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Control of Steer-by-Wire Vehicles with Passivity Approach

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Abstract: Steer-by-wire system (SBW), in which the conventional mechanical linkages between the steering wheel and the front wheel are removed, is suited to active steering control, improving vehicle stability, dynamics and maneuverability. And SBW is applied to autonomous steering control to assist the driver. Conventional controller for SBW system is designed by general feedback control method. However, in this method, the driver cannot exactly feel the reaction torque generated from tire about road friction. And the stability of control system cannot guarantee in spite of highly variable human operators and environment dynamics. The goals of this paper are considered as follow: The one is a reproduction of environmental impedance in steering wheel. The other is the improved maneuverability for SBW system. Moreover, the stability of control system must be satisfied. This paper, first, reviews bilateral control scheme using disturbance observer proposed by us. Secondly, this paper proposes a novel bilateral control scheme with passive approach. We also examine the performance of the proposed control scheme and compare with bilateral control scheme using disturbance observer. The effectiveness of proposed method is demonstrated by experiment with electronic vehicle.

1. INTRODUCTION

Steer-by-Wire (SBW) system is one in which the conventional mechanical linkages between the steering wheel and the front wheel are removed, and is operated by electronic actuators. SBW system has many advantages because it can easily eliminate the interference between the driver and the steering system. For examples, SBW system can increase the freedom to tune the steering feel and also could improve steering maneuverability, using a steering control device such as a joystick. Also, it is suited to active steering control, improving vehicle stability, dynamics and maneuverability, and besides, is applied to autonomous steering control to assist the driver (Segawa et al., 2004).

This paper discusses steering wheel motor and front steering wheel motor control algorithm to generate a conventional vehicle's steering feel and to improve driver's steering feel. In previous works, control steering wheel motor and front steering wheel motor using each control algorithm and the reaction torque is fundamentally determined by the front steering wheel angle (Hayama et al., 2000; Amberkar et al., 2000).

In these cases, the driver is unable to sense road information, such as road conditions, curb or ruts. It is essential to obtain feedback force to the steering wheel in SBW system as in conventional steering system, where the force is transmitted to the front steering wheel through the mechanical link. Besides, the study of increasing control performances while guaranteeing system stability in spite of highly variable human operators and environment dynamics is still an open problem. To solve the problems, the bilateral control method will be key technology.

In this paper, we first reviews general bilateral control scheme using disturbance observer (Im et al., 2006). As the disturbance observer is able to obtain much wider bandwidth than force sensors, it is more suitable for transmission of vivid force sensation than force sensors in motion control (Katsura et al., 2003; Kaneko et al., 1997). Secondly, we propose a novel bilateral control scheme with passive approach. This control method is developed in a general framework since the issue that increasing the performances while guaranteeing stability with wide range of uncertainty sets, is not only confined to the control of SBW. The condition for guaranteeing the stability of the presented network model is obtained based on the concept of passivity. This design method is using "Passivity Observer" (PO) and "Passivity Controller" (PC) (Hannaford et al., 2001). We also study the performance of the proposed control scheme and compare with general bilateral control scheme. The effectiveness of proposed method is demonstrated by experiment with electronic vehicle.

This paper is organized as follow: In section 2, modeling of SBW is described. In section 3, bilateral control scheme using the disturbance observer is described. In section 4, proposed a novel bilateral control scheme with passive approach is described. In section 5, the experiments conducted to verify the effectiveness of the proposed method is described. Concluding remarks are presented in Section 6.

2. MODELING OF SBW SYSTEM

SBW system is divided into two parts, steering wheel and front wheel, and contains of two electronic actuators assisting in their operation. These two electronic actuators receive input signals from ECU, and one actuator generates reactive

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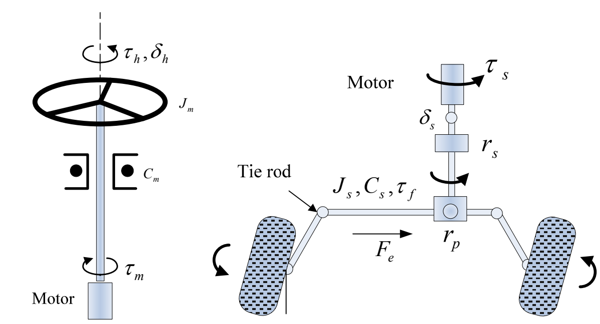
torque to the steering wheel and the other actuator steers the front wheel by following the driver's will. Fig. 1 shows a typical SBW system structure.



