A Study on the Dynamic and Control Performance of New Type EPS systems with Two Magnetic Clutches

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Abstract: This paper validates new type electric power steering (EPS) system which is driven by a uni-direction rotational motor and two electromagnetic clutches. The assist motor of the new type EPS produces a torque for assisting the steering in only one direction and two electromagnetic clutches transmit the assist torque to the pinion gear in either left or right direction with respect to the steering rotation.

In order to evaluate the static and dynamic characteristics of the new type EPS, the EPS has been modeled by using the well known customized software such as MSC.ADAMS and MSC.CarSim. The ADAMS software has been used to investigate the static characteristics of the proposed system. ADAMS, however, can not describe dynamics of a vehicle and perform the simulation under the various road conditions. Thus the dynamic characteristics of the vehicle including the EPS are analyzed very well by using the CarSim software. A sinusoidal steering input command is applied to the propose EPS system in order to evaluate the static characteristics, while the double lane changes are applied to the vehicle with the EPS in order to evaluate the dynamic performance.

Through a series of simulations, we can conclude that the propose EPS shows the stable dynamic characteristics when the rotational direction is changed.

Keywords: Uni-directional Power Steering, Electric Power Steering, Vehicle Dynamics, ADAMS, CarSim

1. INTRODUCTION

Generally, the objective of the steering system for vehicles is to assist the steering efforts of the drivers, especially during driving on curved lane with low speed or maneuvering in parking lots. To assist driver's steering, a lot of the hydraulic power steering systems have been developed so far. An engine driven hydraulic pump and the associated piping system produce not only low efficiency in terms of power saving, but also need more space in the engine room and more assembly time. Therefore, the long lasting obvious dominance of hydraulic power steering system in passenger vehicle is now seriously being questioned. More and more automakers are planning to use electric power steering systems for the next generation vehicles. By 2005, in Western Europe presumably 40-50% of new vehicles will go into series production equipped with such a system [1,2].

There are multiple reasons to accept electrically controlled steering system in passenger car since both environmental and financial advantages are obvious [3]. The electrical steering produces further important arguments to vehicle manufactures by dropping belt, oil reservoir and pipe arrangements in engine room as well as saving consuming time and reducing expensive noise suppression work.

Therefore, some research and development on electric power steering system have been performed, though detailed information on its control logic has not been released. Commercially, Delphi Automotive, TRW Automotive, Koyo Seiko Corporate have already devised EPS system modules. Honda had applied its EPS system to real vehicle model, Acura NSX, and Click mode by Hyundai has Koyo Seiko EPS system [4].

A bi-direction rotational motor has been used to support the steering efforts in most conventional EPS system. By the way, the bi-direction motor has dead-time due to the response time when the rotational direction is changed. When rotational direction is changed suddenly, the motor requires high electric power to change its direction as quick as possible. To accomplish this task, an expensive motor is demanded. It also requires complicated control system such as ECU (Electronic Control Unit) and control logic without any mechanical or electrical error.

To solve these problems associated with bi-direction rotational EPS system, this paper is going to propose the new type EPS system which is controlled by uni-direction rotational motor and two electromagnetic clutches. The rotational direction of the EPS is changed by clutches which eliminates the over current on the motor and allows less complicated motor driver circuits. It not only reduces the possibility of malfunction and electric energy consumption. but also allow s a smaller and cheaper assist motor [3].

The objects of this paper are to investigate and evaluate the performances of the new type EPS. In order to do these tasks, the EPS system has been modeled by using well known customized software such as MSC.ADAMS and MSC.CarSim. MSC.ADAMS is used to analyze the static characteristics of the component of the EPS system. The dynamic effects of the new EPS to the vehicle behavior are also investigated by using MSC.CarSim.

2. THE PROPOSED EPS SYSTEM

The proposed EPS system illustrated in Fig. 1 is a column type EPS, in which a motor drives the column for steering. Because column type EPS consumes less electric power and requires less product cost by easy assemble, it usually employed in small vehicles so far [1]. On the other hand vehicles with a higher comfort demand will require this technology gradually.

