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Investigation on cornering brake stability of a heavy-duty vehicle based on a nonlinear three-directional coupled model

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A B S T R A C T

A nonlinear three-directional coupled lumped parameters (TCLP) model is proposed for a heavy-duty vehicle to investigate the longitudinal, lateral and vertical dynamics of vehicles simultaneously. The nonlinear property of suspension damping is described by a fitted exponent model from experimental data. The nonlinear tire forces in different directions are modeled by the nonlinear Gim model and the vertical single dot contact model with square nonlinearity. The system responses are calculated by numerical integration and compared with the Functional Virtual Prototyping (FVP) model and the test data, so as to verify the validity of this new vehicle model. With Lateral-Load Transfer Ratio (LTR) and yaw rate as evaluation indexes, the influences of system parameters on cornering brake stability are analyzed. The critical vehicle speed table is also obtained. The study shows that high vehicle running speed, large front wheel steering angle, large tire cornering stiffness or small braking moment is harmful to yaw stability and roll stability. Road surface frictional coefficient mainly influences yaw stability, and vertical tire stiffness and road surface roughness mainly influence roll stability.

1. Introduction

At present, vehicle dynamics is divided into three fields including vertical dynamics, lateral dynamics and longitudinal dynamics. The vehicle vertical dynamics researches smooth running and ride comfort of vehicles, which is mainly related to vertical, pitch and roll movements caused by vertical tire forces. The vehicle lateral dynamics studies handling stability and only involves yaw, lateral, side-slide or drift movements resulted from lateral tire forces. The vehicle longitudinal dynamics mainly researches driving or braking property, such as drive slip or brake slip induced by longitudinal tire forces. In order to reduce difficulties and workload in analysis and calculation, scholars built models respectively as to vertical dynamics, lateral dynamics and longitudinal dynamics neglecting certain trivial movements. This independent study method has been playing an important role in vehicle dynamics for many years and achieved a lot of research results. However, under complicated driving conditions including lane change, cornering brake, or barrier avoidance, not only vertical force but also lateral and longitudinal forces are generated between road surface and tires, which cause vehicle movements in different directions. In this case, the vertical, lateral and longitudinal vehicle dynamics are coupled and interacted obviously.

With the wide application of heavy-duty vehicles in highway transportation, the dynamics and stability of heavy-duty vehicles have attracted more and more attention. With bigger inertia, longer wheelbase and higher roll center than cab

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cars, heavy-duty vehicles show much poorer handling stability and stronger movements coupling when steering or braking. As a result, some instable dynamic phenomena are easy to occur such as drift, violent spin, and rollover. In addition, the nonlinearity of tire and suspension in heavy-duty vehicles should not be neglected. Thus it is quite necessary to establish a nonlinear three-directional coupled model for heavy-duty vehicles and research the three-directional vehicle dynamics simultaneously.

