

APAC15-405 Semi-Experimental Results on a Measured Current Based Method for Reproducing Realistic Steering Feel of Steer-By-Wire Systems

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Abstract

In this paper, a measured current-based method to reproduce realistic steering feel and improve the returnability of steer-by-wire systems is proposed. The key contribution presented here is a novel method to recreate the steering feel in term of force feedback with simple and cheap current sensors. The current sensor is used to measure the steering torque on the rack of steering mechanism. This measured steering torque therefore, includes the overall dynamic effects from road conditions, aligning moments, tire properties and so on. Beside that a free control scheme is proposed to improve returnability as well as the handwheel stability in free motions. The frequency effect of handwheel motion is also introduced. And, this could be useful for torque-map based method. In addition, the physical property the lock-to-lock or steering limitation of mechanical connected steering systems is first carried out for steer-by-wire systems. The lock-to-lock property allows the driver to feel the hard contact when he or she reaches the rotating limitation of handwheel movement. The feasibility of the proposed method was tested with simulation and semi-experiment. A handwheel known as a haptic interface was developed for the experiments. The simulation and semi-experiment were conducted with six subjects. The results have shown that the proposed method offers a cheaper and simpler solution for reproducing realistic steering feel in steer-by-wire systems, and hard contact at lock-to-lock position, and improving the stability of handwheel in free motion.

Keywords: steer-by-wire, force feedback, steering feel, driving feel, current sensor, free control, stability, haptic feedback in steer-by-wire, human-vehicle interaction.

1. INTRODUCTION

A steer-by-wire (SBW) system is the innovative version of an automotive steering system. In the SBW system, a steering signal given by a driver is transmitted to the roadwheel (RW) through electrical wires meanwhile this signal was transmitted through mechanical and, or hydraulic linkages in conventional steering systems.

Thanks to the absence of the mechanical connection between the handwheel (HW) and the RW, SBW systems offer several advantages such as larger space in the cabin, freedom in car interior design, no oil leaking, and less injury in case of car accidents. However, there is also a number of disadvantages due to no mechanical connection. In particular, the lack of realistic steering feel, which is expected to be similar to the one with mechanical linkages, failures of electrical components reduce system safety. In addition, the HW behavior after the driver releases his/her hands at a certain steered position of the HW, the so called free control, is also another issue. One of the most challenging issues in SBW is how to give a driver a realistic steering feel. It means that the steering feel in SBW must be equal to the steering feel in mechanical connected steering systems.

In conventional steering systems, the steering feel is transmitted to the driver via mechanical linkages. This steering feel not only includes moment of inertia, moment of damping, and joints' friction of steering systems but also contains the aligning moment. Furthermore, the aligning moment is also affected by the tire properties, road condition, vehicle velocity, and so on. Unlike conventional steering systems, in the SBW system, the

steering feel must be artificially recreated by the HW actuator. To produce realistic steering feel, all the mentioned effects become essential [1-25]. For solving this, there have been several researches, and they can be categorized into three approaches, model based, torque-map based, and torque sensor based approach.

In model based approach, the steering feel could be obtained from a dynamic model using an observer. However, the exact models of steering system and vehicle as well as powerful microcontrollers are required. Details of this can be seen in [1], [3], [4], [5], [24], [29], [30], [31], etc. In torque map-based method, the force control loop has torque map treated as reference input of the force feedback control. This torque map is governed by the combination of several signals such as vehicle velocity, HW angle. Details of this can be referred to [15], [34], [35], etc. In torque sensor based approach, the steering feel is reproduced based on the measured torque signal from the rack of steering systems. The torque signal is acquired from a torque sensor. Details of this are described in [6], [8], [25] [28], etc.

This paper proposes a method to reproduce the realistic steering feel for SBW system, which is similar to the steering system equipped with mechanical linkage. Furthermore, the steering feel is easily adjustable using this method. Along with reproducing steering feel, a control scheme of HW in free motion is proposed to improve HW stability in free motion. In this research, the frequency effect of HW motion is found to be significant. And, this

initializes an idea to improve steering feel quantity by combinations of this method and other approaches.

