Analysis and Experimental Research on Shifting Impact of Loader Transmission

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Abstract. The evaluation index of loader shift quality was analysed, and the model of the evaluation index was established. The main causes of the shift impact of the transmission were analysed, and it was concluded that the disturbance caused by the torque of the transmission output shaft had a direct relationship with the oil filling and discharging rule in the clutch and the change in oil pressure. Based on theoretical analysis, an accurate control strategy of a proportional solenoid valve to realize electro-hydraulic proportional closed-loop buffering control was proposed. The buffer control of the transmission shift is performed by using this method. The effectiveness of the control strategy was verified by the experiment of the shift oil pressure. The shift impact of the transmission was reduced, and the loader shift quality was improved.

1. Introduction
The reliability, durability and comfort of the loader were greatly affected by the harsh working environment of the loader, the complicated working conditions, and the frequent shifting of the driver[1]. The shift quality was to study the smoothness of the shift process[2]. However, in fact, a single pursuit of extremely short shift time may easily cause the clutch engagement action to be too fierce and aggravate the shift impact. A single pursuit of smoothness in the shift process will extend the shift time. To reduce shifting impacts, and improve the ride comfort of the loader and the service life of parts and components. It is necessary to further research on the evaluation indexes of shifting quality. The effective control strategy was put forward to reduce the shift impact. The fast and stable shift operation of the loader was realized[3]. It can be seen that the problem of shift impact was an important issue in the shift process of the loader transmission, and it was necessary to conduct in-depth research[4].

2. The evaluation index of shift quality
The transmission was an important intermediate component in the loader's power transmission process. When the clutch transmitted torque, the sliding friction was appeared between the clutch discs, which made the input and output speeds equal, and finally realized the variable speed shift. In this process, the clutch has been engaged and disengaged alternately. The working process mainly includes: clutch oil filling, clutch disc joint, clutch pressure building, the pressure and flow of hydraulic oil flowing through the reversing valve were transient variables, resulting in a rapid rise in oil pressure, causing
the shift impacts, extremely reducing the shift quality. To reduce the shift impact and extend the service life of the transmission, during the shifting process: the shift response was fast, and reducing the sliding friction work consumed by the friction elements; the shift process was smooth, and reducing the impact on the moving parts of the transmission. Loader operating conditions were complex, and there were many factors affecting shift quality. There are three commonly used evaluation indicators, namely impact degree, sliding friction work and shifting time[5].

2.1. Impact degree
The shifting smoothness can be measured by the degree of impact. It can be obtained by the first derivative of the vehicle's longitudinal acceleration or the second derivative of the vehicle's longitudinal driving speed. This evaluation index can directly reflect the driving comfort of the loader and has an important impact on the service life of the transmission. This mathematical model is as follows.

\[
j = \frac{da}{dt} = \frac{d^2v}{dt^2} = \frac{r_d \omega_i^2 \omega_o}{i_0 I \omega_o dt}
\]

Where \(a\) is the longitudinal acceleration of the vehicle, \(m/s^2\); \(v\) is the longitudinal driving speed of the vehicle, \(m/s\); \(r_d\) is the wheel radius, \(m\); \(\omega\) is the angular speed of the output shaft of the transmission, \(rad/s\); \(i_0\) is the transmission ratio from the transmission to the wheel; \(I\) is the moment of inertia of the component connected to the transmission output shaft, \(kg\cdot m^2\); \(\omega_o\) is the torque of the transmission output shaft, \(N\cdot m\). It can be seen from equation (1) that the wheel radius, moment of inertia and transmission ratio were all constant values, and the degree of the impact was mainly related to the change rate of the output shaft torque.

