Analysis of High Speed Steering Drift of Tracked Vehicle

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Abstract: In order to control the high-speed steering drift of tracked vehicles correctly, the dynamics and kinematics characteristics of tracked vehicles during high-speed steering are analyzed. The expressions of traction force, braking force and steering resistance moment for high-speed and low-speed side tracked tracks are derived. The influence of centrifugal force on the steering of tracked vehicles is analyzed. The steering radius, steering angular velocity and the critical speed and limit speed when the vehicle drifts are given. Finally, the calculation method is used to analyze the safety of high-speed steering vehicle, and an example is given. The conclusion can be used to guide the evaluation of steering performance of tracked vehicle and the correct operation of high-speed steering.

1. Introduction
The steering of tracked vehicles will produce centrifugal force. The higher the steering speed is, the greater the centrifugal force is. When the speed is high enough, due to the influence of centrifugal force, the tracked vehicle will produce drift (cross-slip). In normal driving, in order to ensure the safety of the vehicle, drift should be avoided as far as possible. It is very dangerous, and it is hard for the driver to control the vehicle trajectory accurately through normal control when drifting. However, in the application or competition of professional driving skills, professional drivers often use high-speed steering drift to achieve rapid turning and give full play to the mobility of the vehicle, which may achieve unexpected effects, help the competitors achieve the goal of shortening the time to steer quickly by precise drift control.

2. Dynamics of tracked vehicle in steering

2.1 Force analysis of tracked vehicle steering
In order to simplify the research, the horizontal steering is used to study the problem. Assuming that the center of gravity of the tracked vehicle is coincide with the geometric center of the vehicle, the normal load and steering resistance of the tracked vehicle are evenly distributed on the lower tracked track, the force analysis of tracked vehicle during uniform steering is shown in Figure 1. The steering radius of the vehicle is R, and the centrifugal force P₁ produced during steering is at the center of gravity of the vehicle, and the centrifugal force can be divided into two components, the transverse component Pₓ and longitudinal component Pᵧ. Due to the effect of transverse component of centrifugal force, the steering poles on both sides of the track are offset, and the steering center of the corresponding vehicle is offset, transfer from the point OC to O. The steering angular velocity of the vehicle is ω:
\[ \omega = \frac{v_2}{R + \frac{B}{2}} \]

The steering radius of the tracked vehicle is (Distance from point O to point C):

\[ R_C = R \cos \alpha \]

The centrifugal force of the tracked vehicle is:

\[ P_L = m \omega^2 R_c = \frac{4GRV_2^2}{(2R + B)^2g \cos \alpha} \]

The transverse component \( P_{Lx} \) and longitudinal component \( P_{Ly} \) are:

\[ P_{Lx} = P_L \cos \alpha = \frac{4GRV_2^2}{(2R + B)^2g} \]
\[ P_{Ly} = P_L \sin \alpha = \frac{4GRV_2^2 \tan \alpha}{(2R + B)^2g} \]

The resistance moment (relative to the centre of gravity) in steering is:

\[ M_{\mu} = \frac{G}{L} \left( \frac{L}{2} - \lambda \right) \mu \left( 2\lambda + \frac{L}{2} - \lambda \right) \]
\[ M_{\mu} = \frac{\mu G}{L} \left( \frac{L}{2} + \lambda \right) \left( \frac{L}{2} - \lambda \right) = \frac{\mu G}{L} \left( \frac{L^2}{4} - \lambda^2 \right) \]

The steering moments corresponding to the centre of the lower track on both sides can be calculated as:

\[ (P_{2x} - R_2)B - \frac{B}{2} P_{Ly} = (P_{3x} + R_3)B + \frac{B}{2} P_{Ly} \]

The steering moment and steering resistance moment of tracked vehicle are equal when steering at uniform speed. The required traction force \( P_{x2} \) and braking force \( P_{x1} \) can be obtained.

\[ P_{x2} = \frac{\mu G}{BL} \left( \frac{L^2}{4} - \lambda^2 \right) + \frac{1}{2} P_{Ly} + R_2 \]
\[ P_{x1} = \frac{\mu G}{BL} \left( \frac{L^2}{4} - \lambda^2 \right) - \frac{1}{2} P_{Ly} - R_1 \]

The support forces of the both sides track are:

\[ N_2 = \frac{G}{2} + \frac{h_c}{B} P_{Lx} = \frac{G}{2} + \frac{4GRV_2^2 h_c}{(2R + B)^2 gB} \]
The kinematic resistances of the two sides of the track are as follows:

\[ R_2 = fN_2 = f \left( \frac{G}{2} + \frac{4GRV_c^2h_c}{(2R+B)^2gB} \right) \]
\[ R_1 = fN_1 = f \left( \frac{G}{2} - \frac{4GRV_c^2h_c}{(2R+B)^2gB} \right) \]