2. STEER-BY-WIRE

2.1 Conventional Steering and SBW

In conventional steering system shown in Fig. 1(a), the HW rotation given by a driver is transmitted via intermediate shaft, which is connected to the rack and RW. Therefore, the RW angle is synchronized with the HW rotation. Hydraulic pump is used to reduce the driver's steering efforts. In SBW system in Fig. 2(b), several position sensors and actuators are used instead of intermediate shaft and hydraulic pump. The HW motion is monitored by the encoder and sent to the controller. The controller produces control signal to make the RW follow the HW motion. An actuator at the HW is used to reproduce the steering feel.

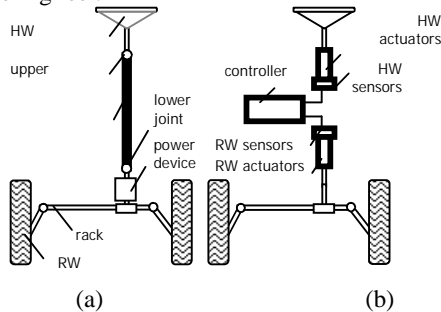


Fig. 1 Conventional power steering and SBW

To make SBW features close to conventional steering systems, several requirements have to be satisfied. Position tracking is the fundamental function of a typical steering system [3], [5]. This ensures the RW exactly copy the HW motions. Realistic haptic feedback, which makes the SBW system has the same steering feel as in the hydraulic steering system, was one of the most difficult issue to realize SBW system [3], [5], [8], [10], [22]. Free control, which refers to the response of the HW after a sudden release from the certain position of the HW, was also one issue to be solved. Usually, quick return to the center with minimal overshoot is desired [6].

2.2 Dynamic Model of a SBW System

A SBW system consists of two parts, HW and RW illustrated in Fig 3. The dynamic modeling of the HW part is described in equation (1).

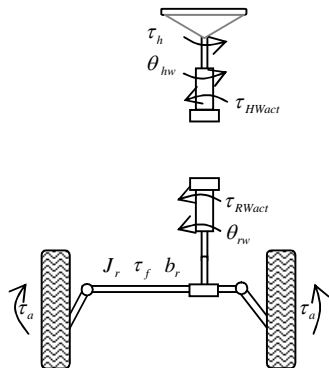


Fig. 3 Dynamic model of a SBW system

Where, J_h and b_h are the HW inertia and damping coefficient, respectively. τ_{fh} is Coulomb friction torque at the HW part, θ_{hw} denotes the HW angle, τ_h presents the human torque applied to the HW, and τ_{HWact} is the motor torque generated by the HW motor.

$$J_h \ddot{\theta}_{hw} + b_h \dot{\theta}_{hw} + \tau_{fh} + \tau_h = \tau_{HWact} \quad (1)$$

The dynamic modeling of the RW part is described in equation (2). Where, J_r and b_r are the RW inertia and damping coefficient, respectively. τ_{fr} is Coulomb friction torque at the RW part, θ_{rw} is the RW angle. τ_a is the aligning torque due to the caster and kingpin angle in the automotive steering mechanism. The aligning torque only occurs when there is contact between tires and the road surface. τ_{RWact} is the motor torque generated by the RW motor.

$$J_r \ddot{\theta}_{rw} + b_r \dot{\theta}_{rw} + \tau_{fr} + \tau_a = \tau_{RWact} \quad (2)$$

3. PREVIOUS METHODS TO REPRODUCE REALISTIC STEERING FEEL

3.1 Model-Based Approach

One of the first steps to realize steer-by-wire systems is the study of effect of steering performance [1], [16] and the steering feel in steering simulators [2]. For example, Liu and Chang studied how the torque magnitude of steering feel has influence on the driver. The results shown that without the additional torque from motor, the drivers were not able to return the vehicle to the prescribed path (the road profile was a sharp curve) after correcting their skid. However, with long turns (the road profile was not a sharp curve), there is no significant difference in the steering performance. In this research, the profile of steering torque was not found. In 2000, Ryu and Soo proposed vehicle model based method to reproduce steering feel in EPS (electronic power steering) Based on this, the interaction between the RWs and environment produces an interactive force. This force then is reduced to give lower steering feel to drivers. Im et. al. designed SBW system with bilateral control method using disturbance observer. Recently, Yih, P. et. al., [13] have developed HW force feedback based on a disturbance observer in which the aligning moment is considered as a source of disturbance in the system dynamics. Therefore, the aligning torque can be estimated without any torque sensors. However, disturbance-based approach requires a powerful microcontroller for calculating the force feedback. And the estimated signal may be not exactly the same as the actual aligning moment.

