

Modeling and Experimental Design Approach for Integration of Conventional Power Steering and a Steer-By-Wire System Based on Active Steering Angle Control

Eid S. Mohamed^{1,*}, Saeed A. Albatlan²

¹Automotive and Tractors Engineering Department, Faculty of Engineering, Helwan University, Mataria, Cairo, Egypt

²Automotive Engineering Department, Higher Technological institute, 10th Tenth of Ramadan city, 6th of October Branch, Cairo, Egypt

*Corresponding author: Eng_eid74@yahoo.com

Received November 21, 2014; Revised December 05, 2014; Accepted December 07, 2014

Abstract With the continuous development of vehicle and electronic industry, Steering by Wire (SBW) is replacing the traditional steering device of vehicle. The SBW is reproducing realistic steering feel, improving the vehicle returnability and it reduces the oscillatory effect of the steering system when the vehicle passes through an uneven road. This paper aims to present an overview of the SBW with integrated hydraulic power steering (HPS) in commercial vehicle. The mathematical model has been used to evaluate the performance of SBW system by using Matlab/Simulink software package, a PID controller and Linear Quadratic Regulator (LQR) optimization techniques are employed to arrive at an optimal controller for the SBW to monitor the system dynamic behavior and stability characteristics. The test rig of SBW system showed a great benefit in modifying a conventional HPS system to be electronically SBW. Necessary sensors and actuators replaced the conventional steering wheel. A microprocessor and interfacing circuits are designed to active control of DC motor. Also a SBW should be considered as requirement for a DC motor actuator vehicle steer angle for operating at given desired reference value and a proper torque to boost undergoing for operating under different conditions. The steering response of practical tests depends upon uncertain quantities like front axle weight, damping and a varying friction condition. Experimental results of SBW show that high performance and robustness are achieved.

Keywords: steering-by-wire, steering feeling, hydraulic power steering, steering torque, SBW dynamic model, a stability analysis of SBW, PID controller and LQR optimization techniques

Cite This Article: Eid S. Mohamed, and Saeed A. Albatlan, "Modeling and Experimental Design Approach for Integration of Conventional Power Steering and a Steer-By-Wire System Based on Active Steering Angle Control." *American Journal of Vehicle Design*, vol. 2, no. 1 (2014): 32-42. doi: 10.12691/ajvd-2-1-5.

1. Introduction

Nowadays, a great development is occurring in the automotive systems due to the introduction of electronics, which act as an integrated part with the mechanical system. The result of this integration appeared as an improvement in all phases of automotive functions as: driving performance, fuel efficiency, exhaust purification, safety and comfort.

Electronic Power Assisted Steering Systems (EPAS) and SBW are replacing hydraulic power steering in many new vehicles today [1].

Active front steering (AFS) system can realize steering intervention independent of the driver, optimize vehicle's response to driver's input and enhance the stability in emergencies by add an additional steering angle to the input of driver. In low-speed section, reduces steering gear ratios, in order to achieve steering lightweight and flexible requirements; In High speed section, increases the steering gear ratios, in order to enhance the high-speed steering stability. So far as safety and steering feelings are

concerned, AFS is a main trend of the development of current steering system, the principle of AFS is add an additional angle to the steering wheel input by motor, so as to improve the stability, maneuverability and keep track ability [2,3].

An Electric Power Steering (EPS) system will be considered in this report. The modeling of this dynamic system will be achieved with both simplicity and usability taken into account. As such, a reduced-order model that reveals the important dynamic distinctions of the system will be developed from a more complex one. This model will be used to analyse various closed loop effects such as torque performance, disturbance rejection, noise rejection, road feel and stability. These fundamental effects (compromises) are used towards the design of a desired control system [4].

In [5] propose a new ideal characteristic curve that can be applied to the EPS. The characteristic curve should be straight when the steering angle is small. When the angle is larger than a special value, the quadratic curve, the tangent slope of which is larger than before, should be chosen, and this paper gives us the basic algorithm for the new characteristic curve.

The term “steering feel” is commonly used as a catch-all phrase for describing the torque that the driver feels in relation to the position of the steering wheel and the motion of the vehicle. It refers to various conditions such as on-center (vehicle traveling nearly straight), off center, and static steer, where various kinds of inputs are applied to the steering wheel such as step, pulse, initial condition, or frequency response sweeps. An attempt to control the feel of a steer-by-wire and an electric power steering (EPS) system, respectively, are presented in [6,7].

The main object of studying SBW control strategy is how to keep the stability, tracking and anti-interference under the complicated condition of work and road. At present, there are a large number of control strategies used in the SBW, and several typical cases acquire some good effect, for instance PID, LQG, Fuzzy, and H^∞ etc [8,9,10].

Figure 1.a; the Steering Wheel (SW) rotation given by a driver is transmitted via a intermediate shaft. The column is connected to the rack and road-wheels. Therefore, the road-wheel angle is proportional to the SW rotation. An amplified hydraulic pump is used to reduce the driver’s steering efforts. In SBW, Figure 1.b, the intermediate shaft, and the hydraulic pump are removed. And several position sensors and actuators are attached to the SW and Vehicle wheel (VW). The encoder at SW is to observe SW motion. The SW motion then converted into electrical signals and wired to an electronic control unit (ECU). The ECU controls a VW actuator for rotating the VW part in the same manner of the SW behaviors. The second encoder at VW is for implementation of closed-loop position control. Because of the absence of physical connection, a DC motor at the SW is needed to recreate driving feelings.

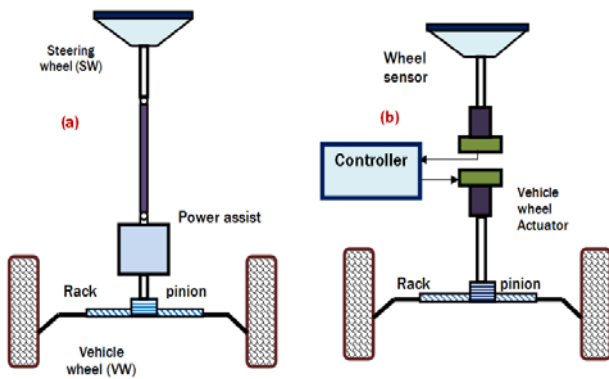


Figure 1. Conversion from conventional steering system to SBW

To make SBW features close to conventional steering systems, several requirements have to be met. Position tracking, which is the fundamental function of a normal steering system. This ensures the VW exactly copy the SW motions for accurate steering control. Realistic force feedback, which makes steer-by-wire system to has the same driving feelings as in a hydraulic steering system [11,12]. The driving feeling is one of the most difficult issues for steer-by-wire development. Free control refers to the response of the SW after a sudden release from the certain position of the SW. In this case, a quick return to center with minimal overshoot is desired [13].

2. Mathematical Models

2.1. Principles of Steering by Wire System

Figure 2 depicts a schematic overview of SBW structure with assist hydraulic steering system. SBW structure formed by the steering column, steering wheel sensor, torque sensor, electric control unit (ECU), DC motor, reduction gears and rack and pinion. The system will set the steering wheel signal, steering wheel torque signal which is collected by ECU as input, the controller calculated the motor angle and torque as output, which transmitted through the reduction gears provided smooth steering torque to help the driver steering with hydraulic assistant system. It can be formally subdivided into two subsystems: (i) The SW system consisting of the side-stick wheel, steering column, torque sensor and SW encoder detects SW movements and sends SW angle as an input to a PID position controller. Then, the controller gives control signal as current signal to VW actuator motor. (ii) The VW system consisting of DC motor, reduction gears, rack and pinion and hydraulic steering assistant system, the hydraulic system (the assist force) to overcome the resistant force from the wheels, at the VW DC motor actuates the road wheels accordingly, a proportional current signal inside the motor driver occurs at the same time. Fortunately, the value of the current signal depends on the load applied on motor shaft because of the current-torque relationship of DC motors.

