Strategy for Transfer Elemental Designing and Employing Physical Characteristic Modeling of Steering Maneuvering (the Third Report)*1

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Our previous report described a theoretical method for improving steering maneuverability and effectiveness based on the performance of high-efficient actuator and actual vehicle evaluation. The higher transfer-efficiency is not enough to achieve expected steering maneuverability, and other element characteristics should be properly established. Steer-by-wire system is well known as an innovative steering system that has a potential to create flexible transfer characteristics. This report describes advantages of the steer-by-wire system for improving steering maneuverability in comparison with conventional steering systems, and design and evaluation technologies of steering transfer system using a steer-by-wire system.

***Key Words**: steering system, maneuverability, steer-by-wire, driver-vehicle system*

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1. Introduction

In recent years, market expectations for steering system have evolved beyond basic steering wheel (SW) operation to include maneuverability factors such as stability and sharpness. The change in steering force on SW when the driver operates or maintains the SW has relationship with the vehicle behavior. The maneuverability for a driver is presumably evaluated by human senses with relating the change of steering force on SW and vehicle behavior. Improving maneuverability will reduce workload of the driver and provide driving pleasure.[1)]

Much research has been conducted and reported for the aim of improving maneuverability. For example, there is a research that attempts to find steering assist control characteristic[2)] analytically through simulations and researches concerning the target characteristic of vehicle roll behavior[3)]. So far, however, a valid proposal for a design method leading to characteristics of component parts to realize such findings has not been established.

Our first report[4)] introduced a detailed analysis model for the steering system and discussed a method of finding the target elemental characteristics required of component parts. The second report[5)] discussed experimentation done by installing a steering system designed using this technique in an actual vehicle and evaluating the effect on maneuverability. The transfer efficiency of input torque was selected as a representative element characteristics, and the effects it had on improving the response of yaw rate against steering angle were demonstrated. However, the second report also recognized the fact that improvement of steering transfer efficiency alone was insufficient to achieve the target maneuverability. It was stated that achieving of the target would require not only an optimization of each element but also an optimization of the vehicle system.

In **Chapter 2** of this report, the performance of the steering system is considered from the perspective as a bilateral interface between the driver and the vehicle. **Chapter 3** discusses the maneuverability transfer structure of conventional steering systems. **Chapter 4** discusses the steering system transfer structure of the steer-by-wire (SBW) system and compares with conventional steering systems. **Chapter 5** examines the steering system transfer characteristic from the human machine interface (HMI) perspective. **Chapter 6** analyzes vehicles equipped with SBW systems and discusses the results of steering system transfer characteristics evaluations.

2. A Steering System as a Bilateral Interface

In conventional steering systems, a mechanical connection exists between the SW and the front wheels. **Figure 1** shows one example of the transfer structure. The driver determines the target SW angle $\tilde{\theta}_h$ as the steering amount from the vehicle's target yaw rate $\tilde{\gamma}$ and

**1 This paper was originally published in the proceedings (No. 20095630) for "Technical paper presentation, 2009 Annual Congress (Autumn) of the JSAE (Society of Automotive Engineering of Japan, Inc.)" and is reprinted herein with the permission of the JSAE with some additions.*

