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Steering Feel Design: The Effect of Mass Variation ⋆

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Abstract: In rubber-wheeled road vehicles, the torque fed back to the driver through the steering linkages and steering wheel, which is called steering feel, helps the driver in controlling the vehicle. The torque feedback is reproduced via artificial methods in steer-by-wire systems due to the lack of mechanical connection. Since the mass of vehicle is one of the essential parameters in the dynamics of vehicle, its effect on the steering feel and on the design of steering feel model needs to be discussed. This study investigates the design of steering feel model so as to involve the mass variation. The novelty of this study is to design a steering feel not to mimic the steering feel of any conventional vehicle, but to search the optimum steering feel value. A 2-DOF bicycle model with the Magic formula tire model was used in the simulations and HIL experiments. The steering feel model was tested with different mass scenarios according to the ISO standard weave test. A HIL experimental setup was used for the driving tests. The weave test has been performed with different drivers in order to evaluate the behavior of the model under mass variation.

Keywords: steering feel, steer-by-wire, hysteresis, physical workload, optimization, mass variation

1. INTRODUCTION

In classical road vehicles, the steering action is performed through the mechanical link between the front wheels and the steering wheel. When the front wheels are steered, a reaction torque, which is mainly based on the self-aligning torque(SAT), occurs, and the driver experiences the steering feel as a tactile feedback through steering wheel. Since the steering feel has a significant effect on the handling quality, it is stated as an essential feedback to the driver Kim and Cole (2011).

In steer-by-wire(SBW) systems, elimination of the steering column results in the loss of mechanical connection between the front road wheels and steering wheel. A force-feedback system becomes indispensable for providing a steering feel to the driver. This feel is provided through an electrical motor attached to the steering wheel, Park TJ et al. (2005).

Most of the studies in the literature mainly or partially use estimated SAT information to generate the conventional steering feel, Salaani et al. (2002); Balachandran and Gerdes (2014). Estimation of SAT brings some difficulties and complexity. An additional approach seems to be needed to reproduce the steering feel in cases such the model based on the SAT is not applicable. For instance SAT is highly dependent on the mass of the vehicle. The SAT and, therefore, the SAT-based steering feel are highly affected by the change of total mass, especially for lightweight and super lightweight vehicles, when the weights of passengers and baggage are added to the curb weight of vehicle. Although the torque requirement in steering is assisted by an EPAS system in conventional vehicles, SBW systems does not include an EPAS system. Hence the use of SAT in steering feel models should be considered.

Based on the studies of steering feel in the literature Shimomura H et al. (2014), the main reason influencing the steering feel is evident in the relation between the steering wheel angle and steering wheel torque feedback. This relation has been identified as a hysteresis curve Pfeffer et al. (2008). A steering feel (SF) model is designed to characterize a lag effect by using the Bouc-Wen hysteresis model in a recent work, Arslan (2015).

There is still no general and sufficient model for designing the SF in the literature. This is still an ongoing research topic, yet a new approach has been introduced in terms of designing an adaptive and online SF model which pay attention to physical workload, Kirli and Arslan (2016 1,2). The proposed approach aims to reduce the physical workload while satisfying the vehicle's path following performance through an online and adaptive hysteresis-based SF model.

Since the mass variation has a significant effect on the SF design, a vehicle with the proposed online optimized hysteresis-based SF model has been compared with the same vehicle having a SAT-based SF model. The main objective of this study is to present the effect of mass variation on the SF, and quantify the ability of SF models

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to achieve the given performance criteria under different mass values. To test the performances of the SF models, hardware-in-the-loop (HIL) simulation experiments with human drivers have been performed. The Magic formula tire model is used, Pacejka (2006), in a bicycle model, Wong (2001), because of their simplicity and wide acceptance.

The outline of this paper is as follows: Section 2 introduces the vehicle dynamics and SF model. Section 3 demonstrates the optimization procedure. The HIL experimental setup takes place in Section 4. Section 5 discusses the results and summarizes this work.

2. VEHICLE DYNAMICS AND STEERING FEEL MODEL

The overall system dynamics includes the tire model, the bicycle model and the SF model. The input of the overall system is the steering wheel angle applied by the driver where the output is the global position of the vehicle.

