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Bilateral control of steer-by-wire vehicle

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Bilateral Control of Steer-by-Wire Vehicle

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Dedicated to my

Dad and Mum

DECLARATION

This is to certify that the work reported in this thesis was done by the author, unless specified otherwise, and that no part of it has been submitted in a thesis to any other university or similar institution.

Peng Zhai

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ABSTRACT

Recent research shows that the Steer-by-Wire (SBW) technology has been applied in the flight area, and it could be used in motor vehicles in the near future. The vehicle SBW system has been recently proposed to replace the traditional vehicle steering system by moving the mechanical linkage between the steering wheel and the front wheel. It has many advantages, including providing vehicle design freedom and improving vehicle handling. Two of the most challenging problems faced by the vehicle SBW system are 1) how to establish the effective force feedback between driver and the wheel so that the driver's steering signal can be accurately followed by the wheels so the road condition can be felt by the driver, and 2) how to design and choose the available hardware so that a reliable transmission with high speed can guarantee the reliability and stability of the SBW system. It is therefore necessary to develop advanced SBW control systems and to design advanced architectures for the SBW system. In this thesis, a new SBW control system with the consideration of the variable gear-ratio is presented and the hardware in-the-loop is designed. This SBW system includes two control loops, which are called upper control loop and lower control loop, to achieve bilateral control. The force feedback motor, which is installed with the steering wheel, and the steering motor, which is installed in the front wheel, are adopted in these two loops, and two PID controllers are designed for them, respectively, so that steering signal and road feeling can be tracked. To improve vehicle handling performance in terms of the change of velocity, the reactive torque map and variable gear-ratio are further considered in the two loops. The practical constraints on the angles of the steering wheel and the front wheel are also considered in the design of the SBW system. A simulation model is established to validate the effectiveness of the developed control system. The

simulation results show that the system is stable and both the desired steering wheel angle and the tyre-road contact can be well reflected. The experimental platform has also been established in this thesis, which uses the HILINK board from Zeltom Company as the Electronic Control Unit (ECU). The experiment shows that the front wheel can track the steering wheel's position accurately and the force feedback can be achieved for the operator. The Hall-Effect current sensors are also used experimentally to detect the currents from the steering motor and the force feedback motor. Then the force feedback can be controlled with the PID controller.

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RESEARCH PAPER COMPLETED

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Chapter I

Introduction

1.1 Development of the Automobile

The automotive industry is now more than 100 years old and incredible technological improvements have been achieved by engineers. With the development of electrical technology and modern control engineering, some advanced control technologies such as anti-lock brake systems, traction control systems, electronic stability control systems and active suspension systems were widely applied in automobile systems. The speed limits of the vehicles are very high, and their safety and stability are imposed only by the passengers and the automobile industries. The safety systems and vehicle dynamics play an important role when the vehicle is at high velocity. The steering systems of passenger cars have evolved from the mechanical steering systems, to hydraulic and electro-hydraulic power assisted steering systems, through to the electric power assisted steering system. Another advanced steering system is the SBW system [1-3].

The stability and manoeuvrability of vehicles have been gradually focused on and improved by the automotive industry. Therefore, the SBW system becomes a wonderful choice to improve the performance of the vehicle, because there are some advantages, such as stability and manoeuvrability for the vehicles, and safety can be guaranteed for the operators. However, disadvantages also exist: the feedback from the front wheel may not be as perfect as the traditional vehicles, which means the drivers can not feel the road condition as easily as without SBW. Therefore, how to improve the

feedback on the hand wheel and enhance the driving feeling to the drivers is the focus of this thesis.

1.2 Main Objectives of the Research

The core issue of SBW system is the communication between steering wheel and the road wheel. There are two elements that should be the focus in the communication system; signal transmission and feedback generated. First, the signal is generated according to the steering wheel turning, and then it is transmitted to the road wheel to indicate to the front wheel what the driver would like to do. Secondly, force feedback is provided to the steering wheel to let the driver know what the road condition is.

There are three main aspects of my research, including 1) system modelling; 2) simulation and controller design; and 3) platform design. In system modelling, the comparison between the SBW system vehicle and the traditional automobile is clarified and the advantages of the SBW system are shown. In simulation and controller design (2), the whole car modelling that I designed is given, by which it is easy to understand the process of the steering. The PID control design is also given, although other researchers have already introduced this control scheme [4-8]. However, my PID control design is different from the other designs because it would make the system more stable and lets the drivers feel the road conditions much more realistically.

In platform design (3), the vehicle model kits, from to start to finish of the experiment, will validate the results between the simulation and the realistic steering process. In this experiment, the front wheel should be steered while the steering wheel is turned by the driver, while the driver should receive the torque feedback from the steering wheel.

It is obvious that the SBW technology principles are suitable for different application fields. According to a large number of simulation data, the results

show that the dynamics of the vehicle could be supported and it is closely similar to the traditional vehicle's dynamics. The front wheel especially can trace the motion of the steering wheel quickly and accurately; and the driver can receive the feedback torque under the SBW technology vehicle, which makes the driver have enough confidence to handle the driving task.

1.3 The Steer-by-Wire System

The steer-by-wire (SBW) technology is a relatively new development compared to the traditional steering system that is widely used for automotive vehicles. It removes the mechanism connection, the steering column and shaft, between the steering wheel and the front wheel. However, despite lacking the mechanism connection, the vehicle can still work like the traditional automobiles. The SBW system consists of two parts: the steering wheel system and the front wheel steering system. The front wheel needs to track the motion of the steering wheel. A steering motor is installed with the front wheel steering system to provide steering power to the front wheel according to the input signal (the angle of the steering wheel). At the same time, the driver needs to feel the torque feedback according to different road situations and this will be realised by using another motor to provide the feedback torque. The feedback relies on the different velocities of the vehicle and the different angles of the front wheel angle.

The SBW system in vehicles brings some advantages in terms of driving safety, cruising comfort and environmental safeguard. Recent research has been done in this area. The conventional steering system modelling and SBW system modelling are established, as are the transfer functions of the systems. The steering feel should be recreated in SBW system vehicles because there is no shaft in that system and force feedback should be similar to the feeling of traditional driving, which has been discussed in [9]. The two control loops including steering wheel position loop and front wheel position loop are also introduced. The sideslip angle and yaw rate are important characteristics and cannot be ignored. These two characteristics are estimated in [10]. According to B. Nguyen and J. Ryu [11], the feedback is the most difficult issue for the

SBW system development. In order to recreate force feedback, the sensors should be settled in the vehicle. In general, angle sensor will be used to observe hand wheel motion, and the current sensor will be applied to measure the feedback torque applied on the steering wheel, which is generated by the motor. Furthermore, the variable gear-ratio steering (VGRS) can reduce the burden for the driver and improve the safety of the dynamics of the vehicle. For example when the driver is turning the steering wheel at low speed, decreasing the gear-ratio could reduce the burden of the driver. On the other hand, increasing the gear-ratio will keep the stability of vehicle and avoid roll when the vehicle is driving at high speed [12-14]. Nevertheless, consideration of the modelling of variable gear-ratio in SBW systems has not been found in most of the existing research papers.

In this thesis, a new SBW control system has been established with the consideration of variable gear-ratio. The structure and control strategy of this SBW system will be presented in this paper and simulation results will be used to validate the effectiveness of the proposed system. Also, the experimental platform will be established and it will show that the bilateral control of SBW vehicle can be achieved. Finally, the front wheel can track the steering wheel's position and the operator can also feel the force feedback when turning the steering wheel.

1.4 The Structure and Characteristics of the Steer-by-Wire System

This innovation in steering system—to remove the steering column and shaft—represents an innovation direction for the future. The substitution of electronic systems in place of mechanical or hydraulic controls is known as SBW technology. The SBW vehicle could save energy because it reduces weight through the elimination of the steering wheel column. It could also reduce noise and vibration from the hydraulic pump. In addition, the SBW vehicle may have space benefits in the engine compartment, resulting from the elimination of the steering-wheel column and the intermediate shaft. The SBW-system could also improve the crash performance of the vehicle and

protect the passenger avoiding damage in a car crash. In addition, active safety functionality can be invoked to provide corrective steering for improved stability and control. Other benefits include variable gain steering, tuneable steering feel, steering lead, and the possibility of novel steering interfaces.

1.4.1 The Structure of the traditional System

The structure of the traditional steering system of the vehicle is shown below in Fig.1. It includes the hand wheel (steering wheel), steering column, intermediate shaft, universal joints, rotary spool valve, rack and pinion, etc. In the traditional steering system, the angle of the steering wheel is recognised as the input signal, which is transferred to the front wheel through the intermediate shaft. The front wheel angle is recognised as the output signal, which can track the input signal and can follow the position of the steering wheel. Meanwhile, the force feedback on the front wheel should be generated when the steering wheel turns a certain angle. This force transmitted to the steering wheel, is the feedback to the driver.

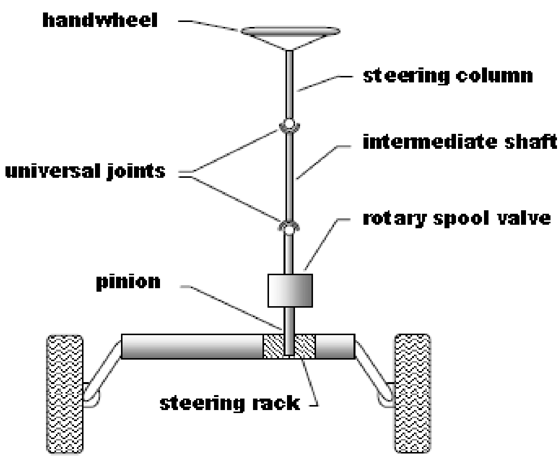

Fig. 1.1 Traditional steering system

Since the steering column and pinion are almost never collinear, they are joined to the intermediate shaft via two universal joints matched to minimize torque and speed variations between steering column and pinion.

1.4.2 The Characteristics of the Steer-by-Wire System

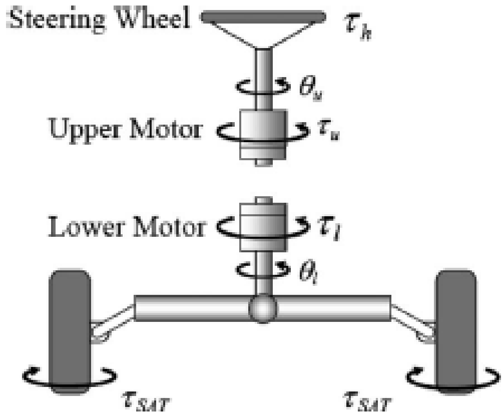

Fig. 1.2 The Steer-by-Wire System [12]

The SBW system includes the steering wheel, angle sensor, upper motor, lower motor, rack and pinion, two current sensors, position sensor, etc, which are presented in the Fig. 1.2. The intermediate shaft is replaced by the electric control unit and two motors in the new system. The ECU and two motors have the same effect as the intermediate shaft.

The two current sensors and position sensor are not mark in Fig. 1.2. The position sensor should be installed with the steering rack to detect the linear movement of the rack. Then the angle of the front wheel can be calculated. The current sensors should be installed with the upper motor and lower motor, respectively. The turning of the steering wheel generates the position input signal which would be transmitted to the front wheel subsystem. Meanwhile, the current sensors are used in the SBW system in order to detect the torque applied on the front wheel. Then the current signal would be transmitted to

the upper motor, and another current would be generated by the upper motor so the driver receives the steering feel.

This is how the bilateral control system works. The new system vehicle would let the front wheel track the steering wheel's position and the driver would also receive the force feedback from the upper motor (feedback motor) at the same time, which would provide the same feeling as driving the traditional vehicle [15].

The electric control unit (ECU) analyses the signal and adjust the response of the vehicle, and the upper motor and the lower motor could be controlled, respectively. The lower motor makes the front wheel turn according to the position of the steering wheel, and the upper motor provides the force feedback to the operator according to the angle of the front wheel. In short, the SBW system is designed much like the traditional vehicle system and would let the operator receive the same steering feeling when driving.

It cancels the mechanical connection between the steering wheel and front wheel, replaced by the electronic control unit to control the dynamics of the vehicle [16]. Therefore, it can reduce the interference in the mechanical connection and set different gear ratios according to the different drivers. Without a direct mechanical connection between the steering wheel and the front wheel, noise and vibration no longer have a path to the driver's hand and arm through the steering wheel.

1.5 The Advantages of the Steer-by-Wire System

The benefits go beyond stability control: for example, a large, heavy vehicle can be made to feel as responsive as a smaller, lighter vehicle during normal driving. The ability to actively steer the front wheels allows artificial tuning of a vehicle's handling characteristics to suit the driver's preference. The entire steering mechanism can be designed and installed as a modular unit and the system designed is much easier than before. The advantage of the SBW vehicle is the improvement of the stability, dynamics and manoeuvrability of the vehicles, and the simplification of the vehicle design process [30]. The advantages are shown in detail below.

- The absence of a steering column greatly simplifies the design of car interiors.
- The steering wheel can be assembled modularly into the dashboard and located easily for either left- or right-hand drive.
- The absence of a steering shaft allows much better space utilization in the engine compartment.
- During a frontal crash, there is less likelihood that the impact will force the steering wheel to intrude into the driver's survival space.
- With SBW, previously fixed characteristics like steering ratio and steering effort are now infinitely adjustable to optimize steering response and feel.
- Improved driving safety and handling performance.

1.6 Thesis Overview

The SBW technology can improve the performance of the manoeuvrability and dynamics of the vehicle, and it has many advantages described in the previous chapter. It would be a popular technology in the automobile industry, and thus deserves investigation.

Chapter 2 is the literature review which is divided into five sections, the directions of the SBW technology. These are force feedback and steering feel, control method and control strategy, yaw stability and lateral force and observer design, variable steering ratio and experimental results.

Chapter 3 introduces the steering system, including the dynamics of the vehicle, and characteristics of the SBW system and the self-aligning torque.

Chapter 4 demonstrates the control strategy. The control strategy is designed and the simulation related to the whole SBW system is also given in this chapter. This chapter will be presented in June 2013, as a conference paper at the 8th IEEE Conference on Industrial Electronics and Applications in Melbourne.

The hardware-in-the-loop experimental platform is described in Chapter 5. Two motors connected to the HILINK board are used to finish two tasks: one motor, recognised as the steering motor, can generate the appropriate angular velocity and provide the appropriate torque on the front wheels; the other motor, called the feedback motor, can provide the force feedback and transmit it to the steering wheel and let the operator receive the steering feel. The experimental platform relied on by the HILINK board, can simulate the real-time results.

Chapter 6 is the conclusion of this thesis and discusses some of the changes that are being implemented in the next generation of experimental SBW vehicles.

1.7 Notation

This section, briefly lists the general notations used in this thesis. In Table 1, we briefly introduce the notation used most in the thesis.

symbol	Description
τ_h	The torque applied on the steering wheel by driver
τ_f	Feedback torque provided by the feedback motor
J_h	The moment of inertia of the steering wheel
B_h	Damping of the steering wheel
δ_{sw}	Steering wheel angle
M	M is the torque generated by friction
J_m	The moment of inertia of the front wheel
B_m	The damping of the front wheel

δ_f	Front wheel angle
τ_{fr}	The friction between the tyre and road
τ_a	Aligning torque
r_s	Steering ratio
r_p	The torque magnification factor of the power steering system
τ_M	The torque generated by the steering motor
k_M	Motor constant
i_M	Motor current
r_g	Gear head ratio
η	Motor efficiency
$F_{y,f}$	Lateral force acting on the tyre
t_p	The pneumatic trail
t_m	Mechanical trail
M_z	Aligning torque generated by tyre drag
M_A	Aligning torque caused by kingpin inclination
u	Speed (m/s)
m	Mass of the vehicle
l_f	Centre gravity to the front axle distance
l_r	Centre gravity to rear axle distance
l	Wheelbase
C_f	Stiffness of front wheel
C_r	Stiffness of rear wheel

β'	Kingpin inclination angle
D	Kingpi inclination value
Q	Wheel load
i_f	Torque ratio
i	Variable gear-ratio

Table 1 Nomenclature of the vehicle model

Chapter II

Literature Review

This chapter is a review of papers on the SBW system and bilateral control.

2.1 Introduction:

This review includes five sections. The first section discusses the steering feel to the operator and the force feedback applied on the steering wheel. Section 2 covers the approaches to the design of the SBW system. Section 3 considers the dynamics of the vehicle, including the yaw stability, lateral force and observer design. Section 4 concerns the variable gear-ratio of the system, and the reasons for designing this transmission in the SBW vehicle. Section 5 introduces the advantages and disadvantages of this SBW system via some valid data and graphs produced in the experiment.

2.2 Force Feedback and Steering Feel

In the process of replacing the traditional vehicle with the SBW vehicle, the challenge facing the engineers is how to rebuild the steering feeling of force feedback applied on the steering wheel.

Researchers have developed 6 methods to improve reproduction of the steering feeling. They are: 1) measuring the front wheel motor's current directly; 2) seeking to estimate the real reaction torque at the road wheel; 3) designing a fuzzy-PID controller to control the road feeling simulating motor in real time to achieve the self-aligning of the steering wheel; 4) a general approach to model accurately amplifier-motor-gearbox assemblies; 5) using a

brushless motor to provide force feedback; 6) combining force feedback with a controller based on lateral and heading error.

According to Nguyen [11], a method to reproduce realistic driving feeling and improve the returnability of SBW systems, by measuring the front wheel motor's current directly, is proposed in this paper. The key contribution presented is a novel method to recreate the driving feeling in terms of force feedback with a simple and cheap sensor. Also, the torque-map method includes angle effect term and velocity effect term. Two equations which calculate the force feedback are presented to improve the road feeling for the driver. This method is investigated with simulation results using the control design and simulation module in LABVIEW programming language. This is compared with other methods to improve the drive feeling, such as using the disturbance observers or force sensor. Nguyen indicated a novel idea to improve the driving feeling in the SBW system. It is a direct current measurement.

The force feedback is from the front wheel part, including the moment of inertia, damping and joint friction. The feedback is also affected by tyre properties, road condition, vehicle velocity and other factors. The angle effect term and velocity effect terms construct the total force feedback, which is also called driving feeling. In the torque map-based method, it is easy to recreate the feedback, because the steering wheel angle and the vehicle velocity can easily be measured through the angle and velocity sensors.

E. Mehdizadeh proposed a novel approach for making force feedback which made use of the virtual vehicle states through a linear vehicle model as the reference model [15]. Creating the reasonable steering feel is an underlying issue in SBW vehicles when a lane keeping assistance system functions along with the driver. In order to artificially force feedback which is familiar to the driver, it must not be built based upon the real front wheel reaction torque simply because this torque could involve the contribution of the lane keeping controller. If this force feedback is fed back to drivers, they might perceive

the force feedback as unnatural behaviour and this force can make the vehicle unstable. The simulation was also presented and the results showed that the new force feedback method does not interfere in the driving task.

According to T. Jie, the steering system angle ratio and force ratio of the steering system were designed in order to insure that drivers could feel the different road conditions while the vehicles were at different velocities. There are 5 sections in this paper: 1) the steering wheel model; 2) the model of aligning torque; 3) the strategy of road feeling control; 4) the design of puzzle PID control; 5)the simulation experiment [16].

Moreover, in the simulation experiments, the authors contrasted the input angle and input torque between SBW system and conventional vehicles in two conditions, low speed and high speed. In low speed conditions, the vehicles with SBW systems could be more sensitive and dexterous than the traditional vehicles and the input angle in the SBW system was less than that in the traditional vehicles. In high speed, the consequence was totally different.

The simulation results showed that the force torque and angles needed in the SBW system were much less than that in the traditional system. The other results showed that the angle ratio could be changed while the speed increased, however, when the speed was less than 20km/h or higher than 100km/h, the angle ratio would not change any more. The simulation results showed that the force torque could be changed while the speed increases, but it would be stopped at a high speed, such as 100km/h.

A general approach to model accurately amplifier-motor-gearbox assemblies has been developed by R. Pastorino [17]. It was explained by applying a particular case: an amplifier-motor-gearbox assembly for a driver’s force feedback system. The assembly considered was composed of a two stage planetary gearbox, a coreless PMDC and a linear four quadrant servo-amplifier. The identification procedures necessary to calculate the parameters of the model were presented. All the parameters of the model had a direct

physical significance, so these identification procedures were easy to realize. In order to evaluate the accuracy of the model, three different tests corresponding to real situations were performed. Comparisons between simulations realized with Simulink and the experimental data for three typical driving situations showed that the model is highly accurate at representing real system dynamics.

A. Bertacchini [18] proposed a preliminary architecture of a force-feedback system in SBW systems. The brushless motor was selected to set up the experimental platform as force feedback actuator. To validate the proposed architecture, the author adopted the hardware-in-the-loop (HIL) approach. The dynamics model of the vehicle was also implemented in virtual hardware and this model was needed to evaluate the realized hardware and to validate the force feedback control algorithms. The experimental results showed that the realized ECU and the implemented control algorithm based on a field oriented control technique were correct and particularly suitable for SBW applications. In particular, it has been shown that the implemented force feedback system recreated a drive feeling similar to that in a traditional steering system.

J. Switkes proposed a method of the force feedback combined with a lane keeping controller based on the lateral and heading error and he analyzed the effect of various sources of force feedback on the stability of the vehicle [19]. An examination of stability was critical for any application of force feedback to an assistance system. A system designed for good driver feel could easily be unstable in the absence of driver input, and at the same time, stability does not ensure good driver feel. This analysis showed that within a range of values that feel reasonable to the driver, changes to the lane keeping controller or force feedback can have marked effects on the response of the vehicle.

2.3 Control Methods and Control Strategies

In addition to steering feel, the control methods and control strategies are also key to the vehicle's SBW system. Some researchers tried to present some ideas about the control methods and strategies. They explored various control methods and strategies, including the bilateral control method, the concept of free control, the SBW model, an advanced SBW system using the high performance permanent motor drives, a new bilateral tele-operated vehicle testing platform, SBW technology to improve the stability of the vehicle, and a generic controller structure to design the SBW system.

According to Im [20], the bilateral control method based on the disturbance observer was established, to improve steering feeling and the design of the sensor fault detection for SBW vehicles using sliding mode observer. The modelling of the SBW system was also presented, and the state space equation for the bicycle model is given and the control system is also designed. The experiment was also performed and the data from the experimental platform was validated.

The advantage was the elimination of the interference between the drivers and the steering system. However, the disadvantage was that the road condition could not be felt by the drivers. The force sensor was expensive and difficult to attach to the SBW system. Aiming to solve these problems, disturbance observers and sliding observers were designed to improve the dynamics of the vehicle, and solved the problems such as the fault tolerant function and steering feeling. The control system was designed by the authors, including the steering wheel control and the front wheel motor control.

The SBW system should include the angle sensor, torque sensor, two motors, and the electrical control unit. The authors mention that a steering angle sensor and a torque sensor were located in the steering wheel. The data obtained from these two sensors could be transmitted to the ECU to generate the output signal so as to control the steering wheel's reactive torque. However, there were some differences between the estimate and real results and the author did not find a solution.

According to S Amberkar [21], the concept of free control was introduced, which referred to response of the steering wheel. The author mentioned that whether the steering wheel comes back to the centre determined the condition of free control behaviour. The steering feel and steering response were also considered. A direct relationship between steering wheel position and steering wheel torque was established, which could be tuned to get the desired steering feel. Selecting a proper transfer function was crucial to good steering feel performance. The position control law could be enhanced using an adaptive scheme. The adaptive scheme included a measurement of load acting on the system as a feedback signal.

The conventional steering system model and SBW system model were constructed by Bertoluzzo [22], then the parameters were given and the SBW system for a truck was designed. Diagrams were supplied to demonstrate the effectiveness of the SBW system. After the conventional steering system model and the SBW system model were set up, the steering system performance was evaluated. The system was assimilated into a tele-operator, where the operator was the driver handling the steering wheel and the remote object was the front wheels. Diagrams obtained from the resultant SBW system substantiated the improvements achievable in the steering performance of the vehicle.

S. Bolognani and M. Tomasini dealt with the control design of an advanced SBW system using high performance permanent motor drives [23]. The main aim of their work was the design of a position control for the front wheel motor for an accurate steering angle control and a torque feedback control for the steering wheel motor for an effective steering feel. The position control had to be precise and stable at load condition, which was very changeable with the steering angle, road conditions and vehicle velocity. The test bench for control validation was setup. The results obtained showed that position control of the road wheel motor and torque control of the steering wheel motor can be designed for excellent steering angle accuracy and steering feel.

A new bilateral tele-operated vehicle testing platform and a new Power-based Time Domain Passivity Control (PTDPC) methods were proposed by Ware [24] in an effort to improve the transparency. To ensure the stability, PTDPC were applied to each side of the communication channel, which further improved the tracking performance as well and reduced the overall effort required of the human operator. Five corresponding components of a bilaterally controlled robotic vehicle tele-operation scheme were described. The theory of the bilateral control of the vehicle was clearly shown. The human operator input model, master hardware, slave device and communication channel were also introduce by the author. The PTDPC approach to the tele-operated robotic vehicle in the author's host lab was successfully applied and the set-up offered a new test platform for future research in the area of tele-operation systems.

A. Baviskar and J Wager [25] developed an advanced concept of SBW technology which was integrated into cars and trucks to improve the stability of the vehicle and the manoeuvrability for the drivers by the ground vehicle industry. The authors in this paper introduced the process of feedback control in SBW systems to replace the traditional linkage between steering wheel and front wheel. The authors indicated that the suit feedback force should be provided to the drivers at the hand wheel. However, the excessive feedback force could result in a larger force to steer the vehicle, which defeated the purpose of easing the driving experience. Therefore, the adjusted force feedback was needed for the control strategy in order to provide a suitable force feedback to the drivers. The authors also referred some novel results researched by other researchers, such as the fuzzy logic controller to prevent vehicles from spinning on wet roads; robust control strategy for SBW systems; vehicle yaw rate control using SBW controller, etc.

In section two, some problems were described by the authors, resulting from the steering system being separated into two subsystems, primary and secondary. The primary subsystem included a driver input device, such as a steering wheel or joystick, and a servo motor to provide the force feedback. The secondary subsystem was composed of the directional control assembly,

which contained the rack-and-pinion system and a servo motor to steer the vehicle through king pin rotations of the wheel assembly.

Some formulations were listed and proved that the servo motor could provide the driver with force feedback, and the stability of the vehicles. Some simulations in the experiments also indicated that the driver could be informed by the force feedback and the realistic feel from the steering operation.

The SBW system of vehicles designed by Q. Yu [26] has proved to be precise. He showed that the tuning radius and the front wheel angle could be decreased. The operators could control the steering wheel to turn at a special angle, which was the ideal angle. Graphs were developed, and some formulations were used to illustrate how to reduce the turning radius. Also, some tables were listed to compare the different angles and the least turning radius between traditional turning radius and the SBW system. After the simulation, the results showed that the precision was increased with the SBW system. The reduction of friction between the tyre and road was suggested by the authors, but there was not sufficient evidence to prove a connection.

A generic controller structure was proposed with bidirectional position feedback by D. Odenthal [27] in an attempt to design a SBW system. In order to copy the properties of the conventional steering system, the power steering system in the SBW system was subdivided into a manual steering part and a generically nonlinear power assistance steering part. However, the stability of this design of the SBW control system was not as sufficient as for the conventional steering system, so the dynamics interaction between the SBW system and its environment had to be considered. Driver impedance was identified via the steering wheel and the vehicle impedance connected via the steering rods. Two high fidelity vehicle dynamics models were introduced, the front wheel actuator (FWA) and the actuator steering wheel (SWA) model. A detailed frequency and time domain analysis demonstrated the high level of equivalence between the designed SBW system and a real power steering system which served as a reference system.

2.4 Yaw Stability, Lateral Force and Observer Design

The yaw stability and the lateral force should not be neglected in designing the SBW system, because they are the key factors that influence the performance and stability of the vehicle. In this section, the concept of the yaw stability and the important influence for the vehicles is described.

A strategy to adjust the performance on a vehicle, and an adaptive control to realize the desired steering characteristics of a vehicle were developed by Yamaguchi [18]. He suggested steering characteristics and handling performance on a vehicle were important for safe driving. Changing steering characteristics depending on the driver's preference was proposed. This method employed three techniques: a linear observer, identification of cornering stiffness and adaptive control for virtual steering characteristics. In the simulation, the vehicle parameters were estimated and the results showed that the proposed parameter identification base was effective. The experiments were also shown in this paper. The validity of the proposed method was confirmed by simulation and the experiments.

S．Katsura [29] proposed that the instability of force control was a major issue in the SBW steering system, and a great many researchers have focused on the novel force control systems and implemented force sensors to detect external force. However, it was difficult to contact with the environment in a stable manner when force sensor was used. The reaction torque observer calculated the disturbance torque of the motor without recourse to the deviation of position. Thus, reaction torque observer was considered as a force sensor. Force control was attainable feedback based on the value of reaction torque observer. Sensor-less force control was one of the fundamental techniques for the evolution from human co-operation to robot, tele-robotics, and to robotic virtual reality.

The yaw stability control algorithm via active front wheel steering has been presented in a paper by B. Zheng and S. Anwar [30]. The vehicle dynamics was introduced and the steering control system was also conducted by B.

Zheng and S. Anwar. First, the stability was analyzed and control parameters were selected. Then, the vehicle implementation and test results showed that the proposed control algorithm had significant safety advantages in critical situations over a conventional vehicle, where the driver has to manually steer the vehicle with an unexpected yaw motion.

M. Hasan and S. Anwar presented a yaw stability control system for a SBW system that utilizes steering to stabilize the vehicle [31]. By using a two track linearized vehicle model as a reference, a PID control system was designed with road wheel steer angle as control input. Simulation results showed that the proposed controller performed reasonably well. The parameters for the Simulink were also given in the paper. The vehicle's dynamics handling behaviors could be realized with accurate PID feedback control of the vehicle state. Thus, the vehicle stability had been introduced and shown to be variable for vehicle control application. The vehicles were shown to be dynamically similar to full-sized vehicles by using the standard linearized vehicle model as a reference.

According to R. Hayama [32], the resistance torque origins from the vehicle variables, such as yaw rate and lateral acceleration, and the front wheel actuation source and the steering wheel angle also generated the resistance torque. Four general guidelines were introduced to evaluate three types of resistance torques, such as the steering wheel angle origin, the steering force origin and the vehicle behavior origin. The first two guidelines were for the 'driver-made' phase to make a turn, while the third guideline was for the 'vehicle-made' phase to return to straight driving, and the forth one was the applicability guideline. The three origins of resistance torque were introduced and the test has also been carried out in this paper.

Aiming to improve the stability of the vehicle, the concept of the 'ideal steering ratio' was presented by C. Kim and S. Yu [33]. The relationship between the yaw ratio, the steering sensitivity, the 'ideal steering ratio' and the front wheel angle were given by the figures. The key points of ideal steering ratio and how to determine a suitable ideal steering ratio were also presented in this paper. Tests showed that the distribution of steering sensitivity had a distinct influence on the motion response of an SBW vehicle

and can be considered a more desirable driving pattern for drivers when steering ratio was set to be a constant. A series of control logics were also proposed in order to improve the handling performance of a SBW vehicle. Two categories of control tests including subjective evaluations and virtual field tests, were conducted to make comprehensive investigations on the series of control logics.

The bilateral control method based on the disturbance observer was introduced in a paper by IM [34]. Two goals were established. One was a reproduction of environmental impedance in the steering wheel. The other was improved manoeuvrability for the SBW system. Using a disturbance observer, a bilateral controller was designed. The experiment vehicle was also set up, which remodelled Toyota's electronic vehicle to a SBW system. To drive front wheel, a DC servo motor was attached on rack and pinion part. The steering wheel actuator motor used a power assisted motor from a conventional EPS system. The experimental results were satisfatory and the estimation of the moment of inertia, damping and coulomb friction for steering wheel appears stable and agrees with the real values.

2.5 Variable Steering Ratio

The variable steering ratio is also the key character in the vehicle SBW system. The variable steering ratio is applied on the BMW vehicle, but just on the luxury series, because it is a hard task to design the variable steering ratio in the traditional vehicle. As a result, it is too expensive to the common consumers. Compared with the traditional vehicle, the variable steering ratio is easy design and much more inexpensive than that in the traditional vehicle. It can be adjust the programming in the SBW system by the experience engineers. However, there are just two papers described this variable steering ratio, which is not enough. As a consequence, the variable steering ratio will be focus on my thesis.

The hybrid-intelligent based variable steering ratio front wheel control algorithm was presented in this paper. According to J. Yao [35], the fuzzy neural network based steering ratio controller was designed to control the

steering performance of the vehicle as a key point, and the linear fitting based steering ratio controller was designed to control the steering stability as another key point. The proper steering ratio was utilized to control the front wheel angel directly, and the control strategy was brought into the model for simulation experiment, simulation showed that the proposed control strategy is effective and feasible. The ideal variable steering ratio was presented by the author and the strategy was introduced based on the steering ratio.

L. Liao and W. Wang presented that the ideal transmission ratio of the dynamics steering system can be determined [36]. The dynamics steering system was based on the dynamics model of the vehicle and the analysis of the vehicle dynamics with the ideal variable steer ratio indicated that steering gain to be constant. As a result, the burden of the driver was relieved. The parameters of the model were given in the paper and the method to determine the ideal steering ratio was also introduced by the author. The formulas with the variable steering ratio showed that it is changed with the different velocities. At last, the figures and the simulation were also given to show the advantage of the variable steering ratio using in the SBW system.

2.6 Experimental Results

After the theory research, the experimental platform should be established and the data from the simulation should be validated and prove the simulation is corrected through the experiment. This is the function and effect of the experiment platform in engineering.

According to S. Data, the object of this investigation was to propose a procedure for parameter identification of a steering system, processing experimental measurements obtained on a test bench by means of a develop software [37]. The two degrees of freedom model dependent by synthesis parameters was used. This model had been developed in the Simulink environment, both for hydraulic and electrical power steering systems. Identification led to a complete characterization of the steering system. In particular, the following parameters were identified: steering ratio, torsional stiffness, power-steering characteristic curve, friction forces, and damping. It

could be concluded that the proposed models were suitable for investigation steering system behavior, for reverse engineering applications, and also for tuning, benchmarking, or diagnostic of actual steering system.

A. Cetin presented an adaptive steering-control system for a SBW was introduced, which included a vehicle directional-control unit and a deriver-interaction unit [38]. A nonlinear 4-degree-of-freedom (DOF) vehicle model was also introduced, including the longitudinal, lateral, yaw and quasi-static roll motion. The system architecture included the steering system dynamics and the vehicle dynamics were introduced in this paper and the experimental was set up. The experiment included the driver-interaction unit and vehicle directional-control unit. The experimental results were performed to demonstrate the efficacy of the proposed adaptive steering-control system.

According to P. Yip and J. Ryu, a physical method for altering a vehicle's handling characteristics through active steering intervention [39]. A full state feedback controller augmented the driver's steering command via SBW to achieve desired handling behavior. The estimation for the dynamics of the vehicle was available from a combination of Global Positioning System (GPS) and Inertial Navigation system (INS) sensor measurement. The experiment was also shown in this paper; the SBW test vehicle was equipped with GPS configured to provide absolute velocity and heading information. INS sensors measured lateral and longitudinal acceleration, yaw rate and roll rate. The experimental results confirmed that it was possible to effectively change the cornering stiffness of the front tyress by full state feedback modification of the driver's steering command. Thus, a vehicle's handling characteristics might be tuned to driver preference or adjusted for variations in operation conditions such as load distribution.

Aiming to evaluate steering feel objective quality indices, the integration of an electric power steering model in a full vehicle model allowed improving vehicle performance in term of steering feel and reducing on-road development time [40]. I. Camuffo also defined a parameter design set up for fine tuning of steering wheel feel of a new car, transferring it to experimental

test team and reducing time for experimental final tuning. This paper showed that the target of the new car has been to have the same steering wheel feel of the referenced car with an hydraulic power steering.

According to Q, Yu and Z. Zhong [41], the feedback control and stepper motor has been introduced and prove that it could be available in the SBW system. The authors showed the graph of the SBW system, including steer-angle-sensor, motor-angle-sensor and reducer. The theory of SBW system could indicate that the steer wheel angle was recognized as the input signal as well as the front wheel angle was recognized as the output signal. According to the feedback, the relationship between the steering wheel angle and front wheel angle could be built, the vehicles could be controlled through the feedback between the input signal (steering wheel angle) and output signal (front wheel angle).

The SBW system simulation was built in this paper, and the module was also shown. In other words, the front wheel angle, which was recognized as the slave device, was following the change of the steer wheel angle (active device). The chip used in this simulation was also introduced, and the results could receive the goal that the author wished. However, the data in the simulation of the experiment was not enough, which could not be convinced

2.7 Summary

In a word, the advantages of SBW system are obviously. First, the precision would be provided to help the operators to control the vehicles even less of the driving experiences. Second, and the reliability and safety of the vehicles could be guaranteed. The vehicles could not slip on the road even in the wet conditional road. However, the force feedback is the most difficult issue for the SBW system, because the higher speed of the vehicle is, the harder of the feedback on the hand wheel is needed. The point is how to design the structure and calculate the different feedback according to the different velocities and different front wheel angles.

Chapter III

Steering System

3.1 System Identification

A system is a combination of components that act together and perform a certain objective. To design a control for the system, it is necessary to assume a relationship between the input and output. In many cases at linear models it is sufficient to use their frequency functions, or impulse responses. This model might be the easiest method to describe the nonlinearity of the system, too. In control theory a mathematical model of the system is commonly used for system description. Physical attributes of a system can be described by ordinary differential equations. It is possible to decompose these higher-order equations into first-order ones. These linear first-order differential equations are often used for process analysis, and are called state equations. In control, linear time-invariant systems are often modelled by their transfer functions. Transfer functions are defined as the Laplace transform of the impulse response, with zero valued initial conditions.

In systems theory, transfer function is often called the frequency domain representation of the system. It describes completely how the system processes the input signals to produce the output signals. Thus, control systems are often designed to meet transfer function specifications. Transfer functions are complex-valued, frequency-dependent quantities, so it is easier to appreciate a systems function by examining the magnitude and phase of its transfer function. Bode diagrams show magnitude and phase with respect to frequency. Usually they use a logarithmic scale for the frequency, and a

decibel scale for the magnitude's great alterations. Models are constructed from observations. Mental models uses empirical information, graphical models are created from measurements [42].

3.2 Vehicle Dynamics

In this chapter, the structure of the vehicle is given and the linear model of the vehicle is introduced, then the slip angle and self-aligning torque are also illustrated, which related to the angles of the front wheel and the velocity of the vehicle. The steering wheel model and the front wheel model are also described.

3.2.1 Linear Vehicle Model

It is assumed that the vehicle operates on a flat plane. The model used for the vehicle module is based on the bicycle, which is shown in Fig. 3.1. The body coordinate system is defined by the longitudinal x-axis and the lateral y-axis of the vehicle. The distance from the front axle to the centre of gravity (CG) is l_f. Similarly, l_r is the distance from CG to the rear axle. The front slip angle α_f is defined as the angle between the centre line of the front wheel and the direction of the velocity of the front wheel. δ is the front wheel angle. The only external forces affecting the vehicle are the cornering forces $F_{y,f}$ and $F_{y,r}$. The cornering forces occur at the contact surface between the wheels and the road.

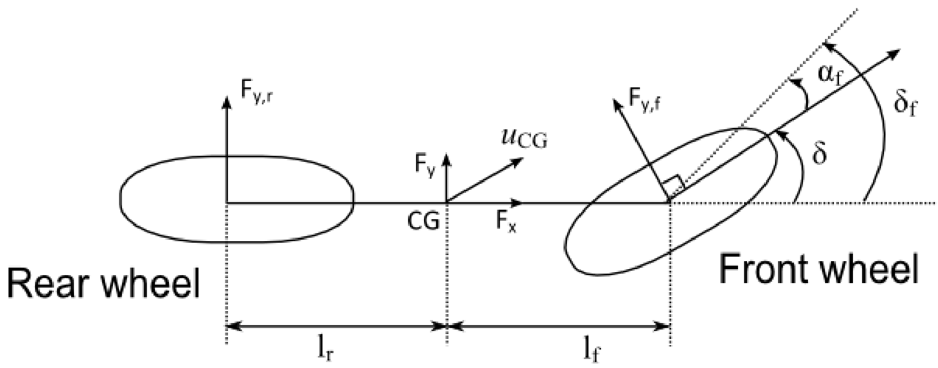

Fig. 3.1 Bicycle Model

The front and rear cornering forces can be separated into x- and y-components, i.e

$$F_x = -\sin\delta \cdot F_{y,f} \quad (1)$$

$$F_y = \cos\delta \cdot F_{y,f} + F_{y,r} \quad (2)$$

Or

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} -\sin\delta & 0 \\ \cos\delta & 1 \end{bmatrix} \begin{bmatrix} F_{y,f} \\ F_{y,r} \end{bmatrix} \quad (3)$$

3.2.2 Slip Angles

Derivation of the equations of motion for the bicycle model follows from the force and moment balance

$$m \cdot a_y = F_{y,f} \cdot \cos\delta + F_{y,r} \quad (4)$$

$$I_Z \cdot \dot{\omega}_r = l_f \cdot F_{y,f} \cdot \cos\delta - l_r \cdot F_{y,r} \quad (5)$$

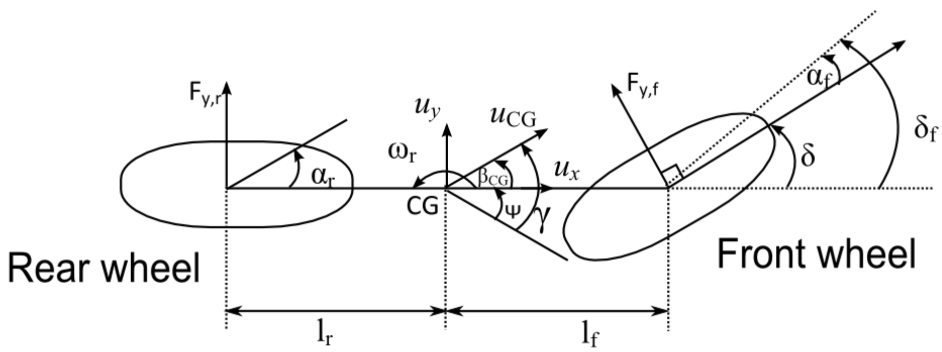

Fig.3.2 Single Track Vehicle Model

m is the vehicle mass, and a_y is the lateral acceleration at the centre gravity (CG). In the linear region of tyre operation, lateral forces at the front and rear are related to slip angle by the total cornering stiffness of the front and rear tyres, I_Z is the moment of the inertia of the whole vehicle about the yaw axle and $\dot{\omega}_r$ is yaw rate. The side slip angle β_{CG} is defined as the angle between the direction of the vehicle velocity and the centre line of the vehicle. In the linear vehicle model, the lateral force is related to the slip angle by the total

cornering stiffness coefficient of the front and rear tyres, which can be represented by these equations below,

$$F_{y,f} = -C_{\alpha,f}\,\alpha_f \tag{6}$$

$$F_{y,r} = -C_{\alpha,r}\alpha_r \tag{7}$$

The slip angle includes front slip angle, represented by α_f and rear slip angle, represented by α_r. Front slip angle is the angle between the centre line of the front wheel and the direction of the velocity of the front wheel and the rear slip angle is defined as the rear wheel lateral velocity divided by the forward velocity. The bicycle model to be employed in the analysis is presented in Fig.3.2.

Hence, the front slip angle is defined as the front wheel lateral velocity divided by the forward velocity minus the steering angle. It is shown below,

$$\alpha_f = \frac{u_y + l_f \cdot \omega_r}{u_x} - \delta \tag{8}$$

Similarly, the rear slip angle is related to the vehicle's velocity, the yaw rate ω_r and the sideslip angle β_{CG}. The rear slip angle is

$$\alpha_r = \frac{u_y - l_r\omega_r}{u_x} \tag{9}$$

Taking small angle approximation, the slip angle can be written in term of u_x, u_y and ω_r:

$$\begin{bmatrix} \dot{\beta}_{CG} \\ \dot{\omega}_r \end{bmatrix} = \begin{bmatrix} \dfrac{-C_{\alpha,f} - C_{\alpha,r}}{m \cdot u_x} & -1 + \dfrac{C_{\alpha,r} \cdot l_r - C_{\alpha,f} \cdot l_f}{m \cdot {u_x}^2} \\ \dfrac{C_{\alpha,r} \cdot l_r - C_{\alpha,f} \cdot l_f}{I_z} & \dfrac{-C_{\alpha,f} \cdot {l_f}^2 - C_{\alpha,f} \cdot {l_r}^2}{I_z} \end{bmatrix} \begin{bmatrix} \beta_{CG} \\ \omega_r \end{bmatrix} + \begin{bmatrix} \dfrac{C_{\alpha f}}{m \cdot u_x} \\ \dfrac{C_{\alpha,f} \cdot l_f}{I_z} \end{bmatrix} \delta \tag{10}$$

In the Fig.3.2, u_{CG} is the velocity of the vehicle, u_x and u_y are represented by the longitudinal and lateral speed, respectively [43].

Given longitudinal and lateral velocity, u_x and u_y at the centre gravity, the sideslip angle is defined by:

$$\beta = arc\tan({}^{u_x}/_{u_y}) \tag{11}$$

Sideslip angle can also be defined by the difference between the vehicle's forward orientation, ψ, and the direction of the velocity, γ.

$$\beta = \gamma - \psi \tag{12}$$

3.3 The Steering Wheel Model

In the steering wheel part, the force feedback motor will be connected to the steering wheel to provide the torque feedback to the driver's hand. The steering wheel component with a feedback motor is shown in Fig.6.

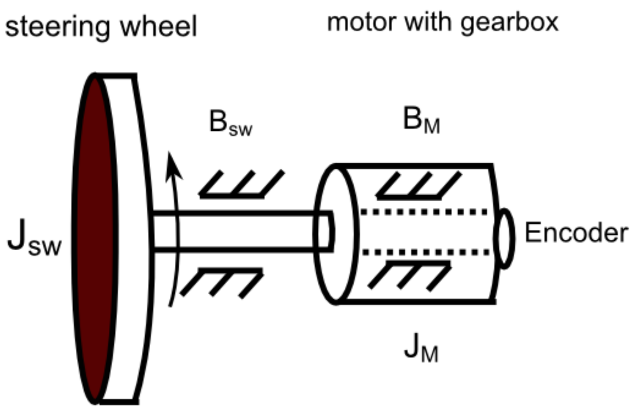

Fig. 3.3 SBW Driver Interaction Assembly

The dynamics model of steering wheel is given as

$$\tau_h - \tau_f = J_h\ddot{\delta}_{sw} + B_h\delta_{sw} + M \tag{13}$$

Or

$$\tau_h - \tau_f = J_h\ddot{\delta}_{sw} + B_h\delta_{sw} + i_G k_A i_M \tag{14}$$

where τ_h is the torque applied on the steering wheel by the driver, τ_f is the feedback torque provided by the feedback motor. J_h and B_h are the moment of initial and damping of the steering wheel, θ is the angle of steering angle and M is the friction torque. i_M is the current of the motor and k_A is motor torque constant.

The driver-interaction unit state equations are written as

$$\dot{x_1} = x_2 \tag{15}$$

$$\dot{x_2} = -a_{sw}x_2 - b_{sw}M - b_{sw}\tau_f + c_{sw}({}^{b_{sw}}/_{i_M}) \tag{16}$$

Where the state variable x_1 is the angular position (δ_{sw}) of the steering wheel, x_2 is the angular velocity ($\dot{\delta_{sw}}$) of the steering wheel, the viscous friction a_{sw} is ${}^{B_h}/_{J_h}$, the input gains b_{sw} and c_{sw} are ${}^{1}/_{J_h}$ and ${}^{i_G k_A}/_{J_h}$, respectively.

3.4 Front Wheel Steering System Model

The dynamics model of the front wheel steering system shown in Fig.2 [20] is described by following equation.

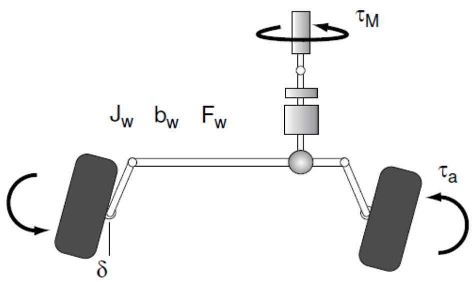

Fig. 3.4 Steering system dynamics [20]

$$J_m\ddot{\delta_f} + B_m\dot{\delta_f} + \tau_{fr} + \tau_a = r_s r_p \tau_M \tag{17}$$

Where τ_a is the self-aligning torque, which is generated by the tyre-road contact, and changes with both vehicle velocity and front wheel angle. J_m and B_m are the moment of inertia and damping of the front wheel, δ is the front wheel angle. T_{fr} is the friction in the steering system, r_s is the steering ratio, r_p is the torque magnification factor of the power steering system, which is always a constant. The torque generated by the steering motor is τ_M, which could be presented by:

$$\tau_M = k_M i_M r_g \eta \tag{18}$$

Where k_M is motor constant, i_M is the motor current, r_g is gear head ratio and η is motor efficiency. The tyre self-aligning moment, τ_a, which is shown in Fig.3.2 [12],

3.5 Self-aligning Torque

The self-aligning torque experienced by the tyres on a vehicle always resists the attempted turn, thus it is the source of an understeer effect. The self-aligning torque, τ_a, is a function of the steering geometry, particular caster angle, and the manner in which the tyre deforms to generate lateral forces,

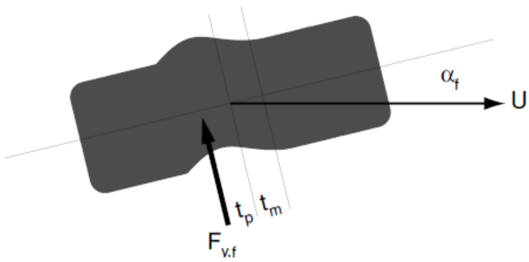

Fig. 3.5 Self-aligning Moment of the Tyre [12]

where $F_{y,f}$ is the lateral force acting on the front wheel tyre, α_f is the tyre slip angle, t_p is the pneumatic trail and t_m is the mechanical trail, the distance between the tyre centre and the steering axis, and U is the velocity of the tyre at its centre. However, the lateral $F_{y,f}$ is changing with the different front wheel angle and vehicle velocity, it is difficult to measure with torque sensors.

$$T_a = F_{y,f}(t_p + t_m) \tag{19}$$

Where t_p and t_m are approximately known. Rewriting (1) in state space from yield:

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{b_w}{J_w} \end{bmatrix} \begin{bmatrix} \delta \\ \dot{\delta} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \frac{r_s r_p}{J_w} & -\frac{1}{J_w} \end{bmatrix} \begin{bmatrix} \tau_M \\ \tau_f \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{1}{J_w} \end{bmatrix} \tau_a \tag{20}$$

And the self-aligning moment, τ_a is treated as an external input to the steering system. The resisting torque, τ_f due to friction is treated as an input:

$$\tau_f = F_w sgn(\dot{\delta}) \tag{21}$$

The self-aligning torque includes two parts which are the aligning torque generated by tyre drag (M_z) and aligning torque caused by kingpin inclination (M_A). The aligning torque generated by tyre drag (M_z) changes with velocity, and aligning torque caused by kingpin inclination (M_A) does not change with the velocity. (M_z) and (M_A) are given as

$$M_z = \frac{m \cdot u^2 \cdot l_r}{l^2 + m \cdot \frac{C_r \cdot l_r - C_f . l_f}{C_f \cdot C_r} \cdot u^2} \cdot (t_p + t_m) \cdot \delta_f \tag{22}$$

$$M_A = \frac{Q \cdot D}{2} \cdot sin\, 2\beta' \cdot sin\, \delta_f \tag{23}$$

$$\tau_a = \frac{M_Z + M_A}{i_f} \tag{24}$$

Where i_f is torque ratio, β' is kingpin inclination angle, D is kingpin inclination value and Q is wheel load. $(t_p + t_m) = 0.07$, $\beta' = 0.14\, rad$, $D = 0.2$ and the torque map generated by Matlab is shown in Fig. 3.6, which changes with the different velocities and front wheel angles [46].

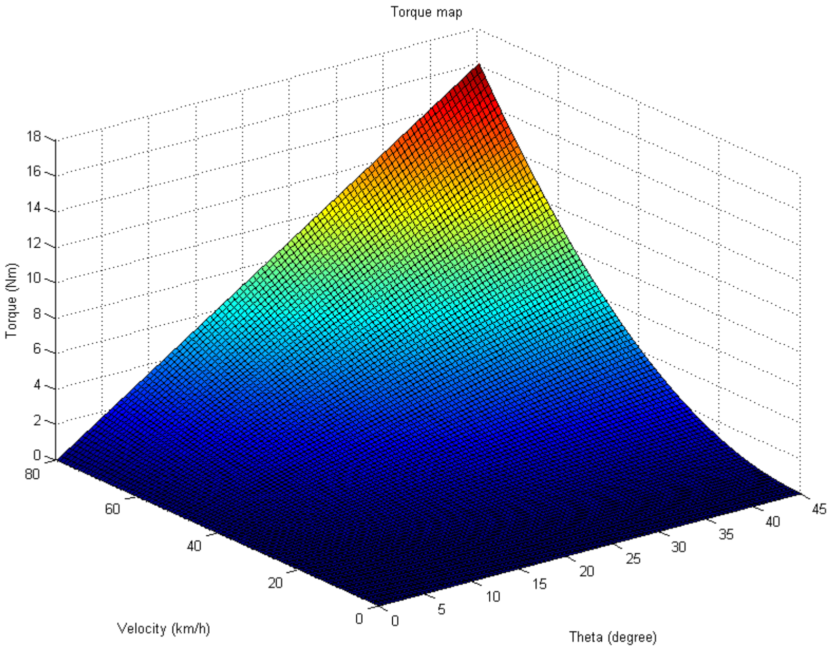

Fig. 3.6 Self-aligning Torque Map

It is clearly that the torque was zero when the velocity of the vehicle and angle of the front wheel are both zero. The self-aligning torque rise while the angle of the front wheel is increasing. The self-aligning also expands when the speed is increasing.

3.6 Conclusion

In this chapter, the steering wheel model and the front wheel system model have introduced and the linear vehicle model is also given. The dynamic of the vehicle can express by the equations in front wheel steering system model. The self-aligning torque is the key point of the SBW system, it is generated the torque by Matlab/Simulink, which show that the self-aligning toque have the relationship between front wheel angles and velocities of the vehicle The self-aligning torque rise while the angle of the front wheel is increasing. The self-aligning also expands when the speed is increasing.

Chapter IV

Control Strategy and Simulation

4.1 Control Strategy

The SBW system controller is divided into the steering wheel motor control and the front wheel motor control. The purpose of the steering wheel control is to improve the driver's steering feel by generating reactive torque. The purpose of the front wheel motor control is to steer the front wheel angle appropriately for improving the vehicle's maneuvrability and stability [43][44]. The proposed SBW control system is shown in Fig. 4.1, where the driver' torque applied to the steering wheel is considered as the input, and the front wheel angle is defined as the output. The system is composed of two loops: upper loop, which mainly consists of steering wheel and torque feedback motor, and lower loop, which mainly consists of front wheel and a driving motor. To achieve the bilateral control performance, these two loops are controlled by two PID controllers, respectively [48]. The PID controller in lower loop is designed to control the actual front wheel angle to track the steering wheel angle. Its input is the error between the desired front wheel angle and the actual front wheel angle. Its output is the control voltage sent to the steering motor. The desired front wheel angle is calculated based on the variable gear-ratio and the defined steering wheel angle. The actual front wheel angle is measured by an encoder installed with the driving motor. In the upper loop, there is another PID controller, which is used to provide the feedback torque to steering wheel so that driver can have a feeling about different steering situation. This feedback torque reflects the tyre-road contact and is generated reactive torque map in the system. When the front

wheel turns to a certain angle, the torque will be generated in terms of this angle and vehicle velocity. This torque is regarded as a reference torque. The error between this reference torque and the measured torque from the torque feedback motor is defined as the input to the PID controller. The output of the PID controller is the control voltage, which is sent to the feedback torque motor so that the output torque of the motor can follow the reference torque. As this motor is connected to the steering wheel, the driver can feel this torque when steering the wheel. The output torque of the motor will be measured by a current sensor as the current of a DC motor is proportional to its torque. In addition, the actual constraints on the steering wheel and the front wheel are also included in the too loops.