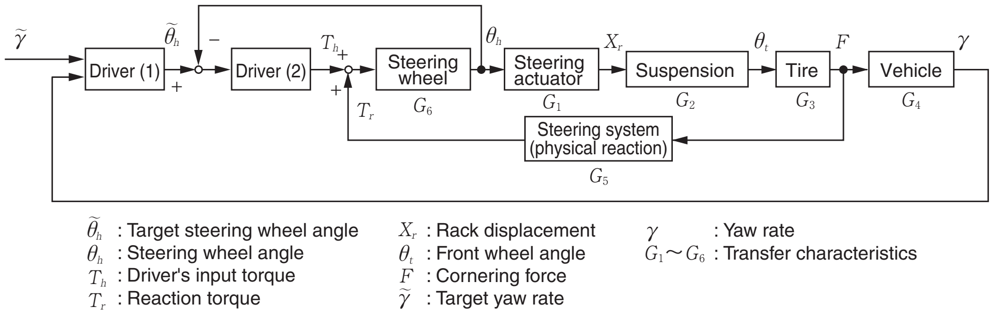

Fig. 1 Conventional steering control on driver-vehicle system

inputs steering torque T_h to achieve this $\widetilde{\theta}_h$. The torque is transferred to the SW, steering mechanism, suspension, front wheels and vehicle in sequence and vehicle turning motion arises.

Furthermore, the reaction force from the wheels, F, is converted into reaction torque T_r on the SW by the steering mechanism and transferred to the driver. Results relating to vehicle behavior such as yaw rate γ are transferred via the driver's senses organs.

In the above way, conventional steering systems have a characteristic of bilateral interface between driver and vehicle via the steering mechanism.

3. Design Requirements of the Steering System

3. 1 Vehicle Behavior Characteristic Related to Steering Input

This section considers the transfer characteristics from driver to vehicle. Here it is assumed that the effect of reaction torque T_r is small due to the adoption of power steering. SW angle θ_h is chosen as driver input and yaw rate γ as vehicle output, and transfer characteristic $G_\gamma(j\omega)$ is shown by equation (1).

$$G_\gamma(j\omega) = \frac{\gamma(j\omega)}{\theta_h(j\omega)} \tag{1}$$

This transfer characteristic $G_\gamma(j\omega)$ is expressed as the product of each sub-system's transfer characteristic, G_1 to G_4 of **Fig. 1**. The following sections discuss these individual transfer characteristics.

3. 1. 1 From SW angle θ_h to Rack Displacement X_r

In the steering system transfer structure of **Fig. 1**, the SW angle θ_h is input into the steering mechanism first, after that rack displacement X_r, which controls front wheel angle, is output.

$$G_1(j\omega) = \frac{X_r(j\omega)}{\theta_h(j\omega)} \tag{2}$$

Figure 2[4)] shows a conventional steering system. The example uses the column assisted type electric power steering widely spreaded in passenger cars for the general public. I and M are inertia, and K, R and C are elasticity, friction and viscosity, respectively. T, θ, F and X are torque, displacement angle, force and displacement amount respectively. The letters attached indicate the position of the element part.

As **Fig. 2** shows, the SW and rack are mechanically connected by various element parts such as the torsion bar and reduction gear. Therefore, the transfer characteristic $G_1(j\omega)$ is affected by the element characteristics and it becomes complicated.

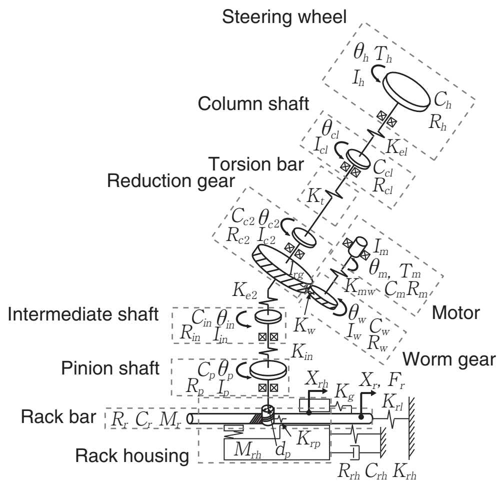

Fig. 2 Conventional steering model

3. 1. 2 From Rack Displacement X_r to Front Wheel Angle θ_t

Suspension is the next activated element after the steering mechanism. Each component element is displaced caused by the rigidity, geometric settings and so on of each link section. The transfer characteristic $G_2(j\omega)$ of front wheel angle θ_t against rack displacement X_r changes according to this affect.

