Development of Control Method for Hydraulic-Electro Power Steering System Using Brushless DC Motor

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Considering environment protection, Koyo is mass producing energy saving power steering systems using brushed DC motors. Now, Koyo has developed a new type of brushless DC motor and started production of power steering with this DC motors. This report presents the control method of the brushless DC motor for the Hydraulic-Electro Power Steering (H-EPS) System.

Key Words: *power steering, brushless DC motor, hydraulic*

1. Introduction

With the increasing spotlight on environmental preservation problems, the automobile industry has been urged to respond in without delay. Electric power steering systems (hereinafter referred to as "EPS") now under mass-production by Koyo offer both energy saving and good steering feeling, but hydraulic-electro power steering systems (hereinafter referred to "H-EPS") that drive the hydraulic pump in the engine drive pump-type hydraulic power steering (hereinafter referred to as "NPS"), which has been widely used for some time now, have also attracted attention.

Conventional DC brush motors for H-EPS have problems concerning controllability and durability. On the other hand, usage of brushless motors is expanding because of enhancement in reliability, performance and cost reduction. This paper reports on the control system of H-EPS using a brushless DC motor.

2. H-EPS System Overview

1) H-EPS system configuration

Figure 1 shows the configuration of the H-EPS system.

The steering gear is the same as in the conventional NPS. The high-efficiency gear pump, which is the hydraulic pressure source, is driven by a low-inertia, inner rotor type, three-phase brushless motor that uses a battery (alternator) as its power source. This system stands comparison with the conventional NPS in its steering feeling, and it is possible to reduce energy to be used.

2) Brushless motor mechanism

Figure 2 shows the configuration of a brush and brushless motor. **Table 1** gives the differences between the two types.

A brushless motor is a motor that replaces mechanical contact switching of a brush commutator that rectifies current of a conventional brush DC motor by a semiconductor that carries out electrical non-contact switching. It solves the durability problem caused by brush wear and provides high reliability.

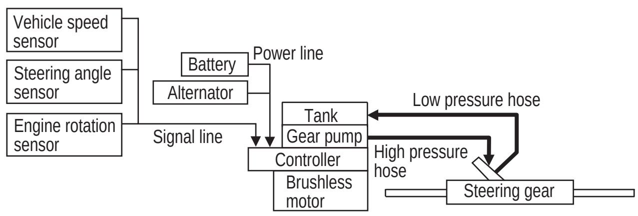
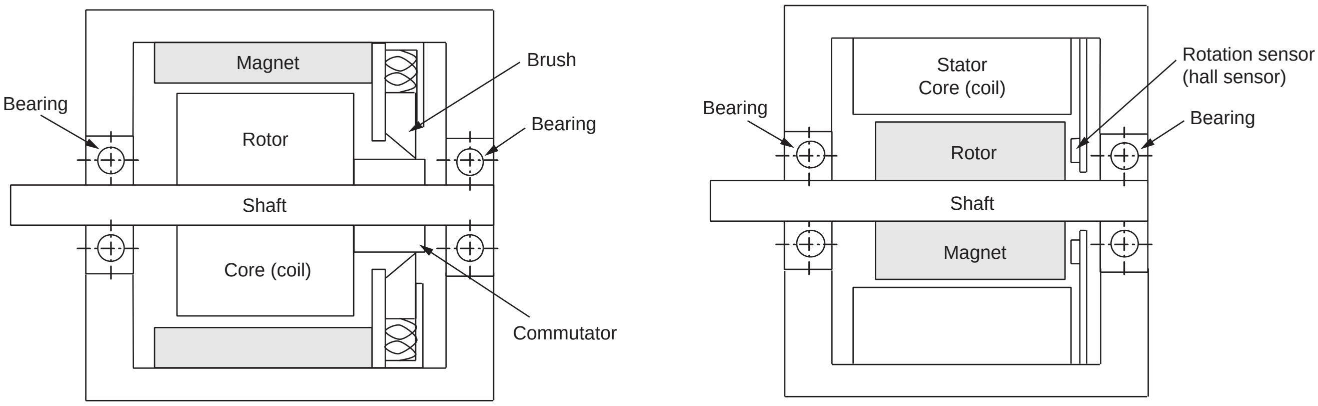


