BIOSYSTEMS ENGINEERING 129 (2015) 20–33

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

A method of optimal traction control for farm tractors with feedback of drive torque

Pavel V. Osinenko[*,1], *Mike Geissler*[2], *Thomas Herlitzius*[3]

Chair of Agricultural Systems and Technology (AST), Institute of Processing Machines and Mobile Machinery, P.O. Box: 01069, Technische Universität Dresden (TU Dresden), Dresden, Germany

ARTICLE INFO

Article history:
Received 20 January 2014
Received in revised form
3 September 2014
Accepted 17 September 2014
Published online 6 October 2014

Keywords:
Slip control
Optimal control
Infinitely variable transmissions
Traction efficiency
Traction parameters

Traction efficiency of farm tractors barely reaches 50% in field operations (Renius et al., 1985). On the other hand, modern trends in agriculture show growth of the global tractor markets and at the same time increased demands for greenhouse gas emission reduction as well as energy efficiency due to increasing fuel costs. Engine power of farm tractors is growing at 1.8 kW per year reaching today about 500 kW for the highest traction class machines. The problem of effective use of energy has become crucial. Existing slip control approaches for farm tractors do not fulfil this requirement due to fixed reference set-point. This paper suggests an optimal control scheme which extends a conventional slip controller with set-point optimisation based on assessment of soil conditions, namely, wheel-ground parameter estimation. The optimisation considers the traction efficiency and net traction ratio and adaptively adjusts the set-point under changing soil conditions. The proposed methodology can be mainly implemented in farm tractors equipped with hydraulic or electrical infinitely variable transmissions (IVT) with use of the drive torque feedback.

1. Introduction

1.1. *Brief description of traction dynamics*

In this section, the main factors contributing to traction efficiency are discussed. First, the wheel dynamics are briefly described. The corresponding force diagram is given in Fig. 1. The soil reaction force F_z acts against the axle load $F_{z,\mathrm{axle}}$ and the wheel weight. The horizontal soil reaction F_h (or horizontal force) is exerted by the driving torque M_d. An opposite force on the wheel, namely, reaction of the vehicle body, is denoted by $F_{x,\mathrm{axle}}$. The point of application of the soil reaction is shifted by Δl_z in direction of motion due to tyre deformation which characterises the internal rolling resistance. Another part of the rolling resistance $F_{rr,e}$ is external, due to soil deformation, and should not be confused with the internal resistance (Schreiber & Kutzbach, 2007).

* *Corresponding author.*
E-mail addresses: osinenko@inbox.ru, osinenko@ast.mw.tu-dresden.de (P.V. Osinenko), geissler@ast.mw.tu-dresden.de (M. Geissler), herlitzius@ast.mw.tu-dresden.de (T. Herlitzius).

[1] Graduate student.
[2] Scientific staff member.
[3] Chairman.

http://dx.doi.org/10.1016/j.biosystemseng.2014.09.009
1537-5110/

Nomenclature

η_t	Traction efficiency
κ	Net traction ratio
μ	Horizontal force coefficient
ω_w	Wheel revolution speed, rad s^{-1}
ρ	Rolling resistance coefficient
a_z	Wheel vertical acceleration, m s^{-2}
b_t	Tyre section width, m
F_h	Horizontal force, N
F_z	Normal force, N
J_w	Wheel moment of inertia around lateral axis, kg m^2
m	Vehicle mass, kg
M_d	Drive torque, Nm
m_w	Wheel mass, kg
r_d	Tyre dynamic rolling radius, m
s	Slip
v	Vehicle travelling velocity, m s^{-1}
v_w	Wheel travelling velocity, m s^{-1}

The equations of motion are written as follows:

$$m_w \dot{v}_w = F_h - F_{rr,e} - F_{x,\mathrm{axle}},$$
$$J_w \dot{\omega}_w = M_d - r_d F_h - \Delta l_z F_z,$$
$$m_w a_z = F_z - m_w g - F_{z,\mathrm{axle}}. \quad (1)$$

