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DESIGN OF THE STEERING FEEDBACK CONTROLLER OF A STEER-BY-WIRE SYSTEM USING ADMITTACNE MODEL

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ABSTRACT− The steer-by-wire (SbW) system is a promising system in the realm of automotive engineering. It substitutes the mechanical connection between the steering wheel and the front road wheels with an electronic signal-based functional connection. The SbW system offers several advantages over conventional steering systems, including weight reduction, reduced vibration, and enhanced steering functionality configuration. However, the absence of a mechanical linkage in the SbW system gives rise to certain challenges. The SbW system requires endowing adquate steering feel such as damping and reaction force using feedback motor, and the road wheel needs robust control of pinion motor for normal load variation by passengers and self-aligning torque as external disturbance. The SbW system is composed of the steering feedback module(SFM) and the road wheel module(RWM). This paper proposes a control approach to generate steering feel for SFM, in which steering feel is generated using an admittance model based on velocity control. A disturbance observer is applied to ensure robustness of velocity control. The steering wheel torque versus steering wheel angle (T-A) curve is used to analyze steering feel characteristic and evaluate steering feel. The proposed steering system is validated through experiments that confirm its ability to provide satisfactory steering feel for vehicles. This work may offer a novel solution for the design of advanced steering systems in the field for the future mobility such as an autonomous driving.

KEY WORDS : Steer-by-wire system, Steering feedback module, Robust control, Disturbance observer, Admittance model

1. INTRODUCTION

A steering system is a crucial mechanism that allows a driver to control the direction of a vehicle by turning the front road wheels. There are different types of steering systems, such as mechanical, hydraulic, and electric with respect to power source. A hydraulic power steering(HPS) uses a pump driven by the engine or motor to provide hydraulic pressure that assists the steering wheel inputs. In comparison with HPS systems, an electric power steering(EPS) systems have been applied in modern vehicles because of their fuel efficiency and simple structure. An EPS uses an electric motor to aid without relying on any other auxiliary system. Recently, the SbW system has drawn attention, since the first passenger vehicle that implemented this technology was introduced in 2013.

One of the advantages of a SbW system over a conventional power steering system is that it eliminates the need for mechanical linkages, hydraulic hoses, fluids, and pumps. A SbW system uses sensors, electric actuators, and electronic controllers to transmit the steering commands from the driver to the wheels. This reduces the weight, complexity, and maintenance of the steering system. It also improves the fuel efficiency, performance, and safety of the vehicle. A SbW system can also offer more flexibility and customization for different driving modes and preferences. The feedback motor of the steering wheel generates steering feel such as damping and reaction torque. The road wheels are moved by a motor mounted on a rack or pinion gearbox.

One of the main challenges of the SbW system, which offers many advantages over traditional steering systems, is to create a suitable steering feel for the driver. Several methods of creating steering feel for SbW systems have been proposed in the previous studies.(Baviskar et al., 2009, Yih et al., 2003, 5-8, Balachandran and Gerdes, 2015 and Salaani et al., 2004) Most of which presented the handling characteristics and the design of steering feel using objective measures for a SbW system.(Balachandran and Gerdes 2015 and Olsson et al., 2998) In some researches, a steering feel model with hysteresis, which is a key component of steering feel, is introduced in this study.(Sun et al., 2016, Bajçinca et al., 2005 and Wang et al., 2014).

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This paper focuses on the issue of the SbW system, where an admittance model is introduced as a novel method of generating steering feel. Impedance or admittance based controls have been studied in robot applications, and even in electric power steering systems. In the conventional electric power steering system, a map-based control model is commonly employed, necessitating a substantial allocation of memory resources based on the experience with extensive vehicle tests. This paper introduces an innovative approach: an admittance-based control logic utilizing an analytical method. This alternative methodology aims to mitigate the memory resource demands associated with the conventional model by offering a more streamlined and analytically driven control logic.

The following sections of this paper are organized as follows. Section 2 provides an overview of the SbW system and the mathematical models of the steering feedback module(SFM), of which model is a two-inertia resonant system. Section 3 discusses the admittance model for reference control input, proportional-integral(PI) controller and disturbance observer for the SFM system. This research also examines the steering feel characteristics using the torque-angle(TA) curve and present the experimental results of the admittance based PI control in Section 4. Section 5 concludes with a summary of the main contributions and future works.

