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Agile tire slippage dynamics for radical enhancement of vehicle mobility

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Abstract

There is a need to radically increase mobility of terrain vehicles through new modalities of vehicle locomotion, i.e., by establishing a new technological paradigm in vehicle dynamics and mobility. The new paradigm greatly applies to military vehicles for the radical improvement of tactical and operational mobility. This article presents a new technological paradigm of agile tire slippage dynamics that is studied as an extremely fast and exact response of the tire–soil couple to (i) the tire dynamic loading, (ii) transient changes of gripping and rolling resistance conditions on uniform stochastic terrains and (iii) rapid transient changes from one uniform terrain to a different uniform terrain. Tire longitudinal relaxation lengths are analyzed to characterize the longitudinal relaxation time constants. A set of agile characteristics is also considered to analyze agile tire slippage dynamics within a time interval that is close to the tire longitudinal relaxation time constants. The presented paradigm of agile tire slippage dynamics lays out a foundation to radically enhance vehicle terrain mobility by controlling the tire slippage in its transient phases to prevent the immobilization of a vehicle. Control development basis and requirements for implementing an agile tire slippage control are also analyzed and considered.
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Keywords: Terrain mobility; Agile tire dynamics; Agility; Mobility enhancement; Tire slippage; Tire longitudinal relaxation length; Tire relaxation time constant

1. Introduction

For more than one hundred years, researchers have been improving *terrain vehicle mobility* by evaluating the tractive force, tractive efficiency, drawbar-pull, sinkage, ground pressures and tire slippage, etc. Significant research was done in the *Waterways Experiment Station* (WES) and the mobility index was proposed to link vehicle design parameters with vehicle mobility. Here, the bevameter technique was also originated. These and other research efforts resulted in *NATO Reference Mobility Modeling* software and its applications.

Mobility of terrain vehicles today have traditionally been estimated as a vehicle's capability of "*to go through*" or "*not to go through*" the given terrain conditions using original data that has been obtained through mathematical modeling or experimental tests. For example, the WES penetrometer and *Vehicle Cone Index*, which is usually assigned for one through fifty passages of the vehicle, can be mentioned here. This framework of research/engineering work cannot provide an analytical basis for *novel system design solutions*. Indeed, modern electronic systems related to vehicle mobility and safety, such as traction control, wheel torque vectoring systems, active suspensions, active stabilizers, active steering, hybrid-electric and fully electric vehicles all possess a control response time within the range of 100–120 ms and greater. This time-response provides fast vehicle–driver–environment interactions, but the actual control of the interaction occurs after the vehicle

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Nomenclature

D	wheel travel (distance)
F_x	circumferential force at the wheel
f	rolling resistance coefficient
i	subscript for axle, 1, 2, or 3 (front to rear)
k	empirical factor
l_2	vehicle wheelbase
l_{rl}	longitudinal relaxation length
n_{driven}	number of revolutions of a wheel in the driven mode
n_{drive}	number of revolutions of a wheel in the driving mode
r_a^o	generalized rolling radius of the drive axle in the driven mode
r_w^0	effective rolling radius of a tire in the driven mode
$r_{w\_cum}^0$	cumulative rolling radius in the driven mode
$r_{w\_inst}^0$	instant rolling radius in the driven mode
r_w	tire rolling radius in the driving mode
r_{w_cum}	cumulative rolling radius in the driving mode
r_{w_inst}	instant rolling radius in the driving mode
r_{we}	effective rolling radius at wheel theoretical velocity
R_z	normal reaction of the wheel
s_δ	tire slippage
t	time
T_w	wheel driving torque
V_t	theoretical wheel linear velocity (at zero tire slippage)
V_x	actual wheel linear velocity (at non-zero tire slippage)
ε_w	wheel angular acceleration
λ_w	tire–terrain longitudinal elasticity
μ_x	current friction coefficient
μ_{px}	peak friction coefficient
τ_{rl}	longitudinal relaxation time constant
ω_w	angular velocity of the wheel
$'$	superscript symbol for the right wheel(s)
$''$	superscript symbol for the left wheel(s)

is reaching to or has reached a critical motion situation. As a result, vehicles lose their mobility and the electronic control system mitigates the effects of the loss in mobility, rather than corrects the instability as the instability progress (less than 60 ms). Although recent electronic control systems have provided improvements to vehicle mobility, performance, and dynamics, there is a need to *radically increase* their response to correct the vehicle instabilities as they evolve, i.e., vehicle agility.

For military applications, there is also a need to radically increase tactical and operational mobility through new modalities of the vehicle locomotion system by fundamentally improving vehicle terrain mobility without sacrificing vehicle survivability. This requires new technological paradigms in vehicle dynamics and mobility as the theoretical foundation of vehicle system design. Indeed, establishing novel research domains in vehicle dynamics and mobility, i.e., new technological paradigms, can lead to fundamentally new system designs, instead of simply providing more incremental advances in vehicle systems and gaining incremental vehicle performance improvements. Novel technological paradigms can overcome this stagnation in vehicle tactical and operational mobility.

The fundamental concept of vehicle agility is by no means a novelty. However, the understanding, implementation, and controllability is still in its infancy. In 1965, M.B. Bekker defined agility as an operational requirement of acceleration, turning radius, stability and maneuverability through lateral impenetrable obstacles which demand a special vehicle configuration, such as articulated vehicles (Bekker and Butterworth, 1965). In the late 1970s, US Army research centers began analyzing mobility, agility, and survivability of ground combat vehicles (Parry, 1975; Martin and Niemeyer, 1977). In work (Parry, 1975), the results led to a conclusion that mobility and agility have a substantial impact on the vehicle's performance. Researchers then understood that the vehicle's survivability was increased through agility. For a number of years, straight-ahead acceleration was the focus (Martin and Niemeyer, 1977). Later, steering behavior prediction was included due to its complexity and the considerable attention given toward agility for increased battlefield survivability through avoiding projectiles and missiles by high-speed and violent maneuvers (Rohani and Baladi, 1982; Dudzinski, 1988). Although the term "agility" and its substantial impact on vehicle performance were introduced, research and technology advancements weren't made until decades later. Then, Murphy (1982) concluded that high mobility and agility is a major payoff in performing fast, dash-to-cover tactics, and that agility cannot be assessed on the basis of a single vehicle parameter. Instead, mobility and agility performance depends on design balance, terrain, weather and a specified mission profile. The need for agility in *tactical and operational mobility* is still present. The Defense Advanced Research Projects Agency (DARPA) is currently striving to increase the operational agility (DARPA, 2014). DARPA considers agility to be a vehicle's ability to quickly react. In an example, and much like in Murphy (1982), a rapid change in speed or acceleration (burst acceleration) or an ability to "dodge" through advance suspension control (DARPA, 2014). The intent and benefit for the development of advanced vehicle agility for military vehicles is to reduce the requirement of armor-based survivability and to increase efficiency through