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Research and Application of Test Bench Method for Jaw Type Electronic Differential Lock

Yumeng WANG [a], Jinjun ZHENG [a] and Xin WANG [b,1]
[a] *College of Automotive Engineering, Jilin University, Changchun 130022, China*
[b] *School of Mechanical and Aerospace Engineering, Jilin University, Changchun 130022, China*

Abstract. The situation is quite rough when using the differential lock when the car is out of difficulty， due to high torque or improper operation, the differential lock fails. This has an adverse impact on car brands and driver safety. With the increasing number of off-road vehicles in China, differential lock as one of the important components of off-road vehicles, it is essential to ensure the reliability of the differential lock. At present, the research on differential locks in China is relatively backward and there is no standardized test standard established. In recent years, there has been an increasing demand for research on the performance and reliability of differential locks among enterprises, however, the research on relevant standards and test benches in China is still incomplete. After analyzing relevant experimental standards and theoretical knowledge both domestically and internationally. Based on the actual needs of manufacturing enterprises and the actual usage of the vehicle. This paper provides a test rig method based on the electronic control differential lock of an off-road vehicle. According to the experimental plan, a differential lock durability impact test bench and a static torsion test bench were built, after analyze the test results after conducting relevant experiments, this indicates that both the test plan and the test bench can meet the testing requirements, it will provide relevant basis for differential lock performance and reliability test.

Keywords. Electronic control differential lock, jaw type, test method, test bench

1. Introduction

In recent years, various car companies have increasingly obvious requirements for lightweight in the process of component development [1]. But the accompanying quality issues are also increasingly prominent. The differential lock is a key component in the transmission system, and with the popularization and increasing frequency of use of the differential lock on off-road vehicles. The reduction of weight in the lightweight design process may reduce the reliability of the differential lock, which can easily cause problems such as tooth tapping, bearing failure, and locking mechanism failure, this can lead to a decrease in user satisfaction and even create danger for drivers. At present, there is relatively little research on the bench test of the electronically

[1] Xin WANG, Corresponding author, Jilin University, School of Mechanical and Aerospace Engineering, Changchun 130022, China; E-mail: wangxin_cau@jlu.edu.cn.

controlled jaw type differential lock, existing test methods are mostly used for traditional limited-slip differential such as viscous coupling type and high friction type. When one side of the wheel slips, the driver directly engages a forced locking differential lock such as a jaw type lock during the process of getting out of the trap, which can cause a significant impact on the differential lock and easily cause it to fail. Therefore, it is necessary to study the testing methods for the performance and reliability of the differential lock and build a test bench.

This article provides a test plan for the electric differential lock with locking static torsional strength and impact performance, and builds a test bench based on the test plan to test its function [2].

2. Development of Experimental Plan

2.1. Calculation of Test Load

Due to the fact that the test object is a differential assembly or drive axle equipped with an electronically controlled differential lock, refer to the provisions of QC/T 533-2020 "Driving Bridge Abutment Test Method", calculate the test load of the entire transmission system firstly. Calculate the maximum torque value of the engine on the half shaft output end based on the maximum output torque of the engine, the first gear ratio of the transmission, the torque distribution ratio of the transfer case, and the drive axle speed ratio. When there is slip on one side of the wheel, the differential lock is locked. At this time, the maximum theoretical torque value borne by the nonslip half shaft end is twice that of the normal state. Considering that the efficiency loss of the transmission system is about 80% [3], the torque calculation method for the output end of the drive axle is as follows:

$$M_{pe} = 2 \times 0.8 M_{emax} \cdot i_{k1} \cdot i_p \cdot i_0 \cdot \frac{1}{n} \tag{1}$$

M_{pe} is the maximum output torque of the nonslip end, M_{emax} is the maximum output torque value of the engine, i_{k1} is the first gear ratio of the transmission, i_p is the low gear ratio of the transfer case, i_0 is the speed ratio of the main reducer of the drive axle, and n is the number of drive axles when using the low gear ratio of the transfer case.