2. SYSTEM MODELING

2.1. SbW System and Experimental Setup

The SbW system is composed of the steering feedback module(SFM) and the road wheel module(RWM). The SFM consists of steering wheel, which a driver manipulates to maneuver a vehicle, steering column, steering angle and torque sensor and feedback actuator. The RWM is made up of rack and pinion(or rack only), pinion angle sensor/rack displacement sensor, tie rod and road wheel actuator, which mounted on pinion or rack with reduction mechanism as depicted in Figure 1.

Figure 1. SbW system configuration with SFM and RWM

The experiment is conducted using RCP(Rapid Control Prototype) with a sampling time of 1ms. The controllers are designed to generate steering feel for the SFM using an admittance model and PI velocity control and a robust position control method for the RWM. The motor angle is measured in an encoder signal installed on each motor, and the motor velocity is approximated by differentiating the encoder signal. The torque sensor is installed between the steering column and worm gear box to measure driver torque.

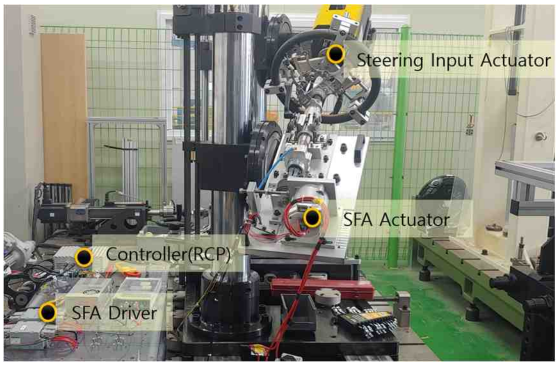


Figure 2. Experiment setup for SFM

2.2. Modeling of Steering Feedback Module

The SFM system consists of three main components: a feedback motor, a steering column, and a steering wheel. Figure 3 illustrates the schematic diagram of the system. The steering wheel and the feedback motor form a two-inertia system that is connected by the steering column.(Yun ET AL., 2013) The system is designed to provide realistic haptic feedback to the driver. Dynamic equations of this system are as follows(Wang ET AL., 2014):

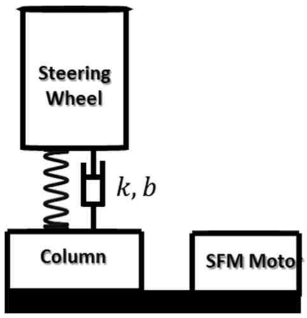


Figure 3. Schematic diagram of SFM

$$J_{fm}\ddot{\theta}_{fm} + B_{fm}\dot{\theta}_{fm} + \tau_{fric} = \tau_{fm} - \frac{1}{N}\tau_{sc} \quad (1)$$

$$\left(\dot{\theta}_{sw} - \frac{1}{N}\dot{\theta}_{fm}\right)B_{sc} + \left(\theta_{sw} - \frac{1}{N}\theta_{fm}\right)K_{sc} = \tau_{sc} \quad (2)$$

$$J_{sw}\ddot{\theta}_{sw} + B_{sw}\dot{\theta}_{sw} = \tau_{sc} - \tau_{sw} \quad (3)$$

Table 1. Symbol and Definition

Symbol	Definition
J_{fm}	Inertia moments of feedback motor
J_{sw}	Inertia moments of steering wheel
B_{fm}	Viscous friction coefficients of feedback motor
B_{sw}	Viscous friction coefficients of steering wheel
$\dot{\theta}_{fm}$	Angular acceleration of feedback motor
$\dot{\theta}_{sw}$	Angular acceleration of steering wheel
τ_{fric}	Static friction
τ_{fm}	Feedback motor torque
τ_{sw}	External torque by driver's effort
B_{sc}	The viscous friction coefficient of steering column
K_{sc}	Stiffness coefficient of steering column
θ_{fm}	Angle of feedback motor
θ_{sw}	Steering angel
τ_{sc}	Torsional torque between feedback motor and steering wheel
N	Gear ratio of feedback motor