In recent years, many coupled vehicle models have been set up and may be divided into four classes including longitudinal–lateral coupled models, lateral–vertical coupled models, longitudinal-vertical models and three-directional coupled models. (1) The longitudinal–lateral coupled models neglect vertical, pitch and roll movements of vehicles and pay attention to cooperative control of steering and driving\ braking performance. Lim [1,2] studied the coupling effects of lateral and longitudinal motions and found that the longitudinal acceleration may change lateral tire forces. Watanabe [3] proposed a longitudinal–lateral coupled model for a multi-axle vehicle and analyzed the effects of running speed, steering angle and drive system on steering and driving performance. Li [4] presented a new comprehensive driver model for critical maneuvering conditions based on a 3-DOF (degree of freedom) longitudinal–lateral coupled model. Cui [5] designed a longitudinal–lateral coupled controller to make vehicles perform path following in the case of straight or curve roads. (2) Assuming that vehicles run at a constant speed, the lateral–vertical coupled models research the handling stability and ride comfort when vehicles steer. Using a lateral–vertical coupled model, Karbalaei [6] studied the integrated control of electric power steering and semi-active suspension in order to improve vehicle handling stability and ride comfort simultaneously. Jo [7] designed a yaw rate controller to enhance vehicle steering ability, lateral stability, and roll stability through brake force assignment. Kim [8] presented a roll motion control of a vehicle based on the 3-DOF vehicle model considering lateral, yaw and roll movements. (3) The longitudinal-vertical models assume that vehicles driving on straight lines and don't consider vehicles' steering and sliding movement. However, unreasonable driving/braking property may lead to slide, drift or direction lost, which is related to lateral dynamics. Consequently, few scholars investigate vehicle dynamics based on the longitudinal-vertical models. (4) The three-directional coupled models are able to investigate vehicle handling stability, ride comfort and driving/braking property simultaneously and often used to study vehicle responses in complex driving situations. Cebon and Cole [9–11] presented two three-dimensional whole vehicle models of heavy vehicles with 14-DOF and 21-DOF, and investigated the effect of heavy vehicle parameters on dynamic tyre forces and road damage. However, they didn't consider the effect of braking or turning on vehicle dynamics. Chou and Poussot-Vassal [12,13] established a 14DOF nonlinear vehicle model and designed a global chassis control strategy using active suspension and brake torque. But their model only considered the coupling effects of lateral-longitudinal, lateral-roll and longitudinal-pitch movements, neglecting the coupling effects between vertical and other movements. Guo [14] researched vehicle stability of cornering brake based on a 12-DOF three-directional coupled model of a two-axle vehicle, but didn't consider the vertical vibrations of unsprung masses. As so far, some three-directional coupled models of two-axle vehicles have been presented, but there are few studies on the three-directional coupled model of multi-axle heavy-duty vehicles.

With the rapid development of multi-body dynamics and computer technology, the Functional Virtual Prototyping (FVP) model attracts scholars' attention [15–17]. Because of being able to reflect vehicle structure in detail and simulate vehicle responses in different driving conditions, FVP models have been used in automotive industry widely and some commercial softwares come forth such as ADAM, SIMPACK and so on. However, the numerical algorithms and driving situations are embedded in the commercial software and might not be suitable to research some specific problems. For example, ADAMS/car is a specialized environment for modeling vehicles. It allows one to create assemblies of suspensions and full vehicles with subsystems and simulate different driving situations easily. However, the angle step, lane change, and stable turn embedded in ADAMS/car neglect road surface roughness and have limitations for studying combined effects of steer angle, brake torque and road roughness excitation on vehicle's three-directional dynamics. In order to meet the needs of users, one has to redevelop the software. In addition, an FVP vehicle model needs a large quantity of vehicle parameters, including geometric size, assembling positions, material and connecting properties of vehicle components, and types of kinematic pairs and constraints. Since it is quite difficult for researchers to acquire so many parameters, some parameters have to be guessed and are probably incompatible, which may lead to lower computational efficiency or even diverging results. On the other hand, the three-directional coupled lumped parameters (TCLP) vehicle model is able to obtain vehicle dynamics essentially and consider coupling effects of different movements with much fewer input parameters. Moreover, represented with ordinary differential equations, the TCLP model can be solved numerically with Matlab, Fortran or other languages. Since the procedure can be compiled to *.exe file and costs much less computer memory than the commercial software, the TCLP model has much higher computational efficiency than FVP model. Assembled by many subsystems and vehicle components, an FVP model created in ADAMS/car usually contains more degrees of freedom than a TCLP model, which also leads to a lower computational speed. As a special case, one can generate an FVP model with exactly the same degrees of freedom as the TCLP model based on ADAMS/view, the basic module of ADAMS. But ADAMS/view doesn't conclude the driver model and running route input tool. In order to simulate different driving situations, one usually redevelops a subprogram with Matlab/Simulink and gets vehicle responses through ADAMS-Matlab co-simulation, which will slow down the computational speed further more.

In the authors' previous work [18], a modified preview driver model with nonlinear time delay was proposed and connected with a nonlinear three-directional coupled lumped parameters (TCLP) vehicle model. Then the directional control and driver behavior when the vehicle making a lane change, were researched. However, with the deepening of the research, the authors have realized that the superiority of TCLP model lies in that it is able to simulate the full-vehicle dynamics