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Side slip angle prediction model of an off-road tire on different terrains

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Abstract

In this paper, two mathematical models were developed to predict side slip angle for driven wheels of a prototype tractor. The independent variables involved moisture content, cone index, normal load, inflation pressure, angular velocity, and steer angle with three levels. Response Surface Method (RSM) was used to extract models and to analyze results. The tractor was driven in circular paths to the left side to apply all experimental treatments. Among different mathematical models, the linear models with coefficient of determination of 0.8978 and 0.8983 were chosen to predict side slip angle of the left and right wheels, respectively. The mathematical models analysis of variance showed that all factors had significant effect on tire side slip angle. In all experiments the inner wheel side slip angle was lower than that of the outer. An inverse effect for cone index and wheel normal load was observed while other factors effects were found to be direct. Also, the angular velocity had the highest impact on side slip angle for both rear wheels.

Keywords: Side slip angle; Tractor; Moisture content; Cone index; Normal load; Inflation pressure; Angular velocity; Steer angle; RSM

1. Introduction

When a vehicle is turning, traversing along slopes or bearing offset drawbar pull, its tires experience side slip. Side slip value is more when vehicle is on a soft surface because of the terrain shearability and deformability. Determination of tire lateral behavior is essential to study vehicle dynamics which is inquired by several researchers [1–5]. Although, some researchers have used theoretical methods [6–8], experimental methods have been more interesting to scientists. Two experimental methods have been used to study the tire lateral behavior. In the earlier method a single wheel moves across a constrained path in different slip angles, and all forces acting on the tire are measured [9–12]. The recent method is based on precision positioning of a vehicle using GPS, Inertial Measurement Unit (IMU), laser scanner, machine vision along with measuring dynamic forces acting on each wheel [13–18].

The magic formula by Pacejka [19] determines not only the relation of side force and traction with side slip angle and slippage but also it relates the normal load, overturning, rolling resistance and yaw moments with radial deflection, camber angle, angular velocity and turn slip, respectively. Besselink et al. [20] improved the magic formula to cope with large camber angles and large inflation pressure changes.

Wheel lateral force measured by Gee-Clough and Sommer [12] illustrated the exponential relationship between side force and side slip angle. This result was extracted at low speed and zero camber angle on undriven wheels using no-tread tires in a soil bin filled with a moist loamy soil at four levels of cone indices. Armbruster and Kutzbach [10] obtained the same result while studying the side force behavior relative to side slip angle at different inflation pressures and normal loads. Also, an exponential equation was obtained by Raheman and Singh [11] in which the

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Nomenclature

Sym.	Description
A	the distance between two arbitrary points of vehicle circular path (m)
a	the distance between front axle and CG (m)
b	the distance from center line to middle of rear wheel (m)
CI	cone index (MPa)
d	difference angle between steering wheels (m)
F_{y1}	side force of left front wheel (N)
F_{y2}	side force of right front wheel (N)
F_{yl}	side force of left rear wheel (N)
F_{yr}	side force of right rear wheel (N)
F_z	normal Load (N)
F_{zl}	normal Load of left rear wheel (N)
F_{zr}	normal Load of right rear wheel (N)
i	ratio of rear axle normal load to tractor weight (−)
L	Wheelbase (m)
M	tractor mass (kg)
MC	moisture content (%)
P	inflation pressure (kPa)
R	turning radius (m)
$r_{1\text{-}4}$	motion resistance (N)
V	forward velocity
W	tractor width (m)
X_0	variable value in the central point (−)
x_i	coded value (−)
X_i	experimental value (−)
α_{fl}	side slip angle of front left wheel (deg)
α_{fr}	side slip angle of front right wheel (deg)
α_{IMU}	angle measured by IMU (deg)
α_{rl}	side slip angle of rear left wheel (deg)
α_{rr}	side slip angle of rear right wheel (deg)
δ	steer angle (deg)
δ_X	step change (−)
γ	heading angle (deg)
ω	angular velocity (rpm)
ω_l	angular velocity of rear left wheel (rpm)
ω_r	angular velocity of rear right wheel (rpm)

coefficients of this equation were found to be linearly related to inflation pressure for any slip angle between 0 and 30 degrees. Daily and Bevly [21] developed a model based on magic formula to investigate side force and slip angle behavior of a radial tire at different normal loads. They found that as the normal load on the wheel increases the side slip decreases accordingly. The side force and side slip angle relation were investigated at different forward velocities in which increasing the vehicle speed increased the side slip angle [22].

This paper presents a model to predict the side slip angle of a rear wheel drive vehicle with steerable front wheels. The goal of this study was to determine factors affecting the slip angle including cone index and moisture content representing soil characteristics and steer angle, angular velocity, tire inflation pressure and wheel normal load as vehicle parameters.

2. Material and methods

To investigate how the effective factors influence on the side slip angle, a prototype tractor was developed as shown in Fig. 1. Common vehicles have no ability to install sensors and change the position of center of gravity with a constant weight; therefore, this tractor was designed to overcome these restrictions, with a remote control, to omit driver weight and its effect on Center of Gravity (CG) position.

2.1. The prototype tractor specification

The drive wheels of the tractor were on the rear axle equipped with high lug farm tractor tires of 4.00–12 bias ply and the steering wheels on the front axle with tires of 4.00–8 bias ply. The tractor had a gasoline engine with a power of 9.5 kW. A remote control pad sending the operator orders to a receiver installed on the tractor was used to control the vehicle. The orders were compiled through the Electronic Control Unit (ECU) and sent to the driver board which delivered the corresponding pulses to the actuators relays. Finally, the orders were carried out by the pneumatic cylinders, to change the CG position, gears, steer angle, throttle and braking.

The tractor was equipped with sensors to monitor its dynamic conditions. The collected data by the sensors were sent to the ECU and then saved in a memory card. The data were being updated each 20 ms. A 9-degree of freedom Inertial Measurement Unit (IMU) manufactured by Sparkfun Company (SEN-09623) was installed on the tractor to display the heading and position of the tractor. The forces acting on the tractor tires were measured by load cells manufactured by Zemic Company (H3 and B8D models). Measurement procedures are quoted in Refs. [23,24].

2.2. Experimental conditions

The field tests were carried out on a bare agricultural soil surface after using a moldboard plough to a depth of 15–20 cm and a disk harrow to make the field ready for experiments. The field was divided into nine equal regions to satisfy three compaction levels (plowed, 2 and 5 passes of roller packer) and 3 moisture content levels (8 ± 0.52, 11 ± 0.37 and 14 ± 0.61 percent). Soil moisture contents were taken at 0–10 cm depth, associated with the