Development Trend of Advanced Steering System

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Demands for additional functions of safety and comfort in steering systems have been increasing in accordance with the progress in electronics technology. Development of integrated vehicle control system has also proceeded with the aim of achieving intelligent vehicle dynamic control by steering technology, which works in cooperation with active braking and driving systems of vehicles. Herein, trends of the latest steering system technologies are introduced as well as Koyo's development strategies based on these movements.

***Key Words**: advanced steering system, electric power steering, ITS, steer by wire*

1. Introduction

Concerning the steering systems for automobiles, the hydraulic power steering system was firstly developed and put into production to satisfy the requirement of reducing the load to the driver in operating the steering wheel and has been widely adopted in accordance with further improving the performance in stability at high-speed driving and in steering feeling, etc. Thereafter, from the viewpoints of global environmental protection and energy saving, Koyo has developed and commercialized the electric power steering system (hereinafter referred to as EPS) first in the world for mini-sized vehicles. EPS is to be applied in the small to medium/large cars and is expected to be widely used and further improved in the future.

Conventionally, steering systems have been developed by focusing on the improvement of performance and functions related to the "turning" of wheels. However, with the wider use of EPS and improvement of the electronic control technology, other supporting technologies for improving the safety and the comfort of vehicles have been also required. Moreover, with the advancement in the intelligent transport system (hereinafter referred to as ITS) technology, and utilizing EPS system control technology as the key technology, the integrated vehicle control technology would be further realized by cooperation with the driving and the braking control systems including automatic steering system.

This report describes the development trend of advanced steering systems and related new technologies developed by Koyo.

2. Technical Trend in Development of Steering System

2. 1 Wide Installation of EPS and Further Prospect

Since the installation for mini-sized vehicles in 1988, EPS has been increasingly installed in small and medium cars in accordance with additional needs for environmental protection, energy conservation, and improved steering feeling. Corresponding to such needs, Koyo has developed and supplied various EPS types depending on the position where the motor generating the assist torque is mounted, such as the Column EPS (C-EPS) system for assisting the column part, Pinion EPS (P-EPS) system for assisting the pinion part of the steering gear, Rack Direct Drive EPS (RD-EPS) and Rack-Cross EPS (RC-EPS) system for assisting the rack bar, and Electro-hydraulic power steering (H-EPS) for driving the hydraulic pump by an electric motor (**Fig. 1**). EPS will be further increasingly installed not only on small and medium cars but also on large cars through developing the technology for motors with higher capacity and higher voltage, and a 42V battery[1].

EPS control can flexibly change the assist force for steering operation depending on information such as steering angle, steering angle velocity, speed and acceleration of the vehicle, speed and acceleration of each wheel, vehicle yaw rate, etc. Thus, EPS can provide not only the function of reducing the steering load but also an additional function of optimizing the assist force depending on the running conditions of the vehicle. Also, the EPS controller allows the responsiveness and accuracy of vehicle behavior control to be improved by appropriately judging the driver's intention or the steering conditions and by locally detecting the difference between the external disturbance and the steering operation of the driver. In these points, EPS is much expected to be further developed as an intelligent system for further improving not only the function of the steering system but also the driving stability and maneuverability of the vehicle. **Figure 2** shows the forecast of the global market trend of steering systems.