Fig. 1 H-EPS system configuration



Brush motor

Brushless motor

Fig. 2 Brush motor and brushless motor configuration

Table 1 Comparison of brush motor and brushless motor

	Brush motor	Brushless motor (inner rotor type)
Configuration	Complicated rectifying section consisting of brush and commutator.	Complicated stator winding
Cost	Low cost because it doesn't require drive circuit.	Slightly high price.
Output/volume	Small because equipped with rectifying section.	Large
Loss	Lots of loss due to sliding section.	Minimal
Noise	Lots of noise produced by brush sliding.	Minimal
Durability	Deteriorates due to brush wear.	Superior
Vibration	Lots of vibration due to rotor imbalance.	Minimal
Starting characteristics	Deteriorates due to rotor inertia.	Superior
Magnetic design	No problem in particular.	May become demagnetized.

3) System control configuration

Figure 3 shows the control block diagram for the H-EPS system.

In order to obtain optimal steering feeling, the controller decides the target value for motor rotation speed based on signals from the vehicle side steering angle sensor and vehicle speed sensor. On the vehicle side, in order to make motor rotation speed coincide with the target value, feedback loop control is executed by signals from the rotation sensor (hall sensor).

3. Brushless Motor Control

1) Motor drive control

Motors for H-EPS are required to drive the pump faster than motors for EPS. That is because the specified oil flow rate must be secured due to the use of oil pressure generated by opening and closing valve. On the other hand, less strict torque control(torque ripple) is required because the piping and reservoir have the adequate damping effect. For this reason, Koyo adopted a 120-degree bipolar drive system using MOS-FET. Three -phase delta connection method was also adopted in order to facilitate high-density winding and simple connection.

Figure 4 shows the sequence of a 120-degree bipolar drive system with three-phase delta connection.

Table 2 gives the merits and demerits of delta/star connection and motor drive methods.

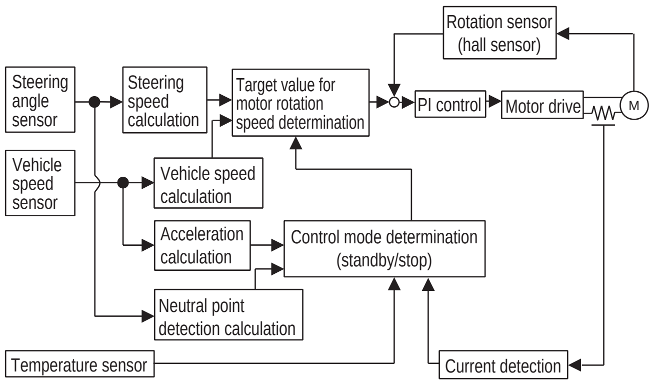


Fig. 3 Control block diagram for H-EPS system

Table 2 Merits and demerits of delta (⊿) and star (Y) connection and motor drive methods

Connection	Drive angle (deg)	Coil continuity (deg)	Characteristics: Merits	Characteristics: Demerits
⊿ (Delta)	120	180	Efficiency: Comparatively high Cost: Low Winding size: Finer than for Y	Torque fluctuation: Large
	180	120 (Square wave drive)	Torque fluctuation: Low	Efficiency: Low
		180 (Sine wave drive)	Efficiency: High Torque fluctuation: Low	Cost: High Circulating current flows if voltage is unbalanced.
Y (Star)	120	120	Efficiency: Comparatively high Cost: Low	Winding size: Thick compared to ⊿ Torque fluctuation: Large
	180	120 (Square wave drive)	Torque fluctuation: Low	Efficiency: Low
		180 (Sine wave drive)	Efficiency: High Torque fluctuation: Low Circulating current does not flow even if voltage is unbalanced.	Cost: High

