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SIMULATION TESTS OF FTIRE TIRE MODEL ON SHOULDER RUMBLE STRIPS

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Abstract. *A vehicle dynamics simulation on uneven road was implemented by the use of FTire tire model. The basic characteristics of FTire model were introduced. Vehicle dynamics model with FTire based on the parameters of the real vehicle was established by using ADAMS. Highway shoulder rumble strips models with the depths of 6mm, 8mm, 10mm, 13mm, and 15mm were built by using UG and HyperMesh. In simulation tests, the vertical vibration accelerations of front axle in vehicle dynamics model and real vehicle were compared at different speeds. The results show that vehicle dynamics model with FTire model are similar to the real vehicle, and the relative error is less than 5%. FTire model is suitable for the vehicle dynamics simulation on uneven road.*
Keywords: Vehicle dynamics, FTire tire model, Rumble road, Simulation test

1. **Introduction.** The tire's structure parameters and mechanical property determine the main driving performance of the vehicle. Therefore, application of tire model to the vehicle dynamics simulation is significant to improve the vehicle performance. While most of researches on uneven road were in low frequency ranges, the researches in high frequency ranges were necessary. A suitable tire model should be selected in the first step.

Most of the tire models available for handling and comfort riding were not suitable for extreme operating conditions (such as the shoulder rumble strips) in high frequency ranges. Therefore, this paper chose FTire (Flexible Ring Tire) [1] model as the major way to study vehicle performance in simulation. The vibrations along three directions induced by road-contact can be up to about 150Hz. The computing time was not more than 5-20 times of the real one. FTire's variation prediction changes due to many other influence factors, like tread depth, road surface curvature or unevenness, tire surface geometry, and so on [2].

In this paper, the shoulder rumble strips models with different depths were used in the simulation and the vehicle test to measure the vertical vibration accelerations of the front axle at different speeds. In the end, the applicability of the simulation to the shoulder rumble strips based on the FTire model was analyzed by the comparison between the simulation test and the real vehicle test.

2. **FTire Model.** FTire model is a typically flexible ring model. It is also a full 3D non-linear in-plane and out-of-plane model based on a structural dynamics approach. FTire model was developed for vehicle comfort simulations, the prediction of tire forces on roads with short wave-length obstacles, and the handle of simulations [3-5]. Additionally, it uses backward differentiation formula to calculate the shape of tire belt, and could maintain high simulation precision when tire rolls through obstacles at high speeds. FTire model

contains mechanical model, thermal model and tread wear model. The mechanical model is the core part. The tire belt is described as an extensible and flexible ring, carrying bending stiffness, damping and mass properties. It adopted a complicated non-linear model to present the tread rubber friction properties which means friction coefficient is the function of pressure and sliding velocity [6]. The belt elements and its parameters were used to simulate the distortion of belt on even or uneven roads under a range of loads, which was similar to the real tire [7].

Figure 1 presents the structure of the in-plane bending stiffness connected to rim in FTire model. For every belt element, a number of mass-less 'tread blocks' are associated. These blocks carry non-linear stiffness and damping properties in radial, tangential and lateral directions. The radial deflections of the blocks depend on road excitation, locus, and orientation of the associated belt elements. In tire structure, tire bead, carcass and belt were divided into 90-360 belt elements. These belt elements were also associated with non-linear stiffness and damping properties. Every belt element has $4 + x$ degrees of freedom, longitudinal displacement, lateral displacement, vertical displacement, and rotation about circumferential axis. X indicates the lateral bending stiffness. Tire tread was composed of 1000 to 10000 contact and friction elements [8].