(a) steering subsystem (b) front wheel subsystem

Fig. 1. Schematic model of SBW system

2.1 Modeling of Steering Wheel System

Fig. 1(a) shows the dynamic model of the steering wheel, where the motor generating reactive torque to the driver and the steering wheel column is modeled using the dynamic method. The modeling element consists of the driver's input steering torque τ_h , the steering reactive motor torque τ_m , and the steering column connecting the steering wheel and the motor. Here, the stiffness of the motor shaft is ignored because it is much smaller than that of the steering column. The equation of the steering wheel is described by

$$J_m \ddot{\delta}_h + C_m \dot{\delta}_h = \tau_m + \tau_h \quad (1)$$

where δ_h is steering angle, J_m and C_m are the moment of inertia and viscous coefficient of the steering wheel system, respectively.

2.2 Modeling of Front Wheel System

The torque from the front wheel motor is transmitted to the front tires through the front wheel system consisting of front wheel steering motor, ball screw gear, and tie rod. The pinion displacement is measured by sensor. The obtained data are transmitted to the ECU, and the desired steering wheel angle and front wheel angle are calculated. Fig. 1(b) shows the modeling of the front wheel. In the front wheel model, only the tie rod stiffness is considered and other stiffness is ignored because stiffness of the tie rod has the greatest effect on a steering angle. Equation (2) represents the front wheel dynamics.

$$J_s \ddot{\delta}_s + C_s \dot{\delta}_s + \tau_f = \tau_s - \frac{1}{r_s}\tau_e \quad (2)$$

where δ_s is front motor angle, J_s and C_s are the moment of inertia and viscous coefficient of the front wheel system, and τ_f represents coulomb friction. r_s is the gear ratio of the front steering motor. τ_s and τ_e are front wheel motor torque and disturbance torque, respectively.

3. GENERAL BILATERAL CONTROL SCHEME

The controller for SBW system is divided into two sub-controls: the steering wheel motor control and the front wheel motor control. The purpose of the steering wheel motor control is to improve the driver's steering feeling by generating reactive torque. And the purpose of the front wheel motor control is to steer the front wheel angle appropriately for improving the vehicle's maneuverability and stability. To achieve these purposes, the bilateral control method is used to control the SBW system in this paper. This control scheme is based on operational force feedback type bilateral control with scaling gains (Im et al. 2006).

3.1 Disturbance Observer

Rewriting (2) in state-space form yields:

$$\begin{cases} \dot{\mathbf{x}}_\mathbf{d} = \mathbf{A}_\mathbf{d}\mathbf{x}_\mathbf{d} + \mathbf{B}_\mathbf{d1}\mathbf{u}_\mathbf{d} + \mathbf{B}_\mathbf{d2}\tau_e \\ y = \begin{bmatrix} 1 & 0 \end{bmatrix}\mathbf{x}_\mathbf{d} \end{cases} \quad (3)$$

where

$$\mathbf{x}_\mathbf{d} = \begin{bmatrix} \delta_s & \dot{\delta}_s \end{bmatrix}^T, \ \mathbf{u}_\mathbf{d} = \begin{bmatrix} \tau_s & \tau_f \end{bmatrix}^T,$$

$$\mathbf{A}_\mathbf{d} = \begin{bmatrix} 0 & 1 \\ 0 & -\dfrac{C_s}{J_s} \end{bmatrix}, \ \mathbf{B}_\mathbf{d1} = \begin{bmatrix} 0 & 0 \\ \dfrac{1}{J_s} & -\dfrac{1}{J_s} \end{bmatrix}, \ \mathbf{B}_{\mathbf{d}2} = \begin{bmatrix} 0 \\ -\dfrac{r_s}{J_s} \end{bmatrix}$$

