Impact Analysis of Track Slip in Sediment on Submarine Tracked Vehicle Steering Performance

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Abstract. In combination with the requirements of the Tracked Vehicle-Cable Salvage project, which is aiming at the characteristics of the submarine crawler slip, the impact of the slip rate on the tangential drive to steering radius and steering angular velocity of the submarine crawler chassis. it is analyzed from the theoretical and experimental levels. Simplify the force model of the working submersible during steady-state steering, and it can obtain the steady-state steering body dynamics equation; in order to solve the arbitrary shear rate and shear displacement of the grounding surface in the steering process. According to the steering geometry relationship, it can combined with the empirical experience of seafloor sediments. The model derives the longitudinal driving, lateral resistance and drag torque of the left and right side of the track when it is during steady-state steering; when we analyzes the instantaneous lateral shift of the track shear rate during steady-state steering; it derives the instantaneous rate of the instantaneous steering rate, which based on the geometric relationship of the steering motion. The relationship between the offset and the steering radius of the body, the steering angular velocity, and the sliding rate as a function of the steering radius and steering angular velocity of the body; when the steering model test is carried out to verify the influence of the slip rate on the steering radius and the steering angular velocity; The slip rate has an effect on both the steering radius and the steering angular velocity. It was measured steering radius becomes larger, the steering angular velocity becomes smaller, and the theoretical prediction curve is basically consistent with the measured data.

1. Introduction
With the development of offshore oil and gas, offshore wind power can be development, coastal and island construction, it can submarine cable pipelines have increasingly become an important channel for the transportation of materials, which is the information and energy in the sea area. The construction speed of submarine cable pipelines is accelerating, and the demand for operation and maintenance of submarine cable pipelines has increased significantly[1-3], submarine cable operation and maintenance equipment was born. When the Sub Marine Tracked Vehicle-Cable Salvage is mainly used to complete thetask related to faulty cable salvage repair[4,5]; the equipment is mainly composed of submarine crawler running mechanism, which we called excavation clearing system, operation hooking system, hydraulic power system, electronic control and sensing monitoring and so on[6]. System and other components, which became the performance of the submarine crawler walking mechanism directly determines the success or failure of the equipment operation[7-8].
In this paper, the characteristics of the submarine crawler slip are analyzed from both theoretical and experimental aspects. The influence of the slip rate on the tangential drive, which is steering radius and steering angular velocity during steady-state steering, when is calculated and analyzed. The validity of the theoretical analysis is verified by the scale model test; it provides a reference for the late design, we call it the performance prediction and offshore application of the submersible.

2. **Tracked Vehicle - Cable Salvage Steady Steering Mechanics Modeling**

Sub Marine Tracked Vehicle-Cable Salvage (SMT-CS) is powered by a submarine self-propelled chassis as a carrier. The left/starboard track drive is adjusted to overcome the steering resistance torque, which is shown in Figure 1.

![Figure 1 Schematic diagram of the working principle and composition of the cable salvage equipment](image)

The lateral resistance \( R_{CL} \) and \( R_{CS} \) expressions for the left and right-side tracks are:

\[
\begin{align*}
R_{CL} &= \int_{t_1}^{t_2} f_{TL} dx_L = \int_{t_1}^{t_2} f_{TL} dx_L = \frac{1}{2} b_r \tau(s_{IL}) dy_L dx_L \\
R_{CS} &= \int_{t_1}^{t_2} f_{TS} dx_S = \int_{t_1}^{t_2} f_{TS} dx_S = \frac{1}{2} b_r \tau(s_{IS}) dy_S dx_S
\end{align*}
\]

The left and right-side track resistance torques \( M_{RL} \) and \( M_{RS} \) are expressed as:

\[
\begin{align*}
M_{RL} &= \int_{t_1}^{t_2} f_{TL} x_L dy_L = \int_{t_1}^{t_2} f_{TL} x_L dy_L = \frac{1}{2} b_r \tau(s_{IL}) x_L dy_L dx_L \\
M_{RS} &= \int_{t_1}^{t_2} f_{TS} x_S dy_S = \int_{t_1}^{t_2} f_{TS} x_S dy_S = \frac{1}{2} b_r \tau(s_{IS}) x_S dy_S dx_S
\end{align*}
\]

