UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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DEVELOPMENT OF STEER-BY-WIRE (SBW) CONTROLLER SYSTEM FOR STEERING RESPONSE

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DEVELOPMENT OF STEER-BY-WIRE (SBW) CONTROLLER SYSTEM FOR STEERING RESPONSE

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A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
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Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2016

DECLARATION

I declare that this thesis entitled “Development of Steer-By-Wire (SBW) Controller System for Steering Response” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

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DEDICATION

To my beloved father, mother, wife, sister and brother

ABSTRACT

This research focuses on the development of Steer-By-Wire (SBW) controller system for steering response. The steering system is an essential part of the interface between the driver and the vehicle that provides the possibility of lateral guidance. SBW system is means as removing the mechanical linkages and hydraulic part with electronic system. The development of vehicle model consists of ride, tire and handling models used in this study. The vehicle model is then validated with CarSimEd. The relation between the rack and pinion is identified for the steering ratio on SBW model. The steering system is modeled combine with actuator model in MATLAB Simulink. There are several types of controller are used on SBW system to find the similar response with the conventional steering. The selected controller will be applied on SBW system to control the actuator in simulation and experimental. The simulation result is validated with Hardware-in-the-Loop Simulation (HiLS) in real time situation using xPC Target application in MATLAB Simulink to control SBW system in experiment. The target outcome of this study for SBW steering system is to get a responsiveness similarity to conventional steering system with selected controller by comparing both steering system. The study shows that such similarity was achieved. The study of SBW system response is beneficial in the SBW system with the proposed controller can be implemented on real vehicles.

ABSTRAK

Kajian ini memberi tumpuan kepada pembangunan sistem kawalan Steer-By-Wire (SBW) untuk respon kemudi. Sistem stereng adalah satu bahagian penting dalam antara muka antara pemandu dan kenderaan yang menyediakan kemungkinan bimbingan sisi. SBW sistem bermakna menghapuskan hubungan mekanikal dan sebahagian hidraulik dengan sistem elektronik. Pembangunan model kenderaan penuh terdiri daripada model perjalanan, tayar dan pengendalian yang digunakan dalam kajian ini. Model kenderaan penuh kemudiannya disahkan dengan perisian CarSimEd Hubungan antara rak dan pinan dikenalpasti untuk nisbah kemudi pada model SBW. Sistem kemudi dimodelkan bergabung dengan model penggerak di MATLAB Simulink. Terdapat beberapa jenis pengawal yang digunakan pada sistem SBW untuk mencari persamaan tindakbalas dengan sistem kemudi konvensional. Pengawal yang dipilih akan digunakan pada sistem SBW untuk mengawal penggerak dalam simulasi dan eksperimen. Hasil simulasi disahkan dengan Simulasi Perkakasan dalaman Loop (HiLS) dalam keadaan masa sebenar menggunakan aplikasi Sasaran xPC dalam MATLAB Simulink untuk mengawal sistem SBW dalam eksperimen. Sasaran bagi kajian ini untuk sistem SBW stereng adalah untuk mendapatkan persamaan tindak balas ke atas sistem kemudi konvensional dengan pengawal yang sesuai dengan membandingkan kedua-dua sistem kemudi. Kajian ini menunjukkan bahawa persamaan itu telah tercapai. Kajian terhadap tindak balas SBW sistem bermanfaat dalam sistem SBW dengan pengawal yang dicadangkan boleh dilaksanakan pada kenderaan sebenar.

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LIST OF ABBREVIATION

a_x	Longitudinal acceleration
a_y	Lateral acceleration
F_{xfl}	Tire force for longitudinal direction front left
F_{xfr}	Tire force for longitudinal direction front right
F_{xrl}	Tire force for longitudinal direction rear left
F_{xrr}	Tire force for longitudinal direction rear right
F_{yfl}	Tire force for lateral direction front left
F_{yfr}	Tire force for lateral direction front right
F_{yrl}	Tire force for lateral direction rear left
F_{yrr}	Tire force for lateral direction rear right
m	Vehicle mass
δ	Steering angle
β	Side slip angle
$\dot{r}$	Yaw rate
v_x	Longitudinal velocity
v_y	Lateral velocity
w	Distance between left and right tires
G	Moment at the vehicle center of gravity
L_1	Distance between center of gravity from front tires
L_2	Distance between center of gravity from rear tires
F_z	Vertical forces
α_f	Tire slip angle for front
α_r	Tire slip angle for rear
s	Tire slip rates
$\ddot{\phi}$	Roll motion
$\ddot{\theta}$	Pitch motion
h	Height of the sprung mass centre of gravity to the ground
g	Gravitational acceleration
k_φ, β_φ, k_θ and β_θ	Damping and stiffness constant for roll and pitch
I_x and I_y	The moments of inertia of the sprung mass around x and y
C_1, C_2, C_3 and C_4	Tire constant parameters
ap	The lengths of the tire contact patch
T_w	Tread width