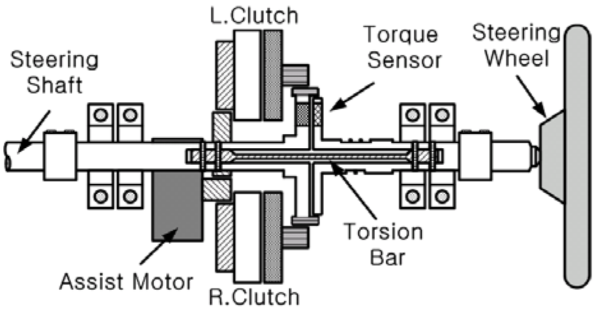


Fig.1 Schematic of electric power steering system

The major components of EPS system are a uni-directional motor, two clutches, a gear box and a torque sensor. Instead of contact type sensor that is usually equipped in a conventional EPS system, the proposed EPS system employs an opto-isolated type torque sensor. A photo-isolated type torque sensor measures the applied torque to the column by measuring the angle difference between the steering wheel and the steering shaft, and produces the electric voltages according the angle difference. The steering input of a driver is transmitted to the control unit by detection of the torque demand in torque sensor.

The control unit decides the amount of assist torque and generates the PWM (Pulse Width Modulation) signal to control the motor. It also determines rotational direction via the torque's output signal. If driver turns the steering wheel to the right side, the control unit connects the motor assist torque to the right clutch and vice versa. The clutches are never engaged together at a time.

A brushless DC motor is used to generate the assist torque. Gear systems moderate the output torque from brushless DC motor and transfer it to the clutches. The DC motor output torque is also controlled according to the vehicle speed such that the sensitivity is in inverse proportion t the vehicle speed.

The motor output power depends on the torque sensor signal and vehicle speed.

3. SYSTEM MODEL USING ADAMS

In general the steering system has a lot of complex mechanical linkages and is operated under with kinematic constraints. Thus it is very difficult to model the EPS system mathematically, and verify the model.

Thus, we will make a mathematical model about the EPS system by utilizing well known and well verified customized software such as ADAMS which produces models and analysis of dynamics of the multi-body systems.

3.1 Configuration of the proposed EPS system

Fig 2 shows the drawing of the proposed EPS system modeled by customizing ADMAS Software. The steering wheel and the steering shaft are connected by torsion bar. One of the clutch ends is always connected to steering shaft and the other one is connected to gear trains with assist motor.

The clutches are on or off with respect to electromagnetic circuits state. When the clutch is on, the two parts of the clutch are unified such that two ends of the clutch connected and the motor torque could be transmitted to steering shaft. On the other hand, when the clutch is off, two ends of the clutch are not connected each other such that the motor torque could not be transmitted to steering shaft. Thus, the direction of the steering can be simplified controlled just by on of off the clutches.

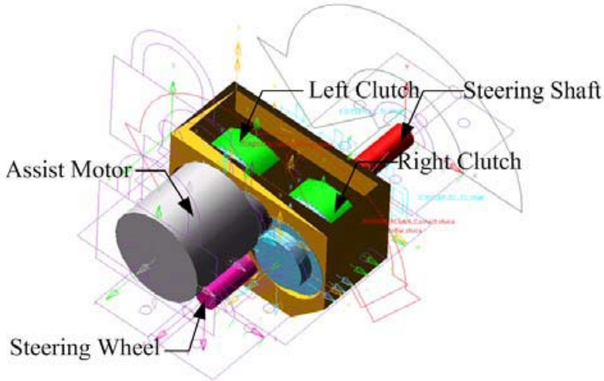


Fig. 2 Configuration of the propose EPS system

In general, the steering wheel and steering shaft are modeled to be mass and torsional spring. The torsion bar is also described by a torsional spring. The clutches can be modeled to be various masses which are changed according to the on-off states of the clutches. And the gear transmit can be also modeled as couplers in ADAMS software.

The parameters used for analysis are represented in Table 1.

