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Tire grip identification based on strain information: Theory and simulations

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ABSTRACT

A novel technique for the identification of the tire–road grip conditions is presented. This is based on the use of strain information inside the tire, from which relevant characteristics of the tire–road contact can be extracted also through a factor named area slip ratio. This process forms the basis of a technology for grip identification that requires a new model of the tire dynamics. The model permits to determine closed form analytical relationships between the measured strain and the area slip ratio. On this basis, a procedure that can extract the contact kinematic parameter from the time history of the internal strain of the rolling tire is presented. Numerical simulations offer the chance to validate the identification algorithm.

1. Introduction

Research and technological advances in tire development are focused on increasing the vehicle safety, improving vehicle stability and control, and attempting to maximize the longitudinal and lateral forces between tire and road. The emerging capability derived from the integration between mechanics, electronics and control, allowed for a radical change in the prospective of vehicle safety that nowadays relies more on active control systems.

Active control systems use information about vehicle dynamics to improve the safety by detecting and minimizing skids. Existing devices, such as Traction Control, Electronic Stability Program, etc, relies on the indirect estimation of vehicle dynamics variables, such as forces, load transfer and tire–road friction, using on board sensors: the more precise and fast the estimation, the better the performances of the control system.

The development of an embedded sensor system for monitoring key variables, such as pressure, strain, temperature, acceleration, wheel loading, friction and tread wear, is a hard task and requires advanced technologies in the field of sensors and data transmission methods. Moreover, the design of data transmission and power supply systems are further challenging tasks.

The use of tire as a sensor has been the focus of numerous research studies and patents in the last twenty years, with special attention to friction identification [1–10]. In spite of the technological advances, commercial transducers to measure directly the tire–road friction coefficient which can be adopted for applications are still not available. However, recent advances in sensors and related electronics that allowed to gain accurate and real time estimation, produced further solutions opening the way to potential industrial products [11] as in the case of Cyber Tyre [12].

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Nomenclature

t	time variable
$R(O, x, y, z)$	road coordinate system
$W(C, x', y', z')$	wheel coordinate system
$G(\Lambda, \xi, \eta, \zeta)$	tire–road contact region coordinate system
Γ	flat tire–road contact region
$\mathbf{V}_C$	velocity vector of the centre C of the wheel
V	scalar velocity of the centre C along x
$\mathbf{\Omega}$	angular velocity vector of the centre C of the wheel
ω	scalar angular velocity of the centre C along z
r	radius of the unloaded wheel
δ	maximum radial tire deflection under F_y
F_y	normal static load vector on the tire
c	semi-length of Γ
$\mathbf{x}_{CT}$	vector identifying the generic point T on Γ
$\mathbf{x}'_P$	vector identifying the tire's material element P in W
$\mathbf{R}(t)$	rotation matrix relating the systems W and R
$\mathbf{u}'_e(\mathbf{x}'_P, t)$	displacement vector of the tire's material element P generated by the tire elastic deformation
u_{tr}	elastic deflection of the brush in the tangent direction
u_{br}	brush-tip displacement in the tangent direction
w_{tr}	brush-tip displacement in the radial direction
h_{tr}	half of the beam cross-section height
h_{br}	half of the brush height
$\mathbf{U}$	matrix relating the position and the elastic displacement at P
φ_P	angular position of P in the frame W
s	curvilinear abscissa along the tread
k_{br}	brush stiffness per unit area
ν	brush dissipation parameter
$\tau(s', t)$	in-plane contact stress
E	tire Young modulus
A	rod section area
ρ	tire density
I	beam area moment of inertia
k_a	air-spring elastic constant
b	width of the beam
Γ_S	non-slipping region of the contact area
Γ_K	slipping region of the contact area
ξ_{LE}	leading edge abscissa of the tire contact region
ξ_{TE}	trailing edge abscissa of the tire contact region
ξ^*	transition abscissa between the two regions Γ_S and Γ_K
σ	longitudinal slip of the tire or slip ratio
AR	area slip ratio
μ_S	static tire–road friction coefficient
μ_K	kinematic tire–road friction coefficient

One of the key points for indirect identification of friction based on tire sensing is the development of dedicated tire models. Several static and dynamic tire force techniques have been proposed in the recent literature, as illustrated below.

The most widely adopted static model, which uses trigonometric functions to relate slip and friction force generated in the contact between the tire and the road, is the Pacejka model, also called magic formula [13]. Canudas-de-Wit et al. have developed the so-called LuGre model [14,15], which has become the most widely used dynamic technique: it is based on Newton's Law and on simple contact dynamic friction models. However, broad testing is required to properly identify the parameters of those analytic models, making extremely difficult the real-time identification for every tire and for different operating conditions.

To overcome these drawbacks, some authors developed robust analytic models from tire-force models, such as least squared methods [16], neural-network identification [17] or fuzzy logic techniques [18]. Nearly all these models employ polynomial curve fittings for the identification process. However, although very interesting, these methods seem hardily useable in real operative conditions because of some restrictive hypotheses they rely on and/or because they require non standard measurements as, for example, the wheel torque.

A detailed analytic model for the tire belts has been proposed by Lecomte et al. [19], which has shown good correlation with experimental results up to 500 Hz. However, this model requires a simplified tread block model to be coupled with. Liu et al. [20] have presented a tread block contact mechanics model, considering the tread composed of discrete viscoelastic springs, which provides the input to the Lecomte model. The two techniques were used to predict the tangential forces and have been applied to a free rolling tire.

Matsuzaki and Todoroki [21] performed wireless strain monitoring through the use of a passive wireless system, embedding a RC oscillating circuit in the tire: the tire deformation induces a capacitance change which alters the frequency of the oscillating circuit and permits the identification of the tire strain wirelessly. For long-term service, a better compatibility of passive sensors with tire rubber is still required.

A different research line is represented by the indirect variable monitoring, where the variable of interest is extrapolated from the sensed parameters, which are mainly the vehicle velocity and the wheel angular speed [22]. Yi et al. [23] used the wheel slip, the vehicle velocity and the normal load on the tire to determine the friction coefficient. Due to nonlinear relationships among tire parameters, quantitative relations are difficult to acquire and fuzzy logic controllers [24] or Kalman filters [25] have been used. Another approach relies on the extrapolation tire–road contact forces from the measurement of three deformations of the wheel rim through strain gauges [26]. Even though indirect methods use existing sensors and are easy to install, their accuracy is low and a calibration is often required when one or more tires are substituted or when the pressure is adjusted.

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