Journal of Southeast University (English Edition) Vol. 25, No. 3, pp. 335 – 339 Sept. 2009 ISSN 1003—7985

Vehicle and terrain interaction based on Adams-Matlab co-simulation

Zhang Xiaoyang Sun Beibei Sun Qinghong Chen Nan

(School of Mechanical Engineering, Southeast University, Nanjing 211189, China)

Abstract: A kind of construction truck model is built in Adams based on multi-body dynamic theory. The rigid and elastic wheels of tire-soil contact models are proposed based on the Bekker pressure model and the Jonasi shear soil model, and they are described in the form of S-function to enhance the calculation efficiency and simulation accuracy. Finally, the interaction of truck and soil is simulated by Adams-Matlab co-simulation to study the influence of soft terrain on the ride comfort of vehicles. The co-simulation results reveal that the terrain properties have a great influence on the ride comfort of vehicles as well as driving speed, road roughness and cargo weight. This co-simulation model is convenient for adding the factor of terrain deformation to the analysis of vehicle ride comfort. It can also be used to optimize suspension system parameters especially for off-road vehicles.

Key words: off-road vehicle; vehicle terramechanics; ride comfort; co-simulation

The interaction of vehicle and terrain is an extremely complicated phenomenon due to high nonlinear contact between tire and soil as well as the sophisticated suspension system of the vehicle. In early studies some linear hypotheses to both soil and vehicle are necessarily proposed to simplify this problem. Moreover, most vehicle researchers focus on the vehicle itself more than the ground or road properties. In their researches, the profile roughness and the friction factor are two considered properties of road or ground, whereas the deformation of the ground crushed by tires is ignored. This ignorance is acceptable for the suspension system design of vehicles running on paved roads; however, the trafficability, ride comfort and handling stability of off-road and agricultural vehicles are mainly determined by the soil sinkage and slippage characteristics[1-2].

Vehicle terramechanics founded by Bekker and Wong for military needs in the 1960s is a subject which specially studies the interaction of terrain and vehicle. In the early stages of its development, it mainly focuses on the research of traction trafficability for military vehicles, and in recent researches the focus has turned to ride comfort of off-road vehicles. However, the research issue remaining unchanged is the tire-soil contact model because all vehicle control forces/moments are generated at the patch where tire and terrain interact, so that tire modeling, soil modeling, and tire-soil interaction modeling are critical[3-4]. In this investigation, soil is modeled using the Bekker and Jonasi approach with parameters from relative literature and two kinds of typical off-road soil are selected as samples to study its effect on the ride comfort of vehicles running on it. Although the Bekker and Jonasi approach is relatively old, effective implementation to achieve its full potential has been possible only recently, with the advent of high capability computers and simulation software packages. A computational algorithm for such implementation is presented. Tire-terrain interaction is modeled using a hybrid approach of empirical and semi-empirical models. Bekker's normal pressure sinkage model and Jonasi's shear-tension-displacement model are applied to build the tire-soil contact model in the form of an S-function, which can calculate the ground reaction force acting on tires.

To reliably predict vehicle performance under realistic off-road conditions, lumped-parameter models commonly used in vehicle dynamics are not adequate. In this work, a high fidelity, multi-body dynamics approach is employed to capture vehicle nonlinear dynamic characteristics. A full 3-D model of an articulated dump truck is developed in the dynamic simulation package MSC. ADAMS, and it is verified with vibration table tests. Because there is no standard for off-road roughness, the PSD of a GB-D road, which is a bad road situation, is adopted and transformed to time domain by trigonal progression to simulate the ground unevenness.

A complete co-simulation environment can be constructed by integrating all the above-mentioned models and ride comfort analyses of vehicles can be performed considering the influence of soil's deformation. Two kinds of soil with different deformability and rigid roads are presented to demonstrate the approach and investigate the interaction of vehicle and terrain.

1 Tire-Terrain Interaction Model

The simulation of tires in an analytical tire-soil-model is quite a complex task. However, if some reasonable hypotheses and simplifications are applied to the tire-soil contact, this problem seems not so difficult. In this work, two kinds of tire-terrain interaction models are presented with the concept of critical pressure p_{cr}, which is a judgment factor for the model selection.

1.1 Rigid wheel model of tire-soil contact

The measured and mathematically approximated soil characteristics are applied to the interaction of tire and terrain as follows. First, the tire-soil contact pressure at the tire's lowest position is calculated provided that the tire remains undeformed and this pressure is defined as critical pressure p_{cr}[5],

$$p_{cr} = \left(\frac{k_c}{b} + k_\varphi\right) z_0^n = \left(\frac{k_c}{b} + k_\varphi\right)^{1/(2n+1)} \left(\frac{3F_z}{(3-n)b\sqrt{D}}\right)^{2n/(2n+1)} \tag{1}$$

Received 2009-02-19.