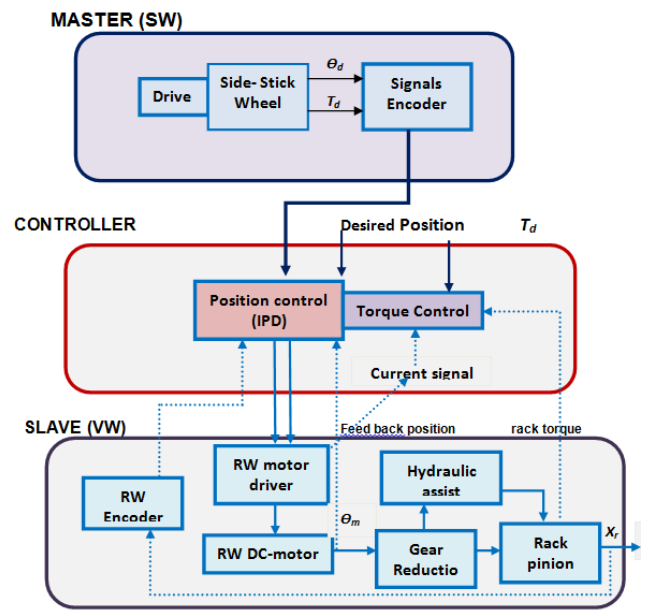


Figure 2. Overview of steer-by-wire structure

2.2. Steering by Wire Model

The most important requirement in modeling a system is the complete understanding of the performance specifications, physical and operational characteristics of each component in the SBW system, the dynamic model of the SBW establishes relation between steering mechanism, electric dynamics of the motor and rack/pinion interaction torque. Figure 3 shows the model of steering mechanism equipped with DC motor actuator. The transmissibility of SBW system from VW load to driver’s SW can be investigated by calculating driver’s SW torque while fixing hand wheel.

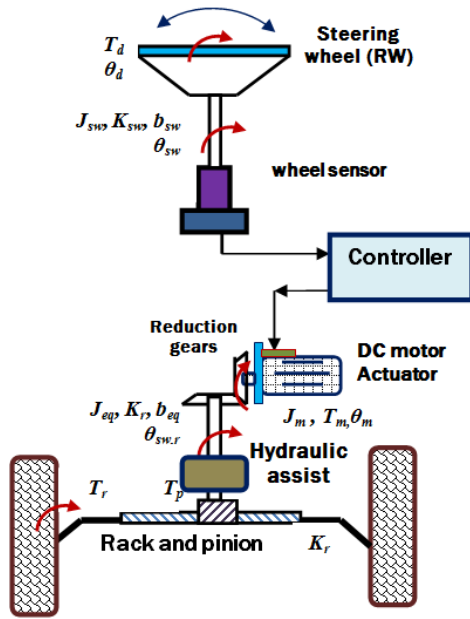


Figure 3. Schematically model of SBW

According to Newton laws of motion, the equations of motion in SW can be written is like equation 1.

$$T_d = J_{sw} \ddot{\theta}_d + b_{sw} \dot{\theta}_d + K_{sc,h} (\theta_d - \theta_{sc,h}) \quad (1)$$

The equations of motion in VW can be written as follows:

$$T_m = J_m \ddot{\theta}_m + b_{sc,r} \dot{\theta}_m + K_{sc,r} (\theta_m - \theta_{sc,r}) \quad (2)$$

Where, $\theta_d, \theta_{sc,h}$ the steering wheel angle and steering column angle in SW

T_d, T_m the human torque applied on the SW and DC motor torque respectively

J_{sw}, J_m the moment of inertia of steering wheel and DC motor respectively

$b_{sc,h}, K_{sc,h}$ the steering column viscous damping and stiffness in SW.

$b_{sc,r}, K_{sc,r}$ the steering column viscous damping and stiffness in VW.

Figure 4 depicts a generic model of a DC motor actuator that includes two windings: a stationary field winding on the stator and a second winding for the rotating armature. This type of motor can be controlled by varying either the field current or the armature current, they can only be controlled by varying the armature current, i_a . In a permanent magnet motor, the output torque T_m is directly proportional to the armature current i_a . The constant of proportionality is referred to as the torque constant of the motor and is represented by K_t , by applying Kirchhoff's Voltage Law (KVL) to the armature [14].

$$V_a(t) = V_b(t) + R_a * i_a(t) + L_a \frac{di}{dt} \quad (3)$$

Where:

$$\begin{aligned} V_b(t) &= K_b * \theta_m(t) \\ T_m(t) &= K_t * i_a(t) \end{aligned} \quad (4)$$

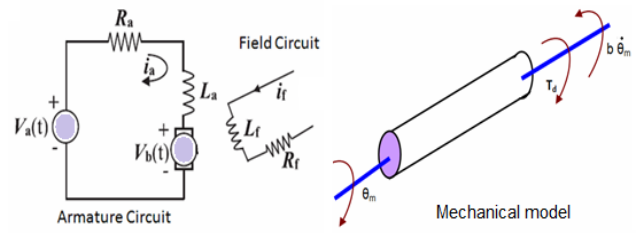


Figure 4. DC motor sub-system model

The torque implementation of the SBW system. Normally, the torque feedback known as driving feelings is from the VW part. This includes moment of inertia, stiffness and damping. And, equilibrium equation of steering in VW is equation (6), the equation of motion for the torsion bar, pinion and rack can be derived from the simplified model of steering rack and pinion system shown in Figure 5. The SBW main parameters of model are as follows Table 1.

$$J_{eq} \ddot{\theta}_r + b_{eq} \dot{\theta}_r + K_r \left(\theta_{sc,r} - \theta_r \frac{x_r}{r_p} \right) = iT_m - T_p \quad (5)$$

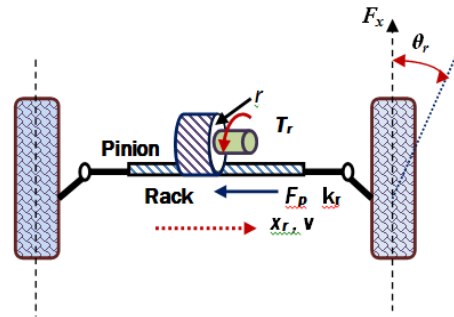


Figure 5. Simplified model of rack and pinion steering

And, equilibrium equation of steering rack bar by:

$$m_r \ddot{x}_r + b_r \dot{x}_r + CF_r * \text{sgn}(x_r) = \frac{T_p}{r_p} - \frac{T_r}{N_L} \quad (6)$$

Where:

$$\begin{aligned} J_{eq} &= J_{scr} + m_p \frac{r_b^2}{i^2} \\ b_{eq} &= b_{scr} + b_r \frac{r_b^2}{i^2} \end{aligned} \quad \text{and} \quad \begin{aligned} x_p &= \theta_p * r_p \\ x_r &= \theta_r * r_w \end{aligned} \quad (7)$$

T_p, T_r are the pinion torque and road wheel torque and $\theta_{sc,r}, \theta_r, x_r$ are, respectively, the steering column angle in VW, the angular position of the road wheel and the rack position. CF_r is the Coulomb friction breakout force on steering rack. N_L is the steering linkage rate. the SBW subsystem Matlab/Simulink model shows in Figure Appendix 1.