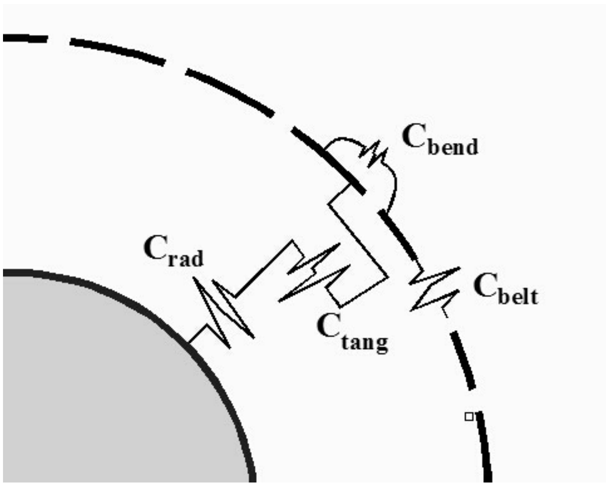


FIGURE 1. The structure between belt element and rim

The normal force is a function of deformation and deformation velocity, describing the tread rubber compression stiffness and damping. Friction of tire contact imprinting could be calculated through the normal force. The direction of friction is aligned with the negative sliding velocity. The force equilibrium was given by Equation (1). The sliding velocity was determined by using the vector-valued force equilibrium condition of frictional force, elastic shear forces and shear damping force of the contact elements (Figure 2) in the road tangential plane [4].

$$sign(v) \cdot F_{friction} + d \cdot (v - v_B) + c(x - x_B) = 0 \tag{1}$$

where, v is the sliding velocity; c is the stiffness; d is the damping; $F_{friction}$ is the friction; x and x_B are the tangential displacement.

This differential equation was discontinuous. FTire model used backward differentiation formula (BDF) to solve this issue. So, Equation (1) could be presented as Equation (2).

$$sign(v) \cdot F_{friction}(v) + (d + c\Delta t) \cdot v = d \cdot v_B + cx_B - cx_{old} \tag{2}$$

$$v = \overset{\bullet}{x} \approx \frac{x - x_{old}}{\Delta_t}$$

$$g(v) = sign(v) \cdot F_{friction}(v) + (d + c\Delta t) \cdot v$$

$$r = d \cdot v_B + cx_B - cx_{old}$$

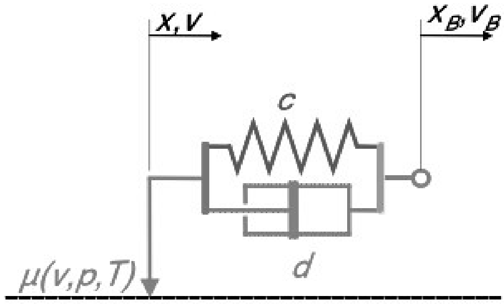


FIGURE 2. Contact elements in the tangential displacement model

Through Equation (2), $g(v)$ was equal to r. The $g(v)$ was superimposed by damping force and friction [2].

Ease of parameterization should be one of the most important objectives of FTire model. FTire model needed geometry dimensions, mass, static stiffness, etc. The main parameters were as below.

(1) Geometric parameters. The basic geometry dimensions of tire and rim were included. Moreover, the tread width influenced the computation of longitudinal and lateral stiffness of the discrete tread blocks that represented the stiffness of the tread area. For this, the following relations hold:

$$c_{radial} = \frac{P}{100} \cdot \frac{\Delta A}{h} E \tag{3}$$

$$c_{tangential} = \frac{1}{3} c_{radial} \tag{4}$$

$$\Delta A = \frac{2\pi r_{belt} \omega_{tread}}{n_{seg} n_{blocks}}$$

$$h = d_{tread} + d_{tread,0}$$

$$E = E(S) = 10^a \frac{N}{m^2}$$

$$a = 5.33905 + 0.020477S$$

where, P is the tread positive; r_{belt} is the belt radius without inflated, loaded or at zero speed; n_{seg} is the number of belt segments; n_{blocks} is the number of contact points per segment; d_{tread} is the tread depth; $d_{tread,0}$ is the rubber height over steel belt at zero depth; S is the stiffness of tread rubber under the operating conditions.

(2) Tire mass and rotational inertia. Tire mass could be gotten through platform scale, and the rotational inertia could be measured by three-line pendulum.

