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A new strategy for minimum usage of external yaw moment in vehicle dynamic control system

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ABSTRACT

Due to the loss of vehicle directional stability in emergency maneuvers, a new complete desired model for vehicle handling based on the linear two-degrees-of-freedom (2DOF) model and tire/road conditions is presented to be tracked by the direct yaw moment control (DYC) system. In order to maintain the vehicle actual motions, yaw rate and side-slip angle, close to the proposed desired responses without excessively large external yaw moment, a complete linear quadratic (LQ) optimal problem is formulated and its analytical solution is obtained. Here, the derived control law is evaluated and its different versions are discussed. It is shown that the side-slip tracking by DYC is more effective than the yaw rate control to stabilize vehicle motions in nonlinear regimes. Also, optimal property of the control law provides the possibility of reducing the external yaw moment as low as possible, at the cost of some admissible tracking errors. Simulation studies of vehicle handling, with and without control, have been conducted using a full nonlinear vehicle dynamic model. The results, obtained during various maneuvers, indicate that when the proposed optimal controller is engaged with the model, improvements in the handling performance through a reduced external yaw moment can be acquired.

1. Introduction

Direct yaw moment control (DYC) system is the latest active safety technology introduced to control vehicle directional stability under emergency situations. In a turning maneuver with high lateral acceleration where tire forces are approaching to or at the physical limit, i.e. the limit of road adhesion, the vehicle side-slip angle grows and the effectiveness of vehicle steering angle in generating yaw moment becomes significantly reduced because of tire force saturation. This fact is first illustrated by the so-called β-method (Shibahata et al., 1993). The decrease of restoring yaw moment generated by tire lateral force when the side-slip angle increases is the basic cause of vehicle unstable motion called spin motion and adding yaw moment will recover the vehicle stability.

A practical approach to generate a required external yaw moment, independent of lateral forces and steering angle, is the transverse distribution of the vehicle braking force between the left and right wheels. This strategy known as differential braking can be achieved using the main parts of common anti-lock braking system (van Zanten et al., 1998).

It is shown that DYC is the most effective method on vehicle motion control compared with the other conventional control systems such as four wheel steering (4WS) (Abe, 1999; Selby et al., 2001). The 4WS control, which depends on the relation between tire lateral force and the steer angle as a control command, is efficient in a range where the lateral acceleration is low. But, in high lateral accelerations, as mentioned before, the steer input loses its direct effectiveness on tire lateral force and thus on the yaw moment. Therefore, the lateral dynamics parameters, yaw rate and side-slip angle, can no longer be controlled by the steer command.

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Despite the high efficiency of DYC in a wide range of operation, the external yaw moment, as the control input of DYC, should be kept as low as possible because of its some undesirable effects. It slows down the vehicle because a corrective yaw moment is applied to the vehicle through the brakes. This effect must be kept to a minimum so that the driver can feel supported rather than overruled. Further to this, tire life is also shortened because of extra braking. One of the recent approaches to limit the excessive use of external yaw moment is integrating and coordinating DYC and 4WS (Selby et al., 2001).

The present study investigates the other effective approach reducing the external yaw moment for stabilizing vehicle handling dynamics. First, a suitable desired model for vehicle handling is developed to be tracked by DYC system. Then, considering some admissible tracking errors, an optimal yaw moment control law is developed to reduce the external yaw moment as much as possible by adequately following the behavior of the desired model. In this way, the calculated external yaw moment can also remain below the maximum admissible value determined by the maximum difference in the longitudinal forces that can be generated by the left and right wheels during every cornering maneuver.

Basically, the yaw rate and side-slip angle are taken as the two controlled variables for vehicle handling. Depending on which variable is controlled, different control types of DYC have been proposed. The yaw rate control by DYC has been studied frequently (Esmailzadeh et al., 2003; Mokhiamar and Abe, 2006; Mirzaei et al., 2008). Some researchers have used the side-slip control type of DYC (Abe, 1999; Abe et al., 2001; Eslamian et al., 2007). However, both variables have been controlled simultaneously by DYC (Zheng et al., 2006; Park et al., 2001; Ghoneim et al., 2000). In the above studies, several control theories with various reference models have been employed.