$$G_2(j\omega) = \frac{\theta_t(j\omega)}{X_r(j\omega)} \tag{3}$$

3. 1. 3 From Front Wheel Angle θ_t to Cornering Force F

The following element is the front wheel. Cornering force F relating to front wheel angle θ_t varies depending on the state of the road surface and grounding load. Further, air pressure, tread shape, material, temperature, and all influential elements make the transfer characteristic, $G_3(j\omega)$, complicated.

$$G_3(j\omega) = \frac{F(j\omega)}{\theta_t(j\omega)} \tag{4}$$

3. 1. 4 From Cornering Force F to Yaw Rate γ

The vehicle characteristic from when the cornering force F is affected to when yaw rate γ occurs is considered. Yaw rate γ occurs in relation to cornering force F, affecting by vehicle inertia, rear wheels generative force, etc.

$$G_4(j\omega) = \frac{\gamma(j\omega)}{F(j\omega)} \tag{5}$$

In the above-mentioned way, the yaw rate in response to SW angle transfer characteristic $G_\gamma(j\omega)$ is expressed by the product of the sub-system transfer characteristics, G_1 to G_4, shown in equation (1) through (5).

3. 2 Transmission from Vehicle to Driver

This section discusses the process by which vehicle behavior is transferred to the driver. In conventional steering, it is not possible to separate the process of vehicle-to-driver transfer from that of driver-to-vehicle transfer. However, for the purposes of explanation, transfer characteristics for the driver to the vehicle, G_1 to G_3, are shown separately (**Fig. 1**).

The cornering force F on the front wheels goes through the steering system and is transferred to the SW as steering reaction torque T_r. $G_5(j\omega)$ is the transfer characteristic from cornering force F to steering reaction torque T_r.

$$G_5(j\omega) = \frac{T_r(j\omega)}{F(j\omega)} \tag{6}$$

As the cornering force is the source of vehicle behavior, it is believed that the driver uses steering reaction torque T_r as one piece of information to predict the state of the vehicle.

Also, the sum of steering reaction torque T_r and input torque T_h affects the SW angle θ_h that the driver operates. The transfer characteristic here is defined as $G_6(j\omega)$.

$$G_6(j\omega) = \frac{\theta_h(j\omega)}{T_h(j\omega) + T_r(j\omega)} \tag{7}$$

In this way, steering reaction torque T_r affects the transfer characteristic from the driver to the vehicle via the steering angle. In other words, transfer characteristics G_5 and G_6 are important design elements of the steering system.

3. 3 Setting the Target Transfer Characteristic

Target transfer characteristic $G_\gamma(j\omega)$ for the vehicle system was investigated with the driver characteristic. Experiments have proven that transfer characteristic of the open-loop system in **Fig. 3**(a) are shown in **Fig. 3**(b)[6~8] when the driver controls the vehicle movement. In other words, in the proximity of the crossover frequency ω_c where the gain is 0 dB, the slope is around –20 dB/dec. Assuming that the driver transfer characteristic $H(j\omega)$ involves time delay, the open-loop transfer characteristic, as equation (8) shows, can be described as the integral formula[6~8]. That is to say, in a closed-loop, it has the characteristic that reduces the steady-state deviation of yaw rate in a low frequent of yaw rate. Furthermore, it has a robustness against high-frequency deviation such as the noise[6~8]. These are important characteristics in regards to driver-vehicle system closed-loop stability.

$$H(j\omega)G(j\omega) = \omega_c \frac{e^{-\tau e j\omega}}{j\omega} \tag{8}$$

ω_c : Crossover frequency
τ_e : Time-delay due to driver

Also, against the transfer characteristic $G(j\omega)$ of target vehicle system, the driver attempts to achieve the characteristic of **Fig. 3**(b) by changing his own characteristic $H(j\omega)$. Actually, the driver controls the vehicle dynamics by adding the compensatory maneuver[9] such as differentiation steering input against to the nonlinearity and delay characteristics of vehicle system that include steering system.