The shear displacement component is:

\[
s_{IL} = \left( L_H - D_{IC} \right) - y_{IL} \left[ 1 - \frac{\alpha_{IL}}{R_{p,H}} R_{g,H} \theta_{p,H} \right] \\
s_{IS} = \left( L_H - D_{IC} \right) - y_{IL} \left[ -\frac{\alpha_{IL}}{R_{p,H}} \theta_{p,H} \right]
\]

3. **Analysis of the effect of slip rate on tangential drive and steering radius**

3.1 The effect of slip rate on tangential drive

Take the Sub Marine Tracked Vehicle-Cable Salvage (SMT) as an example for calculation and analysis. The general characteristics of SMT are shown in Table 1.
Table 1. General characteristics of SMT

| Name                      | Performance parameter description | Name                      | Performance parameter description |
|---------------------------|-----------------------------------|---------------------------|-----------------------------------|
| Dimensions                | 5.8m × 5m × 2.5m                  | Water weight              | 20 ton (buoyancy adjustment)      |
| (L × W × H)               |                                   | Chassis half gauge        | 1.85m                             |
| Strip length and width    | 1.3m                              | Track pitch               | 0.19m                             |
| Grounding half length     | 1.9m                              | Bearing wheel spacing     | 0.38m                             |

During the steady-state steering of the walking chassis, the tangential traction force \( F_t = F_{TL} + F_{TS} \) and the tangential walking resistance \( R_c = R_{CL} + R_{CS} \) are both related to the track slip ratio \( i \). Therefore, the tangential effective driving force \( F_D = F_t - R_c \) of the traveling chassis is also necessarily a function of the slip ratio. Because the actual working conditions are more complicated and the calculation requirements are high, the special working conditions are taken here for analysis. It is assumed that the self-propelled submersibles have a steady-state differential left turn, and the left and right-side track slip ratios satisfy \( i_L = -i_R = i \). The \( F_t - i \) curve, the \( F_D - i \) curve, the \( R_{CL} - i \) curve, and the \( R_{CS} - i \) curve are obtained, as shown in Figure 2 (half logarithmic display).

From the slip curve of Figure 2, it can be seen that:

1) Tangential traction force \( F_t \), effective towing force \( F_D \). The slip curve has a hump-shaped distribution; in the initial stage, the slip rate increases, the tangential traction force and the effective drag force increase to the peak value. At this time, the optimal slip ratio \( i_{opt} = 0.018 \), the corresponding peak value tangential traction force \( F_{t,\text{max}} = 96.85 \text{kN} \), at this time peak effective drag force \( F_{D,\text{max}} = 89.36 \text{kN} \);

2) As the slip rate continues to increase, the tangential traction force \( F_t \) decreases significantly and finally stabilizes at 39.92 kN, while the effective drag force \( F_D \) decreases with increasing resistance \( (R_{CL}, R_{CS}) \). At \( i = i_{lim} = 0.523 \), the effective drag force \( F_D \) decays. Zero, at this time, although the strip continues to shear the deposit, there is no actual propulsion effect;

3) The design of self-propelled submersible crawler is the running mechanism the maximum tangential working load during the steering process, it cannot be lower than 15kN, and the design margin of 1.3 is taken. At this time, corresponding effective drag force \( F_D = 19.5 \text{kN} \), it is rounding takes 20kN, corresponding slip. The lower limit of the transfer rate is \( i = 0.002 \) and the upper limit is \( i = 0.354 \); therefore, the design allowable slip rate interval is \( i_{per} \in (0.002, 0.354) \); when the track trencher is in normal operation, the load change slip rate changes within the allowable interval; the
allowable slip rate interval. In addition, the tangential effective drag force during steady-state steering cannot meet the design requirements of the workload.

