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Conventional power steering system of vehicle and continuous improvement

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ABSTRACT

Steering system helps a driver to change direction of a vehicle. Driver's physical effort is used in mechanical steering system. Power steering system helps a driver to steer front wheels easily. Conventional power steering uses hydraulic power to reduce steering effort. Techniques are being applied in power steering system for two reasons: to give driver a good steering feel and to reduce vehicle fuel consumption as well as to reduce carbon di-oxide emission. The objective of this paper is to review the applied techniques and to make a comparison between them according to steering feel and energy consumption. Hydraulic actuator model is simulated in MATLAB Simulink to show the power consumption at different flow rates. The developed hydraulic pressure difference between chambers is calculated and multiplying by supply flow rate, power consumption is calculated. Flow rate is the key factor of power steering system which determines the steering feel as well as energy consumption.

Keywords: steering system, hydraulic power steering (HPS), electrohydraulic power steering (EHPS), steering torque, motor speed

1. Introduction

Steering system is an important and sensitive part of vehicle. It allows vehicle to follow driver's desired direction. It ensures vehicle safety and controllability. Mechanical steering system is upgraded to power steering to reduce driver's steering effort.

1.1 Mechanical steering system

Mechanical steering system as shown in Fig.1 consists of steering wheel, steering column, steering gear box, pitman arm (used in recirculating ball steering gear), tie rods, steering arms, road wheels and other mechanical linkages [1].

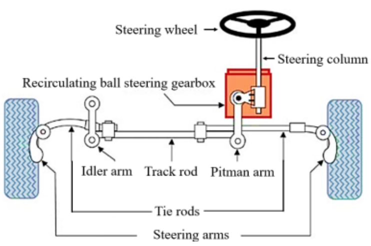

Fig.1 Mechanical steering system.

When driver turns the steering wheel, it turns the steering column. The turning motion acts on steering gear and moves the pitman arm. This movement moves the tie rods and connected steering arms and turns the road wheels.

1.1.1 Steering geometry

Steering geometry is a geometric arrangement of linkages within lengths and angles to provide directional stability. Ackerman, Anti Ackerman and Davis steering

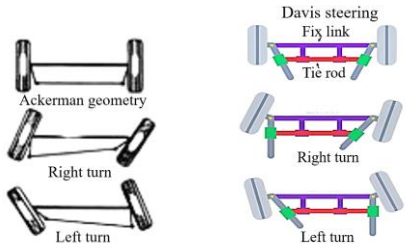

Fig.2 Ackerman and Davis steering geometry.

geometry, shown in Fig.2, are used to follow a curve avoiding sideways slip. Ackerman steering is suitable for low speed maneuvering. For high speed cornering some race cars use anti Ackerman geometry. Davis steering has superior cornering and small turning radius maneuverability. Camber angle, castor angle, king pin inclination, toe in and toe out are the factors of steering geometry [2, 3].

1.1.2 Ackerman steering

If fix link and tie rod lengths are equal in length, steering arms are parallel and both wheels turn at same angle. If tie rod is shorter than fix link like trapezoidal shape, both wheels turn at different angle when steered. This is called Ackerman steering.

$$cotangent(o) - cotangent(i) = \frac{Track}{Base} \qquad (1)$$

As shown in Fig.3, o denotes outer wheel angle and i denotes inner wheel angle. For example, when inner

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wheel lock angle is 30.52°, outer wheel lock angle is 21.89°.

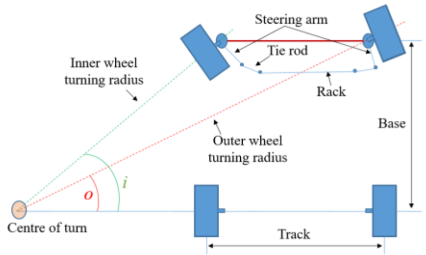

Fig.3 Ackerman steering system.

