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Modeling, simulation and implementation of a proportional-derivative controlled column-type EPS

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Abstract: Automobile market has faced a lot of innovation in the steering systems. Due to their own disadvantages the manual steering and hydraulic steering faced and with the development of the microprocessor, power electronics and high power motor technologies, Electric power steering systems which uses an Electric motor came to use a few years ago. Due to the road wheel load, there will be fluctuations in the Steering wheel torque and therefore a change in the assistance motor torque. A column-type Electric power steering system is considered and it requires a proper torque boost and high frequency fluctuation has to be avoided. Though pure proportional control gives proper torque boost it fails to avoid high frequency fluctuation because of insufficient damping. Hence Proportional-Derivative control is used to give proper damping. Thus Proportional-Derivative control is needed for a CEPS to generate desired static torque boost and avoid the high frequency fluctuation.

The control of the assistance motor is done taking into consideration the vehicle speed and the applied steering wheel torque. As seen, the model of the EPAS system is considered in partial for the implementation purpose in this project, i.e., only the control of the assistance motor is implemented, as the whole system implementation is complicated as the application is a real-time system.

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1. INTRODUCTION

The steering system is the mechanism which has the purpose to turn the guidelines wheels, making that the driver guide his car along the desirable trajectory. A steering system is designed to enable the driver to control the traveled path of a vehicle. The steering system must give the operator some form of information which would allow him/her to feel about the load condition that the tires of the vehicle experiences. This feedback is very important for the driver to easily control the direction.

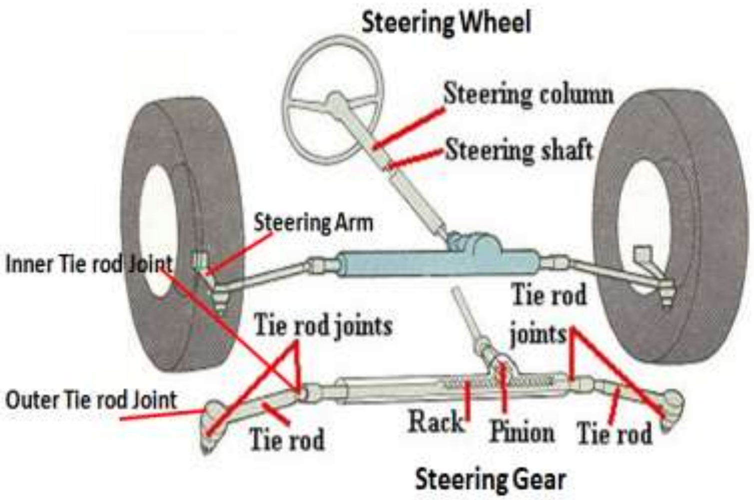


Fig. 1 Steering System

1.1 Types of Steering Systems

1. Rack and Pinion Steering
2. Parallelogram Steering(Pitman Arm Steering, Recirculating Ball Lead Screw)

1.1.1 Rack and Pinion Steering

Rack and Pinion Steering is used in most of small and intermediate size cars and minivans. It has reduced weight and fewer parts helps to allow vehicles to meet fuel economy and emission standards.

1.1.2 Parallelogram Steering

Parallelogram Steering is used on large cars and trucks because of the weight and number of parts. Each joint in this system must allow for rotation and changes in angles, and therefore has a significant amount of "free play" or movement.

2. LITERATURE SURVEY

Steering is the term applied to the collection of components, linkages, etc. which will allow a vessel (ship, boat) or vehicle (car, motorcycle, bicycle) to follow the desired course. An exception is the case of rail transport by which rail tracks combined together with rail road switches (and also known as 'points' in British English) provide the steering function.

EPS systems are called Electric power steering system, EPAS (electric power assisted steering system) and MDPS (motor driven power steering system) according to manufacturers but the basic organizations and principles are similar. EPS system has electric control unit (ECU) to calculate optimum assist torque based upon torque sensor and vehicle speed sensor, to output the calculation results to power unit. And power unit drive a motor according to signal issued by the control unit.

2.1 Types of EPAS

EPAS systems can be categorized as Fig. according to the location of power assist, i.e. column-type EPS, pinion-type EPS, rack-type EPS and electrically powered hydraulic steering system (EPHS).