The mathematical model can be derived into Eq. 4 under the assumption that steering torque by a driver and friction torque are 0 and feedback motor speed is approximately equal to steering angle with gear ratio. Eq. 4 is a nominal model of SFM, with which DOB and controllers are designed.

$$J_n\ddot{\theta}_{sw} + B_n\dot{\theta}_{sw} = \tau_{fm} \tag{4}$$

where $J_n = NJ_{fm} + \frac{J_{sw}}{N}$, $\quad B_n = NB_{fm} + \frac{B_{sw}}{N}$

The objective of this experiment is to identify the system parameters from the frequency response of a nominal model using experimental data of input and output signals. The input signal τ_{fn} is a sinusoidal waveform that sweeps through frequencies between 0.1Hz and 50Hz over 10-second period, and the output signal $\dot{\theta}_{sw}$ is a velocity approximated by differencing from encoder of feedback motor. The frequency response of the system is obtained by applying the Fourier transform to the input and output signals and computing the ratio of their magnitudes and phases as shown in Figure 4.

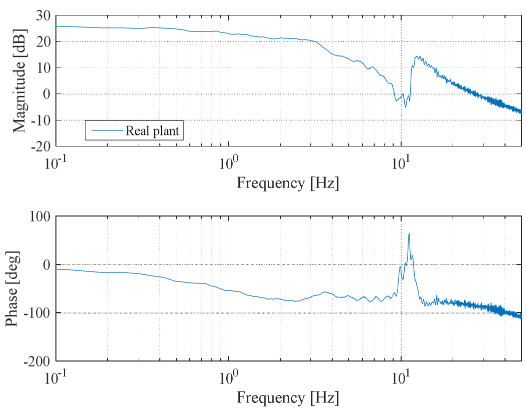


Figure 4. Frequency response of SFM

The frequency response of the SFM discloses discernible instances of both anti-resonance and resonance around 10Hz. The characterization of the system is attained by matching the real plant and the nominal plant with bi-quad filter formulated in Eq. 5 and presented in Figure 5.

$$PB(s) = P_n(s)BQ(s) = \frac{1}{J_n s + B_n}\frac{s^2+2\zeta_2\omega_2 s+\omega_2^2}{s^2+2\zeta_3\omega_3 s+\omega_3^2}\frac{\omega_3^2}{\omega_2^2} \tag{5}$$

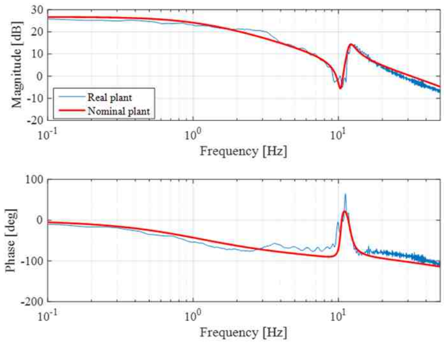


Figure 5. Frequency response with bi-quad filter

3. ROBUST CONTROL DESIGN FOR STEERING FEEDBACK MOUDLE

The column-assist type electric power steering (C-EPS) is mechanically connected to the rack and pinion.(Haggag, S. 2005) In contrast, the SbW system is electrically connected to the rack and pinion. The SbW system is mechanically decoupled and is difficult to produce major torques that make up the steering feel in conventional steering systems. This paper proposes an admittance model as a method to generate steering feel similar to C-EPS and easy to tune steering feel. Figure 6 shows SFM controller block with the admittance model and Figure 7 illustrates a complete control architecture for the SbW system composed of SFM and RWM.

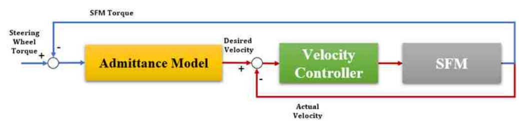


Figure 6. Block diagram of SFM

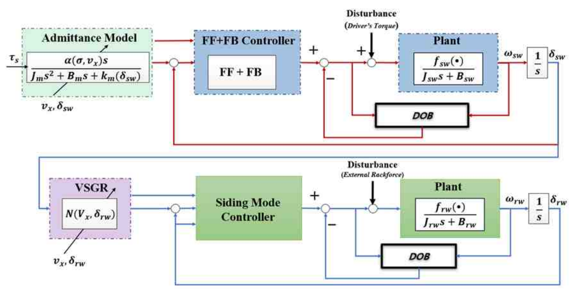


Figure 7. Overall block diagram of the control system

3.1. Admittance model

Admittance or impedance control has been used in robot applications to control the dynamic interaction between a manipulator and its environment. The proposed control approach is valid since the steering wheel is operated by hand, which is the most sensitive part of the human body. The feedback motor of the SFM should generate proper reaction torque to make stable and comfortable steering.

