Transportation Research Part C 24 (2012) 19–35

Contents lists available at SciVerse ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Optimal design of a non-linear controller for anti-lock braking system

Mehdi Mirzaei *, Hossein Mirzaeinejad

Research Laboratory of Mechatronics and Vibrations, Faculty of Mechanical Engineering, Sahand University of Technology, Tabriz, Iran

ARTICLE INFO

Article history:
Received 15 December 2010
Received in revised form 18 January 2012
Accepted 20 January 2012

Keywords:
Anti-lock brake system
Non-linear control
Optimal design
Optimum wheel slip

ABSTRACT

The most effective chassis control system for improving vehicle safety during severe braking is anti-lock braking system (ABS). In this paper, a nonlinear optimal controller is analytically designed for ABS by the prediction of the wheel slip response from a continuous nonlinear vehicle dynamics model. A new reference model for the wheel slip, which considers the effects of variations of tire normal load and tire/road condition, is proposed to be tracked by the controller. The main properties of the designed controller are evaluated and discussed by considering the important practical aspects of the slip control problem. The performed analysis along with the simulation results indicate that the designed controller with different special cases can successfully cope with the strong nonlinearity and realistic uncertainties existing in vehicle dynamics model. Meanwhile, a compromise between tracking accuracy and control energy can be easily made by the regulation of the weighting ratio, as a free parameter in the optimal control law.

1. Introduction

Recently, the development of chassis control systems for improving vehicle active safety has generated considerable interest in research community and automotive industries. Among these systems, the anti-lock brake system (ABS) is used to directly control the longitudinal dynamics of vehicle during braking (Furukawa and Abe, 1997).

The basic function of an ABS is to prevent the wheel form locking, and to regulate the longitudinal slip of the wheel at its optimum value in order to generate the maximum braking force. This permits the vehicle to achieve the shortest stopping distance during braking and at the same time improves the vehicle directional control and stability indirectly. In another application, since the ABS can regulate the longitudinal force acting independently on each wheel, it is used in the lower layer of vehicle dynamic control (VDC) system. In this system, the vehicle braking force is transversely distributed between the left and right wheels in a way that the external yaw moment required for stabilizing vehicle lateral dynamics is generated (van Zanten et al., 1998; Mirzaei et al., 2008). This strategy known as differential braking can be provided by the main parts of common anti-lock braking system.

The hard nonlinearities and modeling uncertainties existing in vehicle dynamics are the two main difficulties arising in the design of ABS controller. The first one is as a result of tire force saturation and the next one is mainly due to variations of road condition and vehicle parameters such as mass, center of gravity of the vehicle. Also, the un-modeled dynamics neglected in the course of modeling together with other practical limitations are considered as the un-structured uncertainties. A suitable controller for the ABS should successfully handle the nonlinearities and uncertainties existing in the vehicle model. On the other hand, the control law of ABS should be found in a way that the calculated control input, i.e. braking pressure, could be regulated easily so that one can keep it to the lowest possible value.

* Corresponding author. Address: P.O. Box 51335-1996, Sahand New Town, Tabriz, Iran. Tel.: +98 412 3444310; fax: +98 412 3444309.
E-mail addresses: mirzaei@sut.ac.ir, mehdi-mirzaei@hotmail.com (M. Mirzaei).

doi:10.1016/j.trc.2012.01.008

It is concluded from the above discussion that a non-linear controller with suitable robustness should be designed in an optimal way for the ABS. Many researchers have frequently applied the sliding mode control methods to ABS because of their potential to cope with nonlinearities and intrinsic robustness (Lin and Hsu, 2003; Unsal and Kachroo, 1999; Drakunov et al., 1995; Lee and Zak, 2002; Kazemi et al., 2000; Harifi et al., 2008; Park et al., 2006; Zheng et al., 2006; Song et al., 2007; Buckholtz, 2002). In these methods, the optimization is not used as the main procedure in finding the control law. Also, the chattering phenomenon is the undesirable effect of the sliding control in practice. Different techniques are introduced to reduce the chattering (Unsal and Kachroo, 1999; Harifi et al., 2008; Slotine and Li, 1991). In these methods, the discontinuous control law is smoothed to achieve a trade-off between control bandwidth and tracking precision. Also, some approaches such as higher order sliding mode controls (HOSM) can reduce the chattering and provide the higher accuracy than the conventional sliding modes. But they require higher control efforts and also the derivative of the control input is appeared in the derived control law (Bartolini et al., 1998).

