Contact and Sliding Simulation of Rubber Disk on Rigid Surface with Microscopic Roughness

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ABSTRACT:

It is crucial to obtain detailed information about frictional interaction between tire and road surface to estimate performance of vehicle brake system or tire on real road surface. Simulation using Finite Element Method (FEM) in addition to experimental procedure is regarded to be useful to investigate contact behavior between tire and road surface. However, indeed, it is difficult to apply FEM simulation for such a problem since contact and sliding of rubber on rough rigid road surface may cause local large element distortion on rubber material and simulation may fail by negative volume error.

In this paper, modeling of a rubber disk and rigid road surface with microscopic roughness, which can be used as a baseline for simulation of contact behavior between tire and road surface, is described. Some investigation for analysis technique to ensure stable computation of rubber disk and road surface model under severe condition has been made. It was shown that proposed modeling technique could avoid extreme mesh distortion during simulation. It is expected that the proposed technique can be used in simulation of rolling/sliding tire on real road surface.

Keywords:

Friction, Microscopic roughness, Hyperelastic rubber,

INTRODUCTION

Sugimura, et al. [1] present the roughness and traction measurement system (RTMS) which can measure friction between rolling/sliding rubber disk specimen and surface with microscopic roughness. The rubber disk has 63.5 mm diameter and 12.7 mm thickness. RTMS can set various slip ratios for rubber disk. Slip ratio, s is defined as

$$s = (U_T - U_R)/U_T \qquad \text{(Eq.1)}$$

where U_T and U_R are translational velocity and rotational velocity of rubber disk respectively. In RTMS alumina abrasive paper is used to represent real road surface with microscopic roughness. The grade of roughness of road surface can be changed using abrasive paper with various grid sizes. The experiment of Sugimura using RTMS was considered as an appropriate starting point of numerical simulation using LS-DYNA. Then, some parts of RTMS were selected to be modeled.

MODEL DESCRIPTION

The model of RTMS specimen was originally modeled by Kuwajima et al. [2]. The geometry and dimensions of the model is shown in Fig.1. A rubber disk of 63.5 mm diameter is modeled with solid elements. As the rubber disk is a thick cylinder, two-dimensional plane strain model was adopted in [2]. However, LS-DYNA has wider capabilities in three-dimensional contact definition rather than two-dimensional contact and it was expected that abundant contact options in three-dimension were necessary in severe cases. Thus, the model is enhanced in three-dimension with one layer of solid elements in this paper. The degree of freedom for axial direction of the rubber disk is fixed according to plane strain assumption. The thickness of the rubber disk is set to 0.02 mm. Since the case of slip ratio = 1.0 is considered as the most severe case for rubber material in rolling/sliding rubber disk on road surface, the edge of the center hole of the rubber disk was fixed to prevent rotation.

As road surface is replaced with abrasive paper in the experiment of Sugimura, the surface of abrasive paper was scanned and digitized. The surface data was also smoothed by spline interpolation and used to generate FE model. The surface data of A120 grid size abrasive paper is adopted in the simulation. As shown in Fig.1, extremely fine profile is included in the rigid surface model, then, high resolution for mesh density in rubber material is also necessary to fit to the rigid surface. This yields the minimum element length of 0.02 mm in rubber disk. Mesh density is coarsened gradually away from the road surface to reduce excessive computation time. The summary of the model size is as follows; 15,802 solids, 3,000 shells (rigid), and 38,650 nodes.