3.2 Torque Map-Based Approach

Torque map-based method is a good way to avoid the calculation of aligning moment for solving force feedback issue. One of the torque maps is developed by Oh [15], et. al. Their main concept was that a torque map is built based on two signals, vehicle velocity and HW position in Fig. 4. In particular, the relationships between the HW angle and vehicle velocity are defined as equation (3), and (4).

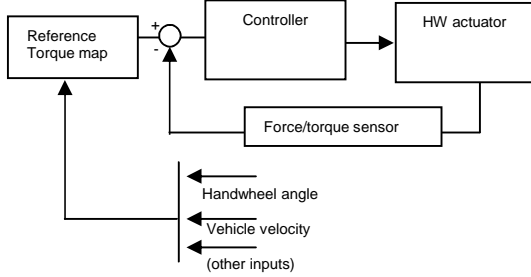


Fig. 4 Control scheme of the torque map method

Angle effect term:

$$y_{SW} = K_{\alpha} \sqrt{\theta} \quad (3)$$

Velocity effect term:

$$y_V = -K_{\beta} x^2 \left(\frac{1}{3} x - \frac{1}{2} V_{V \max} \right) + T_{in} \quad (4)$$

With the torque map, it is easy to recreate force feedback because the HW angle θ , and the vehicle velocity V_V can be easily measured in any today vehicles. However, other factors such as HW frequency, align moment, and so on, are not considered in this torque map.

3.3 Torque Sensor-Based Approach

Researchers from the field of robotics have proposed torque-sensor based solution in which a steer-by-wire system is treated as a teleoperation system with position-force control architecture [6], [21]. One of these research eson this method is done by Amberkar, et. al. In this research, two torque sensors are used. One is to measure steering torque applied on the rack. And the second one is for feedback torque signal in HW control algorithm. The control system methodology of steer-by-wire proposed here is based on position-force control scheme shown in Fig. 5.

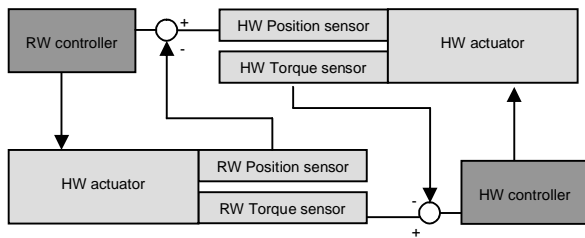


Fig 5 Position-force control scheme for SBW

4. MEASURED CURRENT BASED METHOD

4.1 Overview of Measured Current Based Method

SBW system can be considered as a master/slave two-port teleoperator shown in Fig. 6. The HW part is the master, which can measure driver's steering angle and make driver feel the road information, which is known as the steering feel. RW part is the slave, which follows the driver's steering command and measure road information for sending to the master. There is communication channel in-between master and slave for exchanging signals. Driver's steering angle can be measured by an encoder and motor can display road information from the RW to the driver. Motor at the RW enable the RW follow the command angle from the master, and it actually is an issue on how to estimate the road information.

In this paper, we propose to use current sensor for estimating road information, which is same as measuring steering torque. Current signal at the RW actuator contains properties of tire property, road condition, aligning moment and vehicle dynamics. In addition, these properties govern the steering feel in conventional steering systems. Therefore, based on this current signal the realistic steering feel can be displayed to the driver. In this research, the assistant control is developed to maintain the benefit of assistant steering functions in conventional vehicles.

