Engineering in Agriculture, Environment and Food xxx (2016) 1–9

Contents lists available at ScienceDirect

Engineering in Agriculture, Environment and Food

journal homepage: http://www.sciencedirect.com/eaef

Research paper

Traction and braking force on three surfaces of agricultural tire lug

Mingliang Shao [a], Tadashi Kishimoto [b,*], Tadatoshi Satow [b], Junichi Takeda [c], Thomas R. Way [d]

[a] The United Graduate School of Agricultural Sciences, Iwate University, 3-18-8 Ueda, Morioka, Iwate 020-8550, Japan
[b] Obihiro University of Agriculture and Veterinary Medicine, Inada-cho, Obihiro, Hokkaido 080-8555, Japan
[c] Faculty of Agriculture, Iwate University, 3-18-8 Ueda, Morioka, Iwate 020-8550, Japan
[d] USDA-ARS, National Soil Dynamics Laboratory, Auburn, AL 36832, USA

ARTICLE INFO

Article history:
Received 6 October 2015
Received in revised form
12 April 2016
Accepted 10 July 2016
Available online xxx

Keywords:
Interface pressure
Lug face
Lug side
Wheel
Tri-axial transducer
Slippage
Soil bin

ABSTRACT

The objective of this research was to improve the performance of an agricultural tire by designing the shape of the tire lug. For the first stage of this research, pressure sensors were mounted in the leading lug side and the trailing lug side and tri-axial force transducers were mounted in the lug face of a small agricultural drive tire to find out the function of each lug surface. Traction forces were measured on the lug face and the leading side at 20.0% slippage and on the lug face at 10% slippage, as would be typical when a tractor is used for plowing. Braking forces were measured on the lug face and the trailing side at −10.0% slippage, as would be typical when a tractor is used for rotary tilling. The results of three tire inflation pressure conditions (39.2 kPa, 78.5 kPa and 118 kPa) also show the similar tendency to produce traction and braking forces on three surfaces of an agriculture tire lug. Relationships between forces on the lug surfaces and the soil reaction were determined.

1. Introduction

Traction and braking forces are important performance characteristics of agricultural wheels, and are required for various types of farm working conditions. Net traction, which is longitudinal force developed by a wheel, and braking force should be considered when the performance of a wheel is evaluated. Further, an important element in designing the shape of a tire lug is an understanding of how reaction forces on the surfaces of a lug affect wheel performance.

Many studies have been conducted using rigid wheels. Gee-Clough and Chancellor (1976) analyzed the amount of wheel movement in the vertical and longitudinal directions, caused by wheel rotation. They considered the motion of a point on the wheel and analyzed the shear component which was parallel to the wheel surface and the compression component which was perpendicular to the wheel surface (Sakai et al., 1988). The motion of the wheel and the reaction were analyzed by the application of passive soil pressure theory (Wang et al., 1989a, 1989b, 1990). A kinematic analysis of a wheel was studied by introducing the lift resistance of the wheel with travel reduction (Kishimoto et al., 1991b), and results of this study demonstrated that the reactions on surfaces (lug face, leading lug side, trailing lug side) of a lug were different from one another (Jun et al., 1997; Kishimoto et al., 1990a). To understand the effect of the lug, instead of analyzing only one side of the lug, to the authors suggest it is necessary to comprehensively analyze the three surfaces and the undertread face. Kishimoto et al. developed small-sized transducers of the three-surfaced lug type which can measure normal and tangential forces of each surface simultaneously (Kishimoto et al., 1991a). The normal force distribution was analyzed at the contact surface on a smooth rigid wheel (Hiroma et al., 1989). Yosida measured contact pressure, sinkage and soil dry bulk density by the number of passages with three types of wheel (Yoshida, 1972). The force equilibrium acting on a driven wheel with rubber attached to the periphery of the tread was analyzed theoretically and experimentally by means of photo-elasticity (ISTVS Standards, 1977).

Many studies have been conducted investigating the pneumatic tractor tire. Trabbic et al. installed five pressure transducers on each surface of a lug to measure soil-tire interface pressures with different drawbar loads and tire inflation pressures (Trabbic et al.,

* Corresponding author.
E-mail address: tksmt@obihiro.ac.jp (T. Kishimoto).

http://dx.doi.org/10.1016/j.eaef.2016.07.002
1881-8366/

Please cite this article in press as: Shao, M., et al., Traction and braking force on three surfaces of agricultural tire lug, Engineering in Agriculture, Environment and Food (2016), http://dx.doi.org/10.1016/j.eaef.2016.07.002

1959). Taylor reported the lug angle and lug spacing effect on traction of tire for various tire inflation pressures (Taylor, 1976, 1973, 1974). He also compared the traction performance of tractor tires having various tread shapes (Tanaka, 1960). Ali and McKyes examined for traction characteristics of a lug using various lug angles (Ali and McKyes, 1978). Burt et al. measured three-dimensional deformation of the lug and undertread surfaces relative to the rim, for a tractor drive tire. They also determined the ratio of normal and tangential forces at the soil-tire interface (Burt et al., 1987a, 1987b; Burt and Wood, 1987). Jun et al. developed a three-dimensional stress transducer to measure normal, tangential and lateral stresses on a lug face. They reported the relationships between peak stresses and their rotational angles at 20% slippage (Ito, 1974; Jun et al., 1998).