Fig. 2: Types of EPAS

2.1.1 Column-type EPS

Column-type electric power system is generally applied to midget-class cars which have a small-capacity engine (660cc), where fuel efficiency is important and it can save space in engine room layout because motor and reduction gear are incorporated and installed in interior. The power assist unit, controller and torque sensor are attached to the steering column. This system is compact and easy to mount on the vehicle. This power assist system can be applied to fixed steering columns, tilt-type steering columns and other column types.

2.1.2 Pinion-Assist type EPS

In Pinion-Assist type EPS, the power assist unit is attached to the steering gear's pinion shaft. The power assist unit is outside the vehicle's passenger compartment, allowing assist torque to be increased greatly without raising interior noise. Combined with a variable-ratio steering gear, this system can suffice with a compact motor and offer superior handling characteristics.

2.1.3 Rack -Assist type EPS

In Rack-Assist type EPS, the power assist unit is attached to the steering gear rack. The power assist unit can be located freely on the rack, allowing great flexibility in layout design. The power assist unit's high reduction gear ratio enables very low inertia and superior driving feeling.

2.1.4 Electric power Driven Hydraulic Assist type EPS

In Electric power Driven Hydraulic Assist type EPS This system offers both high power and a smooth steering feeling. Application on a wide range of vehicles from compact cars to trucks is possible. Electronic control by computer enables performance corresponding to vehicle speed and an ideal steering feeling.

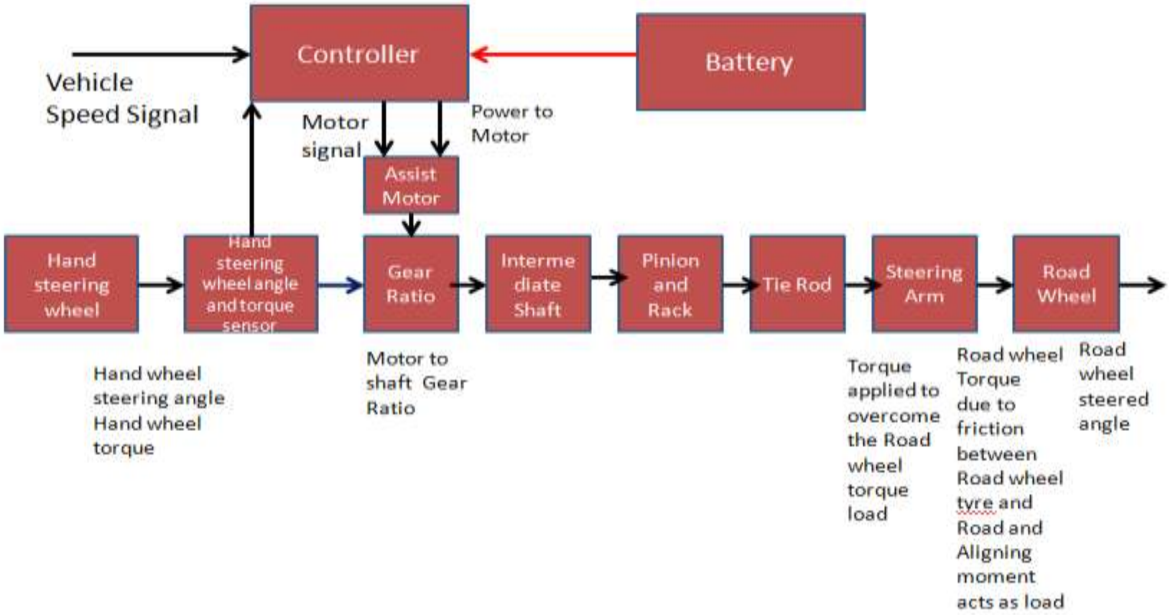


Fig. 3: Motor Assisted-Rack and Pinion Steering System-CEPS

2.2 The Objectives of the Project:

- Modelling of a Column-type Electric Power Steering System
- According to the Model Equations, block diagram is built and simulated using MATLAB-SIMULINK.
- Implementation for Control of the Assistance motor torque according to the Steering wheel Input torque taking five different speeds into consideration as per the derived control maps.

3. MODELLING OF CEPS

Column-type electric power steering (CEPS) system is generally applied to midget-class cars which have a small-capacity engine (660cc), where fuel efficiency is important and it can save space in engine room layout because motor and reduction gear are incorporated and installed in interior. In this project, CEPS system is modeled in consideration of non-linear parameter such as Coulomb friction. A proportional-plus-derivative control can generate desired static torque boost and avoid fluctuation. A pure proportional control can't satisfy both requirements. So it needs both derivative and proportional term of torque sensor in the EPS control to generate proper torque boost and to eliminate fluctuation.

