Simulation and optimization of steady rotation characteristics of middle axle trailer train

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Abstract: In order to optimize the steady rotation characteristics of the van-type middle axle trailer train, an efficient optimization method is proposed based on the response surface methodology and genetic algorithm. Firstly, this paper established the mathematical equations and the steady rotary simulation movement model of the van-type middle axle trailer train, and using TruckSim to simulate in standard conditions, the correctness of the model was verified by comparing with the experimental results of steady rotation. Secondly, according to the established mathematical model, the structural parameters that affect the steady rotation characteristics are analyzed. Finally, the response surface model is applied to obtain the objective function of each parameter, and the parameters are optimized by genetic algorithm(GA). According to the simulation with optimized parameters, the results show that, the comprehensive score of the steady rotation test of the middle axle trailer train was increased by 21.7%, the lateral acceleration and yaw rate of the truck was reduced by 6.65% and 9.92% respectively, and the roll angle of tractor and trailer was reduced by 19.25% and 12.5% respectively.

1. Introduction
The middle axle trailer train will become the mainstream of future highway transportation, but it is inclined to produce risk on corners due to its special structure and long size [3]. In this paper, the correctness of the simulation model in TruckSim is verified by the vehicle test, and then we obtain the influence on comprehensive score with each changed parameter through simulation. The objective function of each parameter is derived based on the response surface methodology. Finally, we optimized the values of each parameter utilizing the genetic algorithm and then carried out the simulation experiment again with optimized data. The results prove the effectiveness of the optimization method.

2. Model description
Based on the coordinate system shown in Figure 1, we translated into matrix form the differential equation of motion for 10 degrees of freedom under the combined effect of the inertial force and the external forces. The matrix form can be expressed as follows:

\[ M \ddot{x} = Ax + BU \]  (1)

where \( x = (u \ v \ p \ n \ w)^T \) is state vector of tractor and trailer, \( U_1 = (\cos \delta \ \sin \delta \ 1)^T \) is the input vector of tractor, and \( U_2 = (F_{XB} F_{YB} 1)^T \) is the input vector of trailer, \( u \) is longitudinal speed, \( v \) is lateral speed, \( p \) is roll angular velocity, \( n \) is pitch angular velocity, and \( w \) is yaw rate, \( \delta \) is the steer angle of front wheel, and \( F_{XB}, F_{YB} \) are the longitudinal and lateral forces exerted on traction hoop respectively.
Figure 1. Analysis of forces on the middle axle trailer train

In the process of steady rotation, it is assumed that the pitch angle is constant, both $\delta$ and $\theta$ are extremely small, so that $|\delta| = |\theta|$. Therefore, the steady yaw rate gain, stability factor, equivalent wheelbase and characteristic speed of middle axle trailer train, can be expressed as follows:

$$\omega = \frac{u_1}{L}$$

$$u_{ch} = \sqrt{\frac{1}{K}} = 164.224 km \cdot h^{-1}$$

$$K = \frac{l_2 k_3 [q_1 m_{1z} - a_1 m_{1u} + (b + c) m_{1}] + [k_1 l_1 + k_2 c] (q_2 m_{2z} - a_2 m_{2u} - d m_2)}{2 l_2 k_3 [k_1 (l_1 + l_2) l_1 + k_2 c (c + l_2)]}$$

$$= 4.805 \times 10^{-4}$$

Table 1. Basic parameters of middle axle trailer train

| Train          | Parameters of mass | Value(kg) | Parameters of structure | Value(m) |
|----------------|--------------------|-----------|-------------------------|----------|
| Middle axle trailer | Curb weight       | Front     | Length                  | 7.910    |
|                 |                    | Rear      | Width                   | 2.511    |
|                 |                    | Total     | height                  | 3.997    |
|                 | Gross weight       | Front     | Wheelbase               | 1.504    |
|                 |                    | Rear      | Traction hoop to axle   | 5.507    |
|                 |                    | Total     | Front track width       | 1.845    |
|                 |                    |           | Rear track width        | 1.846    |
|                 | Curvature          | Front     | Length                  | 10.394   |
|                 |                    | Rear      | Width                   | 2.512    |
|                 |                    | Total     | Height                  | 3.990    |
| Tractor         |                    | Front     | wheelbase               | 6.061    |
|                 | Gross weight       | Rear      | Traction pin to rear axle | 1.418    |
|                 |                    | Total     | Front track width       | 2.060    |
|                 |                    |           | Rear track width        | 1.818    |
3. Vehicle test and model verification

Experimental equipment includes VBOX-3i data acquisition system, gyroscope, side-slip angle sensor (with data acquisition), load sensor, frequency input module, analog signal input module, etc. The test truck is a kind of domestic middle axle trailer train, whose parameters are shown in Table 1.

Firstly, we steadily drove the vehicle at low speed along a circle with a radius of 20 meters, and recorded the steering wheel angle at that time. Secondly, we accelerated the vehicle from 0m/h to 34m/h in 70 seconds, and conducted the steady circular test along both the clockwise and counter-clockwise direction, respectively, for six times, and recorded data.

In Trucksim, the same steady rotation simulation experiment was performed, the front wheel rotation angle was fixed at 19.83 degrees, and we compared the simulation results and the processed truck test results, which is shown in Figure 2. From the result, we have concluded that the simulation data on the lateral acceleration and yaw rate curve are consistent with truck test data. Therefore, the simulation results can be considered correct.