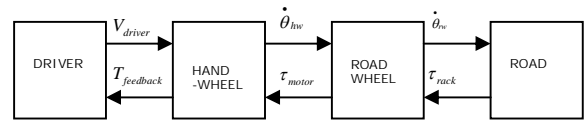


Fig. 6 Steer-by-wire as a two master/slave two-port teleoperator

Once the RW DC motor actuates the roadwheels accordingly, a proportional current signal inside the motor driver of occurs at the same time. Fortunately, for a permanent magnet or shunt wound DC motor, the current drawn by the motor increases linearly with load torque in equation (5). τ_{motor} is the motor's output torque. i , K_t , and η are armature current, motor's torque constant (or motor constant) and motor efficiency, respectively. The torque constant is the same value as the inverse of the speed constant in the same SI units (radian per second). These constants describe how a motor converts electrical current to torque and angular velocity to voltage.

$$\tau_{motor} = i K_t \eta \quad (5)$$

In equation (5), the value of the current signal depends on the applied load (or torque) on motor shaft. This torque contains properties of road condition, align moment, and steering dynamics. In addition, these properties govern the steering feel in hydraulic or electronic steering systems. Therefore, we propose a scheme in Fig. 7 to measure the RW motor' current. This current is applied in equation (6) in the next section to reproduce the steering feel for steer-by-wire systems.

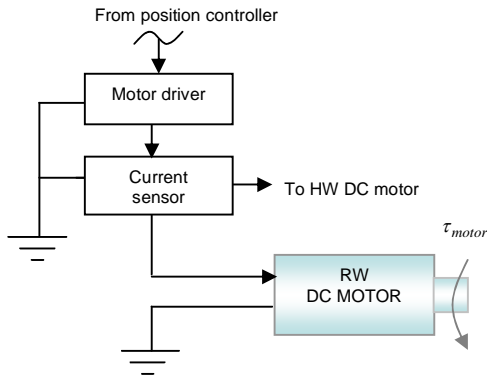


Fig. 7 Connection diagram of current sensor

In proposed measurement method, a current sensor is connected to RW's motor driver and RW's motor in series for measuring current signals. To create realistic feedback, the vehicle speed and the HW angle are employed to produce the assistance force. To make HW stable and easy to be controlled, a free control algorithm is developed based on the HW angle. The next section will comprehensively describe the implementation of force feedback as well as free control algorithm.

4.2 Reproducing Steering feel

Based on the measured current, steering feel $\tau_{feedback}$ is reproduced as follows:

$$\tau_{feedback} = G_{feel} (K_t \cdot i - \tau_{assist}) + T_{fc} \quad (6)$$

In equation (6), G_{feel} is a feel gain which allows us to adjust the steering feel to comfortable feel. K_t is motor torque constant given in the motor's datasheet. i is the mature current in the RW motor. τ_{assist} is assistance torque. This torque must be reproduced by equation (7) because in steer-by-wire, there is no hydraulic pump. T_{fc} is free control torque defined in section IV.3.

Basically, in automotive power steering, the assistant torque is used to reduce the force feedback at the lower speed (the speed of the vehicle) or tighter at the higher speed [6]. Therefore, assistant torque τ_{assist} is introduced in equation (7).

$$\tau_{assist} = K_a \theta^2 - \text{sign}(\dot{\theta}_{hw}) K_v V_v \quad (7)$$

From equation (5) and (6), the total force feedback is produced. In particular, this feedback torque is tuned through three steps. First, pure force is calculated from the measured current signal. This torque obtained from this original current is quite hard like a steering feel without any assistant mean. Therefore, assistant torque based on the equation (7) is done in the second step. We may turn HW angle gain κ_a , and velocity gain κ_v to obtain the

desired force magnitude. In the third step, there is a need to tune two gains (G_{feel} , and κ_{fc}) at the same time to achieve a desired force feedback profile. A gain set selected in this research is provided in the simulation parameters in section V1.

