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Research paper

Analysis of tractive performance of agricultural tractor tire using finite element method

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ABSTRACT

We established the method with finite element analysis of the running tire using an anisotropic elastic wheel model that includes the vertical and horizontal rigidities and inspected it about validity by the experimental results of the running performance and the contact pressure distribution for different inflation pressures. The contact normal stress was greater in the front half of the ground. It was a flat distribution in the vicinity of the maximum value. The running resistance and the contact load obtained by integrating measurement results of contact normal stress are almost equals to the results of calculation by drawbar pull and torque. The calculated coefficients of net traction for the experimental conditions were in good agreement with the experimentally determined values.

1. Introduction

Agricultural tractors are classified as wheel type, half-track type, or crawler type. The crawler type is capable of generating high traction under low ground pressure. The half-track type, which has been popular in Japan in recent years, was developed as a front wheel drive vehicle. It has high traction and is equipped with a back crawler track. The crawler track device has a drive sprocket instead of a rear wheel, and its running quality was studied by Fukushima et al., 2007 The wheel type tractor has, however, been more popular in more recent times. Although the traction of its pneumatic tire is relatively low, it has the advantages of mobility and high speed. Moreover, its passenger car uses pneumatic tires for travelling. However, considering that an agricultural tractor is usually operated on soft ground such as cultivated land, a study of the traveling characteristics of its wheels requires an investigation on the deformation of both the tire and the soil.

A theoretical analysis of the tire deformation requires some assumptions regarding the deformation produced by the contact between the tires and the soil. To analyze the tire, Wong 2001 Q2 approximated the interface by a circle, Karafiath and Nowatzki (1978) assumed that it comprised a straight line and a logarithmic spiral, and Shmulevich and Osetinsky (2003) assumed that it was parabolic.

A finite element method has also been used to analyze the deformation of the tire. Yong et al. (1978) determined the distribution of the normal stress in the soil in contact with the tire using the Hertzian theory of elastic contact. They considered the boundary conditions of the contact and investigated the relationships among the output energy, slip ratio, deformation energy of the tire and the soil, and the energy loss of the ground. Hiroma et al. (1985) analyzed the deformation of the traveling tire of an agricultural tractor using a tire model that comprised a radial arrangement of a number of springs attached to the rim and a finite element model of the soil. Eguchi (1997) used a tire model to simulate the tire/soil interface with the aid of an RBSM (rigid body-spring model). Fervers (2004) developed two-dimensional tire performance prediction models that included an air-filled space. Nakashima and Oida (2004) developed a three-dimensional tire model that included the elastic moduli of the tread and side, and carried out a static analysis of the tires. For their analysis, Nakashima and Oida (2004) combined the distinct element method and the finite element method. They used an FEM model for the analysis of the tire and deep soil, and a DEM (discrete element method) model for the analysis of the soil surface. Oida et al. (2006) developed a three-dimensional method for predicting the traction using a coupled analysis of the tire and soil, which can be applied to any type of tire tread. Xia (2011) analyzed the running performance and compression of the wheel using a three-dimensional finite

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element method and a three-dimensional tire model. Lee (2011) analyzed the running performance and tire contact stress distribution in fresh snow using a three-dimensional finite element method. All these studies, however, only involved simulations.

A farm tractor moves in a straight line when used for plowing, which makes the traction important. It is, however, not very important to consider the side force when the tractor is operating in a straight line. Hence, considering the interaction between the tire and the soil, a two-dimensional analysis is more desirable than a three-dimensional one. In this study, we established the method with finite element analysis of the running tire using an anisotropic elastic wheel model that includes the vertical and horizontal rigidities (Hiroma, 2009). Furthermore, we inspected it about validity by the experimental results of the running performance and the contact pressure distribution for different inflation pressures.

2. Tire/soil finite element model

To analyze the tractive performance of a tire, we used a tire model, soil model, and a model of the friction between the tire and the soil. The soil model was for a soft field soil with relatively high moisture content. We adopted a combined model of the visco-elasticity under loading stress and the elasticity under unloading stress. (Fig. 1) The simplest model of the stress relaxation and the elastic after-effect during loading was adopted, and an elastic model under unloading was adopted. In this paper, K_i represents the bulk modulus, G_i the modulus of rigidity, μ_K the viscoelastic modulus of the longitudinal deformation, and μ_G the viscoelastic modulus of the shear deformation. The viscoelasticity coefficients were determined by a one dimensional compression test. The specimens were compressed using a constant deformation velocity up to 10% strain. After relaxation of the stress under a fixed strain, an unloading test to determine the deformation rate was conducted. A sample comparison of the measurement results and the calculation results using an FEM for axial loading (the strain rate during loading was 0.23 s^{-1}) (Hiroma, 1999) showed that the model was suitable for representing the phenomenon.