The 1st-order system of the vehicle transfer characteristic such as the equation (9) could reduce compensatory maneuver. Thus, the maneuverability could be improved because the characteristic of driver $H(j\omega)$ is composed by the proportional gain and the time delay only such as the equation (10).

$$G(j\omega) = \frac{K}{\tau \cdot j\omega + 1} \tag{9}$$

$$H(j\omega) = K_h \cdot e^{-\tau e j\omega} \tag{10}$$

K : Steady-state gain of Vehicle system transfer characteristic
K_h : Proportional gain of Driver model
τ : Time constant of Vehicle system transfer characteristic

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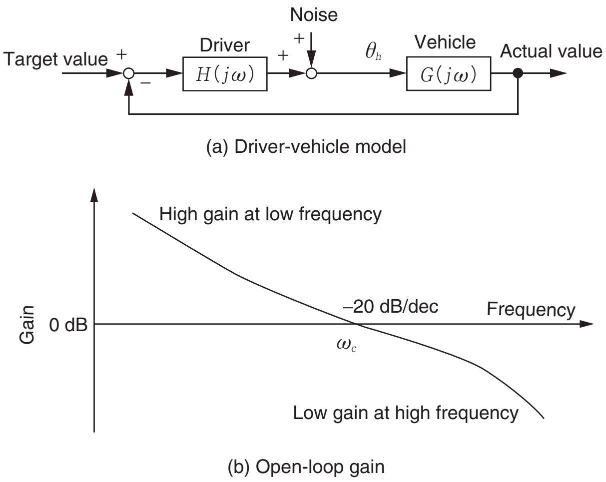

Fig. 3 Dynamic interaction of driver and vehicle

3. 4 The Transfer Characteristic Design of Conventional Steering Systems

As the mentioned above, in conventional steering systems, the bilateral transfer is conducted via the same mechanism by mechanical connection. Moreover, mechanical elements cause nonlinearity, delay characteristic, etc. Consequently, it is not possible to remove the effect of these characteristics from steering input to the beginning of the vehicle motion occurrence. In other words, overall system transfer characteristic cannot be set independently and arbitrarily. Furthermore, the optimizations of element component characteristics are not realistic due to the limitations such as design standards and part commonality.

In the next section, the transfer characteristic between the driver and the vehicle is investigated in view of HMI using a SBW system, which does not have a mechanical connection.

4. Transfer Characteristic of the SBW System

Figure 4 shows schematic diagram of the SBW system. The solid line shows the mechanical transfer route, and the broken line shows the electronic transfer route. Unlike conventional steering, there is no mechanical transfer route between the SW and the rack. Below, two examples of transfer characteristic from the driver to the vehicle using a SBW system are described.

4. 1 Rack Displacement Control

As **Fig. 4** shows, the SW angle θ_h that is input from the driver is converted into an electronic signal and transferred to the rack displacement control unit. The steering actuator is controlled and the rack displacement X_r is controlled in feedback based on the amount of the SW angle θ_h. In other words, it is determined by the transfer characteristic of G_{SBW1}, which is a combination of control unit and steering actuator characteristic.

$$X_r(j\omega) = G_{SBW1}(j\omega)\cdot\theta_h(j\omega) \tag{11}$$

Figure 5 shows the transfer structure of the steering system using this control strategy. Unlike the conventional steering shown in **Fig. 1**, a feedback control system of the rack displacement X_r against to the SW angle θ_h is composed. In other words, the nonlinearity and the delay characteristic included in the conventional steering transfer characteristic G_1 are compensated by this control.