Biographies: Zhang Xiaoyang(1980—), male, graduate; Sun Beibei(corresponding author), female, doctor, professor, bbsun@seu.edu.cn.

Foundation items: The National Natural Science Foundation of China(No. 50575040), the Natural Science Foundation of Jiangsu Province (No. BK2007112).

Citation: Zhang Xiaoyang, Sun Beibei, Sun Qinghong, et al. Vehicle and terrain interaction based on Adams-Matlab co-simulation[J]. Journal of Southeast University (English Edition), 2009, 25(3): 335 – 339.

where k_c and k_φ are the cohesive and frictional modules of soil deformation, respectively; n is the sinkage; exponent b is the short limbic length of the tire; z_0 is the maximal sinkage of the tire; F_z is the load of the tire and D is the effective driving diameter of the tire.

Then comparison of the critical pressure p_{cr} with the sum of the tire's carcass stiffness p_c and the tire's inflation pressure p_i is made. If $p_{cr} \leqslant p_c + p_i$, it is indicated that the tire is "harder" than the soil so that the tire can be regarded as undeformed. A rigid wheel of the tire-soil contact model is proposed in Fig. 1.

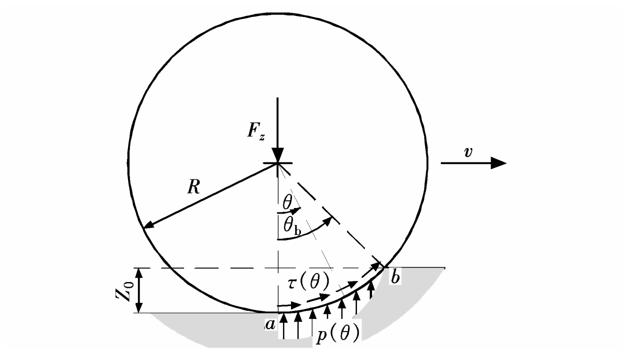

Fig. 1 Rigid wheel of tire-soil contact model

An integration of the local pressure along the contact area gives the vertical reaction force,

$$F_g = \int_0^{\theta_b} p(\theta) BR \mathrm{d}\theta + \int_0^{\theta_b} \tau(\theta) \sin(\theta) BR \mathrm{d}\theta \qquad (2)$$

where B and R are the width and the radius of the tire, respectively. $p(\theta)$ is the vertical component of soil pressure exerting normally on the tire treads, so

$$p(\theta) = \left(\frac{k_c}{b} + k_\varphi\right)(z_0 - R(1 - \cos\theta))^n \cos\theta \qquad (3)$$

and

$$\tau(\theta) = (c + p(\theta)\tan\varphi)(1 - \mathrm{e}^{-j/K}) \qquad (4)$$

Shear deformation j can be approximately obtained by

$$j = (\omega R - V)\frac{\theta_b - \theta}{\omega} = Rs(\theta_b - \theta) \qquad (5)$$

where ω and V are the rotation speed of the wheel and the vehicle's velocity, respectively; s is the slip ratio of the tire which can be obtained by some estimation algorithms.

This rigid wheel model is a practical approximation for the conditions such as a vehicle tire with high inflation pressure with the soil being relatively soft, and for special vehicles with rigid wheels (e. g. robotics). Under these conditions the rigid wheel model is the best choice.

1.2 Elastic wheel model of tire-soil contact

If the soil is hard and the tire's inflation pressure is comparatively low, namely $p_{cr} > p_c + p_i$, then the deformation of the tire should not be ignored and the elastic wheel of the tire-soil contact model needs to be presented. Some researchers utilize a bigger substitution circle to approximate the deflected elastic tire. The diameter of the substitute circle is calculated from equilibrium between the vertical reaction force of the soil and that of the tire. This equilibrium is solved by an iteration process so numerous calculation loads of substitution circle diameters confine this method to deal with simple problems. For integrating the tire-soil contact model with the precise multi-body vehicle model, and performing co-simulation of the ride comfort of the whole vehicle under different work conditions, some assumptions should be made as compromises to the limited computer resources and large amounts of calculation. In this work, a flat-bottomed elastic wheel model is presented in Fig. 2.