In hydraulic steering systems, this force is transmitted to a driver after power modification of based on a hydraulic pump for convenient of SW control. However, in SBW system, this force must be artificially recreated by the VW actuator. Therefore, a realistic force feedback including all the mentioned effects becomes an essential factor in SBW.

Table 1. The main parameters of SBW model

No.	Parameter	Symbols	Unit	Value
2	Mass moment of inertia of the motor armature	$J_m J_m$	$Kg.m^2$	0.0004
2	Inertia constant of the steering column	J_{sc}	$N m s^2/rad$	0.0344
3	Moment of inertia of steering wheel	J_{sw}	$N m s^2/rad$	0.0344
4	motor gear ratio	i	—	49/3
5	Viscous damping of steering wheel	b_{sw}	$N.m/(rad/sec)$	0.36042
6	Viscous damping of steering column	$b_{sc,r}$	$N.m/(rad/sec)$	0.36042
7	Steering wheel rotational stiffness in HW	$k_{sw,h}$	$N cm /rad$	42057
8	Pinion radius	r_p	m	0.0073
9	Steering wheel rotational stiffness in RW	$k_{sw,r}$	$N m /rad$	42057
10	Torsion bar rotational stiffness	k_r	$N m /rad$	14878
11	DC motor armature resistance	R_a	Ω	0.39
12	Pinion mass	m_p	kg	0.26
13	the steering linkage rate	N_L	m	0.12
14	Motor viscous damping coefficient	$b_{sc,h}$	$N.m/(rad/sec)$	0.19
15	Motor back EMF constant	K_b	$V/rad/s$	0.0521
16	Torque constant of the motor	K_t	$N.m/A$	0.052
17	Wheel radius	r_w	m	0.27
18	Motor armature inductance	L_a	H	0.0019

The hydraulic subsystem components consist of a pump, rotary valve, hydraulic cylinder and piston, the flow rate of fluid supplied by the pump, displacement of the rack and rotational displacement of the steering column are the inputs to the hydraulic subsystem. The output of the hydraulic subsystem is the differential pressure across the cylinder. The pump continuously supplies oil flow to the rotary valve. The pump is modeled by a series connection of a flow source with flow control valve, the main parameters of hydraulic subsystem are as follows Table 2. The spool behaviour of the flow control valve and pressure at the chamber (P_{pt}) are determined as follows:

$$\frac{dP_{pt}}{dt} = \frac{K_f}{V_{pt} + x_s * A_s} * \left(Q_t - Q_m - Q_{fr} - A_s * \dot{x}_s \right) \quad (8)$$

$$Q_i = (CA)_i * \sqrt{\frac{2}{\rho} \Delta P_i} \quad i = (1:4) \quad (9)$$

Table 2. The main parameters hydraulic systems

No.	Parameter	Symbols	Unit	Value
1	length of the cylinder	L	cm	15
2	discharge coefficient	CA	—	0.6
3	density of the fluid	ρ	Kg/m^3	830
4	the metering orifice area	A_s	cm	0.274
5	volume of supply port in pump	V_{pt}	cm^3	8.57
6	spool displacement	x_s	cm	4.5

3. Active Steering Control Procedure

3.1. System State-Space Model

The linear model of SBW system of two equations No. 2 and 5 can be expressed in the following state space form:

$$\left\{ \begin{array}{l} \dot{x} = Ax + B_1 u_1 + B_2 u_2 \\ y = C_1 x + D_1 u_1 + D_2 u_2 \\ z = C_2 x \end{array} \right. \quad (10)$$

Where: A is SBW characteristic matrix, B is the input matrix, and the state vector of the SBW system, $u_1 = v$ is the voltage of the DC motor, $u_2 = [T_d \ T_r]$ represents the vector of unknown inputs which is composed with driver torque and road reaction torque, $z = T_r = k_r (\theta_r - \frac{\theta_{sc,r}}{i})$ is the steering torque which acts acted on the steering column, used as indicator of the steering feel because it acts directly on the driver's hands via the steering wheel, $y = [\theta_{sc,r} \ \theta_m \ \theta_r \ i_a]$ is the measurement signal [15].

3.2. Implementation of (PID) Control

The system control of a SBW is described. Proportional-Integral-Derivatives (PID) controllers for both of the DC motor systems to track the reference steer angle and torque, a controller regulates the motion by control the variation of current duration with time. But, however the sensitivity of the transient motion to disturbances depends much on the system stability. The system has to be stabilized with a tuned PID controller before the system identification test could be executed. The PID controller works in a closed-loop system using the schematic in Figure 6. The variable e represents the tracking error, the sent to the PID controller and the controller computes both the derivative and the difference between the desired input value R and the actual output Y . This error signal e will the signal u just past the controller is now equal to the proportional gain K_P times the magnitude of the error plus the integral gain K_I times the integral of the error plus the derivative gain K_D times the derivative of the error [16,18].

$$u = K_P e + K_I \int e dt + K_D \frac{de}{dt} \quad (11)$$

PID controller for position control of steering system aims to have a good position tracking of VW and SW. System closed loop control for torque feedback based on the measured current signal is conducted as algorithms described. Free control quality is evaluated by the returning force verse SW angle, PID controller is tuned by

Ziegler-Nicholas method [18] and we obtained the proportional gain $K_p = 250$ integral gain $K_i = 7.81$ and derivative gain $K_d = 0.23$, The unit step response and performance parameters such as peak overshoot, peak time and settling time for PID control is shown in results.

Table 3. Equation of controller in the time domain

Proportional Control	$u(t) = K_p e(t)$
Integral Control	$u(t) = K_i \int e dt$
Derivative Control	$u(t) = K_d \frac{de(t)}{dt}$

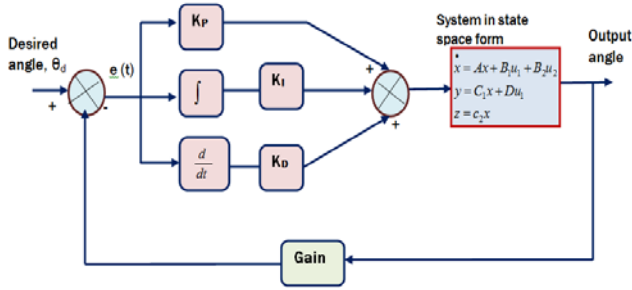


Figure 6. PID Controller of SBW

3.3. Linear-Quadratic Regulator (LQR) Optimal Algorithm Control

Linear quadratic regulator (LQR) design technique is well known in modern optimal control theory and has been widely used in many applications. All steering assist power systems must be able to provide a wide range of assist levels and the prime objective of the SBW control system is to ensure closed-loop system stability at high levels of assist gain. The state-space approach provides a methodical solution to the problem of control of high-order systems. A state-variable feedback control system is proposed. Optimal closed-loop pole locations are computed using a LQR design approach. The LQR approach is chosen as it has good stability and robustness properties, and leads to good gain and phase margins in this section can be a build and evaluation of LQR in SBW model [17].