When, inner wheel turning radius is 2.3 meter, outer wheel turning radius is 3.37 meter.

1.1.3 Steering effort

Friction between tire surface and ground develops steering effort. In front wheel steering system, the front wheels carry vehicle's front axle weight and tire friction load. Steering effort increases with increase of vehicle front axle weight. Calculation shows that for a vehicle with front axle weight of 1100 kg, the required steering effort is 18.8 kg [4]. When vehicle runs at slow speed or during parking, driver feels high steering effort as friction coefficient is high. But the effort decreases with increasing vehicle speed because the friction coefficient decreases with increasing vehicle speed.

1.1.4 Steering gear

The physical effort of driver is amplified by steering gear. Steering gear converts the rotational displacement of steering wheel into linear displacement of rack. Resistance at the road surface is transmitted from road wheels to steering wheel through steering gear. The mostly used steering gears are re-circulating ball type steering gear and rack and pinion steering gear, shown in Fig.4. Re-circulating ball type steering gears are used in heavy vehicles like bus, truck etc [5]. And rack and pinion type steering gears are suitable for light weight vehicles.

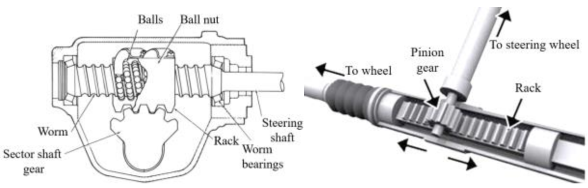

Fig.4 Rack and pinion gear and re-circulating ball steering gear.

Efficient steering gears can reduce steering effort. The ratio of input from the steering wheel (in degrees) to the output on the wheels (in degrees) is defined as steering ratio. There is a relation of steering effort, steering ratio and pinion size. Steering ratio is inversely proportional to pinion size and pinion size is directly proportional to steering effort [3].

1.2 Hydraulic power steering system (HPS)

In order to steer front wheels easily, hydraulic power is used in HPS as a supplementary power. It is a basic hydraulic application of Pascal law. Pascal law states that force is equal to pressure multiplied by piston area [6]. Basic components of HPS system are: hydraulic pump, reservoir, steering rotary valve, torsion bar, pressure tube, pressure relief valve & hydraulic steering gear. 90% of vehicle steering systems are engine driven HPS system.

1.2.1 HPS working principle

A fixed displacement vane pump directly driven by vehicle internal combustion engine, delivers fluid to steering gear to generate hydraulic force. So pump output is proportional to vehicle speed. An open-center rotary valve, directly operated by driver, provides hydraulic force to right or left chamber port, as shown in Fig.6, according to steering wheel turning direction.

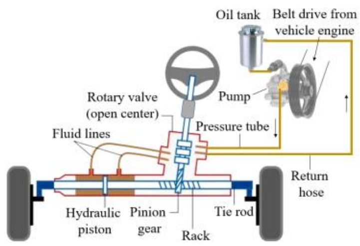

Fig.5 HPS with rack and pinion gear.

Rotary valve [7], is located between input shaft and pinion or worm gear. It consists of a cylindrical inner spool and a surrounding outer cylindrical sleeve. Both spool and sleeve rotate in valve housing, if steering wheel is turned.

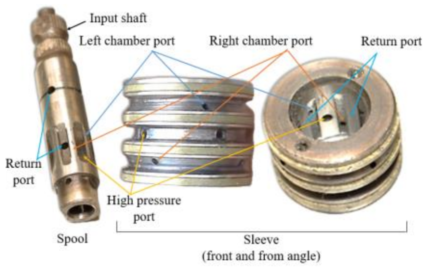

Fig.6 Spool and sleeve.