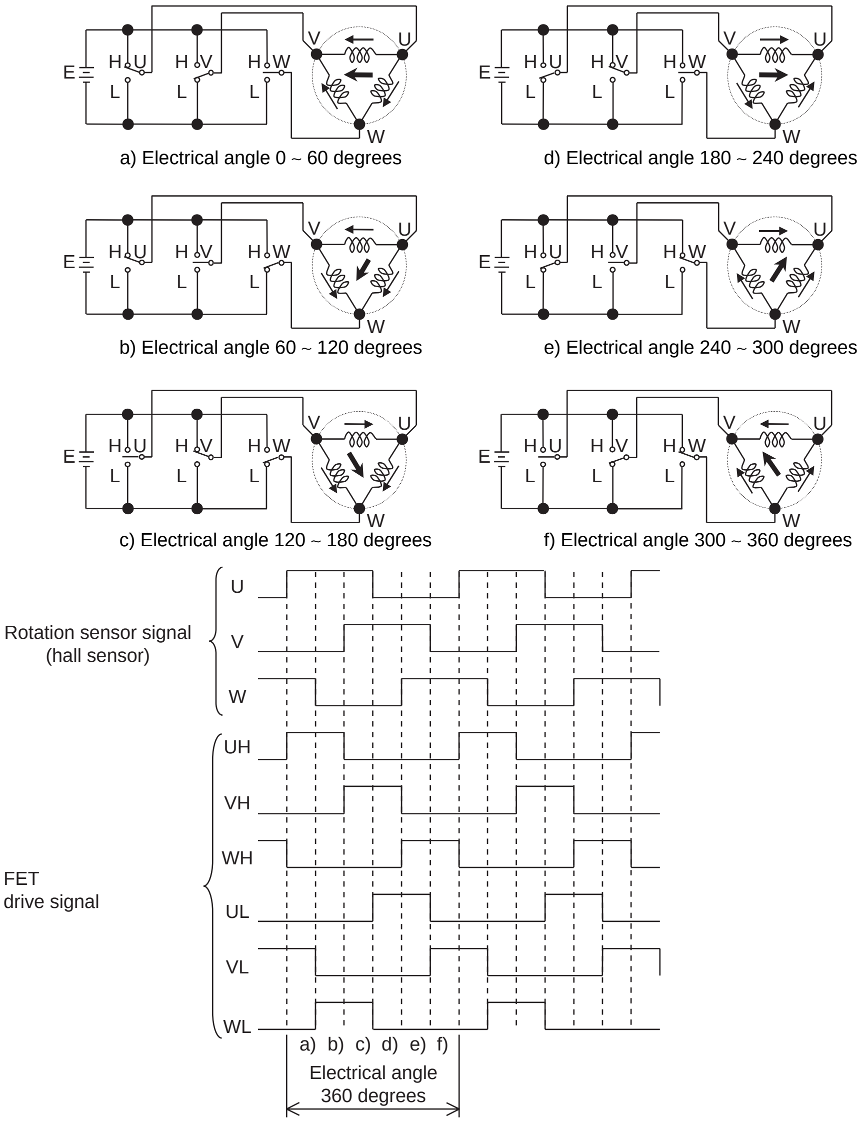


Fig. 4 Sequence by 120 degrees bipolar drive with three-phase delta connection

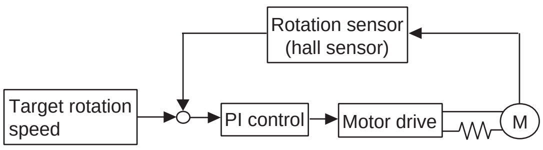


Fig. 5 Motor rotation speed control block diagram

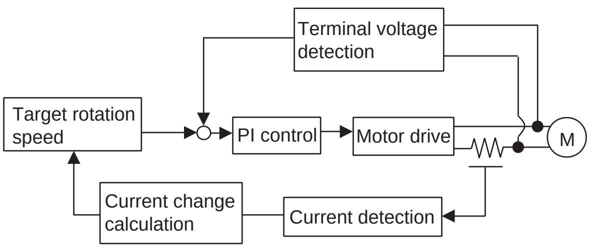


Fig. 6 Standby control block diagram

2) Rotation speed control

Figure 5 shows the control block diagram for motor rotation speed control.

To prevent disturbance of oil pressure caused by pump load fluctuation of the oil pressure source in all actuation areas of power steering (hereinafter referred to as "PS"), the system has superior response and no overshoot by executing rotation speed feedback PI control using speed signals generated from rotor position sensor.

4. H-EPS Motor Control

Koyo's H-EPS system includes three control systems: stand-by control, stop & go control, and idle & go control. Each of these control systems is described in the following section.