However, when the tractor works with a rotary tiller of down cut operation, meaning the tiller rotates clockwise when viewed from the right side of the tiller, the net longitudinal force applied by the soil to the rotary tiller is the same to the travel direction. This force was named “tillage thrust force” (Sakai and Stout, 1999) and it tends to push the tractor forward (Sakai and Zou, 1987). It causes negative slippage of drive wheels on dry and compacted soil. To counteract this force, a braking force is generated by the tractor tires and is applied at the contact surface between the soil and tires. The tractor wheels during rotary tillage act not as driving wheels but as braking wheels in order to maintain a constant travel speed of the machine (Sakai, 1999). Little research has been conducted on the braking performance of agricultural wheels. In particular, very little research has been conducted about the reaction on each surface of a lug at negative slippage. In this study, pressure sensors were mounted in the leading lug side and the trailing lug side and tri-axial force transducers were mounted in the lug face of a small agricultural tire which has been commonly used in Asia. The reaction forces and pressures were measured and the effect of reactions of soil on each surface of a lug are analyzed at positive and negative slippage.

2. Apparatus and procedure

2.1. Apparatus

Fig. 1 shows the single tire tester and soil bin used in the project. The single tire tester is mounted to a carriage which runs on rails along the soil bin (length 11,000 mm, width 850 mm, depth 450 mm). The single tire tester is equipped with a Continuously Variable Transmission motor. A pulling wire controls the motion of the carriage and single tire tester along the length of the soil bin. The desired speed of the carriage is obtained using an arrangement of mechanical transmissions.

The single tire tester frame is connected to the carriage by a slide bearing which allows the frame to move vertically relative to the carriage. The test tire is driven by a variable speed motor. In this experiment, the rotational speed of the tire is set at a constant value. Slippage is adjusted by selecting the carriage speed by changing the gear ratio of the transmission as shown in Fig. 1-a. The tire slippage S is calculated as Equation (1):

$$S = \left(1 - \frac{v}{r\omega}\right) \times 100\% \tag{1}$$

where v is forward velocity, ω is wheel angular velocity, and r is the tire rolling radius. Angle velocity ω is set at 0.15 rad/s, tire rolling radius r is 312 mm, the travel speed of a tire at no load is set to 0.3 m/s.

The tire was a Falken AR1 6.00–12 6 PR 160/85R14 radial-ply tire. The overall diameter and the section width of the tested tire were 624 mm and 161 mm respectively. The lug height was 23 mm. The number of lugs was 26 and the lug angle (ISTVS Standards, 1977) was 65°. The rim of the test tire is mounted to the frame by an axis transducer for measuring the net traction and the dynamic load which is the vertical force applied by the tire to the soil. The principle of an axis transducer was designed and developed as an orthogonally holed cantilever type (Kishimoto et al., 1990b).

A tire rotational angle is detected by a photo-interrupter. The sampling frequency of A/D conversion for analogue data of the photo-interrupter to the slit was set at 50 Hz, or about 330 data points recorded per wheel revolution. The tire rotational angle of 0° is defined at the position where the TC sensor, which is described below, is located directly above the tire axis of rotation.

2.2. Pressure sensor and tri-axial force transducer

A pressure sensor (KYOWA; PS-10KC-F (Kyowa Electronic Instruments Co., Ltd., Tokyo, Japan)) (Fig. 2) was used in the experiment for the measurement of pressures acting on the leading and trailing sides of a lug. The pressure sensor can measure both positive and negative pressures and the capacity of the pressure sensor is 1 MPa. The radius is 3.0 mm and the thickness is 0.6 mm.

A tri-axial force transducer (TEC GIHAN; USL06-H5-200N–C (Tec Gihan Co., Ltd., Kyoto, Japan)) (Fig. 3) was used in the experiment for measurement of normal and tangential forces on a lug face. The maximum force that the tri-axial force transducer can measure is 200 N in the normal direction ($+Z$) and ±250 N in the longitudinal tangential direction ($+Y$) and the lateral direction ($+X$). The detection part is the center of the tri-axial force transducer, on which a screw (radius 3.0 mm, thickness 0.5 mm) is mounted and painted with liquid rubber. A rubber sheet is attached on the transducer, around the detection part. A 7.0 mm diameter hole was cut in the central part of the rubber sheet to allow the detection part to directly contact the soil. The transducers were embedded in the lug so the surface of each transducer was flush with the lug face surface.

2.2.1. Locations of pressure sensors and tri-axial force transducers

Fig. 4-a shows the location of the sensors and transducers on the test tire. Four pressure sensors and two tri-axial force transducers were used in the experiment. Two of the pressure sensors were mounted in the trailing side of a lug, so we called them TC (centerline of a trailing side) and TE (outer edge of a trailing side). Similarly, two of the pressure sensors were mounted in the leading side of another lug, so we called them LC (centerline of a leading side) and LE (outer edge of a leading side). The taper of LC location is about 0°. The taper of the trailing side is about 14°. It is easy to cut the surface of the leading side at LC for embedding the pressure sensor to be in a plane which contained the tire axis of rotation. However, the locations where LE, TC and TE sensors are attached are difficult to cut to attain a vertical orientation in the direction of travel because of the narrow space. Then, the surface of LC was in a plane which contained the tire axis of rotation, and the other pressure sensors were flush with the lug surfaces in which they were embedded. Soil-tire interface pressure in the direction tangential to the tread periphery was measured at location LC. Interface pressures in directions normal to the local lug surfaces were measured at locations LE, TC and TE. Two tri-axial force transducers were mounted in the lug face. One was called FC (centerline of lug face), the other was called FE (outer edge of lug face).

2.2.2. Correction equations of calculation of tangential, normal and lateral forces by a tri-axial force transducer

The $+Fy$ direction of FC in Fig. 4-a is the forward direction