Table 1. The design parameter of EPS system

Ieq = 0.05kg•m2	Icol = 0.01kg•m2
Beq = 35.0N•m	Bcol = 0.5N•m
Keq = 100.0Nm/rad	Kcol = 40.0Nm/rad
N1 = 25	Itire = 1.0kg•m2
Ka = 0.02Nm/A	Cα = 20000N/rad
KE = 0.02V-sec	Cλ = 20000N/unit slip
Ra = 0.1Ω	εr = 0.015
r = 0.3m	rrack = 0.03m

3.2 Reaction force from tire

When a vehicle runs on dry asphalt road with slow speed and turns its direction, such as parking maneuver, the assist steering torque is highly required because of large load on tire. The tire rolls and changes its direction simultaneously. The wheel directional angle is determined by the movement of tie rod. It is assumed that the wheel direction angle of left tire and right tire is the same. The longitudinal and lateral forces occurring in the tire for the study can be referred to Dugoff's tire model [5] as followings.

$$S = \frac{\mu F_z\left[1-\varepsilon_r V\sqrt{\lambda_s^{\,2}+\tan^2\alpha}\right](1-\lambda_s)}{2\sqrt{C_\lambda^{\,2}\lambda_s^{\,2}+C_\alpha^{\,2}\tan^2\alpha}}$$

$$f(S)=\begin{cases} S(2-S) & if\ S<1 \\ 1 & f\ S>1 \end{cases}, \qquad (1)$$

$$F_s = \frac{C_\alpha \tan\alpha}{1-\lambda_s} f(S), \quad F_t = \frac{C_\lambda \lambda_s}{1-\lambda_s} f(S)$$

where, Cα, Cλ, α, λ, μ and εr represent the longitudinal and lateral tire stiffness, slip angle, slip and friction coefficient between tire and road, and road adhesion reduction factor, respectively. The force FR exerted to the rack from the longitudinal and lateral forces of the tires in Eq. (1) is

$$F_R = F_t \times \sin\theta_1 + F_s \times \cos\theta_1 , \qquad (2)$$

The tire movement around the z-axis can be described by following equation.

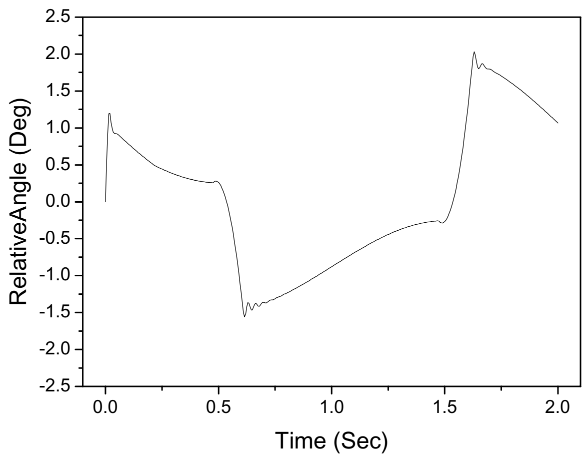
$$I_{tire}\ddot{\theta}_{tire} + B_{tire}\dot{\theta}_{tire} + K_{tire}\left(x_r r - \theta_{tire}\right) = F_R r , \qquad (3)$$

where, Itire, Btire and θtire represent the moment of inertia, damping coefficient and rotational degree of the tire

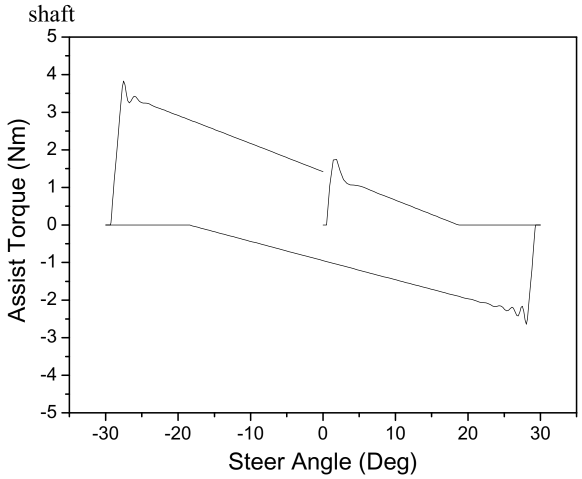
3.3 Operating characteristics of the proposed EPS system when maneuvering in parking lot

When a vehicle with this EPS system is maneuvering with low speed less than 5km/h in parking lot the operating characteristics of the proposed EPS system are shown in Fig. 3.