LQR another design alternative, seeking to improve the previously obtained performance index, is to use full state-space feedback. The system model has two states, the rack position and velocity. The position can be directly measured, and the velocity can be estimated with the differentiation of position measurements. a LQR optimal controller is designed for stabilizing the augmented plant. The cost function that needs to be minimized is $u = -Kx$ minimizes the following cost function:

$$J = \int_0^{\infty} [x^T c^T q c x + u^T R u] dt \quad (12)$$

Where: R and q are the weighting parameters. The weighting matrices q and R are important components of an LQR optimization process. The problem can be solved by introducing the following Riccati equation:

$$SA + A^T S - (SR + N)R^{-1}(B^T S + N^T) + c^T q c = 0 \quad (13)$$

S = Riccati matrix

Matlab program is used to calculate the gain matrix K using the following form $[K, S, E] = lqr(A, B, Q, R, N)$. Note that is derived from by limitations the problem data must satisfy, under the following conditions:

- The pair matrix A and B are sterilisable.
- $R > 0$
- $c^T q c - NR^{-1}N^T \geq 0$
- $A - BR^{-1}N^T \geq 0$

the controllers gains are computed using Matlab LQR function with the parameters state-space model in equation (10). Chooses the values of weighting parameters by return repetition to the minimize value of performance index. The values of weighting parameters are $R = 2.18 \times 10^{-7}$ and $q = 1.18$; the values result of control feedback gains matrix K are:

$$K = \begin{bmatrix} 20.3 & 2.38 & 18.2 & 2.12 \times 10^2 \end{bmatrix} \quad (14)$$

the control input signal is:

$$u(t) = 20.3X_1 + 2.38X_2 + 18.2X_3 + 212X_4 \quad (15)$$

Simulation tests are based on the facts that whether the linear quadratic regulator controller is better the system stability.

4. Experimental Work

4.1. Test Rig Setup

The experiment is focused to observe SBW response with hydraulic assist system; the test rig setup is shown schematically in Figure 8. The steering wheel and column are eliminated and replaced by a side-stick in SW, the hydraulic pump is powered by an electric motor has 1.2 HP at 1400 rpm, and the steering pinion and hydraulic valve connected with DC motor actuator has 100 W.

The proposed control system algorithm takes the decisions based on side-stick input signals (T_{sb} , θ_{sw}) and operates the DC motor actuator in VW that drives the mechanical linkage of the steering system according to the vehicle characteristic data. The control system determines the required steering angle and torque of actuator based on the output as a closed loop system. Figure 7 depicts a simple block diagram of the proposed control system. The control system parameters have consisted of error signal $e(t)$, DC motor actuation signals $v(t)$, $i_a(t)$, steering action road torque $T_r(t)$, rack displacement $x_r(t)$, and angular displacement of motor shaft system $\theta_m(t)$. Figure 9 depicts schematically of experimental setup and measurement installation system.

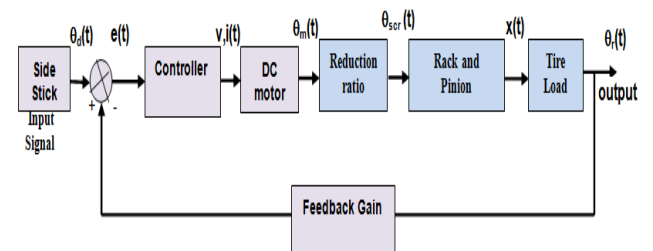


Figure 7. Schematically of steering control block diagram

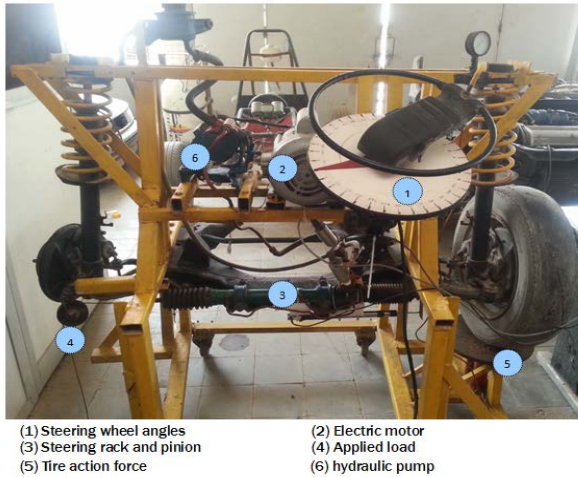


Figure 8. Photograph of the layout of the test rig

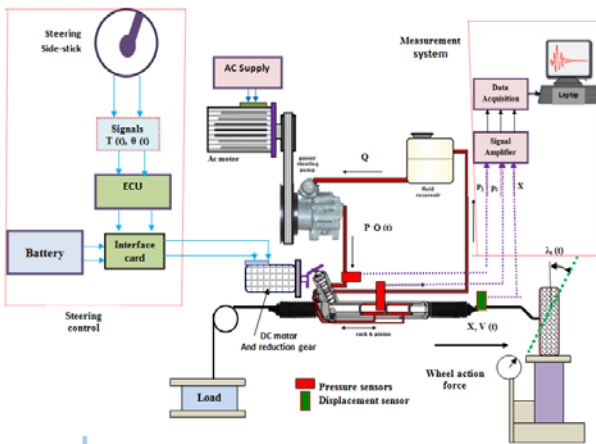


Figure 9. Schematically of experimental simulation setup

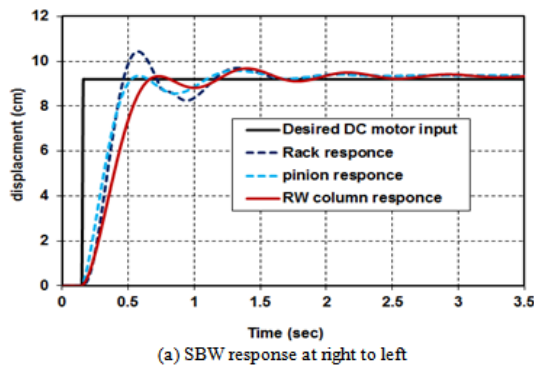
The following equations can be evaluated of mechanical and electrical power consumption of SBW system:

$$P_{mech} = T * \omega = \frac{T * 2\pi(N)}{60} \quad (16)$$

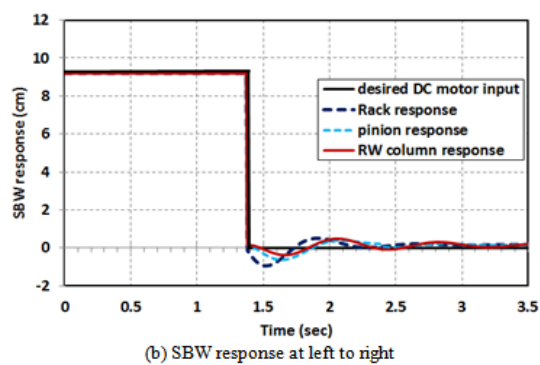
$$P_{elec} = V * I.$$

4.2. Measurements Setup

The SBW responses for the front wheel steer were measured by displacement transducer, torque sensor and two pressure sensors, the sensors signal recorded were passed to the signal processing (charge amplifier, data acquisition system, and laptop) with national instruments LabVIEW™ program version 7.1 was used to create the



(a) SBW response at right to left



(b) SBW response at left to right

Figure 12. the SBW system response at right and left turning

signal recorded. Figure 10 depicts the measurement instrumentation layout of SBW system.

The SBW installation was driven by DC motor of 100 W and selected to drive the shaft VW and sensors locations as shown in Figure 11. This is considered as the main actuator for driving the steering column in VW and effect of hydraulic control valve of power steering in both right and left directions. The control system takes the steering angle given by the driver as input signal; the rack displacement signal is feedback using a displacement sensor, delivery and return pressure line signals and right and left rack position signals. All of these signals are fed to the data acquisition card (DAC) in the controller. Based on the sensor data and the control algorithm, the embedded controller calculates the required outputs using interfacing circuits that output actuator command signals in real-time. A power rack and pinion steering mechanism is mounted on a frame with applied simulated load.