Typical CEPS system is shown in the figure and the major components are a torque sensor, a motor, a reduction gear and a ECU.

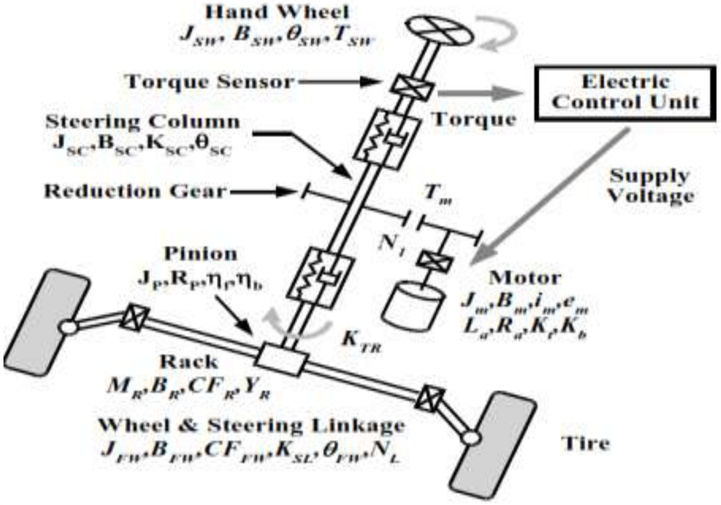


Fig. 4: Typical CEPS system model

3.1 Nomenclature

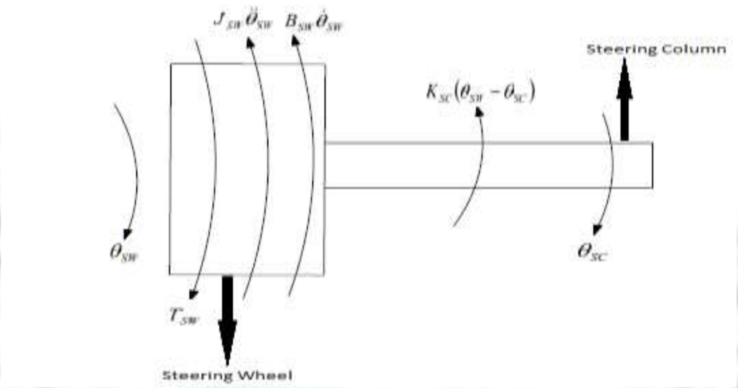
B1: Equivalent viscous damping respect to steering column including damping of motor and steering column(N-m/(rad/sec)).
Beq : Equivalent viscous damping respect to steering column(N-m/(rad/sec)).
BFW : Viscous damping at steering linkage bushing(N-m/(rad/sec)).
Bm : Viscous damping of motor(N-m/(rad/sec)).
BR : Viscous damping of steering rack(N-m/(rad/sec)).
Bsc : Viscous damping of steering column(N-m/(rad/sec)).
Bsw: Viscous damping of steering wheel(N-m/(rad/sec)).
CFFW: Coulomb friction breakout force on road wheel(N).
CF R: Coulomb friction breakout force on steering rack(N).
em : Motor input voltage(V).
Jeq : Equivalent moment of inertia respect with steeringcolumn(kg-m2).
JFW : Moment of inertia of road wheel and rotation mass about steering displacement (kg-m2).
JSC : Moment of inertia of steering column(kg-m2).
JSW : Moment of inertia of steering wheel(kg-m2).
M R: Mass of steering rack(kg).
Kb : Motor back electromagnetic force constant (V/(rad/sec)).
Keq : Equivalent rotational stiffness respect to steering column(N-m/rad).
Kd : Derivative gain.
Kp : Proportional gain.
Ksc: Steering column rotational stiffness(N-m/rad).
KSL : Steering rotational stiffness due to linkage and bushing(N-m/rad).
KSW : Steering wheel rotational stiffness(N-m/rad).
K t : Motor torque constant(N-m/A).
K TR: Torsion bar rotational stiffness(N-m/rad).
L a: Motor armature winding inductance(H).
N1: Motor gear box gear ratio.
N L : Steering linkage rate(m).
R a: Motor armature winding resistance(Ω).
R P: Radius of pinion(m).
T ext: External torque at road wheel(N-m).
T KL: Torque at steering linkage(N-m).
T m: Motor torque with respect to steering column(N-m).
T P: Torque at pinion(N-m).
Tsw: Torque at steering wheel(N-m).
Y R: Translational displacement of the rack(m).