1) Stand-by control

Stand-by control was developed as a control system that controls the electric pump unit efficiently without using external sensors. It generally uses brush motors.

Figure 6 shows the stand-by control block diagram and

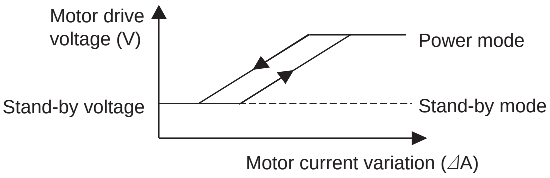


Fig. 7 Control map of motor drive voltage relative to motor current variation

Fig. 7 shows the control map of motor drive voltage relative to motor current variation.

The control method is as follows:

The motor is driven at low rotation speed (stand-by mode) when the steering wheel is not being manipulated (e.g. when driving straight ahead, or when stopped), and driven at high rotation speed (power mode) when the steering wheel is being manipulated and requires steering effort.

Instead of using external sensors for shifting from the stand-by mode to the power mode, motor current is detected by a motor current detection circuit in the controller. Steering status is determined by computing the variation in motor current values and motor rotation speed is controlled by changing the motor drive voltage.

With this system, however, response is poor during mode shifting and steering feeling tends to deteriorate. Therefore, this requires countermeasures such as setting stand-by rotation speed higher and its energy saving effect is small.

2) Stop & go control

In order to further improve energy efficiency of the previously mentioned stand-by control, a low-inertia brushless motor with superior starting characteristics is used as a motor and stop & go control that uses an external sensor as the steering angle sensor has been developed.

System control is basically the same as stand-by control; the motor is stopped when the steering wheel is not being manipulated such as when driving straight or when stopped. When the steering wheel is manipulated, the motor must quickly rise from the stopped condition to the target rotation speed. Motor rotation speed that generates the proper steering effort is therefore decided from the calculated steering speed using the output signals from the steering angle sensor, and the motor rotation speed rises to the target rotation speed.

Thus with this control method steering feeling does not deteriorate as much as with stand-by control described in the previous section, and the system is capable of substantial energy savings.

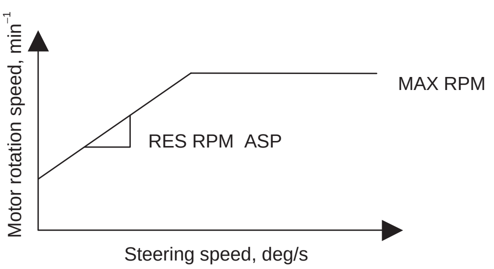


Fig. 8 Control map of motor rotation speed relative to steering speed

(1) Steering speed control

With the stop & go control, in order to prevent deterioration of steering feeling, the oil flow to the valve that generates oil pressure is regulated to be constant by changing motor rotation speed relative to steering speed.

Figure 8 shows the control map of motor rotation speed relative to steering speed.

(2) Motor start control

With conventional control, the motor starts under a constant voltage, so steering feeling is not compatible with both super-low rotation speed steering and high-speed steering. (If super-low rotation speed steering is given priority, steering torque at high-speed steering is heavier than the target torque, and lighter in the opposite situation. See **Fig. 9**)

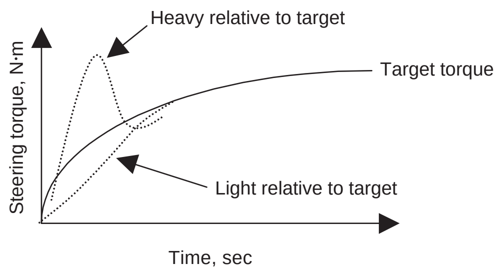


Fig. 9 Steering torque when motor is started at constant voltage

When the motor instantaneously starts up by manipulation of the steering wheel from the stopped condition, it is necessary to prevent deterioration of steering feeling. For this reason, motor starting voltage is changed according to steering speed. The motor is started gently for super-low rotation speed steering and started instantly for high-speed steering.

Figure 10 shows the control map of motor starting voltage relative to steering speed.