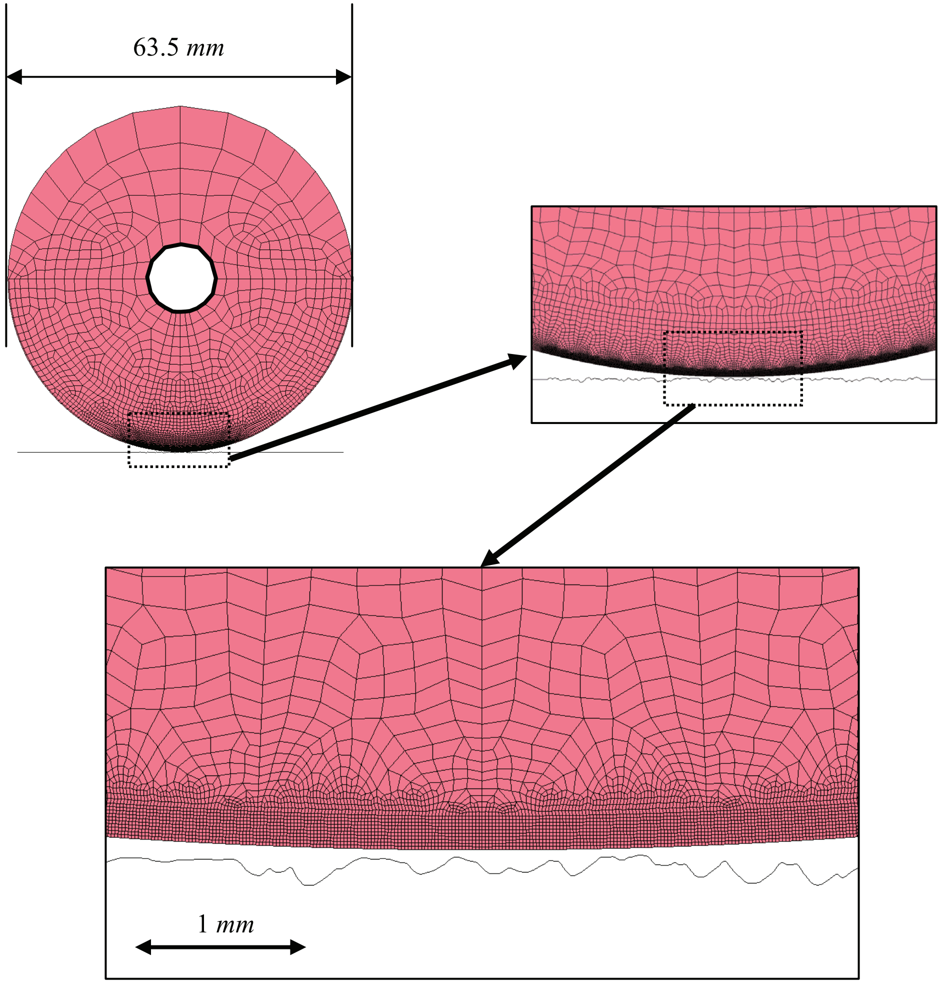


Figure1: Model geometry of rubber disk and rigid surface with microscopic roughness

In the experiment [1], carbon black-filled styrene-butadiene rubber (SBR) was used and stress-strain curve has been measured by uniaxial tensile test. In the paper [2] the stress-strain curve is fit by Yeoh strain energy functional (Eq.2).

$$W = \sum_{i=1}^{3} C_{i0}\left(\bar{I}_1 - 3\right)^i + W_H\left(J\right) \quad \text{(Eq.2)}$$

where $\bar{I}_1$ is reduced invariant of the reduced right Cauchy-Green deformation tensor, C_{i0} (i=1,2,3) are constants, and $W_H(J)$ is the volumetric term. As LS-DYNA has similar strain energy functional as *MAT_HYPERELASTIC_RUBBER or *MAT_077_H (Eq.3), this material model can be used to express Yeoh model.

$$W = \sum_{p,q=1}^{n} C_{pq}\left(\bar{I}_1 - 3\right)^p \left(\bar{I}_2 - 3\right)^q + W_H\left(J\right) \quad \text{(Eq.3)}$$

LS-DYNA has an option to determine the constants in Eq.3 to fit stress-strain curve automatically when number of constants N is specified in input data. But since automatic fitting option of LS-DYNA involves $\bar{I}_2$ terms in addition to $\bar{I}_1$ terms for fit, the constants only for $\bar{I}_1$ terms, i.e., $C_{10,}$ C_{20}, and C_{30} in Eq.4 should be determined without using LS-DYNA to express Yeoh model.

$$W = C_{10}\left(\bar{I}_1 - 3\right) + C_{20}\left(\bar{I}_1 - 3\right)^2 + C_{30}\left(\bar{I}_1 - 3\right)^3 + W_H\left(J\right) \quad \text{(Eq.4)}$$

