Electro-Hydraulic Power Steering System for an Automobile

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Abstract

Automobile steering system is used to steer a car to the desired path. Electro-Hydraulic Power Steering System can be found in Ford, Volkswagen, Audi, and Nissan cars. In this paper, an energy-saving electro-hydraulic power steering system for an automobile is presented. The proposed technique has reduced energy consumption and improved the steering feel as compared to the conventional. In the proposed technique, the use of a DC motor gear pump instead of engine engine-driven pump ensures a good steering feel at high speed and good steering portability at low speed. The adaptive Fuzzy-PID controller reaches the motor speed set point faster than PID hence improving the steering feel compared to the PID controller. The electric and hydraulic power consumption data are collected at 5.23 Nm steering torque. The experimental results show that the hydraulic pressure developed in the hydraulic chamber is proportional to motor speed. In conventional controllers, the power consumption increases with car speed but in manual, PID, and Fuzzy-PID controller, the power consumption decreases with car speed compared to conventional. The electric power consumption of conventional, manual, PID, and Fuzzy-PID controllers at 0-120 km/h vehicle speeds are 5544 W, 1979.8 W, 1915.2 W, and 2017.9 W, respectively. The hydraulic power consumption of conventional, manual, PID, and Fuzzy-PID controllers at 0-120 km/h vehicle speeds are 1192.8 W, 349.85 W, 335.72 W, and 361.19 W, respectively.

Keywords
Power steering, Motor speed control, Fuzzy-PID controller, Energy savings, and Steering system.

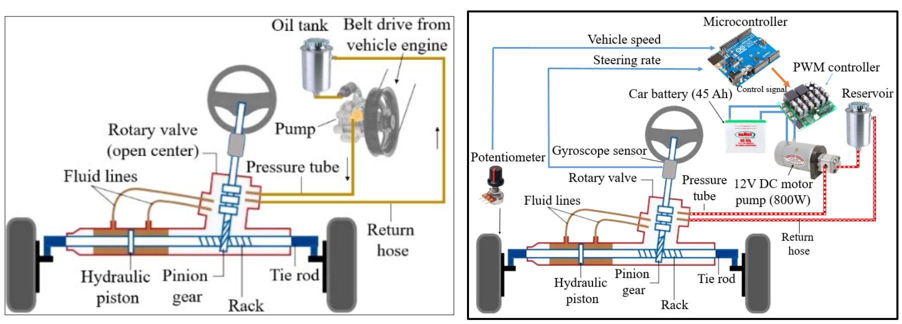
1. Introduction
The automobile steering system is most important as it controls the vehicle's direction according to the driver's steering wheel direction. It ensures the vehicle's safety and controllability. If the steering system is not properly designed, the steering may be pulled to one side. The known problems of the steering system are excessive steering effort or excessive steering wheel free-play (Diagnosis). The two basic types of steering systems are manual or mechanical steering systems and power steering systems. In a conventional power steering system, as shown in Figure 1(a), a vane pump directly driven from the vehicle engine delivers hydraulic power to steer the front wheels of the automobile easily (Heinz 2002). Plenty of automobiles with conventional power steering systems are still on the road. However in a conventional power steering system, the amount of hydraulic power generated is proportional to engine speed. There are two problems in conventional power steering systems. 1) At low speed, the vane pump's discharge rate is minimal. Therefore, the developed hydraulic pressure is minimal which is not sufficient to move the front wheels comfortably. 2) At high speed, the pump discharge rate increases, and the hydraulic power as well as power consumption increases. In conventional power steering system, driver feels very light steering at high speed, and difficult steering at low speed. The assist effort is not suitable as preferred (Tang et al. 2002).

But driving comfort means high-speed steering feel and low-speed steering portability, which plays an important role on driver's behavior (Mammar and Koenig 2002). By replacing the engine driven pump with a controllable motor pump, the steering effort can be changed according to vehicle speed. Figure 1 (b), shows the structure of the proposed electro-hydraulic power steering system, where a DC motor gear pump is used replacing the engine driven pump. This system consists of steering system, hydraulic system, and electric system. The steering system consists of a steering wheel, a steering column, a rack and pinion, road wheels, and mechanical linkages (Barua et al. 2022). The hydraulic system consists of a DC motor pump, pressure tube, return hoses, fluid lines, and rotary valve. The electric system consists of sensing and control parts. The sensing part consists of electrical sensors which are IR speed sensor, gyroscope sensor and potentiometer as vehicle speed regulator. The control part consists of an Arduino microcontroller and a PWM controller. The red dotted lines show the hydraulic connection and the plain blue lines show the electrical connection. A hydraulic system is a non-linear system. So, a fuzzy-PID controller is used to control the speed of the DC motor. It can properly handle non-linear behavior (Nahian et al. 2014). The hydraulic pressure can be changed according to vehicle speed and steering rate to provide the driver a good steering feel. Also, energy can be saved by operating the motor at minimum and high car speeds. Typically, a 12V battery is used as a power source to drive the electric motor. So, EHPS is suitable for small and medium-sized vehicles. Researchers have tested the driver's preferred steering torque in different speed conditions for better steering feeling.

The first motor-driven power steering (MDPS) was developed for the Subaru XT in Japan, where a 12V motor is installed to drive the vane pump instead of the vehicle engine (Iga et al. 1988). A controller decreases the motor speed to decrease power assist at high speed and provides a natural steering sensation. The motor takes power from the alternator, which becomes a load on the engine. But the test result shows that MDPS consumes less fuel as compared to conventional power steering.