η B: Gear ratio efficiency of backward torque transmission.
η F: Gear ratio efficiency of forward torque transmission.
θ FW: Angular displacement of road wheel (rad).
θp : Angular displacement of pinion (rad).
θsc : Angular displacement of steering column (rad).
θsw : Angular displacement of steering wheel (rad).

The transmissibility of CEPS system from road wheel load to driver's hand wheel can be investigated by calculating driver's hand wheel torque while fixing hand wheel. The equation of hand wheel is like Eqn. (1), and displacement, velocity and acceleration of hand wheel is zero by assuming fixed hand wheel that is $\Theta sw = \dot{\Theta} sw = \ddot{\Theta} sw = 0$.

3.2 Steering Wheel Equation

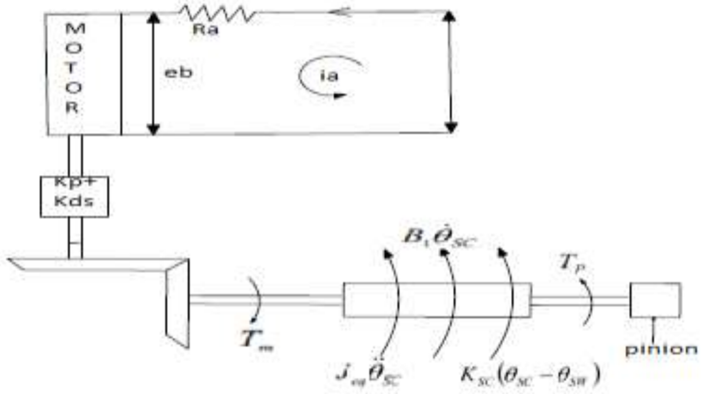
The steering wheel attached to the steering column and the factors acting on them are shown in the below figure,



$J sw\ddot{\Theta} sw + Bsw\dot{\Theta} sw + Ksc(\Theta sw - \Theta sc) = Tsw$……………………Eqn.1
Jsw : Moment of inertia of steering wheel(kg-m2).
Bsw: Viscous damping of steering wheel(N-m/(rad/sec)).
Ksc: Steering column rotational stiffness(N-m/rad).
Tsw: Torque at steering wheel(N-m).
θsc : Angular displacement of steering column(rad).
θsw : Angular displacement of steering wheel(rad).

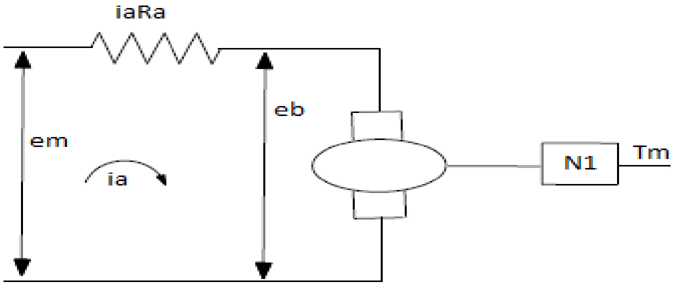
3.3 Steering Column Equation

By assuming dc servomotor is used, motor torque with respect to steering column while neglecting inductance of motor,



$Jeq\ddot{\Theta} sc + B1\dot{\Theta} sc + Ksc(\Theta sc - \Theta sw) = Tm - Tp$…………………..Eqn.2

3.4 Motor Torque Equation



$$\mathrm{em} = \mathrm{ia.Ra} + \mathrm{eb}$$
$$\mathrm{eb} = \mathrm{Kb}.\dot{\theta}\mathrm{sc.N1}$$
$$\mathrm{Tm} = \mathrm{Kt.ia.N1}$$

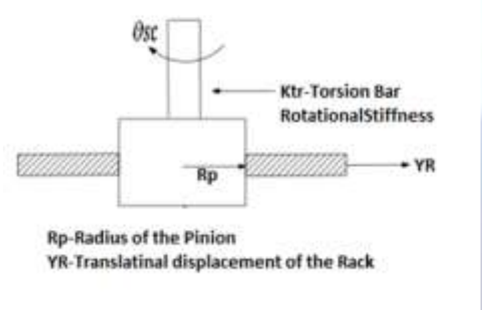
Substituting eb and Tm values in em equation and simplifying them we get,