But a slight relative rotation between them before contacting a stop on pinion or worm gear, activates the rotary valve. Torsion bar, a thin steel rod inside the spool twists, when torque is applied. This twist makes the relative rotation and controls the opening area between spool valve and sleeve. When input shaft contacts the stop on pinion or worm gear, maximum hydraulic assist force is provided. In case of hydraulic power failure, system can be used mechanically as a manual steering with physical effort.

1.2.2 Neutral, left and right turn

In open center rotary valve, when steering wheel stays in neutral position, as shown in Fig.7 A, no relative rotation occurs between spool and sleeve.

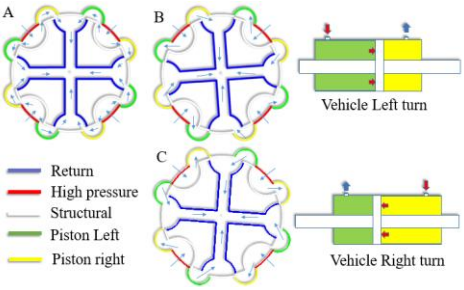

Fig.7 Rotary valve fluid flow diagram.

So, the open orifice area is same and fluid supplied by pump through high pressure line equally passes to piston right and piston left and returns to reservoir through return line. Hence, no pressure difference is developed between right and left chamber and no assistance is provided. For vehicle left turn, when driver turns the steering wheel anti-clockwise, road wheels direction as in Fig.3, torsion bar twists anti-clockwise and relative rotation occurs between spool and sleeve. As shown in Fig.7 B, open orifice area of high pressure to piston left increases and piston left to return or reservoir decreases. And Open orifice area of high pressure to piston right decreases and piston right to return increases. This develops a pressure difference between right and left chamber. Pressure differences multiplied by effective piston area is the hydraulic force that works on piston left to make left turn. Force acts on piston at the same direction as driver turns the steering wheel [8]. Vise-versa happens for vehicle right turn, shown in Fig.7 C. If the steering wheel is turned left or right fully and road wheels reach the stop point, pressure rises high and excessive pressure is released by relief valve.

1.2.3 Boost curve

The more torque is applied to the torsion bar, the more the orifice area is opened. The more the orifice area is opened, the more fluid enters in chamber and thus the pressure is increased. Torque vs pressure (assist power) curve is known as boost curve in HPS system, shown in Fig.8 [9].

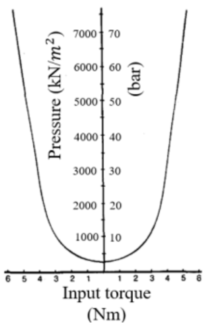

Fig.8 Input torque vs pressure curve.

Table 1 Input torque vs pressure data.

Input torque (Nm)	Pressure (bar)
0	2.5
1	3.5
2	5.7
3	11
4	27
5	57

From Table 1, after 2 Newton-meter (Nm), a small amount of change in Nm changes large amount of pressure. Boost curve can be changed by changing valve geometry or changing torsion bar strength [10]. Conventional power steering has a fixed boost curve.

1.2.4 Limitations of HPS

As described in steering effort section, when vehicle runs at high speed, steering becomes light as friction coefficient decreases. For corrections or lane changing maneuvers, steering force needed is low and power assistance is not necessary. And also, the engine driven pump consumes power, when there is no steering. But during parking or at low vehicle speed, high steering effort is needed due to high friction. But HPS provides less assistance. Conventional power steering system's rotary valve has a fixed boost curve, so this problem exists [11].

2. EHPS

Energy can be saved and steering feel can be improved in EHPS. Analysis shows that HPS needs 1743 W power and EHPS needs 1355 W power [12]. Electrical power source is used in EHPS instead of vehicle engine.

2.1. Energy saving techniques

Energy can be saved by regulating pump's delivery flow rate. There are 5 energy saving techniques described here.

2.1.1 Old technique

This technique was applied to conventional engine driven vehicle with a front weight of 720 kg [13]. Vane pump is disconnected from vehicle engine.

