Optimized Design of Operating Mechanism for Planetary Steering Machine of Tracked Vehicle

LI Guo-qiang¹, Wang Xing-ye²

¹ Department of Vehicle Engineering, Academy of Army Armored Force, Beijing 100072, China
² Troop 63850, PLA, Baicheng 637001, China
*Corresponding author’s e-mail: 2003lgq@sohu.com

Abstract: Due to the limitation of the structure and working principle of the steering device of the secondary planetary steering machine, it is impossible to adjust the braking force of the small brake and the steering radius on the basis of the first position. It is difficult to correct the direction accurately when driving at high speed, which affects the performance of the vehicle. The steering device of a tracked vehicle is analyzed. In order to solve the problems, a hydraulic control device was designed, and the tracked vehicle was reformed. The improved prototype was tested and the steering radius could be adjusted steplessly in a large radius range.

1. Introduction
Tracked vehicles have outstanding advantages including large grounding area, good adhesion, strong climbing ability, small turning radius, strong ability to overcome obstacles and cross-country, so they are widely used in the moving parts of special vehicles, such as military vehicles, construction machinery and forest fire fighting vehicles. The steering devices of special tracked vehicles mostly use steering clutch and planetary steering gear. Two-stage planetary steering gear is widely used in tracked vehicles because of its small size, light weight and simple structure. The operating mechanisms are generally mechanical or hydraulic. Due to the limitation of the structure and working principle of the control device, the steering performance of the secondary planetary steering gear has not been fully developed, which affects the performance of the tracked vehicle.

2. Work analysis of the two-stage planetary steering machine

2.1 Work modes of the two-stage planetary steering machine
The two planetary steering machines are arranged symmetrically on the high speed tracked vehicle, the working principle is shown in Fig.1. The change of the driving status of the tracked vehicle is controlled by the lock-up clutches (C1, C2), big brakes (TA1, TA2) and small brakes (TB1, TB2). Theoretically, the two-stage planetary steering machine has 13 different working modes as shown in Table 1.

2.2 Power analysis
In the process of turning with the two-stage planetary steering machine, the required power of the engine is

\[ N_{eg} = \frac{P_2V}{\eta} - \frac{P_1V(R_g-0.5B)}{(R+0.5B)\eta}, \tag{1} \]
Table 1 Work modes of the two-stage planetary steering machine

| No. | Driving status                              | C1 | TB1 | TA1 | C2 | TB2 | TA2 | R       |
|-----|--------------------------------------------|----|-----|-----|----|-----|-----|---------|
| 1   | Straight driving                            | •  | ○   | ○   | •  | ○   | ○   | <∞      |
| 2   | Partial separated steering                   | ○  | ○   | ○   | •  | ○   | ○   | >Rf     |
| 3   | Separated steering                          | ○  | ○   | ○   | •  | ○   | ○   | Rf      |
| 4   | Central steering in first position          | ○  | ○   | ○   | •  | ○   | ○   | Rg1     |
| 5   | Steering on first position                  | ●  | ○   | ○   | ●  | ○   | ○   | Rg1     |
| 6   | Central steering in the second position     | ○  | ○   | ○   | ●  | ○   | ○   | Rg1 > Rg2 |
| 7   | Steering in the second position             | ○  | ○   | ●   | ●  | ○   | ○   | Rg2     |
| 8   | Thrust augmentation steering                | ○  | ●   | ○   | ●  | ○   | ○   | <∞      |
| 9   | Thrust augmentation separated steering      | ○  | ○   | ○   | ●  | ○   | ○   | Rf      |
| 10  | Thrust augmentation partial brake steering  | ○  | ○   | ○   | ●  | ○   | ○   | Rg1 > Rg2 |
| 11  | Thrust augmentation brake steering          | ●  | ○   | ○   | ●  | ○   | ○   | Rg2     |
| 12  | Vehicle braking                             | •  | ○   | ○   | ●  | ○   | ○   | <∞      |
| 13  | Brake steering in the first position         | ○  | ●   | ○   | ○  | ○   | ○   | Rg1     |

Note: The symbol “○” represent separate completely, symbol “◎” represent the clutch partial combined or partial brake, symbol “●” represent the clutch completely combined or completely brake.

