Vehicle anti-rollover control strategy based on load transferring rate

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Abstract. When vehicles is driven on a low adhesion road or going on a high speed and sharp turn, it is prone to product some lateral stability problems, such as lateral sideslip or rollover. In order to improve the vehicle anti-rollover stability under these limited conditions, a SUV vehicle model with high mass center was built based on the software of CarSim and the rollover stability controller was designed using the static threshold value method for the lateral load transferring rate (LTR). The simulations are shown that the vehicle anti-rollover stability under limit conditions is improved using the SUV model.

Key words: Vehicle; Anti-rollover; LTR

1. Introduction

At a low friction coefficient road or at a turning with high velocity, vehicle is easier to be out of control for the lateral stability. In order to improve the vehicle lateral anti-rollover stability, Chen proposed the Time-To-Rollover (TTR) concept to study the prediction system of vehicle rollover state[1]. To enhance the rollover control function of vehicles in extreme conditions, a vehicle dynamics model with 8-degrees rollover model was established, and an integrated control strategy was proposed[2]. To avoid automobile rollover accidents, a model based on an algorithm for rollover warning and a control strategy for rollover prevention were proposed. In the algorithm, the absolute value of the lateral Load-Transfer-Ratio was taken as the rollover index[3]. At present, some fuzzy controls, neural networks and the artificial intelligence control technology were introduced into the
vehicle lateral stability control system[4]. However, in these lateral stability control, the yawing moment is often used as the controlled objective, it isn’t fit to rollover condition. For instance, at a high adhesion coefficient road, a SUV with high mass center is easier to product vehicle rollover with a high-speed turning or emergency obstacle avoidance, because of the shift dynamic lateral load. In order to improve the rollover stability, a vehicle model with transmission, brake system and suspension system, etc. is built and the vehicle anti-rollover strategy under the limit conditions is studied.

2. Vehicle model
A SUV vehicle model with high mass center is built based on the software of CarSim as shown in Fig.1. The vehicle model is using a type of engine with the power of 200kw, a 6-speed manual transmission and an ABS model. Front suspension is the independent suspension, and rear suspension is the independent suspension.

![Figure 1. SUV vehicle model](image)

The main parameters of the vehicle are as the followings: total mass = 1592 kg; Length/ width/ height = 3800/1875/1800 mm; mass center height = 1000 mm; wheelbase = 2950 mm; Front/ rear wheel tread = 1575/1575 mm; Moment of inertia around X = 614 kg•m² ; Moment of inertia around Y = 2488 kg•m² ; Moment of inertia around Z = 2488 kg•m².

3. Vehicle anti-rollover design based LTR
3.1. Vehicle anti-rollover principle
Roll force analysis at a vehicle turning is shown in Fig.2. In Fig.2, \( F_i, F_o \) - a vertical force for inside and outside wheel, \( t \) - wheel tread, \( h \) - vehicle mass center height, \( e \) - a distance from the roll center to mass center, \( h_R \) - a roll center height, \( a \) - lateral acceleration at mass center. In order to simplify the analysis, the automotive total mass and the sprung mass are considered being equal.
The body roll angle from the roll balance force around the center is shown as Eq.(1)

$$\phi = \frac{m \cdot a_y \cdot e}{K_{\phi} - m \cdot g \cdot e}$$  \hspace{1cm} (1)

LTR (lateral load transferring rate) is used to express the vehicle lateral load transferring rate, namely the vertical load transfer between inside and outside wheel. The LTR from the force equilibrium equation around the center of the wheel track is shown as Eq.(2)

$$LTR = \frac{F_{zo} - F_{zi}}{F_{zo} + F_{zi}} = \frac{2}{t} \left( \frac{h \cdot a_y}{g} + e \cdot \phi \right)$$  \hspace{1cm} (2)

When the LTR is transferring between inside and outside of wheel, the vehicle begins to roll. When $LTR \geq 1$, all of vertical load are sustained by the outside wheel, and the inside wheel is rolled over.

It is difficult to directly measure the vertical load of tire, and the LTR can be approximate expression by static roll coefficient $R$ as Eq.(3):

$$R = \frac{2h}{t \cdot g} a_y$$  \hspace{1cm} (3)

In the Eq.(3), the roll coefficient has a direct relationship with the lateral acceleration, and the $R$ can be calculated by the lateral acceleration, then according to the static threshold to prevent the vehicle rollover.

When $|\vec{R}| = 1$, the inside wheel is off the ground and vehicle happens a quasi static rollover. Considering the elastic deformation of the tire, the quasi static rollover threshold is generally decided as $|\vec{R}| = 0.9$. The quasi static rollover threshold $R$ is far more than the transient rollover threshold under the extreme conditions, therefore the $\hat{R}$ is chosen as the transient rollover threshold. When it is
\(|\dot{R}| \geq \hat{R}\), vehicle has the potential rollover tendency, the stability control is required.

3.2. Vehicle anti-rollover controller based LTR

The basic idea of anti-rollover stability control is to measure some information such as wheel velocity, lateral acceleration, vertical acceleration, etc. Using the lateral acceleration information to estimate the vehicle roll state and calculate the rollover coefficient. If the rollover coefficient exceeds the threshold, rollover controller will be activated. According to the longitudinal acceleration, the wheel cylinder pressure is calculated. By controlling the hydraulic regulator for brake system, the vehicle rollover stability is improved.

3.3. Brake wheel selection and cylinder pressure calculation

Anti-rollover control is mainly to limit the vehicle yawing motion to carry on under steer characteristics by the differential brake method. Because the vertical load on the inside wheel is much smaller than the load on the outside wheel, the braking force distribution inside the wheels should be less than the outside wheel. In order to make the vehicle have a high efficiency under steer tendency, usually only the front outside wheel is braked.

