Active-Steering Control System Based on Human Hand Impedance Properties

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***Abstract*—This paper proposes an active-steering control method that uses human hand impedance properties. In this method, the dynamic properties of a steering device manipulated by the upper limbs are automatically regulated according to the damping coefficient of the human-steering system. Human hand impedance in steering operations is measured and modeled depending on the steering angle and torque for use in the proposed control structure. The effectiveness of the proposed method was demonstrated by performing an emergency avoidance task using a stationary driving simulator.**

***Index Terms*—Human hand impedance, Impedance control, Active-steering**

I. Introduction

Human drivers skillfully manipulate driving interfaces such as a steering wheel or a shifter knob by adjusting the musculoskeletal system according to specific driving situations. As steering operators, for example, humans actively adjust their arm postures and hand forces by perceiving the changes in the reaction torque from the steering wheel according to vehicle speed and load conditions. In such tasks involving physical interaction between a human driver and a mechanical driving interface, drivers regulate the dynamic properties of their limbs on the basis of external and/or internal information to enable the appropriate control of vehicle motion. If the dynamic properties of humans in accordance with driving situations can be quantitatively described, such quantitative information would be useful in the design and development of a novel driving-assist system that would provide greater comfort while driving.

The dynamic properties of human movement can be expressed using mechanical impedance parameters, i.e., stiffness, viscosity, and inertia, and many experimental studies on human hand impedance have been reported. Mussa-Ivaldi et al. [1] pioneered the measurement of human hand impedance and examined hand stiffness within a stable arm posture. They found that stiffness strongly depends on the arm posture. Dolan et al. [2] and Tsuji et al. [3] also showed that human hand viscoelasticity is considerably affected by muscle activation levels during isometric contraction. These experimental studies reveal that humans can control impedance by regulating limb postures and/or muscle contraction levels during multi-joint movement. Some studies on the impedance characteristics of the human hand during steering operation have also been reported. For example, Li et al. [4] analyzed the relationship between the stiffness of the steering wheel and the hand stiffness of the operator through theoretical calculation and experimentation, and they showed that the overall stiffness depends on the internal force and the muscle contraction of human arms. Ikeura et al. [5] developed an apparatus for an automotive steering system using variable impedance control, and they analyzed the relationship between the operational feeling of the steering system and the hand stiffness measured experimentally during the steering operation. However, these studies did not demonstrate the accuracy of estimation of human hand impedance, and their purpose was to analyze/evaluate human motion properties during steering operation rather than to design a steering control system based on these factors.

Recently, research has been conducted on by-wire technology for driving interfaces such as steering systems [6]–[10]. Bajcinca et al. [9] demonstrated, without modeling the physical dynamics of a human, that a steering control system based on model reference-based control algorithms that incorporate a disturbance observer and active observers showed enhanced robustness. However, they dealt with the hand stiffness only as a possible range, and they treated hand viscosity as a constant in their control system, although hand viscosity undergoes changes. Thus, the actual characteristics of human impedance properties in steering operations were considered. On the other hand, Tanaka et al. [12] analyzed human impedance properties according to limb postures and end-point forces during steering operation, and they reported that human impedance properties vary during driving operations. They also proposed the basic concept of a control structure using human impedance properties for the gas-pedal system [13]. However, they did not discuss how the dynamic properties of a steering system might be controlled according to specific driving situations. Thus, in the present study, we aim to develop an active-steering control system based on human hand impedance properties by further expanding on the previous study of the gas pedal [13].

This paper is organized as follows: Section II outlines the proposed active-steering control system using human hand impedance and a function to adjust the damping coefficient of the human-steering system. Section III describes an experimental apparatus developed using a robotic device to measure the human impedance of the upper limbs and explains a method for impedance measurement during steering operations. Section IV describes a design for a regulation function of the damping

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coefficient according to steering operations. This function's purpose is to improve both operational accuracy and reaction quickness during emergency avoidance situations. The performance of the proposed system is demonstrated using the developed experimental system.