### 3.2 Influence of slip rate on steering radius and steering angular velocity

The slip rate can be calculated by measuring the rotational speed of the drive wheel and the absolute displacement of the track relative to the ground; the relationship between the slip ratio and the drive ratio and the steering radius can be used to analyze the steering-related performance. The relationship between $R'/R$ and $K_{Dr}$ is shown in Figure 3.

![Figure 3: Relation curve of $K_{Dr}$, $i$ and $R'/R$](image)

The left figure of Figure 3 is the change relation of $R'/R$ within the interval of $K_{Dr} \in [1.2, 3]$ and $i \in [0, 0.3]$; the right figure is $i = 0.1, 0.2, 0.3$, and $R'/R$ varies with $K_{Dr}$. It can be seen from Figure 3 that:

1. Due to the influence of the slip rate $i$ of the left and right side tracks, the ratio $R'/R$ is always greater than 1, which means that when the driving ratio $K_{Dr}$ is constant, the steering radius increases under the action of the sliding drive and the sliding resistance;

2. When the driving ratio $K_{Dr}$ increases, the effect of the slip rate on the steering radius becomes smaller;

3. There is a steady-state steering minimum driving ratio $K_{Dr\_min} = (1-i_1)/(1-i_2)$, and when $K_{Dr} \leq K_{Dr\_min}$, due to the existence of the slip rate $R'/R \to \infty$, the body steering effect at this time is not obvious.

### 4. Sub Marine Tracked Vehicle - Cable Salvage Model Steering Test

The Sub Marine Tracked Vehicle-Cable Salvage test was carried out using a scale model.

The model steering test solution is shown in Figure 4. The entire system consists of a lifting platform, a circular mud pool and a submersible scale model.

![Figure 4: Steering test solution for SMT scaled model](image)
The geometric relationship between the measured quantities of the steady-state steering process is shown in Figure 5.

**Figure 5** Geometric relationship of motion parameters during a steady-state turn for SMT scaled model

During the steady-state steering process, the traction force and the load are in equilibrium. Therefore, the depth of the load can be inserted into the soil during the test to obtain different slip rates.

According to the heavy-duty slow-moving, medium-load constant speed, when light-load fast port-side steering design test variables, it can be found the scene photo in Figure 6.

**Figure 6** Steady-state tearing tests of SMT scaled model

According to the previous theoretical derivation, the results are shown in Table 2.

**Table 2** Data Processing results of the steady-state steering test

| Test number | Track slip rate \(i_L\) \(i_S\) | \(R\) (m) | \(\omega_{TZ}\) (rad/s) | \(R'\) (m) | \(\omega_{LZ}'\) (rad/s) | \(R' / R\) | \(\omega_{LZ}' / \omega_{TZ}\) |
|-------------|--------------------------|---------|-----------------|---------|-----------------|---------|-----------------|
| 1           | -0.098 0.013             | 3.45    | 0.013           | 4.524  | 4.939           | 0.010  | 0.008           | 1.431  | 0.615           |
| 2           | -0.102 0.049             | 3.45    | 0.013           | 5.189  | 5.352           | 0.009  | 0.009           | 1.551  | 0.692           |
| 3           | -0.188 0.093             | 2.07    | 0.053           | 3.190  | 3.344           | 0.034  | 0.030           | 1.615  | 0.566           |
| 4           | -0.145 0.143             | 2.07    | 0.079           | 3.287  | 3.332           | 0.048  | 0.044           | 1.609  | 0.557           |
| 5           | -0.207 0.223             | 1.38    | 0.264           | 2.058  | 2.256           | 0.158  | 0.146           | 1.634  | 0.553           |
In Table 2, the ratio $R'/R$ of the measured data to the ideal state is greater than 1, which indicates that the slip rate has an influence on the steering radius, and its existence makes the actual turning radius larger; the analysis results are consistent with the previous theoretical predictions; the measured data and the ideal The ratio $\omega_{TZ}'/\omega_{TZ}$ of the state is less than 1, which indicates that the slip rate has an influence on the steering angular velocity, and its existence will slow the steering speed of the body. The previous theoretical predictions are consistent with the experimental results.