Fig. 3(a) shows response of a relative angle between steering wheel and steering shaft. When the sinusoidal input with magnitude of 30 degree is applied to the EPS system, the large degree of the relative angle is detected at initial state. Then the relative angle decreases gradually up to instant when the wheel direction is changed.



(a) Response of a relative angle between steering wheel and shaft



(b) Variation of assist torque via steer angle

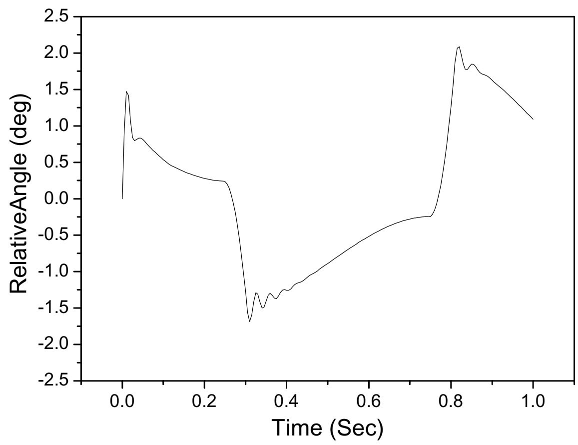
Fig. 3 Operating characteristics of the EPS at 0.5Hz sinusoidal input

This large difference at the initial state is induced from large force necessary to turn the tire. Once the tire starts to more, the reaction force from the road could be decreased gradually. Thus, large assist torque from motor is needed to rotate the wheel shaft at the initial state as shown in Fig. 3 (b).

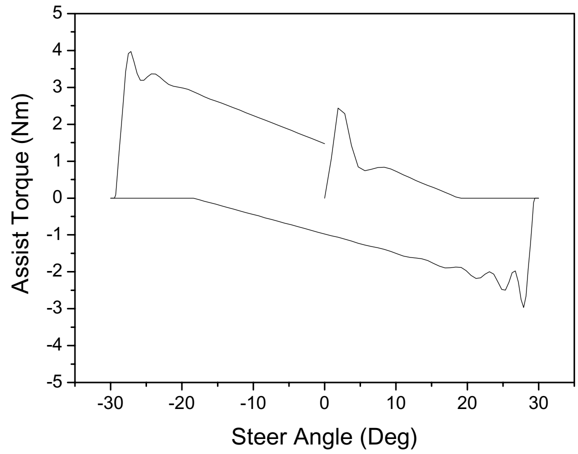
The assist torque will be decrease gradually according to decreasing the relative angle and be zero when the relative angle is less than 0.5 degree, limits of the dead zone of the assist torque, which can be adjusted in control circuits of the EPS system. When the direction of the steering wheel is changed, the large assist torque is also needed to turn the tire in reverse direction as shown in Fig. 3 (a). In Fig. 3 (a), we can see that there are variations of the assist torque according to the wheel direction change. This is due to the inertia of the corner module of the vehicle when the direction is changed.

Fig.4 shows the responses of the proposed EPS system when with 1Hz steering input is applied. The overshoot of the relative angle is Fig 4(a) is large than the case of the Fig. 3 (a), while the operating characteristics are very similar in both cases. This is induced from that one of the clutches produce the step changed of the assist torque to the steering shaft even though the sinusoidal input is continuously varied.

The overshoot of the relative angle at the initial state will be fade out at steady state because of inherent damping effect of the system.



(a) Response of a relative angle between steering wheel and shaft



(b) Variation of assist torque via steer angle

Fig. 4 Operating characteristics of the EPS at 1.0Hz sinusoidal input

Thus, we can see that the faster change of the input signal produces the larger magnitude of the overshoot in response of the relative angle from careful comparing Fig. 3 (a) and Fig. 4 (a).

However, the relative angles between steering wheel and steering shaft are controlled under the 2.0 degree. That means the assisted power can be controlled appropriately by the proposed EPS control system. Therefore, the proposed EPS system produces the acceptable performances.

4. MATHEMATICAL MODEL USING CARSIM

The operating characteristics of the proposed EPS system can be analyzed by using ADAMS software as shown in previous section when the vehicle is maneuvering with low speed less than 5km/h.