II. Active-Steering Control method Using Human Hand Impedance

Fig. 1 (a) shows a block diagram of the proposed steering control system based on human hand impedance. The steering motor is under a variable-impedance control, and the database outputs the human impedance properties on the basis of a combination of steering angle θ and torque τ measurements during operation.

The dynamic behaviors of the steering motor around its rotational axis can be given by

$$M_{\theta s}\ddot{\theta}_v + B_{\theta s}\dot{\theta}_v + K_{\theta s}(\theta_v - \theta_{sc}) = \tau, \qquad (1)$$

where $M_{\theta s}$ is the steering inertia; $B_{\theta s}$ and $K_{\theta s}$ are the variable viscosity and stiffness, respectively; θ_v is a target angle at the next sampling time calculated from the steering impedance properties with the current steering torque τ; and θ_{sc} is an equilibrium for $K_{\theta s}$. On the other hand, the dynamics of human hand movements when handling the steering wheel can be expressed with an impedance model [1] as

$$M_{\theta h}\ddot{\theta} + B_{\theta h}\dot{\theta} + K_{\theta h}(\theta - \theta_{hc}) = \tau, \qquad (2)$$

where $M_{\theta h}$, $B_{\theta h}$, and $K_{\theta h}$ represent the inertia, viscosity, and stiffness of the human hand according to θ and τ, respectively; and θ_{hc} is a virtual trajectory for $K_{\theta h}$.

In this paper, the human-steering system is discussed using a rotational spring-mass-damper system as shown in Fig. 1(b), where two elements are connected in series. Its equation of motion can then be described as

$$(M_{\theta s} + M_{\theta h})\ddot{\theta} + (B_{\theta s} + B_{\theta h})\dot{\theta} + (K_{\theta s} + K_{\theta h})\theta = \tau, \qquad (3)$$

and the damping coefficient ζ is calculated as

$$\zeta = \frac{B_{\theta h} + B_{\theta s}}{2\sqrt{(M_{\theta h} + M_{\theta s})(K_{\theta h} + K_{\theta s})}}. \qquad (4)$$

The driver's load for steering operations increases with the damping coefficient ζ, and vice versa. As the damping coefficient ζ is designed according to the driving situation, it will be expected that the steering device assists the driver's steering operations by actively regulating its own dynamics on the basis of human hand impedance properties.

III. Human Hand Impedance during Steering Operations

A. Method of Impedance Measurement

Human hand movements during steering operations are restricted within the rotational axis of the steering wheel with radius r as shown in Fig. 2. In the impedance measurements during maintenance of the arm posture, the hand is displaced from its position with a small disturbance of short duration. Therefore, the hand impedance properties can be regarded as constant. Assuming θ_{hc} is also constant for the disturbance by the external torque τ_{ext}, the following relationship at time t can be obtained from Eq. (2) as:

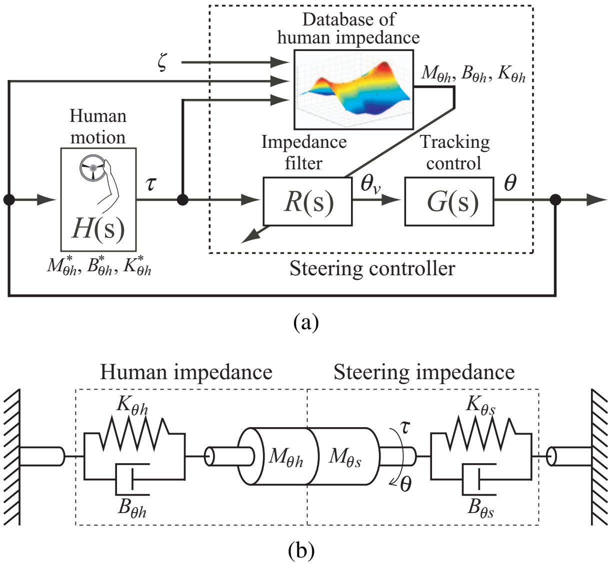

Fig. 1. The proposed active-steering control system

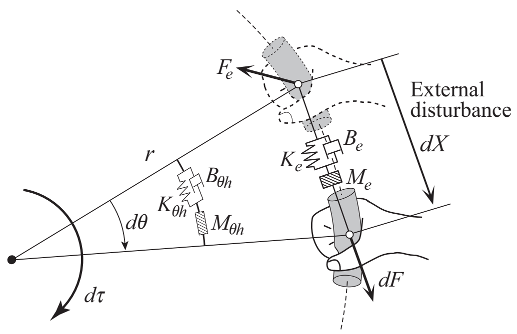

Fig. 2. Schematic description of hand impedance measurement during steering operations

$$M_{\theta h}\ddot{\theta}(t) + B_{\theta h}\dot{\theta}(t) + K_{\theta h}(\theta(t) - \theta_{hc}) = -\tau_{ext}(t). \qquad (5)$$

At the onset time of the disturbance t_0, we have

$$M_{\theta h}\ddot{\theta}(t_0) + B_{\theta h}\dot{\theta}(t_0) + K_{\theta h}(\theta(t_0) - \theta_{hc}) = -\tau_{ext}(t_0), \qquad (6)$$

and θ_{hc} can be eliminated from Eqs. (5) and (6) as

$$M_{\theta h}d\ddot{\theta}(t) + B_{\theta h}d\dot{\theta}(t) + K_{\theta h}d\theta(t) = -d\tau(t), \qquad (7)$$

where $d\theta(t) \equiv \theta(t) - \theta(t_0)$, $d\tau(t) \equiv \tau_{ext}(t) - \tau_{ext}(t_0)$. All the human impedance parameters can be estimated by fitting the measured time sequences of the steering angle and torque to Eq. (7) using the least squares method.

On the other hand, the hand displacement dX during rotational motion with radius r can be approximated with the rotational displacement around the steering rotational axis $d\theta$ as

$$dX(t) \approx r d\theta(t), \qquad (8)$$

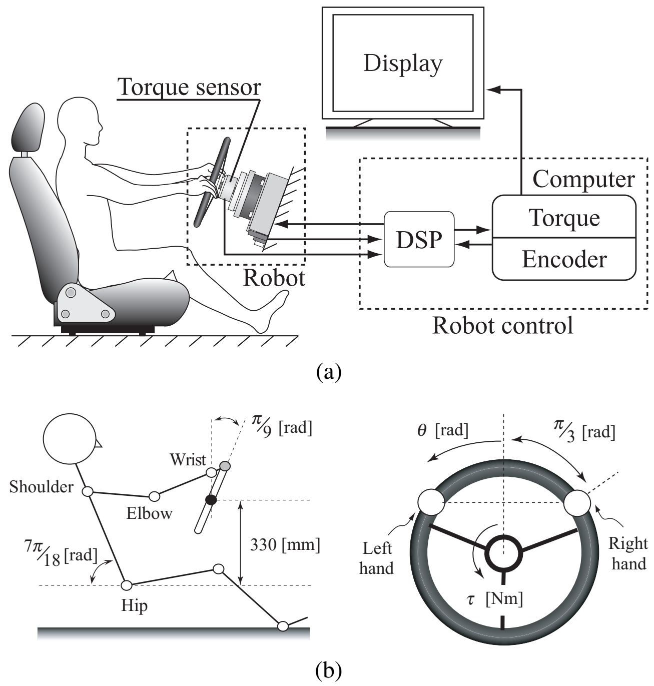

Fig. 3. Experimental system and condition.

