

Objective Evaluation of Steering Rack Force Behaviour and Identification of Feedback Information

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ABSTRACT

Electric power steering systems (EPS) are characterized by high inertia and therefore by a considerably damped transmission behaviour. While this is desirable for comfort-oriented designs, EPS do not provide enough feedback of the driving conditions, especially for drivers with a sporty driving style. The systematic actuation of the electric motor of an EPS makes it possible to specifically increment the intensity of the response. In this context, the road-sided induced forces of the tie rod and the steering rack force provide all the information for the steering system's response. Former concepts differentiate between use and disturbance information by defining frequency ranges. Since these ranges overlap strongly, this differentiation does not segment distinctively. The presented article describes a method to identify useful information in the feedback path of the steering system depending on the driving situation. By applying a suitable driving manoeuvre, useful information can be considered isolated. This is done exemplarily in an understeering situation and characteristics are identified in the behaviour of the steering rack force. Based on this information, the steering torque is influenced by an excitation of the servo motor via a newly developed steering function in order to depict the current driving situation in the steering torque. With the presented method, the parts of the steering rack force associated with use information are made haptically noticeable in the steering torque.

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1. INTRODUCTION

Electromechanical steering systems are - because of the way the system operates - characterized by high inertia and therefore by a considerably damped transmission behaviour. While this is desirable for comfort-oriented designs, especially for drivers with a sporty driving style, electric power steering systems (EPS) provide insufficient feedback of the driving conditions (cf. [1]). The systematic actuation of the electric motor of an EPS results in an increased intensity of response. The aim of those concepts is to transfer the transmission behaviour of a hydraulic steering to an EPS. At the same time, useful steering responses have to be improved and disturbing ones eliminated. At present, the information about use and disturbance are differentiated based on the respective frequency ranges (cf. [1], [2], [3], [4], [5], [6], [10]). Some of the frequency ranges of the response information, however, overlap strongly. Furthermore, there is no standard information about the assignment of information to frequency ranges in literature. Against this

background, this paper presents a method to identify useful steering responses while taking frequency-independent characteristics into account. The method is based on the analysis of steering rack force behaviour of selected driving manoeuvres. These manoeuvres are characterized by purely lateral stimulation. Therefore it is possible to detect useful information of lateral dynamics. In this paper, the lateral force reserve in the case of understeering is used as an example.

In the following, the known information given in the steering response path is used to develop a test procedure based on the information about the remaining lateral force reserve (front wheels). Furthermore, a method to analyse the measured data and the ensuing development of objective parameters is introduced. An objective parameter here is a parameter computed by an algorithm which describes characteristic steering or vehicle performance behaviour as precisely as possible

based on selected measurement signal curves. Finally, the objective parameters are interpreted and information which might be useful for the driver in the steering response path is derived.

2. STEERING RESPONSE

According to [3], steering response is the "ability to transfer information about changes in wheel load, rolling resistance and lateral force by changing the applied steering torque". In the following, the origin and the significance of the information transfer are presented.

2.1. Response Path of an EPS

In order to illustrate the origin of the steering torque information, the impact of lateral force to the steering system is presented. Figure 1 shows the schematic diagram of a steering system and the applied forces. The lateral wheel force results from the deflection of the tread elements in the contact patch. The level of deflection can be quantified based on the tyre slip angle. The deflection of the tread elements is linear in the range of static friction, so the deflection takes a triangular-shape. The application point of the lateral force in this case remains almost constantly in the centroid of the triangular-shaped area of the contact patch. If the maximum possible deflection of the tread elements is exceeded by an increasing slip angle, a range of dynamic friction is added to the range of static friction. In the case of appropriate lateral acceleration, the friction in the contact patch therefore consists of a range of static friction and a range of dynamic friction (see figure 1).

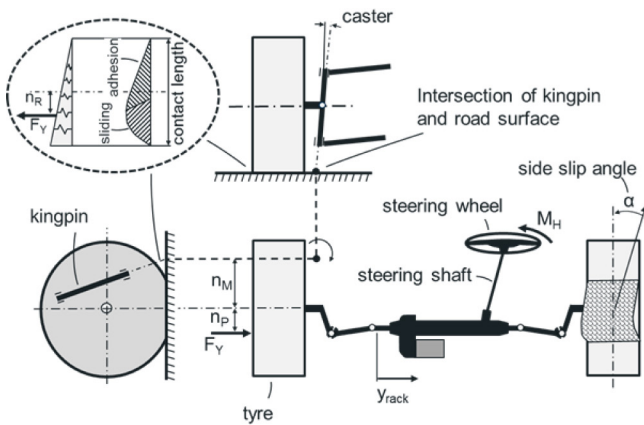


Figure 1. Simplified description of a steering system and the influence of lateral tyre forces caused by tyre slip angle