As the engine torque continues to increase, the friction between the tires and the ground also increases. When the friction is greater than the ground adhesion, the wheels start to slip. At this time, the torque of the transmission system cannot increase. Therefore, it is necessary to calculate the ground adhesion, and the calculation formula is:

$$M_{p\varphi} = P \cdot \varphi \cdot r_k \tag{2}$$

$M_{p\varphi}$ is the maximum adhesion force on the ground, P is the axle load acting on one side of the wheel, φ is the adhesion coefficient, and r_k is the rolling radius of the tire. Compare with and take the smaller one as the maximum test load on the wheel edge.

2.2. Differential Calculation

The experiment mainly simulates the state of a car when it gets out of trouble. When the wheels slip, there is a difference in speed between the two sides of the wheels, and at the limit state, one side of the car wheel spins idle at a speed of ω_1, while one side of the wheel does not move at a speed of ω_0, set the speed of the differential housing to ω_N=n, in the limit state ω_0=0, ω_1=2n, when engaging the differential lock at a speed of ω_0= ω_1=n. Due to the requirement of the maximum differential allowed for engagement in the tooth mounted differential lock, it is necessary to calculate the maximum differential value. Set the maximum allowable differential to ω_{max}. The condition for the smooth combination of the tooth embedded differential lock is that the sliding combination sleeve is under the action of thrust and return spring, and the sliding combination sleeve and fixed combination sleeve are at a speed of ω_{max}, the Central angle turned at max must be less than the Central angle corresponding to the engagement clearance S [4]. The calculation formula is:

$$\omega_{max} < \frac{S \cdot 30}{R \cdot t \cdot \pi} \tag{3}$$

And t is the time when the axial displacement of the sliding joint sleeve exceeds the transitional arc between the side of the fixed joint sleeve and the tooth crown, R is the outer diameter of the sliding joint sleeve. The force relationship during the combination of the sleeve is:

$$F_C = F_P - F_B = ma \tag{4}$$

F_C is the binding force of the combination sleeve, F_P is the thrust of the electronic locking mechanism on the sliding combination sleeve, F_B is the elasticity of the return spring, m is the mass of the sliding combination sleeve, and a is the axial acceleration of the sliding combination sleeve. Assuming the axial clearance between the sliding joint sleeve and the fixed joint sleeve is H, the axial movement distance from the tooth surface to the end of the joint is h, the time is t, the stiffness of the return spring is K, and the axial movement distance of the sliding joint sleeve is S, then:

$$\mathrm{h} = \frac{1}{2}\mathrm{at}^2 \tag{5}$$

$$F_B = KS = K\ (H + h) \tag{6}$$

Thus, it can be concluded that:

$$\mathrm{t} = \sqrt{\frac{2\mathrm{h} \cdot \mathrm{m} \cdot \mathrm{g}}{\mathrm{F_P} - \mathrm{K}\ (\mathrm{H+h})}} \tag{7}$$

Bring (7) into (3) to calculate ω The maximum value of max, g is the Gravitational acceleration value [5].

2.3. Design of Experimental Plan

After calculating the test force and test speed, the differential lock can be tested by building a test bench. In order to simulate the actual working state of the differential lock of the driving axle when one side of the wheel slips on the test bench, and accurately obtain the fatigue and strength values of the differential lock, the test content is divided into differential lock impact durability test and static torsional strength test after locking [6].

2.3.1. Design of Lock Impact Durability Test Plan

The purpose of the lock up impact durability test is to simulate the situation where the wheel on one side of the car slips and uses the differential lock to escape, therefore, the functions that need to be implemented include: Apply resistance to one side of the wheel while the other side is empty, atomatically control the differential lock to engage and disengage at the appropriate time, apply speed to the input end of the drive axle using a motor. The schematic diagram of the test bench connection is shown in figure 1.

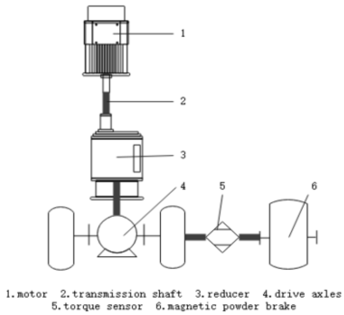

Figure 1. Schematic diagram of locking impact durability test bench.

The magnetic powder brake provides torque to the wheels on the right side of the drive axle, left wheel is free. Connect the FRM01 relay module in series to the control circuit of the motor and the control circuit of the differential lock, thus achieving timed on-off of the motor and differential lock. When the motor is powered on and rotates, the differential speed at both ends of the drive axle is reduced. The control differential lock is electrically combined, and the wheels on both sides of the vehicle rotate simultaneously due to the effect of the differential lock, after a certain period of time, the motor stops rotating and the differential lock is powered off before entering the next cycle [7]. The loop flowchart and relay level variation diagram are shown in figure 2.

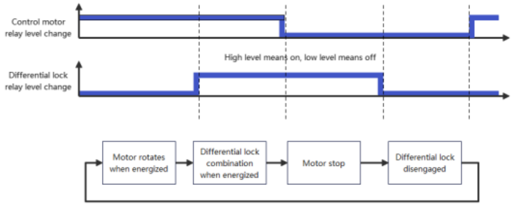

Figure 2. Loop flow diagram and relay level change diagram

2.3.2. Design of Static Torsional Strength Test Plan for Differential Lock Locking

The static torsional strength test for differential lock locking is to test the maximum torque value borne by the drive axle transmission components during differential lock locking. Referring to the provisions of QC/T 533-2020 "Driving Bridge Bench Test Method" for the static torsion test method of the driving axle assembly, set one half axle of the drive axle can be fixed with a bracket, while the other half axle is unloaded. After locking the electronic differential lock, apply a rotational speed to the input end of the drive axle. The test speed of the input end of the drive axle is loaded at n=0.24r/min until any component fails [8]. The schematic diagram of the platform is shown in figure 3.The experimental process is shown in figure 4.

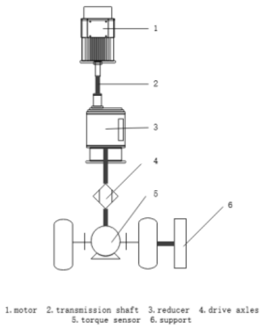

Figure 3. Schematic diagram of differential lock static torsional strength test.

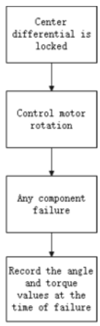

Figure 4. Flow Chart of differential lock static torsional strength test.

3. Construction and Testing of Test Bench

3.1. Test Bench

According to the designed experimental plan and content, the test bench was constructed. The test piece was a front drive axle equipped with an electronic differential lock. The constructed test benches are shown in figure 5 and figure 6, respectively.

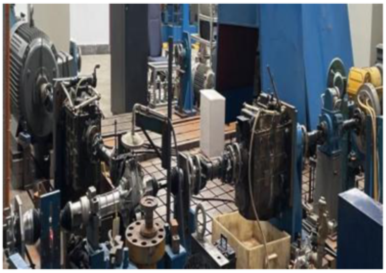

Figure 5. Built Lock Impact Durability Test Bench.

Figure 6. Locking Static Torsion Test Bench.

3.2 Test Process and Results

Install the drive axle equipped with a differential lock on the test bench, control the motor to reach the required test speed, and control the loading of the magnetic powder brake, control the motor to reach the required test speed, control the loading of the magnetic powder brake, and the torque value of the magnetic powder brake can be controlled by the current magnitude of the steady current power supply. Due to the torque of the magnetic particle brake does not vary with the speed under constant excitation current. Therefore, a stable test load can be provided during the test process, and the motor speed is controlled by a frequency converter and set to a constant value. After calculation, the test speed difference between the two wheels of the lock impact durability test is 50r/min, and the loading torque of the magnetic powder brake on the wheels is 2000Nm.Set the closing and opening time of the relay and control the motor to ensure that there is sufficient time to reach the required speed for the test after the motor is started. After the motor stops, there is enough time for the differential lock to fully disengage .The differential lock control relay should meet the requirements for the length of the combined and disconnected time periods and the accuracy of the time points. After debugging, the control conditions of the relay within one cycle are shown in table 1 set a cycle working condition to 18 seconds, with a control stage every 6 seconds. The motor starts from 0 to 6 seconds to achieve a differential speed of 50 r/min on both sides of the drive axle. The motor continues to operate at a stable speed for 7-12 seconds, with the differential lock engaged; From 13 to 18 seconds, the motor stops rotating and the differential lock is disconnected, returning to the initial state and preparing to enter the next cycle [9].

Table 1. Control conditions of relays.