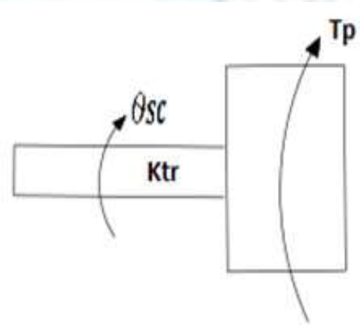
$$\mathrm{em} = \mathrm{ia.Ra} + \mathrm{Kb}.\dot{\theta}\mathrm{sc.N1}$$
$$\mathrm{em} = \frac{\mathrm{Tm}}{\mathrm{Kt.N1}}.\mathrm{Ra} + \mathrm{Kb}.\dot{\theta}\mathrm{sc.N1}$$
$$= \frac{\mathrm{Tm.Ra} + \mathrm{Kt.N1.Kb}.\dot{\theta}\mathrm{sc.N1}}{\mathrm{Kt.N1}}$$
$$\mathrm{em.Kt.N1} = \mathrm{Tm.Ra} + \mathrm{Kt.N1.Kb}.\dot{\theta}\mathrm{sc.N1}$$
$$\mathrm{Tm} = \frac{\mathrm{Kt.N1}}{\mathrm{Ra}}\left[\mathrm{em} - \mathrm{Kb}.\dot{\theta}\mathrm{sc.N1}\right]\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathrm{Eqn.3}$$

For Proportional -Derivative Control,

$$\mathrm{em} = -\mathrm{Kp}(\theta\mathrm{sc} - \theta\mathrm{sw}) - \mathrm{Kd}(\dot{\theta}\mathrm{sc} - \dot{\theta}\mathrm{sw})\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathrm{Eqn.4}$$

3.5 Pinion torque equation





$$\mathrm{Tp} = \mathrm{Ktr}\theta\mathrm{sc} - \mathrm{Ktr}\theta\mathrm{p}$$
$$\mathrm{Tp} = \mathrm{Ktr}\theta\mathrm{sc} - \mathrm{Ktr}\frac{\mathrm{YR}}{\mathrm{Rp}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathrm{Eqn.5}$$

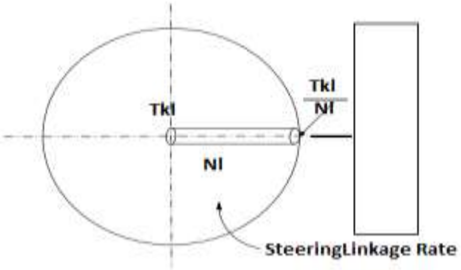
SubstitutingEqn.3 and Eqn.5 into Eqn.2 we get,

$$\mathrm{Jeq}\ddot{\theta}\mathrm{sc} + \mathrm{B1}\dot{\theta}\mathrm{sc} + \mathrm{Ksc}(\theta\mathrm{sc} - \theta\mathrm{sw}) = \frac{\mathrm{N1Kt}}{\mathrm{Ra}}[\{-\mathrm{Kp}(\theta\mathrm{sc} - \theta\mathrm{sw}) - \mathrm{Kd}\left(\dot{\theta}\mathrm{sc} - \dot{\theta}\mathrm{sw}\right)\}$$
$$-\mathrm{Kb.N1}.\dot{\theta}\mathrm{sc}] - \mathrm{Ktr}(\theta\mathrm{sc} - \frac{\mathrm{YR}}{\mathrm{Rp}})$$
$$\mathrm{Jeq}.\ddot{\theta}\mathrm{sc} + \mathrm{Beq}.\dot{\theta}\mathrm{sc} + \mathrm{Keq}.\theta\mathrm{sc} = \mathrm{Ktr}\frac{\mathrm{YR}}{\mathrm{Rp}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathrm{Eqn.6}$$

Where,

$$\mathrm{Jeq} = \mathrm{Jsc} + \mathrm{N1}^2.\mathrm{Jm}$$
$$\mathrm{Beq} = \mathrm{Bsc} + \mathrm{N1.Bm} + \frac{\mathrm{N1.Kt.N1.Kb}}{\mathrm{Ra}} + \frac{\mathrm{N1.Kt}}{\mathrm{Ra}}\mathrm{Kd}$$
$$\mathrm{Keq} = \mathrm{Ksc} + \mathrm{Ktr} + \frac{\mathrm{N1.Kt}}{\mathrm{Ra}}\mathrm{Kp}$$