Similar Electro-Hydraulic power systems can be found in Nissan, Audi, Volkswagen, Mazda, and Peugeot cars. In Nissan, the system provides a natural and smooth feel, improving fuel economy. A power pack generates hydraulic power. A bi-directional motor pump is used to supply hydraulic power according to the steering wheel's right and left turns (Nissan). In Audi, a demand-controlled vane pump is used to supply the fluid needed for a given operating point. An electric pump unit is used in the Audi A2-2005 Model car. In Volkswagen cars, similar steering systems are fitted, supplied by Koyo and TRW. The Volkswagen Polo Model has an electric power steering pump for variable assistance. The Mazda 3 has a similar electric motor power steering pump unit. The Peugeot 308 model has an electric power steering pump.

The above-mentioned technique has reduced energy consumption, but a tuned motor speed map can reduce the energy consumption even more. Also, an overshoot-free and fast motor speed control can provide a good steering feel for the driver at different vehicle speeds. Therefore, in this research, a tuned motor speed map with an overshoot-free motor speed controller is implemented on the electro-hydraulic power steering system for good steering feel and energy-saving operation at different vehicle speeds. Also, the power consumption and motor speed response are compared among different controllers.



(a) (b)

Figure 1. Structure of the (a) conventional and (b) proposed electro-hydraulic power steering system

3. Mathematical Modeling of DC Motor

The actuator in EHPS systems is the DC motor. It directly provides rotary motion and drives the gear pump. Back emf (Back Emf) is the generator output of a motor, and so it is proportional to the motor's angular velocity. It is zero when the motor is first turned on, meaning that the coil receives the full driving voltage and the motor draws maximum current when it is on but not turning. The equation (1) represents the DC brush motor's transfer function (Shamshiri 2009).

Voltage (V) is the input of the DC brush motor's transfer function and angular rotation rate ($\dot{\theta}$) is the output.

$$\frac{\dot{\theta}}{V} = \frac{kt}{jLs^2 + (jR + bL)s + bR + keKt} \qquad (1)$$

The armature resistance is calculated from experimental data. As the motor is 12V, 800W. So, the armature resistance is R=V/I = 12/66 = 0.26 ohm.
Moment of inertia of the motor, J = 0.000117 kg.m^2/s^2.
Damping ratio of the mechanical system, b = 0.00147 Nms
Electromotive force constant (Steering torque = 5.23 Nm), kt = 0.033 Nm/Amp
Electromotive force constant (Steering torque = 0 Nm), kt = 0.039 Nm/Amp
Motor constant, ke = 0.009 Nm/Amp
Electric inductance, L = 0.117 H

After putting the parameter's values in equation (1) the open loop transfer function of the DC motor can be written as,

$$= \frac{0.033}{0.0000137s^2 + 0.0002s + 0.00068}$$

3. Controller Design

There are four controllers used in this experiment which are conventional, manual, PID, and Fuzzy-PID controllers. In conventional, the DC motor is controlled with a PWM controller. The PWM controller has a potentiometer knob to regulate the motor speed. In the manual controller, the PWM controller is modified and connected to Arduino. The motor speed is controlled manually with a potentiometer knob. In the PID controller, the Arduino microcontroller is programmed with the PID control method to reach the motor speed setpoint automatically. In the Fuzzy-PID controller, the PID controller's proportional, integral, and derivative values are tuned according to motor speed to reach the motor speed set point faster than PID.

3.1 PID Controller

A proportional integral derivative (PID) controller is a control loop feedback controller. A PID controller calculates an error. The error is the difference between a process variable and set point. The controller tries to minimize the error by adjusting the proportional, integral, and derivative values, denoted P, I, and D. As shown in Figure 3, the proportional term (P) corresponds to proportional control. The integral term (I) is proportional to the time integral of the error. The derivative term (D) is proportional to the time derivative of the control error. This term predicts future errors. The formula of the PID controller is: (Astrom and Haggalund 1995). The PID values of the simulation are: K_p = 0.1; K_i = 0.08; K_d = 0.09. The PID values of the experiment are: K_p = 0.1; K_i = 1; K_d = 0.09

$$\text{PID (t)} = K_p \text{ (e (t))} + K_i\int(\text{e(t)})\text{dt} + K_d \text{ (} d(e(t))\ dt \text{)}$$

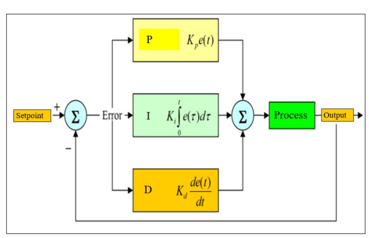


Figure 2. PID controller

3.2 Fuzzy-PID Experimental Procedure:

Membership Function

Seven triangular membership functions are selected. The maximum motor speed is 90 RPS so the range is selected between -90 and 90. There is one input variable and two output variables. The input variable is speed error, and the output variables are kp and ki. In Figure 3, the membership functions of input variables are enl, enm, ens, eze, eps, epm, and epl. The membership functions of output variables(K_p, K_i) are sm, md, and bg, and the range is 1 to 5.