The brake wheel is determined according to the front wheel turning angle \( \delta \). The anti-rollover strategy is designed based on the brake force for front and outside wheel as shown in table 1.

| Decision conditions | Control wheel |
|---------------------|---------------|
| \( \delta > 0 \) (turn left) | \(|\dot{R}| \geq \hat{R}\) right and front wheel |
| \( \delta < 0 \) (turn right) | \(|\dot{R}| \geq \hat{R}\) left and front wheel |
| \( \delta = \) any value | \(|\dot{R}| < \hat{R}\) No |

The brake force for wheel is shown as in Eq.(4).

\[
f_x = \begin{cases} 
0 & |R| < \hat{R} \\
ma \frac{\partial}{\partial t} & |R| \geq \hat{R} 
\end{cases}
\]  

(4)

According to the Eq.(4), the braking force is transformed into the brake wheel cylinder pressure. When the controller is working, the wheel cylinder pressure for recovering vehicle stability is calculated. Through the hydraulic brake adjuster, the brake force is applied to the brake wheel to prevent the vehicle rollover.

4. Simulation analyses
For testing and verifying the controller, the simulations are measured under the typical hook mode. The hook condition is a kind of rapid reverse steering operation with sharp steering angle. Because in the hook conditions it is most likely to happen to rollover. It is often used to assess for the vehicle rollover performance.

The measure data under the controller are compared with the measure data without controller. Fig.3 is the input of steering wheel angle in hook test and Fig.4 is the vehicle driving state. It can be seen that the vehicle without controller happened rollover tendency, and the vehicle didn’t happen rollover with the lateral load transferring rate controller.

Figures 4 are the measure data for the SUV model under the typical hook mode. As seen in Fig.4, the vehicle without controller happen rollover after 3.5s. The vehicle with the lateral load transferring rate controller is initially driving stability and the maximum vertical acceleration is 0.5g's, however after 4.3s it shows a rollover trend with the right and rear tire which is far from the ground. The vehicle with anti-rollover controller is driving stability and its maximum vertical acceleration is only 0.2g's, which is reduced by 60%.
Figure 6. Body roll angle

As seen in Figure 7. Lateral acceleration

Fig. 6, the largest body roll angle of vehicle with the anti-rollover controller is reduced by 50% than the angle of vehicle without the controller, which greatly reduces the vehicle roll amplitude. As seen in Fig. 7, the vehicle lateral acceleration with the anti-rollover controller was reduced by 30% than that without the controller. The vehicle lateral stability with the anti-rollover controller is improved.

5. Conclusion
The SUV model with the suspension system, transmission system, braking system, etc. was established in the CarSim software. The validity of controller based on the lateral load transferring rate is verified using the SUV model. The simulations are shown that the vehicle anti-rollover stability under limit conditions is improved. In future, some new parameters will be considered to add the control strategy to improve the controller.

References
[1] Ou Jian, Chen xiangchuan, Zhou Xinhua, etc. Rollover control strategy based on vehicle stability control system. Journal of Southwest Jiaotong University, 2014, 49(2): 283-285.
[2] Jin Zhilin, Weng Jiansheng, Hu Haiyan. Rollover warning and anti-rollover control for automobiles. Journal of dynamics and control., 2007(5), 17: 365-369.
[3] Huang Jieyan, Liu kun, Xiong Yi. Vehicle rollover warning and control system research. Light vehicle technology, 2011(2): 257-258.
[4] Ahmed Elmarakbi, Chandrasekaran Rengaraj, Alan Wheat-ley. The influence of electronic stability control, active sus-pension, driveline and front steering integrated system on the vehicle ride and handling
[5] Zhang Lei. Robust analysis and optimization design of double front axle steering system [J]. SAE Paper, 2013—01—9124.

[6] L. Mejia, V. Mata, F. Valero, et al. Dynamic Parameter Identification in the Front Suspension of a Vehicle: On the Influence of Different Base Parameter Sets. Multibody Mechatronic Systems, 2015, 25: 165-175

[7] Y. C. Chen, B. J. Zhang*, N. Zhang, M. Y. Zheng. A condensation method of the dynamic analysis of vertical vehicle-track interaction considering vehicle flexibility. Journal of Vibration and Acoustics, 137, 041010, 2015.8. (SCI, IDS: CL7OV)

[8] H. H Hong, L. F. Wang*, M. Y. Zheng, N. Zhang. Handling Analysis of a Vehicle Fitted with Roll-Plane Hydraulically Interconnected Suspension Using Motion-Mode Energy Method. SAE International Journal of Passenger Cars - Mechanical Systems. 2014, 7(1): 48-57. (EI, Accession number: 20142717903868)

[9] ZHENG Minyi, ZHANG Bangji*, ZHANG Jie, ZHANG Nong. Physical Parameter Identification Method Based on Modal Analysis for Two-axis On-road Vehicles: Theory and Simulation. Chinese Journal of Mechanical Engineering, DOI: 10.3901/CJME.2016.0108.004 (SCI, accepted January 8, 2016)

[10] KANG D O, HEO S J, KIM M S. Robust design optimization of the McPherson suspension system with consideration of a bush compliance uncertainty [J]. Proceedings of the Institution of Mechanical Engineers, 2010, 224 (6): 705-716.

[11] FENG C, DING N, HE Y L. An integrated control algorithm of ABS and DYC for emergency braking on a-Split Road [C] // Control Engineering and Communication Technology (IC—CECT). New York: IEEE, 2012 : 516-522.