The velocity-based admittance controller as shown in Figure 6 generates reference velocity from driver's effort, which is measured at torque sensor installed on steering column, and motion is angular velocity of steering wheel. Its transfer function of the controller is as follows:

$$C_{AD}(s) = \frac{s}{J_Y s^2 + B_Y s + K_Y} \tag{6}$$

where J_Y, B_Y and K_Y are the virtual mass moment of inertia, virtual viscous friction coefficient and virtual stiffness coefficient, respectively.

3.2. Velocity Control Model

The velocity controller input for feedback motor is as follows:

$$u = \tau_{FF} + \tau_{FB} - \hat{\tau}_{dist} \tag{11}$$

where τ_{FF}, τ_{FB} and $\hat{\tau}_{dist}$ are output of feedback controller, feedforward controller and estimated disturbance.

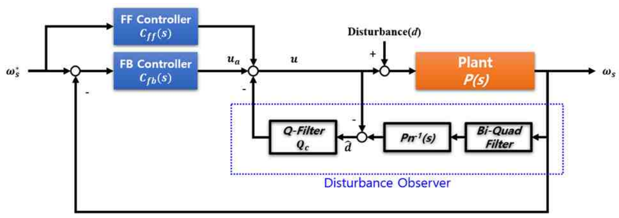


Figure 8. Block diagram of the proposed velocity control

The feedback controller C_{fb} is selected the proportional integral (PI), the transfer function of PI controller is as follows:

$$C_{fb}(s) = \frac{K_P s + K_I}{s} \tag{7}$$

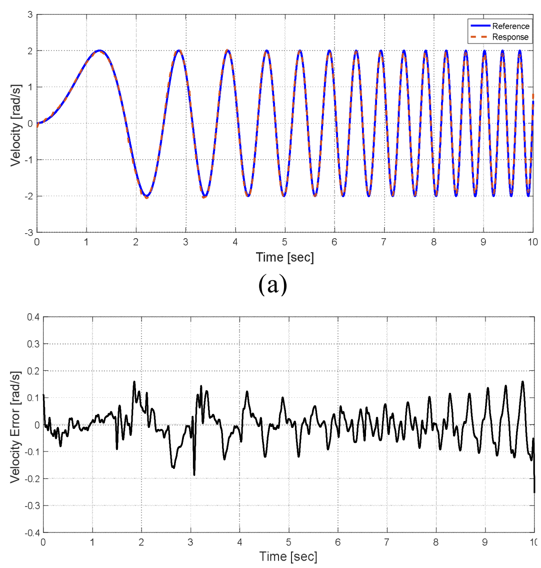
Where K_P and K_I are the proportional and integral feedback gain respectively and the gains are selected with pole placement method. But the feedback control system is considered conservative when the software system has a parameter variation. To improve control performance, a feedforward controller should be designed.(Kempf and Kobayashi 1999) If the real plant and the nominal plant are almost identical, the feedforward controller is very useful. It can guarantee system stability by reducing conservatism about feedback control. Feedforward controller C_{ff} can be designed with inversed nonimal plant multiplied with a first order low pass filter given by the following equation:

$$C_{ff}(s) = (J_{sn} s + B_{sn}) \frac{\omega_{FF}}{s + \omega_{FF}} \tag{8}$$

Finally, a disturbance observer (DOB) is designed to rule out unmodeled dynamics in SFM systems.(Kempf and Kobayashi 1999, Nam et al., 2014, and Neaz et al., 2023) It can improve the performance at low frequency by encountering the friction and backlash between the steering wheel and feedback motor. The disturbance is estimated by nominal parameters of the inertia and friction coefficient, which is obtained through frequency response methodology. In the design of DOB, the design of Q-filter is the most important to ensure stability of the system. It may deteriorate the overall control performance because it can pass high-band noise or modeling uncertainty.