2.2. Sliding friction work
The loader shifting process was achieved through the engagement and disengagement of the different clutches. During the engagement process of the clutch discs, there was a speed difference, which caused wear and heat. The work consumed by this clutch was called sliding friction work. It can be seen from the definition that the magnitude of the sliding friction work directly affected the service life and heat consumption of the transmission. This mathematical model is as follows.

\[
W = \int_{t_1}^{t_2} T (\omega_2 - \omega_1) dt = \int_{t_1}^{t_2} \mu F_n z R_m (\omega_2 - \omega_1) dt
\]

Where \(W\) is the sliding friction work; \(t_1\) is the time when the clutch starts slide; \(t_2\) is the moment when the clutch ends slide; \(T\) is the friction torque, \(N\cdot m\); \(\omega_1\) is the angular speed of the clutch’s active plate, \(rad/s\); \(\omega_2\) is the angular velocity of the driven plate of the clutch, \(rad/s\); \(\mu\) is the dynamic friction factor; \(F_n\) is the normal pressure, \(N\); \(z\) is the number of friction pairs; \(R_m\) is the effective radius of the friction plate, \(m\). It can be seen from equation (2) that the sliding friction work was not only related to the difference between the speed of the active and the driven plates and the friction torque, but also to the clutch sliding friction time. To reduce the sliding friction work, it was necessary to shorten the sliding friction time and to engage the clutch as soon as possible.

2.3. Shift time
Shift time was the time from when the controller sent a shift command to when the new gear clutch was fully engaged and run smoothly. During the shifting process, there would be an overlap between the disengagement and engagement time. The overlap time was beneficial to reduce the shift impact and reduce the sliding friction work of the shift. However, the overlap time should not be too long, or the double gears would easily occur. This mathematical expression is as follows.

\[
t = t_1 + t_2 - \Delta t
\]

Where \(t_1\) is the time from when the clutch starts to drain oil to complete separation, \(s\); \(t_2\) is the time of oil filling and pressure boosting process of the clutch, \(s\); \(\Delta t\) is the overlap time between two clutches, \(s\). It can be seen from the equation (1), (2), and (3) that the shift time was longer, and the impact
degree was smaller, and the sliding friction work was the greater. The shift time was shorter, and the impact degree was greater, and the sliding friction work was smaller. Therefore, the shift time directly affected the impact degree and the sliding friction work, and was an important evaluation index for analyzing the shift quality.

3. The cause of shift impact
During the shifting process of the loader transmission, the engagement and disengagement of the hydraulically controlled clutch was mostly performed, so that different clutches were in an oil-filled or oil-discharged state. This change of the shift oil pressure caused fluctuations of the clutch friction torque. The shift impact was caused by the torque fluctuations[6]. The main reasons are as follows.

3.1. Hydraulic impact
The oil pressure in the clutch is the power to control the engagement or disengagement of the clutch. From Equation (1), it can be known that the impact degree is related to the torque change of the transmission output shaft. The impact degree is related to the oil pressure that controls the friction torque transmitted by the clutch. The proper oil pressure change rule can reduce the torque fluctuation of the output shaft and reduce the wear of the clutch. It is necessary to carry out buffer control on the oil pressure of the clutch, and to reduce the impact disturbance caused by the sudden change of oil pressure.

3.2. Inertial impact
During the shifting process of the loader transmission, the transmission ratio changes from one stable state to another. Due to the inertia of the loader itself, the impact and vibration of the load will inevitably be caused, which will cause the shift impact. The control of the inertia impact is mainly realized by the engine throttle control. To avoid an excessive speed difference when the clutch is engaged, the engine speed should be matched with the vehicle speed to improve the smoothness of the shift and reduce the shift impact of the transmission.

3.3. Shift Timing
During the shifting process of the loader transmission, the clutch friction disc engagement and disengagement should have overlap time, which is called shift overlap. The length of the overlap time mainly depends on the starting time of oil pressure and the law of oil pressure increase and decrease [8]. The difference of the shift overlap of the clutch will result in different rules of the filling oil and discharging oil of the clutch. If the shift overlap is too much, there will be a double shift phenomenon. If the shift overlap is insufficient, and causes the driver to lean forward and back. In summary, the main reason of the shift impact is the disturbance of the output torque of the transmission. This disturbance is directly related to the rule of the oil filling and discharging in the clutch and the change of oil pressure.