Figure 10. system controller with interfacing circuits'

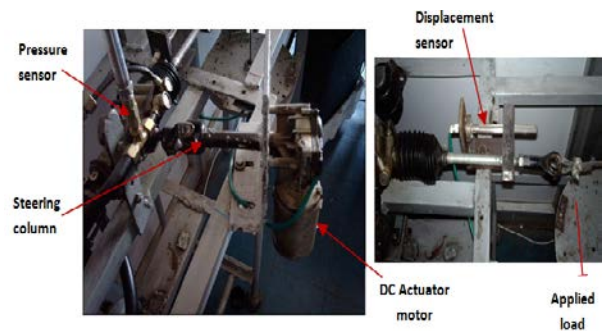


Figure 11. the adaptation and mounting of DC motor with sensor locations

5. Result and Discussions

5.1 Theoretical Model Results

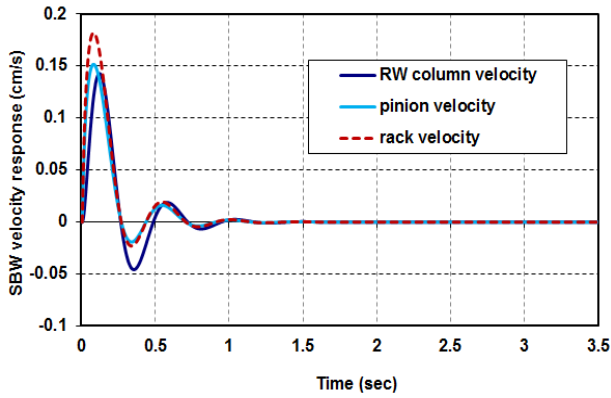
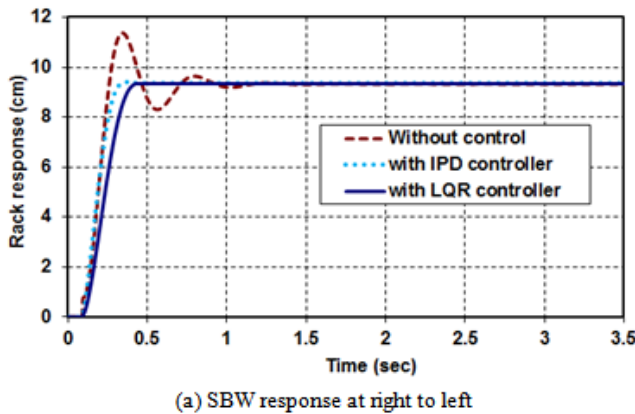
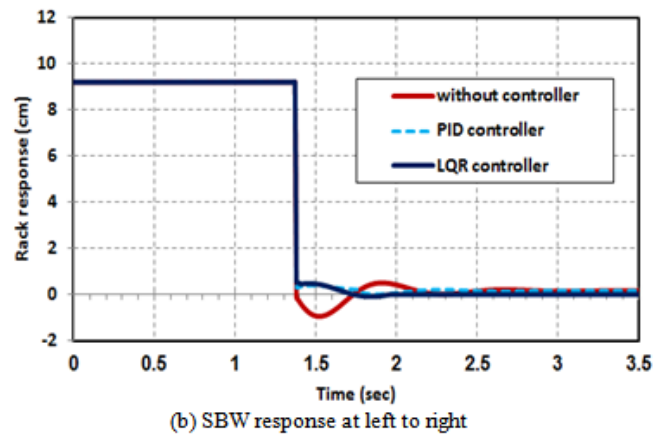


Figure 13. the SBW system velocity response

Simulations were performed on the linearized system as well as the original nonlinear SBW system without system controller, the time domain performance is generally given in terms of the transient response of the SBW system to a given input signal. The maximum overshoot, peak time, and settling time are the main performance criteria. Figure 12a and Figure 12b depicts the SBW system response with step desired input when steering wheel turns from right to left and left to right. Figure 13 shows the SBW response velocity, the max. fluctuation and setting of system reaches in rack response.



(a) SBW response at right to left



(b) SBW response at left to right

Figure 14. the rack displacement response with and without controller

5.2. Experimental Results

This section will present the results obtained from the tests carried on the electronic SBW system in the laboratory. The results will be discussed to determine the performance and response of the SBW system. The experimental results show good agreement between 85 to -85 degree, its output according to the variation of the Side-stick wheel angle, front vertical loads and road type. The practical results have demonstrated that it is a feasible approach to use a SBW system that mimics the characteristics of a conventional HPS system. the performance of the proposed controller and observer, simulations are carried out using track input signal to the system the driver's exerted quadrate wheel angle profile by using side-stick in SW, shown in Figure 15, note that this profile trajectory is designed in order to simulate the effect that the driver turns the steering wheel for 18 sec. The steering wheel moves right up to 85 degree, return

back, moves left up to 85 degree and finally back to its first position. Figure 16 illustrates the SW and DC motor actuator torque profile with different real steer time.

Table 4. Simulated values of two controllers

SBW Response	PID	LQR
Settling Time	0.56	0.63
Rise Time	0.0045	0.0037
Overshoot	4%	0%
Steady State Error (e_{ss})	0	0

back, moves left up to 85 degree and finally back to its first position. Figure 16 illustrates the SW and DC motor actuator torque profile with different real steer time.

