

Optimal Design of On-Center Steering Force Characteristic Based on Correlations between Subjective and Objective Evaluations

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ABSTRACT

To overcome the shortcomings of subjective evaluation, there have been several studies to examine the correlations between subjective and objective evaluations of on-center steering feel, and some useful results are obtained. However, it is still not clear how to design the steering characteristic based on the correlations.

In this paper, we propose a methodology of identifying the optimal on-center steering force characteristic based on the correlations between subjective and objective evaluations. Firstly, significant correlations between subjective and objective evaluations regarding on-center steering feel are established and verified. These verified correlations are then used to design the steering force characteristic. With desired ratings of the subjective evaluation items set as optimization goals, the ideal values of objective evaluation indices are obtained by use of an optimal design method. At last, the optimal steering force characteristic is designed based on the ideal objective indices. To satisfy the requirement of different engineering applications, the desired ratings of subjective evaluation items can be adjusted accordingly. The proposed methodology shows great potential in helping engineers streamline the design and development process of the steering system.

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INTRODUCTION

"On-center" refers to small steering input maneuvers, where the lateral acceleration of the vehicle is between 0.1-0.3 g. The on-center steering feel is very important for vehicle safety and the enjoyment of driving experience. However, the tuning of the steering feel is mainly carried out by test drivers in prototype vehicles, but it is a time-consuming and expensive process for the vehicle manufacturer. To overcome these shortcomings of the driver-based tuning process, several studies have been conducted to establish the correlations between subjective and objective evaluations of the steering feel.

In [1, 2, 3], a lot of work has been done to find the correlations between subjective and objective evaluations regarding vehicle handling. However, the correlations are not specifically for the steering system. Besides, the confidence level of the results needs to be improved. In [4], both linear regression method and neural network are applied to establish the correlations between the steering feel and vehicle handling properties. Results show that there exist correlations between measurements and ratings. Regarding specific aspects and

synthesis ratings of the overall steering quality, significant correlations between subjective evaluations and objective parameters are obtained in [5, 6]. However, only 2 out of the 8 partial aspects are about on-center steering feel and the equations that describe the correlation are not available. In [7, 8], steering torque gradient is found to be the key parameter in defining the on-center steering feel. However, the correlation between objective measurements and subjective evaluations are not explicitly presented. By using spring-mass-damper (SMD) system, it is found that subjective feeling of the on-center handling could be successfully explained by SMD parameters [9]. The map from parameters to subjective ratings is not available either.

So far, few studies have shown how to identify the "ideal" on-center steering feel based on the correlations. For this reason, we have conducted a study to design the "ideal" on-center steering force characteristic based on the correlation. To achieve this goal, the first step is to get the valid correlation equations between subjective and objective evaluations. In the previous research [10], the correlation equations have been

established successfully. However, the research is based on a fixed base driving simulator, the driving condition of which is quite different from that of the real vehicle.

This paper aims to establish reliable correlation equations between subjective and objective evaluations regarding on-center steering feel based on a moving base driving simulator, and identifying the “ideal” on-center steering force characteristic according to the correlation equations.

SUBJECTIVE AND OBJECTIVE EVALUATION TESTS OF ON-CENTER STEERING FEEL

In the following sections, a set of subjective and objective evaluation tests of on-center steering feel are designed. Specifically, 20 on-center steering force characteristics were subjectively evaluated by 15 test drivers in a moving base driving simulator. Meanwhile, objective evaluation tests were conducted in the simulator and objective evaluation indices were obtained.