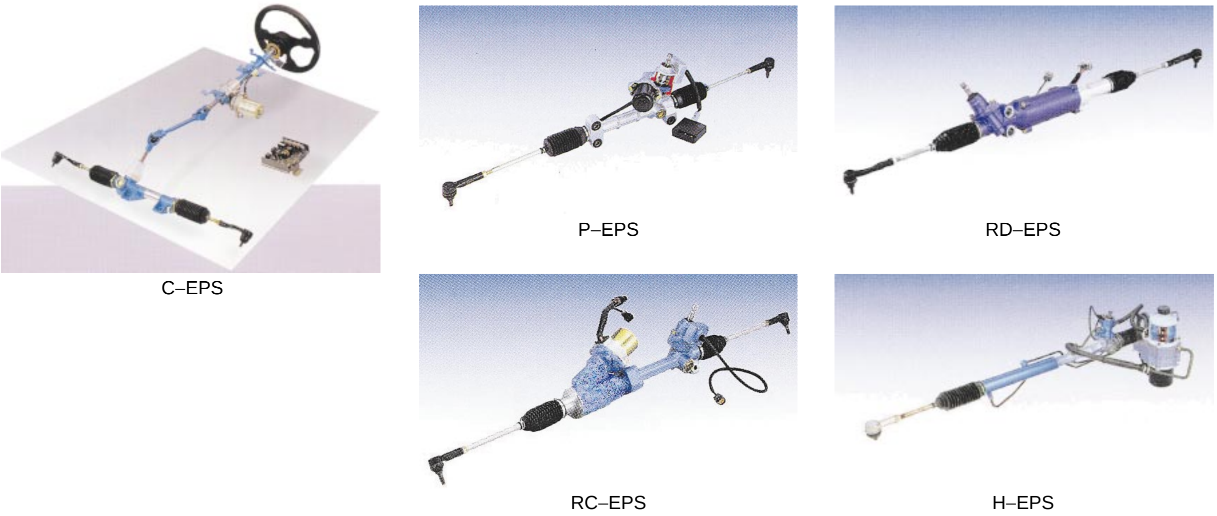

Fig. 1 Classification of EPS

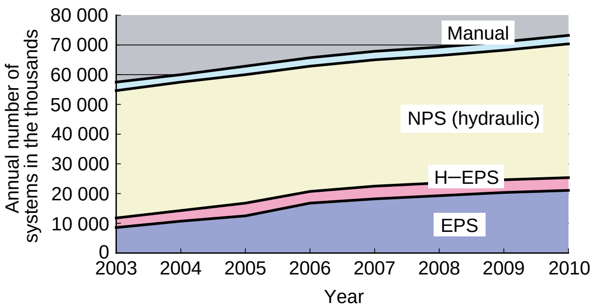

Fig. 2 Global market trend predict of steering systems (data source by J.D. Power-LMC)

2. 2 Elemental and Basic Technology Improvement to Support EPS

In general, EPS shows superior performance in energy saving but has the problems of poor frictional feeling and inertia feeling caused by the motor and the reduction gear comparing to a hydraulic steering system. In addition, improving the reliability and performance of electric components has been an important issue to be newly developed as the additional technology. Here describes the main elemental and basic technologies giving an influence on the steering feeling and the reliability.

(1)Actuator

Conventionally, the motor with brush has been used for EPS. However, in order to satisfy such requirements as significant noise reduction during motor rotation, reliability improvement, smaller size, higher torque, etc., a smaller exclusive brushless motor having higher torque has been developed. Also, by developing a high-efficiency reduction gear, higher torque and lower inertia technology have been achieved so that improvement in controlling the system can be expected. As for actuators or controllers mounted in the engine room, reliability and thermal design are also the important because they greatly influence the system performance and steering feeling.

(2)Motor control

Concerning conventional EPS, various compensation controls (e.g., inertia compensation, friction compensation, return control of the steering wheel) have been added for reducing the influence of the rotor inertia of the motor with brush and friction between the brush and the commutator. Basically, the simple assist control by phase compensation and current control can be achieved only through establishing the hardware improvement technologies in smoothly providing the electric-transmission components of the controller, technologies to prevent the electromagnetic interference, and to achieve higher efficiency in mechanical parts including the reduction mechanism.

(3)Manual gear

Compared with the hydraulic power steering system, in which assist force is applied directly to the rack bar, some EPS provide the assist torque to the pinion shaft, and therefore conventional design specifications need to be reconsidered. Particularly, after providing smooth rolling transmission characteristic by modifying the gear-part specifications, the optimal transmission mechanism must be established by considering efficiency against reverse input.