In addition to the lateral force level, the rate and intensity of the different types of friction also influences the point of force application. With higher slip angles and therefore increasing rates of dynamic friction, the pneumatic trail (n_R) is moved towards the middle of the tyre or even further in case of extreme driving situations [7]. The product of the lateral force and the sum of the mechanical and pneumatic trails form a self-aligning torque centered on the kingpin (see figure 2). The knuckle arm and the tie rod support this torque as a rack force to the steering system. The steering rack force and the appropriate kinematic ratio comply with the aligning torque behaviour and are applied to the steering column and steering

wheel via the steering pinion. The maximum possible intensity of the steering response therefore complies with the curve of the tie rod force and the aligning torque at the front wheels.

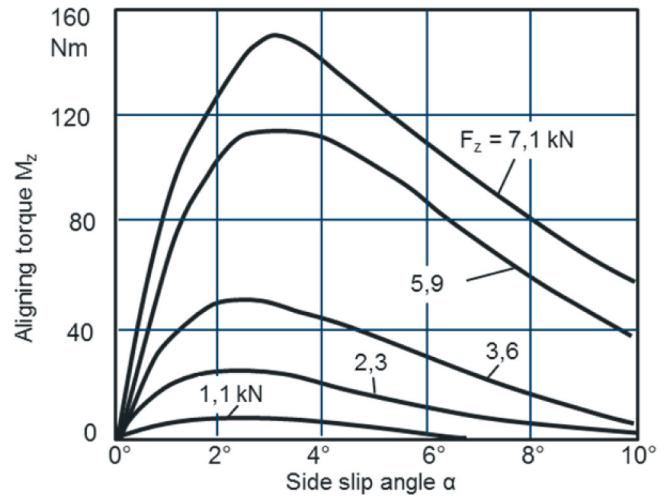


Figure 2. Self-aligning torque behaviour depends on tyre slip angle and wheel load (data based on [2])

The inertia caused by the screw gear of the electric motor, the masses of the different parts of the steering system as well as influences of friction and elasticity between steering wheel and tyres, however, are also included in the chain of reaction between steering wheel and tyres. The inertia of the electric motor and transmission unit in particular lead to an equivalent inertia of approx. 1500 kg for an average steering system in axially parallel design (APA). This leads to the considerably reduced steering response of electromechanical steering systems mentioned above. With regard to the maximum possible steering response, the tie rod force as the system input of the steering offers the most information from a driving dynamics point of view.

The wheel aligning torque, steering wheel torque, assistance torque of the EPS, friction and inertia forces yield the balance of forces on the steering rack. The steering wheel torque is, on the one hand, directly applied from the steering column to the steering rack via the steering pinion. On the other hand, the driver input is measured by the torsion bar and, depending on the implemented steering software, supported by torque applied by the electric motor. The maximum steering response is additionally influenced by the current assistance torque, which can be chosen independently. The force balance is hence the origin of the steering response [9, 10, 11]. If the impact of the lateral force due to changes in camber and toe is neglected, it results in the following force ratio:

$$M_H = F_y \cdot (n_p + n_m) \frac{1}{i_L} - M_{Mot} \cdot i_{SM} \cdot i_{Pinion} - m_{rack} \cdot \ddot{y}_{rack} \cdot i_{Pinion} \quad (1)$$

with:

$$F_y = a_y \cdot m_{veh} \left(1 - \frac{l_H}{l} \right)$$

2.2. Useful Steering Information

In order to meet the requirements of a driving task, the driver (in the control loop driver-vehicle-driving environment) needs information about the driving conditions and the driving environment. This information can be visual, acoustic or haptic. The latter is of special importance since it is processed 20% to 30% faster than visual or acoustic information [12, 13]. In the field of haptic response, the steering plays a crucial role for several reasons. On the one hand the steering system can transfer the driving condition to the driver immediately, on the other hand, the steering system is in the first place in the driving dynamic chain of causality (as seen by the change of the driving state of a vehicle): Lateral dynamics which do not result from external influences or brake interventions are initiated by the steering. For sufficiently accurate knowledge of the vehicle on the basis of the steering wheel angle the driving condition can be predicted. On the other hand, the palm of the hand has one of the highest densities of mechanoreceptive nerve endings [12]. The steering in turn can transfer information to the driver by changing the steering torque: through tyre-road contact, front axle kinematics, steering system and steering column [3]. The haptic response to the driver can be divided into information about use and disturbance and is used to fulfil the driver task. [1, 3, 9]. The differentiation between useful and disturbing information depends on the requirements of the respective type of driver and is therefore a subjective assessment. The literature is mostly consistent on the information of use. Thus, the response in terms of changes in the coefficient of friction, generation of lateral force or existing lateral force reserves as well as aquaplaning situations are considered as useful information [4, 6, 9, 14, 15]. According to [7], the information transfer comprises amplitude and frequency of steering torque changes. The frequencies usually range between 1 and 30 Hz. Various Publications assign different frequency ranges to useful and disturbing information, which can overlap considerably (see figure 3). While - for example according to [5] - mainly low frequencies of up to approx. 15 Hz are assigned to useful information, frequencies associated with changes in the coefficient of friction range between 1 and 30 Hz (according to [1]). But according to [6, 14], frequencies between 20 and 30 Hz represent the relevant range of useful information in the transfer path of the steering system. Hence, a precise objective differentiation of useful and disturbing information based on frequencies is not possible [5].

Another possibility to categorise information in the path of effects of the steering is the categorisation of the causes. The information can be related to a certain cause in the field of chassis, lateral, longitudinal or vertical dynamics (see figure 4). Causes in the fields of chassis can be either due to design or wear, including imbalances caused by inconsistencies in mass distribution (tyre) or different thickness of a brake disc [1]. In the field of vertical dynamics, the causes result from the road profiles. Periodic, stochastic or transient road irregularities lead to changes in the force (tyre), which affect the steering systems during cornering. The impact of longitudinal dynamics on the steering response results from different propelling and braking forces at the right and left front-wheels. Force differences for instance result from different road friction coefficients between the sides of the vehicle, which affect the steering rack force through kingpin offset or disturbing force lever arm. The steering response is furthermore affected by asymmetric drive shafts during

acceleration. In the field of lateral dynamics, the state of friction of the tyres during lateral acceleration is a crucial piece of information. The lateral wheel force during cornering is linear at first before it becomes non-linear with increasing lateral acceleration. The nonlinear behaviour is represented in the tie rod force curves particularly in cases of understeering (cf. the curves of the aligning torque in relation to the slip angle, figure 2).

Further information in the field of lateral dynamics includes external influences, such as changes in the friction coefficient or aquaplaning situations. Both conditions - especially during cornering - lead to changes in the wheel force balance and therefore in the steering torque.

Against this background, an analysis of the information in the steering response path under new constraints is required. The rack force is the central variable for the analysis of useful information (cf. chapter 2.1). It is possible to create a test scenario with respect to the categorisation of the information regarding its origins. The aim of the scenario is to identify and to isolate specific information in the steering response path. This makes it possible to analyse the steering rack force further than just by considering the occurring frequencies. A possible test setup and the appropriate procedure are presented in the following chapter.

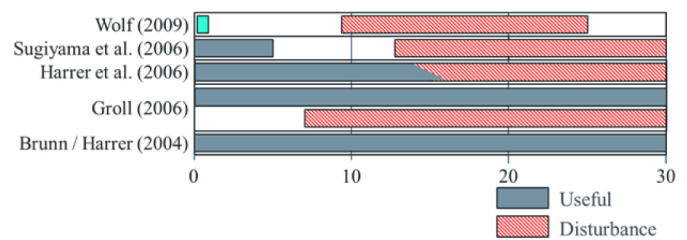


Figure 3. Frequency based classification of useful and disturbance information [1, 4, 14, 16, 17]

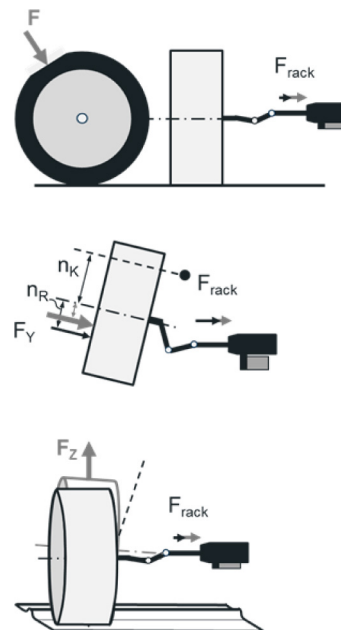


Figure 4. Origin based classification of causes of feedback information