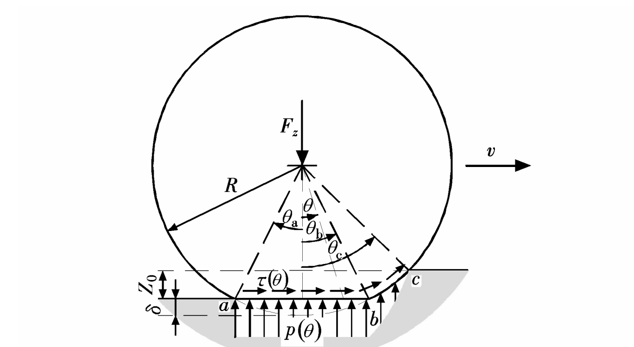

Fig. 2 Flat-bottomed elastic wheel of tire-soil contact model

This approach was primarily suggested by Bekker but it was never put into practice due to the complexity of the calculations. The vertical reaction of the ground is the result of an integration of the local pressure under the wheel. The total vertical tire reaction force can be computed as

$$F_g = \int_{-\theta_a}^{\theta_c} p(\theta) BR \mathrm{d}\theta + \int_{\theta_b}^{\theta_c} \tau(\theta) \sin(\theta) BR \mathrm{d}\theta \qquad (6)$$

The detailed integration is similar to Eqs. (2) to (5), but the major difference of the elastic wheel model against that of the rigid wheel lies in the deformation Δtd of the tire, the value of which is obtained from the co-simulation of vehicle-soil interaction in real time.

2 Ground Profile Model

Although numerous studies have been conducted on the measurement and description of the paved-road profile roughness, and some criteria such as GB7031 and ISO/TC108/SC2N67 have been made, there is no standard for off-road roughness. So the PSD of a GB-D road, which is a bad road situation, is adopted and transformed to time domain by trigonal progression to simulate the ground unevenness.

The form of the road's power spectral density (PSD) equation and the PSD equation's transformation to a road roughness function in time domain are described in Ref. [6] in detail. Where the road profile roughness of the GB-D with a vehicle speed of 40 km/h is used as ground profile excitation for the simulation of vehicle and terrain interaction.

3 Vehicle Multi-Body Model

The vehicle studied in this paper is a type of articulated dump truck, which is normally used for transporting earthwork and other construction materials, so it runs mostly on off-road ground. The traditional concentrated-mass-vehicle-model is not fit for this kind of construction truck because the path of force transferring from the tires to the vehicle body is not as clear as that of ordinary trucks. The geometrical model of the truck is built in Pro/E using individual parts and then they are imported into ADAMS, in which they are connected by constraints and joints. The topological graphics of the half truck model is displayed in Fig. 3.

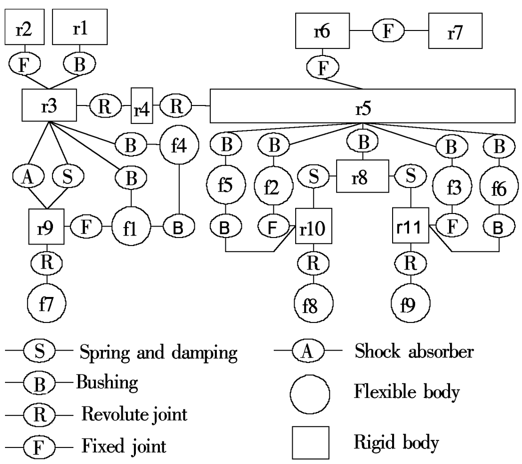

Fig. 3 Topology of half truck model

Tab. 1 lists the part names of the truck which are symbolized in Fig. 4 as r1 to r11 and f1 to f9. The whole truck model consists of 12 rigid bodies and 12 flexible bodies, and they are connected by springs, dampers, shock absorbers, bushings, and ideal joints such as revolute joints and fixed joints. For the sake of symmetry, the other side of the equalizer member and three tires are not shown in Fig. 3.

Tab. 1 Names of symbolized truck parts

Symbol	Vehicle part	Symbol	Vehicle part
r1	Cab	r11	Rear axle
r2	Engine	f1	U-form frame
r3	Front frame	f2	Middle A-form frame
r4	Articulate chain	f3	Rear A-form frame
r5	Rear frame	f4	Front crossbar
r6	Cargo body	f5	Middle crossbar
r7	Cargo	f6	Rear crossbar
r8	Equalizer member	f7	Front tire
r9	Front axle	f8	Middle tire
r10	Middle axle	f9	Rear tire