In this case, the vehicle dynamics does not need to be considered to analyze the characteristics of the system. Because, the most of the reaction force exerted to tires from the road is induced from friction, between tire and road surface.

On the other hand, when the vehicle has high speed more than 60km/h, most of the force exerted to tires is come from the vehicle dynamics. Thus, we need to consider the vehicle characteristics of the EPS system and the interaction between the EPS system and vehicle's behavior.

To evaluate the vehicle dynamics with the EPS, we have utilized the CarSim which is vehicle dynamic simulation software with 27 degrees of freedom of vehicles. This software produces exact motion of the vehicles.

The steering system can be modeled to have many massed or inertias lumped together with spring and dampers (or friction elements) in terms of components.

4.1 Reduced order model of the proposed EPS system

When the steering input is applied to the steering wheel, the motion of steering column can be described by the followings.

$$I_{col}\ddot{\theta}_{col} + B_{col}\dot{\theta}_{col} + K_{col}(\theta_{st} - \theta_{col}) = T_{assist}, \quad (4)$$

where I_{col}, B_{col} and K_{col} represent the moment of inertia, damping coefficient and stiffness of steering wheel and column. The assist torque in eq(4), T_{assist} can be expressed by

$$I_m\ddot{\theta}_m + B_m\dot{\theta}_m = T_m - \frac{1}{N_1}T_{assist}, \quad (5)$$

where I_m, B_m and θ_m represent the moment of inertia, damping coefficient and rotational angle of the assist motor. In the eq (5) Tm is the motor torque and N_1 is the gear ratio.

The relationship between input voltage to the motor and motor speed can be described by the eq (6).

$$R_a i_a + K_E\dot{\theta}_m = u_{EPS}, \quad (6)$$

where R_a, i_a, v_a and K_E are the armature resistance, current, voltage and back EMF constant, respectively

The rotational movement of column shaft is changed to rectilinear movement by rack and tie road. The movement of this part is relative simple such as describing the equation by the following.

$$M_r\ddot{x}_r + B_r\dot{x}_r + K_r(x_r - r_{rack}\theta_{col}) = 0, \quad (7)$$

where Mr, Br and θr represent the mass, damping coefficient and stiffness coefficient of rack and tie rod. rrack is radius of the rack and xr is lateral displacement of a rack and tie a rod.

4.3 Dynamic responses of the proposed EPS due to the double lane changes

Fig. 5, 6, and Fig. 7 show the responses of the proposed EPS when the vehicle runs on dry asphalt with various speeds. To evaluate the drive-ability of the proposed EPS, the vehicle is maneuvered by the double lane changes. The double lane change maneuvering shows the transient road holding ability and the accident avoidance ability of the steering system. Therefore, the sensitivity of the proposed EPS can be verified when the steering input is abrupt or for lane change maneuvering. The performance of the proposed EPS is will be compared with the ideal steering system well defined in CarSim.

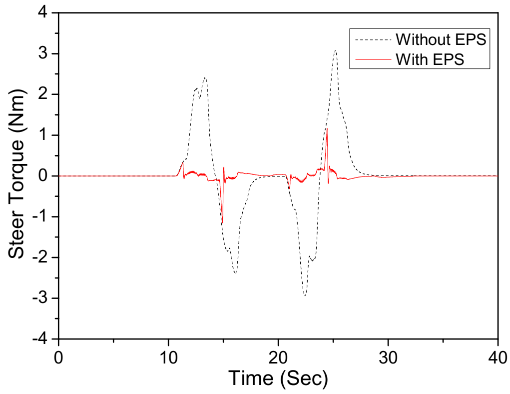
The ideal steering system has no time delay and no deformation of the torsion bar when the rotational direction of the steering wheel is changed.

Fig. 5 shows the responses of the proposed EPS system when the vehicle speed is 20km/h. Fig 5 (b) shows the magnitude of the steer torque to applied the pinion gear. The oscillations of the steer torque when it comes over at 10 seconds are occurred by switching the clutches. When the rotational direction is changed, the assist torque applied to the steering shaft discontinuously due to switching of the clutches. In Fig. 5(a), the proposed EPS needs small torque when the steering input is applied. It means that the proposed EPS assists the driver's steer and makes enough steer torque by using assist motor.