The PID controllers will be designed to reduce the tracking errors. The controller gains are adjusted according to the simulation results referring to the Ziegler-Nicholas rules. As for different velocities the gear-ratio will be different. To account for this variation, several PID controllers will designed for several typical velocities such as 20 km/h, 50km/h, 60km/h, 70km/h, 80km/h, and for other velocities, the PID controllers will be scheduled by interpolating the relevant controller gains.

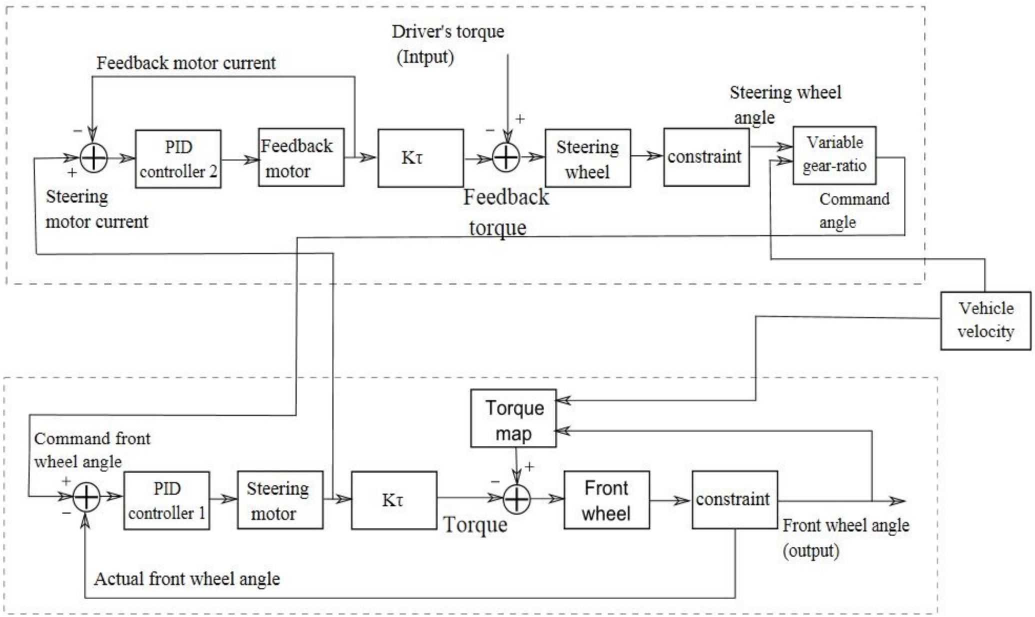

Fig. 4.1 Control System Diagram

4.1.1 Steering Wheel Motor Control

The basic purpose of the steering wheel motor control is to generate reactive torque like a real commercial vehicle when the driver steers. Furthermore, it makes the steering wheel easy to steer at low speed or when parking the vehicle and to make steering wheel tight at high speed for improving the driver's steering feel by adjusting reactive torque. It is relied on the variable steering ratio, which will introduce in chapter 4.2 (steering ratio). PID control method is used to control the steering wheel reactive torque motor in this thesis, as the Fig.4.1 shown above.

4.1.2 Front Wheel Motor Control

For control of the front wheel, the signal from the HILINK board is very important because there is no mechanical linkage between the steering wheel and the front wheel like there is in a conventional steering system. To control the front wheel motor, the PID control method is also used as shown in figure 4.1.

4.2 Gear Ratio

The gear ratio is defined as the ratio of steering wheel rotation to steer angle at the road wheel. Normally these range from 15 or 20 to 1 on passenger cars. A steady-state control strategy for ideal gear ratio was introduced to keep the steering gain of the vehicle as a constant and make the characteristic of the SBW vehicle independent of the speed and steering angle. A stability control algorithm was proposed to correct the steering angle dynamically based on the vehicle state feedback. The results of the simulation and the test in a driving simulator showed that the introduced strategy does keep the vehicle steering gain constant to reduce the driver burden, allowing the unskilled driver to drive the vehicle easily and effectively. The proposed stability control algorithm based on the vehicle state feedback improves safety and stability of the SBW vehicle.

In the mechanical vehicle, the gear ratio was fixed; therefore, the steering characteristic of the vehicle can be non-linear varying with the changes of the

velocity and lateral acceleration in the vehicle. For the control of the vehicle following by the driver's desired trajectory, the driver must adjust constantly the steering wheel to ensure to control the steering of the vehicle, thus, these extra controls are actually increasing the burden for the drivers.

4.2.1 The Steady-state Control Strategy for Vehicle Steering Gain

In the process of driving, keep the steering gain does not change while the steering wheel changes, in other words, it would keep the linear relationship between the angle of steering wheel and the yaw rate with the different velocity and lateral acceleration. This would reduce the operations of the drivers to keep the vehicle steering along the desired route. It is an easier job for the drivers operating a vehicle because the less steering compensate was needed. In the same time, variable steering ratio used in SBW system could improve the safety and stability of the vehicle, which would be suitable for more different kinds of people to control the vehicles, especially for the non-professional drivers or young lady to control the dynamics of automotive.

It could be designed any steering ratio in SBW system, thus, designed a variable steering ratio could keep the steering ratio gain of the vehicle fixed in the steady-state.

4.2.2 The Desired Concept of Steering Ratio

Generally, there are two steering ratio gains that defined by us; the first one is the gain that the angle from front wheel (δ_f) to the vehicle response (y), which introduced by G_δ^y. In the steady state, $G_\delta^y = y/\delta$, which is related to tyre, wheel Alignment, suspension, etc. Another one is the gain that from angle of steering wheel (δ_{sw}) to response of vehicle (y), introduced by G_{sw}^y. In the steady-state, $G_{sw}^y = y/\delta_{sw}$, which is not only related to the tyre, wheel Alignment, suspension, but related to steering characteristic such as gear ratio.

The relationship was shown below;

$$y= G_{sw}^{y} \cdot \delta_{sw}= G_{\delta}^{y} \cdot G_s \cdot \delta_{sw} \quad (25)$$

where

$$G_s = 1/i \quad (26)$$

$$G_{sw}^{y}= G_{\delta}^{y} \cdot G_s= K_s \quad (27)$$

$$\delta_{sw}/ \delta_f = i \quad (28)$$

If G_{sw}^{y} is equal to K_s in any velocities and steering angles, there is the equation of $G_{\delta}^{y} \cdot G_s = K_s$. For SBW system, the steering gain (G_{sw}^{y}) from steering wheel to response of vehicle is a constant if the reciprocal of steering ratio (G_s) was designed reasonable. In summary, the desired steering ratio is the ratio when G_{sw}^{y} is equal to a constant, in other words, designed a reasonable desired steering ratio G_s to ensure $G_{\delta}^{y} \cdot G_s$ to be fixed, which is also ensure the steering gain in vehicle is stable. In a word, the desired steering ratio is to ensure that G_{sw}^{y} to be a constant. In reality, the steering gain in the vehicle is also presented by the yaw rate gain or lateral acceleration gain. [21]

The response of the vehicle can be represented by the yaw rate (ω_r), according to equations 26 and 27,

the ratio can be described like this,

$$i = G_{\delta}^{y} / K_s =\omega_r/(K_{wr} \cdot \delta) \quad (29)$$

4.2.3 The Method to Get the Desired Variable Gear Ratio

According to Fig. 5, in order to research the response of the vehicle, the velocity and front wheel angle were considered as inputs, and the lateral acceleration and yaw rate were considered as outputs.

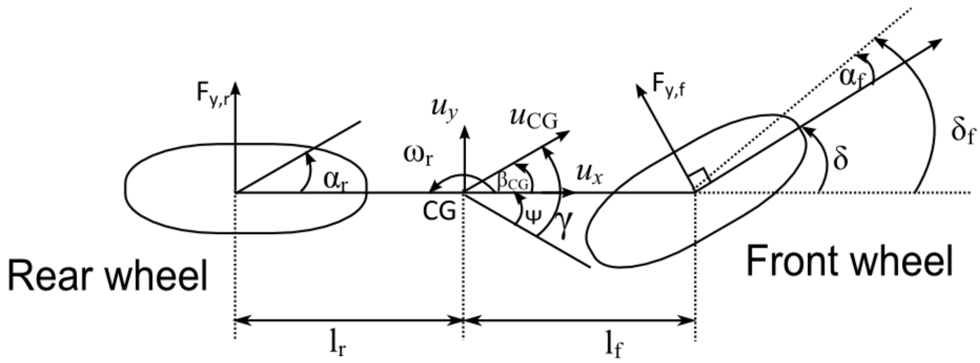

Fig.4.2 Bicycle Model

The dynamics equations should be described like this below if the influence of the front wheel angle,

$$m(\dot{u_y} + u_{cG}\omega_r) = K_{af}\delta\cos\delta - (K_{af}\cos\delta + K_{ar})\frac{u_y}{u_{cG}} - (l_f K_{af}\cos\delta + l_r K_{ar})\frac{\omega_r}{u_{cG}} \quad (30)$$

$$I_z\dot{\omega}_r = l_f K_{af}\,\delta\cos\delta - \left(l_f K_{af}\cos\delta - l_r K_{ar}\right)\frac{u_y}{u_{CG}} - \left({l_f}^2 K_{af}\cos\delta + {l_r}^2 K_{ar}\right)\frac{\omega_r}{u_{CG}} \quad (31)$$

Where m is the mass of the vehicle, u_c is the velocity, a is the distance from the centre gravity to the front axle, b is the distance from the centre gravity to the rear axle, K_{af} , K_{ar} are the stiffness of the front wheel tyre and rear wheel tyre, respectively. δ is the front wheel angle, I_z is the inertia moment of the vehicle. Therefore, according to the equations of 30 and 31, the state space equation can be written like this below.

$$\begin{bmatrix} m & 0 \\ 0 & I_z \end{bmatrix}\begin{bmatrix} \dot{u_y} \\ \dot{\omega_r} \end{bmatrix} + \begin{bmatrix} (K_{af}\cos\delta + K_{ar})/u_{cG} & mu_{CG} + \left(l_f K_{af}\cos\delta - l_r K_{ar}\right)/u_{cG} \\ \left(l_f K_{af}\cos\delta - l_r K_{ar}\right)/u_{cG} & \left({l_f}^2 K_{af}\cos\delta + {l_r}^2 K_{ar}\right)/u_{cG} \end{bmatrix}\begin{bmatrix} u_y \\ \omega_r \end{bmatrix} = \begin{bmatrix} K_{af}\cos\delta \\ l_f \cdot K_{af}\cos\delta \end{bmatrix}\delta \quad (32)$$

If the vehicle has the circular motion, the desired yaw rate can be presented like this,

$$\omega_r = \frac{L \cdot \delta \cdot u_c \cdot K_{af} \cdot K_{ar} \cdot \cos\delta}{[L^2 \cdot K_{af} \cdot K_{ar} \cdot \cos\delta - m \cdot {u_{cG}}^2 (l_f \cdot K_{af} \cdot \cos\delta - l_r \cdot K_{ar})]} \tag{33}$$

Therefore, the gain from front wheel to yaw rate is

$$\frac{\omega_r}{\delta} = \frac{L \cdot u_{cG} \cdot K_{af} \cdot K_{ar} \cdot \cos\delta}{[L^2 \cdot K_{af} \cdot K_{ar} \cdot \cos\delta - m \cdot {u_{cG}}^2 (l_f \cdot K_{af} \cdot \cos\delta - l_r \cdot K_{ar})]} \tag{34}$$

When the velocity is more than u_1 , the steering ratio is fixed, which can be represented by i_{min}, because the when the steering wheel tunes to the maximum angles, the front wheel angle can not exceed to its limited angles δ_{max}, which is always 40-45 degrees. Therefore, the steering ratio at low velocity is

$$i_{min} = \frac{\delta_{swmax}}{\delta_{max}} \tag{35}$$

When the velocity is more than u_1 , the steering ratio is also fixed, because the aligning torque provided by the tyres have reached to the limited. Therefore, the steering ratio can not increase anymore.

Therefore, the ideal steering ratio can be described like this,

$$\mathrm{i} = \begin{cases} i_{min} & (u_c \leq 20\ km/h) \\ \frac{L \cdot u_c \cdot K_{af} \cdot K_{ar} \cdot \cos\delta}{K_s \cdot [L^2 \cdot K_{af} \cdot K_{ar} \cdot \cos\delta - m \cdot u_c^2 (l_f \cdot K_{af} \cdot \cos\delta - l_r \cdot K_{ar})]} & (20 \leq u_c \leq 100\ km/h) \\ i_{max} & (u_c \geq 100\ km/h) \end{cases}$$

(36)

where $L = l_f + l_r$, and we set the mass of the vehicle m = 1615 kg, l_f = 1.348 m, l_r = 1.521 m, K_{af} = 55856 N/rad, K_{ar} = 63567 N/rad., the yaw rate gain K_s is equal to 0.245 s^{-1}. According to the formula in the ideal steering ratio in formula (22), we can get the i_{min} = 5 and i_{max} = 20.7, so the 3−D figure of the variable gear ratio can be represented below.

