Analyzation and solution of disconnecting fault of high-speed and heavy-duty shift gearbox

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Abstract: In order to solve the disconnecting fault of high-speed shift gear box, this paper uses finite element analysis to study the wear of transmission fork, the transmission of axial force by gear and the cause analysis of gear synchronizer disconnecting fault. A kind of oil film technology is put forward to form oil film between the contact working face of gear sleeve and shifting fork slider, so as to achieve the friction effect of separating the two friction surfaces by liquid. At the same time, the improvement scheme of shift fork material is changed to solve the problem of gearbox fork wear and disconnection. The reliability and stability of the transmission shift mechanism are improved.

1. Introduction
Shift transmission is an important part of the power transmission test bench. Its main function is to transfer power safely and reliably, and the speed is adjusted to meet the requirements of multi-range deceleration or growth by switching the variable speed gear. In the test process, the transmission is required to work safely and reliably, and there must be no off-gear and other causes of test parking. 12350KW three-speed gearboxes and 700KW four-speed gearboxes are provided by our company for the comprehensive performance test system of vehicle high-power transmission device for a scientific research institute. The general and mature heavy vehicle transmission synchronizer and inverted bevel gear structure locking gear are adopted, and the positioning pin (steel ball) is used to locate the gear socket. In the first and second gearshift test of high torque gearbox, the gearshift 'dial block' is damaged abnormally. After 100 hours of test, due to excessive wear, there will be a sudden shift phenomenon. That is, the transmission synchronizer gear sleeve and its combination of the “gear seat” off, resulting in tooth beating, power cannot be transmitted. Excessive copper chips are deposited in the lubricating oil to form a mixture of copper chips, which causes the filter to be blocked and the normal work of gearbox cannot be carried out. If re-test, serious safety accidents will be led to, the safety of test system and test products will be directly affected. Therefore, it is of great significance to analyze and study the transmission off-gear fault of the test system and solve the problem of transmission off-gear for improving the reliability of transmission shift.
2. Introduction of Shift Transmission
Because the structure and working principle of 350KW gearbox is same to 700KW gearbox in this paper, the 350KW one will be taken as an example to illustrate, which as shown in Fig. 1:

2.1 Transmission structure and working principle

![Transmission principle diagram](image1)
![Transmission principle physical diagram](image2)

Fig. 1 Transmission Principle of Shift Transmission

The main working characteristics of the shift transmission on the test bench are as follows:

(1) The shift gearbox consists of a two-stage parallel helical gear drive with hard tooth face, input and output shaft center.

![Self-locking pin position](image3)
![Positioning pin position](image4)

Fig. 2 Self-locking pin position
Fig. 3 Positioning pin position

(2) The rated input power is P=350kW, the rated input torque is 4775N.m, motor constant torque speed range is 0-699r/min. Constant power speed range is 699-3800r/min. When the reduction ratio is 1:1, the input speed range is 0-3000r/min. When the reduction ratio is 3.479 and 8.433, the input speed range is 0-3800r/min.
Actual speed ratio: I gearshift is 8.433:1; II gearshift is 3.479:1; III gearshift is 1:1.

Manual fork shifting, the shifting mechanism consists of two fork shifting mechanism, the speed is adjusted by switching between the three gear to meet the requirements. Interlock pins are mounted between two sets of dial fork mechanisms (inside the box) to avoid the simultaneous working state of multiple transmission gears caused by error operation. The shifting box fork or gear sleeve is empty in the middle position; is the work block in the left or right position, respectively.

2.2 Transmission fork mechanism
The fork mechanism are shown in Fig. 4 as follows.

Fig. 4 Substantive diagram of fork-dial mechanism

3. Analysis of the reasons for the failure of transmission box dial block
In this section, 700KW four-shift gearbox is taken as an example to analyze the failure causes of the shift gearbox.

3.1. Analysis of Off-gear Force (Axial Force) of 700KW Four-block Transmission
In general, synchronizers and inverted bevel gear structures are used to lock stop gear, and positioning pins (steel balls) are used between gear sockets in heavy-duty vehicle transmissions and low-power industrial gearboxes. After hanging gear, in generally the shifting mechanism is not necessary to be forced to the dial fork and the dial block to overcome the breaking or breaking force. There is no static pressure between the shifting dial block and the gear sleeve groove, so there is no wear problem.