3.3 Experiment Result for Velocity Control

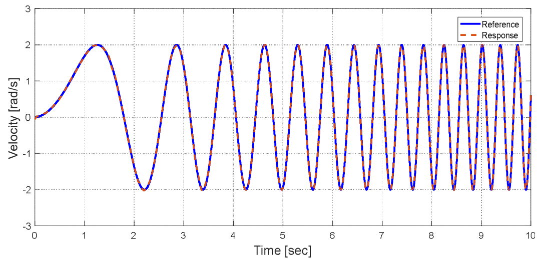
The experiment is conducted to investigate the performance of the proposed velocity controller and the effect of disturbance rejection. The velocity command is given by a sinusoidal waveform with 2 rad/s, where the frequency was first at 0.01 Hz, then increased to 3Hz during 10. The experimental results for velocity control with and without DOB are shown in Figure 9 and Figure 10 respectively. Their subplots (a) and (b) represent velocity response and tracking errors, respectively.



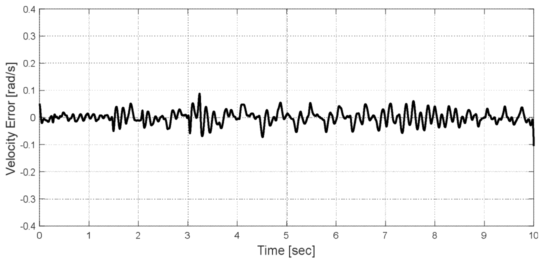
(a)

(b)

Figure 9. Experiment result of tracking control without DOB (a) Steering angle velocity (b) Tracking error



(a)



(b)

Figure 10. Experiment result of tracking control with DOB (a) Steering angle velocity. (b) Tracking error

The velocity tracking performance is improved in the case with DOB. The RMS error reduces from 0.063 to 0.020 (about 60%) in accordance with the effect of DOB shown Table 1. The RMS error with DOB is equivalent to 1.15deg/s, which is less than the resolution of a conventional steering angle rate sensor applied to vehicle systems. It is proved that the proposed tracking control with DOB is effective for velocity tracking performance of SFM.

Table 2. Test result of traking controller with and without DOB

	Without disturbance observer	With disturbance observer
RMS error	0.063 [rad/s]	0.020 [rad/s]

4. PERFORMANCE EXPERIMENT FOR STEERING FEEDBACK MOUDLE

4.1. Steering characteriscs analysis

Steering feeling is an emotional quantity, which has been researched to correlate the subjective evaluation and the objevtive parameters. The on-center handling test is widely adopted to evaluate the steering system and vehicle interactions in automotive industry, which is standardized in ISO 13674-1. Among performance index in ISO 13674-1, the curve of steering torque and steering angle(T-A curve) represents characteristics of the steering system as featured in Fig. 11. The T-A curve is hysterical and non-linear featured with the analytical key performance index as following.

- Steeing Stiffness: Steering stiffness is the parameter denoted by the red line in the T-A curve pertains to steering stiffness. Steering stiffness is characterized as the torque gradient concerning the steering angle at or around 0 degrees. It serves as an indicator of the force required for maneuvering the vehicle when the steering wheel is in a centered position. A higher steering stiffness value corresponds to an increased resistance, imparting a more substantial torque feedback to the driver during steering activities.
- Steering Friction: Steering friction is defined the band between the blue dots in the T-A curve, which is the ordinate deadband observed at 0 degrees of steering angle. Steering friction is construed as a manifestation of response deadband, elucidating the presence of a minimal torque threshold required for steering initiation.(Rothhämel et al., 2011)
- Angle Hysteresis: In the context of the green dots within the T-A curve, angle hysteresis is delineated as the abscissa deadband occurring at 0 Nm of steering torque. This deadband is indicative of the steering angle corresponding to a null torque condition. Angle hysteresis is attributed to the mechanical lag inherent in the steering system, specifically the temporal delay between the initiation of a steering input and the corresponding output. Notably, this hysteresis phenomenon is closely associated with observed torque drop phenomena, as depicted by the black lines, during instances of directional changes in steering.

