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The Simulation and Analysis on Correct Operation of Tire Blowout

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Abstract **– For the driving condition of vehicls' tire blowout at high speed, it is theoretically studied. Analyzing the kinematic response of the tire blowout vehicle, and exploring the correct operation mode after tire blowout, is helpful to ensure the safety of vehicles and personnel. Based on the Dugoff tire model, a tire blowout model is established. And a 7DOF vehicle model is built in the SIMULINK. Assuming that the driver holds the steering wheel after tire blowout. Simulating the vehicle movement state after the tire blowout, the driver adopts two braking modes: continuous braking and intermittent repeated braking, then comparison and analysis the two modes. The simulation results show that the intermittent repeated braking can maintain the stability of the vehicle better under the precondition that the driver holds the steering after the left front tire blowout in a straight line.**

Keywords **– Tire Blowout, 7 DOF Model, SIMULINK.**

I. Introduction

The tire blowout at high speed can cause yaw or even rollover, which is extremely dangerous. In view of the casualties and property damage caused by the blowout accident, the researchers have done a lot of research work on the prevention of blowout accidents and minimizing the losses of people's lives and property. However, some of these researches are not pertinent, some do not have practical application conditions in a short period of time.

According to the dynamic response of the moving vehicle after tire blowout, many scholars have done a lot of theoretical and experimental research. American scholar Fay studied the towing and steering response of a vehicle in the event of a belt failure on a flat tire at different vehicle speeds [1]. Blythe simulated and tested the tire blowout vehicle, and obtained the influence of the driver's reaction and operation on the moving vehicle with a flat tire [2]. In the research of domestic scholars, the reference [4] established the driver model for the trajectory following after tire blowout which improved the precision of the model. According to the low-speed tire characteristic test, the reference [5] obtained some parameters after tire blowout, which are longitudinal stiffness, lateral stiffness, rolling resistance etc. Based on the UniTire tire model, a model describing the mechanical properties of the flat tire was built, and used to simulate before and after tire blowout in Carsim.

Based on the previous research and Dugoff tire model, through the analysis of the force of the tire after tire blowout, a 7DOF vehicle model is built in MATLAB/Simulink. In order to simulate the situation that the left front wheel is punctured, the tire blowout model is established according to the changes of parameters such as tire stiffness and effective rolling radius.

The driver is assumed to hold the steering wheel steady after tire blowout. In the Simulink model, driver adopts two ways of continuous braking and intermittent repeated braking. The movement state of vehicle under the two methods is compared with parameters, such as the sideslip angle, yaw angle and lateral displacement.

II. The Vehicle Model

A vehicle dynamics model with 7DOF is established. Figure 1 shows the vehicle coordinate system.

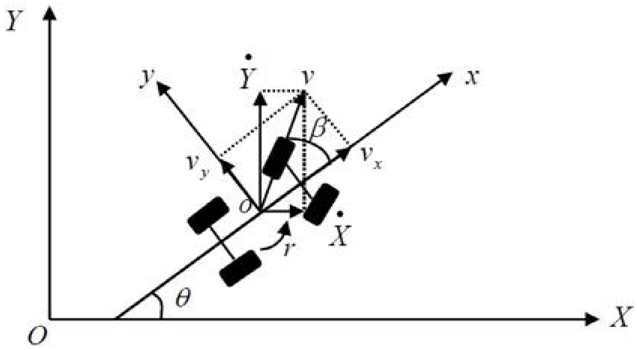


Fig. 1. The definition vehicle coordinate system.

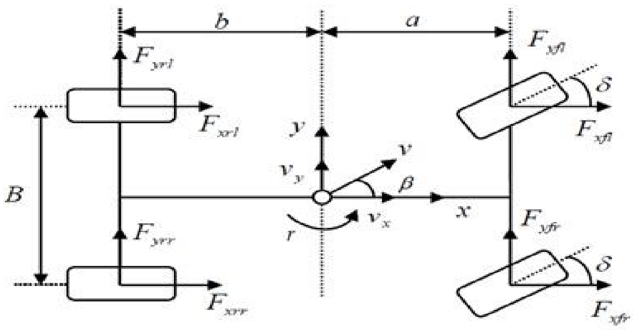


Fig. 2. The dynamic model of seven degrees of freedom.

Figure 2 shows the model used in this research. The 7 DOF vehicle model includes both the lateral and longitudinal dynamics as well as the nonlinearities in the system. The degrees of freedom associated to this model are the longitudinal and lateral velocity, yaw rate, and the wheels rotational speeds.