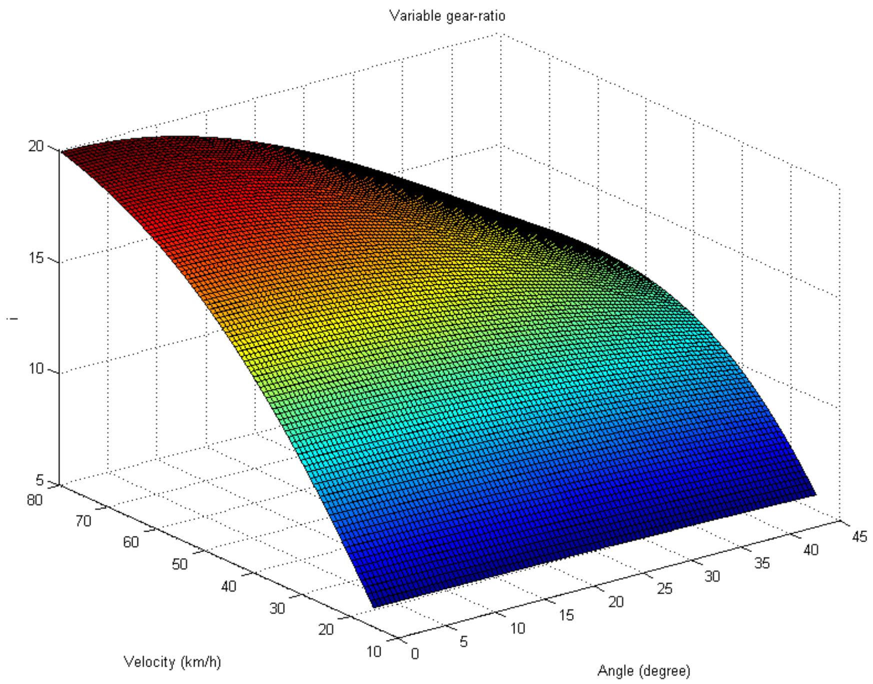

Fig.4.3 Variable Gear Ratio with Different Angles and Velocities

When driving at high speed, we don't want the car to change direction with every tiny movement of the steering wheel; we want the steering transmission to be less direct, i.e., higher steering ratio. This would result in greater vehicle stability due to the compensation for the physically induced increase in steering sensitivity. Driving in the city at low speeding or when parking, we have the opposite demand, that is quick changes of direction from small steering inputs. A more direct response of the wheels to the driver's commands are needed, i.e., a lower steering ratio. The vehicle would thus become more agile and parking could be greatly facilitated. The variable gear ratio steering (VGRS) could achieve these goals according to different velocities.

If the front wheel angle was set to 0 degree for similarity,

$$i = \begin{cases} i_{min} & (u \leq 20\ km/h) \\ \dfrac{u}{L \cdot K_s \cdot (1 + k \cdot u^2)} & (20\ km/h \leq i \leq 100\ km/h) \\ i_{max} & (u \geq 100\ km/h) \end{cases} \quad (36)$$

where

$$k = \frac{m}{L} \cdot \left(\frac{l_f}{k_{ar}} - \frac{l_r}{k_{af}} \right) \tag{37}$$

The comparison between the variable steering ratio in SBW system and fixed steering ratio in conventional vehicle is shown in Fig.4.4. For the same angle of the front wheel, the variable gear-ratio changes with vehicle velocity. The solid line represents the fixed gear-ratio in the conventional vehicle, which is always 16 and the dotted line represents the variable gear-ratio. The variable gear-ratio increases from 8.5 to16 when the velocity is between 20 km/h and 50 km/h, which means the steering wheel would be more sensitive in low speed, and the ratio increases from16 to21 when the velocity increases from 70 to 100 km/h, which helps the driver control the vehicle, avoiding rolling in high speed.

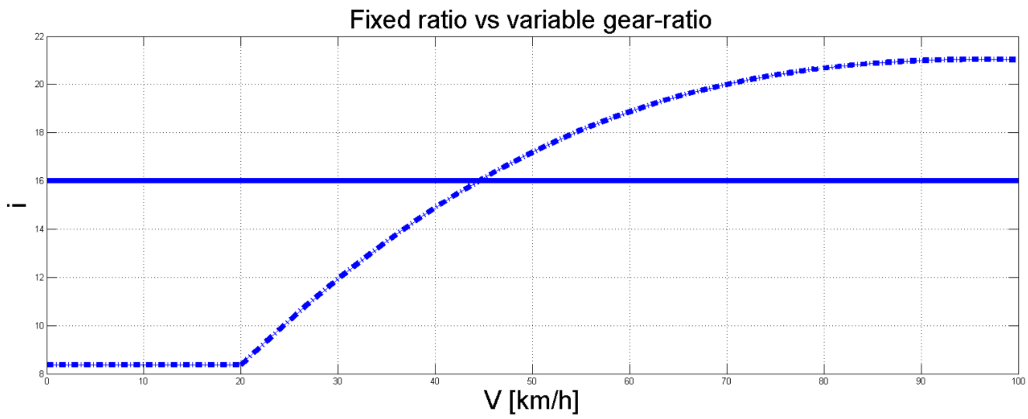

Fig.4.4 Fixed Gear-Ratio vs Variable Gear-Ratio

4.3 Simulation

The simulation model is built by Matlab/Simulink as shown in the Fig. 4.5, the variable gear-ratio in the SBW system is included. The torque map as shown in Fig. 4.3 is also considered in this simulation. The torque relates to the angle of front wheel (or considered as the steering wheel angle) and the velocity of the vehicle. The relationship between the steering wheel angle and the steering wheel torque was shown in [45].

The variable gear-ratio and the torque map both rely on the vehicle velocity and front wheel angle.

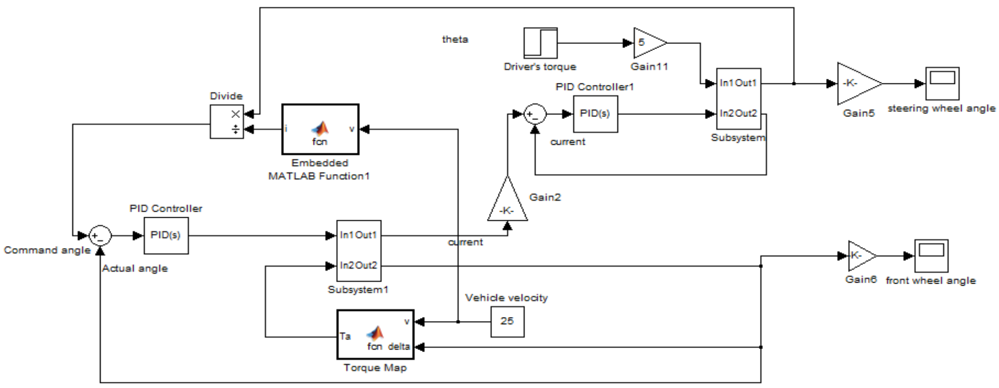

Fig.4.5 Simulation Model of SBW System

The simulation is done by providing a defined steer torque to the steering wheel. The constraints on the inputs and outputs are considered, which are defined as the constraints of the steering wheel angle at the low speed according to the variable gear-ratio. In this paper, the constraint of the steering wheel angle is set to 365.5 degrees because the maximum of the front wheel angle is about 40 degrees.

The relationship between steering wheel angle and front wheel is shown in equation (39)

$$\delta_{sw} = i \cdot \delta_f \tag{38}$$

where δ_{sw} is steering wheel angle, δ_f is the angle of front wheel and i is the variable gear-ratio

As we know, the front wheel angle could always achieve to about 40 degree as its maximum turning angle. According to Fig. 4.4, the maximum angle of steering wheel should be set as 365.5 degree because variable gear-ratio is 8.5 at low speed or parking the car. However, the constraint of the steering wheel angle is not considered because the steering wheel angle could not achieve to 365.5 degree in high speed according to our driving experience.

For brevity, the simulation results on front wheel angle and feedback torque are shown in the following subsections when vehicle velocity is 10 m/s.

4.3.1 Front Wheel Tracking Results

To shown the performance of the designed control system, the comparison between the SBW system with and without PID controllers is done. The results are shown in Fig.4.6 where the upper figure shows the output of the system without PID controllers (no feedback signal are considered) and the lower figure shows the results with the designed PID controllers.

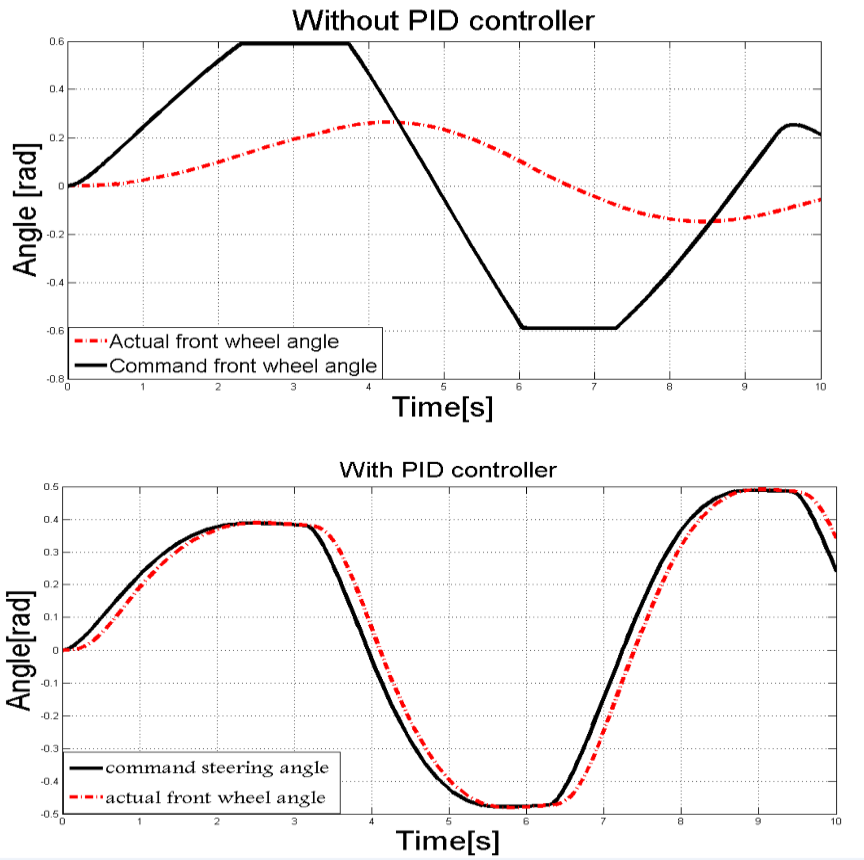

Fig.4.6 PID Controller

In Fig.4.6, the solid line represents the command front wheel angle and the dotted line represents the actual front wheel angle. The upper figure shows that the results without the PID controllers. It can be seen that the front wheel can not track steering wheel if no appropriate controllers are applied. However, with the designed PID controllers, the dotted line can well track the solid line as shown in lower figure, which confirms the effectiveness of the designed control system.

4.3.2 Self-aligning Torque Results

The feedback torque tracking results are shown in Fig. 4.7. The solid line represents the actual aligning torque generated between the front wheel tyre and the road and the dotted line represents the torque generated from the feedback motor. The aligning torque is about 10 Nm and it is a litter heavier for the driver to feel the road condition, therefore, a PID controller is used to control the feedback motor to generate the feedback torque in order to guarantee that it can be proportional to the actual aligning torque and let the driver get the appropriate feeling as driving a conventional car. From Fig. 4.7 it can be seen that the feedback torque is proportional to the aligning torque with smaller values.

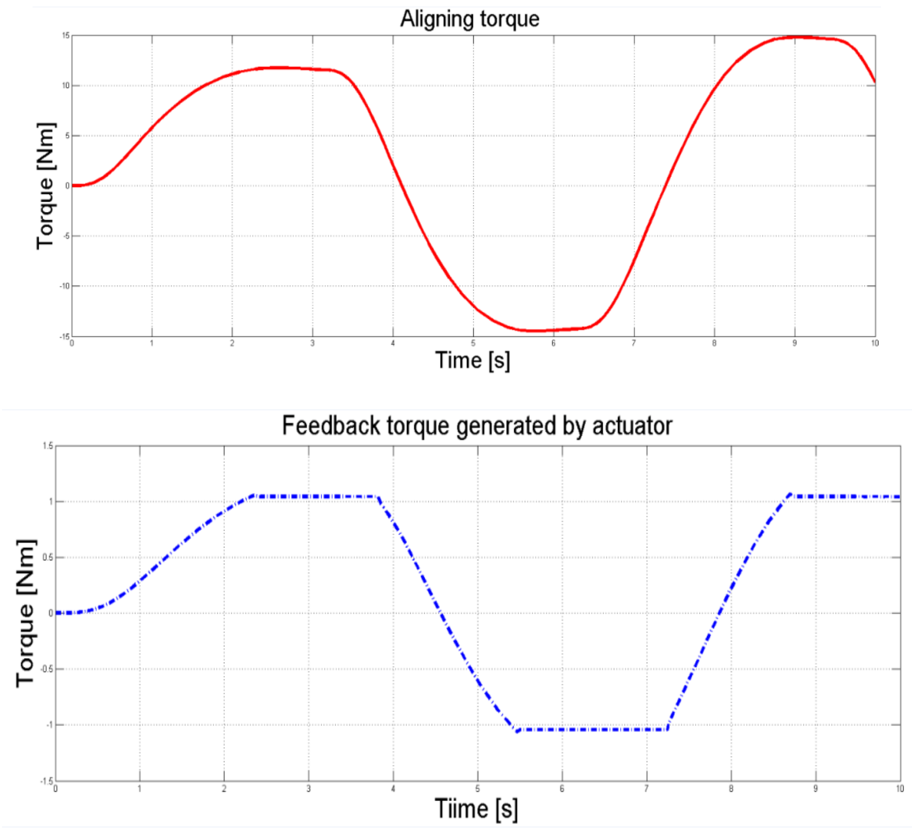

Fig. 4.7 Feedback Torque

4.3.3 Front Wheel Angles at Different Velocities

The front wheel angle at different velocities results are shown in Fig. 4.8. The solid line, broken line and dotted line represent the front wheel angle at 108km/h, 90km/h and 72 km/h, respectively. When the steering wheel angle is fixed, the front wheels have the different performances at different velocities with the design of variable gear-ratio. These three lines illustrate that the front angles will decreases when the velocity increases, and the benefit is the vehicle can be avoided to roll when the steering wheel is turning suddenly by the driver. Compared with the conventional vehicle, the SBW system with variable gear-ratio is the advanced system because the safety of the vehicle is improved when the operator driver the car at the high speed.