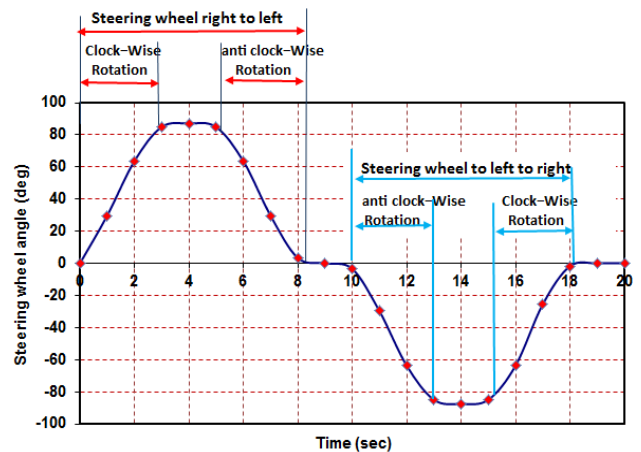


Figure 15. Target simulation: step-like tracking of steering wheel

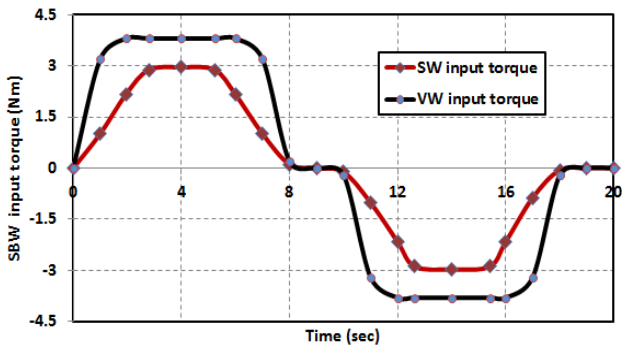
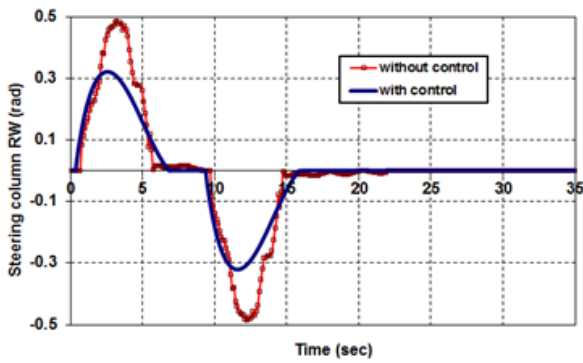
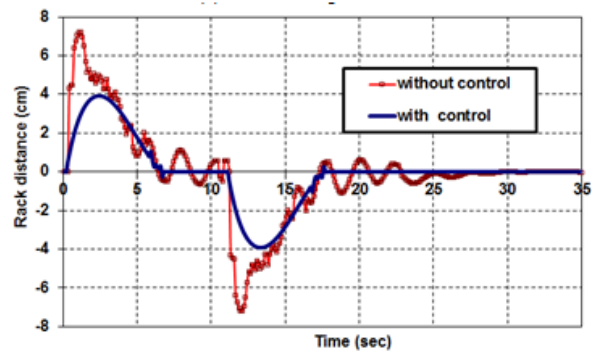


Figure 16. the profile of the driver's torque input and DC motor input torque

Figure 17, a shows the comparisons between practical column displacement and Figure 17, b shows the rack displacement at SBW system with and without system controller. Figure 18 illustrates the comparisons between



(a) column response



(b) rack response

Figure 17. the measured SBW output displacement of column and rack

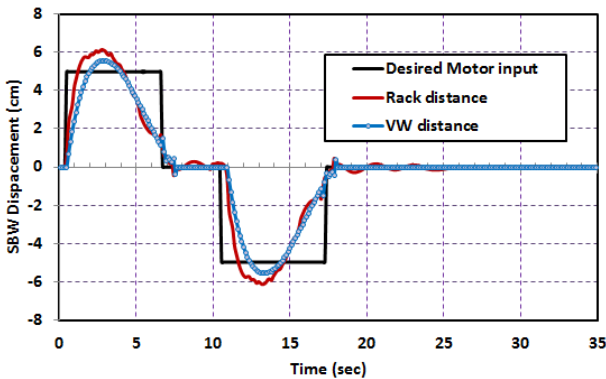


Figure 18. the measured SBW output displacement of column and rack

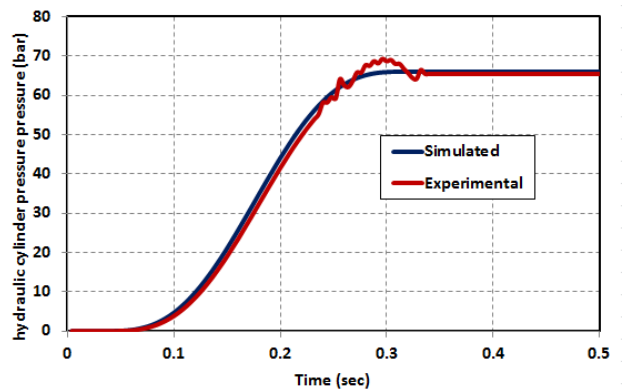


Figure 20. the comparison simulated and measured assist hydraulic cylinder pressure

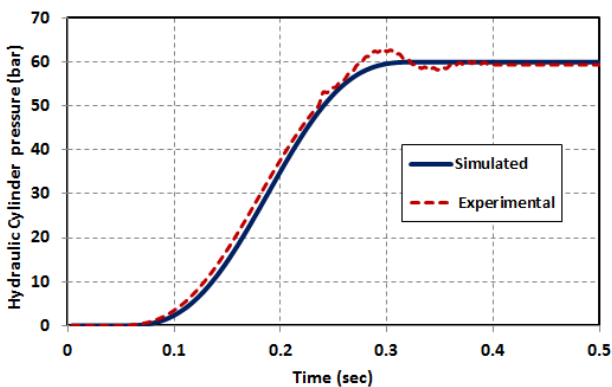


Figure 19. the comparison simulated and measured assist pump pressure.

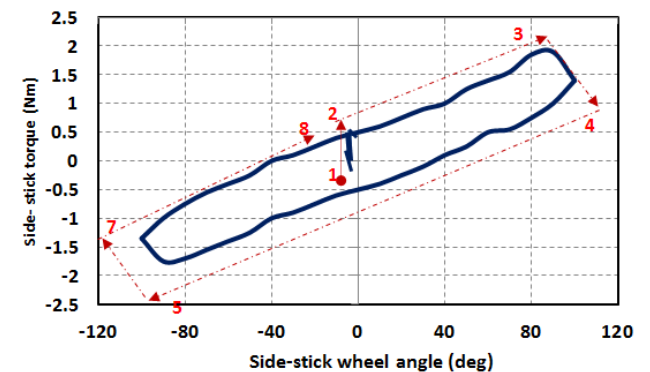


Figure 21. the experimental driver torque in side-stick SW

practical rack and VW displacement with DC motor desired input profile. Figure 19 and Figure 20 show the hydraulic assist subsystem response, and comparison between simulated and measured assist hydraulic pump and cylinder pressure, respectively, when the steering wheel turn from right to left. Figures 21 and 22 illustrate the measured side-stick SW torque and DC motor actuator torque, respectively. Side-stick wheel torque measured by torque sensor and DC motor actuator torque can be estimated by measured the motor current sensor. Figure 23 depicts the relationship between practical assist torque of hydraulic subsystem in VW and real time with different frontal vertical load, the front vertical weight increasing from 500N to 4000N. Figure 24 depicts the practical assist torque of hydraulic subsystem with different road types; when the road surface friction coefficient increases in concrete, the requirement of the assist torque increases.

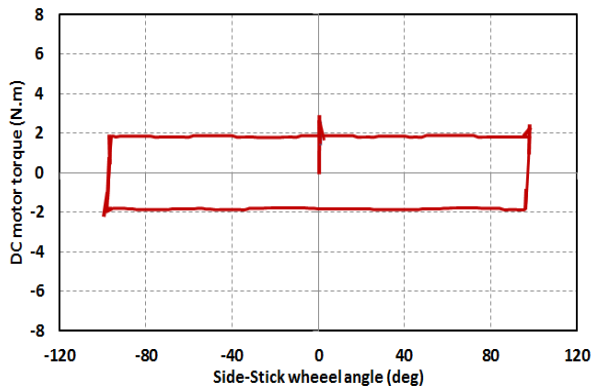


Figure 22. the experimental torque of DC motor actuator VW

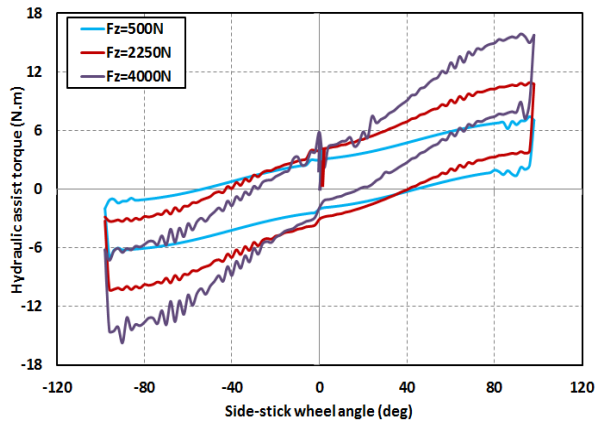


Figure 23. the experimental assist torque of hydraulic subsystem VW with side-stick wheel angle, dry asphalt