A disturbance observer for the front steering system is simply constructed by appending the disturbance to the state vector of the front steering system $\mathbf{x}_\mathbf{d}$. Augmenting the corresponding rows in the state matrices with zeroes, we have

$$\begin{cases} \dot{\mathbf{z}}_\mathbf{d} = \mathbf{F}_\mathbf{d}\mathbf{z}_\mathbf{d} + \mathbf{G}_\mathbf{d}\mathbf{u}_\mathbf{d} \\ \mathbf{y}_\mathbf{d} = \mathbf{C}_\mathbf{d}\mathbf{z}_\mathbf{d} = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}\mathbf{z}_\mathbf{d} \end{cases} \quad (4)$$

where

$$\mathbf{z}_\mathbf{d} = \begin{bmatrix} \delta_s & \dot{\delta}_s & \tau_e \end{bmatrix}^T,$$

$$\mathbf{F}_\mathbf{d} = \begin{bmatrix} \mathbf{A}_\mathbf{d} & \mathbf{B}_\mathbf{d2} \\ 0 & 0 \end{bmatrix}, \ \mathbf{G}_\mathbf{d} = \begin{bmatrix} \mathbf{B}_\mathbf{d1} \\ 0 \end{bmatrix}$$

Then, the disturbance observer is given by

$$\dot{\hat{\mathbf{z}}}_\mathbf{d} = (\mathbf{F}_\mathbf{d} - \mathbf{L}_\mathbf{d}\mathbf{C}_\mathbf{d})\hat{\mathbf{z}}_\mathbf{d} + \mathbf{G}_\mathbf{d}\mathbf{u}_\mathbf{d} + \mathbf{L}_\mathbf{d}\mathbf{y}_\mathbf{d} \quad (5)$$

where the vector, $\dot{\hat{z}}_d$, contains the states of z_d to be estimated, L_d is gain matrix of the disturbance observer (DO). The disturbance torque is represented as

$$\tau_e = \hat{\tau}_e - \tau_{\text{int}} \quad (6)$$

Where τ_{int} is the internal disturbance torque, and τ_e is external disturbance torque that is assumed aligning torque. If the identification result is perfect, internal disturbance is zero

($\tau_{\text{int}} = 0$). The block diagram of reaction force estimation by the disturbance observer shows in Fig. 2.

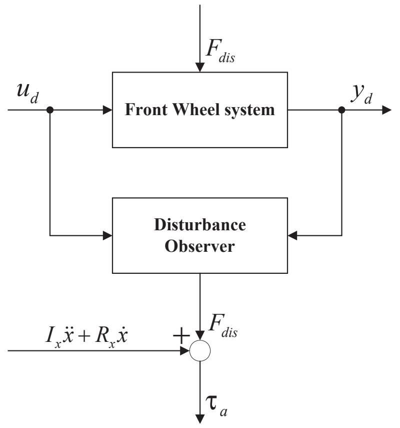


Fig. 2. Block diagram of reaction force estimation by DO

3.2 Design of Bilateral Control

An ideal response between different-scale worlds is defined by the following equations using the force scaling gain γ and the position scaling gain σ.

$$\begin{cases} \tau_h = \gamma\tau_e \\ \delta_s = \sigma r_s \delta_h \end{cases} \tag{7}$$

The force feedback bilateral control that realizes the above ideal response is shown in Fig. 3, where each driving force is given as

$$\begin{cases} \tau_m = -\gamma\tau_e - k_f(\gamma\tau_e - \tau_h) \\ \tau_s = k_p(\sigma r_s \delta_h - \delta_s) - k_r s \delta_s \end{cases} \tag{8}$$