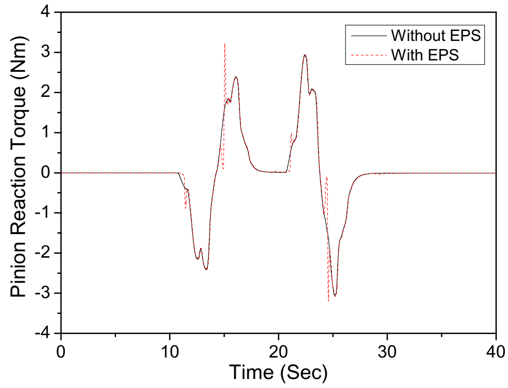
More steer angle produces the high peaks of the oscillation, due to lateral force from the tire according to the vehicle speed. Therefore, the steer toque shows some oscillations at the point that is changed rotational direction. However, the oscillation of the steer torque does not affect the steer angle of steering shaft as shown Fig. 5 (c) by the inherent damping effect of the tires. From the results of Fig. 5, the proposed EPS system shows good responses as compared with the ideal steering system as shown in Fig. 5 (d).

Fig. 6 shows the responses of the proposed EPS system when the vehicle velocity is 60km/h. As shown in Fig. 6 (b), the steer torque has some differences compared with the ideal steering system, because the proposed EPS system has some dead zone up to time when the relative angle is less than 0.5 degrees. If dead zone becomes smaller, the responses of the proposed EPS are similar to those of the ideal steering system. However it may also respond to the disturbances on the road such that the vehicle will have more unstable maneuvering. Therefore for the proposed EPS to have robustness even under the unnecessary, the dead zone shows existed in this kind of EPS system. However, if the dead zone is bigger than disturbance, the proposed EPS will show stable response with slow response.

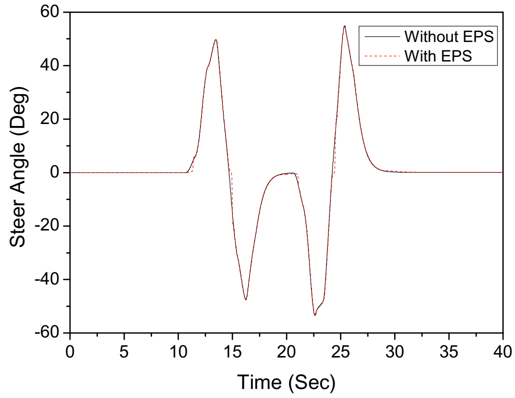
The lateral force from the tire at 60km/h is smaller than 20km/h, so Fig. 6 (b) shows a little overshoot responses and needs small steer torque compared with Fig. 5. That's the reason that when the vehicle speed is increased, the lateral force is also decreased so the proposed EPS system controls the assist torque inversely to the vehicle speed.