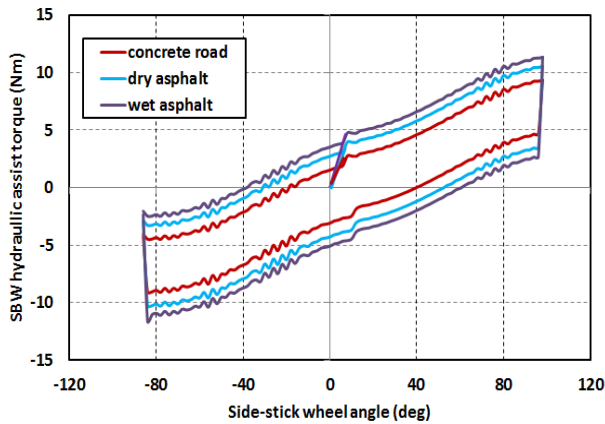


Figure 24. the experimental assist torque of hydraulic subsystem with different friction coefficient, $F_z=2250N$

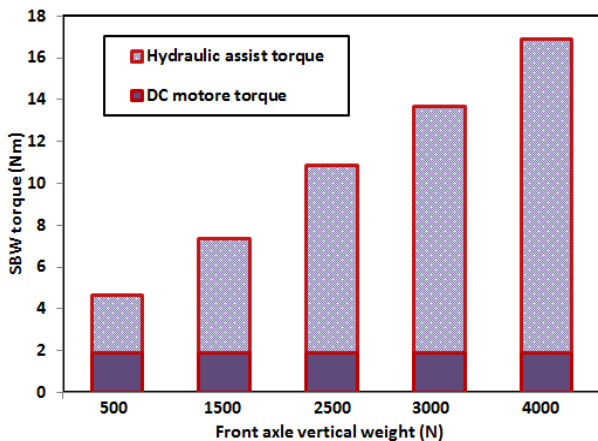


Figure 25. the experimental torque in VW with different front vertical load, dry asphalt

Figure 25 depicts the practical torque in VW with different front vertical load, the SBW system required assist torque increase when vertical load increase, the covers requirement torque by hydraulic assist sub-system. The figure indicates that participate the DC actuator and hydraulic assist sub-system of requirement torque 48% to 52% respectively at 500N load, hydraulic assist sub-system can be achieved for the same reason 70% participate when vertical load increase to 4000N.

Figure 26 depicts the practical rack displacement with and without hydraulic assist at vertical load 500N at the side-stick wheel turn from right to left. It means that the hydraulic assist subsystem can effectively alleviate the oscillation and ameliorate the steering feel. It is necessary for hydraulic system to improve their product in order to retain market share, hydraulic system in SBW increase the damping and improve steering feel.

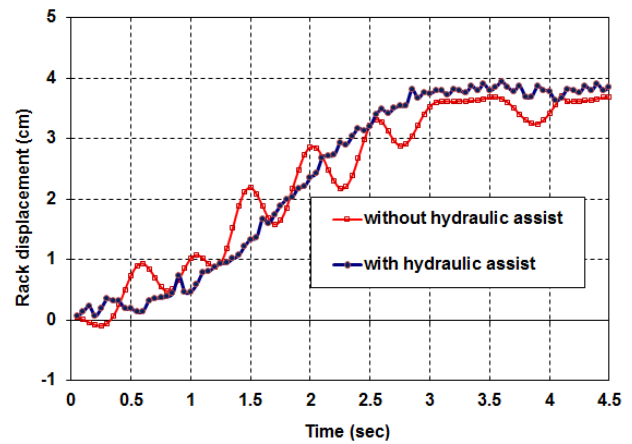


Figure 26. the experimental rack displacement with and without hydraulic assist, $F_z=500N$ and dry asphalt

Figure 27 illustrates the experimental required power of HPS and SBW with HPS, with different front vertical load, when the tire load increase the required power increases.

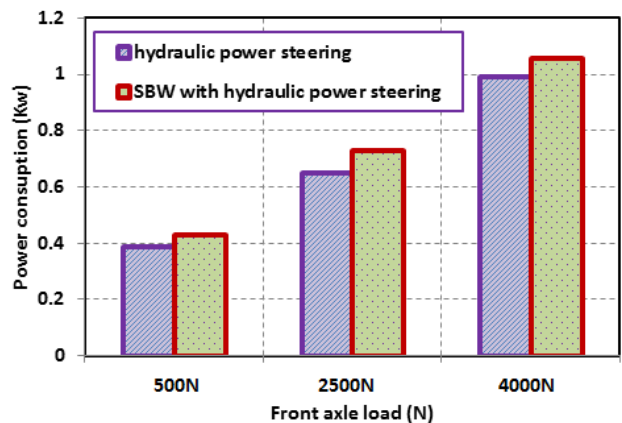


Figure 27. required power of HPS and SBW with HPS VS, front axle load

6. Conclusions and Recommendations

In this paper, we present the one type of a steering system and investigate the dynamic analysis and experimental evaluation of SBW with hydraulic assist

subsystem. The main conclusions from the work carried out are summarized in the following points:

- By applying the different input variable parameters to the SBW system mathematical model, which are SW angle profile and DC motor current at the same value of system moment of inertia, stiffness and damping coefficient that directly affects the SBW system performance.
- Optimal algorithm LQR strategy and PID controller have been considered in this paper for controlling the speed of SBW DC motor actuator. The performance of the two controllers is validated through simulations. The synthesis of an optimal state control LQR to delete oscillations of the steering rack displacement response in closed loop model, and the improved algorithm has a better SBW robust performance.
- The laboratory apparatus and experimental methodology capability established in this work could be utilized for evaluating the SBW of the on road vehicle. Moreover, the state of the vehicle frontal load condition could be identified accurately. From the results of the experiment, it is clear to demonstrate that a hydraulic assist subsystem is beneficial in an SBW application for assisting DC motor actuator and alleviating the oscillatory response and improving the steering feel in real time domain.
- Finally, these results declare that the SBW with hydraulic assist subsystem is meet the requirements and suitable to likely increases weight on a vehicle of frontal axle, where the overload torque coverage by hydraulic assist and while maintaining make steering more convenient with guarantee the driver has the best steering feel in the variety of operating conditions.

References

[1] A.Badawy, J. Zuraski, F. Bolourchi and A. Chandy (1999), "Modeling and analysis of an electric power steering system," SAE Technical Paper, 1999-01-0399.

[2] Parmar M. and Hung JY.(2004) "A sensorless optimal control system for an automotive electric power assist steering system" IEEE Transactions on Industrial Electronics, 2004,51(2): 290-298.

[3] Camuffo I., Caviasso G., Pascali, L. and Pesce, M. (2002) "Simulation Tools and Evaluation Criteria for Steering Wheel Feel Improvement of an Electric Power Steering System," SAE Technical Paper 2002-01-1593, 2002.

[4] Dawane M. (2010) "Modeling and analysis of power steering system", International Journal of Electric and Hybrid Vehicles, vol. 2, no. 3, pp. 211-21, 2010.

[5] Zeng Qun (2012) "The Design of Power Assisted Characteristic Curve for Electric Power Steering System" Journal of Convergence Information Technology (JCIT), Volume 7, Number 17, Sep 2012.

[6] Zaremba A.T., Liubakka M.K. and Stuntz R.M. (1998)" Control and Steering Feel issues in the design of an electric power steering system". IEEE, Proceedings of American Control Conference; pp. 36-40.