The pulling force required for high-speed steering is:

\[ P_{2x} = \frac{\mu G}{BL} \left( \frac{L^2}{4} - \lambda^2 \right) + \frac{fG}{2} + \frac{2GRV_c^2 \tan \alpha}{(2R+B)^2g} + \frac{4fGRV_c^2h_c}{(2R+B)^2gB} \]
\[ P_{1x} = \frac{\mu G}{BL} \left( \frac{L^2}{4} - \lambda^2 \right) - \frac{fG}{2} - \frac{2GRV_c^2 \tan \alpha}{(2R+B)^2g} + \frac{4fGRV_c^2h_c}{(2R+B)^2gB} \]

In the formula, \( V_2 \) is the speed of the track; \( g \) is gravity acceleration; \( B \) is track center distance; \( L \) is track length in contact with the ground; \( \mu \) is steering resistance coefficient; \( f \) is the ground motion resistance coefficient of tracked vehicle; \( \lambda \) is steering pole offset; \( h_c \) is the height of vehicle center of gravity; subscript "1" represents parameters of inner track; subscript "2" represents parameters of outer track.

### 2.2 Influence of the centrifugal force on steering of the tracked vehicle

#### 2.2.1 Steering pole forward migration

Because of the effect of the transverse component \( P_{LY} \) of centrifugal force, in order to maintain the balance of transverse force, the steering pole must be moved forward, and its offset \( \lambda \) is

\[ \lambda = \frac{2LRV_2^2}{(2R+B)^2\mu g} \]

The maximum offset of steering pole is 0.5L when tracked vehicle steers.

#### 2.2.2 The ground normal branching reaction force, motion resistance force and steering resistance force on the outer track are larger than those on the inner track.

Due to the influence of the centrifugal lateral force component \( P_{Lx} \), the tracked vehicle generates an outward moment \( P_{Lx}h_c \), which increases the pressure on the ground from the outer track and decreases the pressure on the ground from the inner track. Therefore, the forces on the outer track are larger than those on the inner track.

#### 2.2.3 The required pulling force and braking force decrease.

When the tracked vehicle steering at a high speed with a certain radius on the given ground, the main factor affects the required traction force \( P_{2x} \) and braking force \( P_{1x} \) is the steering angular speed. At first, the influence of the steering angular velocity on traction force could be analyzed. With the increase of steering angular velocity \( \omega \), the centrifugal force \( P_1 \) increases, the longitudinal component \( P_{LY} \) and the transverse component \( P_{Lx} \) increase, and the increase of longitudinal component \( P_{LY} \) lead to the increases of \( P_{2x} \), the increase of transverse component \( P_{Lx} \) will lead to the increases of the normal branch reaction force and the high-speed side motion resistance force \( R_2 \) slightly, so the required pulling force \( P_{2x} \) increases slightly. While, at the same time, the increase of transverse component \( P_{Lx} \) will also lead to the increase of \( \lambda \), and the increase of \( \lambda \) will result in the significant decrease of \( P_{1x} \). As the later influence is more remarkable, the required traction force decreases with the increase of centrifugal force. Secondly, the influence of the steering angular velocity on braking force is analyzed as follows. With the increase of steering angular velocity \( \omega \), the centrifugal force \( P_1 \) increases, the
longitudinal component $P_{Ly}$ and transverse component $P_{Lx}$ increase. The increase of longitudinal component $P_{Ly}$ will lead to the decrease of the required braking force $P_{x1}$ slightly, the increase of transverse component $P_{Lx}$ will lead to the decrease of the normal branch reaction force $N_1$, the decrease of the low-speed lateral motion resistance $R_1$, and further lead to slightly increase of $P_{x1}$. While the increase of the transverse component $P_{Lx}$ will also lead to the increase of $\lambda$, and a patent decrease of $P_{x1}$. As the latter influence is more remarkable, the braking force required decreases with the increase of centrifugal force.

3. Steering kinematics of tracked vehicle

3.1 Kinematics analysis of the two sides tracks
Considering the actual steering motion of tracked vehicles, the high and low speed tracks will inevitably slip during steering. The steering motion of tracked vehicles is shown in Fig. 2. The instantaneous steering centers of high-speed track and low-speed track are shifted to positions $O_1$ and $O_2$ respectively. The offset values are $A_1$ and $A_2$ respectively, and the actual velocities of high-speed and low-speed tracks are $V_{2S}$ and $V_{1S}$ respectively, as the vehicle has the same angular velocities everywhere.

$$\omega \left( R - \frac{B}{2} \right) - V_1 = \omega A_1$$
$$-\omega \left( R + \frac{B}{2} \right) + V_2 = \omega A_2$$

Actual steering radius and angular speed can be obtained:

$$\omega = \frac{V_2 - V_1}{B + A_2 + A_1}$$
$$R = \frac{V_2 + V_1}{2\omega} - \frac{A_2 - A_1}{2}$$

The trail of the vehicle without drift is shown by the dotted line in Figure 2, and the trajectory after drift is shown by the solid line.

3.2 Determination of the critical velocity in drift
Tracked vehicles may drift when steering at high speed due to the unbalanced centrifugal force and the lateral adhesion of the ground, or overturn due to the excessive centrifugal force. The speed at which drift occurs during steering is called critical velocity in drift and the speed at which overturn occurs during steering is called limit velocity in steering.

When a tracked vehicle steers at high speed, if the centrifugal force is greater than the lateral adhesion of the vehicle, and the lateral adhesion of the ground is not enough to balance the centrifugal force of the vehicle steering, the vehicle will have a lateral move or drift. The maximum lateral adhesion of the vehicle is $G\mu_{\text{max}}$. The critical speed of the drift is the speed of the high-speed side when drifting.

$$P_{LX} = G\mu_{\text{max}}$$

The critical velocity of the high speed steering is:

$$v_{2l} = \frac{2R + B}{2R} \sqrt{\frac{gR\mu_{\text{max}}}{\mu_{\text{max}}}}$$

In the formula, $\mu_{\text{max}}$ is the maximum steering resistance coefficient of tracked vehicle when braking steering with radius $R=0.5B$, and it can be measured by experiment.

When the vehicle drifts, as the steering pole moves forward, the lateral speed of the tail is greater than the lateral speed of the head. The feeling of "tail flick" is obvious.

3.3 Determination of the limit velocity when steering
The lateral centrifugal force $P_{Lx}$ forms a moment which causes the vehicle to overturn outwards when turning at high speed. With the increase of centrifugal force, the overturning moment becomes larger and larger. When the overturning moment is greater than the vehicle's stability moment, the vehicle will overturn. At this time, the vehicle speed is the limit velocity:
\[ P_{Lx} \cdot h_c = G \cdot \frac{H}{2} \]

\[ \frac{4GRV_{2j}^2}{(2R + B)^2g} \cdot h_c = G \cdot \frac{H}{2} \]

The ultimate steering speed of tracked vehicle is:

\[ V_{2j} = \frac{2R + B}{4Rh_c} \sqrt{2gHRh_c} \]

4. Case analysis and calculation

A certain high speed tracked vehicle G=36t, L=3.84m, B=2.64m, H=3.2m, \( h_c = 1.159 \text{m} \), the theoretical turning radius of the vehicle is 7.7m, and the actual turning radius is 10~15m, suppose that the turning radius is 12m, the maximum speed is 50km/h. Typical pavements are selected for analysis: grassland (steering resistance coefficient is the largest), good soil road, cement road, frozen ground. The movement resistance and steering resistance coefficient of different pavements are shown in Table 1.

Table 1 Kinematic resistance coefficient and steering resistance coefficient of typical pavement

| pavement     | grassland | Good soil road | Cement road | Frozen road |
|--------------|-----------|----------------|-------------|-------------|
| \( f \)      | 0.08~0.1  | 0.06~0.07      | 0.03~0.04   | 0.03~0.04   |
| \( \mu_{max} \) | 0.85      | 0.5~0.6        | 0.35~0.42   | 0.19        |

According to the formulas above, the critical drift velocity and the limit velocity of high-speed steering are calculated respectively as shown in Table 2.

Table 2 Critical drift velocity and limit velocity of the typical pavements (km/h)

| pavement     | grassland | Good soil road | Cement road | Frozen road |
|--------------|-----------|----------------|-------------|-------------|
| Critical drift velocity | 34.0      | 24.5           | 22.9        | 16.1        |
| Limit velocity       | 51.1      | 51.1           | 51.1        | 51.1        |

From the calculation results, it can be found that the maximum limit speed of the tracked vehicle is 51.1 km/h when steering, and the maximum critical speed is 34 km/h when steering, which is far less than the limit speed. So theoretically speaking, lateral rollover will not occur when the vehicle steers, because before rollover, the vehicle will drift due to insufficient lateral adhesion. Although tracked vehicles generally will not roll over when steering flat, if the ground resistance suddenly changes dramatically when the high-speed steering drift occurs, the vehicle suddenly decelerates laterally and generates a great inertia force, which acts in the same direction of centrifugal force and acts on the center of gravity of the vehicle. The overturning moment suddenly increases and the vehicle is easy to roll over.

As the critical velocity of vehicle steering is related to many factors, the critical velocity of typical road surface with different turning radius is calculated as shown in Figure 3. It can be seen from the figure that the critical velocity of turning has a great relationship with the properties of pavement. Under the same steering radius, the greater the maximum steering resistance coefficient, the higher the critical velocity.
5. Conclusion

Generally speaking, when the tracked vehicles drift because of high speed steering, the traction force and braking force required for high-speed steering are reduced. And the larger the centrifugal force is, the larger the reduction extent of traction force and braking force is, so the centrifugal force is beneficial to the steering of tracked vehicles.

As the vehicles drift could realize high speed steering, the vehicles can pass through the bend faster and turn round quickly. Using the drift of the vehicle can make full use of the maneuverability of the tracked vehicle. In the actual operation, the drift of the vehicle should be flexible according to the condition of the vehicle and the road. It is necessary to accumulate enough experience through a lot of practice to accurately control the trail of the vehicle and ensure the safety of the vehicle. Otherwise, it is easy to roll over.

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