An anisotropic elastic wheel model was adopted for the vertical and horizontal rigidity of the tire (Hiroma, 2009). It was assumed that the intersection effect of the anisotropic principal axis could be ignored in taking the effect of the interaction into consideration. This is because the normal strain in the radial direction has insignificant effects on the shear strain and normal strain in the circumferential direction of the tire. The anisotropic elastic stress-strain matrix $\boldsymbol{D}_w$ is given by Equation (1) in the local coordinate system of the circumferential direction (t) and the radial direction (r), where E_t and E_r are respectively the modulus of longitudinal elasticity in the circumferential and radial directions, and G_{tr} is the modulus of transverse elasticity.

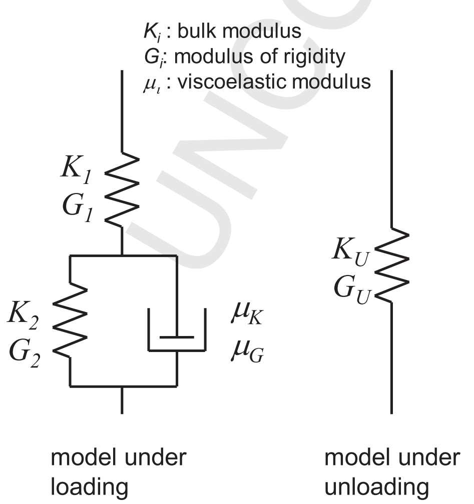

Fig. 1. Soil model under loading and unloading.

$$\boldsymbol{D}_w = \begin{bmatrix} E_t & 0 & 0 \\ 0 & E_r & 0 \\ 0 & 0 & G_{tr} \end{bmatrix} \tag{1}$$

The vertical rigidity and the horizontal rigidity in the traveling direction were obtained by a rigidity test conducted on an iron road, and it was observed that they were not directly correlated with the anisotropic elastic moduli E_t, E_r, and G_{tr}. The values of the anisotropic elastic moduli could therefore be obtained using the following reversely analytic technique. Some finite element analysis modeled vertical and horizontal rigidities using a set of different values of the anisotropic elasticity were carried out. The coefficients that suited the results of the rigidities test were selected. The example of the comparison calculated and experimental result for vertical and horizontal rigidities with the condition of inflation pressure 100 kPa is shown in Fig. 2. From this result, it is obtained that the anisotropic elastic wheel model appropriately represents the vertical and horizontal rigidities of the tire (Hiroma, 2009).

The Coulomb friction law was used for the model of the friction between the tire and the road surface. The limit of the friction between the tire and the road surface with slip was obtained using the following equation:

$$\tau = c + \mu\sigma \tag{2}$$

where τ is the frictional stress, σ is the normal stress on the contact surface, c is the adhesion, and μ is the coefficient of friction. This equation is used in the calculation of the balance of power in the tread of the tire and the ground.

3. Materials and methods

3.1. Apparatus for the running tire

The soil bin of the apparatus for the running tire was 4.5 m long, 0.6 m wide, and 0.5 m deep. The soil was 0.4 m deep and rails were set on the side walls of the bin. The tire was set in a cart. The Schematic diagram of experimental device and sensor of ground normal stress on the tire surface is shown in Fig. 3. The cart was composed of an outer frame and an inner frame and could freely

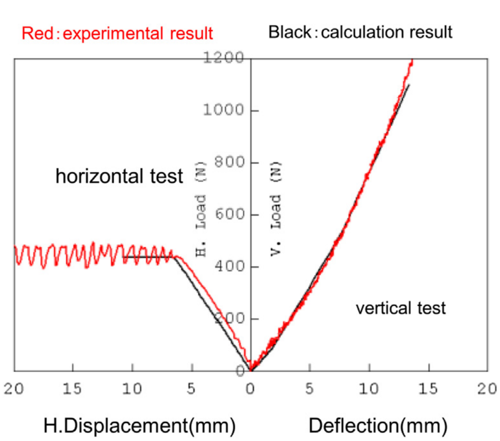

Fig. 2. The vertical and horizontal rigidities of the tire (inflation pressure: 100 kPa).