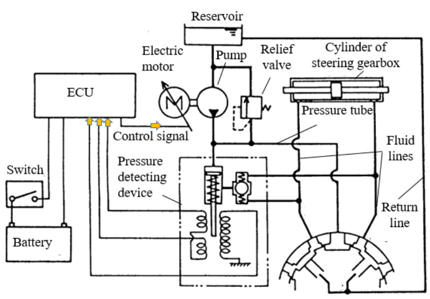

Fig.9 Motor driven and closed loop rotary valve EHPS.

A motor-pump was used to supply fluid and a closed center rotary valve instead of regular open center was used to change flow direction, shown in Fig.9. In closed center servo valve at neutral position, pressure to right or left chamber orifice is closed. And chambers to reservoir lines are opened. So, at neutral position, fluid can't pass to right or left chamber and fluid can't return to reservoir. Electrical energy consumption has been reduced by operating motor and pump at an extremely low speed at neutral position.

2.1.2 Flow control by changing motor speed

This is the most used energy saving technique. Vane pump is disconnected from vehicle engine also. One way is, external motor can be set in position and vane pump's pulley can be connected to the motor with a belt. Another way is, for compactness and to increase mechanical efficiency, electric motor driven power steering pump unit can be developed and used, as shown in Fig.10. Most of the motors which have been used are brushless and powered by 12V DC voltage. But for electric vehicle and 42V automobile, induction motor and permanent magnet synchronous motor can be used [14, 15]. An ECU controls the speed of the motor as per demand.

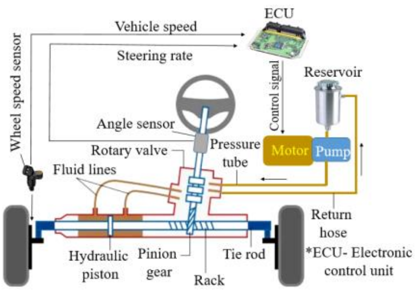

Fig.10 Motor driven and open loop rotary valve EHPS.

In this system, pump flow rate is proportional to the motor speed. In this circuit, the more the motor can be controlled efficiently, the more the energy can be saved. Energy savings also depends on desired steering torque. Obviously, energy has to be saved by fulfilling driver's desired steering torque. For example, desired steering torque is 3.924 Nm at 30 km/h and 90º steering rate [16]. But, if the motor speed is kept less than the desired speed, driver will feel steering torque greater than 3.924.

Table 2 System parameters of EHPS (flow control via motor speed).

Voltage (V)	Power (watt)	Pressure (bar)	Flow rate (l/min)	Motor speed (rpm)	Ref.
12	1202	150	8.3	2200	[17]
42	1500	120	-	4000	[14]
-	1152	80	7	-	[12]

This will decrease energy consumption but will cause bad steering feel. Vehicle speed sensor is used to regulate the motor speed. But using steering rate sensor and angle sensor, energy can be saved further. Because desired steering torque also depends on steering rate and steering angle. System parameters of some experiments are given in Table 2.

2.1.3 Flow control using bypass proportional valve

According to proportional valve connections, this technique has been categorized as Type A and Type B, as shown in Fig. 11. In Type A, an electrohydraulic proportional valve (EHPV) is connected in parallel with an open center rotary valve. A regular engine driven vane pump has been used here. So, pump flow is constant and it works as normal HPS, at low speed. But, at high speed, regulating the flow rate via EHPV, according to vehicle speed and steering rate, it provides good steering feel. In Type B, flow rate is regulated via motor speed and with EHPV [5, 18]. EHPV is connected in series with closed center rotary valve.

