The Study For Anti-Rollover Performance Based On Fishhook and J Turn Simulation

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Abstract. SUV (Sport UtilityVehicle, SUV) HCG (Height of Center Gravity) is higher, relatively low rollover stability, higher rollover accident rate has become an important issue for cars safety. In this paper, Firstly, four-DOF kinematics theoretical vehicle model was established，then combined with a SUV development and design work and built a complete multi-body dynamics model in ADAMS / Car. Based on steady state constant radius handling case and transient sine-swept handling case, the dynamic model was calibrated and corelated to handling test results. At last, to launch a study for the anti rollover performance based on fishook and J Turn simulation, respectively analyzed how front and rear anti-roll bar 、the CGH contribute to the anti-rollover performance of a vehicle, this study is benefcial to the development process of suspension and the design for anti-roll performance of whole vhicle,so it has very important significance.

Introduction

The National Highway Traffic safety administration (National Highway Traffic SafetyAdministration, NHTSA) statistics show that in 2011, caused by the vehicle rollover accidents accounted for only 2.1% of the total Traffic accident, but the deaths of 7382 people, accounting for 34.7% of the total Traffic accident death toll. Rollover accident rate of SUV (Sport UtilityVehicle, SUV)   is significantly higher than other type vehicles[1]. Rollover propensity has a complex dynamic nature involving many factors such as vehicle parameters, road conditions and human driving variations. E.g. generally, the higher height of center gravity (HCG) seems to be related to a lower rollover threshold for SUVs. Thus, the study for anti-rollover propensity in vehicle development process is necessary. It necessitates a comprehensive and reliable procedure to access the roll performance by a large number of design trails under various condition before field testing, aiming at improving anti-rollover safety and reducing casualties.

  To improve the performance of driving safety and reduce rollover accidents, a lot of research have been done on anti-rollover performance. In 2003, U.S. Garrick J. Forkenbrock etal who compared several anti-rollover maneuvers through experiment and established evaluation procedures[2]. Its evaluation results compared fishhook 1a, fishhook 1b, Nissan fishhook, J-turn, etc in objectivity and repeatability, performability, discriminatory capability, appearance of reality to be the best candidate for anti-rollover propensity assessment. Some researchers[3-4] focused on the effect of vehicle parameters on the anti-rollover propensity providing significant information for chassis design. The works done by Some car companies for anti-rollover propensity equipped the vehicles with advanced electronic equipment (ESP, active suspension, DCS, etc.) to achieve more vehicle stability and rollover resistance[5-7].

  Fishhook and J-turn operation, as described in Ref[2], is to approximate the steering a driver acting in panic and perform design trails under various conditions for evaluations of stability and anti-rollover propensity. In this paper, To understand the effect of chassis parameters on anti-rollover performance, comprehensive computer simulation based on fishhook and J-turn procedures are carried out in a new designed SUV without relying on costly, risky, and time-consuming real car testing. Because the minimal tire normal forces can also reflect griping ground ability and be easier to acquire than wheel lift, all through the fishhook simulations use the minimum tire normal force as detected object instead of the commonly used wheel lift.

Theoretical Dynamic Vehicle Model

In order to study anti-rollover propensity in this paper, some assumptions are made as follows: ① Ignoring steering system, the same steering input is directly applied to both wheels of the front axle. ② Ignoring the pitch motion around Y-axis and vertical movement along the Z axis of the vehicle; ③ Ignoring air resistance force and lateral wind force; ④ the vehicle structure including suspension system is rigid, both the stiffness of spring and damping of shock absorber are at linear range. Based on the above assumptions, four degrees of freedom vehicle model including longitudinal, lateral, yaw and roll motion is established and shown in Fig. 1 .

The kinematic equations of four degrees freedom as follows：

1) The force balance equation on longitudinal axis:

$$m\frac{v^2}{r}\sin b + F_{xfl}\cos d + F_{xfr}\cos d + F_{xrl} + F_{xrr} - m\ddot{b}\cos b - F_{yfl}\sin d - F_{yfr}\sin d = 0 \qquad (1)$$

2) The force balance equation on lateral axis:

$$m\frac{v^2}{r}\cos b + m\ddot{b}\sin b - F_{yrl} - F_{yrr} - F_{yfl}\cos d - F_{yfr}\cos d - F_{xfl}\sin d - F_{xfr}\sin d = 0 \qquad (2)$$