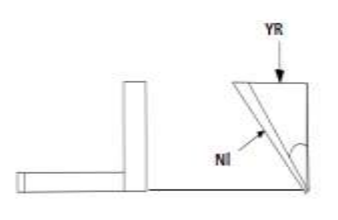
3.6 Rack Equation



$$MR.\ddot{Y}R + BR.\dot{Y}R + CFR * \operatorname{sgn}(\dot{Y}R) = \eta F.\frac{T_P}{R_P} - \eta B.\frac{Tkl}{Nl}\text{.............Eqn.7}$$

$\eta F.\frac{T_P}{R_P}$: Force exerted by the pinion on rack.
ηf : Forward transmission

3.7 Road Wheel Equation



$$Jfw.\ddot{\theta}fw + Bfw.\dot{\theta}fw + CFfw * \operatorname{sgn}(\dot{\theta}fw) = Tkl + Text\text{...........Eqn.8}$$
$$Tkl = Ksl\left(\frac{YR}{Nl} - \theta fw\right)\text{...Eqn.9}$$
$\frac{YR}{Nl}$: Angular displacement of the wheel caused by Steering arm

4. SIMULINK BLOCK DIAGRAM AND IMPLEMENTATION

The frequency response by using Bode diagram in cases of without control (dotted line), proportion control (dash dotted line) and proportion-plus-derivative control (solid line). Proportion gain, Kp =20000 was chosen to make the transmissibility at low frequency range equal to one fifth of without control. In proportion control, the gain of Bode diagram shows larger value around ω=1200rad/sec , which is undesirable and it makes high frequency torque disturbance to pass through. For the system with proportion control, drivers will be felt the high frequency oscillation when road wheel endures an impact. The problems in proportion control can be eliminated by using proportion-plus-derivative control. An appropriate proportion gain (Kp =20000) to achieve desired steering assistance level and derivative gain (Kd=300) to reach required damping ratio is choosen. The transmissibility of a system with proportion-plus-derivative control (solid line) is shown in figure 5 and it realizes proper torque boost in low frequency range, and decrease gain in high frequency range.

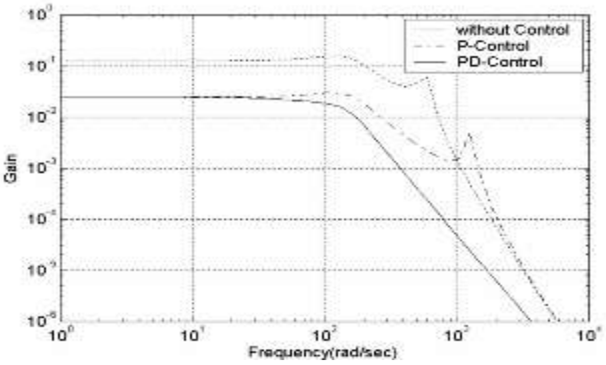


Fig. 5: Frequency response by using Bode diagram

By using Eqs. (1)-(9), driver’s hand wheel torque Tsw in Eq. (1) is calculated from the input of road wheel load Text in Eq. (8). Text is a unit impulse torque at road wheel. MatLab Ver.7.5.0 Simulink was used for simulation and block diagram of Simulink is shown in Fig. 6 and physical parameters are shown in Table.

Each equation is built using Simulink. The physical parameters are substituted as per the values mentioned in the table and the block diagram is executed.

