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Combination of active braking and semi-active suspension systems to improve the roll and yaw vehicle stability

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ABSTRACT: This paper presents a combined use of active chassis systems to enhance vehicle roll and yaw stability using semi-active suspension and active braking systems. The designed active braking system based on sliding mode control reduces the probability of vehicle rollover by decreasing the longitudinal velocity and lateral acceleration. Also, a semi-active suspension is proposed through fuzzy control method to improve the vehicle roll stability, which attenuates the effect of lateral acceleration on roll angle and roll rate. The lateral load transfer ratio is selected as the rollover index based on roll angle and lateral and roll accelerations. A vehicle dynamics model is built in the ADAMS environment, which includes subsystems of steering, braking and front and rear suspension, tire model and body. Also, the nonlinear characteristics of tires, bushings, springs and dampers are considered in the model. So, it can accurately express the dynamics performance of the vehicle. The control algorithm is evaluated under step steer and lane change maneuvers utilizing MATLAB and ADAMS co-simulation. Simulation results show that the proposed system with combined controllers can effectively improve the vehicle yaw stability and the rollover prevention compared with the only active braking and semi-active suspension systems.

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1. Introduction

Recently, vehicle safety is one of the most important topics for sale market in the automotive technology. Vehicle dynamics research indicates that the main causes of severe accidents are the vehicle yaw, lateral and roll instabilities [1]. In the recent decade, vehicle dynamics researchers have presented an approach called "integrated vehicle dynamics control." The main task of such systems is coordination between all chassis control subsystems to enhance the overall vehicle performance, involving safety and comfort. Many studies have been performed for research and development of integrated vehicle dynamics control systems [2-5].

A multi-layer hierarchical control structure designed to integrate active front steering and active rear braking systems to improve the yaw stability. The control strategy was based on combined method of H-infinity, linear parameter varying and linear matrix inequality [3]. The multilayer control structure was used to improve the yaw stability and integrated control of the chassis for fully electric vehicles. In order to better track the desired outputs, the Sliding Mode Control (SMC) method was adopted and to get closer to reality, the driver's behavior was also modeled [4]. Coordination of active front steering system and Direct Yaw-moment Control (DYC) to improve vehicle handling characteristics is a topic discussed in reference [5]. Rahimi et al. proposed a fuzzy logic-based strategy for coordinating active steering, active differential, active braking and active anti-roll bar subsystems with the aim of improving the vehicle yaw and roll stability [6].

In most of the mentioned papers, researchers have investigated the integrated vehicle stability control systems, including four-wheel steering, active front or rear steering, active braking, and active roll angle control. They pay less attention to the integration of Semi-Active Suspension (SAS) and vehicle stability control systems. It is worth mentioning that in this regard, the integrated control of SAS and four-wheel steering systems by the method of robust optimal control studied and a full vehicle model with eleven Degrees Of Freedom (DOF) utilized for simulation [7]. In almost all studies in this field, lumped mass models of vehicles with 7, 8 or 14 DOF were used. These models do not specify the characteristics of nonlinear, bushes, springs and dampers. However, researchers designed anti-lock brakes and active braking systems to reduce the stopping distance and increase the lateral stability, respectively using co-simulation of MATLAB and ADAMS software [8-10]. In each of the papers, only one active safety system is analyzed separately without using the combination of chassis control systems. For this reason, in this research for the first time, the combined control of SAS and active built-in ADAMS software and the control algorithm is evaluated utilizing the co-simulation of MATLAB and ADAMS software.

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2. Vehicle Dynamic Model

In this paper, to analyze the dynamic response of the vehicle, a full vehicle model is used in ADAMS/CAR software. The front suspension is of a Mc-pherson type, anti-roll bar which has been modeled by flexible beams. The vehicle rear suspension is of a compound type (torsion beam axle). For steering system, a rack and pinion as conventional system is chosen. To design the control system of active Differential Braking System (DBS) in order to utilize the full vehicle model in ADAMS software, a non-linear full vehicle model with 14-DOF, including the longitudinal, lateral, vertical, roll, pitch and the yaw motions of the vehicle body, vertical jump and the rotation of four wheels is established.

3. Control System Design

Controller design includes two parts, DBS and SAS. The DBS based on DYC method is proposed to force the vehicle to track a desired predefined yaw rate while keeping the vehicle sideslip angle as small as possible. The desired sideslip angle is assumed zero. The corrective yaw moment, M_{zc}, required to counteract the undesired yaw motion, is created by the DYC system through the DBS by assigning a proper slip ratio to each wheel. The control system consists of two layers. The upper-layer controller determines the M_{zc} value using the SMC in order to track the desired yaw motion. Thereafter, the lower-layer controller computes the required longitudinal tire force to create the M_{zc}, and then according to the Fx-λ curve of non-linear tire model, the desired slip ratio (λ_d) is obtained by interpolation method. Finally, the brake torque is generated through the SMC to maintain the slip ratio near the λ_d as follows:

$$T_{bi} = -R_\omega F_{XW} - \frac{I_\omega a_{xw}\omega_i}{v_x} + \frac{I_\omega v_x k_b e_b}{R_\omega} \tag{1}$$

$$+\frac{I_\omega v_x}{R_\omega}\eta_b \, sat(s_b) \quad (\eta_b > 0) \tag{2}$$

$$e_b = \lambda - \lambda_d$$

$$s_b = e_b + k_b \int_0^t e_b dt \; ; \quad (k_b > 0) \tag{3}$$

where, ω_i is the angular velocity of each wheel, T_{bi} is the active braking torque, v_x is the longitudinal vehicle velocity, αxw is the longitudinal wheel acceleration, F_{xw} is tire-road longitudinal force, R_w is the wheel radius, sat(.) describes saturation function and Iw defines the wheel inertia moment.

