulic hybrid technology in the vehicle field will bring it superior power performance that other technologies cannot match. In addition, the application of this technology can also realize the precise adjustment of vehicle speed in a large range and realize the function of continuously variable transmission [4]. By simplifying the system and reducing the heating of the system, the reliability and service life of the loader can be improved, the use cost can be saved, and considerable economic benefits can be brought to the users.

Power matching of mechanical hydraulic hybrid power transmission system of loader

Dynamic analysis of hydraulic hybrid transmission system of loader

In order to realize the optimal design of the mechanical hydraulic hybrid transmission system of the loader, the dynamic model and kinematic model of the hydraulic hybrid transmission system of the loader are constructed, the unknown load and mass parameters of the hydraulic hybrid transmission system of the loader are calculated, and the maximum energy efficiency parameter matching and power distribution mechanism are adopted to control the electric transmission of the mechanical hydraulic hybrid transmission system of the loader [5]. The high-pressure module and low-pressure module are combined to control the mechanical hydraulic hybrid transmission system of loaders:

$$\frac{\mathrm{d}x_2(t)}{\mathrm{d}t} = g_{x_1}(x_1^0, x_2^0)(x_1 - x_1^0) + g_{x_2}(x_1^0, x_2^0)(x_2 - x_2^0) \tag{1}$$

where dt is the component speed at the intersection of maximum load curve and curve $(x_1 - x_1^0)$, $(x_1^0 - x_2^0)$, and $(x_2 - x_2^0)$ of torque converter.

Considering that the main power source of hydraulic hybrid system is Diesel engine, if the engine working mode changes, the driving torque and braking torque demand of loader shall be prior to the hydraulic energy storage torque demand of accumulator according to logic calculation [6]. The principle lays the foundation for the vehicle control and power parameter matching. Based on the logic control error analysis, the controlled constraint parameter model of loader mechanical hydraulic hybrid transmission system is constructed. The current error of loader hydraulic control sensor is $\left|\Delta i_{\max}^*\right|$, the target current of generator quasi harmonic oscillator module is **A**. The dynamic control problem is considered as an unconstrained optimization problem:

$$V_o = V_{\mathrm{ref}}\left(1 + \frac{\left|\Delta i_{\max}^*\right|}{2}\right) \tag{2}$$

where V_{ref} is the working load torque coefficient.

By adjusting the inertia constraint parameters of the mechanical hydraulic hybrid transmission system of the loader, the process reliability adjustment coefficient matrix of the mechanical hydraulic hybrid transmission system of the loader is obtained:

$$\mathbf{A} = \begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix} \tag{3}$$

By analyzing the steady-state characteristic equation of the mechanical hydraulic hybrid transmission system of loader [7], the dynamic model of the system is obtained:

$$\begin{gathered} \lambda^2 + p\lambda + q = 0 \\ p = -(a_1 + b_2) \\ q = \det \mathbf{A} \end{gathered} \tag{4}$$

where λ is the rated torque value, and the output steady-state characteristic quantity of the control system is described in the form of inertia constraint parameters:

$$h_1 = \omega_0^2 M_{sr}^2 L_l^2 + R_s R_r L_l^2 + R_s R_o M_{rl}^2 \tag{5}$$

By adjusting the variation of stiffness, $f_r(X)$, of hydraulic hybrid transmission mechanism of loader, the multi-objective optimization solution is carried out:

$$PF = \left\{ f(X) = (f_1(X), f_2(X), \ldots, f_r(X)) \mid X \in \{X^*\} \right\} \tag{6}$$

By adjusting the inertia constraint parameters, the magnetic loss function of the mechanical hydraulic hybrid transmission system of the loader is obtained:

$$H_R = \frac{2\dot{M}}{4\pi\mu R^3}\cos\theta(1+KR)\mathrm{e}^{-KR} \tag{7}$$

$$H_\theta = \frac{\dot{M}}{4\pi\mu R^3}\sin\theta[1+jKR+(KR)^2]\mathrm{e}^{-KR} \tag{8}$$

where θ is the discrete disturbance characteristic of the system, K – the transmission power of the continuous system, R – the updated modulus of the data in the subspace iterative solution, e – the average torque value of working pump load, and $\dot{M}$ – the core magnetoresistance of the hydraulic hybrid drive rotor of the loader, and L – the rotor base number of the loader hydraulic hybrid drive.

Through the previous analysis, the dynamic model and kinematic model of the hydraulic hybrid transmission of the loader can be constructed, the unknown load and power parameters of the hydraulic hybrid transmission of the loader can be identified, and the kinematic model of the control system can be constructed [8].