When analyzing the model, the front wheel is the driving wheel. Assume that friction coefficient of road surface is constant. Ignore rolling resistance, aerodynamic drag, the role of the suspension system and the vertical movement of the vehicle. δ represents the front wheel steering angle. When the tire bursts in the straight line, the driver can hold the steering wheel, and the steering wheel angle is 0 at this time, which can be ignored in the calculation.

The equations of motion for the 7DOF model are derive from Figure 2:

- *Longitudinal Motion:*

$$m(\dot{v}_x - v_y\gamma) = F_{xfl} + F_{xfr} + F_{xrl} + F_{xrr} \quad (1)$$

- *Lateral Motion:*

$$m(\dot{v}_y + v_x\gamma) = F_{yfl} + F_{yfr} + F_{yrl} + F_{yrr} \quad (2)$$

- *Yaw Motion:*

$$\begin{aligned} I_Z\dot{\gamma} &= (F_{yfl} + F_{yfr})a - (F_{yrl} + F_{yrr})b + \\ &B_f(F_{xfr} - F_{xfl})\cos\delta/2 + B_r(F_{xrr} - F_{xfr})/2 \end{aligned} \quad (3)$$

- *Wheels Rotational Motion:*

$$\begin{aligned} J\dot{\omega}_i &= T_{di} - T_{bi} - F_{xi}\times R_e \quad (i = fl,\ fr) \\ J\dot{\omega}_i &= -T_{bi} - F_{xi}\times R_e \quad (i = rl,\ rr) \end{aligned} \quad (4)$$

In the formula, $fl,\ fr,\ rl,\ rr$ represent four wheels respectively. v_x is the longitudinal velocity. v_y is the lateral velocity . γ is yaw rate. I_z is the vehicle moment of inertia about yaw moment. a is the distance of the centroid from the front axle. b is the distance of the centroid from the rear axle. B_f and B_r are the front and rear track width. J is the wheel moment of inertia, $\dot{\omega}_i$ represents wheel angular acceleration, T_d and T_b are the driving torque and the braking torque .

This model includes a dynamic lateral and longitudinal load transfer. The load equation for each wheel can be expressed as follows.

Taking into account the distribution of front-axle and rear-axle load when vehicle is stationary, the influence of factors such as the internal and external wheel load transfer caused by the lateral acceleration and the front and rear wheel load transfer caused by the longitudinal acceleration, the vertical load of each wheel is expressed as follows.

$$\begin{cases} F_{zfl} = mgb/2l - m\dot{v}_x h_g/2l - m\dot{v}_y h_g b/B_f l \\ F_{zfr} = mgb/2l - m\dot{v}_x h_g/2l + m\dot{v}_y h_g b/B_f l \\ F_{zrl} = mga/2l + m\dot{v}_x h_g/2l - m\dot{v}_y h_g a/B_r l \\ F_{zrr} = mga/2l + m\dot{v}_x h_g/2l + m\dot{v}_y h_g a/B_r l \end{cases} \quad (5)$$

III. The Nonlinear Tire Model

The nonlinear tire model adopted in the simulation is the Dugoff tire model. It is a spin-off model derived from force balance calculation, which is suitable for the study of vehicle dynamics control algorithms. The Dugoff model is introduced to simulate the lateral and longitudinal forces generated by tyres [6].

$$F_{xi} = C_x \frac{s_{xi}}{1+s_{xi}} f(\lambda_i) \quad (i = fl, fr, rl, rr) \quad (6)$$

$$F_{yi} = C_y \frac{\tan(\alpha_i)}{1+s_{xi}} f(\lambda_i) \quad (i = fl, fr, rl, rr) \quad (7)$$

$$\lambda_i = \frac{\mu F_{zi}(1+s_{xi})}{2\sqrt{(C_x s_{xi})^2 + (C_y\ \tan(\alpha_i))^2}} \quad (8)$$

$$f(\lambda_i) = \begin{cases} (2-\lambda_i)\lambda_i & \lambda_i < 1 \\ 1 & \lambda_i \ge 1 \end{cases} \quad (9)$$

Where C_x is the longitudinal stiffness and C_y is the cornering stiffness. s_{xi} is the slip ratio; λ_i is the dynamic parameter of tyre; μ is the friction coefficient between tyre and ground.

After the tire blowout, its parameters have changed. The rolling resistance coefficient increases to about 12 times of normal value. The radial stiffness is 1/13 of normal value. When the tire is fully deflated, its lateral stiffness decreases to 37.63% of normal value, and its effective rolling radius drops to about 80% of the original. The longitudinal adhesion coefficient increases 1.802 times as much as that of the normal tire and road surface [4].