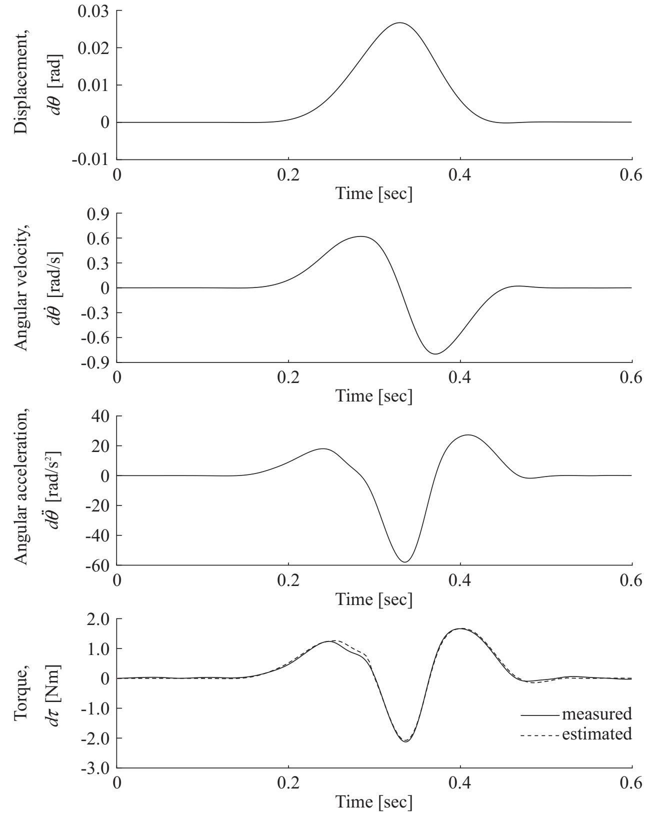

Fig. 4. An example of the measured signals for estimating mechanical impedance.

and the reaction torque to the driver's hand $d\tau$ is

$$dF(t) = \frac{1}{r} d\tau(t). \tag{9}$$

Therefore, the dynamic behavior of the human hand along the tangential direction of the steering wheel can be formulated as

$$M_e d\ddot{X}(t) + B_e d\dot{X}(t) + K_e dX(t) = -dF(t), \tag{10}$$

where M_e, B_e, and K_e denote the hand inertia, viscosity, and stiffness along the tangential direction of the steering wheel given by

$$M_e = \frac{1}{r^2} M_{\theta h}, B_e = \frac{1}{r^2} B_{\theta h}, K_e = \frac{1}{r^2} K_{\theta h}. \tag{11}$$

B. Experimental Apparatus

Fig. 3 shows a schematic view of the virtual steering system developed in this study. The virtual steering system comprises a direct-drive-type motor (NSK Ltd., maximum torque 20 [Nm]); a computer for controlling the motor; a biofeedback display which can show the measured steering angle and torque. A steering wheel (NARDI Ltd., radius: r = 0.185 [m]) and a rotation torque sensor (SOHGOH KEISO Corp., maximum torque 50 [Nm]) are attached to the rotating part of the motor. The rotational angle of the steering wheel is measured by an encoder built into the motor (encoder resolution: 51,200 [pulse/r]). The robot in the system is controlled by a DSP board (dSPACE: ds1103) that can provide stable control and high-quality data measurements under high-frequency sampling conditions (sampling: 1 [kHz]).

A human subject sat in front of the experimental system, and his shoulders were restrained to the seat back using a seatbelt as shown in Fig. 3(b). Both hands were fixed to the steering wheel using a plastic cast to eliminate the passive impedance of the hand pair. When the impedance measurements were performed, the subject was asked to generate the specified steering torque while maintaining his arm posture according to the biofeedback display. In order to estimate human hand impedance while maintaining the arm posture, the steering angle was determined by using positional control at the target point θ_v = 0 [rad] when an external disturbance was not applied. The dual-hand grip position was set as the position of the right hand θ = 0, $\pi/6$, $\pi/3$, ..., $2\pi/3$ [rad] and the target steering torque τ_d = -9, -6, ..., 0, ..., 6, 9 [Nm]. Under the condition of θ = 0 [rad], the specified steering torque was set only in the positive direction. The number of trials was ten for each condition. Six healthy subjects (male university students aged 22-24 years) participated in the measurement study.