(3) Tread pattern parameters. The average depth of tire pattern groove could be measured by vernier caliper.

(4) Inflation pressure. It was used to calculate radial forces acting on the belt nodes. These radial forces generated a membrane tension in the belt, which in turn acted similarly to a bending stiffness for the belt nodes. The absolute value of the pressure force was given by Equation (5).

$$|F_{pressure}| = 0.5 \cdot \frac{2\pi r_{belt}}{n_{seg}} \cdot \omega_{tread} \cdot p \tag{5}$$

where, p is the inflation pressure.

3. **Simulation Model.** The vehicle dynamics model was established by ADAMS. The data was obtained from JMC Ford Transit minibus (JX6541D-H). The pavement model was established by using UG and HyperMesh.

3.1. **Vehicle dynamics model.** FTire model was established based on the ADAMS/Car modeling theory [9]. The geometric parameters of the vehicle, including the basic geometry of the tire and the rim, the section width, the aspect ratio, and the rim diameter of the tire, can be directly measured. Moreover, tire mass could be obtained through platform scale, the rotational inertia could be measured by three-line pendulum, and the stiffness parameter could be calculated by the curve of vertical displacement-load characteristics of the tire [10]. The parameters were shown in Table 1.

TABLE 1. Basic parameters of the FTire model

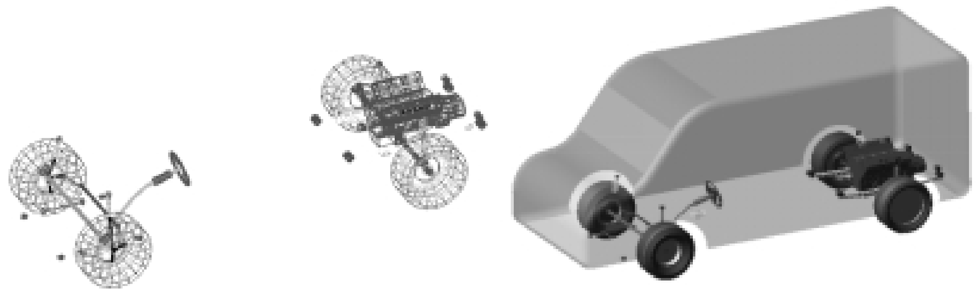
Parameters	Values
Radius /mm	348
Tire section width /mm	225
Aspect ratio /mm	0.7
Rim radius	243
Rim width /mm	205
Vertical stiffness /N/mm	190
Vertical damping /Ns/mm	0.05
Inflation pressure /bar	2.5
Tread depth /mm	8
Tire mass /kg	9.37
Rolling circumference /mm	2185

In JMC Ford Transit minibus, McPherson suspension and the two-way telescopic hydraulic shock absorber were used in the front suspension. Tapered semi-elliptic leaf springs and the two-way telescopic hydraulic shock absorber were used in the rear suspension. The drive mode was FR and the body was monocoque. The vehicle parameters used in the ADAMS were shown in Table 2.

TABLE 2. Parameters of the vehicle

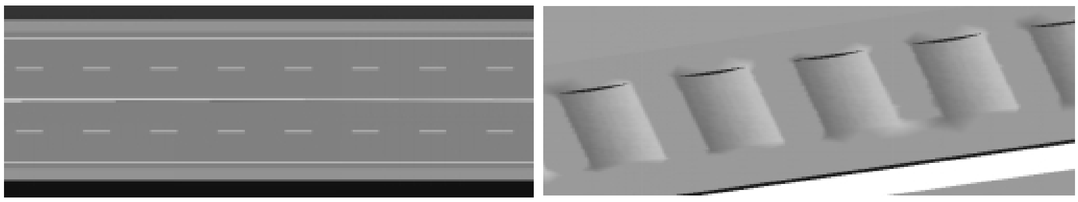
Parameters	Values
Model number	JX6541D-H
Vehicle length /mm	5638
Vehicle width /mm	1974
Vehicle height /mm	2228
Wheelbase /mm	3570
Front track /mm	1692
Rear track /mm	1700
Vehicle mass /kg	1910
Max mass /kg	3300
Center of mass /mm	685
Front axle load /kg	1145
Rear axle load /kg	910
Engine	JX493ZQ3
Tire specification	225/70R15C-8PR
Minimum ground clearance /mm	165