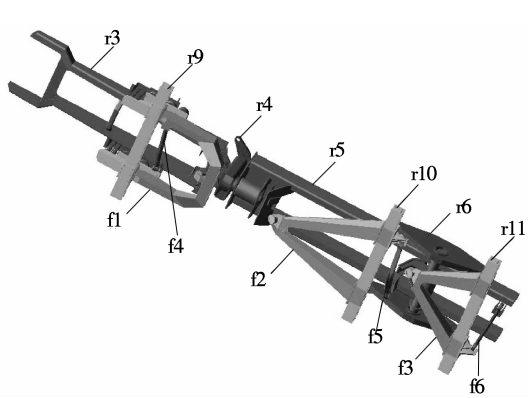

Fig. 4 The truck frame and the suspension system

The truck frame and the suspension system shown in Fig. 4 including an articulate chain, two equalizer members, a U-form frame, two A-form frames, and rubber springs make the suspension system more complex than those of other ordinary trucks. These problems are well solved by utilizing the multi-body dynamic analysis software ADAMS. Moreover, some complicated factors such as ground unevenness and soil deformation can be considered by co-simulation of ADAMS/Simulink, which will be discussed in the following section.

4 Vehicle-Terrain System and Analysis of Ride Comfort of Truck

4.1 Co-simulation system

In order to satisfy the vehicle-terrain interaction co-simulation system, the state variables including output and input variables need to be defined in Adams first[7]. In this work, the motion of six tires (vertical displacement, velocity and acceleration of wheel hubs) and the motion state of the truck (longitudinal direction at the position of cab floor and cargo cg.) are defined as the output variables of the Adams truck model. The ground vertical reactive forces are defined as input variables. So there are in total 20 output variables and six input variables of the Adams model.

Then the multi-body model of the truck is exported by Adams/Control to Matlab/Simulink as a Simulink block named the truck model, which has six input ports and six output ports. The principle of the co-simulation system is shown in Fig. 5. The ground reactive force acting on left front tire is calculated in the S-Function block named Gforce1. For the sake of simplification, the other five ground reactive forces named Gforce2 to Gforce6 are not denoted in Fig. 5. Also, the motion of the other tires is not denoted in Fig. 5 for the same reason. The inputs of Gforce1 including Hub1_dis, Hub1_vel and Hub1_acc, which represent the vertical displacement, velocity and acceleration of the wheel hub, are the outputs of the truck model. In this work, the road profile roughness of GB-D is used. The algorithmic process of the block Gforce1 is shown in Fig. 6, and the other blocks are the same.

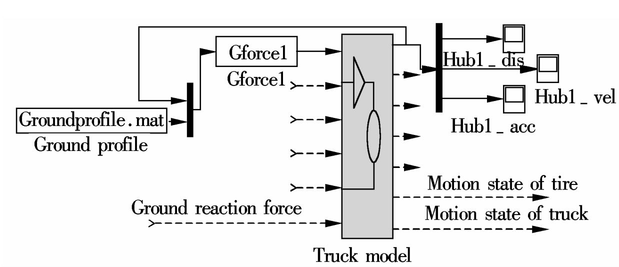

Fig. 5 Principle of vehicle-terrain interaction co-simulation system

Finally, the co-simulation is carried out with the fixed step of 1 ms for 20 s. Two kinds of soil are chosen and their parameters are shown in Tab. 2[8-9].

Tab. 2 Soil parameters of Wong's measurement

Soil type	Moisture content/%	n	k_c/ $(kN\cdot m^{-(n+1)})$	k_φ/ $(kN\cdot m^{-(n+1)})$	φ/(°)
LETE sand	0	0.71	6.94	505.8	31.1
Grenville loam	24	1.01	0.06	5 880	29.8