C. Experimental Results

Fig. 4 shows an example of the steering angle $d\theta$, angular velocity $d\dot{\theta}$, angular acceleration $d\ddot{\theta}$, and torque $d\tau$ measured in estimating mechanical impedance properties of the known spring-mass system under conditions of M = 0.5 [kg] and K = 879 [N/m]. The mean value and standard deviation for five sets of estimated results are $M_e = 0.52 \pm 0.01$ [kg] and $K_e = 874.9 \pm 28.6$ [N/m], respectively. In the bottom figure,

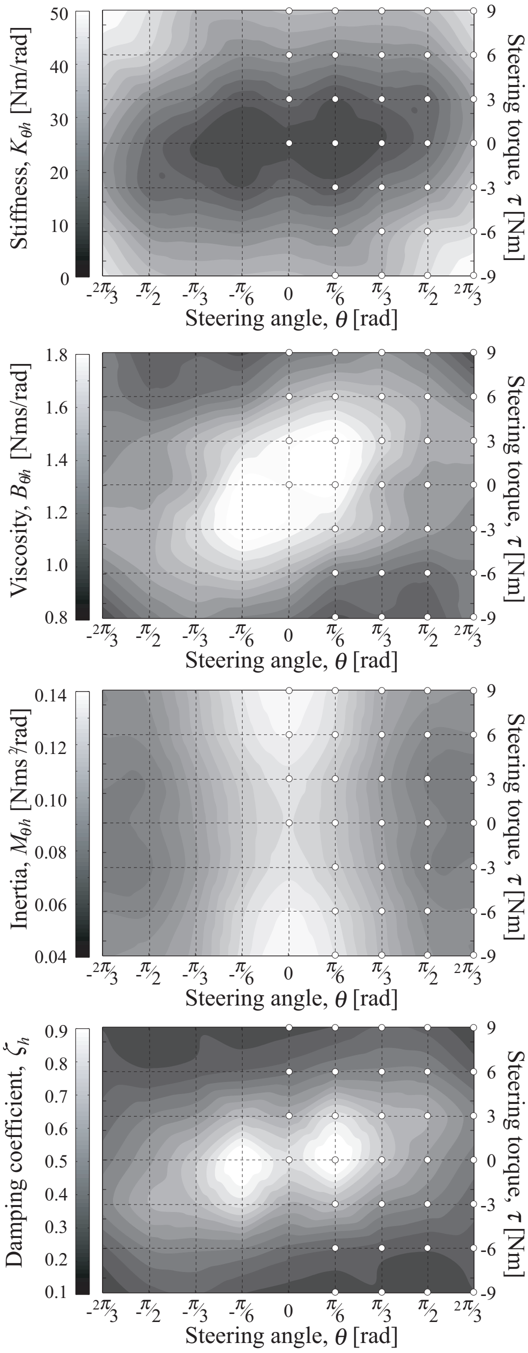

Fig. 5. The database of human hand impedance and damping coefficient

the solid line denotes the measured torque and the broken line denotes the calculated torque obtained using Eq. (7) with the estimated $M_{\theta h}$, $B_{\theta h}$, and $K_{\theta h}$. The results demonstrate that the developed driving system can successfully estimate the impedance properties.

Fig. 5 shows the data maps of human hand impedance properties around the steering rotation axis depending on the steering angle and torque. Each map is composed of the mean values of the estimated results for all the subjects. A white circle indicates the mean value of the impedance parameter

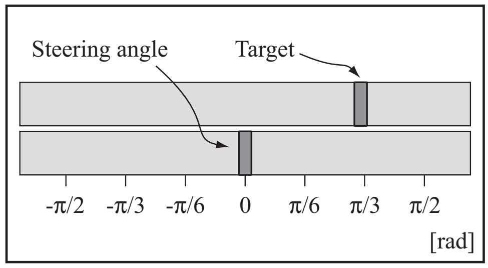

Fig. 6. The feedback display in the obstacle avoidance test

estimated under the experimental conditions, and the data between the white circles is calculated by cubic interpolation based on Delaunay triangulation. The human hand stiffness $K_{\theta h}$ and viscosity $B_{\theta h}$ change with both the steering angle and torque, while inertia $M_{\theta h}$ depends on only the steering angle. It is also observed that the stability of human motion in steering operations improves around the initial angle with smaller torques because the damping coefficient ζ_h is larger. Paradoxically, it becomes more difficult for human drivers to ensure stable control of the steering wheel without any assistance from the steering device in the case of driving situations requiring a larger steering angle and torque, such as emergency obstacle avoidances. The database of human impedance properties was made using these measured data and installed into the proposed control structure presented in Fig. 1 (a).