In the ADAMS, according to the parameters and the connections of vehicle subsystems, the subsystems were established and assembled. The chassis model and vehicle model were shown in Figure 3.



(a) Chassis model (b) Vehicle model

Figure 3. Chassis and vehicle model



(a) Road model with rumble strips (b) Rumble strips model

Figure 4. Model of rumble road

3.2. **The pavement model with shoulder rumble strips.** The design of the pavement model with shoulder rumble strips was mainly based on the cross-section design specification in the highway design. The carriageway, the median strip, the shoulder size and the width and length of pavement were simulated by the specification. The 3D models were built by UG according to the pre-known sizes [11]. Furthermore, HyperMesh was used to get the road surface triangular mesh [12]. The file of carriageway, the median, the earth shoulder, and the road-edge were imported into ADAMS to be assembled and color displayed in the ADAMS/View mode. Then, these files were converted to ADAMS/Car mode to form the pavement model with shoulder rumble strips. The model was shown in Figure 4.

4. Simulation and Analysis.

4.1. **Simulation results.** In the post-processing of ADAMS/Car, the vibration acceleration sensor was set on the front axle (A1). The five different depths of shoulder rumble strips for the road simulation were summarized in Table 3, and the simulation speeds were summarized in Table 4. The simulation times were set as 3 second at the speed of 10-30km/h, 2 second at 30-50km/h, 1.5 second at 50-70km/h, and 1.2 second above 70km/h. The simulation combinations were b1 and c1, b2 and c2, b3 and c3, b4 and c4, b5 and c5. The simulation tests of the vehicle model were carried out in different depths of the shoulder rumble trips. The vertical vibration accelerations of front axle in simulation were shown in Table 5.

Table 3. Parameter settings of shoulder rumble strips in simulation

Road type	b1	b2	b3	b4	b5
Depth (mm)	6	8	10	13	15
Width (mm)	160	160	160	160	160

TABLE 4. Settings of vehicle speed in simulation

Speed modes	Speeds (km/h)						
	1	2	3	4	5	6	7
c1	21.41	33.63	47.15	51.74	62.15	74.48	80.4
c2	20.67	37.69	45.58	50.1	69.45	78.72	82.74
c3	21.24	34.48	49.06	55.6	67.06	73.96	80.45
c4	19.57	31.03	47.06	55.98	64.97	73.95	86.79
c5	19.93	35.18	45.05	58.62	68.23	74.43	89.16

TABLE 5. Vibration accelerations in simulation

Rumble strips depths/mm	Vibration acceleration (m/s^2)							Average vibration acceleration (m/s^2)
	1	2	3	4	5	6	7	
6	25.4	31.4	27.3	32.3	34.8	42.1	45.4	32.18
8	25.7	28.9	27.4	27.6	36.3	39.1	43.2	34.35
10	22.2	29.2	26.4	33.3	36.4	42.8	44.6	38.98
13	34.32	36.8	32.4	44.3	42.3	57	53.1	44.79
15	43.9	45.7	42.5	43.8	57.5	59.1	61.6	54.21

TABLE 6. Vibration accelerations of experimental vehicle

Rumble strips depths/mm	Vibration acceleration (m/s^2)							Average vibration acceleration (m/s^2)
	1	2	3	4	5	6	7	
6	21.8	25.84	29	28.28	33.98	41.21	50.29	31.45
8	24.42	25.75	28.35	22.51	41	42.77	50.19	33.19
10	17.26	23.5	22.55	24.02	44.34	25.83	40.77	36.25
13	31.33	37.33	36.74	42.93	51.05	52.3	71.44	42.61
15	39.93	47.22	40.99	45.39	50.29	57.69	63.95	53.08

4.2. **Experimental results.** On the test road and the suburban freeway in Hangzhou, the test vehicle passed the shoulder rumble strips B1, B2, B3, B4 and B5 at the speed of C1, C2, C3, C4 and C5, respectively. The speed was steady before driving on the experimental road. The vertical vibration accelerations of the front axle were acquired. Finally, the average vibration accelerations were shown in Table 6.

