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Control Engineering Practice 14 (2006) 1011–1022
CONTROL ENGINEERING PRACTICE
www.elsevier.com/locate/conengprac

Modeling and control of a hydraulic unit for direct yaw moment control in an automobile

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Received 10 March 2004; accepted 11 June 2005
Available online 15 August 2005

Abstract

This paper deals with the feedback control of a hydraulic unit for direct yaw moment control, which actively maintains the dynamic stability of an automobile. The uncertain parameters and complex structure naturally call for empirical modeling of the hydraulic unit, which lead to a high-fidelity input/output model. The identified model is cross-validated against experimental data under various conditions, which helps to establish a stringent model uncertainty. Then, the H_∞ optimization technique is employed to synthesize a controller with guaranteed robust stability and performance against the model uncertainty. The decent performance of the synthesized controller is experimentally verified and the results show the viability of the proposed approach for real-world applications.

Keywords: Direct yaw moment control (DYC); Hydraulic unit; Empirical modeling; H_∞ optimization; Robust stability and performance

1. Introduction

The present automotive industry must cope with the ever-stringent demand for driver assistance systems since such features can prevent fatal accidents and protect passengers, objectives which are increasingly recognized in the market as a necessity rather than a luxury (Langwieder, Gwehenverger, Hummel, & Bende, 2003; Rieth & Schwarz, 2004). To reflect on such a trend, extensive research has been carried out on a variety of driver-subsidiary, active vehicle control methods to prevent vehicles from unstable operation. Although the following approaches are not all inclusive, they summarize recent achievements such as steering intervention by differential brakes, vehicle dynamics control (VDC), vehicle stability control (VSC), vehicle stability assist (VSA) as well as direct yaw moment control (DYC) (Pilutti, Ulsoy, & Hrovat, 1998; Van Zanten, Erhardt, Landesfeind, & Pfaff, 1998; Tseng, Ashrafi, Madau, Brown, & Recker, 1999; Yasui, Tozu, Hattori, & Sugisawa, 1996; Nishimaki, Yuhara, Shibahata, & Kuriki, 1999).

A DYC system maintains the rotational stability of a vehicle by applying independently controlled brake forces on the individual wheels and thus generating compensatory artificial yaw moment. The hydraulic unit controls the brake pressure in a DYC system and thereby, plays a key role in the directional stability of an automobile. Despite its practical significance, the lower level control of the hydraulic unit in a DYC system has not been fully addressed as extensively as its upper level counterpart for the overall vehicle dynamics (Van Zanten et al., 1996).

This paper presents a robust control strategy for a hydraulic unit for DYC. Robust control design begins with the building of a control-oriented mathematical model of the hydraulic unit. Although the control design of the hydraulic system is mostly based on the physical model linearized with respect to an equilibrium point

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0967-0661/$ - see front matter
doi:10.1016/j.conengprac.2005.06.002

(Zhang, Alleyne, & Prasetiawan, 2002), an empirical modeling approach (Ljung, 1999) is taken in this paper to obtain a black-box model that captures the prominent dynamics of the hydraulic unit essential to control design since its complex structure with multiple unknown parameters does not allow direct physical modeling of the hydraulic unit. By examining the fidelity of the empirical model under various conditions, a control-oriented model is established with corresponding uncertainty. Then, H_∞ optimization technique is employed to synthesize a feedback controller with guaranteed robust stability and performance (Skogestad & Postlethwaite, 1996; Doyle, Francis, & Tannembaum, 1992; Zhou & Doyle, 1998). The effectiveness of the proposed controller is experimentally verified to show its viability to real-world applications.

This paper is organized as follows. The overall operating principles of a DYC hydraulic unit and the experimental set-up are discussed in Section 2. Section 3 develops a control-oriented model of the hydraulic unit based on the system identification technique and examines its fidelity to establish the corresponding uncertainty. A robust controller is synthesized by using the H_∞ optimization technique in Section 4 and its performance is experimentally verified in Section 5.