The power consumption to overcome external resistance is

\[ N_w = P_2 v - P_1 v \left( \frac{R - 0.5B}{R + 0.5B} \right), \]

(2)

the brake power is

\[ N_{mg} = P_1 v \left( \frac{R - R_g}{R + 0.5B} \frac{\eta_m}{(R_g + 0.5B)} \right), \]

(3)

the cycle power is

\[ N_x = P_1 v \left( \frac{R g_1 - 0.5B}{R g_1 + 0.5B} \eta_{xh} \right), \]

(4)

The cycle power loss in transfer process is

\[ N_{xs} = P_1 v \left( \frac{R g_1 - 0.5B}{(R g_1 + 0.5B)} (1 - \eta_{xh}) \right), \]

(5)

Where \( v \) is the speed of the high speed track; \( P_1 \) and \( P_2 \) are the steering resistance forces of the low speed track and high speed track respectively; \( R \) is the steering radius; \( R_g \) is the required steering radius; \( R_{g1} \) is the required steering radius in the first position; \( R_{g2} \) is the required steering radius in the second position; \( \eta \) is the total efficiency of the vehicle; \( \eta_{xh} \) is efficiency from the low speed side to the high speed side.

The power consumption of two-stage planetary steering gear with different steering radius is shown in Fig.2. In Fig.2, \( N \) denotes power, \( R \) denotes the steering radius, \( B \) denotes the center distance of the tracks. It can be found that with the increase of steering radius, the engine power needed to steer \( N_{fg} \) and the power consumption needed to overcome the external resistance \( N_w \) decreases. There is a cycle.
3. Optimized design of the operating mechanism for the two-stage planetary steering machine

3.1 Work principle and existing problems of the operating mechanism

The operating mechanism adopts a hydraulic-assistance device, the structure and work principle are shown in Fig.3. The control principle and structure of the left and right steering gears are basically the same. The control principles are as follows: pulley arm controls the moving disk of the lock-up clutch ($C_1$, $C_2$), pulley lever controls the inclined pull rod of the small brake belt ($TB_1$, $TB_2$), and the double arm lever controls the inclined pull rod of the big brake belt ($TA_1$, $TA_2$). The pulley arm and the pulley lever are equipped with pulleys and controlled through the angle control of the dispatching board. The angle of the dispatching board is controlled by the front and rear. The core of the control device is the angle of the control board, the control board is controlled by the control rod through the front and rear longitudinal pull rod. There are three positions from front to back: the original position, the first position and the second position, which correspond to (a), (b), (c) in Fig.3 respectively. Fig.3(a) is straight driving corresponding to the status 1 in Table 1, the lock-up clutch is combined, the big and small brake belts are loosened at this moment; Fig.3(b) is steering in the first position corresponding to the status 5 in Table 1, the pulley of the pulley lever and the groove on the dispatching board ensure a gap of 5mm at this moment; Fig.3(c) is steering in the second position corresponding to the status 7 in Table 1. The braking force of the big brake belt is controlled by the force applied on the joystick, and the steering radius can be adjusted within a certain range. When the joystick work between the original position and the first position, the lock-up clutch is separated, the driving wheel of this side is powered off, which is separated steering corresponding to the status 3 in Table 1.

Due to the limitation of steering operating mechanism, the small brake belt can be either fully clamped or completely loosened, and cannot be continuously controlled, which result in the steering radius also cannot be adjusted continuously. The steering radius of this type of vehicle is separated steering $R_f$, first position steering $R_{g1}$ and second position steering $R_{g1~Rg2}$. Affected by ground resistance and engine speed, $R_f$ is about 80–120 m. As the steering radius is too large, it can only be used at high speed. Affected by high and low speed track slippage, the steering radius $R_{g1}$ is about 7.7–15 m. When the big brake belt is fully tightened, the steering radius is $R_{g2}$, about 1.4 meters. When the big brake belt is partly tightened, the steering radius range is $R_{g1~Rg2}$. The second position steering can only be used in the first and reverse gear. When the gear is high, it is difficult for the big brake belt to tighten the brake drum and steer. At present, the maximum speed of tracked vehicles equipped with two-stage planetary steering machine is 50–60Km/h. If steering with radius $R_{g1}$ at high speed, the vehicle is prone to tail flick with a small steering radius. When the ground is hard and the lateral adhesion is small, the vehicle may cross-slip and out of control. When steering with radius $R_f$, the vehicle maybe cannot turn completely because of the large steering radius. In order to achieve the desired steering, the vehicle speed has to be reduced. According to statistics, the turning radius of tracked vehicles below 5 meters is 2%, between 5–20 meters is 15% and above 20 meters is 80%. The two-stage planetary steering machine with the original operating mechanism is difficult to meet the requirements of high-speed steering. High-speed steering must reduce vehicle speed, which affects the performance of vehicles.