4.3 Free Control

Traditionally, free control response has been solved by adding damping (in the case of EPS) or friction to the system [6] (in the case of hydraulic steering). In previous research, a free control algorithm for EPS application is done by Bolourchi and Etienne [12]. Sanket Amberkar, et al mentioned that for the free control of a steering systems as well as SBW systems, a quick return of HW to center with minimal overshoot is desired [6]. However, their research did not mention how a good free control is implemented. Our proposed idea is to add additional damping to SBW system. Thus, we now introduce a new torque to the system called free control torque. This torque is a product of a free control gain κ_{fc} , and HW angle, written in equation (8).

$$T_{fc} = -K_{fc} * \theta_{hw} \quad (8)$$

By introducing this force to the system, the force feedback will change. Fortunately, because the special design of by-wire technology allows us to easily adjust the force feedback by changing the HW angle gain, velocity gain as well as the scaling factor of RW motor's torque in equation (6).

4.4 Lock-to-lock property

The lock-to-lock position is where driver reaches the limit of HW angle in conventional steering systems. Since there is no mechanical connection in by-wire steering system, the force feedback algorithm must take into account this aspect. And to do this, we propose two virtual walls at the lock-to-lock positions. The virtual wall displays high stiffness by increasing motor torque at the limit of handwheel. For this, the feedback torque from equation (6) becomes equation (9).

$$\tau_{feedback} = G_{feel} (K_t \cdot i - \tau_{assist}) + T_{fc} + \tau_{ll} \quad (9)$$

Where, the lock-to-lock torque τ_{ll} is defined as equation (10). The τ_{ll0} is constant force which is defined based on RW motor power. θ_{right} and θ_{lef} are the largest angles when HW is turned left and turned right, respectively. K_{lock} is chosen to adjust the feel of stiffness at the lock-to-lock position. $\Delta\theta_{hw}$ is the angle difference. The torque τ_{ll} produced in equation (10) can be seen as a hard spring in physical meaning.

$$\tau_{ll} = \begin{cases} K_{lock} \Delta\theta_{hw}, & \text{if } \theta_{hw} > 0 \text{ and } \theta_{hw} > \theta_{right} \\ -K_{lock} \Delta\theta_{hw}, & \text{if } \theta_{hw} < 0 \text{ and } \theta_{hw} < \theta_{left} \end{cases} \quad (10)$$

5. SIMULATION AND SEMI-EXPERIMENTAL RESULTS

5.1 Simulation Parameters

First, a model of steering system is modeled in LabVIEW. A PID controller for controlling position of steering system aims to have an accurate position tracking of RW and HW. An open loop control for force feedback based on the measured current signal is conducted as algorithms described in section 4. Free control quality is evaluated by the returning force verse HW angle [15]. Simulation parameters are chosen as follows. the inertia constant of steering system J_w equals 0.019 (kg.m²/s²). The damping constant of steering system b_w is 0.368 (Nms). These two constants are chosen based on steering system identification done by [13]. This feel gain is selected based on comfortable feel of drivers. In this simulation, the feel gain G_{feel} chosen to be 1. The motor torque constant κ_t is 0.581 (Nm/Amp) provided from the motor's datasheet. To obtain a suitable assistant torque, κ_a is chosen to be 0.3 and κ_v is 3. Vehicle velocity v_v is set at 60 (km/h). Free control gain κ_{fc} is 0.02. This free control gain must give the lowest oscillation of the HW in free control test. In the position control loop, proportional gain κ_p is turned to be 5.5 and derivative gain κ_d is 0.08. This simulation was described in depth in [36].

5.2 Simulation result

A good position tracking is achieved using this method shown in Fig. 8. The simulation parameters are: $\kappa_p=5.5$; $\kappa_d=0.08$; Step size: 0.001 (s). The result shows that error of the system is significantly reduced. In this method, the error is about 0.06 rad) while it is normally about 0.1 - 0.59 rad mentioned in [11], [16].

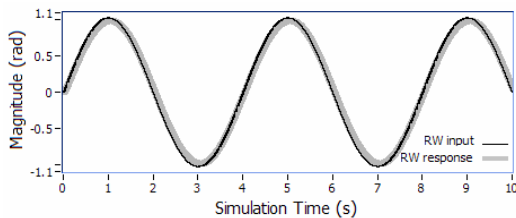


Fig. 8 Position tracking of SBW

Realistic haptic feedback, the force feedback is first recreated based on current signal without any amount of assistant force and free control force. In addition, without tire-to-ground contact, the relationship of HW angle as force feedback is a rectangular profile shown in Fig. 9.