T_p	Tire pressure
F_{ZT} and K_α	Tire contact patches constants
K_s	Lateral stiffness
K_c	Longitudinal coefficients
A_0, A_1, A_2 and CS/FZ	Stiffness constants
σ	Composite slip
μ_o	Nominal coefficient of friction
γ	Tire camber angle
K_μ	Coefficient of friction
emf	Electromotive force
R	Coils resistance
L	Coils inductance
I	Coils current
U	Supplied voltage
k_m	Motor constant
$\emptyset(t)$	Rotor position
$\emptyset_{0j}$	Location of coil
j	The stator
ω	Rotational velocity
n	Numbers of rotor pole pairs
J	Rotor and load inertia
D	Viscous damping
T_f	Torque friction
T_M	Total torque
T_a	Actual torque
b	Kinematic equation for the rack and pinion
w_t	Wheel track
l_r	Rack length
b_1	Rack travel
h	Distance from front wheel axis
l_t	Tie rod length
l	Steering arm length
c and s	Cosine and sine
z_1 and z_2	Displacement at left side and at right side
γ	Learning rate
y_1, y_2 and y_3	Value of PID
e	Error value
Y_p	Plant output
Y_m	Reference model
U_i and U_c	Controller input and output

LIST OF PUBLICATIONS

1. Amir, M.Z., and Hudha, K., 2010. Hardware-in-the-Loop Simulation of an Electronically Controlled Steering System for Automotive Application. *Post Graduate Seminar (PGS UTHM 2010),* Universiti Tun Hussein Onn Malaysia, November 2010.

2. Amir, M.Z., Hudha, K., and Nasir, M.Z., 2011. Multibody Dynamic and Simulation for Steering System. *International Conference on Mechanical, Automotive and Aerospace Engineering 2011 (ICMAAE '11 IIUM)* May 2011.

3. Amir, M. Z., and Samad, M. F., 2015. Hardware-in-the-Loop Simulation of Steer-by-Wire System in Automotive Vehicle. *Journal Teknologi (Sciences & Engineering)*Universiti Teknologi Malaysia *(JT UTM 2015) - under review.*

CHAPTER 1

INTRODUCTION

1.1 Research Background

The main function of steering system is to allow vehicle handling. This is performed by turning the steering wheel to ensure the wheel angle is pointed on desired directions. Therefore, any vehicle can follow the road course control from driver input. By turning the steering wheel, the vehicle is able to move in a straight road or cornering condition (Pape *et. al*., 2011). Consequently, there are several types of steering system applied on current vehicles; moreover, the steering system is different according to the requirements of the vehicle (Yao, 2006). Nowadays, it has an advanced technology that gives more advantages in steering mechanism to improve handling situation such an active steering to counter wind disturbance. However, the conventional steering system using mechanical components is still applied for a low-cost vehicle (Calva *et. al*., 2012).

With advanced technologies, driver can control the vehicle easier after the additional parts of hydraulic and electronic system implemented. Furthermore, those parts will assist pinion rotation or rack displacement to reduce force on steering wheel, for better handling. Meanwhile, there are different types of power steering such as hydraulic, electro-hydraulic and electric power steering. Besides that, it has improved steering effort and gives advantages to the driver in handling maneuver.

Automotive industry has improved the steering performance where more electronic and controllers are applied towards to current steering system. Many researchers from automotive field try to propose new technology called "drive-by-wire". This technology will replace mechanical parts with electronic system and intelligent controller. The following stage to improve vehicle handling is the evolution of steering system called Steer-By-Wire (SBW) technology. SBW is an advanced steering system with new technology of steering developed by removing mechanical parts such as steering linkages, steering shaft, steering column with an electronic system with controller.

SBW system will control the angle of wheel using the actuator attached on the pinion with advanced controller input from the driver. Without any mechanical linkages and hydraulic parts, SBW steering system gives more advantages to improve the steering behavior. An intelligent controller is developed to control the pinion rotation to follow the desired direction. The implementation of SBW steering system to a real vehicle is still under research because there are several functions that must be considered to avoid system failure from occurring.

The main factor that must be considered is the controller and source. When the system fails to give any command to the actuator, a vehicle cannot follow the desired input from the driver. Some of the researchers try to develop the SBW system based on a conventional steering system related with the response, ratio of steering and wheel angle and torque feedback. This system can produce a better steering feel and easy to steer the vehicle in any condition. They have created more like a vehicle simulator combined with real hardware. This system called Hardware-in-the-Loop Simulation (HiLS) is to test the SBW system for automotive environment.

