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A tire model for vehicle motion analysis on dry sand

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Abstract

In order to perform vehicle motion analysis, a model of the interaction between the traveling tire and the ground surface is necessary. The interaction model or the tire model needs to adequately obtain the forces exerted on the tire based on the ground characteristics, besides being simple and easy to use. This research aims to construct a simple tire model for the motion analysis of a vehicle traveling on dry sand. A single small rubber tire was driven on evenly flattened dry Toyoura standard sand to measure the longitudinal and lateral forces on the tire. During the wheel drive test, the tire was dug into the sand to keep the sinkage constant. In addition, the tire was given a sideslip angle, which is the attack angle to its travel direction. The collected data demonstrated that the sand–tire interaction produces a tire force in the same direction as the tire slippage, and the definition of the tire force norm for each sinkage value well approximates the data using a single curve independent of the sideslip angles. By using those characteristics, the tire model can be expressed by relatively simple functions of the sideslip angle and sinkage. A turning motion experiment on a four-wheel model vehicle on evenly flattened sand was conducted, and the result was compared with the result from the numerical simulation with the tire model, which confirmed the model's accuracy.

Keywords: Tire model; Dry sand; Sinkage; Tire force; Sideslip angle; Tire–ground interaction

1. Introduction

It is said that about 30% of the land on the Earth is desert, and that number may increase due to global warming. People living in such areas with insufficient road infrastructure need to drive their cars on sandy ground. In order to estimate the traveling performance of vehicles on sand, a tire model compatible with the interaction between the tire and sand is necessary. There are several tire models for vehicles running on paved roads (for example, Gim and Nikravesh [1] and Pacejka and Besselink [2]). However, such tire models cannot be used for a soft ground environment in which wheel sinkage is significant. For this reason, a dedicated tire model is necessary for the analysis of vehicles traveling on sand. For example, for vehicle motion analysis with multi-body dynamics, simple and reliable tire models that connect the kinematic variables and forces acting on the tires are desirable, as shown in Fig. 1. Recently, planetary exploration has been pursued in several countries, and the traveling performance of planetary rovers is becoming of great interest (for example, Asnani et al. [3] and Wakabayashi et al. [4]). Simple-to-use wheel–ground interaction models are also applicable to the computation of the necessary forces on the wheels for unmanned vehicle systems designed to explore the moon or other planets.

Although the interaction problem of wheels on soft ground has been investigated by many researchers (for example, reviews by Wong [5] and Muro and O'Brien [6]), including Bekker [7], analyses for wheels traveling straight were their main concern. Analyses for turning wheels have also been conducted by Karafiath [8].

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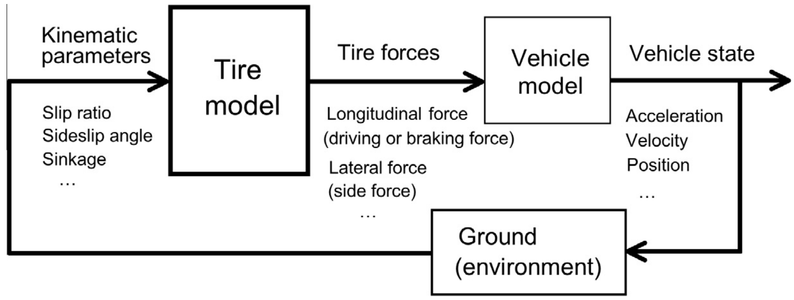

Fig. 1. Vehicle motion analysis with both a tire model and a vehicle model.

However, a versatile tire model that includes all of the parameters affecting the travel performance of the wheel has not been established yet since the characteristics of the soil, wheel sinkage, shape, stiffness, and others complicate the interaction model. One of the practical and safe approaches to estimate the travel performance of a specific vehicle on a specific soil is to construct a tire model from the data collected by wheel travel experiments on the same tire and the same soil. This paper describes the construction of a simplified interaction model for a certain tire and dry sand combination based on the data from a single tire test with the sideslip effect.

In this research, a small-size wheel that moves on dry sand in a bin was used to mimic the wheel–sand interaction for various sideslip angles. The longitudinal and lateral forces on the wheel due to the interaction were measured and collected. Based on the collected data, a tire model that calculates the longitudinal and lateral forces on dry sand for vehicle motion analysis was expressed using simple functions of the sinkage, slip ratio, and sideslip angle. In order to verify the tire model, experiments on a four-wheel model vehicle turn on flat sand were numerically simulated.

2. Single wheel experiment on dry sand

2.1. Test equipment and sand

Fig. 2 shows the single wheel test equipment. A guide frame used for the wheel to avoid toppling down was spanned over the sand bin, whose dimensions are approximately 3 m in the wheel travel direction, 2.5 m in width, and 0.2 m in depth. The soil bin was filled with dry *Toyoura* standard sand, which was raked and flattened for every wheel run. The wheel, driving motor, and measurement devices move together along the guide in the longitudinal direction and are allowed to move in the vertical direction. The slider in the vertical direction can be fixed to allow the wheel to maintain a constant sinkage. A velocity-controllable motor drives the wheel, and another motor pulls the wheel via a tension belt. The wheel rotational velocity and wheel pulling velocity can be independently set to control the slip velocity or slip ratio. The wheel can also be rotated about the vertical axis to give an attack angle with respect to the wheel's moving direction, which will be referred to as the sideslip angle.

The pneumatic rubber tire is 215 mm in diameter, 65 mm in maximum width, and 40 mm in tread width. The tread surface has repeated patterns (shown in Fig. 3) in the circumferential direction of 2 mm depth. The air pressure was adjusted to the standard value for the tire (200 kPa), which is much stiffer than the sand bed. The distance from the sand surface measured by a laser displacement sensor on the wheel's base frame indicates the amount of wheel sinkage in the sand. A load cell measures the forces exerted on the wheel in the longitudinal and lateral directions.

The Toyoura sand in the bin has minimum and maximum bulk densities of 1.34 g/cm^3 and 1.65 g/cm^3,

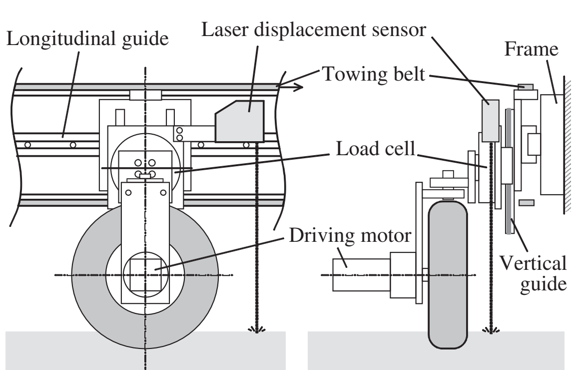

Fig. 2. Apparatus for single wheel drive test.

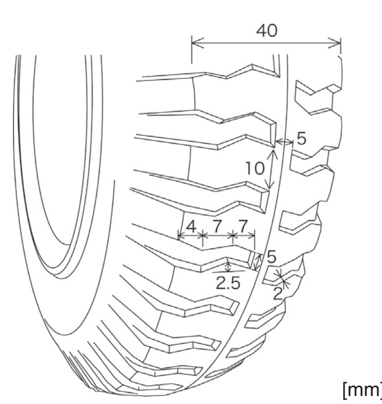

Fig. 3. Tread of the model tire.