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LPV feedforward control of semi-active suspensions for improved roll stability

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ABSTRACT

This work augments an existing LPV feedback controller by a new LPV feedforward filter to improve the stability of a vehicle subject to driver-induced roll disturbances. In particular, the proposed LPV feedforward filter is designed by a Full-Information control approach and uses the saturation indicator concept to consider the restrictive state-dependent force constraints of semi-active dampers. Hence, in the event of saturation, the feedforward filter reduces its contribution to the control signal. The roll stability improvement due to the LPV feedforward filter is demonstrated by lane change experiments.

1. Introduction

Semi-active suspensions offer a large potential to improve essential vehicle properties like ride comfort, road-holding and handling compared to passive suspensions (Guglielmino, Sireteanu, Stammers, Ghita, & Giuclea, 2008; Mitschke & Wallentowitz, 2004). The exploitation of this potential relies on suitable semi-active suspension control algorithms which consider the restrictive state-dependent actuator force limitations due to the passivity constraint of semi-active dampers. The optimal values of the design targets ride comfort and road-holding cannot be simultaneously achieved during suspension control design. Hence, the design always has to seek the best compromise between them (Savaresi, Poussot-Vassal, Dugard, Sename, & Spelta, 2010; Tseng & Hrovat, 2015). The two main disturbances to be attenuated by the semi-active suspension controller are road disturbances and driver-induced roll and pitch disturbances. These two disturbances have distinct frequency ranges meaning that the relevant frequency range of road disturbances is 0–20 Hz, while the relevant frequency range of driver-induced disturbances is 0–3 Hz. In most vehicle applications, road disturbances are unknown during runtime, but driver-induced disturbances can be estimated from the driver inputs by a planar vehicle model. The driver-induced disturbances considered in this work emerge from the steering inputs of the driver e.g. when driving on a curvy country road. They significantly affect ride comfort, road-holding and handling. As shown in Brezas and Smith (2014) and Williams and Haddad (1997), controllers which minimize the effect of road disturbances only achieve medium ride comfort and road-holding regarding driver-induced disturbances and vice versa. The authors in Smith and Wang (2002) address the control design of an active suspension system in the presence of road disturbances and driver-induced disturbances by a special parametrization of an LTI controller for decoupled tuning of the two disturbance transmission paths. Compared to road disturbances, driver-induced disturbances, however, feature the advantageous property that they can be estimated from the driver inputs and the vehicle states. This knowledge can be explored by a feedforward controller within a two-degree-of-freedom structure. The authors in Brezas and Smith (2014) present a two-degree-of-freedom optimal LQ control design of an active suspension system which simultaneously considers road and driver-induced disturbances. In particular as mentioned above, the authors in Brezas and Smith (2014) have observed that the LQ controller without feedforward shows a vital degradation of ride comfort and road-holding. In Brezas, Smith, and Hoult (2015), the authors adjust their approach to semi-active suspensions and present experimental results of a cornering manoeuvre. Alternatively, the author in Ahmadian and Simon (2004) present a so-called steering input augmentation (SIA) of a Skyhook control such that the SIA-Skyhook controller increases its control signal proportional to the steering input. The roll stability enhancement of the SIA-Skyhook controller is then validated by lane change experiments.

In contrast to Brezas and Smith (2014), this work pursues a feedforward–feedback decoupling approach as theoretically described

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in Prempain and Postlethwaite (2001), i.e. the separate design of the feedforward and feedback paths. The two-step control design has the appealing property that the feedback controller can focus on attenuation of unknown disturbances and the feedforward filter can achieve fast tracking and rejection of known disturbances. Examples of LPV feedback controllers dedicated to attenuate road disturbances are (Do, Sename, & Dugard, 2010; Poussot-Vassal et al., 2008). These papers present a quarter-vehicle control approach based on polytopic LPV methods. The control design of Poussot-Vassal et al. (2008) relies on the appropriate selection of scheduling parameter-dependent weighting filters such that the final controller always stays within the actuator limits. In the follow-up research in Do et al. (2010), the polytopic LPV framework is use to approximate the nonlinear damper by an LPV model and subsequently directly incorporate the LPV damper model in the quarter-vehicle plant model. In this way, parameter-dependent weighting filters are no longer mandatory and parameter-independent ones are used. The presented feedforward control design assumes a preexisting LPV feedback controller, which employs the saturation indicator concept introduced in Wu, Grigoriadis, and Packard (2000) to model the actuator force constraints in the LPV plant (Fleps-Dezasse, Svaricek, & Brembeck, 2017, 2018). The proposed LPV feedforward filter can be obtained by solving a Full-Information (FI) problem. The FI control approach is simple and naturally extends to LPV plants as shown in Prempain and Postlethwaite (2001). Moreover the FI control approach can be applied to a multitude of feedforward design problems as illustrated by the LPV helicopter control design application presented in Prempain and Postlethwaite (2000) and the LPV missile control design example given in Theis, Pfifer, Knoblach, Saupe, and Werner (2015). Regarding semi-active suspension control design, the FI control approach features the essential property that the saturation indicator concept is coherently applicable to the feedforward and feedback control design. In this way, the proposed feedforward filter can be designed similar to an existing feedback controller such that the feedforward filter and the feedback controller equally reduce their control signal in the event of saturation according to the value of the saturation indicators. The resulting two-degree-of-freedom LPV controller attains guaranteed stability for all admissible actuator saturation conditions and good performance regarding both disturbances. The feedforward control design presented in this work focuses on shaping the body response of the vehicle subject to driver-induced roll disturbances. The feedforward filter takes the estimated lateral vehicle acceleration as input and generates appropriate damper forces. The estimation of the lateral vehicle acceleration is obtained from the steering angle and the vehicle speed using a single-track model. The effectiveness of the feedforward filter is emphasized by the simulation of a lane change scenario and by double lane change experiments with the *SC3-Bulli* (based on a VW T5 van) of the Institute of System Dynamics and Control (SR) of the German Aerospace Center (DLR) depicted in Fig. 1.