Moving Base Driving Simulator

Subjective and objective evaluation tests were conducted in a driving simulator with 6 degrees of freedom (Figure 1). Tests conducted in a driving simulator have four advantages over tests in real vehicles:

1. Wider range: In a real vehicle, only a limited number of parameters can be changed in the steering system. The steering-by-wire system in the simulator is free from these limitations, which makes it possible to design a wide range of different steering characteristics [10].
2. Rapid switch: Switching from one characteristic to another can be finished rapidly. Because the human memory for feeling is quite short, the fast transition between characteristics makes it much easier for test drivers to compare a new steering feel with the previous one.
3. Reduced testing models: Different steering characteristics can be evaluated in one simulator. If test vehicles are used, the number of test vehicles will increase with the number of steering characteristics to be evaluated [4].
4. Variable controlled: The simulator makes it possible to have the same “vehicles” differing only in the desired parameter.

During the tests, 20 different steering force characteristics were evaluated in the simulator. The steering force characteristics are defined by 5 parameters: M_{f1} , T_{max} , P , θ , θ_1 , illustrated in Figure 2. θ is set as a constant of 5° and uniform design is used to define the distribution of the other 4 design parameters [10]. Distribution of design parameters of the steering force characteristics is shown in Appendix 1.



Figure 1. Moving base driving simulator

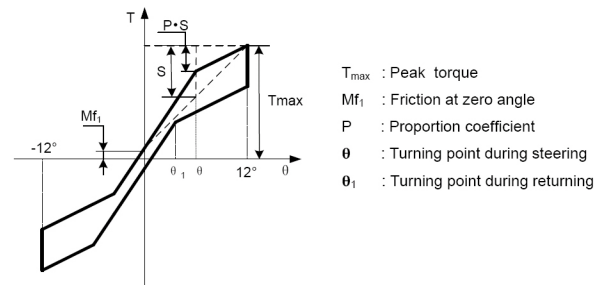


Figure 2. Design of the steering force characteristic

Subjective Evaluation Test

Test Drivers

To make sure that solid subjective evaluation results can be obtained, a group of “insiders” are required. Because they are able to understand thoroughly each question and connect it with sensations perceived during the test. For this reason, 15 research staffs were selected for the subjective evaluation test. Since different age groups have different preferences, which may impose a confounding factor on subjective evaluation [8], the biggest age gap is set no more than 10 years.

Questionnaire

In the automotive industry, the subjective evaluation is usually performed with a subjective assessment questionnaire. In this study, a questionnaire was developed for the assessment of on-center steering feel specially. It contains 6 partial evaluation items and an overall evaluation item (Table 1).

Among all these items, LST is expressed by using a semantic differential scale ranging from 1 to 5. The higher the rating, the better LST is. Similarly, OE is expressed by a scale ranging from 1 to 9. All the other items are expressed by bipolar scale ranging from -4 to 4 between two antonymous descriptive words of the feeling, where zero represents the perfectly appropriate feel.

Table 1. Subjective evaluation items

Items	Evaluation Contents
Steering Effort(SE)	Whether the reaction torque over the whole steering angle range is appropriate.
Steering Stiffness(SS)	Whether the steering stiffness over the whole steering angle range is appropriate.
Linearity of Steering Torque(LST)	Whether steering torque change with respect to steering angle smoothly. No uncomfortable feeling occurs. Whether steering angle is foreseeable as steering torque is increased gradually.
Solid Feel(SF)	Whether it is easy to keep the steering wheel at a fixed angle and the friction is appropriate.
Steering Aligning Torque(SAT)	Whether the steering aligning torque is appropriate.
Centering Feel(CF)	Whether it is possible to feel the center position of steering wheel according to the reaction torque.
Overall Evaluation(OE)	Whether the overall steering feel of this characteristic suits to drivers' preference.

To reduce the burden of the test drivers for more accurate results, all ratings are given by two judgments. Taking SE as an example (Figure 3), the first step is to determine if the current SE is acceptable or not. Based on the first judgment, the corresponding rating is then given according to the rating chart.

The rating chart for each evaluation item is listed in Appendix 2. It is also acceptable for drivers to give a score of 0.5, which helps to increase the resolution of the scale.