According to the 7DOF vehicle model, each wheel has an independent slip angle [9]:

$$\begin{cases} \alpha_{fl} = \delta - \arctan(v_y + a\gamma)/(v_x - \gamma\cdot B_f/2) \\ \alpha_{fr} = \delta - \arctan(v_y + a\gamma)/(v_x + \gamma\cdot B_f/2) \\ \alpha_{rl} = -\arctan(v_y - b\gamma)/(v_x - \gamma\cdot B_r/2) \\ \alpha_{rr} = -\arctan(v_y - b\gamma)/(v_x + \gamma\cdot B_r/2) \end{cases} \quad (10)$$

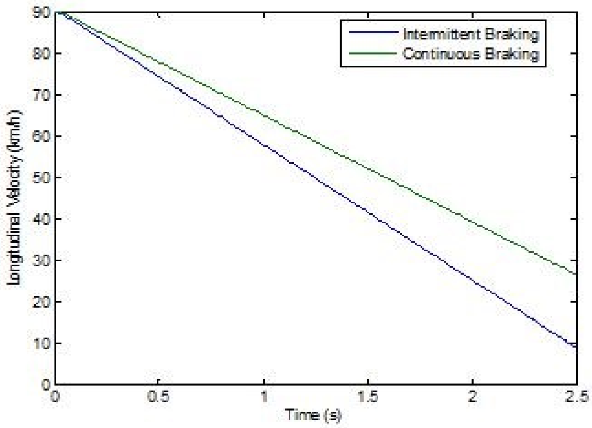
Moreover, the longitudinal wheel slip is defined as:

$$s_i = \frac{v_x - R_e\omega_i}{v_x} \quad (i = fl, fr, rl, rr) \quad (11)$$

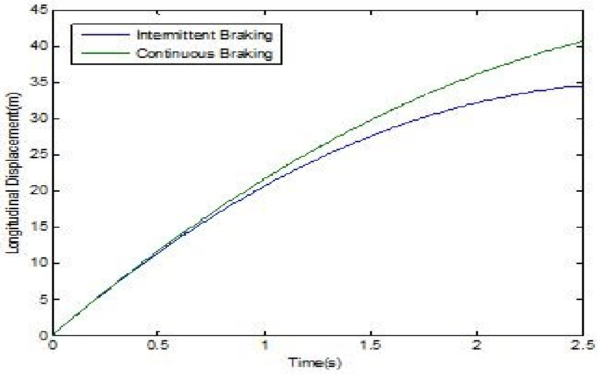
IV. Simulation Analysis

According to the deduction of the above mathematical formula, the vehicle model with seven degrees of freedom is built with the front wheel steering angle as the input, and the longitudinal velocity, lateral velocity and yaw rate as the output in the Simulink. Under the straight line condition, the vehicle tire movement state under two modes of continuous braking and intermittent repeated braking is simulated. The parameters used in simulation are as follows: $m = 1780\text{kg}$, $a = 1.4\text{m}$, $b = 1.7\text{m}$ $B_f = 1.52\text{m}$, $B_r = 1.56\text{m}$, $I_z = 1750\text{kg}\cdot\text{m}^2$, $C_x = 38647\text{N/rad}$, $C_y = -25765\text{N/rad}$, $J = 1.5\text{kg}\cdot\text{m}^2$, the initial velocity is 90km/h. The simulation time is 2.5 seconds. The driver holds the steering wheel in the whole tire burst. The response time of the braking system and the reaction time of the driver are not considered in this paper.

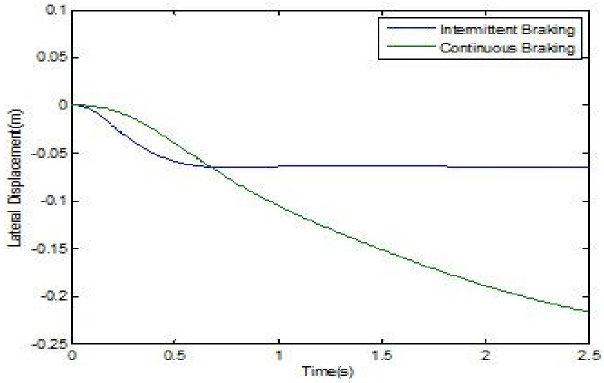
One method is that after the tire blowout, the driver takes continuous braking to control the puncture vehicle. Under the ABS anti-lock system, the driver depresses the brake pedal urgently. Another method is to allow the driver to take intermittent repeated braking to control the vehicle after a puncture. The models are used to simulate two types of driver's actions respectively. In simulation, the intermittent repeated braking is set to 0.5 seconds per brake, and braking once every 0.5 seconds. In order to stop as soon as possible, moderate brake pressure of 5Mpa is applied. The simulation results are shown in Figure 3.