IV. Emergency Obstacle Avoidance Test

A. An outline of the target task

The effectiveness of the proposed control system was examined by means of a quasi-ELK test [14], in which a human driver needs to avoid a suddenly appearing obstacle, such as an elk, on the road. The target task in this paper was to match a current steering angle to a target angle as quickly and accurately as possible according to the visual feedback display as shown in Fig. 6.

Four subjects (male university students aged 22-23 years) participated in this study. The subjects were instructed to grasp the steering wheel with both hands and carry out the steering operation continuously and as quickly as possible. The start time of each operation and the target angle θ_d were provided randomly within $\pm\pi/6$, $\pm\pi/3$, or $\pm\pi/2$ [rad] from the initial angle $\theta_{init} = 0$ [rad].

B. Experimental conditions

The damping coefficient ζ is regulated according to the steering angle as shown in Fig. 7. It can be expected that the downward shape will enhance quickness around the initial state of the steering operation at smaller operational loads, while the upward shape will improve the accuracy of positioning around the target angle at larger operational loads.

The function is defined as follows:

$$\zeta = \frac{(1-\theta_n)^{p-1}(1-\alpha(1-\theta_n))^{q-1}}{\gamma B(p,q)} + \zeta_{\max 2} \quad (12)$$

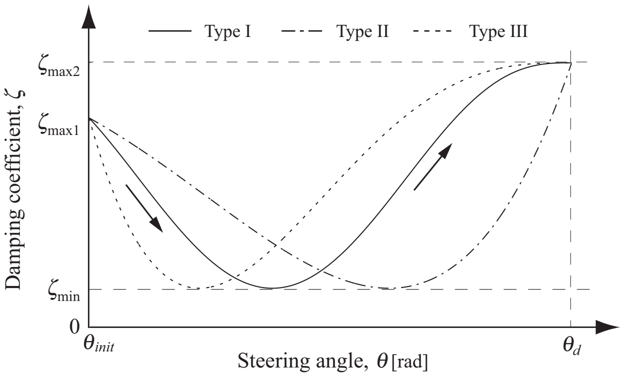

Fig. 7. The designed shapes of the regulation function with respect to the steering angle.

TABLE I
THE PARAMETER VALUES OF THE REGULATION FUNCTION UTILIZED IN THE TESTS.

Type	p	q	β	ζ_{max1}	ζ_{max2}	ζ_{min}	d
I	4	4	4.64				
II	4	2	2.55	0.98	1.2	0.3	1
III	2	4	3.55				