4.3. **Results comparison.** The vertical vibration accelerations of the front axle were gotten from the 35 groups of simulations on different shoulder rumble strips pavements. The comparison of the average vertical vibration accelerations between the FTire model and the experimental results was shown in Figure 5 and Table 7.

From the comparison of the acceleration mean values between FTire model and experimental results, the conclusions were as follows.

(1) The vertical vibration accelerations of the front axle in FTire model and experimental vehicle increased when the depths of the shoulder rumble strips increased.

(2) The vertical vibration accelerations of the front axle increased slowly when the rumble depths were in the range of 6 $\sim$ 10mm. The front axle's acceleration growth rate became larger when the rumble depths were more than 10mm.

(3) Basically, the curves of vehicle dynamics simulation and the experimental vehicle had the same changing tendency.

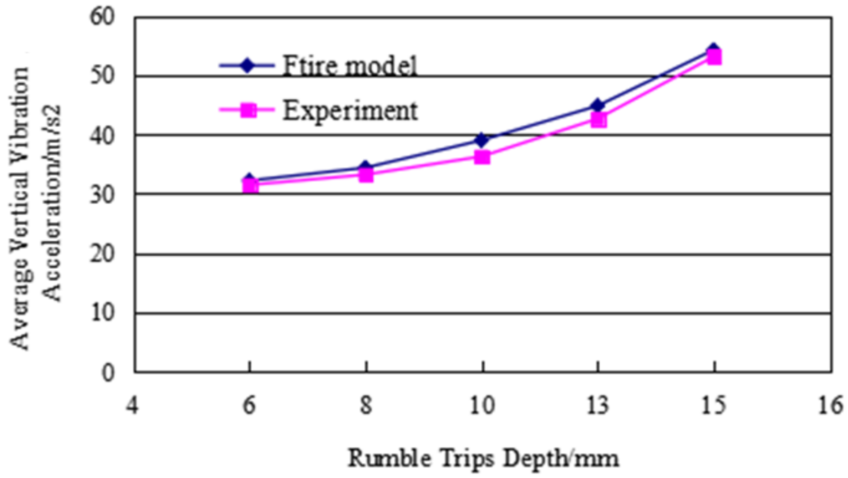


Figure 5. Comparison between FTire model and experimental result

Table 7. Data analyses between the simulation and the experiment

Depths (mm)	Experiment (m/s^2)	Simulation (m/s^2)	Error (m/s^2)	AME	Relative error (%)	Average Magnitude of Relative error (%)
6	31.45	32.18	0.73		2.27	
8	33.19	34.35	38.98		3.38	
10	36.25	38.98	2.73	1.586	6.85	3.89
13	42.61	44.79	2.18		4.87	
15	53.08	54.21	1.13		2.08	

(4) In the numerical, the simulation result was $1.6m/s^2$ higher than the real vehicle test.

5. Conclusions.

(1) The FTire model and the vehicle model can be used in the vehicle dynamics simulation, which had important reference value to analyze the vehicle handling, comfort riding, safety and traffic ability.

(2) From the results of the simulation and the test, the relative error of the vertical vibration accelerations was less than 5% at different depths of shoulder rumble strips pavements. So the FTire model can be applied to the vehicle dynamics simulation on shoulder rumble strips pavements.

In this study, only one vehicle was tested. For further studies, different vehicle types should be tested to verify the feasibility of FTire model.

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