Flexible road and tyre modelling based on ADAMS

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Abstract

MSC. ADAMS, a multibody dynamics software, is powerful in modelling of complex mechanical systems and realizes fine simulation on vehicle-pavement coupled system (VPCS). Existing MSC. ADAMS treats pavement as a rigid body and simplifies tyres as a group of mathematical formulas. Therefore, finite element model of tyre and road is the basis of flexible VPCS modelling. In this paper, finite element model of tyre and road was established and introduced into MSC. ADAMS through the MNF file. After the spatial position of finite element model was adjusted, a three-way force could be applied between tyre and road surface by setting their contact pattern. An elaborate VPCS model can be established by combining the universal vehicle prototype model and the established flexible road and tyre model based on MSC. ADAMS.

Keywords: Multibody Dynamics; Finite Element; Flexible Road Model; Tyre Model

1 Introduction

Vehicle-pavement coupled system (VPCS) modelling and dynamics analysis are the research hotspots of vehicle engineering and road engineering. Abundant research fruits have been achieved based on analytic method.

In existing models, simplifying vehicles into moving load is the simplest processing. Kim et al. [1] got the deflection analytical solution of infinite plate on the Winkler foundation traversed by moving biaxial load through integral transformation. Ansari et al. [2] calculated vibration of finite Euler-Bernoulli beam on the nonlinear viscoelastic foundation traversed by moving load.

Such modelling could not support research on vehicle response. To reflect dynamic properties of vehicles, multiple-degree-of-freedom (MDOF) system is widely used. Esmailzadeh et al. [3] established a vehicle-passenger-structure interaction equation and analyzed the dynamic mechanical behaviours of bridges traversed by moving load. In his model, drivers and passengers were simplified as a six-degree-of-freedom half-car plane model. Hardy et al. [4] adopted 1/4-car model and simplified road structure as a piece of elastic beam on the elastic foundation. Yang et al. [5] simulated vehicle-pavement coupled system as the uniform motion of a two-degree-of-freedom oscillator along the linear viscoelastic foundation.

Although new analytical models are emerging continuously, they simplify practical situations signifycantly and could not reflect actual dynamic behaviours of VPCS. Multibody dynamics software is powerful in complex system modelling [6]. It can introduce flexible road into complex vehicle model [7, 8] and establish an elaborate VPCS model to reflect the complicated dynamic behaviours of VPCS truly.

MSC. ADAMS is the current mainstream of multibody dynamics software. The built-in full vehicle model can be used directly. However, this full vehicle model simplifies tyres as a group of mathematical formulas and treats pavement as a rigid body. Building flexible pavement in MSC. ADAMS is the prerequisite for further implementing VPCS modelling and dynamics analysis based on MSC. ADAMS.

2 Multibody dynamics equation of VPCS

The coordinate system location of VPCS is determined by its Descartes coordinates in the inertial reference system ($r=\left[x\ y\ z\right]^{\mathrm{T}}$) and the Euler angles ($\pi=\left[\psi\ \theta\ \phi\right]^{\mathrm{T}}$) that reflects direction of rigid body. Deformation of the flexible body is depicted by generalized coordinates (q_f). Therefore, the generalized coordinates of the flexible body can be expressed as:

$$\xi=\left[r^{\mathrm{T}}\quad \pi^{\mathrm{T}}\quad q_f^{\mathrm{T}}\right]^{\mathrm{T}}. \tag{1}$$

Kinetic energy of the flexible body is:

$$T=\frac{1}{2}\dot{\xi}^{\mathrm{T}}M\dot{\xi}, \tag{2}$$

where M is mass matrix.

Potential energy of the flexible body is:

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$$W = \frac{1}{2}\xi^{\mathrm{T}} K\xi + \int_W \rho\left[r_0 + A\left(s_P + \Phi_P q_f\right)\right]^{\mathrm{T}} g dW\ , \qquad (3)$$

where K is generalized stiffness matrix corresponding to the modal coordinates, and g is gravitational acceleration vector.