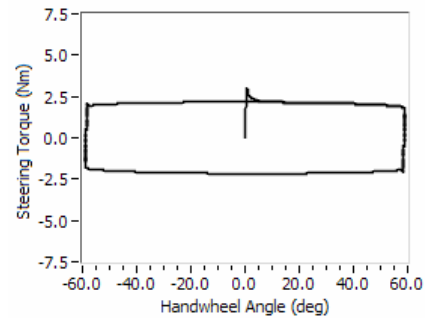


Fig. 9 HW position vs. Force feedback without tire-to-ground contact.

In normal working conditions, the tires travel on road surface and aligning torques at two front wheels happen. Once the steering angle increases, the aligning torque become larger because of the increment of the pneumatic trail displayed in Fig. 10.

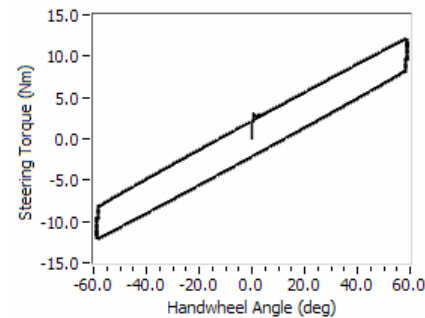


Fig. 10 HW position vs. Force feedback with tire-to-ground contact

The final force feedback is achieved after introduction of assistant torque based on HW angle and vehicle velocity ($v_v=60$ km/hour). In Fig. 11, the magnitude of force feedback at larger angle is reduced. This makes the steering wheel lighter at larger position.

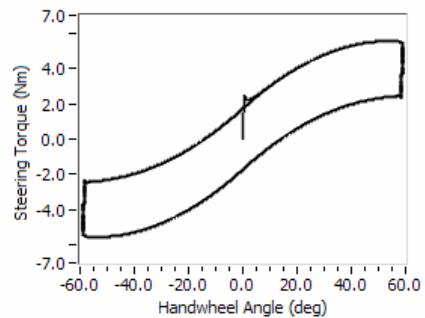


Fig. 11 HW position vs. Force feedback with assistant torque

Fig 12 is the comparison of simulation of torque map method and the proposed method. The simulation result clearly shows that the realistic haptic feedback which provides the realistic steering feel can be achieved by proposed method. This is because the steering dynamics is included to implemented force feedback. These dynamic effects are represented in term of the measured current signal. Therefore, the obtained force feedback not only

depends on HW angle and vehicle velocity, but also relates to road condition, tire properties, yaw movement of vehicle and so on. This is the most benefit and important contribution which is not solved in torque map-based approach.

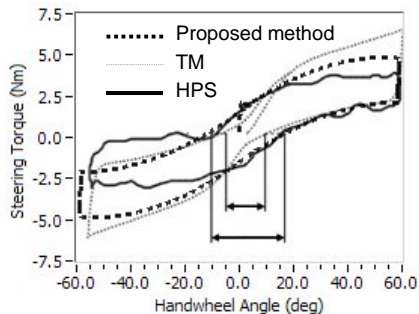


Fig. 12 Force feedback profile (FFP) in proposed method versus FFP in HPS and TM

HPS: hydraulic power steering, TM: torque-map method

In addition, with the direct current measurement method, the force feedback can be abstained and easily adjusted shown as Fig. 13. In this result we have three torque profiles equivalent to the free control gains are 0.01, 0.02, and 0.03. For the result of total force feedback shown in Fig. 12, the free control gain is chosen as 0.02.

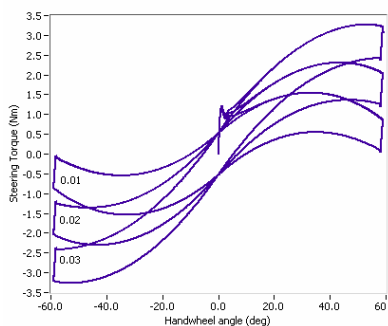


Fig. 13 Different force feedback magnitude with varying free control gain

The frequency of HW is changed from 0.05 to 2Hz in different experiments. The results in Fig. 14 show that steering torque is significantly affected by HW frequency. This is an important finding because this effect is ignored in torque-map based method.