1.2 Problem Statement

In a conventional steering system, it uses mechanical parts without any hydraulic and electric systems installed. The driver uses much force to the steering wheel when the vehicle is not moving. It is hard to turn the steering wheel when the vehicle is in a static condition. The ratio of conventional steering is large and more rotation is required. The implementation of power steering on the vehicle can produce a problem if the mechanical system fails to function because of small ratio. When power steering fail to work, it is then difficult to turn the steering wheel. This is caused by a complex steering linkage with hydraulic and electrical components, especially in the maintenance of the system.

The conventional steering system with mechanical linkages still give advantages during mechanical failure but poor handlings during complex maneuvers can produce an unwanted yaw motion effect because of fixed and larger ratio of a conventional steering system. The mechanical and hydraulic friction loses effect from oil rotation in using hydraulic on steering system (Peter and Gerhard, 1999). An advanced steering system called SBW system is developed to improved conventional system where the mechanical linkages, hydraulic parts are removed and replaced with actuator attached on the pinion to rotate the pinion. The advantages of this system it is reduces engine load, easy to maintain and improve vehicle handling.

1.3 Objectives of Study

By considering the problem had occurred on the conventional steering system on a current vehicle, here are some of the objectives that are related with the problem. The objectives are listed to develop an advanced steering system where it uses intelligent controller and tested the system to produce a better system before it is applied on a real vehicle. The objectives of this study are listed below to replace the previous technology on conventional system to latest system such that the fixed ratio and friction losses can be improved.

1. To model SBW system using MATLAB Simulink from equation and simulate the model by get the necessary data
2. To validate vehicle model by comparing the model with CarSimEd software.
3. To develop control structure of steering system for SBW system
4. To develop SBW system CAD model using CATIA software and fabricate the prototype of the SBW system design.
5. To evaluate the response of SBW system in simulation and experiment by comparing actual and desired data to reducing error
6. The fundamental of this study to develop SBW model steering system similar response to conventional steering system.

1.4 Scope of Study

The main target for this project is to develop SBW system and study about the performance of the system using different controller for steering control. There are several cases that shall be tested to optimize the parameter for every controller. The scopes for following study are as follow:

1. Development of SBW test rig for SBW system is carried out using CATIA software
2. Development of 9 Degree of Freedom (DoF) vehicle model in MATLAB Simulink
3. Comparison between vehicle model with CarSimEd software for validation

4. Position tracking for actuator model validate with SBW test rig
5. Development of control structure to simulate the SBW system
6. Performance evaluation of steering response with selected controller

1.5 Research Methodology

The research methodology for this project starts from a study of the previous works that are related with SBW system from other researchers. The modeling, simulation and control structure are studied to determine the response of steering system for vehicle handling and other related topics from other researchers.

A 9 Degree-of-Freedom (DoF) vehicle model is developed from mathematical equation including handling model, tire model and ride model into MATLAB Simulink from equation to simulation. The vehicle model validated with CarSimEd model by comparing the result for both model. The validation process are compare the trajectory of x and y direction, yaw motion and lateral acceleration

The controller structure is developed for SBW system such Self-Tuning and Model Reference Adaptive Control (MRAC) using PID as a benchmark. Both controllers are used to compare steering response in simulation tests. It have three test will be selected in this study such Step Steer test, Slalom test and Double Lane Change (DLC) test. The suitable controller will be applying on the SBW system after doing the experimental test using the SBW test rig.

MRAC controller are selected based on simulation result from every test are done. The simulation result and experimental result will be comparing between MATLAB Simulink and Hardware in the Loop Simulation for experimental validation process. Figure 1.1 shows the research methodology for the present study. The flowchart show the process on this study to develop the controller system for steering response on SBW system.