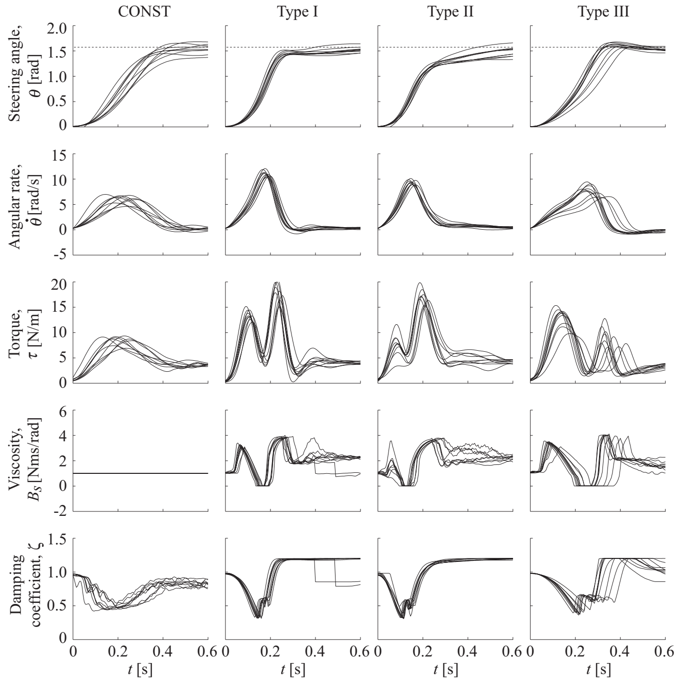

Fig. 8. The time histories of steering operations by Sub. A for all the control systems.

where

$$\alpha = 1 - \{\gamma(\zeta_{\max2} - \zeta_{\max1})B(p,q)\}^{\frac{1}{q-1}}, \qquad (13)$$

$\theta_n = (\theta - \theta_{init})/(\theta_d - \theta_{init})$; θ_{init} and θ_d are the initial angle and target angle of the steering wheel, respectively; and p and q are parameters that determine the characteristics of the beta function $B(\cdot,\cdot)$. The value of γ is analytically derived in accordance with the specified minimum value of ζ_{min}.

In this paper, three profiles of the regulation function (Type I, II, and III) were designed using the parameters in Table 1 to investigate the influences of the change in ζ on the task performance. The parameter $\zeta_{\max1}$ was configured in order to set the steering viscosity at $B_{\theta s}$ = 1.0 [Nms/rad] around θ_{init} and other parameters were determined by considering the specifications of the experimental setup. The steering viscosity $B_{\theta s}$ is automatically adapted so that the specified damping coefficient of the overall system ζ is realized in accordance with the regulation function, and the steering inertia $M_{\theta s}$ and stiffness $K_{\theta s}$ were considered to be natural characteristics of an existing automobile. Note that the values of $K_{\theta h}$, $B_{\theta h}$, and $M_{\theta h}$ are obtained from the database of human hand impedance properties. Thirty trials were conducted for each regulation function, and comparative tests were performed by fixing the steering viscosity at $B_{\theta s}$ = 1.0 [Nms/rad] (CONST), which was determined on the basis of the general characteristics of an automobile.

C. Experimental results

Fig. 8 shows the typical time histories of the steering angle θ, angular rate $\dot{\theta}$, steering torque τ, steering viscosity B_s, and damping coefficient ζ during the target task for each type of steering control for Sub. A. The figure plots the measured waves for ten sets of experiments, and the time at which the steering angular rate was first greater than 0.05 [rad/s] after the target angle appeared on the display was defined as 0 [s].

The waves are considerably different between the proposed steering control system (Type I, II, and III) and the existing system (CONST). The peak value of the angular rate is larger in the proposed systems because ζ becomes smaller around the initial state of the steering operation, while better stability can be observed around the target angle because ζ increases. Furthermore, the time profiles of the steering torque are obviously different: a single-peaked profile appears for CONST while a double-peaked profile appears for the proposed control system. These results demonstrate that the proposed control system is able to actively control a driver's steering motion by adjusting the damping coefficient of the overall system without any degradation in the task performance during steering operations.

The operational performance was quantitatively evaluated by two indices: 1) the operation quickness T_r, i.e., the time taken to reach the time taken for an increase from 10 Note that smaller values of the indices indicate better performance. Fig. 9(a) shows the evaluation results to all the three target angles for Sub. A, in which the label in each mark represents the type of control systems and the mean of ten trials is presented with the standard deviation. It can be seen that the quickness becomes worse as the target angle is bigger while the accuracy becomes better, and that the operational performance with the proposed control systems (Type I $\sim$ III) is superior to that with the existing system (CONST) for each of the target angle.