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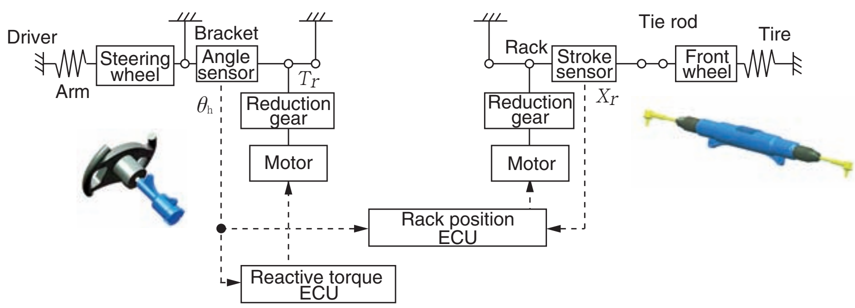

Fig. 4 Schematics of SBW system

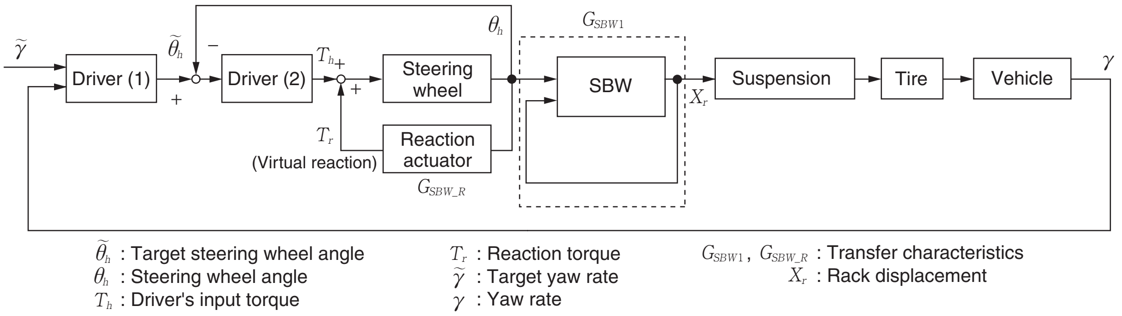

Fig. 5 Steering control of SBW system with virtual reaction and rack position control

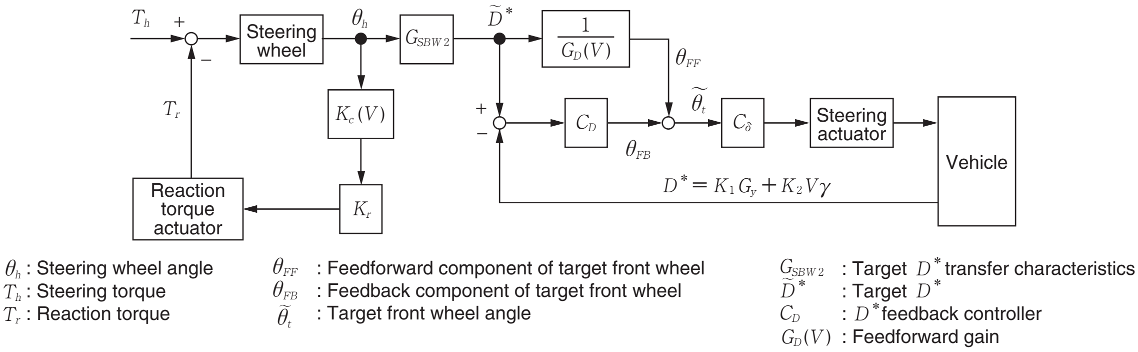

Fig. 6 Control block diagram of SBW D^* control

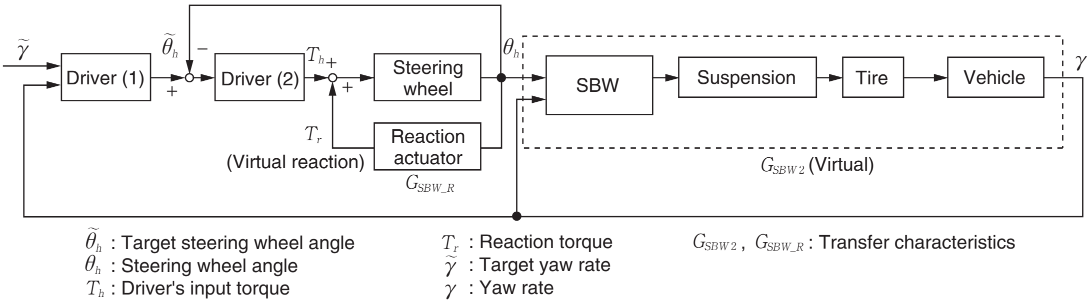

Fig. 7 Steering control of SBW system implementing virtual reaction and vehicle control