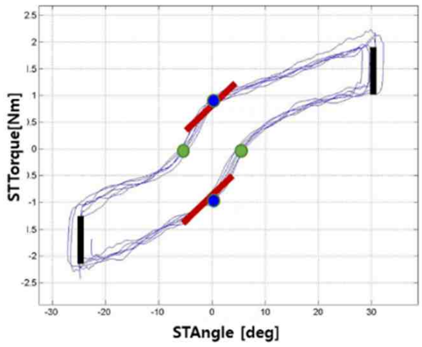


Figure 11. Steerung Characteristics in Torque-Angle curve of the C-EPS system

4.2. Experiment results

The efficacy of the proposed admittance controller featuring variable parameters is systematically assessed through a weave test conducted under diverse conditions. These conditions encompass variations in admittance parameters and steering velocity, as visually depicted in Figure 12. The main parameters of admittance model proposed in this paper are the inertia, the viscous friction and the stiffness coefficient, denoted as J_{sn} , B_{sn} , and K_{sn} .

J_{sn} and B_{sn} are selected as the nominal parameters of SFM system.

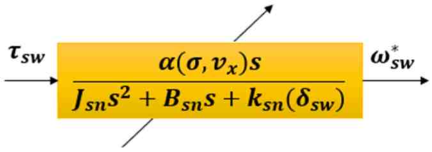


Figure 12. Proposed admittance model

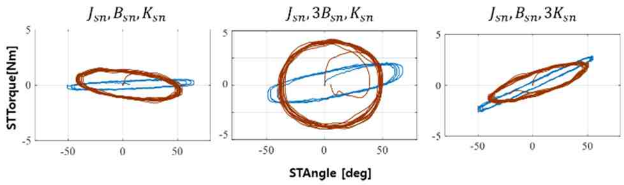


Figure 13. Experiment results for various admittance parameters and conditions

The experiments are undertaken with various admittance parameter variations shown in Figure 13, wherein the virtual viscous friction coefficient B_{sn} is tripled and the virtual stiffness coefficient K_{sn} is tripled. An observable correlation emerges in the case that the steering velocity and the friction is increased, coupled with a concomitant reduction in torque gradient. Furthermore, a positive relationship is discernible, wherein heightened values of the virtual viscous friction coefficient and virtual stiffness coefficient correspond to amplified steering friction and torque gradient, respectively.

However, a distinct observation arises when maintaining the virtual stiffness coefficient at a constant value, resulting in heaviness in the steering feel when off-center. This phenomenon necessitates the introduction of a hysteresis tendency within T-A curve, which encapsulates the relationship between steering wheel torque and steering wheel angle. As aforedmentioned, the hysteresis characteristics assumes significance in generating the steering feel. Specifically, the introduction of a hysteresis tendency on the T-A curve serves to mitigate the torque gradient during steering wheel turns. Figure 14 portrays the experimental results depicting this hysteresis tendency, with the red and blue curves signifying results under conditions of a constant virtual stiffness coefficient and a variable virtual stiffness coefficient, respectively.

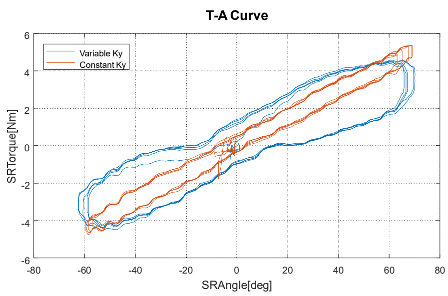


Figure 14. Experiment result of variable K_Y

The optimization of steering feel is imperative, given its inherent variability in accordance with individual driver preferences. Thus, it becomes indispensable to engineer a tunable steering system that affords drivers a nuanced level of control over their preferred steering feel. Moreover, to accommodate varying steering preferences based on vehicle velocity, such as a desire for a lighter steering feel during high-speed travel and a heavier steering feel during low-speed travel, a weighting factor is methodically designed as follows:

$$\alpha(\sigma, v_x) = ae^{-\sigma v_x} + b \tag{9}$$

In Eq. 9, α denotes the weighting factor, v_x represents the vehicle velocity, σ signifies the driving mode, and parameters a and b are the tuning components determining the maximum and minimum values of the weighting factor. The weighting factor with respect to driving mode and vehicle velocity is shown in Figure 15. It is noteworthy that a diminished weighting factor corresponds to an augmented perception of heaviness in the steering feel. Figure 16 shows the experimental results when the driving mode is comfort(Mode1), normal(Mode2) and sport(Mode3) mode, respectively. These results are carried out under the condition that the vehicle velocity is 60km/h and steering input is sinusoidal signal with 60deg amplitude and a frequency of 0.2 Hz.

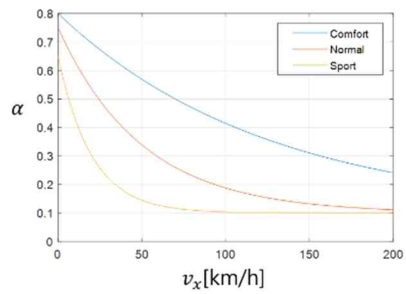


Figure 15. Simulated result of weighting factor

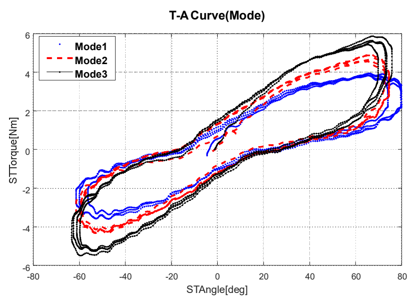


Figure 16. Experimental result with respect to modes

SbW system is a crucial component of a vehicle, which maneuvers a vehicle with respect to a driver desire and generates a steering reaction feeling as good as conventional EPS systems. Figure 17 shows an experimental resut of the on center handling tests on both EPS and SbW systems. As aforementioned, the experimental results are analyised with respect to ISO 13674-1 standard in Table 3.

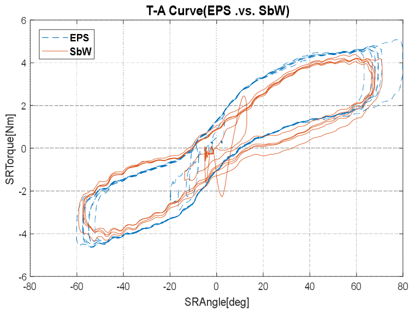


Figure 17. Experimental result of EPS and SbW

Table 3. Analysis of experimetal results with EPS and SbW

	Hysteresis Angle(deg)	Steering Friction(Nm)	Steering Stiffness(Nm/deg)
EPS	1.148	10.544	0.141
SbW	1.047	11.495	0.110

5. CONCLUSION

In conclusion, the proposed admittance model-based controller emerges as a novel and effective approach for enhancing the steering feel in SbW systems. Experimental results substantiate the controller's capability to deliver a satisfactory steering feel, resilient even in the presence of disturbances. The tuning of the stiffness coefficient within the admittance parameter offers a valuable means to tailor the steering feel according to driver preferences. The velocity controller is systematically designed utilizing system modeling and identification techniques, while a disturbance observer is employed to estimate the impact of external disturbances, such as road unevenness and wind gusts.

The T-A curve serves as a objective method for the analysis and evaluation of steering feel. Experiments present that admittance model-based control consistently produces a favorable steering feel with existence of undesired disturbances. The adjustability of the stiffness coefficient within the admittance model further allows for customization of the steering feel, with higher values yielding a heavier feel and lower values imparting a softer feel. While the admittance-based controller shows promise in optimizing steering feel in SbW systems, challenges persist.

The inherent complexity of the admittance controller, comprising both a velocity controller and a disturbance observer, poses a notable challenge. While the velocity controller is relatively straightforward, the disturbance observer introduces additional intricacies. Robustness remains a key concern, necessitating further exploration to enhance the controller's resilience to disturbances. Notwithstanding these challenges, the admittance-based controller represents a promising avenue for achieving a adquate steering feel in SbW systems, as underscored by empirical evidence demonstrating its efficacy, even in the presence of disruptive factors.

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