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LPV-based Variable-Geometry Suspension Control Considering Nonlinear Tyre Characteristics ⋆

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Abstract: The paper proposes a method for the LPV-based (Linear Parameter-Varying) control design of the variable-geometry suspension system. The tilting actuation of the front wheel improves the lateral dynamics of the vehicle and assists for the driver in avoiding critical situations. The novelty of the method is the consideration of the nonlinearities in the tyre characteristics. The tyre forces are approximated by polynomials, which are used in the linearizing of the vehicle model. A parameter-varying vehicle model is derived, on which a robust LPV control is designed. The proposed method improves the performances of vehicle dynamics, and handles the critical maneuvers caused by e.g. a skidding car and high velocities. The proposed method is illustrated through CarSim simulation examples.

Keywords: suspension control, LPV design, nonlinear vehicle modeling

1. INTRODUCTION AND MOTIVATION

The variable-geometry suspension system provides a new possibility in driver assistance systems to enhance road stability and safety. The advantages of this novel type of active system are the simple structure, low energy consumption and low cost compared to other mechanical solutions such as active front wheel steering, see Evers et al. (2008). Since various safety and economy properties of the vehicle are determined by the suspension geometry it has an influence on the control design.

The control input of variable-geometry systems is the camber angle of the front wheels, with which the driver is supported to perform the various vehicle maneuvers, such as a sharp cornering, overtaking or double lane changing. During maneuvers the control system must guarantee various crucial vehicle performances such as trajectory tracking, roll stability and geometry limits. The wheel tilting is realized by the motion of the suspension arms. Since the positions of the arms determine the camber angle, the points of the suspension are influenced by electro-hydraulic or electric actuators.

Several papers for various kinematic models of suspension systems have already been published, see e.g. Fallah et al. (2009); Németh and Gáspár (2012). The vehicle-handling characteristics based on a variable roll center suspension were proposed by Lee et al. (2008). A rear-suspension active toe control for the enhancement of driving stability was proposed by Goodarzia et al. (2010). Another field of variable-geometry suspension is the steering of narrow vehicles, see Piyabongkarn et al. (2004). These vehicles require the design of an innovative active wheel tilt and steering control strategies in order to perform steering similarly to a car on straight roads but in bends they tilt as motorcycles, see Suarez (2012).

In this paper the control design of a variable-geometry suspension system to improve vehicle stability is proposed. The novelty of the paper is the incorporation of the nonlinear tyre characteristics in the control design through an LPV formulation. The characteristics are formulated using polynomials, which are linearized in a parameter-varying form. In this way the validity region of the control is extended. Preliminary analysis and control design results have already been presented in Németh and Gáspár (2014, 2013).

The paper is organized as follows. Section 2 presents the construction of the variable-geometry suspension, the LPV modeling of the tyre characteristics and the lateral vehicle dynamics. Section 3 proposes the control design based on the LPV method for the suspension system. Section 4 demonstrates the efficiency of the method and, finally, Section 5 gives some concluding remarks.

2. LPV MODELING OF LATERAL VEHICLE DYNAMICS

In this section the constructional aspects of the variable-geometry suspension, the nonlinear modeling of the tyre

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characteristics and the lateral dynamics are presented. Moreover, a control-oriented state-space representation of the vehicle for control design purposes is derived.

2.1 Construction of the variable-geometry suspension

A double-wishbone construction type of variable-geometry suspension system is illustrated in Figure 1. The wheel tilting is realized by the modification of the lateral position of A, denoted by a_y. The relationship between the motion a_y and γ is determined by the geometrical positions of the points A, B, C, D. Moreover, intervention a_y is able to influence the steering angle at the track-rod connection point. In the paper the effect of a_y on δ is ignored. This approximation is suitable for low track-rod connection points, see Németh and Gáspár (2014). Moreover, the variable-geometry suspension intervention also indicates half-track change. Since the lateral motion of wheel-road connection point T increases tyre-wear, the control actuation and the construction must be designed to reduce the motion of T.

As introduced above, there are are several interrelations between the constructional and the control design aspects. The details of an integrated consideration of variable-geometry suspension control and construction design are proposed in Németh and Gáspár (2013). In this paper the trajectory tracking performance of the controlled vehicle is improved through suspension actuation.