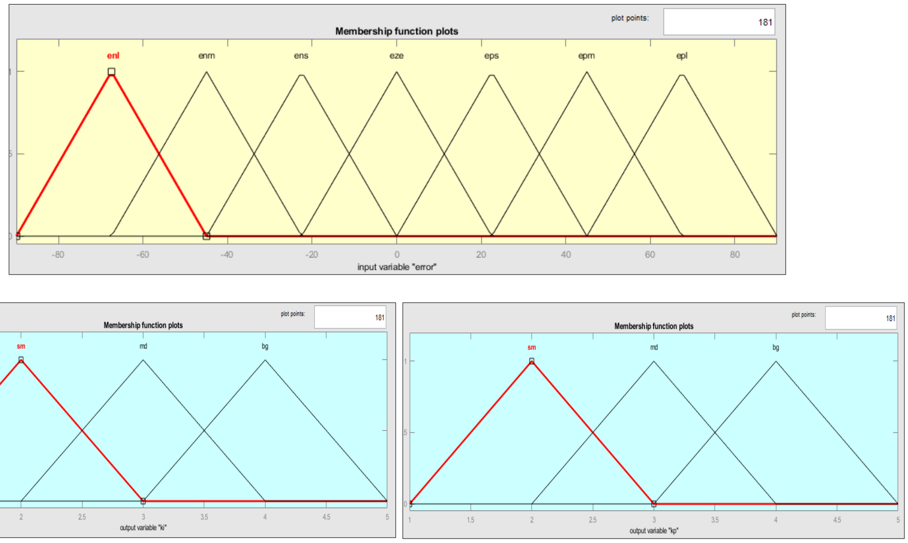


Figure 3. Membership functions of input and output variable

Surface View of K_p and K_i, and Fuzzy Rules

The surface view is a 2D curve as there is only one input variable. Figure 4 shows the surface view of K_p and K_i according to speed error. At different errors, the PID values K_p and K_i change to go to the set point first.

As there is one input variable and 7 membership functions, we have set 7 rules. The rules are:

Rule 1: If error is epl then K_p is sm and K_i is sm.
Rule 2: If error is epm, then K_p is md and K_i is md.
Rule 3: If error is eps, then K_p is bg and K_i is bg.
Rule 4: If error is ens, then K_p is bg and K_i is bg.
Rule 5: If error is enm, then K_p is md and K_i is md.
Rule 6: If error is enl, then K_p is md and K_i is md.
Rule 7: If error is eze, then K_p is sm and K_i is sm.

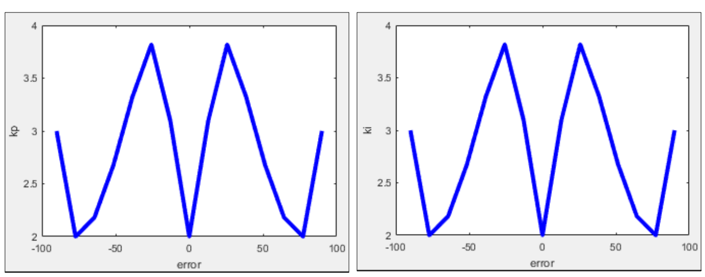


Figure 4. Surface view of K_p and K_i and Fuzzy Rules

3.3 Simulation of Motor Speed Control with PID

Voltage is the input of the DC brush motor's transfer function and angular rotation rate (rad/sec) is the output. The speed of the DC brush motor is controlled via the PID control method. Figure 5 shows the Matlab block diagram of motor speed control with PID.

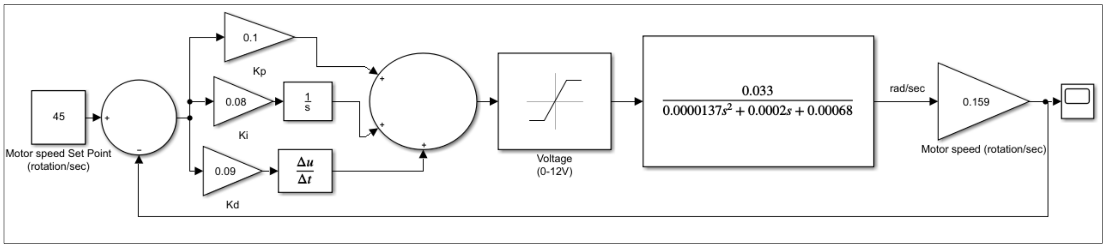


Figure 5. Matlab simulink block diagram of motor speed control with PID

4.1 Experimental Test Bench

Figure 6 shows the schematic diagram of the EHPS system. In the rotary valve, for the car's right turn, orifice A1 opens and A2 closes. So, fluid delivered by pump passes through orifice A1 and creates a force on the right piston. Fluid from left chamber passes to the reservoir through other orifice A1. For left turn, orifice A1 closes and A2 opens. So, fluid delivered by the pump passes through orifice A2 and creates force on the left piston. Fluid from the right chamber passes to the reservoir through other orifice A2. The force acts on piston depends on the developed hydraulic pressure in the chamber. The steering feel and energy consumption are related to hydraulic pressure. And the hydraulic pressure is proportional to motor speed. So, the fuzzy-PID controller is used to control the motor speed.

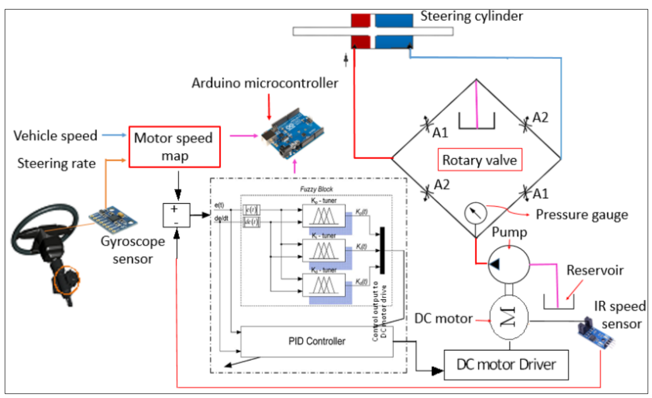


Figure 6. Schematic diagram of the electro-hydraulic power steering system

The motor speed map is a motor speed vs vehicle speed graph (Chang-gao 2011). The steering rate is an input of the motor speed map for activating obstacle avoidance feature. This does not effect on the motor speed unless the vehicle speed is steering rate is greater than 300 deg/sec. Figure 7 shows structure of the EHPS system. We have setup the car's front wheel steering system using Ackerman steering. We have used forklift DC hydraulic power pack unit (12V, 800W), which includes a drive motor, hydraulic pump and reservoir. A pressure gauge is installed in pressure line to measure the developed pressure.

