MOTION RESISTANCE ANALYSIS OF A CIRCULAR STEEL WHEEL IN STICKY SOIL

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ABSTRACT

The objective of this study is to measure rim surface adhesion and to calculate motion resistance produced by the adhesion acting on the rim section of a circular wheel under sticky soil condition. The mechanisms of generating motion resistance by the adhesion on a circular wheel were analyzed through wheel motion. Experiments were conducted in an indoor soil bin that contains loam soil. A circular steel wheel was used for experiments. A part of the wheel rim was cut off, and transducers which can measure normal and tangential forces were installed in this section. Calculated motion resistance at a part of the rim section was superposed for one wheel rotation as motion resistance produced by the rim surface adhesion. The motion resistance increased with increasing the dynamic load. Ratio of the motion resistance to total motion resistance measured by an axis transducer was about 23 to 46 % in this study.

[Keyword] Agricultural wheel, Tractor dynamics, Adhesion, Motion resistance, Lift resistance

INTRODUCTION

Motion resistance, net traction and the reaction to the dynamic load have been investigated to improve the performance of traction and transport devices. These devices receive adhesion which is named as rim surface adhesion for a circular wheel and lug surface adhesion for a lugged wheel when they are operated under sticky soil condition such as in paddy field (Sakai et al., 1991, Kishimoto et al., 1993). The vertical component of rim or lug surface adhesion is defined as the lift resistance which resists the upward motion of the wheel. The existence of these forces on steel wheel was proved by experiments (Sakai et al., 1991, 1994) with newly designed transducers (Sakai et al., 1990, Kishimoto et al. 1991b). The lift resistance has been investigated for the last ten years as an important and new factor in Asian lowland paddy farming. However, the horizontal component of the resultant force has not been investigated.

In general, soil compression by the traction or transport devices produces the motion resistance. However, motion analysis of an arbitrary point on the wheel rim indicated that the horizontal component of the resultant force acting on the rim surface becomes a part of motion resistance when the rim surface adhesion occurs.

In this study, experiments were conducted to determine the motion resistance produced by the rim surface adhesion with a circular steel wheel operated under towed condition. The effect of motion resistance caused by the rim surface adhesion on the total motion resistance acting on the wheel was investigated through the experiments.

EXTERNAL FORCES ACTING ON RIM SURFACE

Fig. 1 shows the schematic diagram of external forces acting on a rim surface when a part of the rim retracts from soil surface. The direction of the normal force on the rim surface of a transport wheel becomes slant backward as *Fn* in Fig. 1 when the rim retracts from the soil. *Fn* in Fig. 1 is named as the "rim surface adhesion".

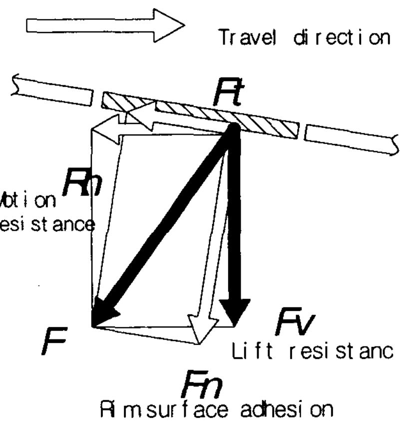

Fig. 1 External forces acting on a rim surface

The direction of the tangential force *Ft* becomes backward as shown in Fig. 1 in the case of a transport wheel so that the direction of the vertical component *Fv* of the resultant force *F* becomes downward. The vertical component *Fv* is called "lift resistance".

The direction of the horizontal component *Fh* of the resultant force *F* in the Figure becomes backward so that this force is considered as a part of the motion resistance of the wheel. The horizontal component *Fh* is the motion resistance *Rh* produced by the rim surface adhesion. This motion resistance may be very small or negligible unless the rim surface adhesion occurs.

APPARATUS AND PROCEDURE

Rim Sectional Transducers

Fig. 2 shows the rim sectional transducers installed to a tested wheel (Kishimoto et al., 1993). Normal and tangential forces acting on a part of the wheel rim were measured independently by these transducers with strain gauges. As those transducers have three adjacent sensing elements, rim surface adhesion can be measured successively.