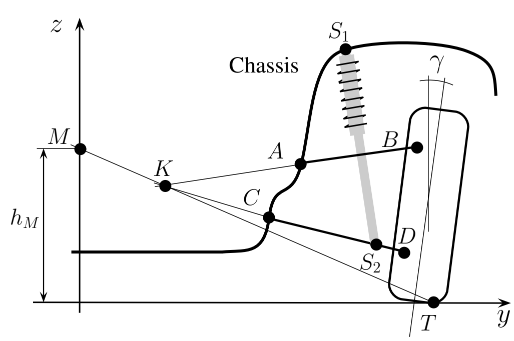

Fig. 1. Variable-geometry suspension construction

2.2 Tire modeling

The nonlinear characteristics of the lateral tire forces and the effects of wheel tilting on them are crucial in the modeling. Several methods for the modeling of the tire have already been published, see e.g., Pacejka (2004); Kiencke and Nielsen (2000); de Wit et al. (1995). In the paper a polynomial approach to the tire is applied, which is linearized for control design purposes, see Németh and Gáspár (2014).

In the case of the variable-geometry suspension system two nonlinearities of the tire characteristics must be considered in a given operation range.

- Lateral tire force $\mathcal{F}(\alpha)$ depends on the lateral tire slip α nonlinearly. Although in several control applications the lateral forces are approximated with linear functions, which results a simple description, it can be used in a narrow tire side-slip range. Vehicle motion is significantly characterized by this nonlinearity.
- The generated lateral tire force from camber angle $\mathcal{G}(\alpha)$ depends on α nonlinearly. Thus, the efficiency of actuator intervention is influenced by tire slip.

The nonlinear model of the tire is constructed from the polynomial approximation of the previous two effects, $\mathcal{F}(\alpha)$ and $\mathcal{G}(\alpha)$:

$$\mathbf{F_{lat}}(\alpha) = \mathcal{F}(\alpha) + \mathcal{G}(\alpha)\gamma = \sum_{j=1}^{n} c_j \alpha^j + \sum_{k=0}^{m} g_k \alpha^k \gamma \tag{1}$$

where γ is the camber angle of the wheel.

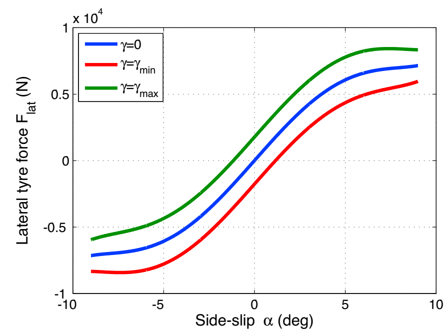

Fig. 2. Modeling of lateral tire force $\mathbf{F_{lat}}$

An example of the nonlinear characteristics in the function of tire side-slip α is illustrated in Figure 3.

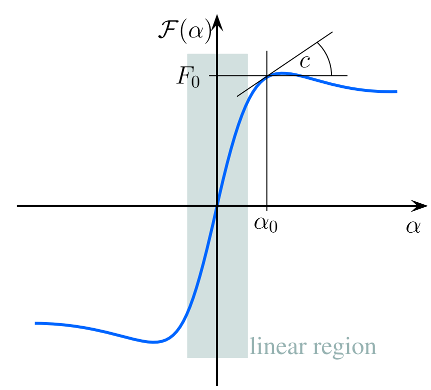

Fig. 3. Modeling of lateral tire force

In the following the polynomial description of the tyre model is transformed into a control-oriented form. The linearizing of $\mathbf{F_{lat}}(\alpha)$ around a given α_0 leads to the following expression:

$$F(\alpha)\big|_{\alpha_0} = F_0(\alpha_0) + c(\alpha_0)\alpha + G_0(\alpha_0)\gamma \tag{2}$$

where $c(\alpha_0)$ is cornering stiffness. In (2) the parameters $F_0(\alpha_0)$ and $c(\alpha_0)$ depend on the slip value α_0 in the tire model. These parameters are derived from the fitted polynomial model (1). $F_0(\alpha_0) = \mathcal{F}(\alpha_0)$ and $G_0(\alpha_0) = \mathcal{G}(\alpha_0)$ are the values of the lateral tire force at α_0, while

$$c(\alpha_0) = \frac{d\mathcal{F}(\alpha)}{d\alpha}\bigg|_{\alpha_0} \tag{3}$$