3) The torque balance equation around Z axis:

$$I_{zz}\ddot{y} + (F_{yrl} + F_{yrr})l_h - (F_{yfl} + F_{yfr})l_v \cos d - (F_{xfl} + F_{xfr})l_v \sin d = 0 \qquad (3)$$

4) The torque balance around both front and rear roll center axis:

$$I_{xx}\ddot{q} - (F_{zfr} - F_{zfl})\frac{b_v}{2} - (F_{zrr} - F_{zrl})\frac{b_h}{2} - (F_{yfl} + F_{yfr} + F_{yrl} + F_{yrr})(h + h_r) = 0 \qquad (4)$$
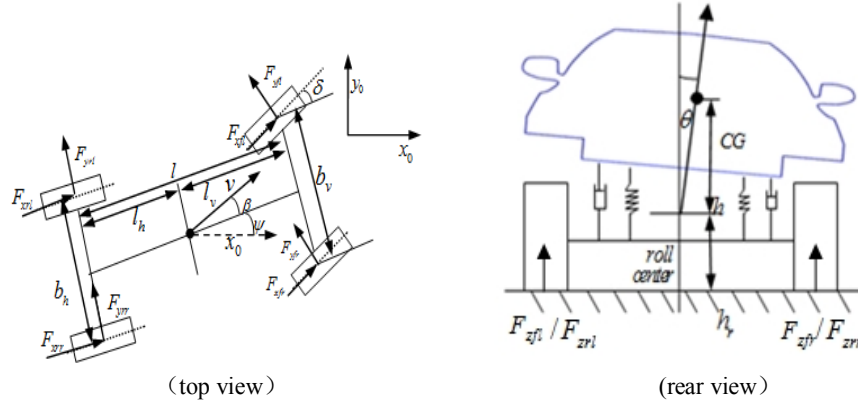

（top view）　　　　　　　　（rear view）

Fig. 1.　The lateral model when cornering

m is the mass of whole vehicle, I_{xx} is the inertia around longitudinal axis, I_{zz} is the inertia around normal axis through center mass, v is longitudinal velocity, r is the cornering radius, b is the side slip angle through center mass, y is the yaw angle of the vehicle, q is the roll angle of the vehicle, d is the steer angle of front wheel, b_v is wheel track of front suspension, b_h is wheel track of rear suspension, l_v is the distance from the center mass to front axle, l_h is the distance from center mass to rear axle, h is the distance from center mass to roll center, h_r is the distance from the roll center to ground, F_{xfl}, F_{xfr}, F_{xrl}, F_{xrr} are four wheels longitudinal forces, F_{yfl}, F_{yfr}, F_{yrl}, F_{yrr} are four wheels lateral forces, F_{zfl}, F_{zfr}, F_{zrl}, F_{zrr} are four wheels normal forces。

Establishment And Calibration Of Simulation Model

Multi-body dynamic model

With chassis and integrated parameters of a SUV, a whole vehicle model (including front and rear suspension, front and rear wheel, front and rear stabilizer bars, braking system, steering system,

power system, body system) is established in Adams/car, which is suitable for handling and stability simulation to evaluate anti-rollover propensity of vehicle, shown in Fig. 2. The model will be calibrated through comparing simulation results with experimental data.

Handling and stability objective test of prototype

Usually, both the steady state constant radius cornering steering case and transient sine sweep steering case are chosen for evaluating handling and stability propensity [8-9].

Steady state constant radius cornering test method for handling and stability: The vehicle is driven at the lowest stable speed on the locus circle radius of 40 m, keeping the vehicle on the trail of the circle, then starts to accelerate slowly and evenly until the vehicle cannot be maintained on the circle. In the test, the operation represents basic handling and stability propensity and mainly reflects steady driving response propensity of vehicle. Generally the steady under-steer gradient, roll angle gradient of body and maximum lateral acceleration are chosen for evaluating the response state.

Fig. 2. Multi-body dynamic model of Whole vehicle   Fig. 3. prototype and instruments of Handling test

Transient sine swept test method for handling and stability: The vehicle is at static, adjusting the steer wheel on the center position and setting the initial measure parameters to 0 value, then starts the engine to accelerate to 100km/h and keep the speed, steering slowly until lateral acceleration reaching to 0.3g, reading steer wheel angle and marking the value as A. Giving the steer wheel sine swept input at the A amplitude and inputting frequency increase from 0.2Hz to 4 Hz. Fig. 3. shows the handling and stability test work. In the test, the operation could reflect the general characteristics of the vehicle dynamic response when different frequency sine swept input was applied to the steering wheel. Generally, yaw rate gain, roll angle gain and delay time are chosen for evaluating the response state.