3.2 General scheme of the optimized operating mechanism
As the operating mechanism has a hydraulic-assistance device, and there is a hydraulic system on the vehicle, the optimized steering operating mechanism is changed to hydraulic control, and the actuator is connected directly with the manipulator by hydraulic cylinder. The lock-up clutch moving disk, small brake drive linkage lever and big brake drive linkage lever are manipulated respectively. The general installation of the actuator is shown in Fig.4.

There are six hydraulic cylinders: left and right lock-up clutch cylinders (LG3, RG3), left and right small brake belt cylinders (LG1, RG1), left and right big brake belt cylinders (LG2, RG2). The hydraulic circuit is as shown in Fig.5, the lock-up clutch cylinder adopts switch control to realize the separation and combination of the locking clutch when the cylinder extension and retraction. The big and small brake belt cylinders adopt servo control to control the cylinder extension and retraction, which can continuously adjust the output of the cylinder and realize the force adjustment of the big and small brake belts.

3.3 Selection of the hydraulic components

3.3.1 Determination of cylinder diameter of the lock-up clutch

The push force of the cylinder should satisfy

\[ F_c = \frac{1}{4} \pi D_c^2 p \geq F_{c_{\text{max}}} \]  

In the formula, \( F_c \) is the push force of the lock-up clutch; \( D_c \) is the diameter of the cylinder; \( p \) is the pressure of the system; \( F_{c_{\text{max}}} \) is the maximum push force required by the lock-up clutch.

3.3.2 Determination of cylinder diameter of the big and small brake belts

The vehicle adopts floating brake belt, which has the effect of bidirectional assistance. The diameter of brake belt cylinder can be calculated according to the following formula:

\[ F_z = \frac{1}{4} \pi D_z^2 p \geq \frac{2M}{(e^\mu - 1)D} \]  

In the formula, \( F_z \) is the push force of brake belt cylinder; \( D_z \) is the diameter of brake belt cylinder; \( \mu \) is the friction coefficient between brake belt and brake drum; \( \alpha \) is the wrap angle of brake belt; \( M \) is the maximum braking torque of brake drum; \( D \) is the outer diameter of brake drum.
3.3.3 Selection of the pressure control components

In order to realize the continuous adjustment of the brake force, two electro-hydraulic proportional pressure relief valves are used in the hydraulic system. The input pressure of the brake cylinder is adjusted by the electro-hydraulic proportional pressure relief valve, satisfying the adjustment of braking force during steering and braking.

4. Working principle of the optimized operating mechanism

The optimized hydraulic operating mechanism of planetary steering machine is manipulated by steering handle. When manual driving, the steering handle sends out steering signal to control each cylinder action, and when unmanned, the computer sends out control signal. When the vehicle is running in a straight line, the solenoid reversing valve is not electrified. The piston rods of each cylinder (LG3, RG3, LG2, RG2, LG1, and RG1) are not extended. The left and right locking clutches are combined and the big and small brakes are loosened.

4.1 Separated steering

Take the left turning as an example. Turn on the left solenoid valve LF3. When the vehicle needs to turn (take manual left turning as an example), the steering handle is pulled to the left side, the reversing valve LF3 is turned on, the left locking clutch cylinder LG3 piston rod is extended, the clutch is completely separated, the power of the active wheel is cut off on this side, the other cylinders are not manipulated, and the vehicle is separated steering to the left.

4.2 Steering in the first position

Continue to turn the handle to the left. Under the circumstance that the LF3 is electrified, the steering handle sends out a switch signal and an analog signal. The switch signal controls the electrification of the solenoid valve LF1, solenoid valve LF1 reverses direction, the piston rod of the small brake cylinder LG1 extended. The analog signal controls the current of the electro proportional pressure reducing valve BL1. The larger the left turning angle of the steering handle is, the larger the control current is, the higher the outlet pressure of the electro-hydraulic proportional pressure relief valve BL1 is, the greater the force of the small brake belt is, and the smaller the turning radius. When the handle moves to the first position.

(a) Original position

(b) The first position

(c) The second position

1. Moving disk of the lock-up clutch; 2. Inclined pull rod of the big brake belt; 3. Inclined pull rod of the small brake belt; 4. The double arm lever; 5. Pulley arm; 6. Rear longitudinal pull rod; 7. Pulley lever; 8. Dispatching board; 9. Hydraulic assistance device; 10. Front
on the left, the braking force of the small brake belt reaches the maximum. At this time, it is the first position turning, and the steering radius is $R_{g1}$. Since the braking force of the small brake belt can be steplessly adjusted, the turning radius can be adjusted in a certain range continuously. The range of the adjustment is $R_{g1} - R_{f}$.