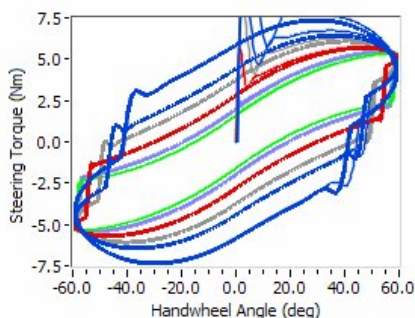


Fig. 14 Force feedback with varying free control gain

Free control, the simulation result in Fig. 15 and Fig. 16 has proved that, the free control torque has significantly reduced the oscillation of HW. This could be explained easily because when the free control factor is added to the system, the hysteresis of steering system is reduced as shown in Fig. 12. The hysteresis of proposed method is reduced to -5 to 5 degrees while it was from -10 to 10 degrees in torque map method.

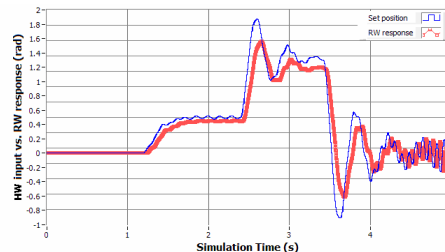


Fig. 15 HW behavior without free control torque (T_{fc}) (Without scaling of HW angle and WR angle)

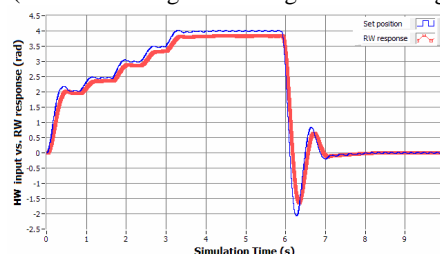


Fig. 16 HW behavior with free control torque (T_{fc}) (Without scaling of HW angle and RW angle)

Lock-to-lock property of steer-by-wire systems described in equation (10) is conducted to give a high torque value at the limits of handwheel. In this simulation, K was chosen to be 50. HW movement range was set as $2\pi/3rad$. Virtual walls produced a bigger steering moment applied on HW when the driver reached lock-to-lock position shown in Fig. 16. In order to produce the bigger torque in this simulation, the 120watt motor was used and the gear ratio was 111/1.

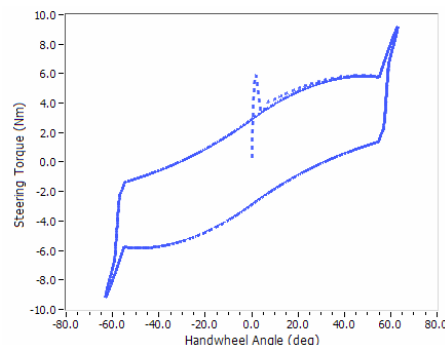


Fig. 17 Virtual walls at limitation of HW

5.3 Semi-experimental result

The semi-experiment was conducted to investigate and demonstrate the proposed method. Fig. 18 shows the semi-experimental testbed. A physical HW equipped with a Maxon DC motor, motor driver and 4096pulse/rev encoder is developed. The RW part is simulated in LabVIEW environment and is interfaced with the HW via a NI PCI motion controller 7356.

