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Development and evaluation of an in-situ tire testing facility with variable side slip angles

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Abstract

An in-situ tire test rig was developed for field research on tire tractive and maneuverability performances. The Single Wheel Tester (SWT) was mounted on a tractor and a tested wheel was driven by a hydromotor, along a frame of 3 m length. In the SWT, four load cells were utilized to measure longitudinal and lateral forces, input and self-aligning torques, and two optical counters were applied to calculate forward and angular velocities. Response Surface Methodology was used to execute experimental design and to analyze the collected data. Afterwards, reduced form of a 2 Factor Interaction model was extracted to predict rolling resistance using seven factors. The test results show that increasing the normal load and side slip angle will cause an increment of rolling resistance. The incremental growth rate of the rolling resistance due to the normal load increment was observed. At higher cone index values, increasing the angular velocity reduces the rolling resistance, although at lower cone index values, the effect of angular velocity on rolling resistance is in reverse order. In addition, the increasing moisture content effect on rolling resistance at lower side slip angle values was observed.

Keywords: Single wheel tester; Rolling resistance; Side slip angle; Normal load; Drawbar pull; Angular velocity; Cone index; Moisture content; Tire inflation pressure; Response Surface Methodology

1. Introduction

Dynamic behavior of off-road vehicles, differs widely from that of road vehicles due to deform-ability and shear-ability of contact patch. For many decades, the interaction between ground and off-road vehicles, such as agricultural tractors, has been an important field of study (Muro and O'Brien, 2004; Macmillan, 2002; Pytka, 2010). The performance of tractors greatly depends on the soil–tire interaction. This interaction provides traction, supporting, handling, and braking (Slaughter et al., 2008). The poor interaction between tire and soil, causes nearly 20–55% of tractor power losses (Zoz and Grisso, 2003). Forces and moments acting on tires should be studied in order to design vehicles, improve traction efficiency, and enhance handling, motion dynamic stability and steer-ability (Más et al., 2010).

Traction performance analysis can be carried out by the study of a single wheel moving over a deformable terrain in which wheel velocity, lateral and longitudinal slips, applied forces and moments are measurable (ASABE, 2009). Researches on traction performance have been done in soil bin (Gee-Clough and Sommer, 1981; Kawase et al., 2006; Krick, 1973; Tiwari et al., 2009; Yahya et al., 2007; Raheman and Singh, 2004) and on field using a Single Wheel Tester (SWT) Ahmad et al., 2011; Alcock and Wittig, 1992; Way, 2009; Nagaoka et al., 2001; Armbruster and Kutzbach, 1991; Upadhyaya et al., 1985 or via an instrumented vehicle (Pearson and Bevly, 2007;

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Nomenclature

d	lever arm of R (m)
eh	longitudinal distance between wheel center and R_v (m)
rt	vertical distance between wheel center and rolling resistance application point (m)
CI	cone index value (kPa)
CR	carrier resistance (N)
DP	drawbar pull (N)
F_{AT}	the force acting on the load cell 4 measuring aligning torque (N)
F_T	the force acting on the load cell 1 measuring drive axle input torque (N)
F_x	longitudinal force measured by load cell 2 (N)
F_y	lateral force measured by load cell 3 (N)
F_z	wheel normal load (N)
GT	gross traction (N)
MC	moisture content (%)
NT	net traction (N)
Pr	tire inflation pressure (kPa)
R	resultant of surface reaction force (N)
R_h	horizontal surface reaction force (N)
R_r	rolling resistance (N)
R_v	vertical surface reaction force (N)
R_x	longitudinal reaction force applied to chrome shaft by the carrier (N)
R_y	lateral reaction force applied to chrome shaft by the carrier (N)
S	tire slippage (%)
T	input torque (N m)
V_a	actual velocity (m/s)
X	lever arm of lateral force (m)
Y	lever arm of longitudinal force (m)
z_{AT}	normal distance between load cell 4 and center of chrome shaft (m)
z_T	normal distance between load cell 1 and center of axle (m)
α	side slip angle (°)
θ	the angle between R_v and R (°)
ω	tire angular velocity (rpm)

Baffet et al., 2008; McLaughlin et al., 1993; Gu and Kushwaha, 1994; Shoop, 1992; Gobbi et al., 2005; Goli et al., 2012; Hajiahmad et al., 2013, 2014; Pytka et al., 2011).

Researches based on SWT can be divided into driven and undriven wheels with variable side slip angles or zero side slip angle. Gee-Clough and Sommer (1981) measured steering forces on undriven, angled wheels, using tires with no tread, in a soil bin. They assumed that aligning torque is extremely small and its effect could be neglected in their analysis. Krick (1973) measured the forces of driven wheels with side slip angles (adjustable from 0° to 35°) in a soil bin, by a six degree of freedom recording device.

Ahmad et al. (2011) developed a test rig pulled by a tractor for field use on different terrains, to measure motion resistance of towed narrow wheels. They investigated the effect of wheel size, normal load and inflation pressure on the motion resistance. The SWT developed by Armbruster and Kutzbach (1991) was based on a rig connected to a four-wheel-trailer. Tractive and lateral forces on driven tires up to a side slip angle of 16° were measured by a six-component wheel dynamometer.

Studies on vehicle dynamic behavior have been done using instrumentation of a conventional vehicle or development of a prototype vehicle. Gobbi et al. (2005) developed an instrumented wheel hub (connected directly to the rims of a tractor), to measure all forces and moments acting on the front wheels. They applied the longitudinal and the lateral slips and measured the corresponding longitudinal and lateral forces. Baffet et al. (2008) applied a dynamometric hub on a passenger car tires in order to study the dynamic behavior of wheel–road interaction. A few researchers developed prototype vehicles with required instrumentation to study traction performance, vehicle dynamic behavior, etc. (Goli et al., 2012; Hajiahmad et al., 2013, 2014).

However, there were some methods of measuring tire forces and moments in the literature, but they were limited to measuring few parameters or their methods were not economical. This paper presents an in-situ and flexible tire traction testing facility, with minimum time consumption for experiment execution, to obtain reliable data for measuring forces (including lateral) and moments acting on angled driven wheels in each intended surface. In addition, the rolling resistance of a high lug agricultural tire investigated as a function of seven important variables.

2. General description

A general view of the SWT and its components are shown in Fig. 1. A linear bushing is attached to the carrier part which allows the driving system to slide freely in vertical axis guided by a chrome shaft. The driving system, including wheel, hydromotor, gearbox and dynamometric mechanism had been designed. To provide wheel drawbar pull, one end of a wire rope was attached to the carrier part and the other supported a dead weight.

3. Driving system

The wheel was powered by a hydro-motor with a displacement of 165 cm^3/rev. A 4.67 reduction ratio gearbox