Research on Steering Wheel Control Strategy as Man-Machine Interface for Steer-by-Wire System

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The steering reactive torque control is a keen subject to improve operationality in SBW (steer-by-wire) system and maneuverability by utilizing the feature of SBW.

The research described in this paper aims at realization of steering feeling harmonized with vehicle behavior, as well as establishment of the reactive torque control logic that can be applied to any kind of vehicles. The control logic that feeds back lateral acceleration and yaw rate which have close relation to the vehicle turning performance to the steering reactive torque directly was developed. Also the evaluation test by actual vehicle using this control logic was conducted, result of which is described. The relation between the reactive torque reflected on the vehicle behavior and the driver's characteristics was analyzed.

***Key Words**: steer-by-wire, man-machine interface, reactive torque control, vehicle behavior*

1. Introduction

Various types of power steering systems have been developed so far, but recently, from the viewpoints of environmental protection and energy conservation, new types of electric power steering systems have been put into practical use that electronically controls steering assist force by an electric motor. Furthermore, steering systems are also required to have not only conventional "turning" function but also intelligent "turning" function through integrated control with other components such as chassis and driving systems. As one of the steering systems that can realize these functions, Steer-by-Wire (hereinafter referred to as SBW) system has been developed.

With SBW, steering gear operation is controlled electronically, and therefore automated control that ensures safe, pleasant vehicle movement is possible. Since there is no mechanical linkage between the steering wheel and steering gear, interference between the driver and the steering system during active steering is easily avoided, which was impossible in the case of conventional systems. As a result, vehicle behavior control through active steering using SBW in sudden-braking testing on a μ-split road was confirmed to be superior in vehicle behavior stabilizing performance compared to the case of conventional method of braking/driving force distribution[1), 2)].

In conventional steering systems, steering torque characteristics for operating a steering wheel and maneuverability have been directly influenced by factors other than a steering gear itself, such as suspension geometry and road situation like wheel ruts. In contrast, SBW controls transmission of such information to the driver appropriately, so that there is a possibility of realizing optimal operability and torque characteristics for a driver. In this regard, through the use of SBW, researches have been performed in pursuit of intelligent steering operation differing from that of conventional systems to create a driver-oriented steering system that operates as a man-machine interface, by which the driver can drive by receiving linear feedback of physical properties of a vehicle or environment characteristics such as road conditions.

2. Steer-by-Wire System

Figure 1 shows the outline of SBW system used in this research. Steering operation of a driver is measured by the steering wheel angle sensor and torque sensor. The controller governs the steering angle of the front wheels through a steering actuator using information from various sensors. A rack-assist type electric power steering is used as a steering actuator in this study.

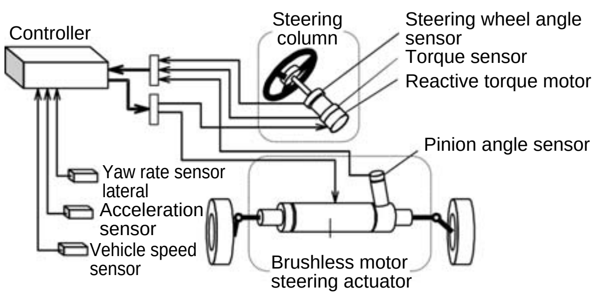

Fig. 1 System construction

Operability of SBW is significantly influenced by characteristics of the steering input device that functions as an interface with the driver. Believing the shape of the steering input device and the torque for operating it to be important factors, the authors selected a conventional type of steering wheel considering marketability and driver's sensitivity. A motor was also connected as the mechanism for providing response feeling to the driver.

3. Reproduction of Conventional Steering Feeling

With an idea that a driver evaluates the operability based on the rotation rate of the steering wheel and accompanying torque generation, steering reactive torque was assumed to be a closed-loop between the driver and the steering wheel, and input by the driver was assumed to be steering wheel angle δ_h only. In order to reproduce conventional steering feeling as accurately as possible, the steering reactive torque to the driver was calculated by multiplying the cornering force coefficient $K_c(V)$ and steering reactive torque proportional gain K_T as shown in formula (1). The control block diagram based on this system is shown in **Fig. 2**.

$$T_r = K_T \cdot K_c(V) \cdot \delta_h \qquad (1)$$

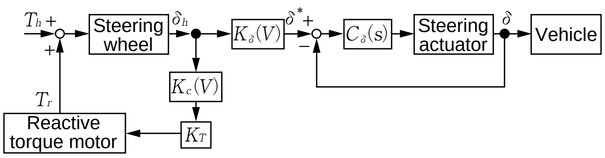

Fig. 2 Block diagram of reactive torque

T_h : Driver input torque
T_r : Reactive torque
δ_h : Steering wheel angle
δ^* : Target front wheel steering angle
δ : Actual front wheel steering angle
$C_\delta(s)$: Front wheel steering angle controller
$K_\delta(V)$: Front wheel steering angle gain
$K_c(V)$: Cornering force coefficient
K_T : Steering reactive torque proportional gain

Further, the front wheel steering angle control is performed by correlation between the target front wheel steering angle δ^* and the feedback information of the actual front wheel steering angle δ, while the target steering angle δ^* is determined by multiplication of the steering wheel angle δ_h by the ideal front wheel steering angle gain $K_\delta(V)$ that can be set as the vehicle speed coefficient.