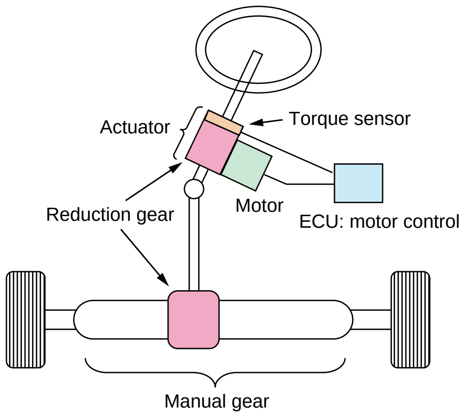

Fig. 3 Structure of C-EPS system

2. 3 Improvement of ITS Technology

In order to solve such problems as traffic congestion, accidents, and environmental problems, and optimize transportation environments, R&D on ITS has been promoted as a national project using latest information communication and control technology. Specifically, ITS has been researched and developed in the following nine fields: ① sophistication of navigation system ② automatic toll receipt system, ③ support of safe driving, ④ optimization of traffic control, ⑤ efficient road management, ⑥ support of public transportation, ⑦ efficient distribution by commercial vehicles, ⑧ support for the safety of pedestrians etc., and ⑨ operation support of emergency vehicles.

In the field of "support of safe driving" that supports the vehicle's basic function of "driving," "turning," and "stopping" to secure more safety from the viewpoint of drivers, various advanced systems shown in **Fig. 4** have been strenuously developed by automakers and system control makers.

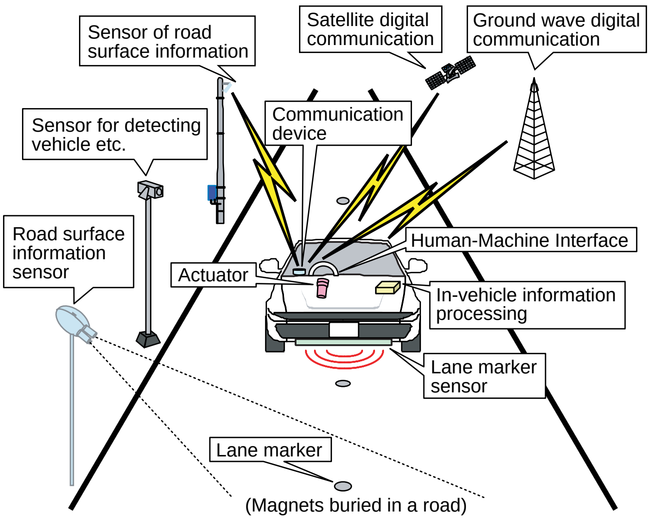

Fig. 4 Example of ITS technology

(1)Provision of information regarding driving environment

By using various sensors installed in roads and vehicles, conditions of the roads and surrounding vehicles are detected, and various information and warning are provided on real time by vehicle-mounted devices or road information devices.

(2)Warning and driving assistance

By mounting automatic control functions (e.g., target recognition and control by radar and CCD camera, etc.) in the vehicle, position information regarding one's own vehicle and surrounding vehicles, vehicle behavior and any obstacles can be recognized. In case of danger to vehicle driving, speed control (e.g., braking), steering wheel control, etc. is automatically carried out and helps the driving assistance and the safe operation.

(3)Automatic driving

Automatic driving can be achieved through further improving the technology for controlling the driving assist functions (e.g., steering, accelerator, braking, etc.), grasping the information of the surrounding running environment (e.g., obstacle detection), and controlling the automatic operation of braking, acceleration and steering. This technology has been developed both for infrastructure cooperation and for autonomous driving.

2. 4 Practical Application Items of Next Generation Steering System

In accordance with the research and development of ITS-related technologies in the field of steering system, various systems also have been developed for reducing the load to the driver and supporting the safe driving. Some specific examples are introduced below.