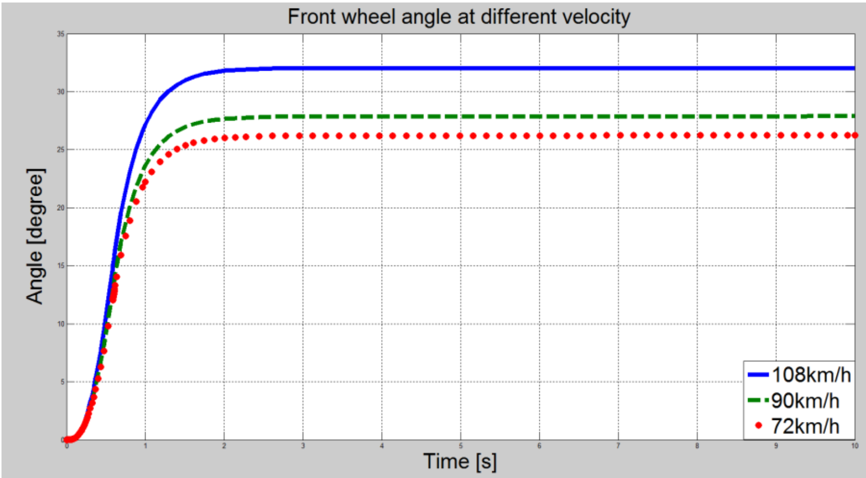

Fig.4.8 Front Wheel Angle at Different Velocities

As we see in the Fig. 4.8, the front wheel angles are proportional to the steering wheel angles if the velocity of the vehicle is constant, like 36 km/h. For example, the maximum angle of the steering wheel is always 200 degree while the front wheel angle is 12.5 degree. The gear ratio is ${}^{\delta_{sw}}/_{\delta_f} = 16$, which is suitable to the setting in the simulation. Therefore, the results show that the experiment is totally perfect as we thought.

4.4 Conclusion

In this chapter, the method of get the desired variable gear-ratio has given and the simulation of the SBW model has also described. Two controllers are used in the SBW control System.

Front wheel tracking results and the self-torque results are illustrated by the figures, which shows the effectiveness of the two PID controllers. The front wheel can track the position of the steering wheel. At the same time, the operators can receive the force feedback when they turn the steering wheel.

CHAPTER V

Experiment Platform

5.1 Experimental Platform

The purpose of this chapter is to designed an experimental platform of vehicle SBW system in order to validate the data that received from the Simulink in Chapter 4.

It includes two parts, position control and the force feedback control. Position means a master manipulator (steering wheel) can be used to control an identical slave device (front wheel); and force feedback control means the front wheel can provide the force feedback to the steering wheel in order to let the operator receive the steering wheel when they are turning the steering wheel. The force feedback is measured by the value of the current through the feedback motor. This experimental platform can also be considered as the teleoperation system [50].

5.1.1 Steering Wheel

This system will be implemented using inexpensive components that can be easily attained and assembled in an educational or research environment. The driver interaction unit used in this thesis is shown in Fig. 5.1, including a steering wheel and a brushed motor. An encoder located on the motor regarded as the angle sensor, which can calculate the tuning degree of the steering wheel.

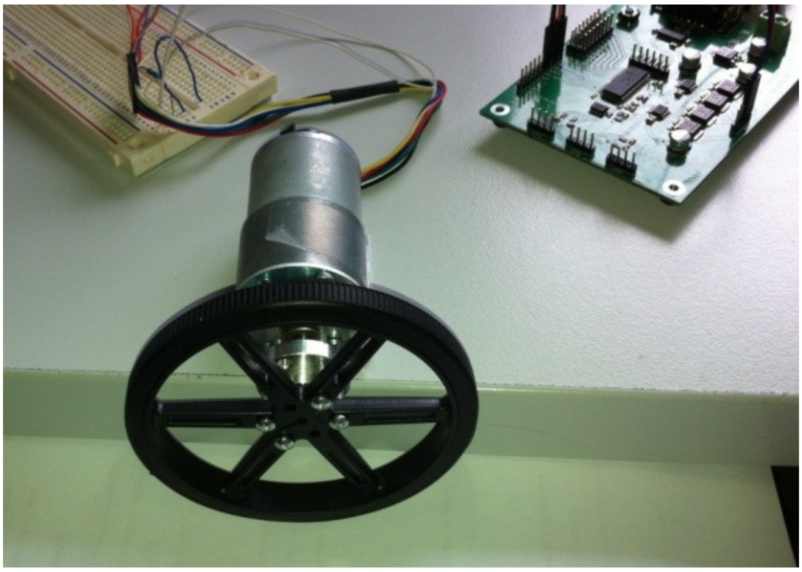

Fig.5.1 The Steering Wheel Component with Feedback Motor

The brushed motor is selected from the production of the Pololu Robotics and Electronics Company. This gear motor is a powerful 12V brushed DC motor with a 18.75:1 metal gearbox and an integrated quadrature encoder that provides a resolution of 64 counts per revolution of the motor shaft, which corresponds to 1200 counts per revolution of the gearbox's output shaft.

5.1.2 The SBW Vehicle

As we see in the Fig. 5.2, it is the platform of the SBW vehicle. Actually, there are two HILINK boards, regarded as the ECU, in this platform. The simulation in chapter 3 is focused on the variable gear-rato, which related to different velocities. As a consquence, how to control the velocity of the vehicle should be considered.

The angular velocity of the two motors installed at the rear wheel on the vehicle should be controlled by one HILINK board. As a consquency, the velocity of the vehicle can be caculate with the angular velocity of the two motors and the radius of the rear wheels. The equation can be described as below:

$$v = v_m \cdot r_w \tag{39}$$

v is the velocity of the whole vehicle, v_m is the angular velocity of the motor and r_w is the radius of the wheels.

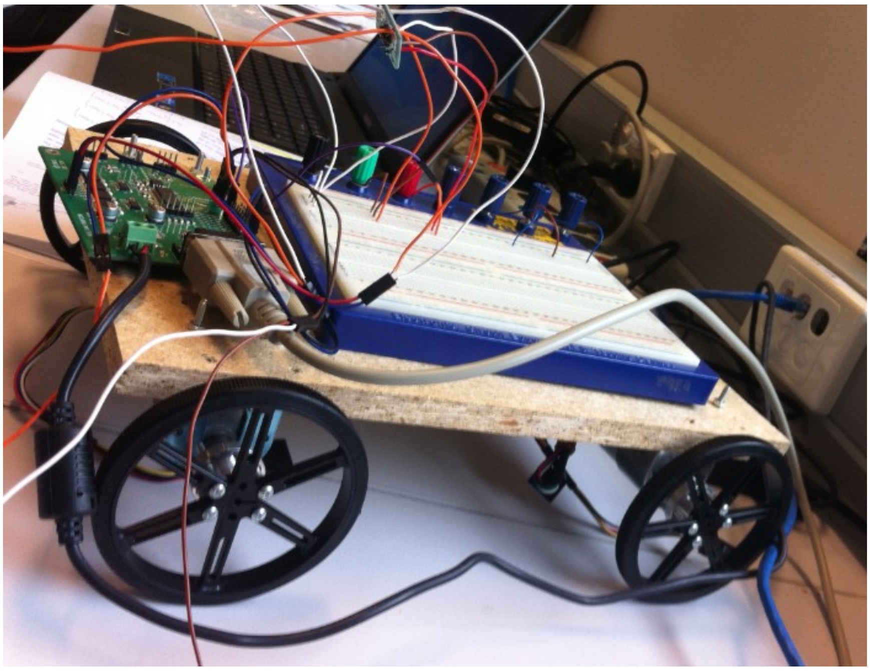

Fig. 5.2 The Platform of the SBW Vehicle

The front wheel angle can be contolled by another HILINK board. According to different of the angular velocities of the two motors installed at the front wheel, the angle of the front wheel can be measured. The idea is from the tracked vehicles [47].

5.2 The Hardware Component

The hardware chosen for this experiment includes the Zeltom HILINK boards, the steering motors (installed at the front wheels) and the feedback

motor (installed at the steering wheel), the simple carrier of Allegro's ±5A ACS714 Hall effect-based linear current sensor and the wheels.

5.2.1 The HILINK Platform

The HILINK platform offers a seamless interface between physical plants and Matlab/Simulink for implementation of hardware-in-the-loop real-time control systems, which is shown in Fig. 5.3. This platform enables Matlab/Simulink/Real-Time Windows Target to communicate with the control board in real-time. The bilateral control of SBW vehicle is achieved and the HILINK board is used as an ECU.

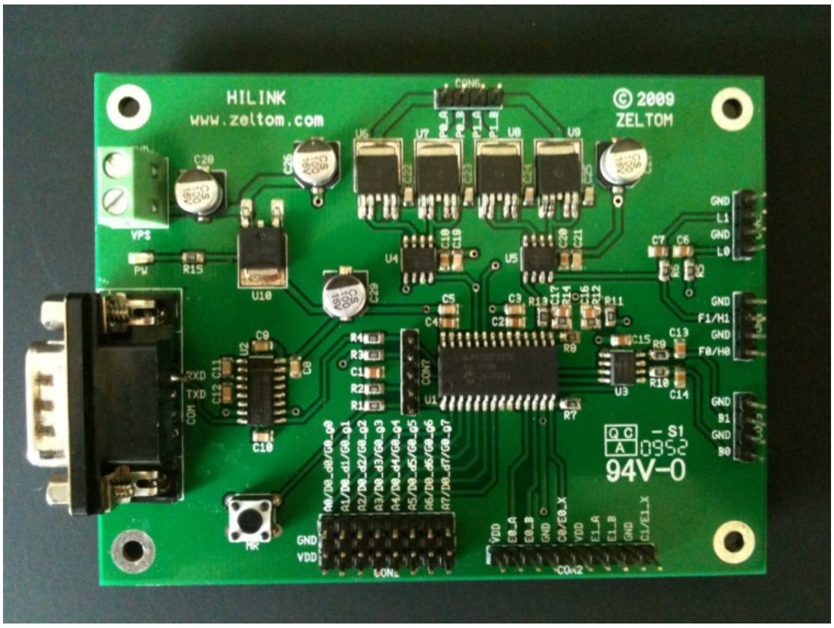

Fig. 5.3 HILINK Board

5.2.2 The Motors with the Encoder

Researchers provided the method of using a position sensor or angle sensor to detect the angle of the steering wheel, but those methods have the disadvantage. [30][31] For example, the angle sensor can just be available for the certain vehicle, such as the Toyota vehicle, but not for the all of the vehicles. Obviously, it could not be applied on the design of the platform. In this thesis, a two-channel Hall Effect encoder is used to sense the rotation of a magnetic disk on a rear protrusion of the motor shaft, and it can provide the

position of the steering motor and the feedback motor. Therefore, the angle of the steering wheel and the front wheel were received by the encoders.

5.2.3 Hall Effect Current Sensor

Some other researchers always get the force feedback with the torque sensor, which is not a good idea for design a system, because the torque sensor is expensive and hard to install on the steering wheel [33]. In order to improve the method to detect the force feedback, the Hall Effect current sensor is used to provide force feedback control with another PID controller, because the Torque generated in the feedback motor is linear to the value of the current.

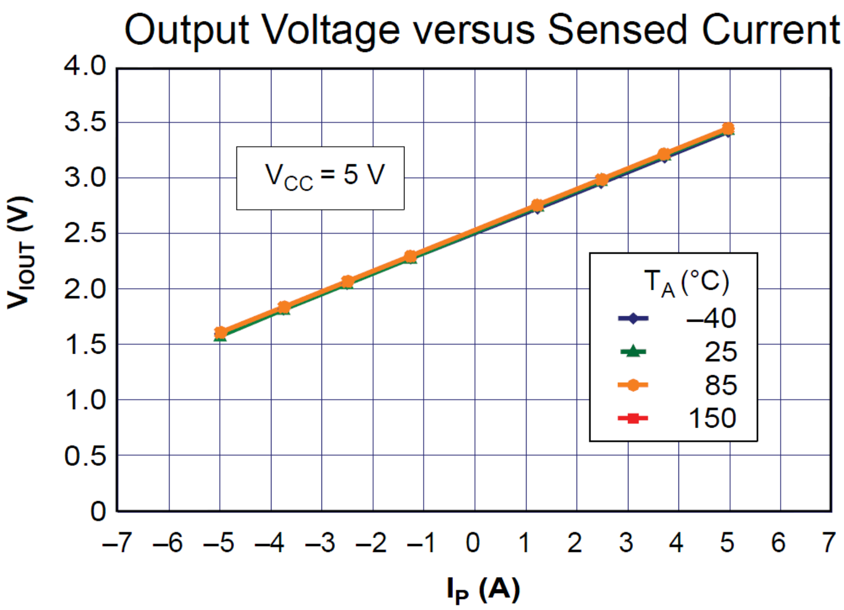

Fig. 5.4 Output voltage VS sensed current

It is shown the relationship between voltage and current in the circuit in the Fig. 5.4. This formula shown below can be expressed the relationship between voltage and current:

$$i = (v - 2.5)/0.185 \quad (40)$$

When the voltage is 2.5 volt, which means the current is zero. When the current is equal to 1 A, the voltage should be shown 2.685. However, the direct current was transferred from the 220V alternating current, so the wave of the voltage was always oscillated, therefore, the data we observed in the

scope through the Hall Effect current sensor is also oscillated, it can be absolutely accepted.

5.3 The Software Component

The software chosen is Matlab/Simulink. It enables the model-based design of control system, which can be implemented on hardware in real time. The real-time control board is supplied with the associated software for a seamless interface between the board hardware and Matlab/Simulink. The software is tightly integrated into Matlab/Simulink and comes with simulink blocks associated with each hardware input and output.