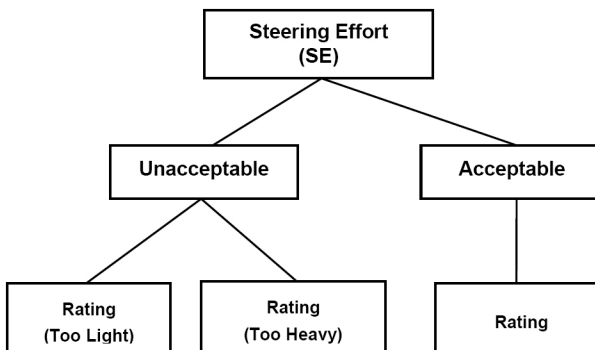


Figure 3. Rating procedure of steering effort

During the test, the car needs to be driven along the simulated freeway with a speed of 100km/h and changing lanes is constantly requested to simulate the driving condition on the freeway. The questionnaire should be finished during or after driving in the setup of each characteristic.

Objective Evaluation Test

Test Condition

In objective evaluation test, standardized handling maneuvers corresponding to on-center weave test by sinusoidal input is implemented according to ISO13674-1 [11]. The test condition is driving speed of 100km/h and steering input pattern of 0.2Hz sine wave. The amplitude of the sine wave is to ensure that it produces the required peak value of vehicle lateral acceleration (0.2g).

Objective Evaluation Indices

During the test, steering angle, steering torque, and lateral acceleration are recorded separately. Then the steering torque vs. steering angle and steering torque vs. lateral acceleration are mapped in a Cartesian coordinate system. The corresponding hysteresis curves are thus generated, which enables the derivation of objective evaluation indices (Table 2). The majority of these objective evaluation indices are defined in ISO13674-1 [11]. Other indices have also been introduced to further describe the on-center steering feel. Definitions of indices are shown in Figure 4 and Figure 5.

Table 2. Objective evaluation indices

No.	Symbol	Indices	unit
1	K1	Steering Stiffness	Nm/°
2	K2	Torque Gradient at 10°	Nm/°
3	MF1	Torque Hysteresis at 0 °	Nm
4	MF2	Torque Hysteresis at 10 °	Nm
5	Tp	Steering Torque at 10 °	Nm
6	AH	Angle Hysteresis	°
7	ay0	Lateral Acceleration at 0N.m	m/s ²
8	T0	Steering Torque at 0 m/s ²	Nm
9	T1	Steering Torque at 1 m/s ²	Nm
10	G1	Torque Gradient at 0 m/s ²	Nm/(m/s ²)
11	G2	Torque Gradient at 1 m/s ²	Nm/(m/s ²)
12	Fr	Torque Hysteresis at 1 m/s ²	Nm
13	K2/K1	K2 divided by K1	
14	K1/K2	K1 divided by K2	

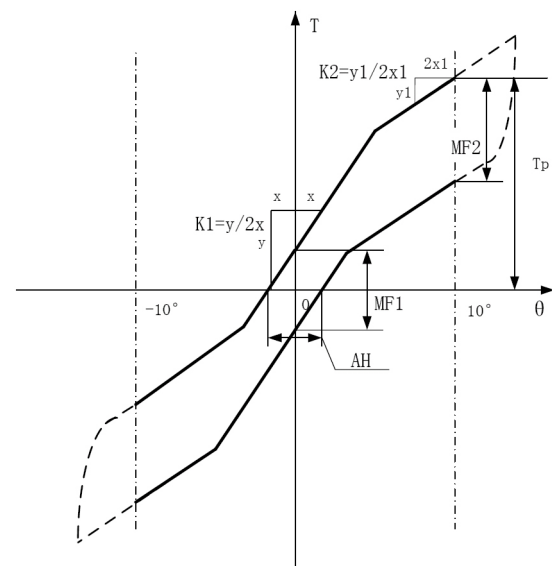


Figure 4. Objective evaluation indices derived from steering torque vs. steering angle curve