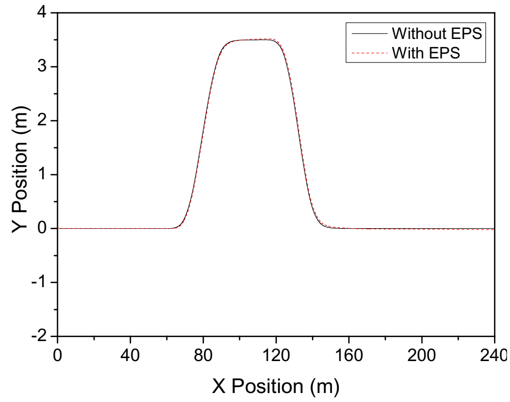
(a) Profile of steering torque input



(b) Variation of the steer torques

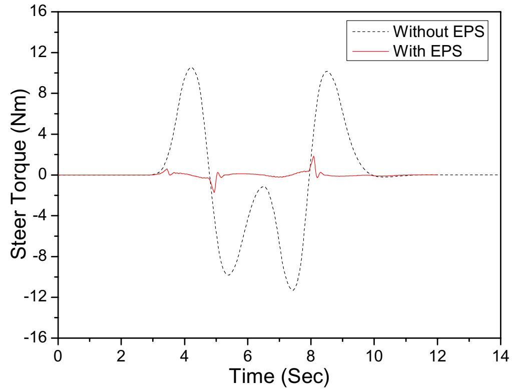


(c) Responses of the steer angles

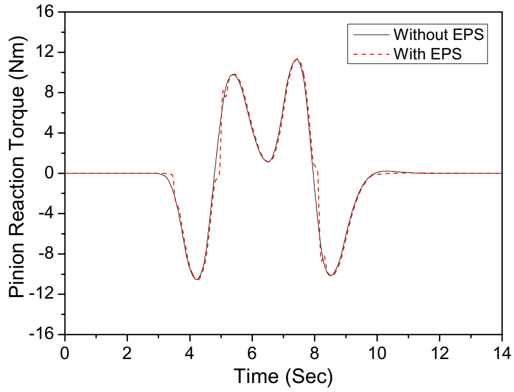


(d) Results of the vehicle maneuver

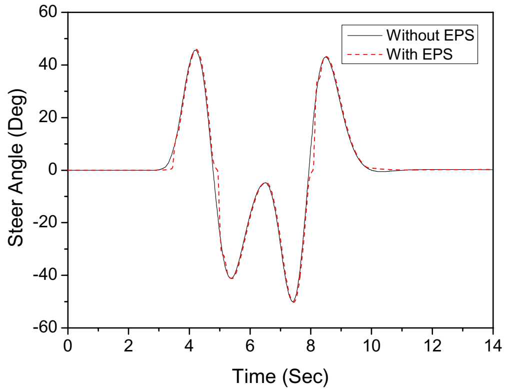
Fig. 5 Dynamic responses of the EPS for double lane change at 20km/h



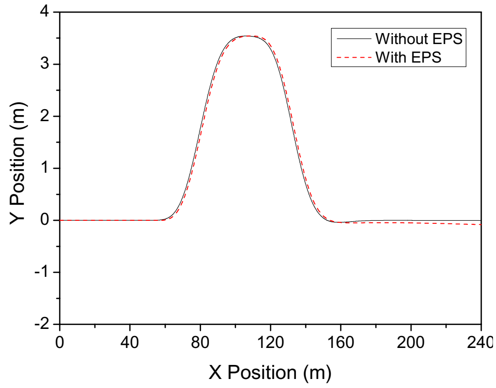
(a) Profile of steering torque input



(b) Variation of the steer torques

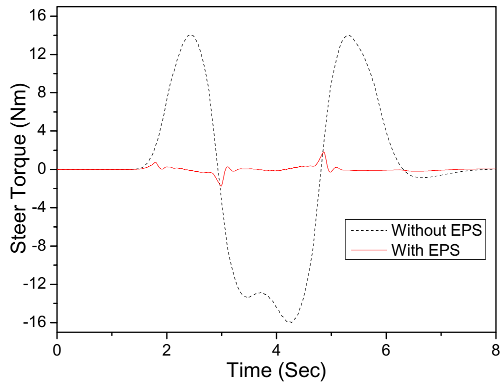


(c) Responses of the steer angles

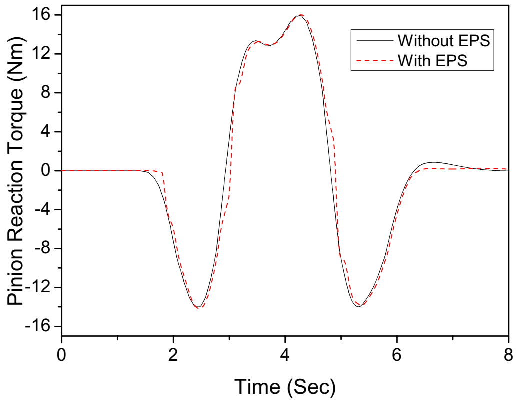


(d) Results of the vehicle maneuver

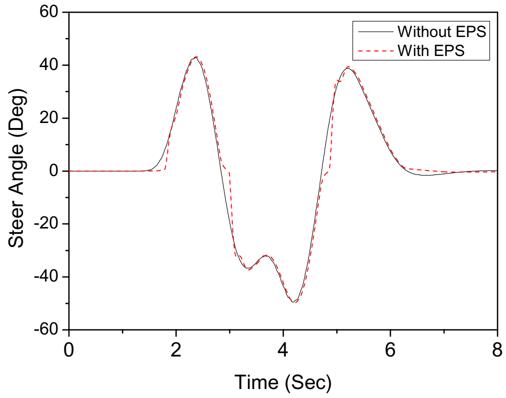
Fig. 6 Dynamic responses of the EPS for double lane change at 60km/h