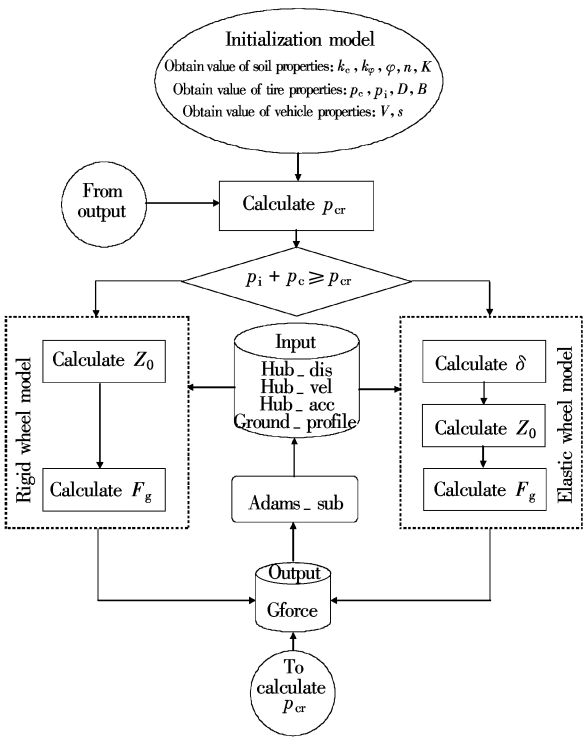

Fig. 6 Algorithmic process of the block Gforce1

4.2 Results and analysis

Fig. 7 shows the comparison of vehicle hub displacement among arbitrary grounds with different deformabilities. According to the simulation results, when the ground deformability is extremely low (hard soil, Grenville loam), the displacement response of the wheel hub position is 0.025 m below that of a rigid road. The sinkage increases as the ground deformability increases, and the displacement response of the wheel hub position of LETE sand is 0.17 m below that of the rigid road. Fig. 7 also indicates that the higher the deformability, the smoother the curves of wheel hub positions on the ground.

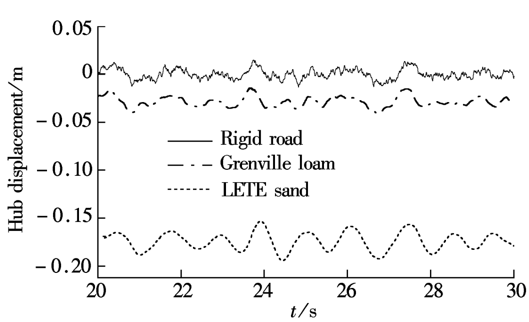

Fig. 7 Comparison of wheel hub position among arbitrary grounds with different deformabilities

Fig. 8 shows the comparison of the PSD of cab floor acceleration among arbitrary grounds with different deformabilities. It is obvious that the vehicle vibration energy distribution in the frequency domain is very sensitive to the ground deformability. The dominant frequency of the vehicle is about 3.2 Hz when it runs on a rigid road. With the stiffness of the ground decreasing, the dominant frequency of the truck changes in the same direction, whereas the peak of the PSD curve increases, which means that vibration energy tends to be concentrated to a low frequency with the soft soil.

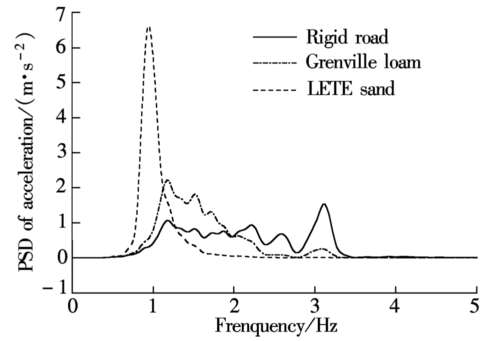

Fig. 8 Comparison of PSD of cab floor acceleration among arbitrary grounds with different deformabilities

5 Conclusion

A vehicle-terrain interaction model is developed in this paper, which includes the FEM tire model, the terrain model and the tire-terrain contact model, the ground profile model and the multi-body vehicle model. A co-simulation based on Adams and Matlab is conducted to investigate the influence of ground deformation on the ride comfort of vehicles. Results of the co-simulation show that the soil stiffness determines the dynamic characteristics of the vehicle specifically in the frequency domain. Ground deformability must be regarded as an important factor in the process of vehicle suspension system design and the optimization of vehicle ride comfort.

Acknowledgments The authors sincerely acknowledge the invaluable assistance of doctor Zhou Changfeng and doctor Xu Zhihua, and the favourable cooperation with Xuzhou Construction Machinery Group Inc., China.

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基于 Adams-Matlab 联合仿真的车辆地面相互作用研究

张晓阳　孙蓓蓓　孙庆鸿　陈　南

（东南大学机械工程学院，南京 211189）

摘要：根据多体动力学在 Adams 环境中建立了某款工程车辆的模型，以汽车地面力学中 Bekker 承压模型和 Jonasi 剪切模型为基础建立了刚性轮和弹性轮模型以模拟轮胎地面接触，并将轮胎地面接触模型用 S 函数描述，以提高仿真运行速度和计算精度. 最后借助 Adams-Matlab 联合仿真工具，对车辆与松软地面相互作用问题进行了仿真计算，研究了地面特性对车辆行驶平顺性的影响. 仿真计算结果表明，同车辆行驶速度、路面不平度和载荷一样，地面土壤力学特性对车辆行驶平顺性也有重要影响. 该联合仿真模型能将地面变形因素考虑到车辆平顺性分析中，为非公路车辆悬架优化设计提供了思路和研究基础.

关键词：非公路车辆；车辆地面力学；平顺性；联合仿真

中图分类号：U461.33