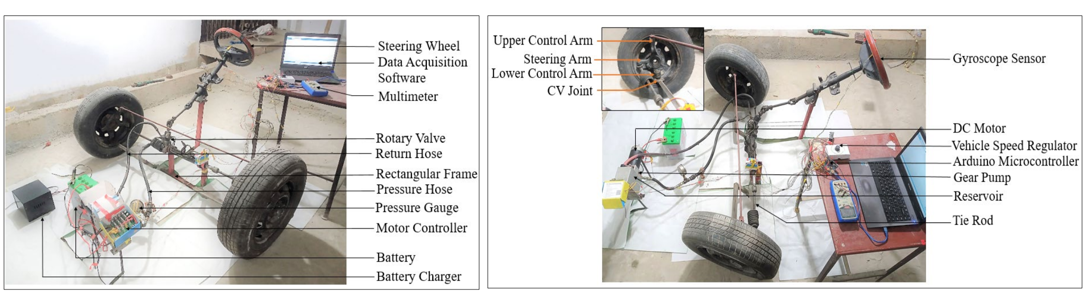


Figure 7. Structure of experiment electro-hydraulic power steering system

The hydraulic lines are opened from vane pump and connected to the hydraulic power pack unit. We have used a "weight scale" to measure the steering torque. In our experiments, at 5.23 Nm torque, the developed hydraulic pressure is maximum. So at 5.23 Nm, the opening area of orifice is maximum. All the data shown in this paper is at 5.23 Nm torque. The 12 battery is always connected to the charger during experiment. The power consumption and steering feel of conventional power steering depends on vane pump speed. The vane pump consumes power from vehicle engine.

4.2 Data Acquisition Procedure

Figure 8 represents the flowchart of control program and data acquisition procedures. The data acquisition procedures are as follows:

(1) First, the steering torque is selected and applied to the steering wheel.
(2) The Arduino UNO has been connected to the computer. As the controller gets power from the computer, the control loop starts to work.
(3) It reads data from sensors and displays it on a serial monitor. The data have been collected in Excel Data Streamer.
(4) According to the motor speed map, the controller gives a motor speed set point, and the fuzzy-PID controller reaches the motor speed at the set point.
(5) To measure hydraulic power, the hydraulic pressure has been measured from the pressure gauge, and to measure electric power, the electric current has been measured through the shunt resistor. Voltage is measured from the output PWM signal and the pump discharge rate is calculated from the motor speed. The pump discharge rate is 2 lpm (max) at 5340 rpm (89 RPS) motor speed.

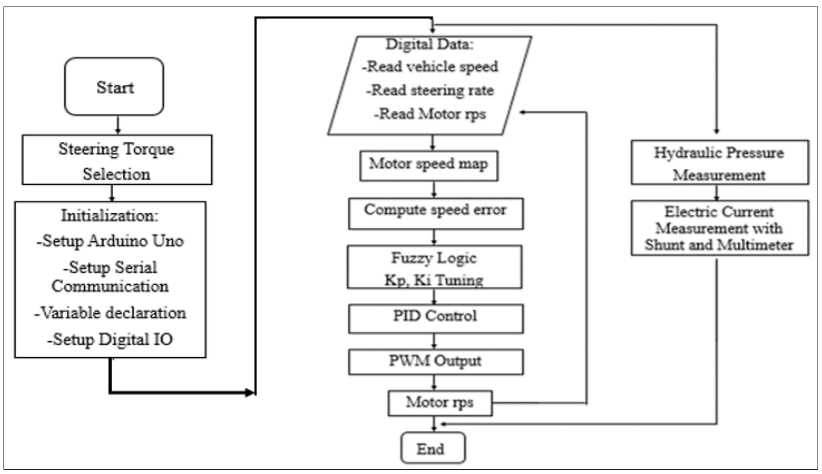


Figure 8. Flowchart of the control program and data acquisition procedure of energy-saving electro hydraulic power steering system.

4.3 Motor Speed Map

The engine rotational speed is linear to vehicle speed (Bera and Wędrychowicz 2016). The speed of the vane pump is proportional to engine speed. For conventional power steering, the vane pump speed is proportional to the engine speed. Figure 9 shows the vehicle speed vs. motor speed curve. At 0 km/h, the rotational speed of the motor is 15 RPS, and it increases according to vehicle speed. At 20 km/h, the motor speed is 90 RPS. The equation of vehicle speed and motor speed for conventional power steering is y = 0.625x+15.

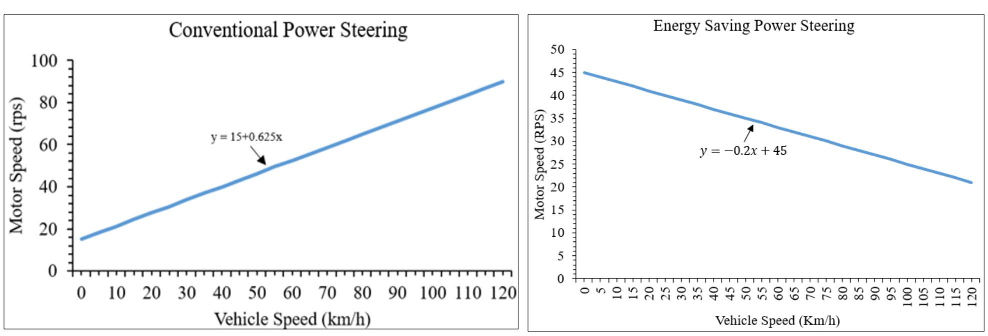


Figure 9. Conventional and Energy saving Power Steering: Vehicle speed vs Motor Speed

For energy-saving operation, the preferred motor speed is tested earlier (Chang-gao). At 0 km/h vehicle speed, the motor speed is set at 45 RPS, and with increasing vehicle speed, the motor speed decreases. At 120 km/h vehicle speed, the speed is set at 21 RPS. The maximum motor speed is 90 RPS (100%). At 0 km/h vehicle speed, motor speed is 50% (45 RPS). At 20 km/h vehicle speed, motor speed is 40%, 36 RPS. At 40km/h, motor speed is 37.5%, 33.75 RPS. At 60 km/h, motor speed is 32.5%, 29.25 RPS. At 80km/h, motor speed is 31.2%, 28.08 RPS. At 100 km/h, the motor speed is 30%, 27 RPS. Vehicle speed is between 0-120 km/h. Figure 9 shows the relation between vehicle speed and motor speed for energy-saving operation, and the equation is $y = -0.2x + 45$ when the steering rate is less than 300 deg/sec.