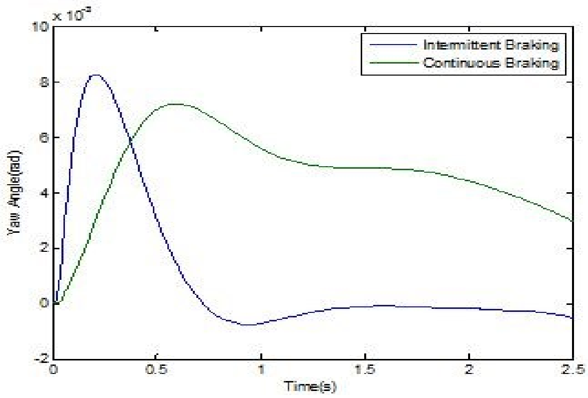
(a) Longitudinal velocity



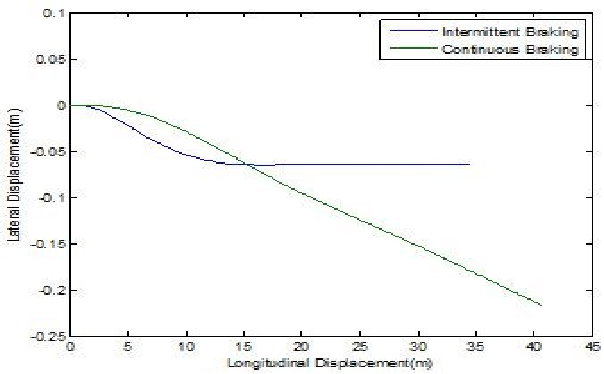
(b) Longitudinal displacement



(c) Lateral displacement



(d) Yaw angle



(e) The trend of longitudinal and lateral displacement

Fig. 3 Simulation contrast curve

In these figures, when the constant braking is applied, the speed is reduced to 26.3km/h in 2.5 seconds, the longitudinal displacement is 40.6 meters; the lateral displacement is 0.22 meters and the vehicle is in lateral slip during simulation; yaw rate reaches a maximum of 0.02 rad/s at 0.25 seconds, yaw angle is always positive and tends to be steady at a slower rate. When the intermittent repeated braking is applied, the speed drops to 8.7 km/h in 2.5 seconds, the longitudinal displacement is 34.5 meters; the lateral displacement is about 0.06 meters and the vehicle tends to be stable at 0.5 seconds; the yaw rate reaches a maximum of 0.08 rad/s at 0.1 seconds; the vehicle swings to the left first and then to the right, and stabilizes at 1.2 seconds. However, the intermittent repeated braking makes stable the vehicle motion.

These indicate that the vehicle has changed the steering characteristics under the braking pressure. This change causes the vehicle to deflect the side of the tire and then biased to the other side, while the vehicle should only bias the tire side. We can observe that the response of the intermittent repeated braking is better than the continuous braking. Both yaw rate and sideslip angle almost exactly track to the ideal values. This is because the torque generated by the driver's steering wheel counteracts the counterclockwise yaw torque produced by the difference between the longitudinal forces of the two front wheels. The effect of the intermittent repeated braking is more appreciable for vehicle of tire blowout. If the response time is considered, the vehicle motion taking the continuous braking is easier to deviate from the original track.

V. Conclusion

Based on the Dugoff tire model, a tire blowout model is built and applied to a seven-DOF vehicle model. The driver adopts two braking modes which include continuous braking and intermittent repeated braking, in order to control the vehicle with the left front tire blowout in the straight state. The model is used to simulate the impact of both on the high speed vehicle. According to the simulation results, the difference between the two braking modes is analyzed under the premise that the steering wheel angle is invariable.

The simulation results show that the effect of the intermittent repeated braking is better than the continuous braking. The vehicle is in a stable state in the safe range. The comparative analysis shows that the braking time, braking distance and offset of intermittent repeated braking are smaller than those of continuous braking. Therefore, when the tire is flat, the intermittent repeated braking should be adopted on the premise of stabilizing the steering wheel.

This paper only analyzes the vehicle motion state with the left front tire blowout in the straight line. In order to study the effect of continuous braking and intermittent repeated braking on the stability of vehicle after tire blowout, more accurate tire and vehicle models need to be built, and the dynamic response of tire blowout under more driving conditions will be studied.

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