For the design of the SAS, a fuzzy controller is applied to reduce the vertical tire deflection. The corner sprung mass velocity and the relative velocity between the sprung and un-sprung mass are considered as fuzzy system input and its output is the control force of SAS. Five linguistic variables and easily calculated triangle membership functions are selected for both the input and output. Table 1 shows the fuzzy rules of the roll stability improvement strategy, where, NB, NS, ZE, PS, PB represent 'negative big', 'negative small', 'zero', positive small' and 'positive big', respectively. A Mamdani method is employed in the fuzzy reasoning based on Table 1 whereas max-min inference method is chosen as aggregation operator, and defuzzification is performed using the center-average method. According to Fig. 1, co-simulation model of combination control of active braking and semi-active suspension systems is built using Simulink and ADAMS software.

Table 1. The fuzzy rules of SAS system [11]

Control force of SAS		Relative velocity ($\dot{z}_{su} = \dot{z}_s - \dot{z}_u$)				
		NB	*NS*	*ZE*	*PS*	*PB*
$\dot{z}_s$	*NB*	*PB*	*PB*	*PB*	*ZE*	*ZE*
	NS	*PB*	*PB*	*PS*	*ZE*	*ZE*
	ZE	*PB*	*PS*	*PS*	*ZE*	*NS*
	PS	*PS*	*PS*	*ZE*	*NS*	*NB*
	PB	*ZE*	*ZE*	*ZE*	*NS*	*NB*

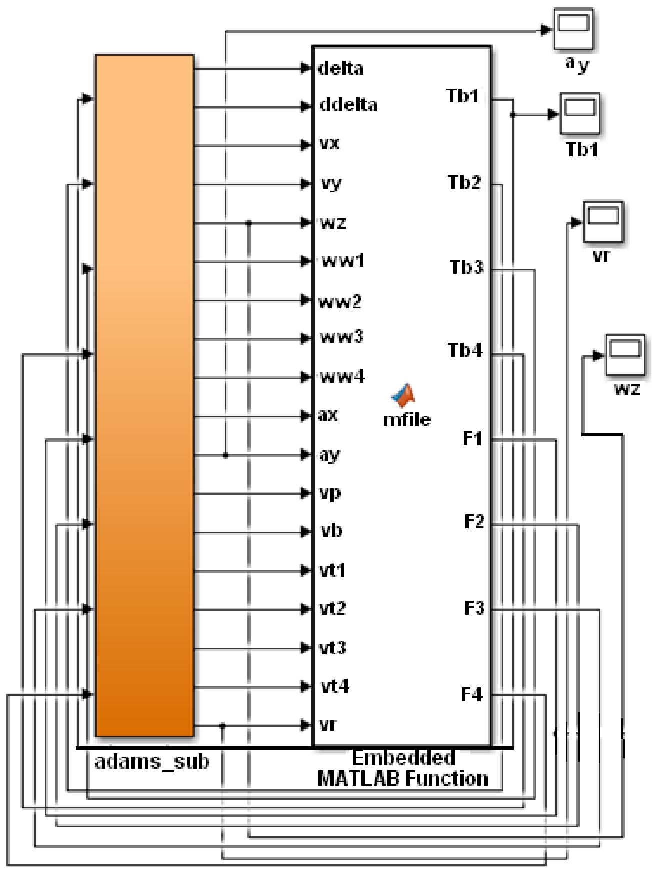

Fig. 1. Co-simulation model of combined control of chassis system

Table 2. The Maximum value and RMS of tracking error of yaw rate for step steering input maneuver

Control strategy	Error maximum (rad/s)	Error RMS (rad/s)
Passive	0.137	0.124
AB only	0.03	0.015
AB with SAS	0.019	0.006

Table 3. The Maximum value and RMS of tracking error of yaw rate for lane change maneuver

Control strategy	Error maximum (rad/s)	Error RMS (rad/s)
Passive	0.335	0.181
SAS only	0.357	0.188
AB only	0.042	0.023
AB with SAS	0.016	0.009

4. Simulation Results

Simulation of step steering input and lane change maneuver is utilized to evaluate the effectiveness of the proposed control system in the lateral and roll stability. The vehicle runs at an initial velocity of 25 m/s on a B class of road. To evaluate the performance of the control systems, the passive system, active braking system alone (AB only), SAS alone (SAS only), active braking system with semi-active suspension (AB with SAS) are simulated. In Table 2, the values of Root Mean Square (RMS) and maximum of error are applied to compare the active chassis systems for step steering input.

Table 3 shows the values of RMS and maximum of error to compare the active chassis systems for lane change maneuver.

5. Conclusions

In this research, the combination of active chassis subsystems is presented to improve the yaw and roll stability using the SAS and the AB systems based on a validated full vehicle model in ADAMS software. The AB system causes the reduction of vehicle rollover probability by decreasing the longitudinal velocity and lateral acceleration. Since the vehicle's normal tire forces affect the lateral and longitudinal ones, control of vertical tire forces through the SAS can enhance the vehicle handling and stability performance. The lateral load transfer ratio based on roll angle and lateral acceleration was chosen as rollover index. The control algorithm was evaluated under maneuvers of step steering input and lane change utilizing the co-simulation of Simulink and ADAMS software. The simulation results demonstrated the effectiveness of proposed control system for combined active chassis subsystems than the only AB system to track the desired yaw rate, accurately, reduce the lateral load transfer ratio, improve the vehicle yaw stability and also prevent the rollover.

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