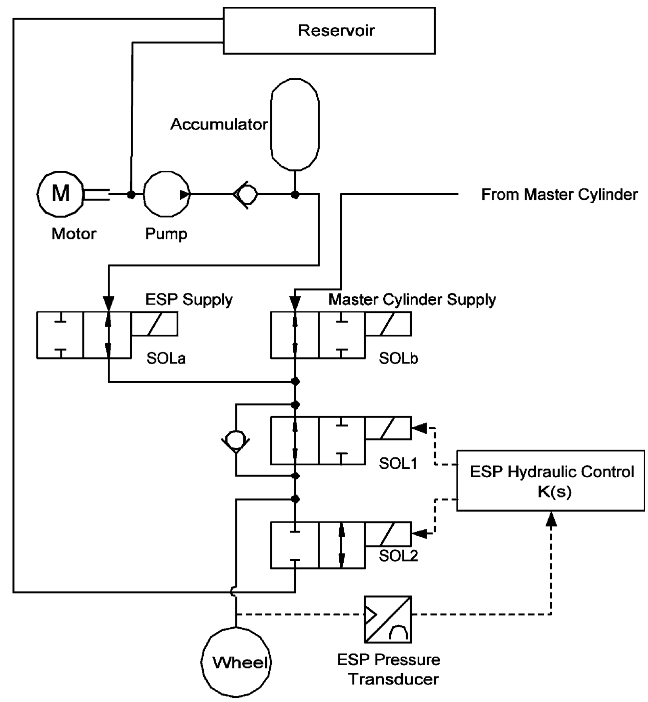

Fig. 1. Schematic diagram of the hydraulic unit for DYC.

2. Hydraulic unit for DYC

2.1. Operating principles

Fig. 1 shows the schematic diagram of a hydraulic unit for the brake pressure control in an individual wheel. The term 'SOL' in Fig. 1 is an abbreviation for a solenoid valve. The pressure at each of the brake chambers is formed by oil flows from two sources: the master cylinder through SOLb and the hydraulic pump for the DYC system through SOLa. In the absence of DYC, the oil flow only from the master cylinder is supplied to the brake chamber in response to the driver's brake pedal command. On the other hand, with DYC activated, the hydraulic pump also provides oil flow into the wheel in addition to the one from the master cylinder. In other words, the trigger of DYC incurs extra pressure increase/decrease on the brake chamber, which produces larger/smaller brake force at the corresponding wheel. With DYC as a primary concern of this paper, the valves SOLa and SOLb are manipulated in our experimental set-up (which is detailed in the following subsection) in such a way that the former is always open whereas the latter is always closed so that the wheel brake pressure is solely generated by the hydraulic pump.

In addition to SOLa and SOLb, there are two more PWM-type two-way solenoid valves that are used to control the pressure at the brake chamber: an NO-type (normally open) solenoid valve SOL1 and an NC-type (normally closed) solenoid valve SOL2. The valves SOL1 and SOL2 control the wheel brake pressure in a rather indirect way: they control the rate or variation (increment or decrement) in the brake pressure rather than the pressure at the brake chamber itself. Specifically, SOL1 regulates the amount of oil influx from the hydraulic pump to the brake chamber, while SOL2 manages that of oil discharge from the brake chamber to the reservoir. The absolute amount of pressure increment or decrement is determined by the PWM duty ratio signals of SOL1 and SOL2. It is noted that the duty ratio signals fed to SOL1 and SOL2 cannot be uniquely determined to realize a given pressure increment or decrement since SOL1 and SOL2 have counterbalancing effect on the resultant pressure variation. In order to circumvent this ambiguity and allow the controller (discussed in detail in Section 4) to determine a unique control, it is assumed throughout this paper that two solenoid valves SOL1 and SOL2 are never activated simultaneously. More precisely, the pressure increase is achieved by the activation of SOL1 only, and the pressure decrease by SOL2 only. Such an assumption greatly simplifies the control problem in this paper so that it may be cast into a SISO framework with the control input confined between –100% and +100%, where positive control input activates SOL1, and negative control input, SOL2.

The ultimate objective of this paper is to synthesize a feedback controller that enables the hydraulic unit to track the desired pressure command from the upper