Fig. 1. *SC3-Bulli* experimental vehicle on test track during double lane change manoeuvre.

2. Problem statement

This work addresses the feedforward control design of a full-vehicle equipped with four semi-active dampers. The control design target is the rejection of driver-induced body roll disturbances, while retaining the closed-loop road disturbance attenuation of a preexisting LPV feedback controller. Moreover, the resulting two-degree-of-freedom controller should firstly feature guaranteed stability for all admissible actuator saturation conditions. Secondly, the feedforward filter should not dominate the two-degree-of-freedom controller near the actuator constraints such that the feedforward filter and the feedback controller enjoy equal priority over the constrained control signal. The preexisting LPV feedback controller is assumed according to Fleps-Dezasse et al. (2017, 2018), i.e. to employ saturation indicator scheduling parameters to model the actuator force limits directly in the LPV plant (Wu et al., 2000). Furthermore, the LPV feedback controller is assumed to linearly reduce its control signal depending on the saturation indicators.

A detailed introduction to LPV control design including recent developments and many application examples can be found in Mohammadpour and Scherer (2012) and Sename, Gáspár, and Bokor (2013).

2.1. LPV modeling of actuator constraints

The general control configuration of a closed-loop with actuator constraints is depicted in Fig. 2. The open-loop plant $\boldsymbol{G}_{\Theta}$ consists of the unconstrained open-loop LTI plant $\boldsymbol{G}$ and the saturation block. The control signals $\boldsymbol{u}$ of the LPV controller $\boldsymbol{K}_{\Theta}$ are fed into the saturation block yielding the saturated control signals $\boldsymbol{\sigma}(\boldsymbol{u})$. Based on the anti-windup LPV control approach of Wu et al. (2000), the saturated control signal can be expressed by

$$\boldsymbol{\sigma}(\boldsymbol{u}) = \boldsymbol{\Theta}\boldsymbol{u} \tag{1}$$

with the saturation matrix given by $\boldsymbol{\Theta} = \operatorname{diag}(\boldsymbol{\theta})$. The saturation matrix gathers the saturation indicators of the individual actuators $\boldsymbol{\theta} = \begin{bmatrix}\theta_1 & \theta_2 & \dots & \theta_{n_u}\end{bmatrix}^T$ under the assumption of decoupled actuator constraints, i.e. the control signal of one actuator has no influence on the saturated control signals of other actuators. The saturation indicator of the ith actuator is defined as

$$\theta_i = \begin{cases} \dfrac{\sigma(u_i)}{u_i} & u_i \neq 0 \\ 1 & u_i = 0 \end{cases} \quad \forall i \in \{1, 2 \dots, n_u\}. \tag{2}$$

with n_u the number of actuators and the saturation function $\sigma(u_i)$ according to

$$\sigma(u_i) = \begin{cases} u_i & u_i^{\min} < u_i < u_i^{\max} \\ u_i^{\min} & u_i^{\min} \geq u_i \\ u_i^{\max} & u_i^{\max} \leq u_i \end{cases} \tag{3}$$

The upper and lower limits are assumed $u_i^{\max} > 0$ and $u_i^{\min} < 0$, respectively, to achieve a proper actuator constraint representation by the saturation indicators. Moreover, during the LPV control design, the saturation indicators $\boldsymbol{\theta}$ are assumed to continuously evolve over time, to be either measurable or estimable in real-time, and to be bounded by $\theta_i \in (0, 1]$ $\forall i \in \{1, 2 \dots, n_u\}$. The unconstrained system, i.e. when the control signals can be realized by the actuators, is indicated by a saturation indicator value of one, and values smaller than one reflect the degree of saturation. The state–space realization of proper plants $\boldsymbol{G}_{\Theta}$ can then be stated by

$$\begin{bmatrix}\dot{\boldsymbol{x}} \\ \boldsymbol{y}\end{bmatrix} = \begin{bmatrix}\boldsymbol{A} & \bar{\boldsymbol{B}}_2\boldsymbol{\Theta} \\ \boldsymbol{C}_2 & \boldsymbol{0}\end{bmatrix}\begin{bmatrix}\boldsymbol{x} \\ \boldsymbol{u}\end{bmatrix}, \tag{4}$$

with $\boldsymbol{A} \in \boldsymbol{R}^{n_x \times n_x}$, $\boldsymbol{B}_2 \in \boldsymbol{R}^{n_x \times n_u}$, $\boldsymbol{C}_2 \in \boldsymbol{R}^{n_y \times n_x}$, and the vectors $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{u}$ of appropriate dimension.

2.2. Vehicle model with roll disturbance input

The behavior of the full-vehicle subject to driver-induced roll disturbances is modeled as proposed in Brezas and Smith (2014) by