In both side-slip control and yaw rate control by DYC, the desired (reference) models of these variables should be established according with driver steering commands and tire/road conditions. The precise desired model not only results the enhanced performance but also prevents the use of extra control effort. Several researchers have used the steady-state behavior of linear vehicle model during a cornering maneuver as a desired model for the yaw rate (Esmailzadeh et al., 2003; Zheng et al., 2006; Bang et al., 2001). The desired side-slip angle has been considered as zero in their studies. van Zanten (2000) pointed out that on dry asphalt the physical limit in which the vehicle shows unstable motion, is reached at a slip angle of approximately ±12°, while on icy roads this value is about ±2°. These models do not include the transient response for vehicle motions and therefore make large tracking errors at the beginning of maneuvers. In the other researches, a linear 2DOF vehicle plane model (bicycle model) has been adopted as a desired model to be followed by the controller (Mokhiamar and Abe, 2006; Ghoneim et al., 2000). Although the linear bicycle model shows a stable motion, it is unable to predict the tire/road conditions. In the present study, a complete desired model for vehicle handling based on the linear 2DOF model and tire/road conditions is presented.

On the other hand, there are several control methods for tracking the desired model by DYC in the literature. Ghoneim et al. (2000) introduced a feedback control using yaw rate with proportional-derivative (PD) structure. They further enhanced the performance of PD yaw rate control with a full state feedback utilizing both yaw rate and side-slip angle. Another yaw rate control type of DYC has been presented using proportional-integral-derivative (PID) control method (Bang et al., 2001). Sliding mode control method has been also employed in finding the yaw moment control law (Abe, 1999; Abe et al., 2001; Mokhiamar and Abe, 2006). In these methods, the optimization is not used as a main procedure in finding the control laws. A predictive optimal yaw stability controller based on a linearized vehicle model which was discretized via a bilinear transformation has been developed by Anwar (2005). Some researches have developed the well-known LQ theory to improve vehicle handling and stability (Park et al., 2001; Zheng et al., 2006). These studies use on-line numerical computations in optimization which are not suitable for implementation. Esmailzadeh et al. (2003) have presented an analytical solution for LQ problem, but their proposed control law is based on tracking only the reference yaw rate obtained by the steady-state behavior of vehicle during a cornering maneuver. Another yaw rate control by DYC has been developed by a predictive optimal approach (Mirzaei et al., 2008). The same approach has been employed for the side-slip control type of DYC (Eslamian et al., 2007). In the present paper, a complete LQ optimal problem is formulated to track the proposed new desired models for both yaw rate and side-slip angle. The derived control law is developed in an analytical closed form which is easy to solve and implement. Also, the different control types of DYC are examined and the effect of weighting factors on the control system performance is further investigated.

2. Vehicle system dynamics

2.1. Vehicle model for simulation

In order to accurately predict the vehicle response during various maneuvers, simulation studies have been conducted using a comprehensive vehicle dynamic model. In this respect, an eight-degrees-of-freedom vehicle model which has been previously developed and validated by experimental results (Smith and Starkey, 1995) has been used as the vehicle plant model. The longitudinal velocity, lateral velocity, yaw rate, roll rate and rotational speeds of four wheels constitute the degrees of freedom for this model. Therefore, the saturation property of tire lateral force at high slip angle, the effects of normal load transfer on the balance of the front and rear tire lateral forces, the roll steer, the roll camber and other characteristics which influence vehicle stability in reality are considered for simulation.

Since, the nonlinear 8DOF vehicle model described above is too complicated for use in control system design, a simpler vehicle model referred to as the design model has to be employed for the controller design. In this paper, according to the LQ