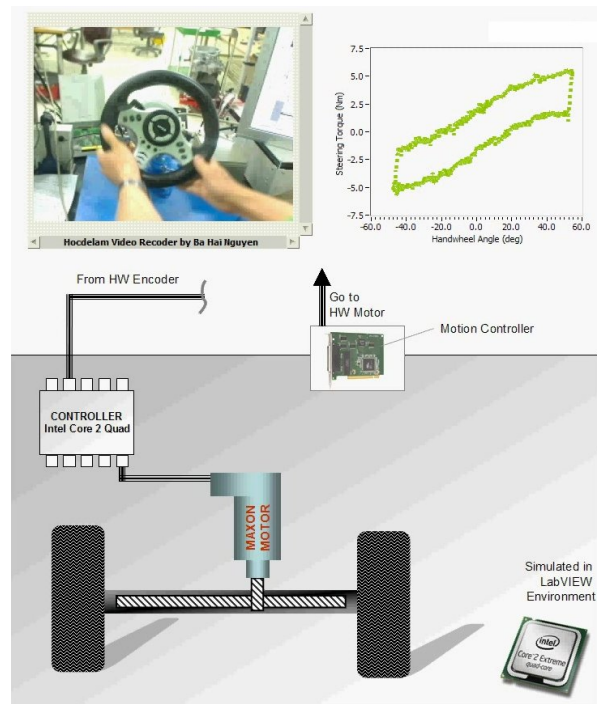


Fig. 18 Semi-experimental testbed

During the experiment, six subjects were asked to involve the experiment. All subjects have experience in commercial vehicle driving. Subject were asked to give score of four evaluation factors, realistic steering feel, returnability, stability of HW, and hard contact feel in three methods. In the first method, steering feel in term of force feedback was only from a spring model, the second method was the torque-map based method and the third one was measured current based method.

The results of semi-experiment of six subjects are reported in Fig. 19. In general, the proposed method has higher scores. This means the measured current based method not only provides a steering feel closest to conventional power steering systems but also improves returnability, and gives users the hard contact feel at lock-to-lock positions. With the steering feel from the spring model, subjects were not able to see realistic steering feel as well as hard contact feel shown in dark red columns. Also, the returnability in this case was worst. For torque map based method, better performance and quality in all four evaluation factors except the lack of hard contact feel at HW limitation shown in green columns.

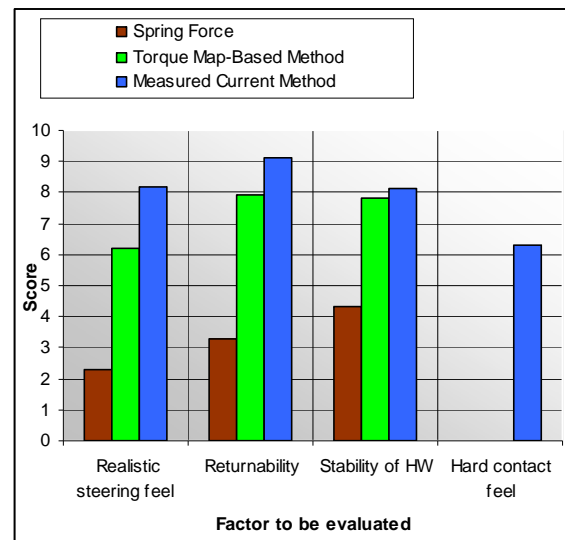


Fig. 19 Evaluation chart of semi-experiment

6. CONCLUSION AND FUTURE WORK

This research has proposed a novel control scheme for steer-by-wire development in which the current sensor could be used to fully measure steering torque. Since, current sensors are cheap and available in typical industrial and automotive applications. This solution offers a cheaper and simpler method to reproduce the steering feel. The force feedback control algorithm is developed not only to give the realistic steering feel, but also to improve the returnability and free control performance while the fundamental requirements of conventional steering systems such as position tracking, mechanical lock-to-lock is remained. The proposed method offers a number of benefits such as avoiding complex dynamic model or disturbance observer, neglecting the requirement of torque measurement at both HW and RW. Finally, the proposed method was investigated with simulation and semi-experimental results.

To extend this research, it is suggested to study of force feedback for handwheel with very low mass in future design of human/vehicle interfaces or handwheel for the handicapped. In this case, Force calculation scheme must include virtual mass to recreate steering feel. Also, the study of different force feedbacks of different handwheel types might be benefit for automotive handwheel manipulations and control. The improvement of steering feel in torque-map based approach may be possible with the combination of measure current signal. In addition, the stability of HW in hard contacts may be a future challenges for SBW development.

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