(1)A system which, using the information such as the steering wheel angle, vehicle speed and obstacles surrounding the vehicle, supports the driver's steering operation and makes the operation of parallel parking in the garage easy for reducing the load to the driver.

(2)A steering assist system by which the spinning of the vehicle caused when the brake is suddenly applied on the two different surfaces of the road (e.g., one side wheels are on the ice and the other side wheels are on the asphalt) can be corrected to the safer direction depending on the vehicle's situation by controlling the steering assist torque of the EPS with cooperation of the ABS system and/or the stability control system.

(3)A system for monitoring the white lines of the road indicating the traffic lane with the CCD camera and assisting the driver to correct the steering operation through EPS in order to prevent the vehicle's deviation from the traffic lane.

(4)A system for providing the slow steering operation during high-speed driving and the prompt steering operation during low-speed driving by controlling the reduction gear ratio depending on the vehicle speed and the steering angle.

(5)A system for providing, in addition to the above function of changing the reduction gear ratio of the steering system as shown in (4), the stable cornering performance to realize the optimization of under-steering and over-steering operations by the active control of the front-wheel angle through cooperatively controlling the stability control system.

2. 5 Prospect of Technologies Related to Future Steering Systems

(1)Steer-by-wire system

As is clear from the technical trend for developing the next steering systems as described in section **2. 4**, the steering system was improved from one having only the function of a steering system to the one that works as a component with the new function of integrated control of the vehicle in order to further improve the vehicle safety. The steer-by-wire system is a further improved next-generation steering system having the objective of mechanically separating the steering gear from the steering column so that the steering system can be freely controlled by the transmission and receipt of information via electric signals. As the steering system can transmit vehicle behavior more sensitively than the accelerator or brakes, it significantly influences the driver's operation. Particularly, securing the reliability when the system fails is essential for the steer-by-wire system, and is the most important item to be developed for its practical application. For practical application, laws and an exclusive communication protocol (e.g., FlexRay etc.) have been prepared. Thus, the steer-by-wire system will be mass-produced in the near future.

(2)New steering mechanism

A new steering mechanism has also been suggested that is quite different from the conventional steering system requiring a rack bar and can realize the steering operation by controlling the tire camber angle and the suspension linkage mechanism. Another steering system has also been researched that controls the running direction of the vehicle by individually controlling the rotation of each tire using a wheel-in-motor.

3. Simulator for Developing Steering System

Recently, with the advance in simulation software and tools, efficiency in product development has been remarkably improved due to high-speed and high-accuracy analysis of behavior using computers. Thus, evaluation by the computer simulation has become indispensable for reviewing the design of steering systems, predicting vehicle behavior, and examining control logic including fail-safe functions. Currently used simulator types and their applications are described below.

(1)Modeling Simulation
(MATLAB/Simulink, dSPACE)

- This simulation tool is used for modeling the steering system or vehicle and predicting the behavior under various conditions.

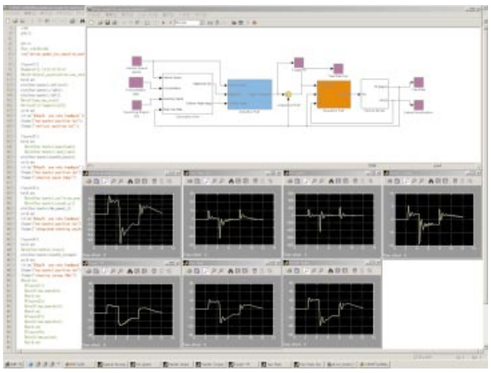

Fig. 5 Simulation by MATLAB/Simulink

(2)HIL (Hardware In the Loop) simulator

- Steering simulator (SS): This simulator is constructed by combining the actual components such as the steering gear, column, intermediate shaft, gear, front suspension, and tires, and the modeling function prepared by software for a vehicle or ECU.