Damping force depends on generalized modal velocity and can be deduced from:

$$\Gamma = \frac{1}{2} q_f^{\mathrm{T}} D q_f\ , \qquad (4)$$

where Γ is energy loss function, and D is the damping coefficient matrix of components.

Due to interaction of components, the kinetic equation of VPCS can be inferred from[9]:

$$\begin{cases} \dfrac{d}{dt}\left(\dfrac{\partial L}{\partial \dot{\xi}}\right) - \dfrac{\partial L}{\partial \xi} + \dfrac{\partial \Gamma}{\partial \xi} + \left[\dfrac{\partial \psi}{\partial \xi}\right]^{\mathrm{T}} \lambda - Q = 0 \\ \psi = 0 \end{cases}, \qquad (5)$$

where L is the Lagrange term ($L = T - W$), ψ is constraint equation, λ is Lagrange multiplier, and Q is generalized forces.

Substitute calculated T, W and Γ into (5) to get the final differential equation of motion:

$$\begin{aligned} & M\ddot{\xi} + \dot{M}\dot{\xi} - \frac{1}{2}\left[\frac{\partial M}{\partial \xi}\dot{\xi}\right]^{\mathrm{T}} \dot{\xi} \\ & + K\xi + f_g + D\dot{\xi} + \left[\frac{\partial \psi}{\partial \xi}\right]^{\mathrm{T}} \lambda = Q \end{aligned}, \qquad (6)$$

where f_g is generalized gravity.

3 Modal calculation of the flexible body

Rayleigh-Ritz method and modal synthesis method are two popular treatments of flexible components at the moment. Major multibody dynamics software also uses either one of them to process flexible components. ADAMS uses Craig-Bampton fixed interface modal synthesis method.

In undamped system, the motion equation of any substructure a is:

$$M^a \ddot{x} + C\dot{x} + K^a x = F^a + f^a\ , \qquad (7)$$

where M, C and K are mass, damp and stiffness matrix of a; x and $\ddot{x}$ are the displacement vector and acceleration vector of a; f^a is applied force on nodes within the interface of a; f^a is external force on nodes beyond the interface of a, $f^a = 0$ at free system vibration.

The Craig-Bampton method divides branch modal set (ϕ) of the flexible body into master mode (ϕ_k) and constraint mode (ϕ_c). It divides nodes on a into non-interface nodes and interface nodes. Their subscripts are i and j, respectively. For example, x_i and x_j represent non-interface displacement and interface displacement, respectively. Therefore, ϕ of a can be expressed as:

$$\phi^a = \begin{bmatrix} \phi_k^a & \phi_c^a \end{bmatrix} = \begin{bmatrix} \phi_{ik}^a & \phi_{ic}^a \\ 0_{jk}^a & I_{jc}^a \end{bmatrix}. \qquad (8)$$

The master mode of the fixed interface of the system can be acquired by calculating the characteristic equation of (7). Previous orders of modes can be taken as retained master modes (ϕ_{ik}^a).

In (8), ϕ_c^a is calculated from the static equation:

$$\begin{bmatrix} k_{ii}^a & k_{ij}^a \\ k_{ji}^a & k_{jj}^a \end{bmatrix} \begin{bmatrix} \phi_{ic}^a \\ I_{jc}^a \end{bmatrix} = \begin{bmatrix} 0_{ic} \\ R_{jc} \end{bmatrix}. \qquad (9)$$

where k is stiffness coefficient matrix and R_{jc} is constraint matrix.

Therefore, (8) can be rewritten as:

$$\phi^a = \begin{bmatrix} \phi_k^a & \phi_c^a \end{bmatrix} = \begin{bmatrix} \phi_{ik}^a & -k_{ii}^{-1} k_{ij} \\ 0_{jk}^a & I_{jc}^a \end{bmatrix}. \qquad (10)$$

Equation (10) shows that ϕ_k^a can be determined according to needs, while ϕ_c^a is determined by degrees of freedom of interface. During structural vibration, high-order modes contribute less energy to the whole system and are insignificant to the whole structural vibration. To reduce degree of freedom of the system, ϕ_k^a shall be kept as small as possible within allowed errors.