2.1 Tire model

A well known and widely used semi-empirical tire model to calculate the tire forces and moments is the Magic Tire Formula. Once the tire forces were obtained, a two degree-of-freedom dynamic model for lateral vehicle motion was developed by using the bicycle model, Wong (2001). The nominal values of a passenger car have been used for vehicle dynamics. The parameters of the vehicle were taken from a large front wheel drive saloon car, Genta (1996).

2.2 Self-aligning torque

The SF occurs as a result of the tire-road interaction during the steering of front wheels. The self-aligning torque plays the main role in generation of the SF in conventional vehicles. One design approach for SF is to feed the SAT back to the driver. To calculate the SAT and the pneumatic trail, the Magic Formula tire model was used with the empirical parameters given in Wong (2001). Note that the tire parameters are based on the mass of the vehicle. Therefore, the SAT is highly dependent on the mass of vehicle.

2.3 Hysteresis-based steering feel model

Bouc-Wen model of hysteresis introduced by Bouc, Bouc (1971) and generalized by Wen,Wen (1976). This model describes the output restoring force to the input displacement in the form of a first order nonlinear differential equation. The hysteric behaviour for input $x(t)$, and output $\Phi(x)(t)$, relation can be described by the Bouc-Wen hysteresis model:

$$\Phi(x)(t) = \alpha k x(t) + (1-\alpha) D k z(t) \quad (1)$$

$$\dot{z} = D^{-1}(A\dot{x} - \beta\,|\dot{x}|\,|z|^{n-1}\, z - \gamma\dot{x}\,|z|^{n}) \quad (2)$$

where, A, B, D, n, α, β, and γ are the parameters controlling the shape of hysteresis loop. Another model exactly equivalent to this standard model is preferred, since it needs the identification of less parameters. By defining,

$$\omega(t) = \frac{z(t)}{z_0} \quad (3)$$

with an initial condition $\omega(0)$, and where

$$\rho = \frac{A}{Dz_0} > 0, \quad \sigma = \frac{\beta}{\beta+\gamma} \geq 0,$$
$$\kappa_x = k\alpha > 0, \quad \kappa_\omega = (1-\alpha)Dkz_0 > 0.$$

the model can be rewritten to form the normalized Bouc-Wen model, where $\rho(u)$ was designed as a function of longitudinal velocity, u. A linear function was given as: $\rho(u) = k_u u$, where, k_u is a constant coefficient.

The hysteresis-based SF model used in this study has been introduced by Arslan Arslan (2015) and is as follows (see aforementioned studies for details of the model):

$$T_{sw} = \kappa_x\theta + \kappa_\omega\omega \quad (4)$$

$$\dot{\omega} = \rho(u)(\dot{\theta} - \sigma\left|\dot{\theta}\right| |\omega|^{n-1}\,\omega + (\sigma-1)\dot{\theta}\,|\omega|^{n}) \quad (5)$$

3. OPTIMUM STEERING FEEL DESIGN

The optimization strategy produces the optimum values of hysteresis parameters, which are redefined as the time dependent functions of vehicle dynamics and some measures, during the steering of a vehicle. The reason behind studying the online optimization approach is to create an adaptive model-based optimization on the vehicle dynamics while minimizing the given performance criteria.

The hysteresis-based model includes five constant coefficient parameters to form the hysteresis curve. These parameters have different effects on the form of the curve and, as a result, on the SF. Since the objective is to design an online and adaptive model for the SF, the effects of these parameters are need to be investigated.

The physical workload, the lateral acceleration and the vehicle's path following performance are defined as the performance criteria. In evaluating the steering response of a vehicle, the lateral acceleration is a commonly used parameter. By selecting the physical workload as another performance criterion, it was possible to make a comparison between the models from the exerted energy of human driver point of view. Thus, we have shown that the driver using the system with hysteresis-based model has not exerted more force than that of the system with SAT-based model. Also, the workload has been used as a measure to show how a driving task can be completed with less effort by selecting the parameters of hysteresis-based model.

Physical workload The workload has been used as a measure to show how a driving task can be completed with less effort by selecting the parameters of hysteresis-based model. Although there are a few suggestions on the calculation of physical workload in the literature, there has been no general and widely accepted model so far. We suggest a formula based on the formula in Arslan (2015); Kirli and Arslan (2016 1,2) for the physical workload J_w as: