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Finite element analysis of tire traveling performance using anisotropic frictional interaction model

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Abstract

The traveling performance of off-the-road vehicles, such as construction machinery and exploration rovers, significantly depends on the interaction between the ground and the traveling mechanism, since inelastic ground deformation and frictional sliding phenomena are induced by the vehicle's movement. In general, a tread surface causes anisotropic frictional interaction behavior on a macroscopic scale. In this study, an acceptable frictional interaction model was implemented to finite element method to rationally examine the anisotropic frictional interaction behavior between the tire and the ground. Finite element analysis of the single tire traveling performance, including certain slippage and side slip (skid), was then carried out to examine the effect of the anisotropic frictional interaction on the numerical results for the drawbar-pull and side force.

Keywords: FEM; Tire–soil interaction; Friction; Anisotropy; Slippage; Slip angle

1. Introduction

Handling the contact and friction behavior of soil and mechanical systems is important for computer-aided engineering (CAE) in terramechanics. Numerous terramechanics studies have been conducted using the finite element method (Young and Fattah, 1976; Regli et al., 1993; Fervers, 2004; Chiroux et al., 2005; Hambleton and Drescher, 2008, 2009; Xia, 2011) and distinct element method (Li et al., 2010; Nakashima et al., 2010; Knuth et al., 2012; Smith and Peng, 2013; Smith et al., 2014; Johnson et al., 2015); however, the contact conditions of soil and mechanical systems are often not characterized by uniform and even surfaces, but rather by textured shapes because of the tread patterns of tires and crawler belts. Interactions between the soil and a machine, such as frictional sliding and shear, can occur at boundaries. In some cases, they can also occur within the soil, so they can be considered to be normally mixed.

In numerical analysis, if the geometric shapes of lugs or grouser patterns on tire and crawler belts can be rigorously discretized and the discretization of elements/particles in the soil can be refined, the above interactions can be naturally described in an appropriate manner even if only the simple law of frictional interaction is used. However, rigorous discretization requires treatment of local deformations and to consider discontinuous fields, which increases the pre-processing and calculation costs. Thus, the use of rigorous discretization is not realistic for conceptual designs or real-time controls at present. In contrast, if a phenomenological friction interaction model that reflects the effect of recurring tread patterns can be applied to analysis by using uniform surfaces at low cost, practical designs requiring systematic examinations should be possible. The latter method seems effective, but friction interaction models that

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can appropriately reflect the effects of tread patterns without divergence from experimental results are necessary even if the complexity increases to some extent.

Anisotropic frictional phenomena such as the dependence of frictional resistance on the sliding direction and the path, and the mismatch between the sliding and the friction force directions because of microscopic orientations and inclinations of relief patterns have been observed for contact surfaces with recurring texture structures (Feng et al., 2006; Zmitrowicz, 2006; Konyukhov et al., 2008; Ozaki et al., 2012). This means that isotropic friction models such as Coulomb's law can no longer be applied to contact and friction problems at the macroscopic scale between objects with textured surfaces.

This paper suggests a practical finite element analysis procedure that uses a phenomenological friction interaction model to express the anisotropic frictional sliding characteristics between tires with tread patterns and the soil. The anisotropic interaction model incorporates the concepts of orthotropic and rotational hardening (Ozaki et al., 2012) based on an elastoplastic formulation for friction. Thus, the directional dependency of the frictional resistance can be described in a rational manner. The proposed procedure is used to analyze the travel of a single-wheel pneumatic tire under various slippage and slip angle conditions, and the numerical results of the drawbar-pull and side force are systematically examined.

2. Anisotropic friction model

The anisotropic friction model based on elastoplasticity is formulated in this section. Since this model operates under the same concept as does the penalty method, all frictional contacts can be easily incorporated into the finite element method as constraint conditions (Ozaki et al., 2012; Oden and Martines, 1985; Wriggers, 2003). In the following, subscripts $()_t$ and $()_n$ stand for normal and tangential components, respectively, whilst superscripts $()^e$ and $()^p$ stand for elastic and plastic components, respectively. Refer to Ozaki et al. (2012) for more details on the formulation and basic response characteristics.

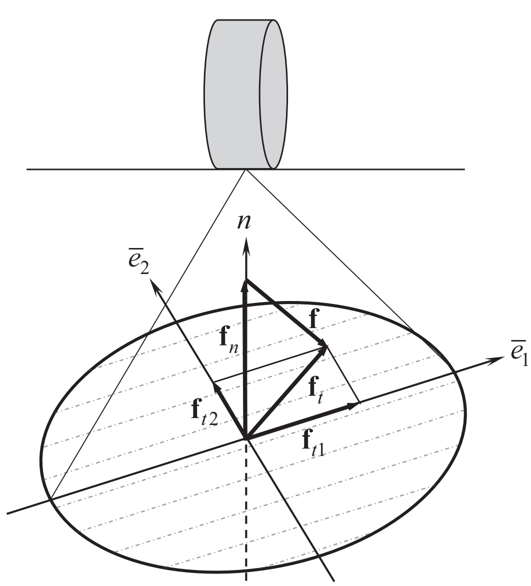

Fig. 1. Schematic diagram of orthotropic sliding surface on coordinate system $(\bar{e}_1,\ \bar{e}_2,\ n)$.

2.1. Elastic relation

The bases in the orthotropic long- and short-axis directions are denoted by $\bar{\mathbf{e}}_1$ and $\bar{\mathbf{e}}_2$, respectively, as shown in Fig. 1. $\bar{\mathbf{e}}_3$ matches the unit normal vector $\mathbf{n}$, which is directed outward from the contact surface. Based on the coordinate system described above, the contact traction vector is described as follows:

$$\mathbf{f} = f_{t1}\bar{\mathbf{e}}_1 + f_{t2}\bar{\mathbf{e}}_2 + f_n\mathbf{n} \tag{1}$$

where $(f_{t1},\ f_{t2},\ f_n)$ is the component of traction vector $\mathbf{f}$. The normal and tangential component of the contact traction vector $\mathbf{f}$ are derived as follows:

$$\left.\begin{aligned} \mathbf{f}_{t1} &= (\bar{\mathbf{e}}_1 \bullet \mathbf{f})\bar{\mathbf{e}}_1 = (\bar{\mathbf{e}}_1 \otimes \bar{\mathbf{e}}_1)\mathbf{f} = f_{t1}\bar{\mathbf{e}}_1 \\ \mathbf{f}_{t2} &= (\bar{\mathbf{e}}_2 \bullet \mathbf{f})\bar{\mathbf{e}}_2 = (\bar{\mathbf{e}}_2 \otimes \bar{\mathbf{e}}_2)\mathbf{f} = f_{t2}\bar{\mathbf{e}}_2 \\ \mathbf{f}_n &= (\mathbf{n} \bullet \mathbf{f})\mathbf{n} = (\mathbf{n} \otimes \mathbf{n})\mathbf{f} = f_n\mathbf{n} \end{aligned}\right\} \tag{2}$$

$(\bullet)$ and $\otimes$ represent the scalar and tensor products, respectively.

The sliding velocity vector $\bar{\mathbf{v}}$ additively decomposes to the normal and tangential components, i.e.

$$\bar{\mathbf{v}} = \bar{\mathbf{v}}_n + \bar{\mathbf{v}}_t, \quad \bar{\mathbf{v}}_t = \bar{\mathbf{v}}_{t1} + \bar{\mathbf{v}}_{t2} = \bar{v}_{t1}\bar{\mathbf{e}}_1 + \bar{v}_{t2}\bar{\mathbf{e}}_2 \tag{3}$$

In addition, the sliding velocity is assumed to additively decompose to the elastic and plastic sliding velocities. In other words,

$$\bar{\mathbf{v}} = \bar{\mathbf{v}}^e + \bar{\mathbf{v}}^p = (\bar{\mathbf{v}}_n^e + \bar{\mathbf{v}}_n^p) + (\bar{\mathbf{v}}_{t1}^e + \bar{\mathbf{v}}_{t1}^p) + (\bar{\mathbf{v}}_{t2}^e + \bar{\mathbf{v}}_{t2}^p) \tag{4}$$

The elastic relationship is given by the following equation:

$$\overset{\circ}{\mathbf{f}} = \mathbf{C}^e\bar{\mathbf{v}}^e, \quad \mathbf{C}^e \equiv \alpha_n\mathbf{n} \otimes \mathbf{n} + \alpha_t(\bar{\mathbf{e}}_1 \otimes \bar{\mathbf{e}}_1 + \bar{\mathbf{e}}_2 \otimes \bar{\mathbf{e}}_2) \tag{5}$$

where α_n and α_t are moduli of the contact elasticity and is equal to the penalty coefficient for boundary value problems (Ozaki et al., 2012; Oden and Martines, 1985; Wriggers, 2003). $(^\circ)$ expresses the co-rotational rate with objectivity.

2.2. Sliding surfaces

The friction criterion of the following equation, which includes orthotropy and rotational hardening, is adopted as the sliding surface (frictional cone), as shown in Fig. 2.

$$\hat{\chi} = \mu \tag{6}$$

where μ is a friction coefficient. $\hat{\chi}$ indicates the shape of the sliding surface on the tangential traction plane and is defined by the following equation:

$$\hat{\chi} \equiv \sqrt{\hat{\chi}_1^2 + \hat{\chi}_2^2}, \quad \hat{\chi}_1 \equiv \frac{\hat{\eta}_1}{C_1}, \quad \hat{\chi}_2 \equiv \frac{\hat{\eta}_2}{C_2} \tag{7}$$