This control logic was installed on the driving simulator shown in **Fig. 3** and its maneuverability was evaluated. In this evaluation, road surface friction was set as equal to that of dry asphalt road and pylons were arranged at 30 m intervals. Slalom driving was simulated with a vehicle speed of 22.2 m/s. As can be seen from the results shown in **Fig. 4**, steering torque values vary when the vehicle passes by the pylons. This is due to driver's steering operation to compensate for the difference between expected and actual vehicle behavior resulting from the driver's steering torque input.

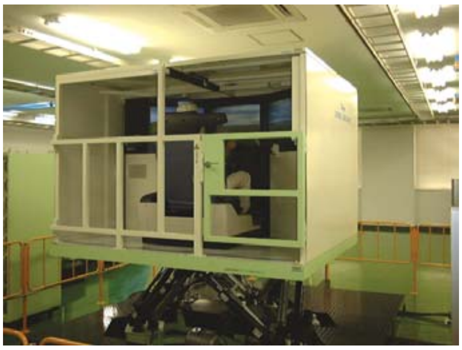

Fig. 3 Driving simulator

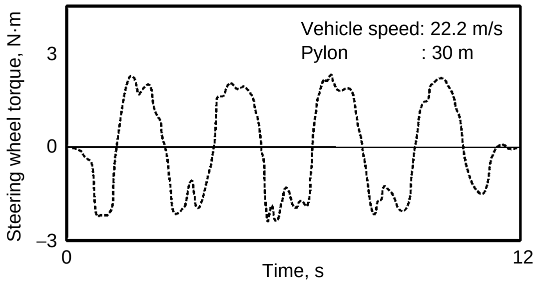

Fig. 4 Test result of driving simulator

This is similar to conventional steering operation by drivers to compensate for the phase delay in the steering input system, in which case the driver performs feedforward control depending on the vehicle's dynamic characteristics to stabilize the dynamic characteristics of the driver-vehicle system. This kind of compensation has been a mental burden on the driver[3), 4)] and a problem that is difficult to solve in conventional vehicles. The reason is considered to be the fact that the driver detects imitated information regarding front wheel angle from the reproduced steering feeling and based on that attempts to control the vehicle.

A steering reactive torque in SBW can be designed from a new viewpoint, different from the reproduction of the steering reactive torque by normal vehicles. Specifically, if the driver can directly control the vehicle behavior, not only will the burden of feedforward control be eliminated but also operability will be improved. In order to realize this, a method for controlling the steering reactive torque with improved maneuverability was examined by recognizing the steering system as a direct man-machine interface between the vehicle and the driver.

4. Appropriate Steering Reactive Torque Control for SBW

4. 1 Concept of Reactive Torque Control

In the test described above done as part of preliminary research, it was demonstrated that reproducing only conventional steering feeling was not sufficient as a role of usability of controlling the reactive torque. Thus, in order to provide further improved operability and maneuverability, concepts of this research were made clear.

Figure 5 shows general driver's characteristics. As can be seen in Fig. 5, the driver operates the vehicle based on vehicle behavior. It can be said that the driver basically tries to achieve the same vehicle behavior regardless of the specifications of the vehicle he is driving. Based on this observation, the first concept was determined as the realization of the steering feeling harmonized with the vehicle behavior.

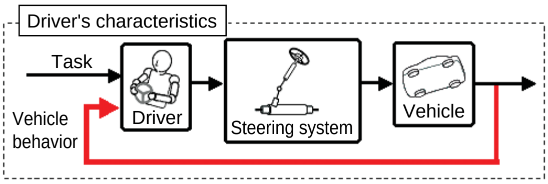

Fig. 5 The driver's characteristic

Since SBW has no mechanical linkage between the steering gear and the steering wheel, SBW can provide optimal steering reactive torque to the driver regardless of the vehicle specifications. Thus, the second concept was determined as the establishment of reactive torque control adaptable to vehicles of any specifications (**Fig. 6**).