5. Results

5.1 Motor Speed Control: PID Simulation and Experimental

Figure 10 shows the speed response of Matlab simulation and experiment via PID controller. The current motor speed is 22 RPS and the set point of PID controller is 45 RPS. The simulation is run for 10 seconds and experimental data are taken for 10 seconds. The Matlab step info data shows that the settling time in simulation is 7.53 and experiment is 8.65, and the difference is very small. There is an overshoot in simulation. The R-square value of the experimental data is 0.9909, which indicates a good correlation. The experimental data follows the second-order polynomial equation. The simulation curve tends to follow the experimental curve.

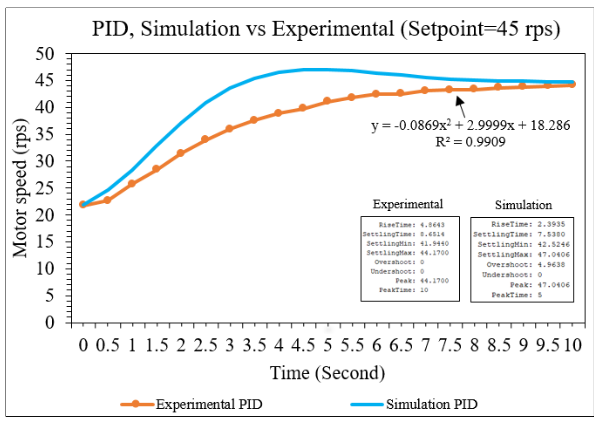
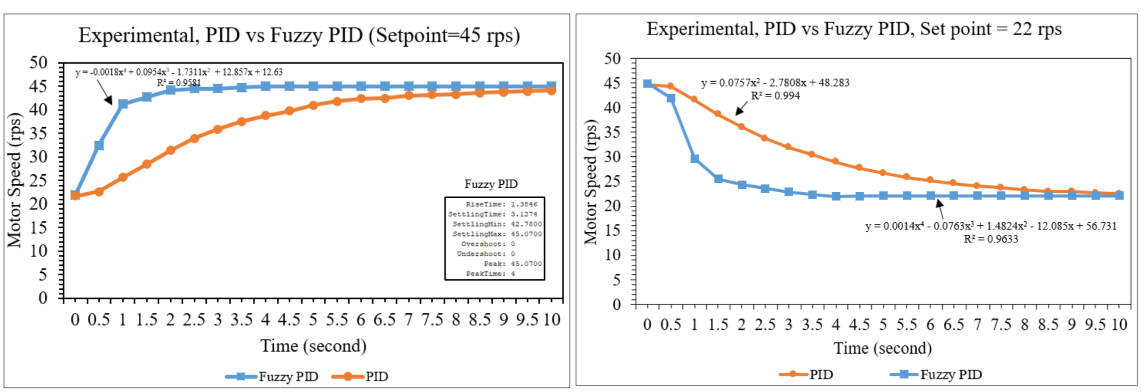


Figure 10. PID motor speed control of Matlab simulation, and experimental

5.2 Motor Speed Control: Experimental PID and Fuzzy PID

Figure 11 shows the experimental speed response curve of PID and fuzzy-PID. The current speed of the motor is 22 RPS, and the set point is 45 RPS. The rise time of the PID is 4.86 sec, and the fuzzy-PID is 1.38 sec.



(a) (b)

Figure 11. PID and Fuzzy-PID speed response for motor speed setpoint 45 RPS (a) and 22 RPS (b).

Comparing the PID and fuzzy-PID controller, the fuzzy-PID controller reduces the settling time and rising time significantly. The fuzzy-PID speed-time characteristics curve follows the 4th-order polynomial equation. The current motor speed is now 45 RPS and the set point has been changed to 22 RPS. For 22 RPS set points, comparing the PID with fuzzy-PID, the fuzzy-PID control reaches the set point quickly. The speed-time characteristics curve of fuzzy-PID follows the 4^{th}-order polynomial equation and the PID follows the 2^{nd}-order polynomial equation.

5.3 ELECTRIC POWER COMPARISON OF DIFFERENT CONTROLLERS AT TORQUE=5.23 NM (SETPOINT=45 AND 22 RPS)

The voltage and current of conventional, manual, PID, and Fuzzy-PID controllers at Torque=5.23 Nm for setpoint 45 RPS are shown in Figure 12 (A, B). In the conventional controller, the voltage is constant because to reach the setpoint from 22 RPS, the time required is negligible, as the conventional controller is a PWM controller. As the voltage is constant, the current is constant. For manual control, we have modified the conventional PWM controller and connected it to the Arduino. Now, the conventional PWM output signal is off, and the Arduino PWM control signal is given to control the motor speed. So, in manual control, the voltage takes about 1.5 seconds to go saturation, as the Arduino is loaded with programs. For PID control, it takes 8.5 seconds to go saturation. For Fuzzy-PID control, it takes about 3 seconds to reach the saturation point. The current curve follows the voltage curve in all controllers. For setpoint 22 RPS, the voltage and current curves are now different, as shown in Figure 12 (D, E).