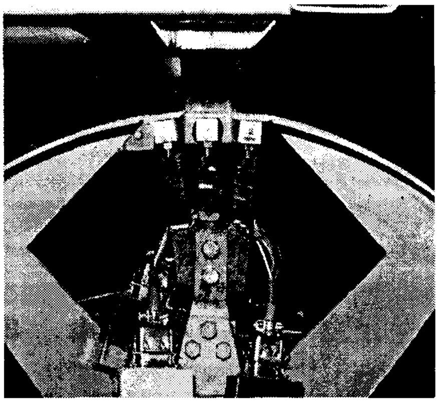

Fig. 2 Rim sectional transducers

Horizontal component *Fh* such as motion resistance and vertical component *Fv* such as reaction to the dynamic load and lift resistance can be calculated from the normal and the tangential forces. Those forces were calculated from following equations.

$$Fh = -Ft\cos(\theta+\gamma) - Fn\sin(\theta+\gamma) \quad (1)$$

$$Fv = Ft\sin(\theta+\gamma) - Fn\cos(\theta+\gamma) \quad (2)$$

Where *Fh*: horizontal component of resultant force
Fv: vertical component of resultant force
Fn: normal force acting on rim surface
Ft: tangential force acting on rim surface
θ: wheel rotational angle
γ: transducer phase angle
(Transducer No.1 6°, No.2 0°, No.3 −6°)

Motion resistance produced by the rim surface adhesion is obtained from the horizontal force during the wheel rotational angles where the rim surface adhesion occurs. The motion resistance for one wheel rotation is obtained from the superposition of the horizontal force.

Apparatus

Fig. 3 shows the schematic view of an experimental apparatus. The apparatus consists of a carriage, trailing arms, a wheel mounting frame, a pulling wire, a tested wheel and a soil bin (length 1100 cm, width 85 cm, depth 45 cm).

The tested wheel is driven by a variable speed motor when it is operated as a traction wheel. When the wheel is operated as a zero torque input of the wheel, so called a transport wheel, the motor is removed from the frame, and a wire-pulling system operates the carriage. The desired speed of the carriage is obtained by the arrangement of mechanical transmissions. Experiments were conducted as a transport wheel in this study.

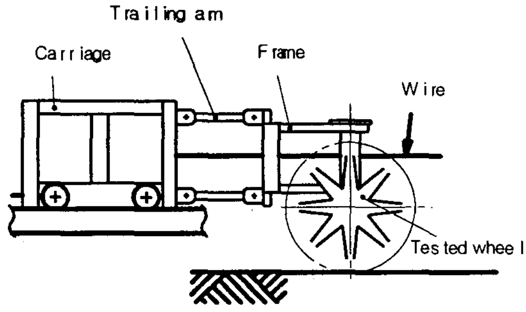

Fig. 3 Schematic view of an experimental apparatus for a transport wheel

The outside diameter and the width of the tested wheel were 600 mm and 120 mm respectively. The rim sectional transducers are assembled and connected to the frame by an axis transducer (orthogonally holed cantilever type) developed by Kishimoto et al. (1991a) for measuring the motion resistance and the reaction to the dynamic load.

A wheel rotational angle is detected by a photo-interrupter. The wheel rotational angle of zero degree is defined at the position where the rim sectional transducers are located just above the wheel axis as shown in Fig.2.

Procedure

Experiments were conducted in an indoor soil bin that contains loam. Preparation of soil for experiments was done by rotary tilling, compacting and leveling after adding adequate water for desired moisture content. Moisture content of the soil was 18.7 % in wet base through the experiments. Average cone index in 10 cm depth was 370 kPa.

Traveling speed was kept constant about 0.1 m/s through experiments. The experiments were designed with five levels of dynamic loads. Sinkage and distance per wheel revolution were measured after each experiment. Data from the photo interrupter as the rotational angle detector, the rim sectional transducers and the axis-transducer were recorded to a data-recorder. All recorded data were converted to digital signals by an A/D converter and processed by a microcomputer.

RESULTS AND DISCUSSION

Horizontal and Vertical Components of Resultant Force

Figure 4 shows an example of normal force *Fn* and tangential force *Ft* measured by the rim sectional transducers. *Fn* from 188°to 197° of the wheel rotational angle becomes negative value. This shows the rim surface adhesion is generated when the rim retracts from soil surface. Other four experiments also show the similar tendency to produce negative force. In dry soil, the tangential force might be zero when the normal force becomes zero. In Fig. 4, the tangential force does not become zero at 187°rotational angel where *Fn* is zero. The tangential force *Ft* from 188°to 197°is thought to be produced by the rim surface adhesion

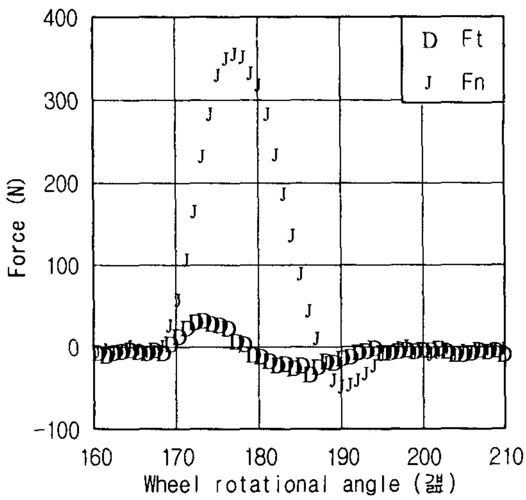

Fig. 4 Example of normal and tangential forces measured by rim sectional transducer

Figure 5 shows an example of horizontal component *Fh* and vertical one *Fv* of a resultant force calculated from the normal and the tangential forces in Fig. 4. The vertical component in Fig. 5 becomes negative at the end of rim acting to the soil, though it is positive when the rim starts to act. It shows that the lift resistance is produced at the rim section by its retraction from the soil.