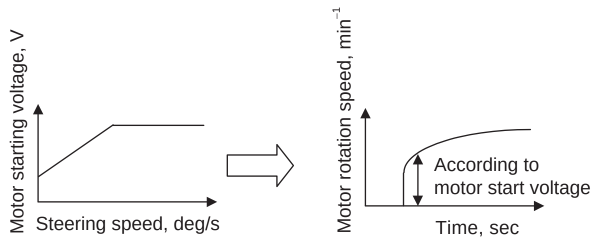


Fig. 10 Control map of motor start voltage relative to steering speed

(3) Neutral point detection control

With the stop & go control, the motor must be stopped at the neutral steering wheel position when moving straight forward. There is also the method of using a steering angle sensor to detect the absolute angle, but this is currently difficult to be realized because there are many problems such as mountability on a vehicle, cost and precision of position detection.

For this reason, using a steering angle sensor that detects relative angle, a control algorithm that calculates and detects the neutral position of the steering wheel has been developed. In this control algorithm, calculation and detection are performed by using motor current and steering amount during low-speed traveling, and steering position and travel distance during high-speed traveling.

A brief description of the development is shown as follows.

Figure 11 shows the control block diagram for neutral point detection.

When steering is maintained during low-speed traveling, the steering position and current value are detected.

When steering is maintained on long curves, these are continuously detected. In order to prevent the neutral point from being fixed at the wrong position, a neutral point limiter function is provided so that once detection is executed, the next detection is not executed until the steering wheel is manipulated significantly. By comparing several sets of current value data detected with this method, the smaller ones are selected as a potential neutral point, and the neutral point is decided by comparing these steering positions.

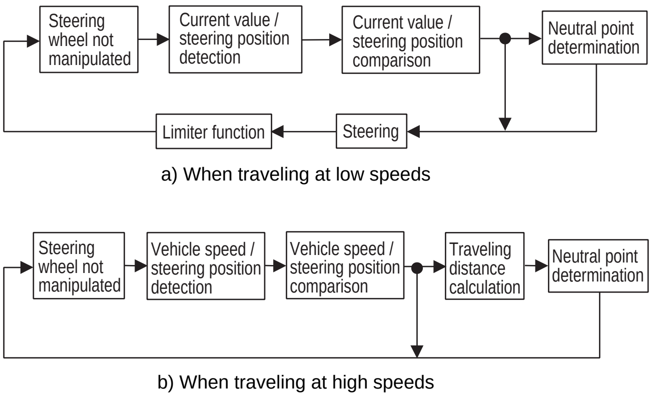


Fig. 11 Neutral point detection control block diagram

When traveling at high speed, the steering wheel is manipulated less often and the wheel is not turned far, so neutral point decision is almost not carried out, with only the neutral position detection method during low-speed traveling. In order to solve this problem, a method of detecting the neutral position even when the steering wheel is not manipulated was also developed.

When a certain type of traveling is conducted within a steering position range while constantly monitoring vehicle speed and steering position under maintained steering condition, the steering positions are selected as a potential neutral point, and the neutral point is decided by comparing those steering positions.

3) Idle & go control

In order to prevent deterioration of steering feeling even if a low-resolution steering angle sensor is used, a control method was also developed that makes the motor stand-by at super low rotation speed (idle mode) without completely shutting off the motor.

This control method has the same type of algorithm as the stop & go control except for control that stops the motor when traveling straight is changed to super-low rotation speed condition.

5. Other Controls

1) Vehicle speed control

Figure 12 shows the control map for the motor speed relative to the vehicle speed.

With the PS system, it is desirable to lighten steering effort when traveling at low speed and make it heavier at high speed to provide steering stability. With H-EPS therefore, better steering feeling is achieved by using the following four values to control vehicle speed.

① Stand-by rotation speed
② Idle rotation speed
③ Steering speed-motor rotation speed characteristic slope
④ Maximum rotation speed

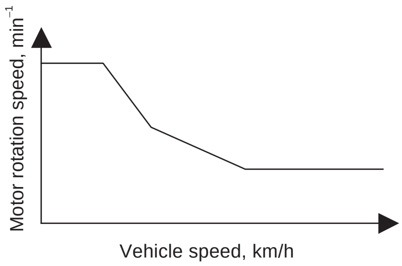


Fig. 12 Control map of motor rotation speed relative to vehicle speed

(1) Stand-by rotation speed and idle rotation speed

If stand-by and idle rotation speed are raised, steering power becomes lighter, and if lowered, steering power becomes heavier. Stand-by and idle rotation speed are basically highest when the vehicle is stopped.