Table. 1   Handling and stability test instruments

Number	Instrument	Measuring range	Accuracy
1	Velometer	0-200km/h	±1km/h
2	Torque Steering Wheel	steer angle：-1000°～1000° torque：-30N.m～30N.m	steer angle：±2° torque：±0.3N.m
3	IMU (Inertia Measurement Unit)	acceleration：-2g～2g angular acceleration：-100°/s～100°/s	acceleration：±0.15m/s2 angular acceleration：±0.3°/s
4	Altimeter	distance：100mm～800mm	linearity：±0.2%
5	Vbox3i data Acquisition Instrument	-	sampling frequency≥100Hz

When doing the above tests, some dynamic variables of vehicle must be measured, including speed, yaw rate, steer wheel angle, roll angle of body, lateral acceleration. The prototype and some instruments for the tests are shown as Table 1 and Fig. 3.Velometer could test the speed by GPS manner. GPS is integrated with host system, so it could be competence for measuring the dynamic performance. Steer wheel is fixed to original steer wheel by flange and could display the steer wheel angle. Altimeter is installed both sides of the vehicle, it could calculate the roll angle of two points. IMU (Inertial measure unit) is mounted between front and rear axle by bracket. IMU has the function of acquisition of lateral acceleration, longitudinal acceleration, yaw rate and roll rate of vehicle. Above all   sensors could transfer test variables to Data acquisition instrument and

computer.

The Prototype demands: checking the tire pressure and wheel alignment, adjusting the steer wheel to the center position, setting load condition as curb vehicle + two persons + Instrument, Proving ground in China xiangfan.

Comparison between test and simulation

Some variables including speed, steer wheel angle, roll angle of body and so on can be read from Vbox3i Data Acquisition Instrument and compare with simulation results, shown in from Fig. 4 to Fig. 9.

1)Steady-state constant radius cornering steering

The operation condition represents steady cornering states, which controls the vehicle travel along constant radius route on proving the ground and increases the speed gradually to reach the maximum lateral acceleration. In Fig. 4, the gradient of the curves of the steer wheel angel versus lateral acceleration from 0.1g to 0.4g is at liner range and represents steady under-steer propensity of vehicle.The gradient of test result from 0.1g to 0.4g is a little larger than simulation. In Fig. 5, the gradient of the curves of roll angle of body versus lateral acceleration from 0.1g to 0.4g represents steady roll angle gradient propensity of vehicle. The difference of roll angle gradient between test and simulation is very small.

2) Transient sine swept condition

The operation reflects the transient response propensity of vehicle. In Fig. 6, the gain of yaw rate versus steer wheel angle represents the transient under-steer propensity of vehicle under different frequency inputs. It can be seen the yaw rate gain of test is smaller than simulation. In Fig.7 the gain of lateral acceleration versus roll angle of body represents transient roll propensity of vehicle under different frequency inputs. The difference of roll rate between test and simulation is small. In Fig. 8 and Fig. 9, those curves present the delay time from steer wheel input to yaw movement, from yaw movement to inducing lateral acceleration.
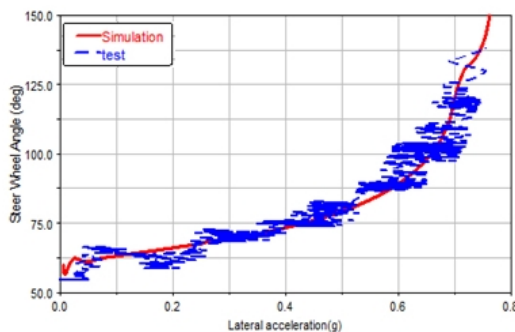

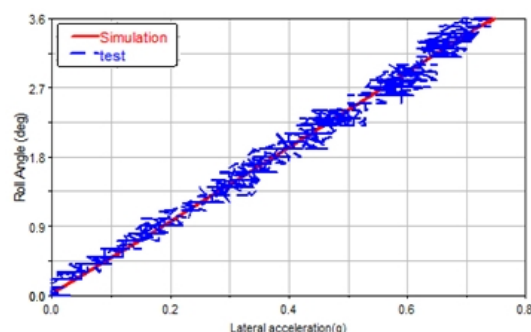Fig. 4.　Steady steer wheel angle-lateral acceleration　　Fig.5.　Steady body roll angle-lateral acceleration