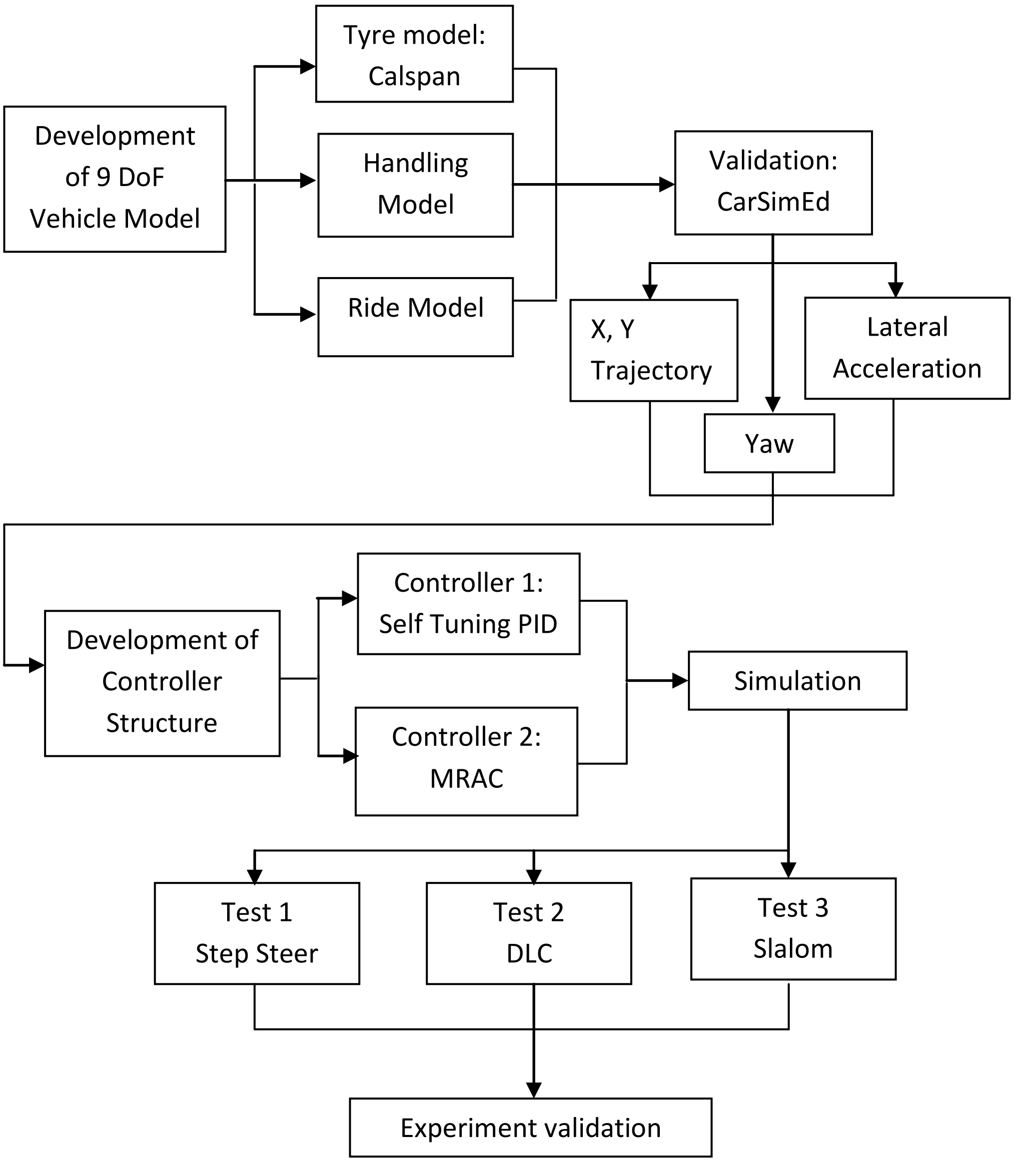

Figure 1.1: Research Methodology flowcharts

1.6 Thesis Outline

There are 7 chapters for this thesis including the introduction of research project, literature review of SBW system, vehicle modeling, position tracking of stepper motor, control structure, Hardware-in-the-Loop Simulation (HiLS) application and conclusion. Chapter 1 is an introduction about this project. The first chapter includes introduction of research, problem statement, research objectives, research scopes and research methodology.

Chapter 2 is literature review by overview of steering system with advanced technology and the method to control the steering and produce good steering response. The development of an advanced steering system like Steer-By-Wire (SBW) system has an advantage based on steering response.

Chapter 3 consists of vehicle modeling and model verification of SBW system by developing vehicle model in MATLAB Simulink from mathematical equations. The vehicle model is developed and validation of the vehicle model is carried out using CarSimEd software.

Chapter 4 presents the stepper motor modeled using MATLAB Simulink and the position tracking with simple controller. The actuator model follows the desired input by reducing error from rotary encoder reading where the encoder is attached on the pinion.

The next chapter is chapter 5 that introduces the development of control structure for SBW system. The controller is selected to control the steering system for SBW. The proportional integral derivative (PID) control and adaptive PID of Model Reference Adaptive Control (MRAC) is used to give good response for SBW system compared to conventional steering system in simulation.

Chapter 6 is about application of Hardware-in-the-Loop Simulation (HiLS) on SBW system. The experiment of SBW system uses HiLS for real time situation where the output will be displayed while the experiment is running and the parameters can be adjusted in real time.