Research and Optimization of Vehicle Handling Stability Based on Multi-body Dynamics

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Abstract. Based on multi-body dynamics virtual simulation method, the vehicle simulation model is built and the transient response characteristics of the vehicle are analysed under the steering angle step input. According to the results, the improving method is given. The optimization and stiffness test of tuning bushing are carried out, and the better bushing stiffness is obtained. The vehicle steering transient response performance improvement effect is obvious. This method provides theoretical reference for structural engineers.

1. Introduction
Vehicle handling stability is one of the important performance indicators affecting active safety of vehicles [1-2]. It not only affects the convenience of vehicle handling, but also determines the safety performance of high-speed vehicles. Vehicle handling stability needs to satisfy two performance indicators: handling and stability. Poor handling will lead to sideslip, turn and capsizing, which will destroy the stability. Poor stability will lose control, leaving the car in a dangerous state. In actual driving, vehicles with poor handling stability are shown as drifting, slow reaction, sway, loss of road sense and loss of control. In addition, vehicles with poor handling stability are shown as response overshoot. The drivers give stable steering instructions, but the vehicles swing from side to side and the driving direction tends to be stable after a period of time. Therefore, in order to ensure the safe driving of vehicles, it is necessary to have good handling stability.

During the research and development of vehicle products, two evaluation methods are usually used to study the vehicles’ handling stability. One method of evaluation is subjective evaluation method, which is usually used to evaluate all aspects of vehicle handling stability by experienced and professional drivers after driving a certain distance. This method is influenced by the subjective factors of the evaluator. Different evaluators may give different evaluation results. The other is the objective evaluation method, which measures the physical Characteristic parameters through road tests and bench experiments carrying on sample car in the design stage. That increases the evaluation cost and design cycle.

Now, with the maturity of virtual simulation technology, vehicle model can be accurately built. By means of computer simulation analysis, the dynamic characteristics can be predicted in the product development phase with no prototype. It can save time and cost for structural optimization design.

In this paper, multi-body dynamics virtual simulation method is mainly used to study step response characteristics of the vehicle in the early stage of product development. Based on the result, structural parameters are optimized to reach the optimal performance. This method provides theoretical reference for structural engineers.
2. Influence Factors of Vehicle Handling Stability
Vehicle system is a closed-loop system which is composed of man and vehicles. Its control stability is affected by many factors, including tire lateral stiffness, vehicle moment of inertia, center of mass position, vehicle lateral resistance coefficient, vehicles lateral stiffness, vehicle lateral steering degree, etc. Usually the steering stability can be improved by properly increasing the lateral stiffness of the front and rear wheels. The understeering degree can be changed by changing the lateral stiffness of front or rear wheels. The vehicle handling stability can be improved by reducing the moment of inertia at low speed. The stability of high-speed vehicles can be improved by moving back the center of mass. The inclination speed can be improved by changing the vehicles' inclination direction, inclination stiffness ratio and inclination damping coefficient.

In addition to providing flexible links for torsion and tilt, tuning bushing on the suspension will greatly improve vehicle comfort and handling stability. The viscoelastic properties of the tuning bushing which is equivalent to the vibration and noise isolation device of the suspension can improve the vehicle performance. The stiffness of tuning bushing in each direction will affect the stiffness of the suspension side inclination angle. It is generally believed that the contribution of tuning bushing to the anti-inclination performance of the body is about 10%.

In this paper, based on multi-body dynamics simulation, the influence of rear suspension tuning bushing stiffness on vehicle handling stability is analyzed. Meanwhile by adjusting the stiffness of rear suspension tuning bushing, the step response of the vehicle reaches a better state.

3. Simulation Analysis of Vehicle Handling Stability
Taking a certain vehicle as the research object, this paper analyses the dynamics characteristics based on its vehicle dynamics model. The transient response characteristics of the vehicle to the steering wheel is studied from three aspects: the lateral acceleration, roll angle changes and yawing angular velocity. According to the analysis results, the evaluation score of vehicle yaw angular velocity response is obtained, so as to the handling stability is judged.

3.1. Theoretical Basis of Simulation Analysis
The handling stability characteristics studied in this paper is based on the steering system dynamics of the vehicle. It studies the transient response characteristics of the whole vehicle while it takes the angular displacement of the steering wheel as the input condition, and treats the driver and the vehicle as a whole system to study.

Transient response analysis mainly refers to the dynamic response process between constant speed straight line driving and constant speed circular driving. The instantaneous change process of yaw angular velocity is studied under front wheel step input.