Now, the current motor speed is 45 RPS, and the setpoint is 22 RPS. For conventional, the voltage at 45 RPS is about 5.4 volts. But to reach saturation (3.17 V), the time required is negligible. So the voltage curve is constant, and at Time = 0 sec, the voltage value is 3.17. For manual, PID, and Fuzzy-PID, the voltage gradually decreases, and when motor speed reaches the setpoint, the voltage is constant. The current curve follows the voltage curve. The electric power consumption of the controllers is the product of voltage and current. For setpoint = 45 RPS, as shown in Figure 12 (C), for conventional, the power is a constant curve as voltage and current are constant. For manual, PID, and Fuzzy-PID controller, the power consumption gradually increases as voltage and current increase, and when voltage and current are constant, then the power is constant. For setpoint 22 RPS, as shown in Figure 12 (F), the power consumption is constant for conventional. For the other three controllers, the power consumption gradually decreases. When motor speeds reach the setpoint, power consumption is constant.

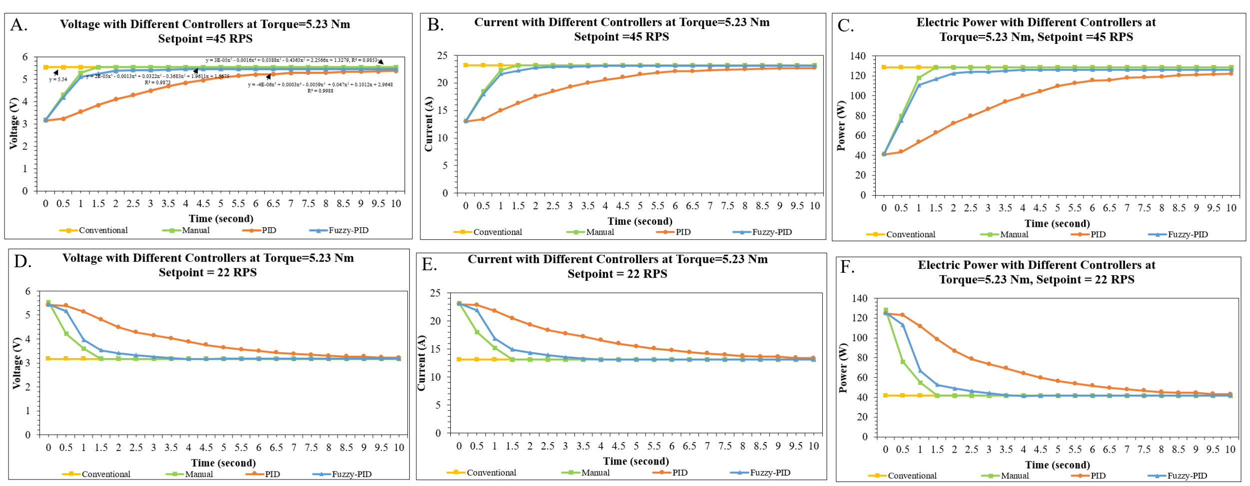


Figure 12. Voltage, current and electric power of different controllers at Torque=5.23 Nm (set point =45, 22 RPS)

5.4 HYDRAULIC POWER COMPARISON OF DIFFERENT CONTROLLERS AT TORQUE=5.23 NM (SETPOINT=45 AND 22 RPS)

The pump discharge rate and hydraulic power of conventional, manual, PID, and Fuzzy-PID at Torque = 5.23 Nm for setpoint 45 RPS are shown in Figure 13 (A, B). For conventional, the pump discharge rate is constant, so the hydraulic pressure is constant. The hydraulic pressure is constant because to reach the setpoint from 22 RPS, the time required is negligible, as the conventional controller is a PWM controller and there is no control method. It takes about 1.5 seconds for manual to reach the saturation of the hydraulic pressure. The time required for PID control to reach the saturation of the hydraulic pressure is 8.5 seconds. For Fuzzy-PID control, it takes about 3 seconds to reach the hydraulic pressure saturation point. For setpoint 22 RPS, the pump discharge rate and hydraulic pressure curves are now different, as shown in Figure 12 (D, E). For conventional, the hydraulic pressure at 45 RPS is about 14.98 bar. But to reach saturation (5.6 bar), the time required is negligible. So the hydraulic pressure curve is a constant curve, and at Time = 0 sec, the hydraulic pressure value is 5.6 bar. For manual, PID, and Fuzzy-PID the hydraulic pressure gradually decreases, and when motor speed reaches the setpoint, the pressure is constant. The hydraulic pressure curve follows the pump discharge rate curve. Figure 12 (C, F) shows the hydraulic power consumption of different controllers. Power consumption is the product of hydraulic pressure and pump discharge rate. For setpoint = 45 RPS, for conventional, the power is a constant curve as pressure and pump discharge rate are constant.

