BIOSYSTEMS ENGINEERING 106 (2010) 352–366

Available at www.sciencedirect.com

ScienceDirect

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

Research Paper

Local and global sensitivity analysis of a tractor and single axle grain cart dynamic system model

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ARTICLE INFO

Article history:
Received 5 July 2009
Received in revised form
26 March 2010
Accepted 26 April 2010
Published online 2 June 2010

Tractor and towed implement system models have become increasingly important for model-based guidance controller design, virtual prototyping, and operator-and-hardware-in-loop simulation. Various tractor and towed implement models have been proposed in the literature which contain uncertain or time-varying parameters. Sensitivity analysis was used to identify the effect of system parameter uncertainty/variation on system responses and to identify the most critical parameters of the lateral dynamics model for a tractor and single axle grain cart system. Both local and global sensitivity analyses were performed with respect to three tyre cornering stiffness parameters, three tyre relaxation length parameters, and two implement inertial parameters. Overall, the system was most sensitive to the tyre cornering stiffness parameters and least sensitive to the implement inertial parameters. In general, the uncertainty in the input parameters and the system output responses were related in a non-linear fashion. With the nominal parameter values for a Mechanical Front Wheel Drive (MFWD) tractor, a single axle grain cart, and maize stubble surface conditions, a 10% uncertainty in cornering stiffness parameters caused a 2% average uncertainty in the system responses whereas a 50% uncertainty in cornering stiffness parameters caused a 20% average uncertainty at 4.5 m s^{-1} forward velocity. If a 5% average uncertainty in system responses is acceptable, the cornering stiffness parameters must be estimated within 25% of actual/nominal values. The output uncertainty increased as the forward velocity was increased.

1. Introduction

Off-road vehicle system models are becoming increasingly important as mechatronic engineers increasingly rely on model-based controller design, virtual prototyping, and real-time hardware-and-operator-in-loop simulation in the design process (Antonya & Talaba, 2007; Castillo-Effen, Castillo, Moreno, & Valavanis, 2005; Cremer, Kearney, & Papelis, 1996; Howard & Vance, 2007; Karkee & Steward, 2008; Karkee, Steward, Kelkar, & Kemp, 2010; Schulz, Reuding, & Ertl, 1998). As the cost of computational power required for numerical simulation is decreasing, vehicle models have become increasingly complex often possessing dozens of model parameters. Accurate estimation of those parameters is often difficult because of the high variability in field conditions. Because uncertain parameter estimates will have an effect on the model responses, off-road vehicle simulations may often be unrealistic, limiting the applicability of the

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1537-5110/$ – see front matter
doi:10.1016/j.biosystemseng.2010.04.006

List of variables

α	side slip angle or the angle between the direction the tyre is going and the direction it is facing. The velocity vector to the right of the tyre is positive and reverse is negative (rad)
α_0	steady state side slip angle (rad)
γ	yaw-rate (rad s^{-1})
δ	steering angle (rad)
λ	angle between tractor heading and implement heading (rad)
σ	relaxation length (m)
φ	heading angle (rad)
a	distance between front axle and CG of tractor (m)
b	distance between rear axle and CG of tractor (m)
c	distance between hitch point and CG of tractor (m)
C_α	cornering stiffness (N rad^{-1})
d	distance between hitch point and CG of implement (m)
e	distance between rear axle and CG of implement (m)
F	force (N)
I_z	yaw moment of inertia (kg m^2)
$\overline{M}'$	global sensitivity measure (%output/%input)
m	mass (kg)
p	parameter vector
S	local sensitivity measure (%output/%input)
u	longitudinal velocity (m s^{-1})
v	lateral velocity (m s^{-1})
X–Y	world coordinates
x'–y'	vehicle coordinates
y	position of CG in y-axis of the world coordinate system (m)
Superscript	
t	tractor
i	implement
Subscript 1	
x	x axis
y	y axis
z	z axis
Subscript 2	
f	front tyre axle
r	rear tyre axle
c	centre of gravity
p	hitch point

models and model-based studies (Kioutsioukis, Tarantola, Saltelli, & Gatelli, 2004). It is important to understand and quantify the effect of these parameter uncertainties or variations on the system response (Fales, 2004). Sensitivity analysis is one approach to identify and quantify the relationships between input and output uncertainties (Xu & Gertner, 2007).

Sensitivity analysis evaluates the variation in dynamic model outputs with respect to (w.r.t.) variation in model parameters (Crosetto & Tarantola, 2001; Deif, 1986). Thus, sensitivity analysis can be used to perform uncertainty analysis, estimate model parameters, analyse experimental data, guide future data collection efforts, and suggest the accuracy to which the parameters must be estimated (Rodriguez-Fernandez & Banga, 2009).

Sensitivity analysis has been used to optimise vehicle system design (Jang & Han, 1997; Park, Han, & Jang, 2003). Jang and Han (1997) used a direct differentiation method to study the sensitivity of on-road vehicle lateral dynamics on tyre cornering stiffness, location of vehicle centre of gravity (CG), vehicle mass, and vehicle moment of inertia (MI) using a bicycle model of a front wheel steered vehicle. The study was performed at typical on-road vehicle velocities ranging from 9 m s^{-1} to 53 m s^{-1}. Park et al. (2003) performed a dynamic sensitivity analysis for a pantograph of a rail vehicle. Dominant design variables were identified using derivative-based state sensitivity measures and were modified for optimal design. Ruta and Wojcicki (2003) also applied sensitivity analysis to a dynamic railroad track vibration model. They focused on developing an analytical solution for derivative-based sensitivity analysis of a system represented by a set of differential equations. Both first and second order derivatives were used to isolate a set of parameters to which the model outputs were the most sensitive. Eberhard, Schiehlen, and Sierts (2007) performed a vehicle model sensitivity analysis with various design variables of a passenger car and found that vehicle dynamics were highly sensitive to MI and the CG location. The study was conducted at 10 m s^{-1} forward velocity. In off-road vehicle systems, the application of sensitivity analysis to understand the effect of uncertain parameters on a tractor and towed implement lateral dynamics is important to support emerging farm automation technology such as implement guidance and coordinated guidance.

Various tractor and towed implement steering models have been proposed in the literature for both on-road (Chen & Tomizuka, 1995; Deng & Kang, 2003; Kim, Yun, Min, Byun, & Mok, 2007) and off-road (Feng, He, Bao, & Fang, 2005; Karkee & Steward, 2008) operations. As suggested by these models, the lateral dynamics of an off-road tractor and towed implement system depend on the lateral forces generated by soil-tyre interactions. A vehicle tyre, when subjected to a steering side force, does not move to the direction it is facing resulting in an angular difference between the two directions called the side slip angle (Wong, 2001). Vehicle tyres go through some level of deformation when they move to a direction different from the direction they are facing. This deformation produces shear stress at the tyre–soil interface. This shear stress causes some level of lateral soil deformation as well, which releases part of the shear stress developed at the interface (Metz, 1993). The resultant shear stress will generate a force at the contact patch called lateral tyre force or cornering force (Crolla & El-Razaz, 1987).

In addition to tyre and lateral soil deformation, phenomena such as tyre-soil friction and soil sinkage effects also affect the characteristics of lateral tyre force development (Metz, 1993). Because most of these phenomena are dependent on soil