4 Flexible body construction based on ABAQUS software

4.1 BASIC STEPS

Although there are three ways in MSC.ADAMS to construct flexible body, complex flexible body still requires pre-processing by finite element software. Construction of flexible body includes two steps. Firstly, flexible components are built and their modals are calculated in the finite element program. Secondly, calculated results are stored in the modal neural file (MNF) which will be import into MSC.ADAMS. Most mainstream finite element software support MNF generation. In this paper, the flexible body was preprocessed using ABAQUS.

Before modelling, CAE_NO_PARTS_INPUT_FILE in the ABAQUS_V6.ENV shall be set ON. INP file will be generated after modelling based on the ABAQUS CAE module. Edit the INP file to make *FREQUENCY and *SUBSTRUCTURE GENERATE as the last two analysis steps.

Later, start the ABAQUS COMMAND interface to run the INP file firstly and then the command of

ABAQUS ADAMS JOB = JOB_NAME to generate MNF.

The generated MNF does not include stress-strain information of the flexible body. Therefore, stress-strain of nodes on the flexible body still could not be observed after the MNF is imported into MSC.ADAMS for flexible body construction and simulation.

4.2 STORING STRESS-STRAIN INFORMATION IN MNF

Firstly, add stress-strain output requirement in the *FREQUENCY based on the INP file. Run the INP file on the ABAQUS COMMAND interface firstly and then the command of ABAQUS ADAMS JOB = JOB_NAME MAKE_SE_RECOVERY to generate a new INP file.

Run the new INP file again and then the command of ABAQUS ADAMS JOB = JOB_NAME SE_ RECOVERY_JOB= SE_RECOVERY_ JOB_NAME to generate MNF containing stress-strain information.

4.3 PRELOADING OF THE FLEXIBLE BODY

Stress-strain relation of the flexible body in the MSC.ADAMS is a linear one. For components with non-linear stress-strain relation, preload can be applied in the finite element analysis, so that components will produce pre-deformation when approaching to the normal working load. Based on the pre-deformation, MSC.ADAMS will linearize the original nonlinear stress-strain relation. Effect of preload is shown in Figure1.

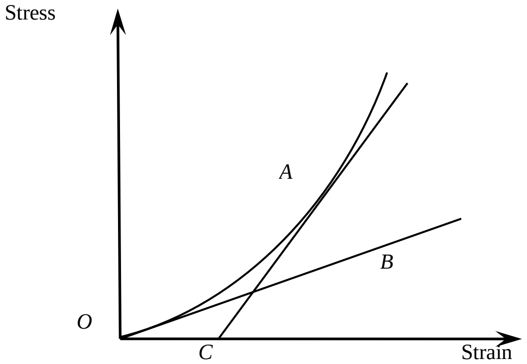

FIGURE 1 Stress-strain relation of the flexible body

In Figure1, *OA* is stress-strain curve of the flexible body, *O* is strain of the flexible body without external forces, and *A* is strain of the flexible body under normal working condition. Practically, strain-stress relation of the flexible body changes along *OA*. MSC.ADAMS linearizes the nonlinear stress-strain relation partially. If no preload is applied to the flexible body, its strain-stress relation in the MSC.ADAMS changes along *OB*. If pre-load is applied in the finite element software, the flexible body will produce pre-deformation which increases strain to *A* along the curve. After import pre-deformation into MSC.ADAMS, the strain-stress relation of the flexible body will change along *AC*. Apparently, the preload makes the strain-stress relation of the flexible body at *A* closer to practical state.

During preprocessing of the flexible body using ABAQUS software, any amount of analytical steps can be set for preloading before *FREQUENCY.

5 Flexible road and tyre modelling

To verify feasibility of the proposed modelling method, an imaginary 1m(L)*1m(W)*1m(H) road structure was used for modelling. Constraints were only imposed to the bottom surface. It has four structural layers. Material parameters of different layers are listed in Table 1.