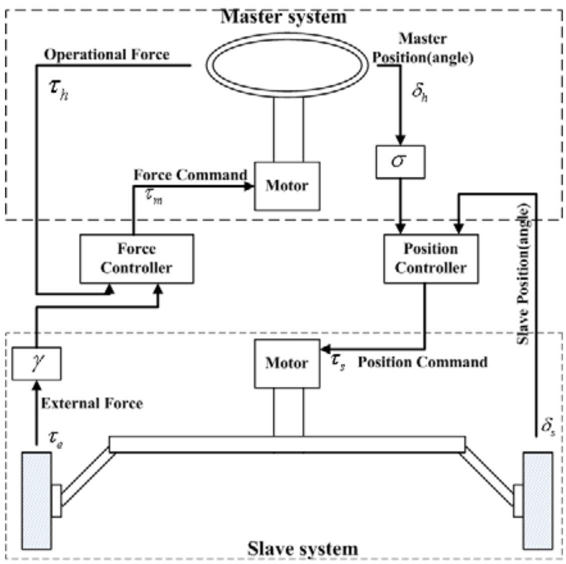


Fig. 3. Control scheme of bilateral control based on force feedback

From (2), the reaction force occurs when the front wheel interacts with the road. The force of front steering actuator can be written as (9) using environment impedance Z_e and front motor angle δ_s.

$$\tau_e = \frac{Z_e}{r_s}\delta_s \tag{9}$$

by Substituting τ_m into (1), and τ_s and (9) into (2), the transfer function from the driver's input steering torque τ_h to the steering angle δ_h can be obtained as

$$\begin{aligned} G_h &= \frac{\delta_h}{F_h} \\ &= \frac{Z_t}{PZ_t + \alpha\sigma k_p Z_e(s)} \\ &: p = \frac{J_h s^2 + C_m s}{1 + k_f} \\ &: Z_t = J_s s^2 + (C_s + k_r)s + k_p + \frac{1}{r_s^2} Z_e(s) \end{aligned} \tag{10}$$

In the steering control of vehicle, it is important problem which is following steering command of driver. At the slowly steering, k_p is designed to be high as possible while retaining stability. In this case, (10) approximates to

$$G_h(s) \approx \frac{1}{\gamma\sigma Z_e(s)} \tag{11}$$

As a result, the driver feels only the virtual environment impedance $\gamma\sigma Z_e(s)$. By applying this method, generation of steering feel and front steering angle can be realized.

3.3. The Bilateral Control Scheme with Passive Approach

Fig. 4 shows a network model of a SBW system. v_m and v_s denote the velocity of the master and slave system, respectively. τ_h represents the force that the operator applies to the master system, and τ_e denotes the force that the slave system applies to the environment, i.e., reaction torque. To investigate the overall stability of the SBW system, we analyze the network model based on the idea of passivity. The passivity allows a global stability conclusion to be drawn from considering system blocks individually. In the case of master-slave systems, if we assume that the operator and the environment are passive, the master-slave system must be passive to meet the sufficient condition for stability (Yokokohji et al., 1994). Generally, the environments are passive, and Hogan (1989) has demonstrated experimentally that the human operator can be modeled as a passive network. Thus, we are only to make the master-slave 2-port passive to satisfy the overall stability of the SBW system.

We then use the following widely known definitions of passivity for a multi-port network.

Definition 1: An M-port network with initial energy storage $E(0)$, is passive, if and only if

$$\int_0^t (f_1(\tau)v_1(\tau)+\cdots+f_M(\tau)v_M(\tau))d\tau + E(0) \geq 0 \quad (12)$$

for admissible forces $(f_1,\cdots,f_M)$ and $(v_1,\cdots,v_M)$. The sign convention for all forces and velocities is defined to make their product positive when power enters the system port. The system is also assumed to have initial stored energy at $t=0$ of $E(0)$. Eq. (12) states that the energy supplied to a passive network must be greater than negative $E(0)$ for all time (Van der schaft, 2000; Willems, 1972).