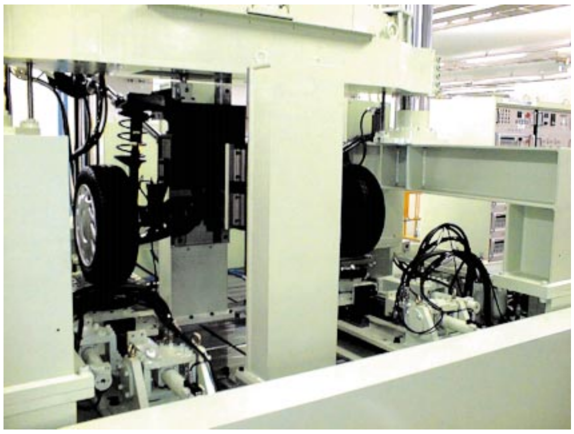

Fig. 6 Steering simulator

(3)Vehicle behavior simulator

- Driving simulator (DS): This simulator simulates the three-dimensional vehicle behavior during steering operation using the six-axes-controlled hydraulic cylinders.

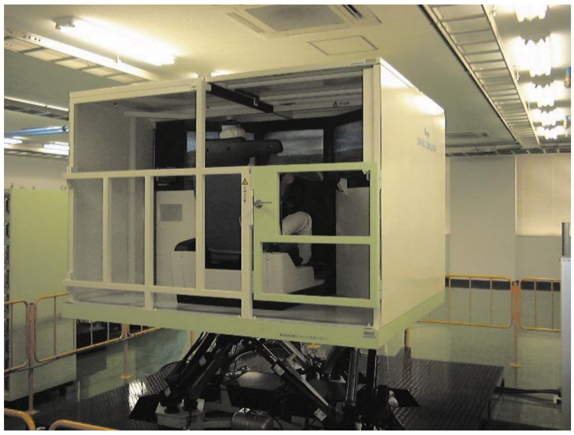

Fig. 7 Driving simulator

The above simulators are selectively used and the method of utilizing their data and the application field are determined considering both machine parameters such as degree of difficulty in introducing the simulator, reproduction accuracy, running cost and compatibility, and evaluation item parameters such as steering feeling of the system, behavior and performance.

4. Development of Control Technology for Steering System

(1)Steering torque control for Advanced Safety Vehicle (ASV)[2]

With this control, the change in steering torque, by which the driver's intention for steering operation can be known most quickly, is detected. When the steering operation to turn the vehicle to the direction in which another car is running is detected, warning control is automatically operated by providing the reactive torque to the driver using EPS. Also, the steering torque and acceleration change are used to judge the driver's intention of steering operation in case of emergency avoidance or driving into the curved roads. When the driver has an intention to avoid danger by steering operation, then the control is released respecting the driver's intention. However, the driver's response for warning control and the influence on preventive safety are the current problems against practical use.

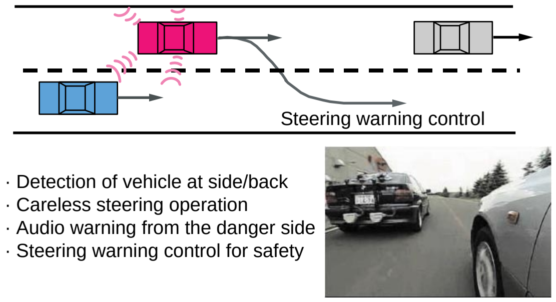

Fig. 8 Steering torque control for ASV

(2) External disturbance compensation control in automatic steering system[3)]

External disturbance compensation control technology in the steering local system has been developed in the automatic steering system. The difference in outputs of two rotational sensors mounted on the upper and lower parts of the motor is detected for the purpose of providing automatic steering operation by controlling the valve of the hydraulic power steering system by the motor. The output data and calculation/determination logic of the system model judge whether the torque is the external disturbance torque or the input torque by the driver. When the torque is judged as being the external disturbance torque, then the motor generates the torque for canceling the external disturbance torque to stabilize the vehicle behavior. When the torque is judged to be driver input, then the automatic steering operation is released, respecting the driver's intention.