4. The control strategy of shift impact
The purpose of controlling shift impact is to improve the smoothness of shifting and driving comfort. However, the rapid shift will inevitably lead to a large shift impact. On the contrary, the slow shift will increase the sliding friction time and affect the transmission life[7]. To find the best control strategy to improve the shift quality of a loader, it is necessary to reasonably match the change rule of the shift impact, shift time and sliding friction work.

4.1. Buffering control
The disturbance of output torque is related to the engagement and disengagement process of the friction elements. The commonly used method is to adopt shift buffer control, and use pressure accumulators, throttles, smooth combination valves and proportional solenoid valves in the shift execution hydraulic system. Among them, the proportional solenoid valve is a pilot control element in
the electro-hydraulic shift control loop, which can realize the electro-hydraulic proportional closed-loop buffer control during the engagement of the shift clutch. It has the characteristics of fast movement of the spool valve and small stroke of the spool valve, which can achieve accurate control of the oil pressure in the clutch, and can meet the comprehensive requirements of high precision, low cost and anti-pollution proposed by the loader transmission shift control[8-9]. Therefore, in this paper, the proportional solenoid valve was selected to control the shift oil pressure and reduce the shift impact.

4.2. Timing control
The shift process of the transmission requires smooth shift and fast response, which requires time control of the disengagement and engagement of hydraulic elements. Therefore, the timing control is the coordinated control of the filling and discharging processes of the two clutches, so that the two clutches can alternately engage and shift at the best time. The common methods are to use timing valves, buffer timing valves, and intervention shift timing valves to achieve effective reduction of impact within a given shift time. In summary, the above two methods can reduce the shifting impact to different degrees, but they have certain limitations when used alone. Therefore, the comprehensive design and use of the above two control strategies, which can better solve the shift impact problem.

5. Oil pressure test of loader shifting
According to the test standard, and the loader started a hot car, and under the condition of the transmission hot oil and no-load, the transmission was tested for the shift process at an input speed of 850rpm (idle speed) and 2350rpm (maximum engine speed). When the input speed was 880rpm, the oil pressure test curve of each shift gear was shown in Figure 1.

![Figure 1: The oil pressure curves of the forward gear](image)

Taking the II gear to the III gear in the forward gear as an example. The depressurization stage of the gear pressure PII of the forward II clutch was the AC stage, and the depressurization time was 0.95s. The pressure build-up phase of the forward III oil pressure was the DF stage, and the total pressure build-up time was 0.65s. The oil-filling stage of the clutch was the DE stage, and the oil-filling time was 0.5s. The fast boost stage was the EF stage, and the boost time was 0.15s. The entire shift process was completed at point G, with a total shift time of 1.1s.

It can be seen from the analysis results that the shift time controlled by the proportional solenoid valve selected in this paper was about 1.1s, and the more precise control of the rising oil pressure was achieved. This was different from the general mechanical shift or the smooth combination of valve shift. The clutch oil pressure curve was divided into four stages, namely, the fast filling oil phase, free stroke oil filled phase, buffer the boost phase, and step boost phase. In the boosting phase, the phases were clearly distinguished. By adjusting the duty cycle of the control current, the pressure of the shift engagement elements can be flexibly adjusted to achieve precise and continuous control of the
pressure. The shift impact was reduced. The shift quality of the loader was greatly improved. The effectiveness of the proportional solenoid valve shift control strategy was verified[10].

6. Conclusion
This paper analyzed the evaluation indexes of the shift quality, and established an evaluation index model, and elaborated the internal relationship among the three evaluation indexes of impact degree, shift time and sliding friction work. The main causes of the shift impact of the transmission were analyzed, and it was concluded that the disturbance caused by the transmission output torque was directly related to the oil filling and discharging rule of the clutch and the change of the oil pressure. The common control strategies of the transmission shift impact were analyzed. A proportional solenoid valve was proposed as a pilot control element in the electro-hydraulic shift control loop to achieve accurate closed-loop buffer control of the electro-hydraulic ratio during the engagement of the shift clutch. The analysis results show that the effectiveness of the proportional solenoid valve shift control strategy was verified, and the shift impact of the transmission was reduced, and the shift quality of the loader was improved. The reference basis for the design of the intelligent automatic shift control rule of the loader was provided. It has important engineering practical value.

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