### 4.3 Steering in the second position

Continue to turn the handle to the left. The solenoid valve LF$_3$ is still electrified and the solenoid valve LG$_1$ is cut off. So that the solenoid valve reverses, the piston rod of LG$_1$ cylinder with small brake belt retracts, the small brake belt loosens the small brake drum, and the steering handle sends out a switch signal and an analog signal. The switch signal controls the electrification of solenoid valve LF$_2$, and the solenoid valve LF$_2$ reverses direction. The piston rod of big brake belt cylinder LG$_2$ extends. The analog signal controls the current of electro-hydraulic proportional decompression valve BL$_2$. The bigger the left turning angle of steering handle, the bigger the control current, the higher the outlet pressure of electro-hydraulic proportional decompression valve BL$_2$, the bigger the control force of small brake belt and the smaller the steering radius. When the handle moves to the second position to the left, the braking force of big brake belt reaches the maximum. At this time, it is the second position steering, and steering radius is $R_{g2}$. Since the braking force of the big brake belt can be steplessly adjusted, the steering radius can be adjusted in a certain range continuously, and its adjustment range is $R_{g1} - R_{g2}$.

When the steering handle is loosened, all the solenoid valves turn off, the lock-up clutch cylinder and the brake cylinder retract, the locking clutch engages, the brake is loosened, and the vehicle enters a straight line running state.

### 4.4 Working process of brake

The big brake of the vehicle is the parking brake of the vehicle. When the brake pedal is stepped down, the solenoid valves LF$_2$ and RF$_2$ are electrified, the valve core reverses direction, the piston of LG$_2$ and RG$_2$ of the big brake belt is extended to push the big brake belt to wrap the brake drum. The larger the stroke of the brake pedal is, the higher the oil pressure at the outlet of the electro-hydraulic proportional pressure relief valve BL$_2$ is, the greater the braking force is.

### 5. Experiment and conclusion

#### 5.1 Experiment

In order to verify the feasibility of the optimized operating mechanism, a vehicle was retrofitted according to the above scheme, and the vehicle test was carried out. The test curve of the first position steering of the vehicle is shown in Fig.6.

![Curves of the vehicle steering angular speed under different pressures of the small brake belt cylinder](image)

**Fig.6** Curves of the vehicle steering angular speed under different pressures of the small brake belt cylinder

When the vehicle steers, the engine speed remains basically unchanged, the speed of the high-speed side track is basically unchanged, and the steering angular speed of the vehicle varies with the control
pressure. The steering radius of the vehicle can be calculated by formula (8). The higher the control pressure, the higher the steering angular speed, and the smaller the steering radius.

\[ R = \frac{V^2}{\omega} - 0.5B \]  

(8)

5.2 Conclusion

Tracked vehicles have high transmission power and bad working environment. After the steering operating mechanism is changed to hydraulic control, the operation is labor-saving, the executing mechanism responds quickly, the vehicle steering is flexible, and the automation of steering control is realized. The main advantages are as follows:

5.2.1 As the steering operation is more simple and labor saving, only one hand is needed when steering, the other hand of the driver is liberated, so that the driver will have more energy to do other things.

5.2.2 When the brake is worn, the hydraulic control device can compensate for the mechanical gap within the range of cylinder stroke, which means that the operation device is self-adaptable in a certain degree, improves the reliability of steering operation system and simplifies the operation and maintenance.

5.2.3 Stepless steering is realized on the basis of the first position of the tracked vehicle, which greatly improves the steering performance of the vehicle at high speed, and further develops the motor performance of the vehicle.

Reference

[1] Mingde Wang. Running Principle of Tank [M]. Beijing: National Defense Industry Press, 1983: 188-192.
[2] Ruiyin Xu, Yinhao Hou, Zhian Song, et al. Hydraulic transmission technology [M]. Shandong: Shandong science and technology press, 2009: 76-88.
[3] Lian Huang. Tank Structure and Calculation [M]. Beijing: Academy of Armored Forces Engineering, 1986: 145-154.
[4] Chuang Lu, Yingrong Ye, Hongwei Yuan, et al. Analysis of 552 tank crew with low back pain [J]. Clin J Med Offic, 2002(2):34-35.