As seen from the above comparison result, the simulation result is in good agreement with test. Considering the random errors from the acquisition of test data to different prototypes states, The simulation model express well the vehicle at designed condition, so it could be used for the study of the subject.
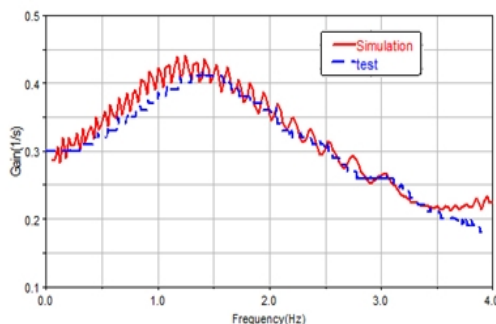

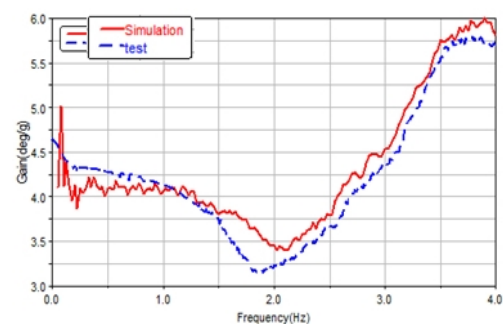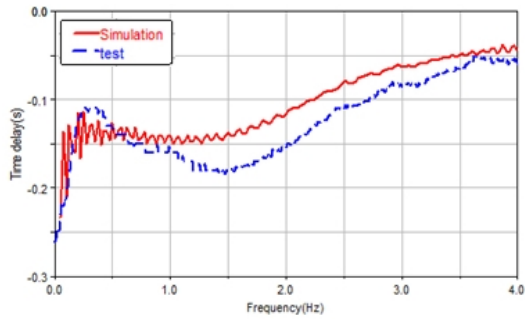Fig. 6.　Yaw rate-steering wheel angle gain　　Fig. 7.　Roll angle of body-lateral acceleration gain

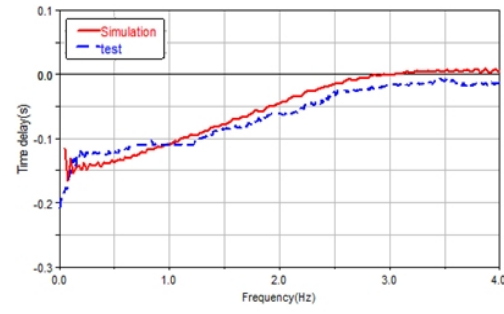Fig. 8.   Lateral acceleration VS steer wheel angle delay   Fig. 9.   Lateral acceleration VS yaw-rate delay

Fishhook test

Fishhook test is a comprehensive experiment for evaluating the vehicle dynamic anti-rollover propensity, It reflects the ability of chasing trail, avoiding obstacle in emergency and detecting roll stability limit of the vehicle. So it is one of the worst driving conditions .The fishhook test method : the vehicle is driven in straight line at the speed of 50km/h on the proving ground, then first steer input in one direction, holds until roll rate equals or goes below 1.5 degrees per second, followed by second counter-steer, holds for 3 seconds, and finally a return to zero steer wheel angle. The first steering magnitude and counter-steer magnitude are symmetric, and are calculated by multiplying the steer wheel angle that could produce a steady state lateral acceleration of 0.3 g at 50 kmph on pavement by 6.5. The steer wheel rates of the first steer and counter-steer ramps are 720 degrees per second.In this paper, the steer wheel input angle for fishhook test is shown in Table. 2 and Fig. 10. Fig. 11 is the trail of the fishhook test and Fig. 12 is tire normal force. It can be seen that the normal tire force of right rear wheel is the smallest, so the wheel lift off the ground at the greatest risk. The smallest normal force of the tire and roll angle of the body are chosen to be observed values.

Table. 2   Parameter input for fishhook test

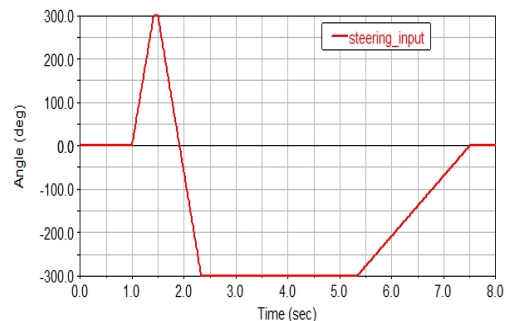| parameters	unit	value
Steady ramp input at 0.3g acceleration	deg	46.1
The first ramp input angle A	deg	299.7
Ramp input velocity	deg/s	720
Holding Time after the first ramp input T1	s	0.1
Holding time after reverse ramp input T2	s	3

