ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Journal of Terramechanics xxx (2015) xxx–xxx

Journal of Terramechanics

www.elsevier.com/locate/jterra

Investigation into use of piezoelectric sensors in a wheeled robot tire for surface characterization

Elizabeth G. Armstrong [a], Corina Sandu [a,b,*], Saied Taheri [b]

[a] Advanced Vehicle Dynamics Laboratory, CVeSS, Virginia Tech, Blacksburg, VA 24060, USA

[b] Center for Tire Research, Virginia Tech, Blacksburg, VA 24060, USA

Received 23 April 2014; received in revised form 10 May 2015; accepted 9 July 2015

Abstract

A differential steered, 13.6 kg robot was developed as an intelligent tire testing system and was used to investigate the potential of using piezoelectric film sensors in small tube-type pneumatic tires to characterize tire–ground interaction.

The robot was instrumented with low-cost piezoelectric film sensors between the inner tube and the tire. An unlaminated and a laminated sensor were placed circumferentially along the tread and an unlaminated sensor was placed along the sidewall. The analog signal passed to the robot via a slip ring. The robot was tested with a controlled power sequence carried out on polished cement, ice, and sand at three power levels, two payload levels, and with two tire sizes.

The results suggest that the sensors were capable of detecting normal pressure, deflection, and/or longitudinal strain. Added payload increased signal amplitude for all sensors. On the smaller tires, sensors generally recorded a smaller, wider signal on sand compared to cement, indicating potential to detect contact patch pressure and length. The signals recorded by the unlaminated sensor along the tread of the smaller tire were smaller on ice than cement, indicating possible sensitivity to tractive force. Results were less consistent for the larger tires, possibly due to the large tread pattern.

Keywords: Intelligent tire; Wheeled robot; Terramechanics; Piezoelectricity; Full width at half maximum

1. Introduction

In the past two decades, a focus of tire research has been on implementing sensors into tires to gather information about the tires, the vehicle, or the operating environment (APOLLO, 2005; Ergen et al., 2009). Tires with embedded sensors are known as 'smart' or 'intelligent' tires.

While a large amount of research has been done on development of 'smart' tires for passenger vehicles, less work has been conducted on instrumentation of small tires, like those that are used in small wheeled robots. Instrumenting tires of small wheeled robots with sensors to detect the forces or moments acting on a tire has potential to both improve robot mobility and enable a robot to sense its external environment. Sensors in a small robotic tire could be used to detect terrain type (e.g. terrain roughness, soil properties), geometry of terrain and any obstacles, contact patch pressure (Roth, 2010), or tire sinkage. This type of information gathered by 'smart' robot tires could be used to:

- Improve traction, handling, and steering (Cheli et al., 2010; Iagnemma et al., 2004).
- Improve vehicle durability (Pinto, 2012).

* Corresponding author at: 460 Old Turner Street, Blacksburg, VA 24061, USA. Tel.: +1 540 231 7467.

E-mail addresses: egarms@vt.edu (E.G. Armstrong), csandu@vt.edu (C. Sandu), staheri@vt.edu (S. Taheri).

http://dx.doi.org/10.1016/j.jterra.2015.07.003

0022-4898/

Please cite this article in press as: Armstrong, EG et al., Investigation into use of piezoelectric sensors in a wheeled robot tire for surface characterization, J Terramechanics (2015), http://dx.doi.org/10.1016/j.jterra.2015.07.003