By reducing the value as speed increases, steering stability at around high speed neutral position can be obtained.

(2) Steering speed - motor rotation speed characteristic slope

Steering response is improved if the steering speed - motor rotation speed characteristics slope shown in **Fig. 8** is made larger. This slope is basically smallest when the vehicle is at high speed. By increasing the value as speed decreases, steering response and effort are enhanced.

(3) Maximum rotation speed

If stand-by rotation speed and steering speed-motor rotation characteristics slope are altered, motor rotation speed may rise too much and produce unpleasant pump and motor sounds because under the vehicle stop condition, there is no particular road noise and the engine is operating at low speed.

The maximum motor rotation speed of the steering speed-motor rotation speed characteristic curve shown in **Fig. 8** is suppressed and sound is therefore reduced when the vehicle is stopped.

2) Acceleration control

When suddenly reducing speed to avoid danger, etc., smooth steering must be made possible even if the front load is increased by inertia of the vehicle. The fact that the vehicle will be steered is predicted in advance by calculating acceleration from vehicle speed sensor signals. Acceleration control shifts the motor from being stopped or idling rotation speed to stand-by rotation speed, or oppositely if at the stand-by rotation speed, does not allow speed to be shifted to stopped or idling speed.

Figure 13 shows the acceleration control block diagram.

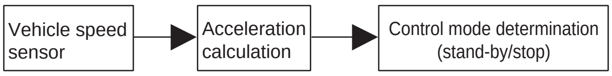


Fig. 13 Acceleration control block diagram

3) Low temperature start control

Compared with conventional engine drive pumps, the motor is affected by PS oil viscosity at low temperature and startability of the pump becomes a problem.

With this system, therefore, a temperature sensor is used when temperature is low so that the motor turns to full-driven mode and returns to normal control after appropriate oil temperature is reached.

Figure 14 shows the control map of motor drive voltage control relative to temperature.

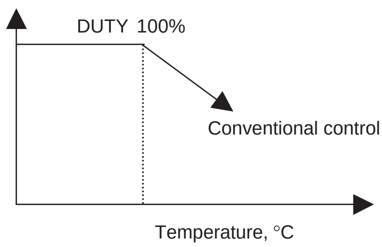


Fig. 14 Control map of motor drive voltage relative to temperature

4) Failsafe control

Concerning belt drive system by engine such as conventional NPS, it is difficult to predict when a belt will break, but driving by a motor equipped with a controller provides various failsafe functions such as those of EPS. In the case of failure, it is detected by results of FMEA design analysis and the system is stopped safely.

This also enables the system to be equipped with a self-diagnosis function to determine the cause of the failure.

It is also possible to provide freedom of control that only PS operates even when the engine is stopped in order to enhance vehicle safety if required by the customer.

Table 3 shows typical failure detection items of the failsafe function.

Table 3 Failure detection items

Motor internal failure	Motor external failure (vehicle side)
Motor lock function	Vehicle speed sensor failure (disconnection, short-to-battery/ground)
Excessive motor current (short)	Steering angle sensor failure (disconnection, short-to-battery/ground)
Excessive motor temperature	Engine rotation speed sensor failure (disconnection, short-to-battery/ground)
ECU circuit failure	Battery voltage drop

5) Communications control (CAN communication)

In addition to K line communication conforming to the conventional ISO9141, the system is capable of using CAN communications (Control Area Network) which many automobile manufacturers, especially in Europe, are considering to adopt in the future.

Most European automobile manufacturers currently use a CAN based network for drive systems and multiple communications, and this will tend to increase in the future. In the United States as well, automobile manufacturers are already considering a CAN base network (J2411 or J2284) in place of J1850.

As for the merits of CAN, compared to vehicles using existing serial communications control, it is said that the amount of cable per vehicle can be reduced by approximately 200 meters to 1 kilometer, and weight can be reduced by 9 to 17 kilograms. The controller can also reduce the amount of circuits needed for direct interface with the sensors, so there are many merits.

