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Research Paper

Semi-empirical model for elastic tyre trafficability and methods for the rapid determination of its related parameters

Zhun Cheng, Zhixiong Lu *

College of Engineering, Nanjing Agricultural University, Nanjing 210031, China

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To build an accurate and practical model for trafficability, experiments were conducted in a soil bin on elastic–tyre interaction. Wheel–soil interaction used a semi-empirical model and compared parameter identification methods based on improved an simulated annealing (SA) algorithm, an improved artificial fish swarm algorithm (AFSA), and an improved particle swarm optimisation algorithm (PSO) to calculate the maximum stress angle and the departure angle of the elastic tyre. The trafficability experiment included the acquisition of stress distribution, sinkage, and properties of soil of the contact length between elastic tyre and soil with different slip rates. The study proposed an improved semi-empirical model for the calculation of maximum stress angle, an improved slip sinkage semi-empirical model, and a method of determining the departure angle and tyre–soil contact length according to parameter identification research. The results indicated that the improved SA was most efficient algorithm to obtain the maximum stress angle and the departure angle, with the average number of iterations equal to 3.94 and the average time consumption of computer equal to 15.41 s. The method proposed can closely estimate the tyre–soil contact length and the elastic tyre sinkage, requiring only the slip rate and the vertical load on tyre. In addition, the method can provide the maximum stress angle for calculation, approach angle, and departure angle necessary for a wheel–soil interaction semi-empirical model.

1. Introduction

As components of a vehicle in direct contact with the ground, tyres play an important role in the overall performance of a vehicle, particularly its trafficability. Advanced wheeled vehicles have replaced track vehicles which entail high manufacturing costs. Thus, most non-road vehicles, such as tractors, use elastic wheels. Studying the mechanism of action between elastic tyre and soft-soil ground is significant in the analysis of vehicle terramechanics and trafficability (Wong, 2010).

Tyre–soil interaction is an important part of research into vehicle terramechanics (Huang, Li, Dang, Wu, & Zou, 2016; Iagnemma, Kang, Shibly, & Dubowsky, 2004; Kiss, 2003; Roşca, Cârlescu, & Ţenu, 2014; Shibly, Iagnemma, &

* Corresponding author.
E-mail address: 1003765165@qq.com (Z. Lu).
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Nomenclature

R_{eff}	Effective radius of elastic wheel, m
R	Static radius of elastic wheel, m
θ_e	Approach angle, °
θ_b	Departure angle, °
θ	Included angle between the centrally vertical line of the elastic wheel and any central line of the tyre on the contact surface, °
β	Fixed parameter of the calculation model for the elastic tyre radius
δ	Fixed parameter of the calculation model for the elastic tyre radius
ξ	Fixed parameter of calculation model for elastic tyre radius
θ_f	Front-contact end of the straight-line segment of the contact area, °
θ_r	Back-end of the straight-line segment of the contact area, °
Z_0	Static sinkage, m
W	Vertical load on tyre, N
D	Diameter of elastic tyre, m
n	Sinkage index of soil
k_c	Cohesion modulus of soil, N $m^{-(n+1)}$
k_ϕ	Friction angle modulus of soil, N $m^{-(n+2)}$
b	Width of elastic tyre, m
Z	Total sinkage, m
θ_m	Maximum stress angle, °
s	Slip rate
h_g	Height of tyre burr, m
H_p	Soil deformation depth, m
σ_n	Normal stress, Pa
c	Soil cohesion, Pa
γ	Volume–weight of soil
τ	Shear stress, Pa
j_x	Shear displacement of soil, m
k_x	Shear deformation modulus of soil
ϕ	Internal friction angle of soil, °
F_w	Vertical reacting force of soil to elastic tyre, N
F_x	Driving force of the tyre, N
j	Soil deformation under shear action, m
L	Length of contact area between tyre and soil, m
υ	Driving speed of elastic wheel, m s^{-1}
t	Time spent by the elastic wheel entirely passing through the pressure sensor, s
θ'_m	Maximum stress angle for calculation, °
r	Disturbing function
i	Current number of iterations
N	Maximum number of iterations
S_0	Optimal value of previous generation calculated with the improved SA
$rand$	Random number in $0 \sim 1$
P	Probability of accepting the poor solution
ΔE	Difference in fitness between two generations
T	Temperature variable in SA
T_i	Value of Tin the ith iteration
T_0	Initial value of T
T_{end}	Final value of T
C_{i+1}	Value of C in the $(i+1)$th iteration
C_i	Value of C in the ith iteration
F_{opt}	Objective function of optimisation algorithm
F'_w	Theoretically calculated value of vertical load on tyre, N
F_w	Actually calculated value of vertical load on tyre, N

Dubowsky, 2005). Several studies (Michael, Vogel, & Peters, 2015; Nishiyama, Nakashima, Shimizu, Miyasaka, & Ohdoi, 2017; Nishiyama et al., 2018; Nishiyama et al., 2016) have developed wheel–soil models using finite element–discrete element coupling to simulate the contact process. The technique can solve basic problems with a certain degree of accuracy but it involves high computational costs and requires further calculations to obtain the driving force and normal bearing capacity of tyre–soil contact, and building the contact model takes time. Moreover, it is difficult to describe the interactive relationship between tyre and soil using purely analytical methods. Therefore, after years of development, the semi-empirical models have been increasingly studied and used. This study focuses on wheel–soil semi-empirical modelling.

With regard to normal stress calculation, the static pressure bearing and sinkage model proposed by Bekker (1969) can be used to determine the sinkage and normal stress. The static pressure bearing and sinkage model has been applied and widely used because of the ease of parameter acquisition as well as providing a straightforward and clear calculation (Wang, Ren, Liu, & Zhao, 2014). However, the model proposed by Bekker can only calculate sinkage under static conditions. Wong and Reece (1967a, 1967b) improved the model and introduced a soil property parameter to make the predictions closer to real situations (Jiang, Liu, & Jiang, 2013). With regard to research on tangential stress, Janosi and Hanamoto (1961) proposed a shear force semi-empirical model to calculate the shear force produced by a tyre and Wong and Reece (1967a) proposed an equation for shear displacement in the semi-empirical calculation model. Follow-up studies have mostly explored the interaction between wheel and soil on the basis of these models. However, in addition to determining the parameters of soil and tyre, calculating the vertical force of the tyre and ground tangential driving force by using the calculation model for normal stress and shear stress requires the approach angle θ_e, the departure angle θ_b, and the maximum stress angle θ_m for the tyre–soil interaction. The three parameters cannot be measured directly and vary with changes in the vertical load of the tyre and the slip rate. Therefore, determining the three parameters presents a challenge.

Senatore and Iagnemma (2014) studied the stress distribution of rigid wheel with a light load. The results show that normal stress distribution laws slightly vary in different positions along the width of a rigid tyre. This variation increases the difficulty of calculating θ_e, θ_b, and θ_m. On the basis of a real-vehicle equipment, Yang, Lin, Zhang, and Wang (2016)