The set of constants obtained by simple least square approximation and the result of fitting to the given stress-strain curve are shown as follows;

C_{10}=-4.7116e-2

C_{20}=5.7685e-3

C_{30}=-6.2442e-5

C_{01}=C_{11}=C_{02}=0.0

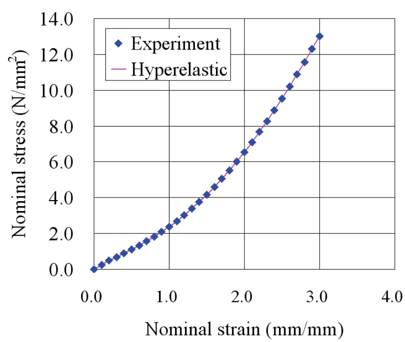


Figure 2: Stress-strain curves of tensile test and hyperelastic rubber model

ANALYSIS CONDITION

In the experiment [1], the rubber disk is pressed on the surface with vertical force 2.46 N per unit thickness and forced to rotate/slide on the surface. Hence two prescribed displacement conditions; one for vertical direction to generate 2.46 N per unit thickness contact force and another for horizontal direction to slide the rubber disk are applied to the rigid surface in this simulation. Although real event time of the experiment [1] is order of one second, the termination time of the simulation is set to 0.00255 seconds to reduce CPU time. In addition automatic surface to surface contact is used to define contact between the rubber disk and the rigid surface since this type of contact is considered as one of most stable contact definition in LS-DYNA. Velocity dependent friction coefficient

$$\mu = FD + (FS - FD)e^{-DC|v_{rel}|} \qquad \text{(Eq.5)}$$

where *FS* is static friction coefficient, *FD* is dynamic friction coefficient, *DC* is decay constant and v_{rel} is relative velocity on contact surface, and numerical values *FD*=1.0, *FS*=0.2, and *DC*=0.001 s/m are proposed in [2]. However, since our simulation takes very fast relative velocity, velocity dependent friction approaches almost *FD*, lower than *FS*. Considering severer condition, *FS*=*FD*=1.0 are adopted instead in our simulation.

MODEL REFINEMENT AND RESULTS

Early versions of the model caused numerical problems as supposed prior to execution (Fig.3). Then several trials and errors using various options in LS-DYNA were needed to fix instability in the simulation. Recent revisions of LS-DYNA version 970 and version 971 have excellent hourglass control option, that is, type 7 (IHQ=7) developed mainly for rubber like materials. As IHQ=7 is the combination of stiffness form and viscous form, there are two parameters QM for stiffness and VDC for viscosity. QM=1.0 and VDC=0.50 were adopted in the simulation. Furthermore, since so-called "checkerboarding" pattern was observed in pressure distribution, the coefficient of linear bulk viscosity term Q2=6.0 was used to reduce numerical noise (Fig.4). However Q2=6.0 is 100 times larger than the default of Q2=0.06 and may cause undesirable side effect. Then care should be taken to change default of artificial viscosity. The quadratic bulk viscosity coefficient Q1 remains default in this simulation. Regarding contact definition between rubber disk and road surface, the segment based contact option SOFT=2 may be necessary to improve penetration problem in certain cases. The result of improved model is shown in Fig.5. Clearly numerical problems including hourglassing and penetrations in contact can be suppressed.

The time step size in this simulation became 1.46 nanosecons because of small element size (0.02 mm). Shortening of time step size for solid element is also affected by large bulk viscosity coefficient value. CPU times for execution are 9.6 hours for SMP 2 CPUs and 3.75 hours for MPP 4 CPUs on Pentium Linux machine.