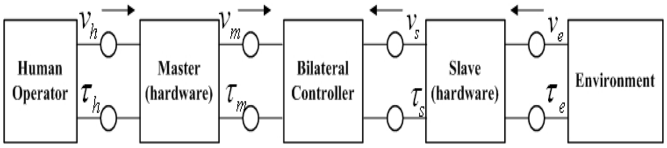


Fig. 4. Network model of a SBW system

To guaranteeing stability with wide range of uncertainty set like SBW system, we approach the passivity theory.

$$E_{obsv}(n) = \Delta T \sum_{k=0}^{n} \tau(k)^T v(k) \quad (13)$$

where ΔT is the sampling period. If $E_{obsv}(n) \geq 0$ for every n, this system dissipates energy; else if there is a instance that $E_{obsv}(n) < 0$, this system generates energy and the amount of generated energy is $-E_{obsv}(n)$.

Equation (13) is introduced "passivity observer" (PO) that is measurement of the amount of energy. And the PO may or may not be negative at a particular time. However, if it is negative at any time, we known that the one-port may then be contributing to instability. Moreover, we know the exact amount of energy generated and we can design a time varying element to dissipate only the required amount of energy. This element is called a "passivity controller" (PC). The PC takes the form of a dissipative element in configuration (Fig. 6). The configuration obey the constitutive equation

$$\tau_h' = \tau_h + \alpha(n)v_h \quad (14)$$

where

$$\alpha(n) = \begin{cases} E_{obsv}(n)/\Delta T v_h^2(n) & \text{if } E_{obsv}(n) < 0 \\ 0 & E_{obsv}(n) \geq 0 \end{cases}$$

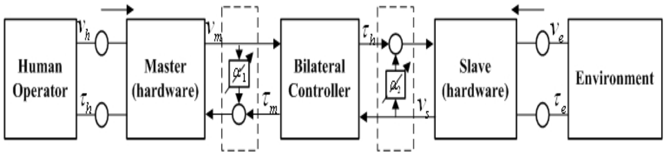


Fig. 6. Block diagram of the bilateral control with passive approach

5. EXPERIMENT

This section describes the experiments conducted to verify the effectiveness of the proposed method.

Fig. 7 Experimental vehicle with SBW system

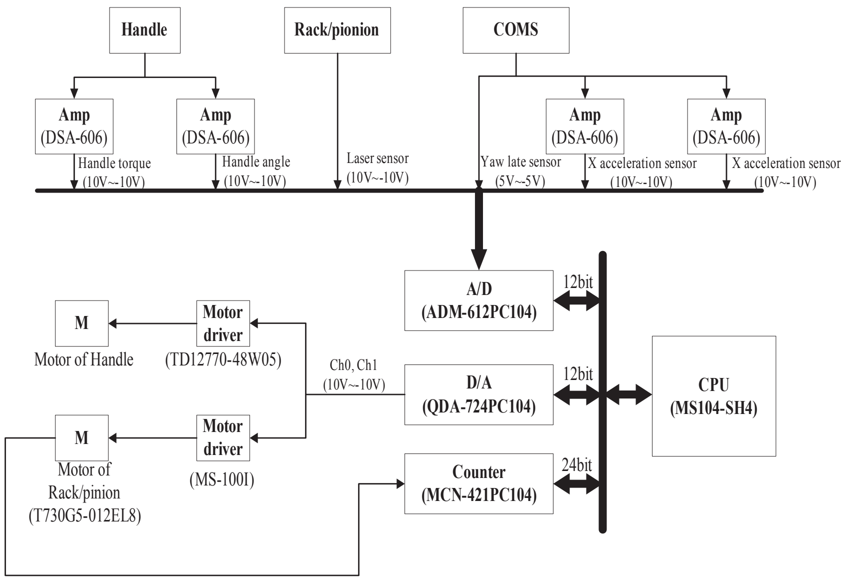


Fig. 8 Blockdiagram of control system

5.1 Experimental Setup

Fig. 7 illustrates the experiment vehicle of the SBW system. The experiment vehicle was remodeled into SBW system using Toyota's electronic vehicle (COMS). The SBW experiment system (Fig. 7) uses conventional steering system components except intermediate steering shaft. To make the reactive torque, conventional EPS system which is column type power steering unit is used. DC servo motor (300W) is attached on rack and pinion part to drive front steering wheel. The position signal is measured by encoder (1000PPR) attached DC servo motor. Steering torque and angle are measured by strain type of steering handle sensor (SFA-A-1003S). The electronic control unit (SH4) for both the steering actuator and force feedback motor consists of AD converter running real-time by RT-LINUX. And the sampling time is 20[ms]. Fig. 8 illustrates the flow of power and signals through the system.