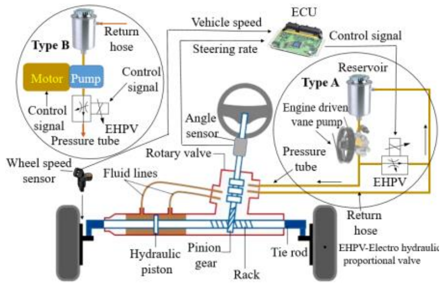

Fig.11 Proportional valve EHPS

This system responses fast because of using accumulator and closed loop rotary valve. And it can save more energy by turning off the motor and providing right amount of assistance as per demand. Only a 500W motor is sufficient for 2700 kg front load vehicle.

2.1.4 Closed loop system

It's very similar to Type B EHPS of section 2.1.3. The difference is that, no rotary valve is used here, shown in Fig.12. Instead two closed center solenoid valves control the pressure of each chamber [19]. By controlling orifice size of both valves, pressure difference is controlled.

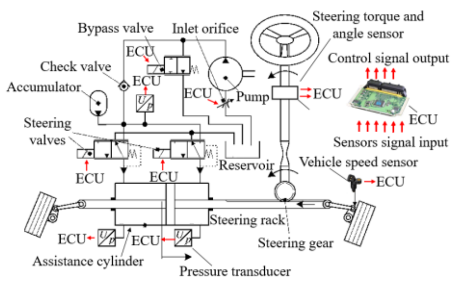

Fig.12 EHPS with no rotary valve

Variable assist force is provided according to vehicle speed and steering torque. Torque sensor has been used here. This is very energy efficient system. It consumes 75% less energy compared to a traditional HPS system. Auto restoration of steering wheel to center is performed. Pump is driven from vehicle combustion engine.

2.1.5 Electro-magnetic clutch system

In this circuit [20], energy is saved by an electromagnetic clutch, installed between vane pump and pulley. The pulley is always driven by a belt from vehicle internal combustion engine. If vehicle speed is greater than 40 Kilo-meter per hour (kmph) and steering angle exceeds 7°, the clutch system connects the pulley to vane pump. And fluid is supplied to the circuit. If vehicle speed is greater than 40 kmph and steering angle is less than 7°, clutch system detects it as power saving mode, as shown in Fig.13, and disconnects vane pump from pulley.

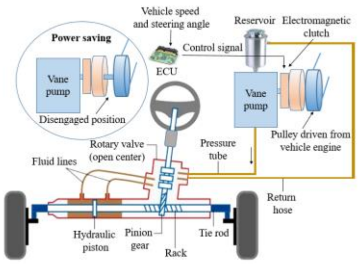

Fig.13 EHPS with electromagnetic clutch

2.2 Steering feel improvement

All the systems described above improve steering feel. The more sensors are added to the system, the more the steering feel is gained. It also depends on efficiently controlling of all electrical equipment's. Steering feel is a function of vehicle speed, steering rate and steering angle. Driver's desirable steering torque is the steering feel. System that can keep the steering torque stable at target value can provide good steering feel. Measuring the force at rack and pinion gear via torque sensor and making a closed loop circuit can give more precise desirable torque. Desirable steering torque can vary from person to person. But by testing desirable torque of different drivers, average value can be found.

3. MATLAB simulation for power consumption

Hydraulic power consumption is the product of pressure and flow rate. Double acting cylinder is used in HPS. The flow rate is delivered by vane pump or motor driven pump. The derivative equation of pressures of left and right chambers are given in Eqn. (2) and Eqn. (3), respectively.

$$\dot{P_a} = \frac{\beta}{V+A_p x_p}(Q_{pump} - A_p \dot{x}_p) \qquad (2)$$

$$\dot{P_b} = \frac{\beta}{V-A_p x_p}(A_p \dot{x}_p) \qquad (3)$$

If vane pump is rated as 2.2 cc per rev, vehicle travels at 20 kmph and engine speed is 2000, vane pump fluid supply will be 4.4 liter. Power consumption model is simulated in MATLAB Simulink for left turn, shown in Fig.15. Steering left turn makes the actuator to move right, Fig. 14. The tie rod load is assumed that total 250 kg. So, the total rack force is 2450 Newton. Power needs to move the load is calculated which is the power consumption during steering.