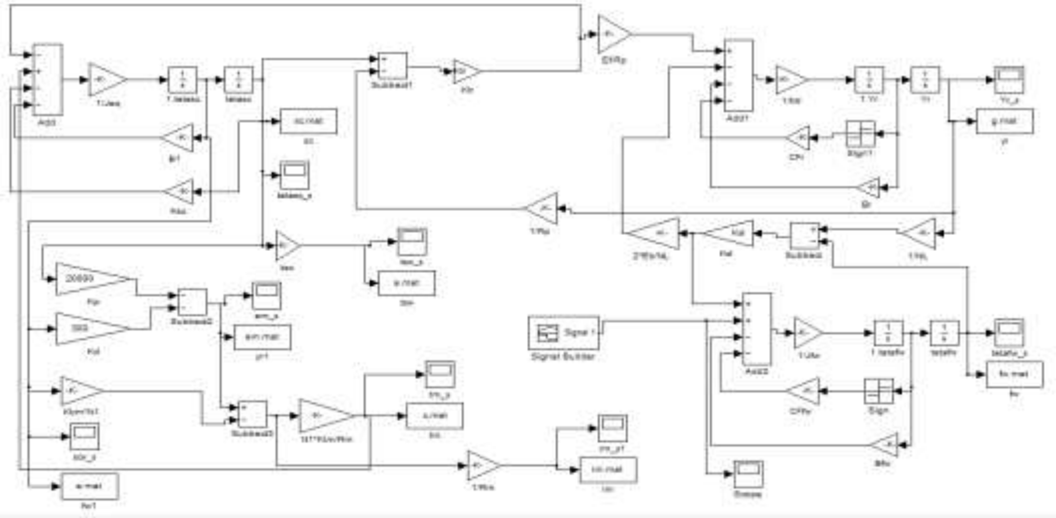


Fig. 6: Simulink Block Diagram by using the modeling equations

4.1 Physical Parameters of CEPS system

BFW = 88.128 N-m/(rad/sec)
BR = 88.128 N-m/(rad/sec)
Bsw = 0.36042 N-m/(rad/sec)
CF R = 0.4 N
Jsw = 0.03444 kg-m^2
Kb = 0.0533 V/(rad/sec)
KSL = 14878 N-m/rad
Kt = 0.0533 N-m/A
La = 0.001 H
NL = 0.11816 m
RP = 0.007367 m
ηF = 0.985

Bm = 0.05 N-m/(rad/sec)
Bsc = 0.36042 N-m/(rad/sec)
CF FW = 0.04 N
Jsc = 0.03444 kg-m^2
MR = 2.0 kg
Ksc = 42057 N-m/rad
KSW = 42057 N-m/rad
KTR = 42057 N-m/rad
N1 = 49/3
Ra =0.1 Ω
ηB = 0.985

4.2 Steering Characteristics

Steering Wheel torque as a function of Lateral Acceleration is as shown in the figure.

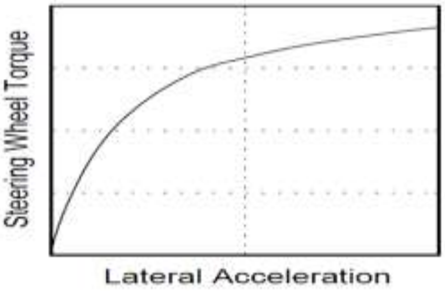


Fig. 7: Steering Characteristics

Steering assistance is controlled via a map referred to as the control maps, which is stored permanently in the program memory of Power Steering Control Module. Maps are activated in the factory depending on requirements (e.g. vehicle weight).

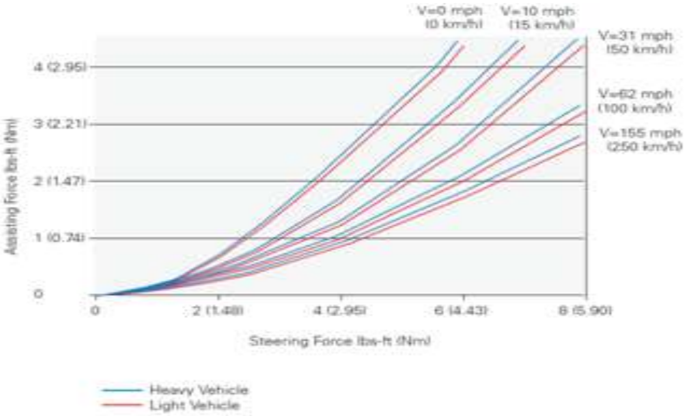


Fig. 8: Control Map

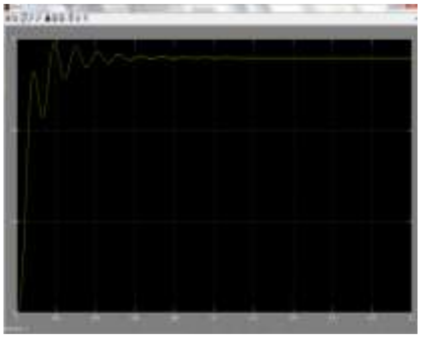
The implementation in this project takes into consideration the corresponding values in this map and the assistance torque value to the corresponding Steering wheel torque is cross-checked using this control map.The control of the assistance motor is done taking into consideration the vehicle speed and the applied steering wheel torque. As seen, the model of the EPAS system is considered in partial for the implementation purpose in this project, i.e., only the control of the assistance motor is implemented, as the whole system implementation is complicated as the application is a real-time system.The block-diagram of the hardware implemented is as shown below in Fig.9,