5.2. Experimental Results

All results presented here are based on the following test procedure: First, the steering command is generated by human. And second, the experimental results obtained from the proposed operational force feedback type bilateral control method when the force scaling gain γ is 1 and the position scaling gain σ is 1. Besides, the control gain found to produce a similar characteristic with conventional steering system, i.e., connecting the mechanical link between the steering wheel and the front wheel without power assist unit.

For the first test, the vehicle does not contact on ground to analysis basic system characteristic such that the road friction is zero. The control result of the pinion angle for the steering command using proposed method show in Fig. 9. In the test, the steering angle is sinusoidal waveform about $\pm$ 90[deg] that slowly steers about 0.2[Hz]. Form Experimental data, the pinion angle show a corresponding to the steering command. Therefore, we can understand that the proposed control method can be guaranteed stability of system at the small amount of road friction. To verification of stability during the driving, the vehicle is accelerated from a standing stop to steady speed 15[Km/h]. The steering command is turning the left side from 15[s] to 22[s]. The control results of driving test show in Fig. 10. These results in spite of during driving show stability of system. The results of changing scaling gain for the steering torque show in Fig. 11. These experimental results also show that the driver can feel different the reaction torque using scaling gain. This means we can easily design the driving feeling using scaling gain. The reactive torque is estimated by the disturbance observer in section 3.

In order to verify the steering feeling, lissajous figure which is composed of a steering angle and steering torque shows in Fig. 12. The experiment result compare conventional steering system and SBW for the steering feeling. Two results in this experiment are about the same because each scaling gain is 1. The estimation result by disturbance observer is somewhat noisy due to testing. However, the effective of the noise is few for the stability of control, and these results are expected we can design steering feel by SBW.

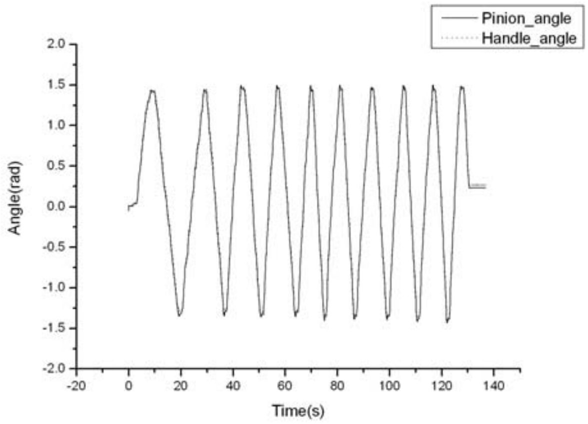
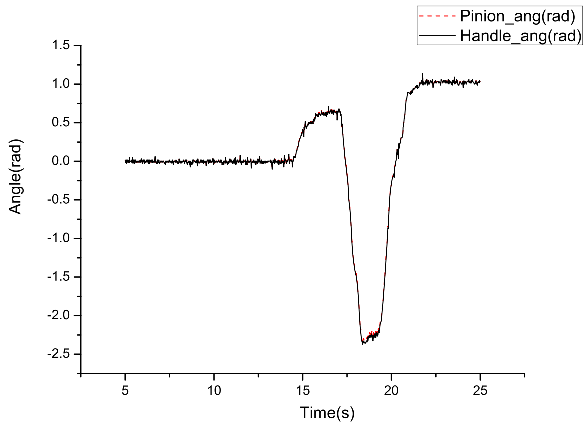
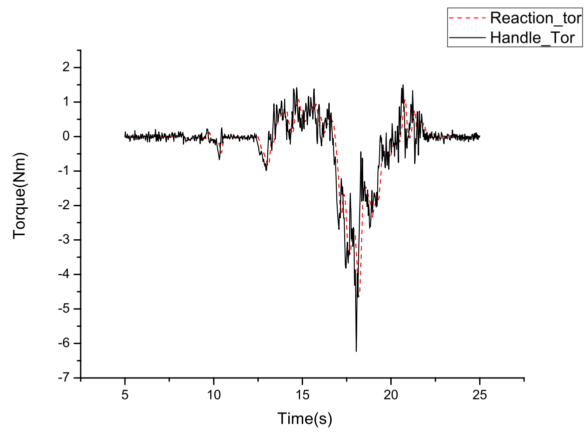