For the transmissions with high-power, high-torque and high-speed, if the ordinary heavy-duty gear shifting technology is adopted, the small tripping force generated by the transmission during operation only can be overcome. In order to ensure the transmission capacity, the diameter of the gear shifting combined tooth is generally designed to be larger, and the tooth width is also several times of the ordinary heavy trucks. In this paper, the transmission combined with the locked inverted bevel gear cannot be designed with a large angle. In order to ensure that the gear is not off, the locking pin is usually added to the gearshift mechanism.

In the structure of automobile transmission, the internal and external spline tapering process is used to eliminate the influence of its force and prevent the phenomenon of off-gear. The tapering angle is generally 2–3°. Since the transmission torque of 700KW four-speed transmission is large, the effective length of spline is much longer than that of the similar structure of automobile transmission. 2–3° chamfering angle been not allowed for the long effective length of spline. The maximum chamfering angle of 700KW four-speed transmission can only be 1.5° at present. However, this angle is found from the bench load test of the gearbox that is not enough to offset the influence of axial force. That is, the axial force applied on the shift fork is difficult to eliminate, although the fixing pin is added outside the box at the first and second gear positions in the design. Reaction force exerted by locking pin of dial block through shifting fork mechanism, and the dynamic off-gear force generated during operation is overcome by the dial block presses the gear sleeve. At low speed or low torque, due to the small
deformation of the combined tooth, the vibration of the gearbox and the dynamic breaking force is small. When running at high speed and high torque, the breaking force is large, the pressure and linear velocity between the dial block and the gear sleeve are high, and the wear of the dial block will occur.

Because the spline in gear shifting sleeve is gap fit (7H/6d) with gear seat and gear shifting gear, after the gear shift is connected, an axial force pointing to the empty gear direction is generated by the gear sleeve under the action of two forces (opposite direction) of gear spline and gear seat spline. The greater the transfer torque, the greater the axial force.

3.2. Estimation of maximum breaking force of 700KW four-speed gearbox

The second gear off-shield force and operation are analyzed and estimated by according to 700KW four-speed gearbox test conditions. When the 700KW four-speed gearbox is loaded at the factory table, the locking pin is not added to the side of the fork, the fork and the handle mechanism return after hanging. After adding the locking pin, the force of the shift handle lock stop pin is larger. When the second gear is tested, bending phenomenon of locking pin also occurred, as shown in Fig. 5. According to the bending deformation of the locking pin to estimate the size of the breaking force, the locking pin support model is established as shown in Fig. 6:

![Fig. 5 Deformation diagram of locking pin at shift handle](image)

![Fig. 6 Locking pin support model](image)

The finite element model of locking pin deformation is established based on KISSSOFT software, and the deformation of locking pin is obtained by simulation as shown in Fig. 7.

![Fig. 7 Screenshot of finite element analysis](image)

According to the above figure, the deformation angle of locking pin is approximately 10°, and the transformation displacement is about 5mm. According to this model and based on the displacement of 5mm, the calculation method of the breaking force can be obtained.

\[ F_\text{1} = \frac{L_1}{L_2} \cdot F_0 \]

In this formula: \( F_\text{1} \) is the breaking force on dial block, \( F_0 \) is the deformation force of locking pin, \( L_1 \) is locking pin force arm, \( L_2 \) is force arm of dial block. After calculation, the off-arching force on the dial block is 9.7kN.
3.3. Estimation of Action Pressure and Shear Stress of Pin Shaft

Since the breaking force is overcome by one or two gear shifting mechanism through the dial fork side locking pin, the deformation of shifting fork is caused, in actual operation, the force of two shifting blocks is obviously unbalanced. Therefore, the pressure on the working side of the dial block and the shear stress of the shaft pin are calculated according to the working limit of a dial block. The working linear velocity is calculated by the outer diameter linear velocity of the gear sleeve, and the following can be obtained:

\[
PV = P_1 \cdot v = \frac{F_1 \eta}{S_1} \cdot \frac{2\pi r n}{60}
\]

\[
\tau = \frac{F_1}{S_2}
\]

In this formula: \( P_1 \) is pressure on working side of dial block, \( \eta \) is unbalance coefficient, \( S_1 \) is side area of dial block, \( \tau \) is shearing stress, \( v \) is sliding linear velocity, \( r \) is outer diameter of gear sleeve, \( n \) is top speed, \( PV \) is PV value of action surface.