Identification and correction of power parameters of hydraulic hybrid transmission structure of loader

Double fuzzy PID control is a kind of intelligent control. The corresponding controller is established by double fuzzy PID algorithm. The controller can effectively retain the advantages of conventional controller. At the same time, on the basis of double fuzzy PID control theory, it can realize PID promotion and improve control accuracy. Let the output of the j^{th} neuron be $x_1, x_2,\ldots, x_n$, considering the uncertain factors of the torque coupler and other components, the adaptive weighting algorithm is used to divide the control term of the mechanical hydraulic hybrid transmission system of loader into two parts: deterministic and uncertain, which are multiplied by the weight values of $w_{1j}, w_{2j},\ldots, w_{nj}$. After that, the output state parameters of fuzzy neuron in the generator linear decoupling state u_j are obtained [9]:

$$u = u_{\text{eq}} + u_0 = h_n(\varphi_a, \dot{\varphi}_a) + M_n\ddot{\varphi}_{ad} - M_n c e_2 - \text{sgn}(M_n)\bar{\rho}(t)\,\text{sgn}(s) \tag{9}$$

When the deviation between the output state parameters and the actual demand is large, various types of control laws are switched through fuzzy language variables to ensure the accuracy and rapidity of the control results. When the deviation is small, PID control should be selected in this process to avoid steady-state error in the control process [10]. The aforementioned two control modes are mainly controlled according to the adjustment deviation, and the specific operation logic is:

$$\tilde{U} = \beta U_{\text{PID}} + (1-\beta)U_{\text{fuzzy}} \tag{10}$$

where U_{fuzzy} represents the final output of fuzzy controller, U_{PID} – the final output of PID controller, and Z – the language variable of fuzzy switching [11].

Changing the values of a and b means adjusting the control intensity of different controllers. When the input error is e, assuming $\beta = Z(e)$ the output strength coefficient of PID controller is β, the output strength coefficient of fuzzy controller is $1 - \beta$ and the final output of controller is $\tilde{U}$:

At this time, the fuzzy controller can be controlled to input and output through the control requirements, and the relevant criteria can be used to shrink at the same time, so as to comprehensively improve the comprehensive performance of the controller. The universe corresponding to output and input is affected by the value of different factors. In order to achieve effective scaling factor of universe, it is necessary to realize online adjustment and enhance the quality of control [12].

For the Mamdani type fuzzy controller with double input and single output, the input of the fuzzy controller is set as control deviation and range change rate, Δe, the output is u, the corresponding quantization factors are K_e, $K_{\Delta e}$, and scale factor K_u, which can be calculated by:

$$\begin{aligned} K_e &= K_e\left(k-1\right)+\delta_1 \\ K_{\Delta e} &= K_{\Delta e}\left(k-1\right)+\delta_2 \\ K_u &= K_u\left(k-1\right)+\delta_3 \end{aligned} \tag{11}$$

where δ_1, δ_2, and δ_3 represent the dynamic correction factors corresponding to different quantization factors K_e, $K_{\Delta e}$, and scale factor K_u, respectively, [13].

Because the influence of quantization factor and scale factor on the system is non-monotonic, the influence in different time periods is also completely different. At the same time, each factor restricts each other, which can control the value of deviation and deviation change rate at the same time, and finally complete the correction of different factor values.

At this time, the modified double fuzzy PID control results are introduced, and the outer loop controller is used to adaptively adjust the power parameters of the hydraulic hybrid transmission of the loader:

$$\begin{aligned} \dot{e}_1 &= e_2 \\ \dot{e}_2 &= M_n^{-1}u - M_n^{-1}h_n(\varphi_a, \dot{\varphi}_a) - \ddot{\varphi}_{ad} \end{aligned} \tag{12}$$

Through PID variable structure control, the total input net_j of low pressure of mechanical hydraulic hybrid transmission system of loader is equal to the output x_1, x_2, …, x_n of bidirectional variable pump connected with it. The new training vector of PID output layer of hydraulic hybrid drive of loader is obtained:

$$x(t) = \left[x_0(t), x_1(t), \cdots, x_{k-1}(t)\right]^T \tag{13}$$

Because the shovel operation of loader occupies the most of its working time, the research based on this state is more practical. According to the research, the average torque value of the working pump load is about half of the rated torque value when the loader is working. The working condition is described and defined as the combined working condition. The load value of the working pump is taken as the average value of the load torque, and the adaptive fuzzy PID control of the hydraulic hybrid transmission structure of the loader is carried out considering the hydraulic iterative tracking error and the iterative update rate of the control input. The weight $\omega_j'(j=1,2,3)$ from the hidden layer to the output layer of the hydraulic hybrid transmission of the loader is taken as the constraint, and the output characteristic curve of the engine is obtained by using the fuzzy adaptive decoupling control method. The optimal power matching state of the control input is obtained by inverting the rotational speed at the intersection of the maximum load curve and the curve:

$$\begin{aligned} \frac{\mathrm{d}w}{\mathrm{d}t} &= \frac{w_\infty(V) - w}{\tau_M(V)} \\ w_\infty(V) &= \frac{1}{1+\mathrm{e}^{-0.1(V+35)}} \\ \tau_M(V) &= \frac{400}{3.3\mathrm{e}^{0.05(V+35)} + \mathrm{e}^{-0.05(V+35)}} \end{aligned} \tag{14}$$

So far, the output of the final power matching results, complete the loader mechanical and hydraulic hybrid transmission system dynamic power matching method.