Fig.10.   the steer wheel input of fishhook test

Influence of Anti-roll bar

Both front and rear anti-roll bar have important influence on anti-rollover propensity. Analysing the influence to the minimum tire normal force by increasing front and rear anti-roll bar diameter 4mm, Respectly. It can be seen from Figure 13 to16, increasing the diameter of front anti-roll bar, the minimum tire normal force of front suspension is reduced, and the minimum tire normal force of rear suspension is increased. Increasing the diameter of the rear anti-roll bar, the minimum tire normal force of front suspension is increased, and the minimum tire normal force of rear suspension is reduced.
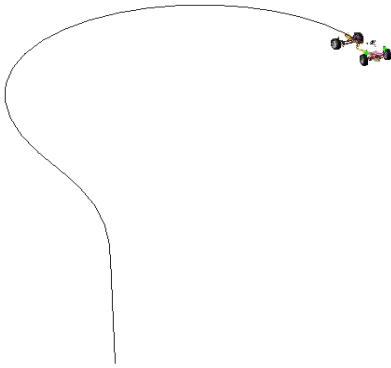
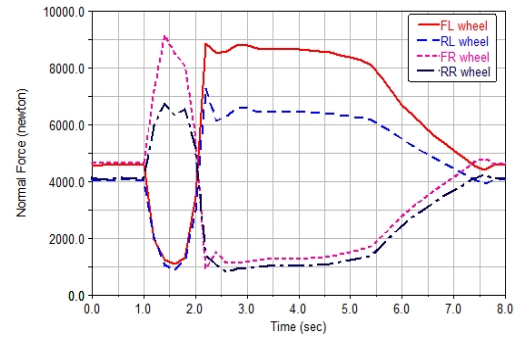Fig.11.   the trail of fishhook test

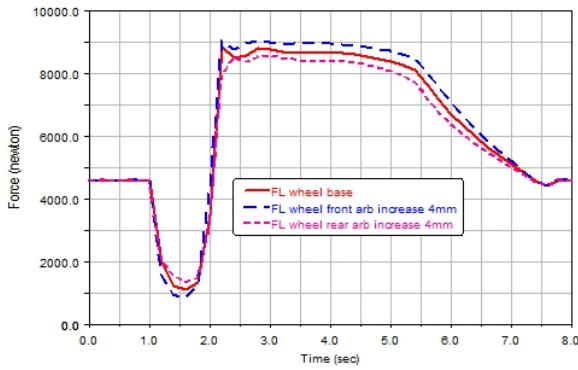Fig.12.   the tire normal force of fishhook test

Fig.13   the normal force of front left wheel
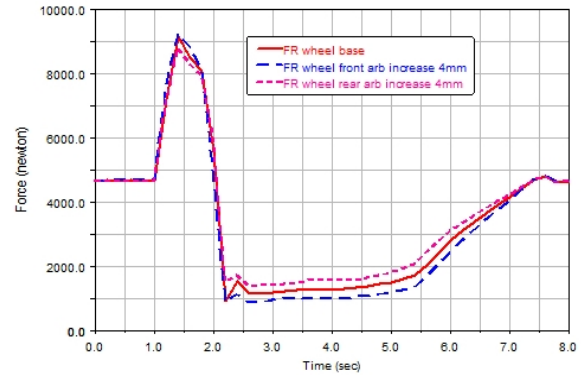

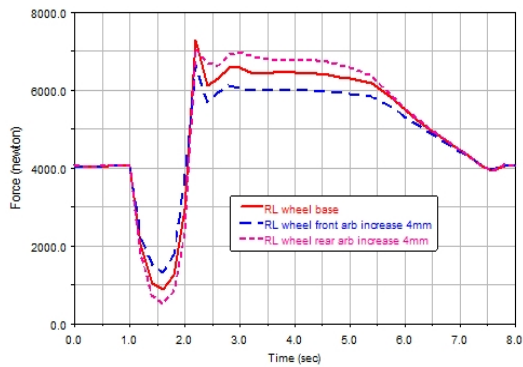Fig.14   the normal force of front right wheel