[7] D. Odenthal, T. Bunte, H. Heitzer and C. Eiker (2002) "How to make steer-by-wire feel like power steering". In Proc. 15th IFAC World Congress on Automatic Control, Barcelona, Spain, 2002.

[8] Se-Wook OH, Ho-Chol, Seok-Chan and et al. (2004) "The Design of a Controller for the Steer-by-Wire System", JSME international Journal Series C, Vol.47, No3, 2004, pp. 38-44.

[9] Huipeng C., Qiqi Yu, Lingjun Z. and Guojin C. (2013) "Study on Steering by Wire Controller Based on Improved H ∞ Algorithm"

IJCSI International Journal of Computer Science Issues, Vol. 10, Issue 1, No 2, January 2013 ISSN (Print): 1694-0784.

[10] Asai, S., Kuroyanagi, H., Takeuchi, S., Takahashi, T. and et al., (2004) "Development of a Steer-by-Wire System with Force Feedback Using a Disturbance Observer," SAE Technical Paper 2004-01-1100, 2004.

[11] Oh S., Yun S., Chae H., Jang S. and et al, (2003) "The development of an advanced control method for the SBW system to improve the vehicle maneuverability and stability", Proceedings of SAE International Congress and Exhibition, 2003-01-0578, 2003.

[12] Cortesao R. and Bajcinca N.(2004) "Model-matching control for steer-by-wire vehicles with under-actuated structure", Intelligent Robots and Systems, Proceedings. 2004 IEEE/RSJ International Conference, vol. 8, pp. 1148-1153, 1966.

[13] Amberkar S., Bolourchi F., Demerly J., and Millsap S., (2004) "A Control System Methodology for Steer by Wire Systems," SAE Technical Paper 2004-01-1106, 2004.

[14] Ronnberg, M. (2004) "Implementation of a Control System for a Scaled Series Hybrid Electric Vehicle" Master of Science Thesis, Department of Machine and Vehicle Systems Chalmers University of Technology Gothenburg, Sweden, September.

[15] A.Marouf, C. Sentouh, M. Djemai and P. Pudlo (2011) "Control of an Electric Power Assisted Steering System Using Reference Model"2011 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC), Orlando, FL, USA.

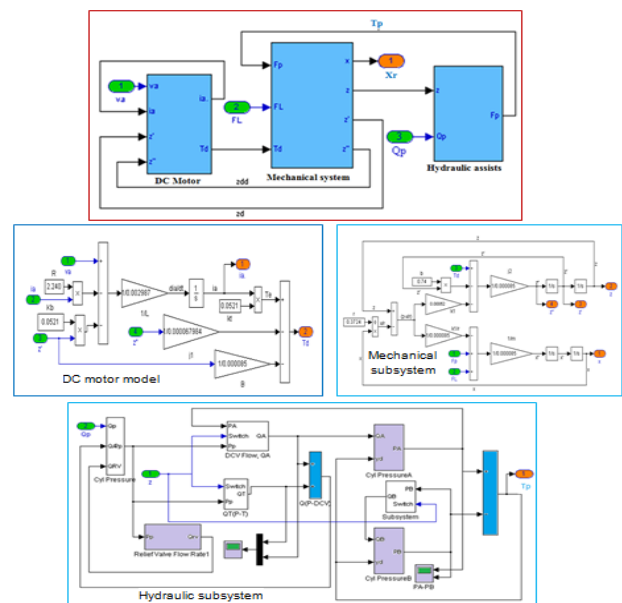
[16] Huang, G. and Lee S. (2008) "PC-based PID speed control in DC motor" International Conference on Audio, Language and Image Processing, ICALIP 2008, pp. 400-407.

[17] Shwetha G. N., H. R. Ramesh, and S. R. Shankapal (2013) "Modeling, simulation and implementation of a proportional-derivative controlled column-type EPS" International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463, Vol. 2 Issue 9, September-2013, and pp: 10-19.

[18] Ankit R., and Pratibha T. (2013) "Optimal Tuning of Fractional Order PID Controller for DC Motor Speed Control Using Particle Swarm Optimization" International Journal of Soft Computing and Engineering (IJSC) ISSN: 2231-2307, Volume-3, Issue-2, pp 150-157.

Appendix

Appendix: 1 SBW model subsystems simlink



Appendix 2: Nomenclature

List of acronyms:

AFS	Active front steering
DAC	Data acquisition card
DC	Direct current
ECU	Electrical control unit

EPHS	Electrically powered hydraulic steering
EPS	Electric Power Steering
HP	Horse power
SW	Steering wheel
VW	Vehicle wheel
SBW	Steering by wire

List of symbols:

θ_{vw}	: Angular displacement of vehicle wheel(rad).
θ_p	:Angular displacement of pinion(rad).
$\theta_{sc.h}$: Angular displacement of steering column in SW (rad).
$\theta_{sc.r}$: Angular displacement of steering column in VW (rad).
θ_{sw}	:Angular displacement of steering wheel(rad).
ρ	:Density of fluid (kg/m^3)
A_s	: Spool cross section area (m^2)
b_{eq}	:Equivalent viscous damping respect to steering column($\text{N.m}/(\text{rad}/\text{sec})$).
$B_{sc.r}$:Viscous damping at steering column in VW ($\text{N.m}/(\text{rad}/\text{sec})$).
b_r	:Viscous damping of steering rack($\text{N.m}/(\text{rad}/\text{sec})$).
$B_{sc.h}$:Viscous damping of steering column in SW ($\text{N.m}/(\text{rad}/\text{sec})$).
B_{sw}	: Viscous damping of steering wheel ($\text{Nm}/(\text{rad}/\text{sec})$).
CF_r	: Coulomb friction breakout force on steering rack (N)
CA	:Coefficient of discharge and area of valve opening
J_{eq}	:Equivalent moment of inertia respect with steering column(kg.m^2).

J_{vw}	:Moment of inertia of vehicle wheel and rotation mass about steering displacement(kg.m^2).
J_m	:Moment of inertia of DC motor (kg.m^2).
J_{sw}	:Moment of inertia of steering wheel (kg.m^2).
i_1	:Motor gear box gear ratio.
m_r	:Mass of steering rack (kg).
K_b	:Motor back electromagnetic force constant ($\text{V}/(\text{rad}/\text{sec})$).
K_{eq}	:Equivalent rotational stiffness respect to steering column($\text{N.m}/\text{rad}$).
K_d	:Derivative gain.
K_p	:Proportional gain.
K_I	:Integral gain
K_{sc}	:Steering column rotational stiffness ($\text{N.m}/\text{rad}$).
K_{SL}	:Steering rotational stiffness due to linkage and bushing ($\text{N.m}/\text{rad}$).
K_{sw}	:Steering wheel rotational stiffness (Nm/rad).
K_t	:Motor torque constant ($\text{N.m}/\text{A}$).
K_{TR}	:Torsion bar rotational stiffness ($\text{N.m}/\text{rad}$).
L_a	:Motor armature winding inductance (H).
N_L	:Steering linkage rate (m).
Q_t	:Pump discharge flow rate (m^3/s).
Q_{fr}	:Flow rate into return port (m^3/s)
Q_i	:Flow rate through orifice (m^3/s)
r_a	:Motor armature winding resistance(Ω).
r_p	:Radius of pinion(m).
Tr	:Torque at steering rack linkage(N.m).
T_m	:Motor torque with respect to steering column (N.m).
T_p	:Torque at pinion (N.m).
T_{sw}	:Torque at steering wheel(N-m).
x_r	:Translational displacement of the rack(m).
v	:Motor input voltage(V).