In the following, the most important control methods used for the anti-lock braking systems are reviewed. Unsal and Kachroo (1999) used the sliding mode control to regulate the wheel slip at its optimum value. In their study, a PI-like controller was used near the switching surface instead of sign function to reduce chattering. Harifi et al. (2008) designed a sliding mode controller for ABS and used the integrated switching surface instead of sign function to reduce chattering. In this work, they had to find the proper bound of parametric uncertainties used in the designed control law. In another work, a fuzzy controller combined with the sliding mode control was introduced to reduce the dependency of controller on vehicle model (Lin and Hsu, 2003). Lee and Zak (2002) proposed a genetic neural fuzzy ABS controller that consists of a non-derivative neural optimizer and fuzzy-logic components. The non-derivative optimizer finds the optimal longitudinal wheel slip and then the fuzzy components compute the brake torque to track the optimal longitudinal wheel slip.

There are fewer optimal control laws for the ABS in the literature. Petersen (2003) designed a controller using gain scheduled LQR design method. A predictive optimal wheel slip controller based on a linearized vehicle model which was discretized via a bilinear transformation has been presented by Anwar and Ashraf (2002). These methods apply the linearized vehicle models and use on-line numerical optimization in finding the control law, whereas the use of non-linear model can broaden the valid range of operations as well as improve the accuracy of the controller. Also, numerical computation methods need online dynamic optimization and are not easy to solve and implement.

Generally, application of classic optimal control theories to the non-linear system requires that the derived non-linear two-point boundary value (TPBV) problem or Hamilton–Jacobi–Bellman (HJB) partial differential equations are solved. It is very difficult or even impossible to find an analytical solution for these problems.

In this paper, an optimal predictive approach is applied to design a nonlinear model-based controller for braking pressure. The proposed optimal control method is based on the predictive concept introduced by Lu (1995) for continuous nonlinear systems. In this method, a pointwise minimization performance index that penalizes the tracking error at the next instant, yet is not excessive, is used to find the current control input. The method analytically leads to a closed-form control law which is suitable to implement and the online numerical computations in optimization are not required (Lu, 1995; Mirzaei et al., 2008; Eslamian et al., 2007). In the development of this approach for the ABS, authors have already designed a nonlinear controller with increased robustness to track a constant wheel slip during braking for all road conditions (Mirzaeinejad and Mirzaei, 2010). In this earlier work, the weighting term of the control input is not included in the performance index to be minimized. In this case, referred to the cheap control, no limitation on the control input is assumed and the control law is obtained by minimizing only the tracking errors.

But, in the present study, the expensive control approach is considered. In this case, to achieve a minimum control effort and to make a compromise between the tracking error and control input, a complete optimization problem is defined. In this way, a weighted combination of tracking error and control expenditure is considered to be penalized in the performance index. Therefore, the optimal control law can be adjusted to keep the tracking error within the admissible range through the minimum control effort. At the rest, the main properties of the derived control law are analyzed and its different special cases are discussed. Following the performed analysis, the robustness of the proposed controller with respect to the important realistic uncertainties existing in practice is investigated. In this way, the effects of un-modeled dynamics and uncertain control gain due to fading the actuator dynamics are considered.

In another contribution of this study, a new reference model compatible with braking conditions is proposed for the wheel slip to be tracked by the controller. In this reference model, the variations of tire normal load and tire/road condition, which affect on the peak value of braking force, are considered. Also, according to the practical considerations, the new reference model is presented in a way that the slip controller is only active at the physical limits in which the wheel slip is beyond a threshold. As long as the slip resulting from the braking action of the driver is below the threshold, there is no control action. Tracking this model can generate the maximum braking force during braking on different roads and reduce the vehicle stopping distance remarkably.

It should be noted that the actual wheel slip is difficult to determine accurately due to a lack of practical means for directly measuring the linear speed of the tire center. Therefore, in many cases, the tire wheel slip is calculated from the estimated linear speed of the tire center and the measured angular speed of the tire, using various estimation methods (Ray, 1997; Gustafsson, 1997; Unsal and Kachroo, 1999). The estimation of road friction coefficient is also required to use in ABS controllers. The error caused by the estimation leads to some uncertainties which will be considered in the performance evaluation of the designed control system.