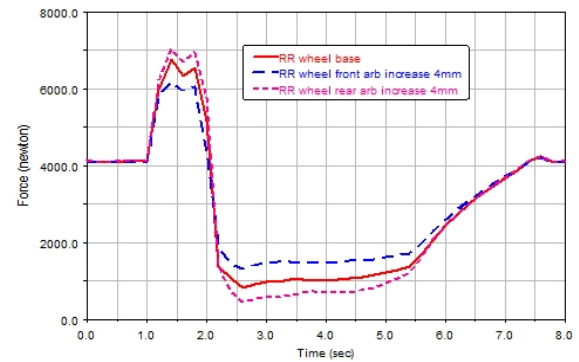Fig.15   the normal force of rear left wheel

Fig.16   the normal force of rear right wheel
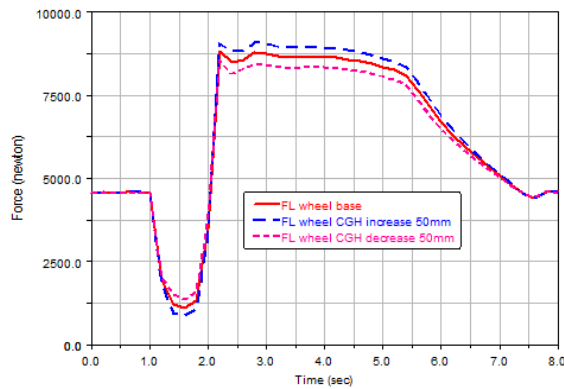
Influence of HCG
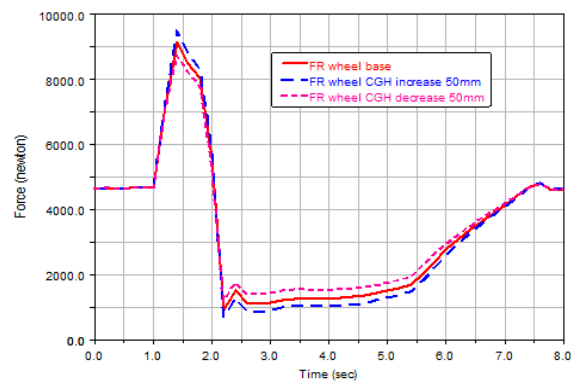

Fig.17   the normal force of front left wheel
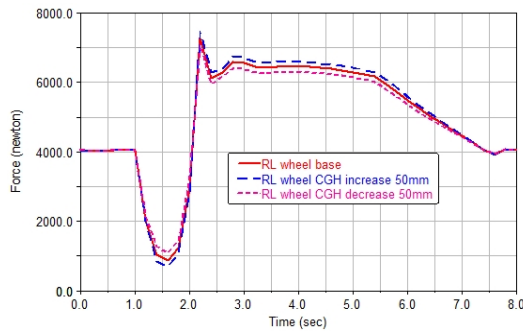

Fig.18   the normal force of front right wheel

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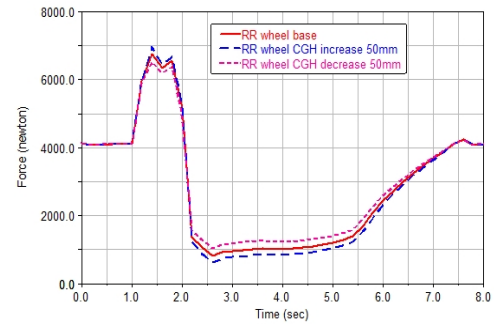Fig.19   the normal force of rear left wheel

Fig.20   the normal force of rear right wheel

The HCG of vehicle has important influence on vehicle anti-rollover propensity, analyze influence to the minimum tire normal force vehicle by inceasing and reducing 50 mm of HCG. It can be seen from Figure 17 to 20, increasing the HCG, both front and rear minimum tire normal force reduce, reducing the HCG, both front and rear minimum tire normal force increase.

J-turn test

J-turn test is also a comprehensive experiment for evaluating the vehicle dynamic anti-rollover propensity, It reflects the ability of chasing trail, avoiding obstacle in emergency and detecting roll stability limit of the vehicle. So it is one of the worst driving conditions .The J-turn test method: the vehicle is driven in straight line at the speed of 50km/h on the proving ground, then first steer input in one direction for A angle. The first steering magnitude A is calculated by multiplying the steer wheel angle that could produce a steady state lateral acceleration of 0.3 g at 50 kmph on pavement by 8, and the steer wheel rates of the first steer and counter-steer ramps are 1000 degrees per second, then holds for 4 seconds. followed by second counter-steer, return to zero steer wheel angle, it takes 2 seconds form A to zero angle. In this paper, the steer wheel input angle for J-turn test is shown in Table. 3 and Fig. 21. Fig. 22 is the trail of the fishhook test and Fig. 23 is tire normal force. It can be seen that the normal tire force of right rear wheel is the smallest, so the wheel lift off the ground at the greatest risk. The smallest normal force of the tire and roll angle of the body are chosen to be observed values.