Experiment

When the loader starts from the original speed of zero to the stable speed, the power output value is required to increase with the continuous acceleration of the whole vehicle. At this moment, the most ideal matching working state needs to be satisfied: When the speed ratio of the hydraulic torque converter meets the input of the component with the highest working efficiency, the input characteristic curve of the component just meets the working point near the rated torque value of the engine, and the output power of the system power component engine can be fully utilized to improve the overall energy utilization. The method of [2] is compared with that of [3], and the stability of the loader from starting at zero speed to running at a stable speed is taken as an index for experimental test. Under different control errors, the stability changes of each method are shown in fig. 1.

The experimental data in fig. 1 show that the stability of each method changes with the increase of control error. But compared with the other two methods, the stability of this method is obviously higher, because it adds the double fuzzy PID algorithm and establishes the corresponding controller. With the increase of variables, the sensitivity and freedom of each controller will also increase greatly, and the stability of the system will be improved comprehensively.

For complex systems with multi domain components or interaction subsystems, the complexity of its method application has always been one of the indicators to be measured in the practical application process. Therefore, the comparison between the method in this paper and the method of [2] and [3] is made. The results of the complexity comparison of different methods are given by using fig. 2.

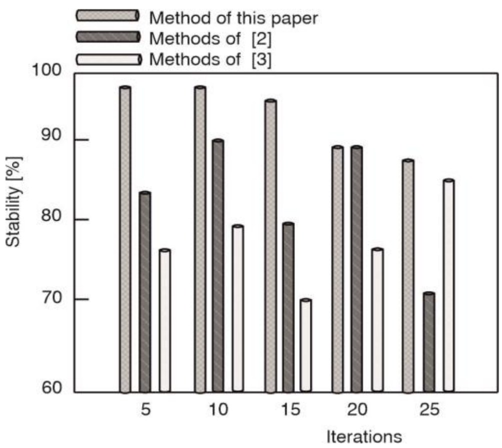

Figure 1. Stability comparison results of different methods

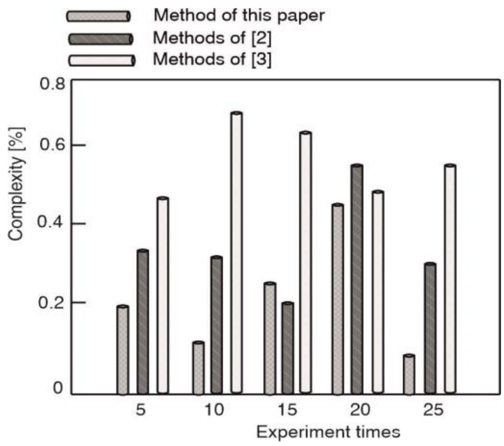

Figure 2. Comparison results of complexity of different methods

The experimental data in fig. 2 shows that the complexity of this method is significantly lower, because this method identifies and modifies the unknown load and power parameters of the loader hydraulic hybrid transmission. On this basis, a parameter matching optimization method based on the loader operating conditions is proposed to ensure that the average power output of the loader in this state is higher than the original scheme, and the average fuel consumption is lower The consumption rate is reduced to meet the requirements of working conditions.

Conclusion

In this paper, based on the analysis of the power characteristics of the hybrid loader, aiming at the working characteristics of the key components in the hybrid drive system and the hydraulic energy regeneration system, the double fuzzy PID control method is adopted to identify and modify the unknown load and power parameters of the hydraulic hybrid drive of the loader. When the output state parameters deviate greatly from the actual demand, the load value of the working pump is taken as the load value. Considering the average torque, the hydraulic iterative tracking error and the iterative update rate of control input, the power parameter matching and optimization of the system are studied, and good application results are obtained.

In this paper, the research on hybrid parameters matching problem, make some results, but there are still some shortcomings to be improved and perfected as follows.

- In this paper, the mathematical models of the key components of the whole vehicle, power transmission system and hydraulic energy recovery system of the hydraulic hybrid loader are established, and the existing theoretical research results are used for reference. The model also needs a large number of actual test data provided by the manufacturer to improve or modify the model to improve the accuracy of the mathematical model. It is helpful to get more accurate constraint conditions of parameter matching. At the same time, we also need a large number of effective data to verify the rationality of the simulation model.
- Due to the lack of effective data, in the parameter matching optimization problem, the production and manufacturing cost of the whole vehicle components of the hydraulic hybrid loader are not used as constraints. Taking the service life of accumulator, the service life of hydraulic torque converter, and the production and manufacturing cost of the system into consideration as the objective optimization function, the parameter matching results obtained in this way will be more practical.
- This paper focuses on the research of parameter matching, but fails to put forward the complete control strategy of energy management of hydraulic hybrid system, which is consistent with the existing models, and cannot guarantee the reasonable and accurate calculation model of vehicle energy consumption. Therefore, in the future research, we need to explore the hydraulic hybrid power system through a large number of practical and effective data, further improve the formulation methods and Strategies of the system, and establish a good foundation for improving the efficiency of the power system.

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