The PV value of action surface is 75.6, and the maximum shear stress is 13.74MPa.

Through the above reasons and data analysis, it is believed that the excessive wear of the dial block is due to the lack of sufficient lubrication under the axial force, an excessive friction is caused (PV value is too large), and also a partial load due to uneven force.

3.4. Analysis of gear – synchronizer shafting

The mechanical model of gear shifting gearbox bearing, input shaft, intermediate shaft, output shaft, gear, synchronizer (inner ring, combined with sleeve installation) shafting dynamic change is established, as shown in Fig. 8. Finite element analysis is carried out [2]. The analysis results are shown in Fig. 9 and Fig. 10.
It can be seen from Fig. 9 and Fig. 10 that during the load operation of the gearbox, bending elastic deformation of tooth shaft occurred under radial force and gyroscopic moment. The maximum axial force of about 300N is generated by the deformation of the shaft system in the gear shifting gearbox, and the maximum strain of about 440MPa is generated by the locking ring. Transmission off-gear occurred when the axial friction between the lock ring and the gear sleeve is less than the axial force on the gear sleeve.

3.5. Cause analysis of block material
The original block material was designed as QAL10-3-1.5 and the mechanical properties of the material were as follows: $\sigma_b = 540\text{MPa}$, $\delta = 20\%$, HB=117.5, allowable sliding velocity is 4m/s. 4m/s is the maximum linear velocity available for and the sliding velocity at the position of shift block is 7.2 m/s. It can also be seen from the failure picture that the wear is relatively serious, and there are two reasons for the failure of the dial block. First, the material used in the original design is weak, and the requirement of allowable sliding speed cannot be satisfied by QAL10-3-1.5. Second, effective lubrication cooling is lacked of in the working side, wear is aggravated by dry and excessive friction. The reasons of Aluminum bronze structure, lack of stiffness, lack of strength of the material itself can be basically eliminated However, the friction reduction performance is weak. See Fig. 11 below:

4. Improvement scheme
Based on the analysis of the above failure causes, the following improvement schemes are proposed for the wear failure of shifting fork dial block.

4.1. Material improvement
Replacing the dial material, the material is replaced by the casting copper alloy with high friction reduction characteristics of lead or other copper alloy materials with similar properties, such as: ZCuSn10P1. The mechanical properties of the material are as follows: $\sigma_b = 320\text{MPa}$, $\delta_5 = 5\%$, HB = 88.5. The material has good wear resistance, good friction reduction characteristics, and is not easy to
bite. It has good casting performance and cutting performance. Under high load (20MPa) and high sliding speed of 8 m/s, the performance is stable and reliable, which is higher than that of raw materials.

4.2. Block structure improvement

The oil film is formed between the contact face of gear sleeve and fork slider under the action of oil film technology. The friction effect of two friction surfaces separated by liquid is achieved [4]. The working face with block structure is designed with lubricating oil circuit. The gear oil with pressure of 0.15-0.25MPa is led out from the gearbox lubrication system, and enters the working face from the inside of the shift block, so as to ensure that the working face combined with the shift block and gear sleeve is in an effective lubrication state.

![Fig. 12 Block Structure Improvement Diagram](image1)

![Fig. 13 schematic diagram of lubricating oil scheme for shift mechanism](image2)

5. Conclusion

In this paper, the finite element analysis technology, material mechanical properties and other methods are used to analyze the fork wear and off-gear of the shifting transmission of the test bench. A new method of using oil film technology is proposed. A certain pressure oil film is formed between the contact face of the gear sleeve and the shifting block, and the oil film friction effect between the two friction surfaces is achieved. The safety, reliability and stability of gearbox shifting mechanism are improved. The gearbox has been used continuously for 5 years without exception.

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