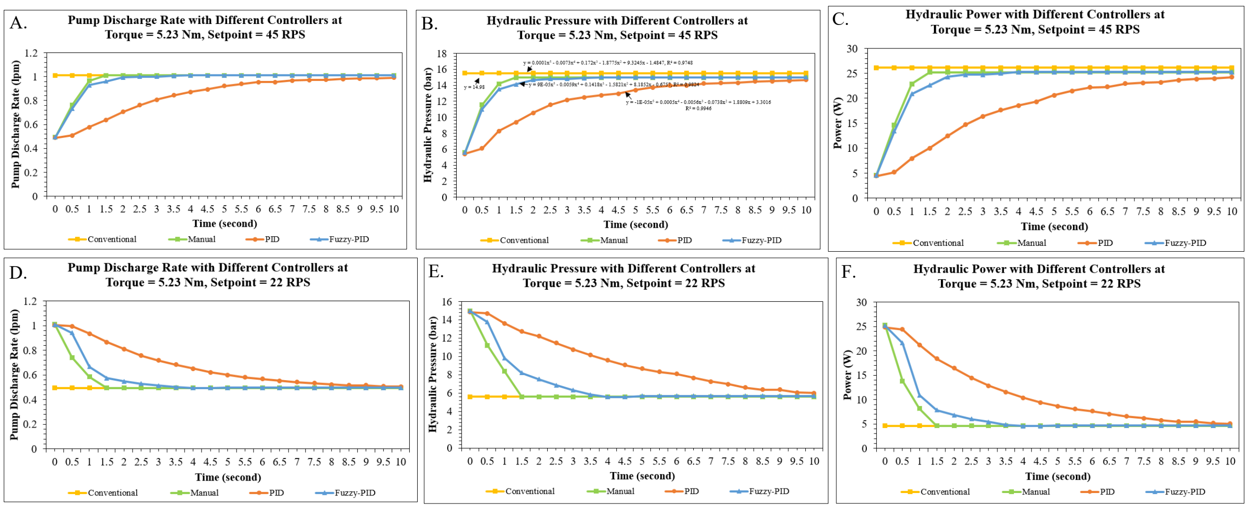


Figure 13. Pump discharge rate, hydraulic pressure and hydraulic power of different controllers at Torque=5.23 Nm (set point =45 and 22 RPS)

For manual, PID, and Fuzzy-PID, the power consumption gradually increases as pressure and pump discharge rate gradually increase, and when pressure and pump discharge rate are constant, then the power is constant. For 22 RPS, the hydraulic power consumption is constant for conventional. For manual, PID, and Fuzzy-PID, the power consumption gradually decreases. When motor speeds reach the setpoint, power consumption is constant.

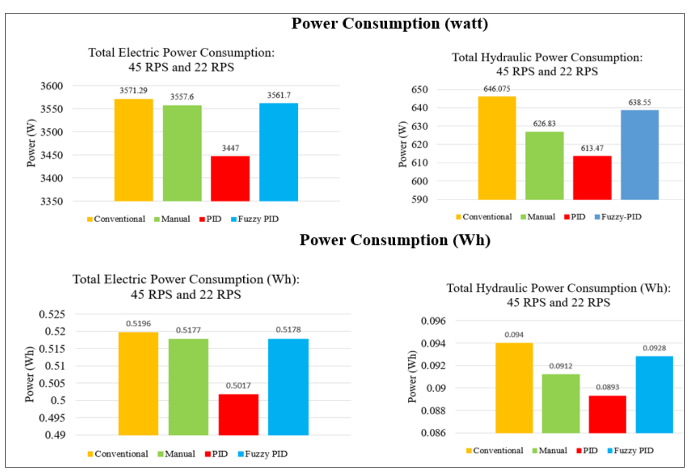


Figure 14. Total electric and hydraulic power consumption of different controllers at torque=5.23 Nm (set point =45 and 22 RPS)

Figure 14 shows the power consumption in watts and watt-hours. The total electric power in watts is the sum of the power consumption of 45 RPS and 22 RPS. The total hydraulic power in watts is the sum of the power consumption of 45 RPS and 22 RPS. The power consumption in watt-hours is calculated using Matlab. First, power consumption is calculated in watt-sec by integrating the power consumption from 0 to 10 sec. Then, by dividing the result by 3600, watt-sec has been converted to watt-hour. The energy consumption of the conventional is the highest and PID is the lowest.

5.5 Electric Power and Hydraulic Power Comparison at Different Vehicle Speed of Different Controllers at Torque=5.23 nm

Figure 15 (A, B) show the voltage and current of conventional, manual, PID, and Fuzzy-PID at different vehicle speeds at Torque=5.23 Nm. In conventional control, with an increase in vehicle speed, the motor speed increases. Therefore, the voltage and current increase with vehicle speed. For manual, PID, and Fuzzy-PID the voltage and current decrease with vehicle speed. The voltage and current for manual, PID, and Fuzzy-PID controllers are almost the same.