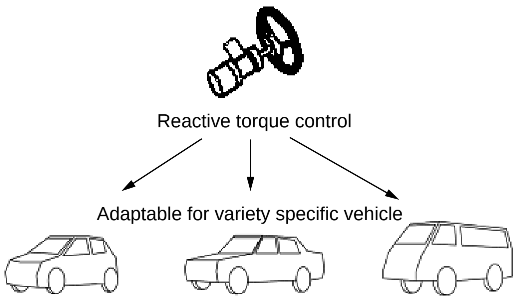

Fig. 6 Concept of reactive torque control for SBW vehicle

In order to achieve these two concepts, the vehicle behavior was used as the parameter that was common among various vehicles. Among vehicle behavior parameters, a lateral acceleration and a yaw rate of vehicles that have high relation with turning movement of vehicles were selected in this research.

4. 2 Reactive Torque Control Reflecting Vehicle Behavior

In past research[5] done for the purpose of improving vehicle dynamics, the authors evaluated control in which vehicle behavior is presented to the driver as steering wheel angle. In this control, vehicle lateral acceleration and yaw rate, selected in the above section, were used as parameters for steering reactive torque. Specifically, as shown in **Fig. 7**, the steering reactive torque T_{r1} calculated by the steering wheel angle δ_h was overlaid with the vehicle behavior feedback term T_{r2}. As a result, steering wheel angle δ_h was made to follow the target steering wheel angle $\delta_h{}^*$ calculated by vehicle behavior.

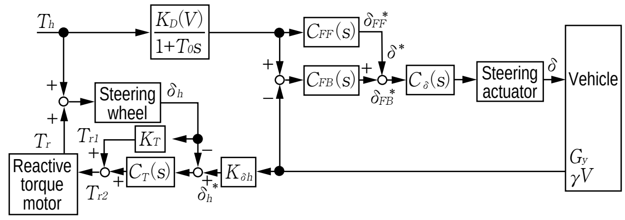

Fig. 7 Block diagram of reactive torque reflecting vehicle behavior

In order to evaluate the effect of this control logic, influence on operation by the driver was investigated by means of a driving simulator. Test conditions were the same as those shown in Section **3**.

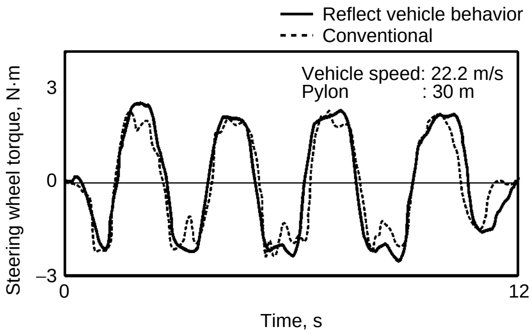

Fig. 8 Comparison of control logics using driving simulator

As a result, steering torque fluctuation seen in conventional control for reproducing steering feeling was reduced. The reason is that vehicle behavior felt by a driver corresponds to actual vehicle behavior. As a result, the load placed on the driver by feedforward control was presumably reduced.

In this steering reactive torque control, steering reactive torque is generated by the difference occurring between the steering wheel angle generated by driver steering input and the target steering wheel angle calculated based on the vehicle behavior. With this control, the driver can drive easily because when there is deviation between steering wheel angle and the target steering wheel angle calculated based on vehicle behavior, steering reactive torque is generated to compensate for it. However, when driver input corresponds to vehicle behavior, steering reactive torque reflecting vehicle behavior is not generated, and only the steering reactive torque proportional to steering wheel angle is applied to the driver. As a result, the problem of there existing many regions in which the driver cannot feel vehicle behavior through the steering reactive torque during normal driving remains unsolved.

4. 3 Vehicle Behavior Feedback Control

In order to solve the problem described above, it is necessary to determine regions in which harmony with vehicle behavior is needed and those in which it isn't, and find a method for returning vehicle behavior appropriately. In order to clarify the relation between vehicle behavior and driver characteristics, vehicle behavior in the form of lateral acceleration and yaw rate is directly fed back to steering reactive torque, as shown in the **Fig. 9** block diagram, so that the driver can continually feel vehicle behavior characteristics as steering feeling, and a comparative test was performed. In this research, the control using lateral acceleration as a parameter is referred to as G_yFB control, and the control using yaw rate as a parameter is referred to as γ FB control.

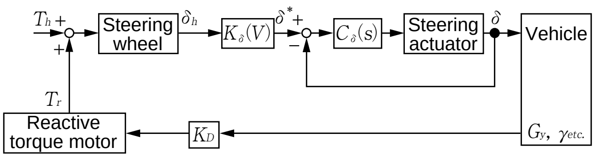

Fig. 9 Block diagram of reactive torque control with feedback of vehicle dynamics parameter

4. 3. 1 Vehicle Running Test

In order to verify the effectiveness of the above-described control logic, a vehicle running test was performed on a running course enabling a lane change operation. **Figure 10** shows the course used for this test and **Table 1** shows the test pattern.