Nomenclature

F_z	force in the z direction, vertical load [N]
F_y	force in the y direction, lateral force [N]
F_x	force in the x direction, longitudinal or tractive force [N]
s	slip
v	linear velocity of vehicle $\left[\frac{m}{s}\right]$
ω	angular velocity of tire $\left[\frac{rad}{s}\right]$
r_{eff}	effective rolling radius of tire [m]
μ	coefficient of friction
μ_{static}	static coefficient of friction
$\mu_{sliding}$	sliding coefficient of friction
μ_p	peak coefficient of friction
CI	cone index [kPa]
PPR	pulses per revolution
GRR	gear reduction ratio
$PVDF$	polyvinylidene fluoride
V	voltage [V]
V_0	initial voltage [V]
V_p	voltage measured across a piezoelectric sensor [V]
q	charge [C]
C	capacitance [F]
I	current [A]
Y	Young's modulus
l_p	length of piezoelectric sensor electrode [m]
w_p	width of piezoelectric sensor electrode [m]
t_p	thickness of piezoelectric material between electrodes [m]
t_s	thickness of piezoelectric sensor, measured outside of protective film and/or laminate [m]
w_f	width of piezoelectric sensor protective film [m]
l_f	length of piezoelectric sensor protective film [m]
Z_C	electrical impedance of a capacitor [Ω]
Z_R	electrical impedance of a resistor [Ω]
τ	time constant of a circuit [s]
k_B	Boltzmann's constant
T	absolute temperature [K]
C_p	capacitance of a piezoelectric sensor [F]
f	frequency [f]
Z	electrical impedance [Ω]
R	resistance [Ω]
R_p	resistance of a piezoelectric sensor [Ω]
W_{front}	measured weight of the front of the robot [kg]
W^*_{front}	adjusted weight of the front of the robot [kg]
W_{rear}	measured weight of the rear of the robot [kg]
W^*_{rear}	adjusted weight of the rear of the robot [kg]
W_{left}	measured weight of the left side of the robot [kg]
W^*_{left}	adjusted weight of the left side of the robot [kg]
W_{right}	measured weight of the right side of the robot [kg]
W^*_{right}	adjusted weight of the right side of the robot [kg]
W_{total}	measured total weight of the robot [kg]
W_{FL}	calculated front left weight of the robot [kg]
W_{FR}	calculated front right weight of the robot [kg]
W_{RL}	calculated rear left weight of the robot [kg]
W_{RR}	calculated rear right weight of the robot [kg]
I_{max}	maximum allowable current for a motor channel [A]
I_{mot}	current from one motor channel, measured by motor controller [A]
V_{batt}	battery voltage [V]
P	applied relative power level for a motor channel $[\%P_{max} \times 10]$
P_{rel}	measured relative power level for a motor channel $[\%P_{max} \times 10]$
P_{mot}	measured power level for a motor channel [A]
P_{max}	maximum theoretical power level for a motor channel [A]
ω_{rel}	relative motor speed, measured by the motor controller $[\%\omega_{max} \times 10]$
ω_{max}	maximum specified motor speed [RPM]
t_{mot}	set of time values recorded corresponding to motor measurements [ms]
t_{daq}	set of evenly spaced time values recorded corresponding to the DAQ measurements [s]
θ	angle [rad]
θ_{12}	angle by which sensor 2 leads sensor 1 [rad]
θ_{13}	angle by which sensor 3 leads sensor 1 [rad]
$AVDL$	Advanced Vehicle Dynamics Laboratory, Virginia Tech
$CVeSS$	Center for Vehicle Systems and Safety, Virginia Tech
CMS	Computational Multi-Physics Systems Laboratory, Virginia Tech
$FWHM$	Full Width at Half Maximum
A	gain $\left[\frac{V}{V}\right]$ or $\left[\frac{V}{C}\right]$
σ_m	applied stress, 6×1 vector $\left[\frac{N}{m^2}\right]$
D_i	dielectric displacement, 3×1 vector $\left[\frac{C}{m^2}\right]$
τ	time constant [s]
e_{ij}	dielectric permittivity, 3×3 matrix $\left[\frac{F}{m}\right]$
d_{ij}	piezoelectric strain constant, 3×6 matrix $\left[\frac{C}{N}\right] = \left[\frac{m}{V}\right]$
p	pyroelectric coefficient $\left[\frac{C}{m^2}K\right]$
$\frac{\epsilon}{\epsilon_0}$	dielectric constant where $\epsilon_0 = 8.85\,\frac{pF}{m}$