The term $\Delta l_z F_z$ is substituted by $r_d F_{rr,i}$ where $F_{rr,i}$ denotes the internal rolling resistance (due to tyre deformation). Longitudinal dynamics are characterised by several parameters: the horizontal force coefficient μ, the internal and external rolling resistance coefficients ρ_i,ρ_e respectively and the net traction ratio κ. They are computed with the following formulas:

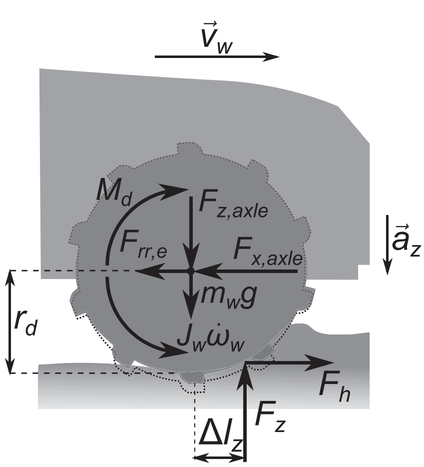

Fig. 1 – Forces and torques acting on a wheel in longitudinal motion. $\vec{v}_w$ is the wheel travelling velocity, ω_w is the wheel revolution speed, m_w is the wheel mass, J_w is the wheel moment of inertia around the lateral axis, r_d is the dynamic rolling radius which is the distance between the wheel's centre and bottom points, a_z is the wheel vertical acceleration.

$$\mu = \frac{F_h}{F_z}, \quad (2)$$

$$\rho_i = \frac{F_{rr,i}}{F_z}, \rho_e = \frac{F_{rr,e}}{F_z} \quad (3)$$

$$\kappa = \mu - \rho_e, \quad (4)$$

The rolling resistance coefficient is computed as sum of ρ_e and ρ_i in (3): $\rho = \rho_e + \rho_i$. The wheel slip is defined as follows:

$$s = 1 - \frac{|v|}{r_d|\omega_w|}, \quad \text{if } |v| \le r_d|\omega_w|,$$
$$s = -1 + \frac{r_d|\omega_w|}{|v|}, \quad \text{if } |v| > r_d|\omega_w|. \quad (5)$$

It ranges from −1 (locked wheel) to 1 (spinning on the spot). The traction efficiency is defined as follows:

$$\eta_t = \frac{\kappa}{\kappa + \rho}(1 - s). \quad (6)$$

Usually, the traction parameters κ,ρ and the traction efficiency η_t are considered as functions of slip. Some characteristic curves for different soil types are illustrated in Fig. 2. The curves of the net traction ratio are shown without bias at zero for simplicity. Details of zero-slip conditions have been described by Schreiber and Kutzbach (2007).

It can be seen that, in general, maxima of $\eta_t(s)$ as well as maximum achievable traction effort, characterised by κ, are different for different soil types.

1.2. *Improvement of traction*

The main factors, which affect the traction efficiency of farm tractors, include the tyre pressure, properties of tyres or tracks, the vertical load and the drive train slip. In most cases, only the drive train slip is adjusted during the field operation, i.e. online. The main possibilities of balancing traction efficiency and productivity include drive train slip control, dynamic vertical load adjustment, automatic tyre pressure

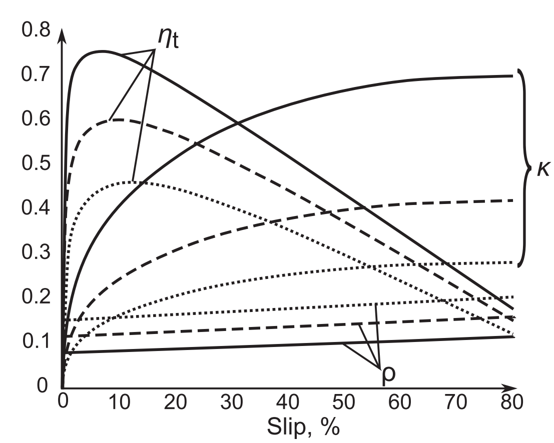

Fig. 2 – Modelled traction characteristics for different soil types (Wünsche, 2005). Solid lines – stubble, dashed lines – wet loam, dotted lines – muddy soil. ρ is the rolling resistance coefficient, η_t is the traction efficiency and κ is the net traction ratio.