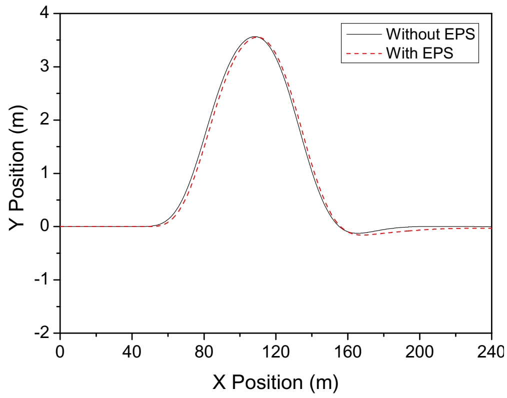
(a) Profile of steering torque input



(b) Variation of the steer torques



(c) Responses of the steer angles



(d) Results of the vehicle maneuver

Fig. 7 Dynamic responses of the EPS for double lane change at 100km/h

Therefore, even the overshoot of the steer torque is still remained, the responses of the proposed EPS system shows stable responses with various vehicle speed.

Fig. 7 shows the responses of the proposed EPS, when the vehicle speed is 100km/h. Compared with the ideal EPS, the proposed EPS shows a little difference of the steer angle. However, the steer torque which is applied by driver is much smaller than the ideal EPS. Therefore, the proposed EPS well assists steer of drives and makes enough the assist torque with stable responses under the various vehicle speed.

CONCLUSIONS

In this paper, the new type electric power steering system is proposed. The proposed EPS system is configured by uni-directional assist motor and two electromagnetic clutches.

To evaluate the responses of the EPS, the well known customized software such as MSC.ADAMS and MSC.CarSim is used. By using ADAMS, the operating characteristics of proposed EPS is performed when the vehicle speed is low. And the characteristics of the vehicle dynamics with proposed EPS are verified by using CarSim. The vehicle dynamics with EPS system are considered with comparing the ideal steering system.

As the results of this study, the dynamic responses of electric power steering system with two electromagnetic clutches show some oscillation of steer torque when the rotational direction of steering wheel is changed. However, the oscillation does not affect the vehicle drive-ability and stability.

REFERENCES

[1] Peter, D. and Gerhard, R., "Electric Power Steering – The First Step on the Way to "Steer by Wires,"", *SAE* 1999-01-0401, 1999.

[2] Chen, J. S., "Control of Electric Power Steering Systems,",*SAE* 81116, 1998.

[3] Boo, K., Lee, J., Song, J., Hong, S., "analysis of a new electric power steering system,",*International Conference on Control, Automation and Systems, 2002,* pp. 1545-1549, 2002.

[4] Kim, J., and Song, J., "Control logic for an electric power steering system using assist motor,", *Mechatronics*, Vol 12, pp. 447-459. 2002.

[5] Dugoff, H., Fancher, P. S. and Segel, L., "An Analysis of Tire Traction Properties and Their Influence on Vehicle Dynamic Performance,", *SAE* 700377, 1970.

[6] Song, J., Boo, K., and Lim, C., "A Study on the Performances of Hydraulic Type Electric Brake System,", *Transactions of Korean Society of Mechanical Engineering A*, No. 27, Vol 9, pp. 1492-1498. 2003.

[7] Smith D. E., and Starkey J. M., "Effects of Model Complexity on the Performance of Automated Vehicle Steering Controllers; Model Development, Validation and Comparison,", *Vehicle System Dynamics,* Vol 24, pp. 163-181. 1995.

[8] Hendrick, E., and Sorenson, S. C." Mean Value Modeling of Spark Ignition Engines,", *SAE* 900616, 1990.