5.4 Simulink Model

This is the simulink model designed by myself with the HILINK platform, which is shown in Fig. 5.5 below. This model is similar as that model in chapter 4. In this model, E0 and E1 are both encoder input blocks. These block can transfer the actual angles of the steering wheel and feedback motor to the Matlab/Simulink in the PC, then, the data of the steering wheel and front wheel's angular would be shown in the scope in the simulink. E0 represented the position of the steering wheel and E1 represented the position of the front wheel. The function of the E0 and E0 is to convert the analog signal to digital signal, and is easy to observe from the scope. The output of the Encoder Input block should be filtered with a low pass filter to get rid of the high frequency noise resulting from the numerical differentiation. The function of $\frac{1}{0.01s+1}$ is acting as a filter.

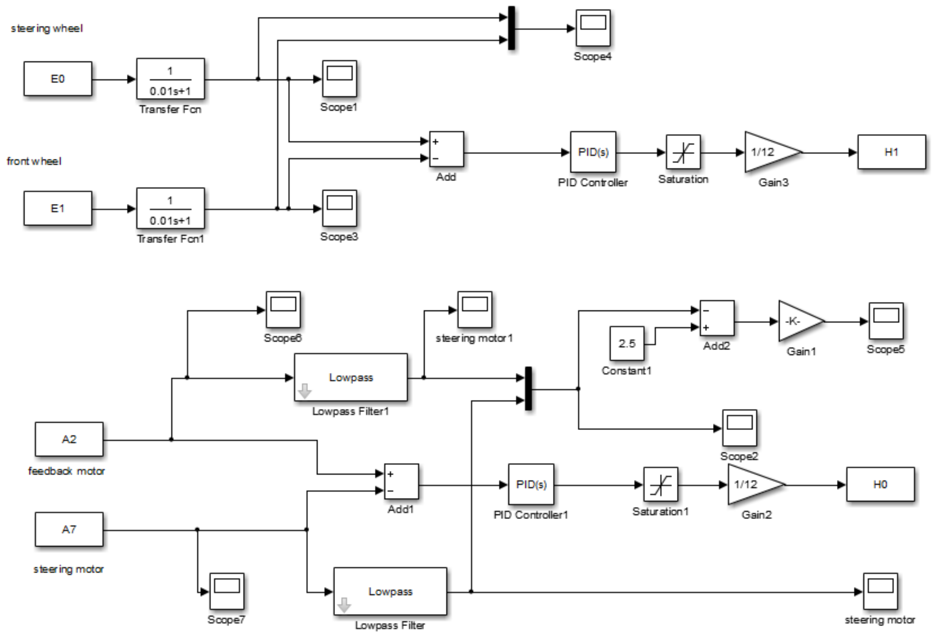

Fig. 5.5 Simulink Model

H0 and H1are pulse output block, it means applied the voltage on the motors. The gain of $\frac{1}{12}$ is defined by the Zeltom Company, which means the voltage applied on the board is 12V. For example, if the constant input of 3V connected to the gain of $\frac{1}{12}$, it means that the voltage applied on the motor is 3V, which is shown in the Fig. 24.

Fig. 5.6 Voltage Applied on the Motor

5.5 The validation of the experimental platform

The position control and current control are designed in this chapter. In order to satisfied the bilateral control of SBW vehicle, the position control and the current control must be satisfied at the same time.

5.5.1 Position control

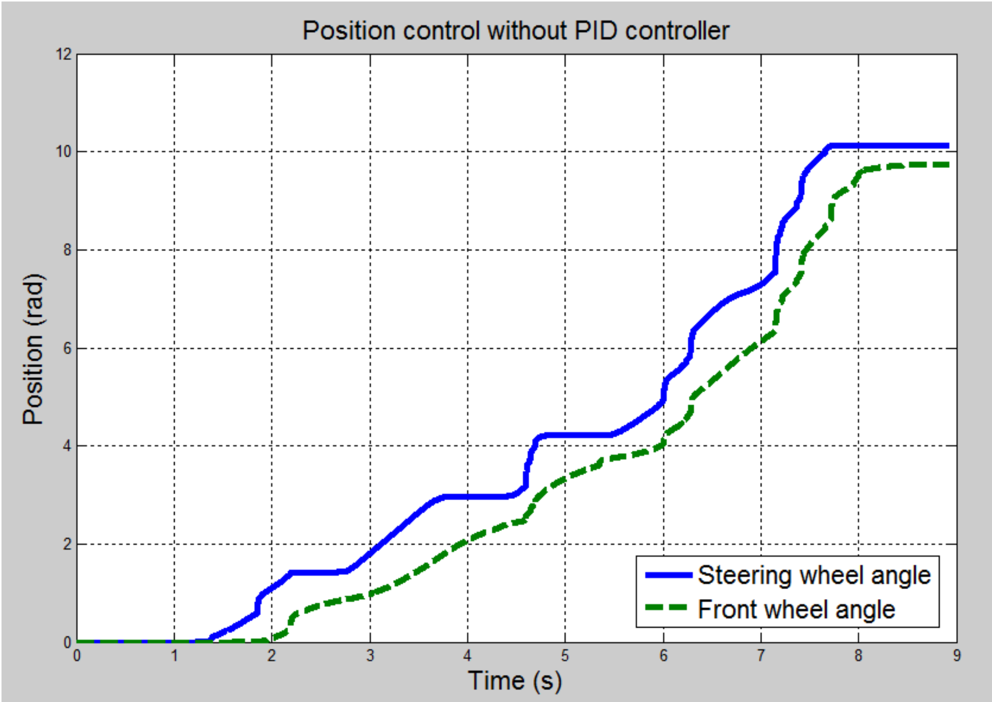

Fig. 5.7 Position control without PID control

As we see in the Fig. 5.7, the solid line represented the steering wheel angle and the dotted line represented the front wheel angle, respectively. The position of the front wheel can track the position of the steering wheel, even without the PID controller, but the delay was obvious observed in the scope and it was not very accurate. In order to limit the delay of the position control, and to improve the accurate of the system, the PID controller has to apply in the system.

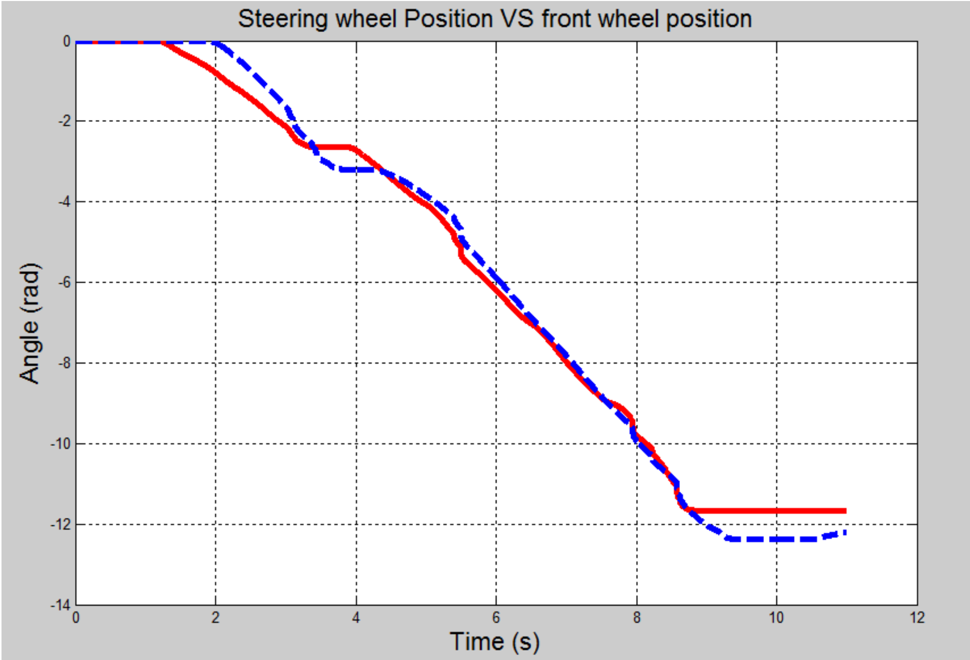

Fig. 5.8 Position control with PID control

As we see in the Fig. 5.8, position control with the PID controller is better than that without PID controller. The front wheel angle can be tracked the position of the steering wheel accurately, especially at the period of 4s to 8s. The negative value of the position means the steering wheel was steering to the opposite direction.

The steering wheel was not steering all the time, for example, from 0s to 1.5s, and 8.5s to 10s, the steering wheel keep the same position, because it was not steering at that time, so the front wheel keep the same position at that period. Starting from 1.5s, the steering wheel was beginning to steering, so did the front wheel, but there was some delay happed on the front wheel because of the friction happened on the shaft of the motor installed on the shaft of the feedback motor.

However, at the period from 8.5s to 10s, when the steering wheel stopped turning, the front wheel still turned a little angle, because of the inertia of the steering motor, it is influenced by the wheel installed at the shaft of the motor.

5.5.2 Current control

How to generate the force feedback is the difficult issue in bilateral control of SBW vehicle. In order to solve the problem, the current control is used in this chapter. Instead of using the torque sensor or observers to detect the torque applied on the front wheel, the two Hall Effect current sensors were used in the SBW system to detect the currents through the steering motor and feedback motor. Then, the PID controller is used to control the current through the feedback motor to generate the torque, which applied on the steering wheel. Therefore, the operators can feel the force feedback when they turn the steering wheel.

However, the noises were generated by the current sensor, so two lowpass filter were used in the Matlab/Simulink to filter out the noise partially [49].

According to the equation of (40), the current of the two motors can show in Fig.5.11 below.

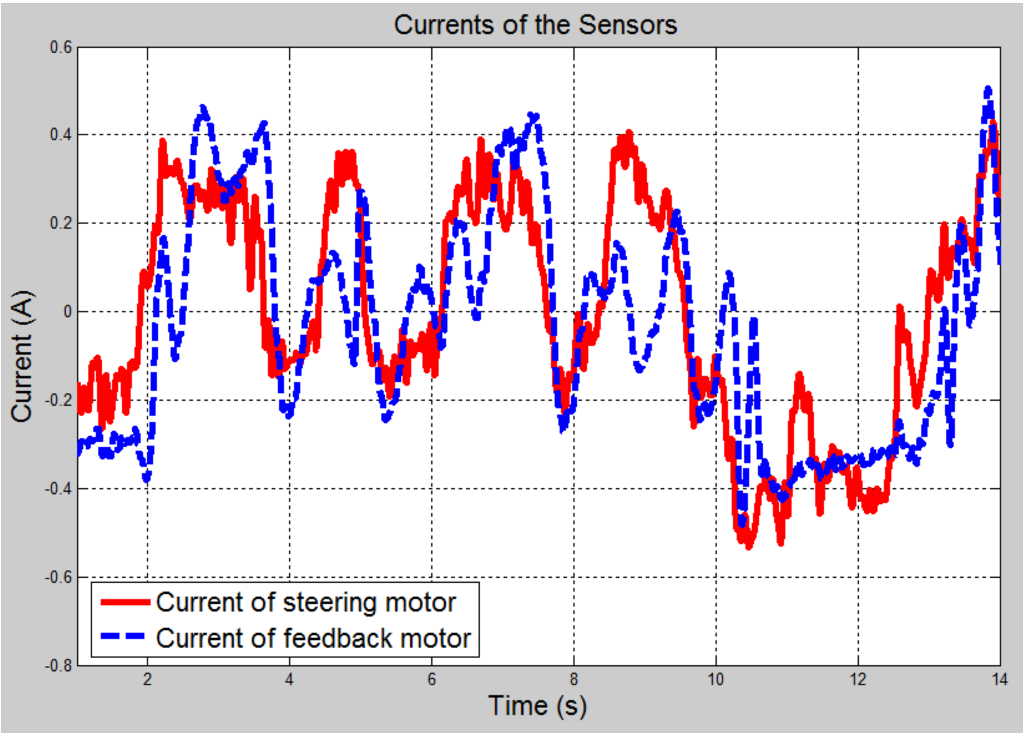

Fig.5.12 Current of the motors with lowpass filters

It is shown in Fig. 5.11 that the currents of steering motor and the feedback motor are easily to observe and noises have filtered out by the lowpass filters.

The solid line represents the current of the steering motor and the dotted line represents the feedback motor. It is obviously shown that the current of the feedback motor has followed the current of the steering motor. It can be recognize that the current control act the perfect results. As a consequence, the operator could feel the force feedback from the steering wheel.

5.6 Conclusion

In this chapter, the experimental platform has been established and the SBW system has been controlled by two PID controllers. The Position control and the current control are also successful in the experiment. The front wheel can track the steering wheel's position and the force feedback has also been generated applied on the steering wheel.

The current control is the key point in this chapter. The two Hall Effect sensors have been used in the experiment. The currents were generated by the steering motor and the feedback motor have the noise. The lowpass filters are also used to filter out the noise. As a consequence, the currents from two motors are much better observed after filter out the noise.

Chapter VI

Conclusion

In this thesis, a new SBW control system with variable gear-ratio is presented. The modelling dynamics has been illustrated and the feedback control is also designed by the Matlab/Similink embedded function to duplicate the real force back from the environment. The variable gear-ratio is the most important characteristics in steer-by-wire technology that focus on in the research and received the ideal results from the simulation. The variable gear-ratio is related to the different velocity of the vehicle and the different front wheel's angle. The PID controllers are designed according to the variation of velocities. The appropriate parameters setting for the PID controllers achieve the best simulation results such that the front wheel can track the steering wheel accurately and the driver can feel the torque feedback from the road at the same time.

The experimental platform is also established and the bilateral control of SBW vehicle is achieved. In this experiment, the position control and current control are successful. The difficult issue of how to generate the force feedback to the operator is solved by using the Hall Effect current sensor with the HILINK board.

Future Work

Overall, the dynamics of the system has been given in the research and the force feedback has duplicated conventional steering wheel force feedback. The simulation of the steer-by-wire system is set up and the experimental platform has also been established. In the future, the force feedback will be

further improved by tunning parameters of controllers in the experiment to achieve the best driving feeling in practice. In addition, advanced control strategies will be considered by simultaneously designing controllers in two loops to guarantee the overall system’s stability and performance.

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