Fig. 9 Proposed control result of the steering command and pinion angle (no tire-to-ground contact)

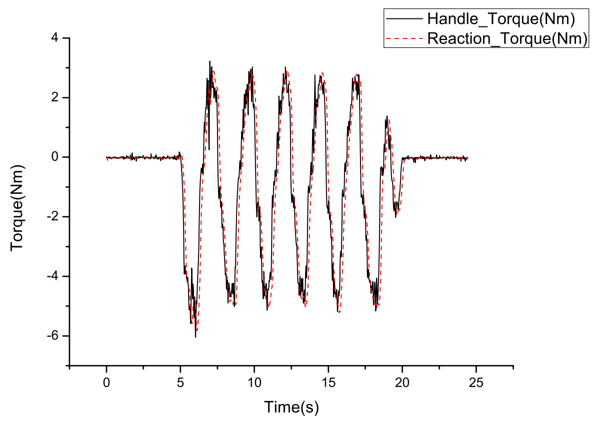


(a) steering command and pinion angle

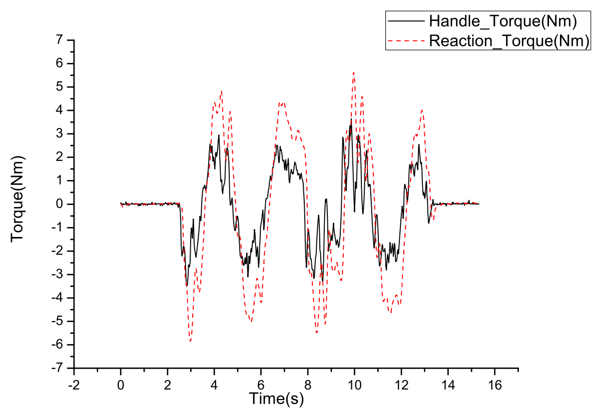


(b) Reaction force and estimated disturbance by DO

Fig. 10 Control result of SBW system with 15[Km/h] driving



(a) $\gamma = 1$



(b) $\gamma = 1$

Fig. 11 Comparison of reaction force changle γ (steer without driving)

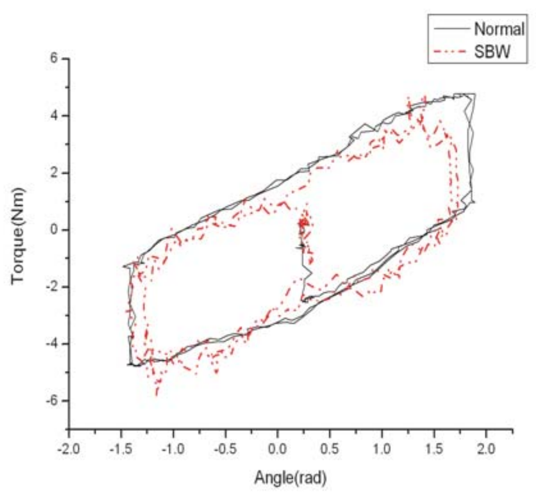


Fig. 12 Lissajous figure of proposed system (steer without driveing)

6. CONCLUSIONS

In this paper, we have developed the new control scheme to generate a conventional vehicle's steering feel and to improve driver's steering feel. SBW control algorithm has been proposed bilateral control scheme based on the time domain passivity concept. The algorithm has been demonstrated in the design of stability guaranteed controller for experiment vehicle of the SBW system.

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