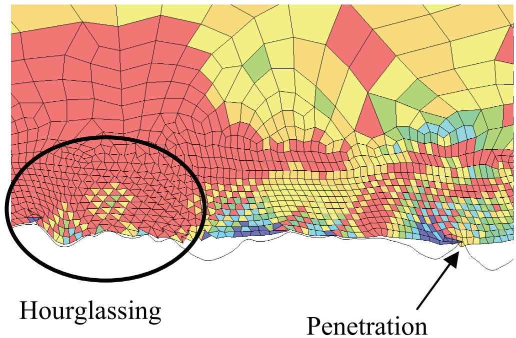
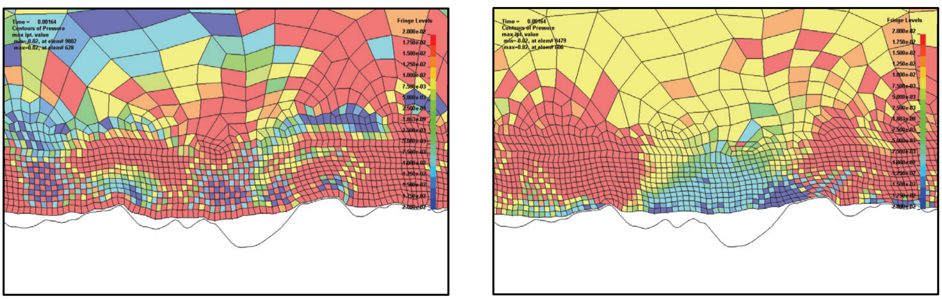


Figure 3: Typicalnumerical problems on rubber like materials



Q2=0.6 : Checkerboarding

Q2=6.0 : Checkerboarding suppressed

Figure4: Reduction of checkerboarding for pressure using artificial viscosity

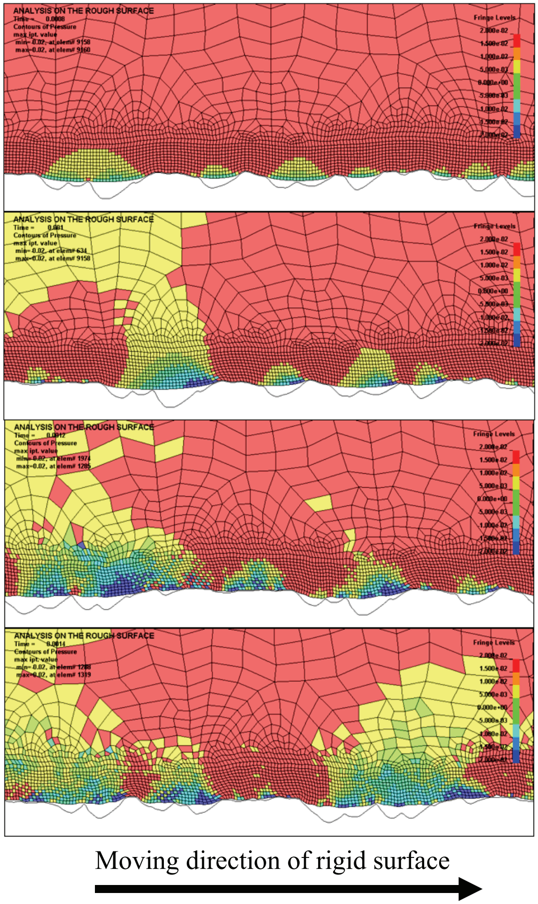


Figure5: Sliding behavior of the rubber disk on the rigid surface

SUMMARY AND CONCLUSIONS

It is, in general, difficult to perform realistic simulation of soft materials like rubber because of numerical instability. This paper proposed suitable parameters of options in LS-DYNA which can be helpful in overcoming numerical instability. General recommendation for the simulation of rubber like materials is summarized below:

i) Rigid surface coming to contact with rubber material should be smoothed as much as possible.

ii) Hourglass type 7 (stiffness form + viscous form with linear total strain formulation) is useful.

iii) Artificial linear bulk viscosity can suppress oscillation in pressure distribution.

iv) Segment based contact SOFT=2 may improve contact condition.

v) Nearly cubic shape of solid element is always desirable for many features in LS-DYNA (contact, hourglass control, artificial viscosity etc.).

It will be expected that the techniques used in the paper can be applied to simulations to investigate tire performance.

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LS-DYNA Keyword User's Manual Version 971, Livermore Software Technology Corporation, Livermore, March, 2007.