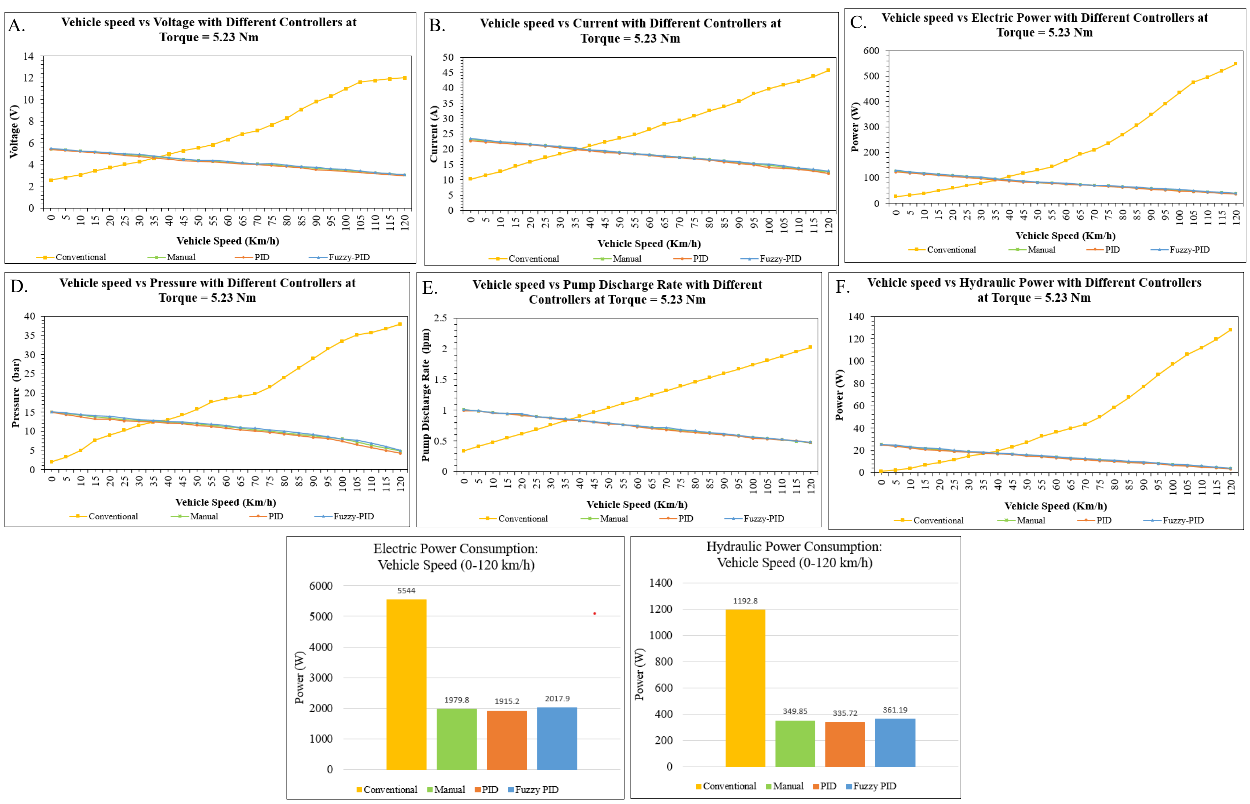


Figure 15. Voltage, current, electric power and hydraulic power of different controllers according to vehicle speed at Torque=5.23 Nm

Figure 15 (D, E) show the hydraulic pressure and pump discharge rate of conventional, manual, PID, and Fuzzy-PID at different vehicle speeds at Torque=5.23 Nm. In conventional control, the motor speed decreases with vehicle speed. So, hydraulic pressure and pump discharge rate increase. For manual, PID, and Fuzzy-PID, motor speed decreases with vehicle speed. So, the pump discharge rate decreases, and hydraulic pressure decreases.

The pump discharge rate and hydraulic pressure for manual, PID, and Fuzzy-PID controllers are almost the same. Figure 15 (C, F) show the electric power and hydraulic power consumption for conventional, manual, PID, and Fuzzy-PID at different vehicle speeds at Torque=5.23 Nm. In conventional control, voltage, current, hydraulic pressure, and pump discharge rate increase. So, electric and hydraulic power consumption increase with vehicle speed. For manual, PID, and Fuzzy-PID, voltage, current, pump discharge rate, and hydraulic pressure decrease. So, electric and hydraulic power consumption decrease with vehicle speed.

6. Conclusion

Energy-saving by electrification of the power steering system has been presented in this paper. It has been found that the conventional controller motor speed response is faster than other controllers but the power consumption is the highest. The power consumption of the PID controller is the lowest but the motor speed response is the slowest. The manual controller has better speed response than PID and fuzzy-PID but it can't reach the motor speed automatically. The fuzzy-PID is faster than PID and consumes less power than conventional and manual and it can reach the set point automatically at different vehicle speeds. Though it consumes more power than PID it ensures a good steering feel. The steering feel of conventional is not suitable at different vehicle speeds.

References

Astrom, K.J., Hagglund, T., PID controllers, International Society for Measurement and Control, 1995.

Back Emf, Available: https://www.coursehero.com/study-guides/physics/23-6-back-emf/

Barua, R., Islam, M. T., Ahmmad, S. M., Rana, M. M., Sen, R., Rahman, M. M., Conventional power steering system of vehicle and continuous improvement, *International Conference on Mechanical, Industrial and Energy Engineering*, Khulna, Bangladesh, December 22-24, 2022.

Bera, P., Wędrychowicz, D., The influence of number and values of ratios in stepped gearbox on mileage fuel consumption in NEDC test and real traffic, *Scientific Conference on Automotive Vehicles and Combustion Engines*, 2016.

Chang-gao, X., Zhong-ming, Z. and Rong-liang, Realization of Control Algorithmfor Electro-Hydraulic Power Steering System Based on MC9S08AW32 Microcontroller, *International Conference on Informatics, Cybernetics, and Computer Engineering,* pp.581-589, 2011.

Diagnosis based on customer concerns, Available: https://autoedu.info/en/auto-mechanic/steering-systems/diagnosis-based-on-customer-concerns/

H. Heinz, Advanced vehicle technology, 2nd Edition, 2002.

Iga, S., Sakazaki, A. and Shibata, N., Motor Driven Power Steering- For the Maximum Steering Sensation in Every Driving Situation, *International Congress and Exposition*, Detroit, Michigan, SAE Technical Paper Series 880705, 1988.

Mammar, S., Koenig, D., Vehicle Handling Improvement by Active Steering, Vehicle System Dynamics*: International Journal of Vehicle Mechanics and Mobility*, vol 38, no 3, pp. 211-242, 2002.

Nahian, S.A., Truong DQ, Ahn K.K., A self-tuning brain emotional learning–based intelligent controller for trajectory tracking of electrohydraulic actuator, *Journal of Systems and Control Engineering*, vol 228, no 7, pp. 461-475, 2014.

Nisssan, Electro-Hydraulic Power Steering System, Available: https://www.nissanglobal.com/EN/INNOVATION/TECHNOLOGY/ARCHIVE/EHPSS/

Shamshiri, R.R., A Lecture Note on DC Motor Speed Control, Available:https://www.academia.edu/36416803/DC_Motor_Speed_Control, 2009.

Tang, B., Jiang, H., Gong, X., Optimal design of variable assist characteristics of electronically controlled hydraulic power steering system based on simulated annealing particle swarm optimization algorithm, *International Journal of Vehicle*, vol 73, pp. 189, 2017.

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