influence of Anti-roll bar

Analysing the influence to the minimum tire normal force by increasing front and rear anti-roll bar diameter 4mm, Respectly. It can be seen from Figure 24 to 27, increasing the diameter of front anti-roll bar, the minimum tire normal force of front suspension is reduced, and the minimum tire normal force of rear suspension is increased. Increasing the diameter of the rear anti-roll bar, the minimum tire normal force of front suspension is increased, and the minimum tire normal force of rear suspension is increased small. Front anti-roll bar have greater influence to minimum tire normal force than rear.

Table. 3   Parameter input for J-turn test

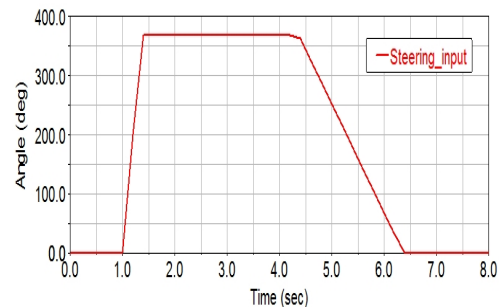| parameters	unit	value
Steady ramp input at 0.3g acceleration	deg	46. 11
The first ramp input angle A	deg	369
Ramp input velocity	deg/s	1000
Holding Time after the first ramp input T1	s	4
Holding time after reverse ramp input T2	s	2

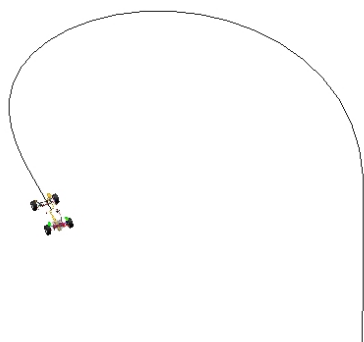Fig.21.   the steer wheel input of J-turn test

Fig.22. the trail of J-turn test

Fig.23. the tire normal force of J-turn test

Fig.24 the normal force of front left wheeL

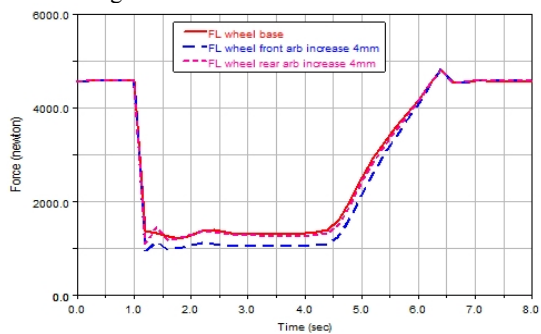Fig.25 the normal force of front right wheel

Fig.26 the normal force of rear left wheel

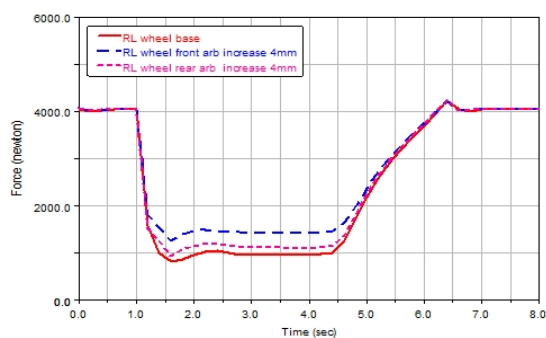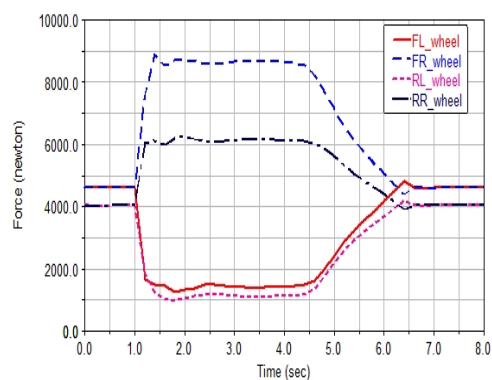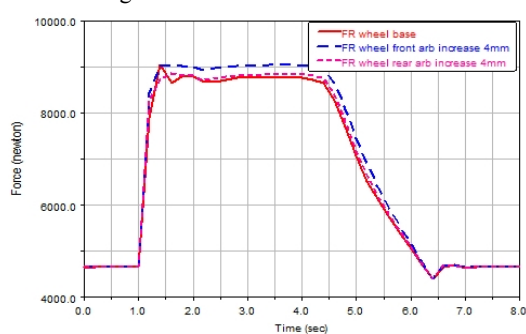