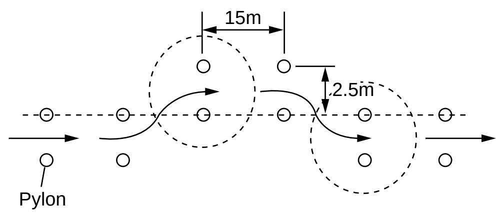

Fig. 10 Test course layout

Table 1 Test pattern

Parameters / Vehicle speed	Lateral acceleration : G_y	Yaw rate : γ
8.3m/s	1	2
13.9m/s	3	4
19.4m/s	5	6

Pylons were arranged in gate-like pairs sandwiching the dry asphalt road centerline at 15 m interval in a pattern to allow repeated lane changing. Three running conditions having the target vehicle speeds of 8.3 m/s, 13.9 m/s, and 19.4 m/s were used and the test drivers were instructed to keep these target vehicle speeds as much as possible. The vehicle speed of 19.4 m/s is close to the limit of the driver's ability to perform the required maneuvering. Three test drivers were randomly selected from engineers. In this test, the maneuverability of the vehicle when the vehicle entered the pylon gates shown by the dotted circular lines in **Fig. 10** was evaluated and analyzed. The test results are shown in **Fig. 11**.

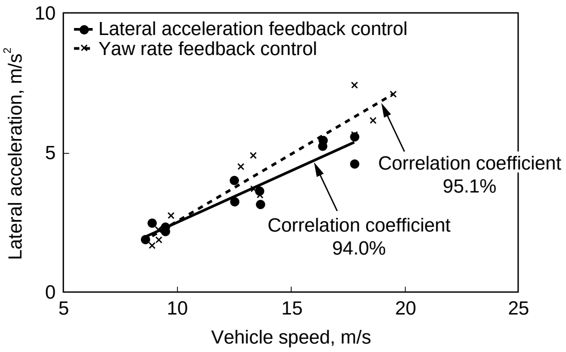

Fig. 11 Lateral acceleration peak values

As described above, the authors focused attention on lateral acceleration during the driving on the test course as an evaluation index for vehicle maneuverability and considered that, the smaller the lateral acceleration peak value when the vehicle enters the pylon gates, the more closely to the target the vehicle can be operated. Based on this idea, lateral acceleration peak values compared to vehicle were presented in the graph. The result was that the characteristic of more than 90% correlation was founded at all points between vehicle speed and lateral acceleration peak values. It was also found that the vehicle speed close to 19.4 m/s showed the characteristic in which the peak value of lateral acceleration of G_yFB control was lower than that of the γ FB control. This shows that it can be judged that the G_yFB control is superior to γ FB control in maneuverability. However, the difference between G_yFB control and γ FB control was small and thus the sensory test described in the section below was additionally performed.

4. 3. 2 Sensory Evaluation Test

Sensory evaluation test was performed based on the evaluation items shown in **Table 2** in which the results were evaluated based on four ranks.

As can be seen in **Table 2**, the results of the sensory evaluation test also showed the difference among evaluation results depending on the kind of control. It was found that G_yFB control could provide superior "matched" feeling with the vehicle behavior as compared to the case of γ FB control.

Table 2 Result of sensory evaluation test

Evaluation items		Control: Lateral acceleration feedback control	Yaw rate feedback control
Operation	Smoothness of rotational torque	3	3
	Resistance feeling (inertia, viscosity, friction)	3	3
Maneuver ability	Steering wheel returnability	4	4
	Stability (convergence)	3	2
	Feeling of matching with vehicle behavior	4	3

Ranks: 4–Excellent; 3–Borderline; 2–Unsatisfactory; 1–Impossible

5. Conclusion

Through this research, it was confirmed that control using feedback of vehicle behavior provides steering reactive torque with maneuverability superior to that of conventional control to reproduce steering torque. It was also demonstrated that use of lateral acceleration as a parameter could provide more harmonized feeling to vehicle behavior than the use of yaw rate.

The authors intend to carry out detailed analysis from the viewpoint of phase and gain, and determine more detailed steering reactive force dynamic characteristics as vehicle behavior parameters to optimize steering feeling. In regard to static characteristics such as steering torque characteristics when the driver begins to turn a straight-moving vehicle as well, the authors intend to clarify characteristics most suitable to the driver, and in the end establish optimal steering operation as a man-machine interface.

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