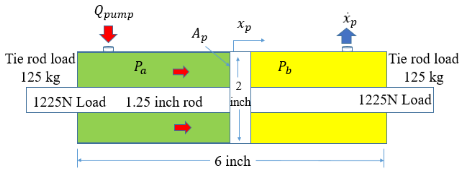

Fig.14 Hydraulic actuator diagram (for steering left turn)

Table 3 Parameters for Hydraulic Actuator.

Parameter	Value
Bulk modulus, β	1.5*10^9 N/m2
Pressure acting area, A_p	pi*(0.01905)^2 m^2
Flow rate, Q_{pump}	4, 6,8,10 litre per minute
Volume, V	Ap*3 inch
Piston position, x_p	6 inch (lock to lock)

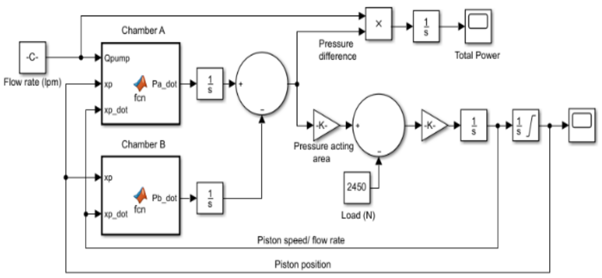

Fig.15 MATLAB Simulink Block Diagram

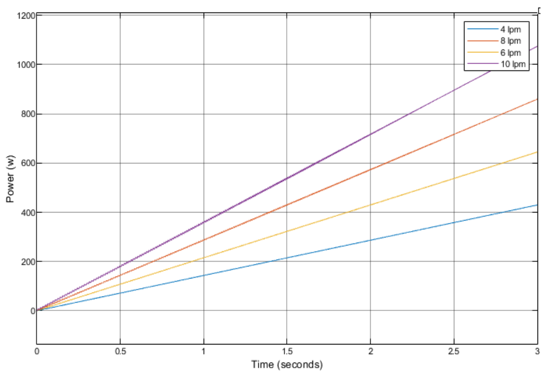

Fig.16 Power consumption at different flow rates

The graph in Fig. 16 shows that, the increase of flow rate increases the power consumption. The power consumption is linear with flow rate. The above five techniques goal is to reduce the flow rate. Result is that, flow rate determines the steering feel and power consumption.

4. Comparison

If we compare the 5 different techniques, we find that closed center valve system performs better than open center system. But the complexity is high. Efficient control of motor can reduce energy consumption and improve steering sensation of 2.1.2. But, in motor driven pump, the power is limited. So, flow rate is limited and the energy consumption is less at low speed. And to switch from off or dormant to working state, motor takes some time to build pressure. Use of the proportional valve and accumulator, Type B of section 2.1.3, can increase system response and can mitigate the delay. Electromagnetic-clutch system is simple and energy efficient and can provide steering feel but there is no motor speed map with respect to vehicle speed.

5. Conclusion

Energy consumption is reduced in HPS by using the above different circuits. Also, steering feel has improved a lot. Electrical components such as motor, solenoid valve, accumulator, electromagnetic clutch and sensors are consuming power. But if we compare consumed electrical power with consumed power from vehicle combustion engine, we will see that energy consumption is less in flow control techniques. Because electric power can be controlled. Flow control by changing motor speed is simple and effective method.

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NOMENCLATURE

o : outer wheel angle, degree º
i : inner wheel angle, degree º
$\dot{P_a}$: derivative of chamber A pressure, pa
$\dot{P_b}$: derivative of chamber B pressure, pa
β : bulk modulus, N/m^2
V : fluid volume of half cylinder, m^3
Q_{pump}: flow rate, m^3/s
A_p : piston pressure acting area, m^2
x_p : piston position, m
$\dot{x_p}$: piston velocity, m/s