Fig.27 the normal force of rear right wheel
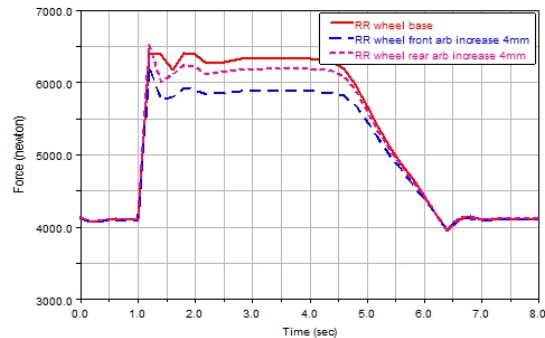
Influence of HCG
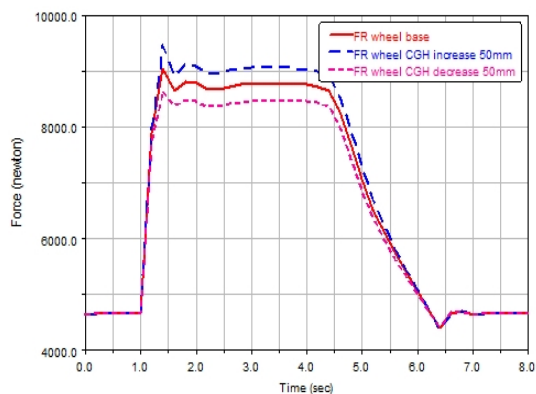

Fig.28 the normal force of front left wheel

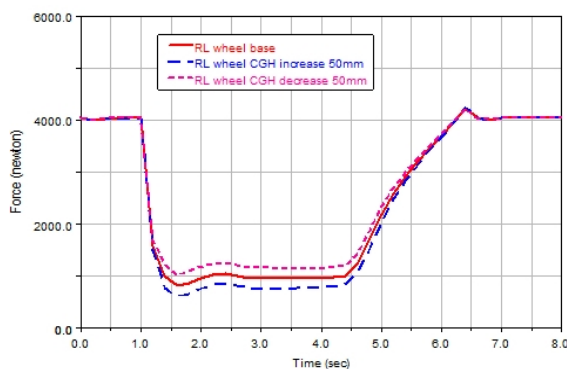Fig.29 the normal force of front right wheel
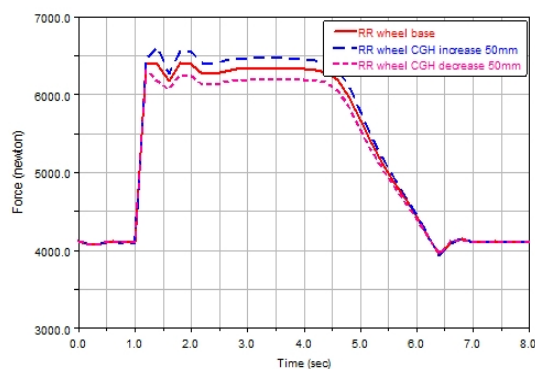
Fig.30　the normal force of rear left wheel

Fig.31　the normal force of rear right wheel

The HCG of vehicle has important influence on vehicle anti-rollover propensity, analyze influence to the minimum tire normal force vehicle by inceasing and reducing 50 mm of HCG. It can be seen from Figure 28 to 31, increasing the HCG, both front and rear minimum tire normal force reduce, reducing the HCG, both front and rear minimum tire normal force increase.

Conclusions

Although some electronic stability control devices for anti-rollover of vehicle have been developed and applied rapidly, the design of kinematic performance of the suspension is still basic and important. Combined with product development works of a SUV, Some good guides can be concluded as follows:

1) Both front and rear anti-roll bar have obvious impact on vehicle anti-rollover propensity. When matching front and rear anti-roll bar, it is concerned with steady roll propensity and steady under-steer propensity[10]. From the study in this paper, it appears that the roll stiffness has great impact on anti-rollover propensity. So when setting roll stiffness of suspension of the SUV, it is necessary to consider the anti-rollover propensity of the vehicle.

2) The HCG of vehicle has obvious impact on anti-rollover propensity. With increasing of HCG, the anti-rollover propensity of the SUV becomes worse. So in order to keep good anti-rollover propensity, the HCG of SUV should be controled .

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