Finally, an integrated evaluation was carried out for

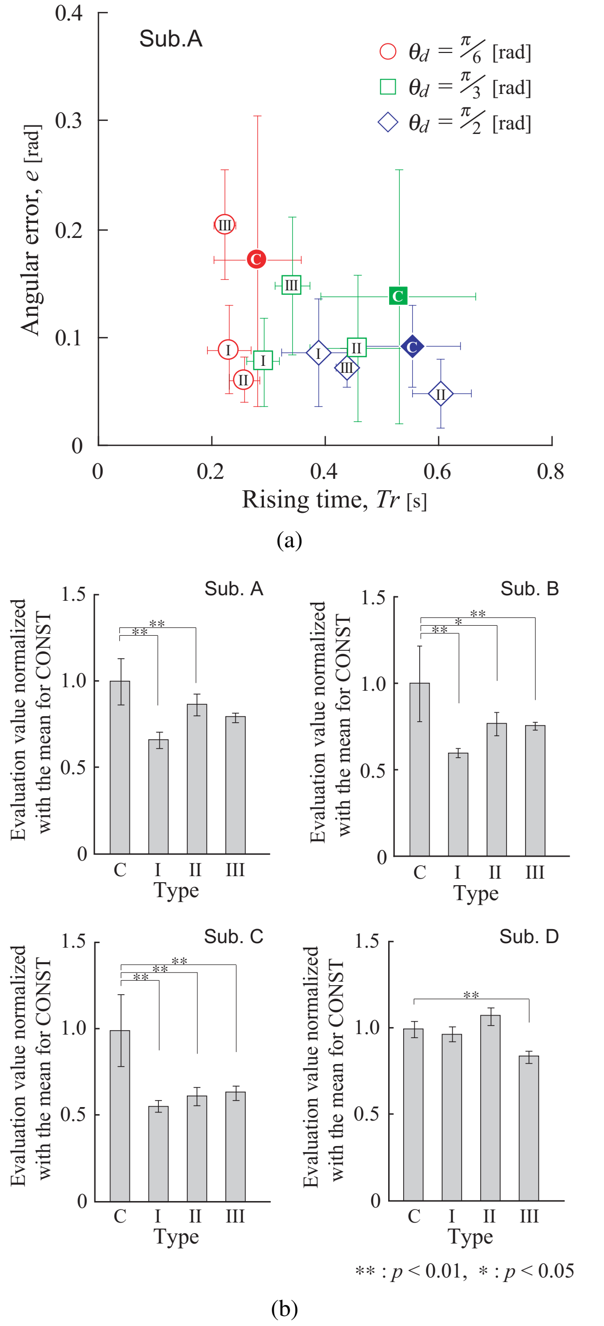

Fig. 9. Evaluation results of positioning quickness and accuracy for all the control conditions.

the observed data using the index $I(\theta_d) = \sqrt{T_r^2 + e^2}$. Fig. 9(b) shows the evaluation results for all the subjects, where the vertical axis is a value calculated by $I_{all} = I(\frac{\pi}{6}) + \frac{1}{2}I(\frac{\pi}{3}) + \frac{1}{3}I(\frac{\pi}{2})$ and is normalized with the value for CONST. It can be seen that the operational performance is improved by the proposed control system using the designed functions of ζ, especially in Type I, although some individual differences exist. Consequently, the proposed active-steering control system can effectively assist a driver's steering operations by modifying the damping coefficient ζ according to the driving situation.

V. Conclusions

This paper proposed an automobile steering control system based on human hand impedance properties, which in turn depend on the steering angle and torque. Functions that adjust the damping coefficient of the system according to the steering operations of a human driver were added to improve the reaction quickness and position accuracy, especially under emergency situations. Operational experiments were carried out using a virtual steering system that implemented the proposed control structures. The effect of the damping coefficient of the overall system was analyzed with regard to the steering operation, and the operational performance was quantitatively evaluated using a set of experimental results. To be specific, by setting the damping coefficient according to various operational situations, further improvements can be expected in operational performance and emergency avoidance.

Future research will focus on further improvements in the operational performance during a continuous task, as well as the design of the damping coefficient for situations other than emergency avoidance.

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