Fig. 9 Implementation –Block Diagram and hardware

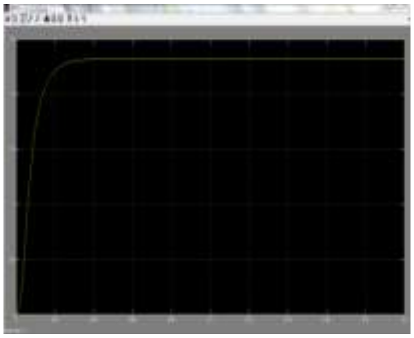
5. RESULTS

- ### Steering Wheel Torque

No Proportional-Derivative Control

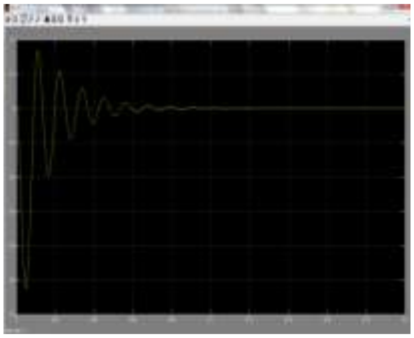


With Only Proportional Control

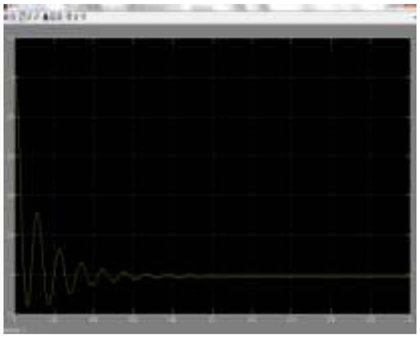


With Proportional and Derivative Control

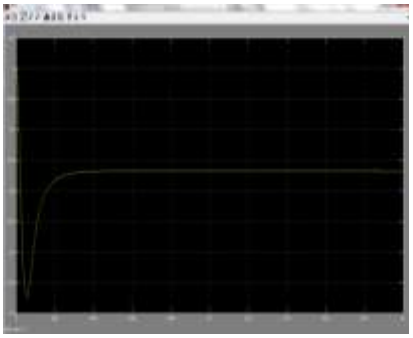
- **Assistance Motor Torque**



No Proportional-Derivative Control

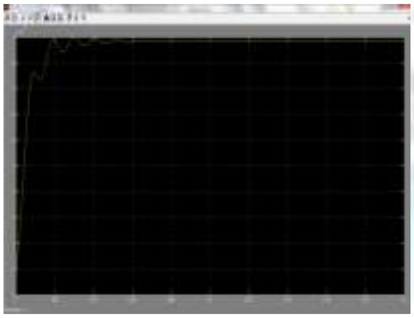


With Only Proportional Control

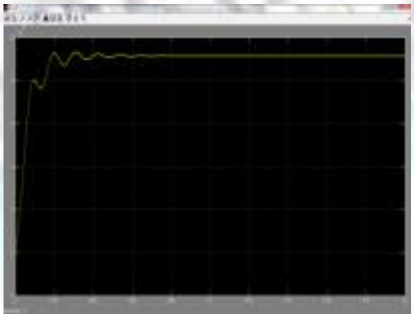


With Proportional and Derivative Control

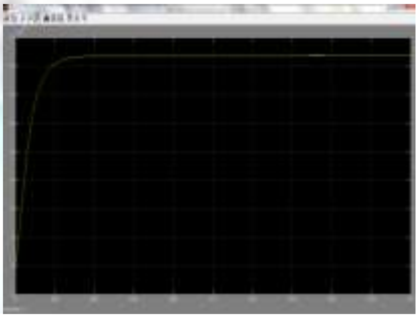
- **Steering Rack Displacement**



No Proportional-Derivative Control



With Only Proportional Control



With Proportional and Derivative Control

6. CONCLUSION

A column-type Electric power steering system is considered and it requires a proper torque boost and high frequency fluctuation has to be avoided. Though pure proportional control gives proper torque boost it fails to avoid high frequency fluctuation because of insufficient damping. Hence Proportional-Derivative control is used to give proper damping. Thus Proportional-Derivative control is needed for a CEPS to generate desired static torque boost and avoid the high frequency fluctuation.

According to the inputs, Steering wheel torque and Vehicle speed the assistance wheel torque is calculated and displayed on the LCD screen which is the output. According to this value the Assistance motor produces the torque calculated which displaces the rack.

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