When the car's front wheel Angle step input, the transient response can be expressed as in equation (1).

\[
\dot{\omega}_r + 2\omega_0 \zeta \dot{\omega}_r + \omega_0^2 \omega_r = B_0 \delta
\]

\[
B_0 = \frac{Lk_1 k_2}{m u I_z}
\]

In which, \(m\) is the vehicle quality, \(u\) is the component of the velocity at the center of mass on the x axis, \(\omega_r\) is the yaw angular speed of a car, \(\delta\) is the front wheel angle, \(k_1\) and \(k_2\) are the Lateral stiffness of front and rear tires, and \(I_z\) is the moment of inertia of a car around the Z axis.

In transient response, several parameters, such as natural frequency, damping ratio Zeta, reaction time and overshoot are commonly used to characterize the quality of the response.

Natural frequency can be calculated as in equation (2). It is determined by the following factors: tire lateral stiffness, vehicle mass, greater moment of inertia and vehicle speed.
\[ \omega_0 = \sqrt{\frac{c}{m}} = \sqrt{\frac{mu_0k_1 - bk_2 + \dot{L}k_3}{mul_z}} = \frac{L}{u} \sqrt{\frac{k_2}{ml_z(1 + Ku_0^2)}} \]  

(2)

In which, \( L \) is the overall length.

The damping ratio can be calculated as in equation (3). It is proportional to the lateral stiffness of tires. It is inversely proportional to the vehicle mass, moment of inertia, wheelbase and vehicle speed.

\[ \zeta = -\frac{m(a^2k_1 + b^2k_2) - I_z(k_1 + k_2)}{2L \sqrt{mI_zk_1k_2(1 + Ku_0^2)}} \]  

(3)

The reaction time can be calculated as in equation (4). It is determined by the following factors: the tire cornering stiffness, moment of inertia of vehicle quality, wheelbase, and vehicle speed.

\[ r = \arctg \left[ \frac{\sqrt{1 - \zeta^2}}{\frac{(-mu_0/ Lk_2 - \zeta)}{\omega_0 \sqrt{1 - \zeta^2}}} \right] \]  

(4)

3.2. Dynamic simulation modeling

In order to improve the calculation speed, the vehicle system is simplified.

3.2.1. Body structure. It is equivalent to rigid body model. The external shape is imported and relevant parameters are given.

3.2.2. Front and rear suspension systems. Based on the kinematics simulation, systems are simplified. The main structures as front shock absorbers, coil spring, wheel hub, steering knuckle, steering wheel and the swing arm, front string, tie rod, steering rack, transverse stabilizer bar, wheel assembly, rear shock absorber, coil spring, wheel hub, transverse stabilizer bar, and wheel assembly are retained. Corresponding joints are added between the front and rear suspension parts.

3.2.3. Steering system. The steering wheel and steering column are simplified into an object that can be rotated around the body. The steering machine only considers the rotation of its shaft around the body. Universal joints are used to connect the steering column and the shaft of the steering machine.

3.2.4. Tires. Tires are neither rigid nor flexible. It is a set of mathematical formulas.

3.2.5. Powertrain. Using own shape model of power system, the transmission is simplified. Sliding fork of the transmission shaft and engine power output shaft are connected using universal joint. The casing is associated with sliding fork using sliding constraints. Casing is connected with the main reducer shaft using universal joint. Main reducer shaft rotates around the rear axle half axle. Its’ angular velocity is satisfied a certain relationship [3-4].

Based on the above vehicle subsystem model is built, the whole vehicle simulation model is assembled as shown in figure 1.
3.3. Simulation analysis

3.3.1. Working conditions of analysis and basis. This paper mainly simulates the steering angle step test and analyzes the transient response characteristics of vehicle. The test is based on the national standard GB/T6323-2014. The vehicle runs in a straight line with a test vehicle speed. The steering wheel is rotated at a fast speed. When the vehicle enters a turning movement state, the yaw rate and lateral acceleration are measured. According to the test data and data processing results, the vehicle speed is obtained as a curve of the lateral acceleration and the body yaw rate over time [5-7].

3.3.2. Simulation results. In the simulation analysis, when the lateral acceleration of the vehicle is 0.2g, the input angle of the steering wheel is 15°. When the vehicle speeds up to 100km/h, the steering wheel is turned to the pre-calculated position within 0.15s as input, as shown in figure 2. After the vehicle reaches the stable driving state again, the response curves of lateral acceleration and yaw angular velocity are obtained. According to the simulation, the change curve of each parameter is obtained, as shown in figure 3 and figure 4.
3.3.3. Result determination. According to the QC/T480-1999 criterion thresholds and evaluation of controllability and stability for automobiles, the yaw angular velocity response time $T$ is evaluated and scored when the steady-state lateral acceleration is 2 m/s². It can be calculated as in equation (5).

$$N_j = 60 + \frac{40}{T_{60} - T_{100}} \cdot (T_{60} - T)$$  \hspace{1cm} (5)

In which, $N_j$ is the evaluation score of the response time of yaw angular, $T_{60}$ is the lower limit value of yaw angular velocity response time, $T_{100}$ is the upper limit of the yaw angular velocity response time, and $T$ is the calculated value of the vehicle yaw angular velocity response time when the lateral acceleration is 2 m/s².