4. 2 Vehicle Behavior Direct Control

The control which set the target such as the yaw rate of the vehicle directly from the steer input by the driver[11] is considered in this section. It is called as "Vehicle dynamic direct control" and is indicated an example as follows. The target vehicle dynamics index $\tilde{D}^*$ is set from SW angle taking account of the vehicle speed V. The actual D^* value is fed back which is defined as the linear sum between lateral acceleration and yaw rate indicated by the equation (12). The front wheel angle is controlled based on this deviation. The **Fig. 6** shows this control block.

$$D^* = K_1 G_y + K_2 V\gamma \qquad (12)$$

K_1, K_2 : Weight coefficient (however, $K_1+K_2=1$)

For example, the equation (12), in case of K_1=0, means the control to follow the target of yaw rate. The transfer structure of the steering system becomes like the **Fig. 7** according to this control. Unlike the conventional steering system, the actual yaw rate is fed back in the section surrounded by the broken line of **Fig. 7**. Thus, the influences of the transfer characteristic of suspension, front wheel, and the vehicle(G_2, G_3, G_4) are automatically compensated. As the consequence, compensation maneuver described in the **section 3. 3** is not necessary, the workload of the driver is reduced[10].

$$\gamma(j\omega) = G_{SBW2}(j\omega)\cdot\theta_h(j\omega) \qquad (13)$$

5. The Design of Steering System Transfer Characteristic

The transfer characteristics of the steering system were investigated using SBW in view of HMI in order to achieve the target maneuverability. The transfer characteristic of rack displacement X_r against to the SW angle input θ_h was examined in order to improve maneuverability of the beginning of the steering as the second report as an example.

The input wave indicated in the **Fig. 8** was assumed as the input condition of SW angle θ_h. The SW angle speed increases rapidly at increasing of the SW angle of the beginning of steering and the SW angle input transfers to the sine wave form.

The following three kinds of the rack displacement transfer characteristics (**Fig. 9**) have been designed in order to study an ideal transfer characteristic.

First, the nonlinearity and no delay characteristic which cannot be avoided on the conventional steering system with mechanical connections are studied. The characteristic A that the gain of rack displacement X_r against to the SW angle θ_h of the driver is linear as an example (solid line A of **Fig. 9**).

Next, the characteristic B is simulated of conventional system that has been described in second report as an example of improvement of the rigidity and the friction characteristic. This characteristic included the nonlinearity and the delay caused by mechanical connections (broken line B of **Fig. 9**).

Additionally, the transfer characteristic C taking account of HMI is considered. This characteristic is taken account of the closed-loop transfer characteristic in the driver-vehicle system which is indicated in the **Fig. 3** as an example. It is assumed that gain lowering and delay of the steer sub-systems G_2, G_3, G_4, except steering system, are small. Under this assumption, the steering transfer characteristic G_1 can be set as the characteristic with 1^{st}-order lag according to the open-loop transfer characteristic in **Section 3. 3**. Characteristic C is set so that the change of the gradient of the rack displacement transfer characteristic is equivalent to −20 dB/dec (dot-dash line C of **Fig. 9**) under the steering input conditions indicated in the **Fig. 8**.

