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Modeling of steady-state performance of skid-steering for high-speed tracked vehicles

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Abstract

This paper presents a high-fidelity, general, and modular method for lateral dynamics simulation of high-speed tracked vehicle. Based on classic terramechanics, a novel nonlinear track terrain model is derived. The track terrain model meets the needs of longitudinal and steering motions, comprehensive track slips, and modular modeling for tracked vehicles with various configurations. The proposed lateral dynamics model is in reasonably agreement with the available experimental data. Using the lateral dynamics model, the main factors (normal pressure distribution, position of gravity center, and ratio of track-ground contact length and tread L/B) effecting the steady state characteristics of skid steering are discussed. The normal pressure distribution is idealized as trapezoid and dual trapezoid distribution to reflect same common driving situation. The under-steer parameter is introduced in this paper to quantitatively evaluate the steady-state characteristics of skid steering for tracked vehicle. The results show that the ratio of theoretical speed difference and average speed of both side tracks $\Delta u/u$ as the steering input is more suitable for the high-speed tracked vehicle. The vehicle with dual trapezoid normal pressure distribution slightly tending to localize in the middle of track or with slightly rearward position of gravity center has better handling stability characteristics.

Keywords: Tracked vehicle; Unmanned vehicle; Skid steering; Lateral dynamics; Steering characteristics

1. Introduction and related research

Tracked vehicles have great mobility, traversability, and payload carrying capacity on extremely difficult terrain that wheeled vehicles haven't (Hohl, 2007). They have been widely used in many fields such as unmanned/manned military, agriculture and construction operations (Wong, 2008; Wong et al., 2015; Janarthanan et al., 2011). Whether wheeled or tracked vehicles, steering characteristics is a primary research field in their design, manufacture, test, and control. In recent years, steering characteristics is widely concerned in the unmanned ground vehicles research field, because it has large impact on the motion planning and path tracking, especially in high-speed operation (Urmson et al., 2008; Genya et al., 2007). Researchers have broadly studied the lateral dynamics of wheeled vehicle and made a great number of achievements (Gillepie, 1992; Pacejka, 2006; Vantsevich, 2015). These achievements have formed a complete theoretical system to support the development of high-speed wheeled vehicle. In contrast, there are not enough researches on lateral dynamics of tracked vehicles to support the development of high-speed tracked vehicles.

The initial research on steering characteristics of tracked vehicle was presented by Merritt (1939), who assumed that the forces generated between the track and terrain obey the

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Nomenclature

Δu	velocity difference
ϕ	terrain internal friction angle
φ	heading angle
ω	yaw velocity
ω_s	rotating angular speed of sprocket
ω_t	yaw angular velocity of track coordinate system
θ	the angle between the comprehensive absolute velocity and the longitudinal direction of the track coordinate system
δ	longitudinal slips of track
τ	the shear stress on an element of the track-ground interface
κ	under-steer parameter
b	width of track
B	tread of vehicle
c	terrain cohesion
dF	shear force developed on track element dA
dA	area of track element
F_y	lateral force acting on the track
F_x	longitudinal force acting on the track
h	height of center of gravity
I_z	rotational inertia about z axis of vehicle
j_x	shear displacement along the x_t direction at point (x_t, y_t)
j_y	shear displacement along the $y_t$direction at point (x_t, y_t)
j	resultant shear displacement at the point (x_t, y_t)
K	terrain shear deformation modulus
k	concentration factor of normal pressure distribution
k_2	front and rear distribution factor
L	track-ground contact length
l_x	longitudinal offset of center of gravity to the geometrical center of the vehicle
m	mass of vehicle
M_r	turn resistance moment acting on the track
$p(x_t, y_t)$	normal pressure distribution on the track
r	radius of sprocket
R	turning radius
$s(x_t)$	the normal distribution density function on the track
t	duration of track element from contacting the ground initially to point (x_t, y_t)
u	Actual forward velocity of vehicle
u_t	longitudinal velocity of the track coordinate system
u_r	theoretical driving velocity of vehicle
v	Actual lateral velocity of C.G.
v_t	lateral velocity of the track coordinate system
V_y	relative velocity component of arbitrary point (x_t, y_t) on the track-ground interface in the y_t direction
V_x	relative velocity component of arbitrary point (x_t, y_t) on the track-ground interface in the x_t direction
W	gravity of vehicle
W_L	normal load on left track
W_R	normal load on right track
xyz	body fixed coordinate system with origin at the C.G.
$x_t y_t z_t$	track coordinate system is fixed on the center of track-ground interface and moves with vehicle
XYZ	global coordinate system

law of Coulomb friction. Subsequently, many researchers established kinds of dynamic models and obtained many innovative conclusions, taking different factors and assumptions into consideration. Micklethwait (1944) presented the friction between the track and terrain is anisotropic in the longitudinal and lateral directions. Hock (1961) and others introduced some empirical formulas to characterize the phenomenon that the lateral friction coefficient decreases with the increase of the turning radius. Crosheck (1975) introduced the pull-slip equation to describe the interaction of track and terrain. In order to find out the adequate vehicle model for the control of PAISI tracked vehicle test system, Ehlert et al. (1992) used the tank Jaguar to do some test. Based on test results, he modified the Hock model, IABG model, and Kitano model and finally found out an adequate model. Wong and Chiang (2001) presented a general theoretical steady-state model of tracked vehicles, considering the shear stress-shear displacement relationship on the track-terrain interface. The purpose of above-mentioned researches is to predict steering ability of tracked vehicle and estimate the load on the steering mechanism of tracked vehicle.

Kitano and Kuma (1977) established a theoretical non-stationary model based on pull-slip equation to analyze and predict steady-state and transient steering response of tracked vehicle on different velocity. In the same way Janarthanan et al. (2011) developed a 5 DOF non-stationary model to study the handling behavior at high or low speeds employing different types of steering input. Base on the law of Coulomb friction Purdy and Wormell (2003) established the mathematical model of CVR (Combat Vehicle Reconnaissance) tracked vehicle to analyze the steering performance. Similar with tires model in lateral dynamics of on-road wheeled vehicle, the track-terrain interaction model is the mechanical foundation of dynamics model of tracked vehicle, which directly influences the accuracy of tracked vehicle simulation, particularly the lateral mechanics. Above-mentioned track-terrain models have different lateral shear stress distributions along the longitudinal direction, which may have significant effects