Item	Status		
Time(s)	0~6	7~12	13~18
Motor relay status	energize	energize	outage
Differential lock relay status	outage	energize	outage

During the testing process, torque and speed sensors are used to view and read the changes in the speed and torque values of the test piece. The test bench uses Xiangyi JCZ series sensors, and the sampling equipment uses JX-3 efficiency meter. The sampling frequency is set to 0.1s.The torque speed variation curve within a cycle is shown in figures 7 and 8.

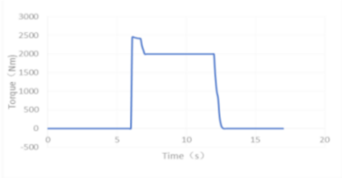

Figure 7. Torque variation within one cycle

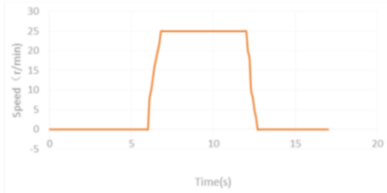

Figure 8. Speed variation within a cycle.

According to the curve analysis, when the differential lock is combined with the instantaneous torque value, it will experience a brief peak and then tend to stabilize. The instantaneous impact of this torque is the main reason for the failure of the differential lock and even the entire transmission system [10]. According to the fatigue damage theory, as the number of cycles increases, the fatigue damage of the entire transmission system also increases. Therefore, it is possible to determine whether its reliability meets the requirements based on the number of cycles, and targeted strengthening can be carried out for the failure form and location. The statistical results of the experiment are shown in table 2.

Table 2. Statistics of test results.

Test piece number	Number of cycles	Failure situation	Failure location	Test Conclusion
1	2237	does not engage	Engaging gear failure	Need to enhance gear strength
2	3341	cannot be disengaged	Locating pin broken	Need to enhance the strength of the positioning pin
3	5570	does not engage	Pusher failure	Need to improve the pushing material
4	15000	Not expired	None	meets the requirements

The locking static torsional strength test uses a motor to drive a cycloidal pinwheel reducer, rotating the differential locking drive axle assembly at an input speed of 0.24r/min until any component fails. The locking static torsional strength test uses a motor to drive a cycloidal pinwheel reducer, rotating the differential locking drive axle assembly at an input speed of 0.24r/min until any component fails. The sensor can also use the Xiangyi JCZ series, and the torque meter adopts the JW-3 model, with a sampling frequency set to 1s. The variation curve of angular torque and failure location of the test are shown in figures 9 and 10.

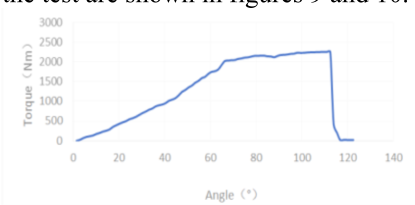

Figure 9. Locking Static Torsion Test Angle and Torque Variation Curve.

Figure 10. Photos of failure parts.

Calculate the loss of effectiveness reserve coefficient K according to QC/T 534-12020"Evaluation Indicators for Drive Bridge Abutment Test

$$K = \frac{M_k}{M_p} \tag{8}$$

M_k is the failure torque, M_p is the test calculated torque, and K should be greater than 1.8.

4. Conclusion

With the increasing number of off-road vehicles in China, In recent years, there has been an increasing demand for research on the performance and reliability of differential locks among enterprises. Based on the actual needs of manufacturing enterprises and the actual usage of the vehicle. This article provides a test plan for an electronically controlled tooth embedded differential lock. Using magnetic particle brakes to simulate road loads, and combining equipment such as reducers, torque sensors, and motors to build an experimental platform, the microcontroller can control the combination and disconnection time of the differential lock, the cycle can be set according to the actual situation. Build a test bench according to the experimental plan and conduct testing. The experimental platform has a simple structure, the cost is low and it is easy to build and Capable of meeting the testing requirements during use. And it is easy to maintain. After analyze the experimental data, the test results indicate that the test method and the constructed test bench can meet the performance and reliability testing requirements of the differential lock. It can propose key influencing factors for designers. Key influencing factors can be proposed for designers, namely, focusing on reasonable design for reliability and performance requirements, it can improve work efficiency and shorten product development cycle.

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