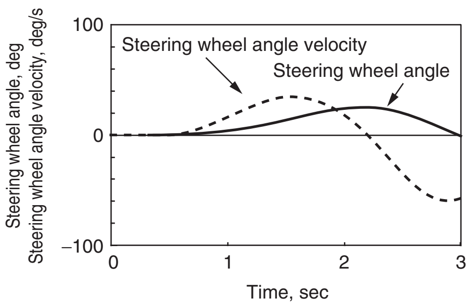

Fig. 8 Steering input conditions

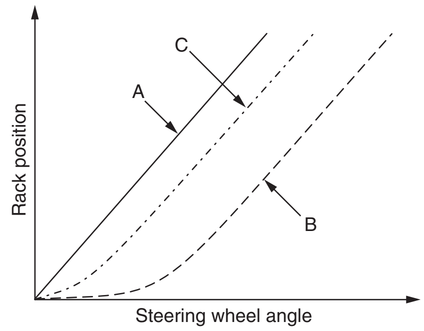

Fig. 9 Steering transfer characteristics

6. The Evaluation by the SBW Test Vehicles

The three kinds of transfer characteristics indicated in the **Chapter 5** have been realized by the SBW system and evaluated using a test vehicle. The **Fig. 10** shows the driving course. The test driver has engaged in the vehicle and the steering system evaluations for 15 years continuously.

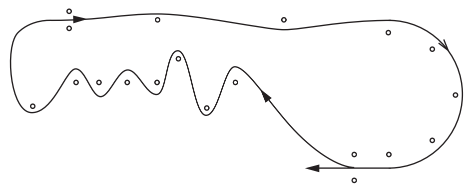

Fig. 10 Test track for sensory evaluations

Here are their evaluation comments.

Characteristic A:
Vehicle yaw motion occurs immediately after steering maneuver. When the SW is turned back, it is accompanied by a large yaw rate and the SW angle must be returned by the driver.

Characteristic B:
Vehicle yaw rate that occurred at the beginning of steering maneuver is not enough, therefore the amount of SW angle must be increased. It is difficult for the driver to achieve the target yaw rate from time to time.

Characteristic C:
A suitable yaw rate occurs. Additional compensatory maneuver is not required and the driving course can be easily cleared.

In the case of characteristic A, there is minimum steering system delay, sufficient yaw rate is generated from the beginning of steering maneuver. However the corrective steering by the driver is necessary because the rack is moved by the driver's steering input with noise element.

In the case of characteristic B, the yaw rate at the beginning of steering maneuver is small. Therefore, the driver has to compensate by changing velocity of the

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steering maneuver, etc., in order to compensate for the lack of yaw rate. Additionally, it is difficult to correct steering maneuver because the gain changes significantly at the increasing of the SW angle. It may be the cause of disagreeableness for the driver.

In the case of the characteristic C, it is robust against to the noise element which is included in driver's steering maneuver and the increasing of yaw rate is suitable at the beginning of steering maneuver. This means that it has suitable responsiveness, damping and steady characteristic in the transfer characteristic which is indicated in **Fig. 3**. It is considered that the characteristic C has been set in taking account of this test vehicle characteristic and HMI characteristic. This characteristic is the best in the three characteristics. The driver can realize the best steering control by the steering transfer characteristic which has been designed to achieve an open- and closed-loop characteristic which is suitable for the driver. It can be said that this characteristic C is ideal as the vehicle dynamics characteristic of the vehicle.

7. Summary

(1) It is possible to set the ideal steering system transfer characteristic in view of HMI by the SBW system which has no mechanical connections. On the other hand, it is difficult for conventional steering system to realize the ideal transfer characteristic due to the nonlinearity and the delay characteristic caused by the mechanical connections.

(2) Three kinds of steering transfer characteristics have been set and their features have been evaluated by a SBW test vehicle.

(3) The excellent steering maneuverability has been achieved by the transfer characteristic whose target is the realization of ideal characteristic taking account of symbiosis of driver and vehicle in closed-loop.

8. Conclusion

Steering system is a bilateral interface between the driver and the vehicle. A research that is taking account of the ideal adaptation for delay of recognition, judgment and operation of human characteristic is necessary.

Next report will be introduced a case study of the improvement for the conventional steering system maneuverability using a design approach of the second report as well as this report.

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