According to the test analysis results, the slip rate-steering radius curve and the slip rate-steering angle speed curve are shown in Figure 7 and Figure 8.

![Figure 7 Relation curve of $i_L, i_R - R'$](image)

![Figure 8 Relation curve of $i_L, i_R - \omega_{TZ}'$](image)

It can be seen from Figure 7 and Figure 8 that the theoretical calculation curves of the relationship between the left and right side track slip ratios ($i_L, i_R$) and the body turning radius $R'$ and the body steering angular velocity $\omega_{TZ}'$ are consistent with the trend of the measured results, so when the foregoing relates is the steering radius and the steering angular velocity. It can be seen the theoretical analysis is effective.

5. Conclusion
(1) The dynamic model is established by the force analysis of Tracked Vehicle-Cable Salvage during steady-state steering; the calculation shows that the track slip rate $i$ has an effect on the steering drive performance of the walking chassis during steady-state steering; tangential traction $F_T$, The tangential effective drag force $D_F$ has a hump-shaped distribution with the change of the slip rate $i$; there is a limit slip rate. When $i \geq 0.523$, the strip plate continues to shear the sediment, but there is no actual propulsion effect;

(2) According to the geometric relationship analysis of the amount of walking chassis movement during the steady-state steering process, which can be shown the relationship between the steady-state steering special operating condition slip rate $i$, the driving ratio $K_D$, and the actual turning radius $R'$ is derived; the simulation calculation shows that the track Under the action of slipping, the steering radius $R'$ becomes larger and the steering angular velocity $\omega_{TZ}'$ becomes smaller. The analysis results show that the effective allowable slip ratio of the Tracked Vehicle-Cable Salvage is $i_{max} \in (0.002, 0.354)$, beyond which the chassis drive cannot meet the workload demand;

(3) Laboratory model test results show that the slip rate has an effect on the steering radius and steering angular velocity. The measured data is consistent with the trend of the theoretical prediction curve, which can provide reference for the later offshore engineering application.

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References

[1] Le A T, Rye D C, Durrant-Whyte H F. Estimation of track-soil interactions for autonomous tracked vehicles. Proceedings of IEEE International Conference on Robotics and Automation. Vol. 2 (1997) No.28, p. 1388-1393.

[2] Song Z B, Zweiri Y H, Seneviratne I D, et al. Non-linear observer for slip estimation of tracked vehicles. Proceedings of the Institution of Mechanical Engineers - Part D. Vol. 2 (2008) No.22, p. 515-533.

[3] Iagnemma K, Kang S, Shibly H, et al. Online terrain parameter estimation for wheeled mobile robots with application to planetary rovers. Robotics. Vol. 5 (2004) No.20, p. 921-927.

[4] Tchamna R, Youn I. Yaw rate and side-slip control considering vehicle longitudinal dynamics. International Journal of Automotive Technology. Vol. 1 (2013) No.14, p. 53-60.

[5] Liu Wei, Wu Hongyun, Jiang Min, et al. Research on differential steering performance of submarine self-propelled four-track vehicle. Mining research and development, Vol. 11 (2017) No.18, p. 81-85.

[6] Wong J Y, Preston-Thomas J. On the characterization of the shear stress-displacement relationship of terrain. Journal of Terramechanics. Vol. 4 (1983) No.19, p. 225-234.

[7] Choi J, Hong S, Kim H W. An Experimental Study on Steering Performance of Tracked Vehicle on Cohesive Soft Soil by DOE (Design of Experiment) Using Orthogonal Arrays. Vol. 4 (2004) No.28, p. 103-105.

[8] Edwin P, Shankar K, Kannan K. Soft soil track interaction modeling in single rigid body tracked vehicle models. Journal of Terramechanics, Vol. 7 (2018) No.7, p. 1-14.