TABLE 1 Material parameters of different structural layers of the road

Layer	Thickness /cm	Density /kg·m^{-3}	Modulus /MPa	Poisson's ratio
AC13	10	2500	1500	0.35
CCR	20	2300	1600	0.25
LFS	20	1800	500	0.2
S	50	1800	40	0.4

The flexible road established in MSC.ADAMS is shown in Figure 2.

The tyre model in MSC.ADAMS is a group of mathematical formulas, which are independent from the flexible road. To integrate flexible road into the VPCS model, a finite element model of tyre has to be built.

In this paper, ABAQUS generates the MNF of 175 SR14 tyre to discuss the modelling method. The flexible tyre model in MSC.ADAMS is shown in Figure 3.

Such finite element model of flexible tyre is characteristic of nonlinear material structure, preload application, deformation of the contact area with pavement, and no autorotation.

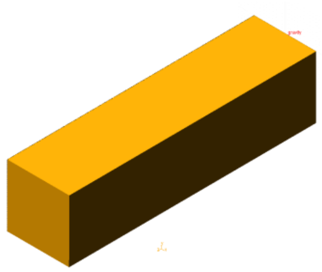

FIGURE 2 Flexible road established in MSC.ADAMS

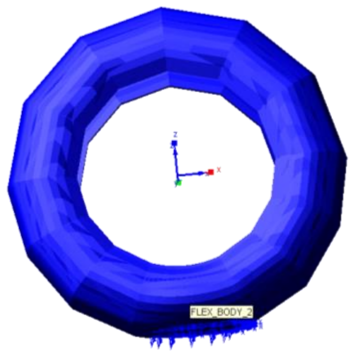

FIGURE 3 Flexible tyre model in MSC.ADAMS

6 Application of flexible tyre and road models

The established flexible tyre and road models were imported into MSC.ADAMS. The relative positions of tyre and road were adjusted and a CONTACT parameter was set between them. CONTACT TYPE was selected FLEX BODY TO FLEX BODY. Friction force can be set through FRICTION FORCE. After essential constraints and load are set, simulation can be started (Figure 4).

The stress and strain of any node in flexible body can be plotted by durability plugin (Figure 5).

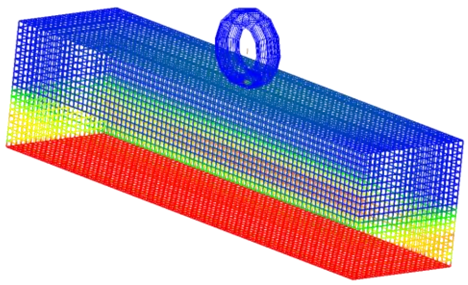

FIGURE 4 Simulation of flexible tyre and road models

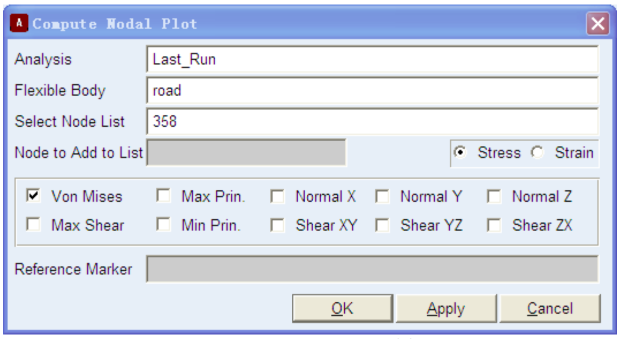

FIGURE 5 Plot stress and strain of flexible body

7 Conclusions

The strong functions of MSC.ADAMS in vehicle modelling provide foundations for VPCS simulation. However, existing MSC.ADAMS treats road as a rigid body and simplifies tyres as a group of mathematical formulas. It is necessary to explore flexible road and tyre modelling methods.

Flexible roads and tyre models were established base on the finite element software. In the MSC.ADAMS, connection between flexible road and tyre is achieved by setting the CONTACT parameter.

Flexible road and tyre models lay foundations for further VPCS modelling and simulation based on MSC.ADAMS. However, this paper only analyzes an imaginary road structure when establishing the road model. Actually, road is an infinite continuum. Reasonable geometric parameters of the road structure shall be analysed specifically before VPCS modelling.

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