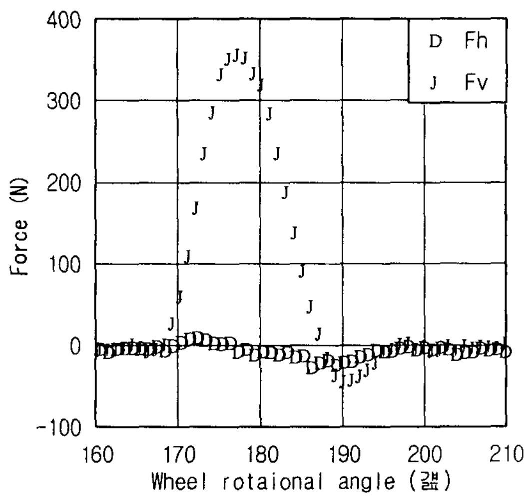

Fig. 5 Example of horizontal and vertical component of resultant force calculated from Ft and Fn in Fig. 4

The horizontal component in Fig. 5 becomes positive from 170°to 177°of the rotational angle. This force is thought to be the same characteristics as net traction, but is quite small. The horizontal component becomes negative from 177°to 197°. This shows that the motion resistance is produced at the rim section.

Superposition of Horizontal Force

The motion resistance produced by the rim surface adhesion occurs at the rim section by its retraction from the soil. The negative part of the horizontal component is superposed for one wheel rotation. This becomes the motion resistance produced by the rim surface adhesion.

Fig. 6 shows the result of the superposition of the negative part of the horizontal component. *Rh* in the Figure is the superposed motion resistance.

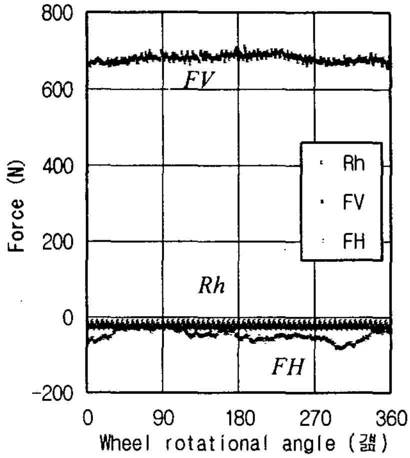

Fig. 6 Superposition of motion resistance *Rh* produced by the rim surface adhesion

The results of the calculations for the experiments are shown in Table 1. Average of the superposed motion resistance Rh is in the rage from 21.5 to 34.8 N in this study. The motion resistance increased with increasing the dynamic load. Ratios of the motion resistance to total motion resistance measured by an axis transducer were about 23 to 46 % in this study. The motion resistance increased with increasing the dynamic load. Ratio *Rh/FH* of the motion resistance to total motion resistance measured by an axis transducer was about 23 to 46 % in this study. The motion resistance produced by the rim surface adhesion is not negligible from these results.

Table 1 Results of experiments

	FV (N)	*FH* (N)	*Average Rh* (N)	*Rh/FH* (%)
L 0	681.1	-47.1	-21.5	45.6
L 1	833.0	-57.6	-22.0	38.2
L 2	1007.1	-89.0	-25.8	29.0
L 3	1170.0	-117.2	-31.4	26.8
L 4	1358.8	-153.7	-34.8	22.6

FV: Reaction to dynamic load measured by axis transducer

FH: Total motion resistance measured by axis transducer

Rh: Motion resistance by rim surface adhesion

In the sticky soil, the motion resistance of a circular wheel is produced not only by the soil compression but also the rim surface adhesion. Reducing the motion resistance produced by the rim surface adhesion is one of the important points of improving wheel performance in sticky soil.

CONCLUSIONS

Motion resistance produced by rim surface adhesion was calculated from the normal and the tangential forces measured with rim sectional transducers of a circular steel wheel. Effects of the motion resistance to total motion resistance were analyzed. The main results from experiments and analyses were as follows.

(1) The direction of the normal force on the rim becomes slant downward when a circular wheel is operated on adhesive soil condition. This is caused by "rim surface adhesion".
(2) The superposition of the negative part of the horizontal component shows that the motion resistance caused by the rim surface adhesion increased with increasing the dynamic load.
(3) Ratios of the motion resistance to total motion resistance were about 23 to 46 % in this study. The motion resistance produced by the rim surface adhesion is not negligible from these results.
(4) Reducing the motion resistance produced by the rim surface adhesion is one of the important points of improving wheel performance in sticky soil.

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