Fig. 9 Disturbance compensation control in automatic steering control system

(3) Driving pattern rule-based control[4)]

This control judges typical vehicle driving patterns based on the change in steering torque such as the circle driving or the slalom driving, etc. and reduces the load to the driver's steering operation by changing the EPS assist control depending on the driving pattern. In the circle driving, the assist force is increased or reduced in accordance with the increase or decrease in the steering torque to reduce the load to the driver in correcting the steering operation. The control effect has been quantitatively measured by adopting an electromyogram measurement technique for evaluating the load to the driver in performing the steering operation. In the slalom driving, it has been evaluated and confirmed by the general quantitative measurement method of steering feeling that the maximum steering torque value can be reduced without getting the steering feeling worse.

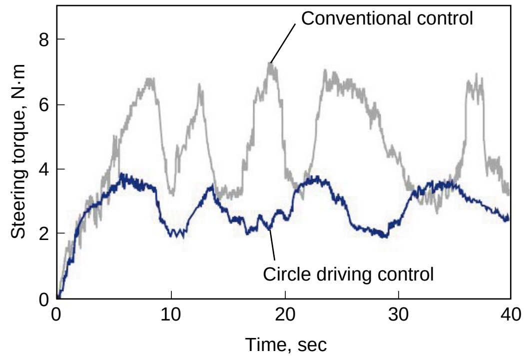

Fig. 10 Driving pattern rule-based control
(reducing steering load by circle-driving control)

(4) SBW-*D** control for vehicle dynamics control

This control uses the steer-by-wire system[5), 6)]. A driver inputs the linearly linked value *D** of the vehicle yaw rate and lateral acceleration as the target momentum to the operation device (steering wheel), so that the controller controls the steering actuator so as to follow this value. Since this allows the driver to directly control the vehicle behavior, the load of lead compensation control to the driver for the front wheel angle that was required for conventional driving operation is reduced and also even a beginner can easily drive the vehicle on the snowy road or the like. The effects both for compensating the automatic steering operation due to the external disturbance from the crosswinds and stabilizing vehicle behavior on low friction roads has been evaluated using actual vehicles, and remarkable effects have also been obtained.

Fig. 11 Winter test by using SBW-*D** control for vehicle dynamics control system

5. Conclusion

Recently, research and development of the by-wire technologies for automobile components has been rapidly attracted and some accelerator or brake control technologies have already been mass-produced. By-wire technology will be also the key technology for providing the steering system with more enhanced function, higher performance, and further developing the possibility of the integrated vehicle control system. However, extremely deep and wide is the development field of the by-wire system controlling the steering interface of the steering wheel, conventionally operated by hands, which are very sensitive, in bilateral relation with the active control of the vehicle behavior. At the same time, cost and reliability should be also further examined and established as other development items. With the increase in batteries using 42V and the increase in adopting EPS for medium- and large-sized cars, the steering system or the integrated vehicle control system including by-wire technology will be further developed. Such development will no doubt be supported by further development in the basic technologies concerning EPS system.

References

1) W. Ijiri: Koyo Engineering Journal, 162E (2003) 27.
2) S. Nakano, K. Nishizaki: Proceedings of the 4th Congress on ITS, Berlin, (1997).
3) S. Nakano, T. Takamatsu: Proceedings of the 26th Congress on FISITA, Paris, (1998).
4) S. Nakano, T. Kada, O. Nishihara, H. Kumamoto: Proceedings of the 27th Congress on FISITA, Seoul, (2000).
5) S. Nakano, T. Takamatsu, O. Nishihara, H. Kumamoto: Proceedings of the 6th Congress on ITS, Tronto, (1999).
6) M. Segawa, S. Nakano, O. Nishihara, H. Kumamoto: JSAE Review, 22 (2001) 383-388.

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