From the above simulation analysis results, it can be obtained that the upper limit of yaw angular velocity response time is 0.09s, and the lower limit of vehicle yaw angular velocity response time is 0.31s. The experimental value of yaw angular velocity response time is 0.35s. Thus, the evaluation score of the yaw angular velocity response time is 52.7. The maximum mark is 100. The higher the score value is, the better the step response will be. It can be seen from the calculation results that the original vehicle's yaw acceleration response time is relatively long, and the step response effect is poor, which will bring the feeling of steering delay to the driver, and it needs to be improved.

4. Structural improvement and feasibility verification

From the above result, the yaw acceleration response time is relatively long. In terms of vehicle design theory, this problem can be solved by increasing the car's quality or increasing the wheelbase to reduce response time. While this improved method can be reached before the sample car comes out in the process of new product research and development. And it is not suitable for the object of this study.

Another way of improvement is to increase the rear wheel laterality stiffness, which can improve the vehicle transient response. This method needs to test the tire lateral stiffness accurately, and the chassis adjustment process needs high cost.

In engineering practice, it is the least cost and the most effective method to adjust the tuning bushing stiffness of front and rear suspension. In general, several tuning bushing parts with different rigidity are prepared and the effect of system reform is verified by testing and simulating. This paper adopts this method to improve the transient response characteristics of the vehicle.

4.1. Structural improvement

In this paper, the stiffness of the tuning bushing of the rear suspension is continuously adjusted, and the step response of the vehicle is simulated and verified. Thus, the step response of the whole vehicle reaches the best state.

In general, the stiffness characteristics of bushing are expressed through the curves of force (or torque) and displacement (or angular displacement). With the increase of loading force (or torque), the stiffness of bushing gradually changes from approximate linear to nonlinear. The stiffness characteristic of the tuning bushing can be calculated as in equation (6).
\[ F = k \cdot x + k \cdot x_0 \left( \frac{x-x_0}{x_0} \right)^n \]  

In which, \( F \) is the load in a single direction of bushing, \( x \) is the deformation of bushing in this direction, \( x_0 \) is the length of the linear segment on the stiffness curve, \( k \) is stiffness of the corresponding linear segment, and \( n \) is the stiffness characteristic of the nonlinear section on the stiffness curve.

Commonly the bushing stiffness characteristic curve can be obtained through the tuning bushing radial stiffness testing and optimization. The stiffness test results follow figure 5, which is suitable for the original car B0 tuning bushing, Bs for simulation optimization results. Considering the differences of the simulation results and the actual manufacturing, the tuning bushing parts need to be calibrated. The best effect can be confirmed after the adjustment of the real car. In figure 5, Bs-1, Bs-2, Bs+1 are the stiffness characteristic curves of bushing adjustments.

![Figure 5. Radial stiffness characteristics of tuning bushing.](image)

In the process of adjustment, through the subjective evaluation of single shifting line and double shifting line tests, the overall response of bushing Bs+1 is significantly improved compared with the original vehicle, and the overshoot feeling is better than the bushing Bs. In double shift test, the vehicle dynamic predictability is better. So Bs+1 was selected.

4.2. Feasibility verification
Step response simulation of the whole vehicle using bushing Bs+1 is performed. And its response curves of lateral acceleration and yaw angular velocity are shown in figure 6 and figure 7.

![Figure 6. Improved lateral acceleration response curve.](image)
According to the simulation results, the lower limit of vehicle yaw angular velocity response time is 0.21s. The upper limit of vehicle yaw angular velocity response time is 0.055s. When the lateral acceleration is 2m/s², the response time of the vehicle yawing angular velocity is 0.165s, so the evaluation score of the yaw angular velocity response time is 74.

By improving the bushing stiffness of the rear suspension swing arm, the transient response is better and the response speed is faster than the original vehicle.

5. Conclusion
Based on the vehicle simulation model, this paper analyzes the transient response characteristics of the vehicle under the steering angle step input, determines the improvement objectives according to the results of the analysis and selects the object of improvement. The optimization and stiffness test of tuning bushing are carried out. The better bushing stiffness is obtained. Meanwhile, the transient response characteristic of the improved whole vehicle is simulated and verified, so that the transient response performance can be better enhanced using the improved bushing.

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