4. Steady rotation characteristic optimization

4.1. Evaluation method of steady rotation test

According to Eq. (2), it can be derived:

\[ \delta = \frac{L}{R} + LK\alpha_y \]  \hspace{1cm} (5)

Therefore, the deflection between the front and rear axle slip angles for the middle axle trailer train can be calculated by:

\[ \Delta\alpha = \frac{k_1l_1(\alpha_1 - \alpha_2) + k_2c(\alpha_2 - \alpha_3)}{4k_1l_1 + 2k_2} \]  \hspace{1cm} (6)

When the lateral acceleration tends to zero and the vehicle speed is very low, the tyre slip angle is close to zero and the ratio of turning radius can be expressed as follows:

\[ \frac{R}{R_0} = 1 + Ku^2 \]  \hspace{1cm} (7)

It is known from the above analysis, the stability factor \( K = 4.805 \times 10^{-4} > 0 \), the ratio of turning radius \( R/R_0 > 1 \), and \( \Delta\alpha > 0 \) thus the middle axle trailer train is understeer.

In order to evaluate the steady rotation performance of the truck more specific, the steady rotation performance was evaluated by using the scoring method. The evaluation score includes three items, namely, the lateral acceleration value \( a_n \) at the neutral steer point, the understeer gradient \( U \), and the roll angle \( K_{\phi} \) of the truck. All are based on QC T 480-1999 Limits and Evaluation Methods for Vehicle Handling Stability Indexes.

The body roll angle \( \phi \) required for scoring can be calculated by Eq. (8).

\[ \phi = \frac{180}{2\pi}(\phi_1 + \phi_2) \]  \hspace{1cm} (8)

where \( \phi_1 \) is roll angle of the tractor and \( \phi_2 \) is roll angle of the trailer.
The analysis results show that the middle axle trailer train has understeer, but the overall score is low, therefore it will be optimized and improved in the next section.

Table 2. Steady rotation test score

| Evaluation index | Measured value | Average value | Overall score |
|------------------|---------------|--------------|---------------|
| $a_n$            | 3.867         | 5.000        | 79.11         |
| $U$              | 1.007         | 1.090        | 81.86         |
| $K_g$            | 0.718         | 0.998        | 87.36         |

4.2. Objective function based on the response surface methodology

By the analysis of the differential equations of movement and steady rotation in Section 2, an optimized design is carried out without changing the length of the train. The parameters to be optimized are the length from the centroid of tractor to front axle, the length of traction pin to tractor’s rear axle, the stiffness of front and rear suspension of the tractor, and the suspension stiffness of trailer. The steady rotation comprehensive score is used as the optimization goal, and make the score value be the highest.

Approximate function of quadratic polynomial response surface model is

$$y(x) = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} \sum_{j=1}^{n} b_{ij} x_i x_j + \varepsilon$$  \hspace{1cm} (9)

where $n$ is the number of variables, $b_i$ is the regression coefficient, and $\varepsilon$ is the error of the function, which is small to negligible.

By centralized $x_i^2$, linear transformation can be written as

$$x_i' = x_i^2 - 0.7187$$  \hspace{1cm} (10)

The experimental design adopts orthogonal method, the two levels of five factors, $L_2^5(2^{31})$, 31 columns, in which 1, 2, 4, 8 and 16 are the basic columns. After the simulation in TruckSim, the simulation results were substituted into the comprehensive scoring formula, and the regression equation of the objective function can be obtained by further fitting the scoring data.

4.3. Genetic algorithm optimization

After obtaining the objective function from last section, the genetic algorithm is used to optimize the parameters.

When the genetic algorithm is optimized, the maximum value of the objective function is 101, which converted to 100 points according to the standard. The value of the five variables are 2000, 500, 6000, 1200.5 and 15000 respectively. The optimized results were substituted into TruckSim for steady rotation simulation test, and compared with the results before optimization, as shown in Fig. 3. According to the results, the comprehensive score is 99.18 (100, 98.4, 99.2). The simulation results demonstrate that the steady rotation performance of middle axle trailer train is improved by 21.7% after optimization.
5. Conclusion
In this paper, the steady rotation test of the truck is designed to verify the correctness of the simulation model, the objective function of the comprehensive evaluation score of the steady rotation test is proposed based on response surface methodology, and the parameters are optimized by using the genetic algorithm. The results of optimization can be seen as follows:

The lateral acceleration value of the middle axle trailer train is reduced by 6.65% compared with that before optimization, and the lateral acceleration instability during steady rotation is eliminated. The yaw rate decreased by 9.92%, and the unsteady steering component is reduced during rotational acceleration.

The roll angle of the middle axle trailer is reduced by 12.5%, and the tractor roll angle optimization is the most effective, decreased by 19.25%. This has a significant role in the truck safety during rotation of the middle axle trailer.

In terms of improvement measures, the rear suspension stiffness of the tractor relatively vary little, thus the main optimization measures are the improvement of the suspension stiffness of the trailer and front of tractor. The position of the traction pin (ring) has great influence on the steady rotation characteristics of the truck. Further research on the handling stability of middle axle trailer train can be conducted on this basis.

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