6. Preparation of Development Environment

1) Development of tuning tool (parameter altering function)

At Koyo, a PC base tuning tool was simultaneously developed that optimally matches the H-EPS system with the concerned development vehicle in a short period of time.

Figure 15 shows the configuration of the tuning tool, and **Fig. 16** shows an example of the display of the parameter alteration tool.

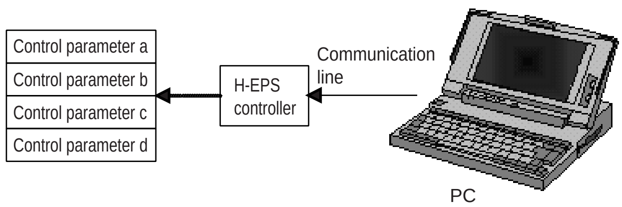


Fig. 15 Tuning tool configuration

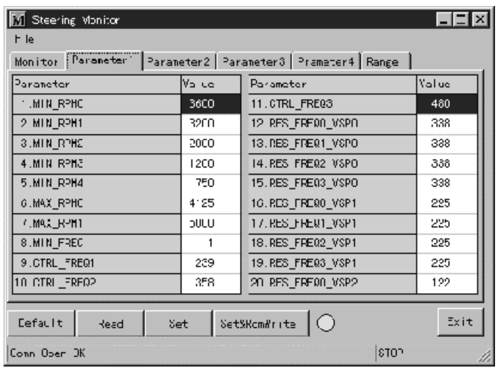


Fig. 16 Example of parameter alteration tool display

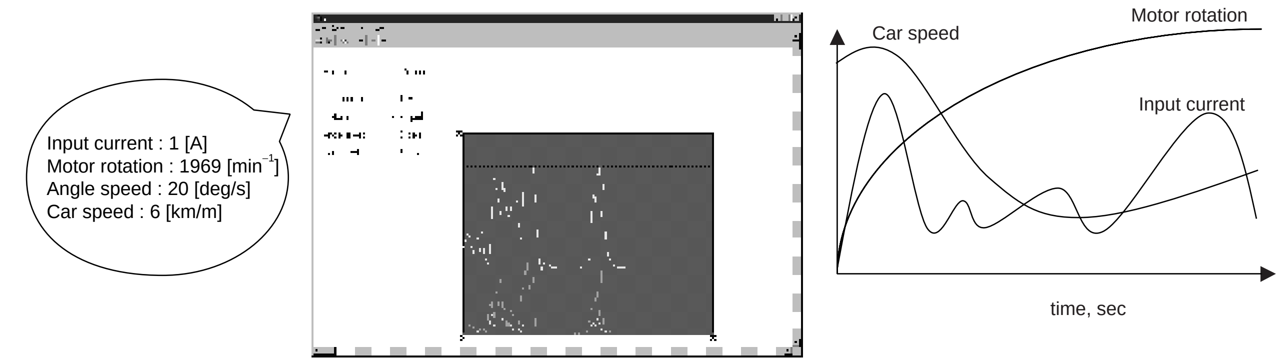


Fig. 17 Real time monitor display

This tuning tool can rewrite control parameters in controller by simply changing the values on the PC screen. Because the tuning tool can be used while mounted on the vehicle, it enables development period to be dramatically shortened.

2) Development of real time monitor

The required data can be easily monitored and collected in real time online. A real time monitor that can facilitate development has also been developed, thereby enhancing added value of the tuning tool function.

Figure 17 shows a display of the real time monitor.

This enables the test driver to easily know the effect on steering response caused by altered tuning parameters even while driving the vehicle, and precise tuning in real time is achieved.

7. Effect on Energy Savings

To measure automobile fuel consumption, measurement is generally performed with a chassis dynamometer in the 10.15 mode or in various modes.

With these measurements, however, only the speed change mode under straight-ahead driving is input. Therefore Koyo performed measurements using TOWN mode or EU mode that includes a steering mode closer to actual driving by introducing fuel consumption measurement method that takes the steering system into consideration. As a result, it was determined that much greater effect than conventional NPS could be obtained for energy consumption with the stop & go system.

Figure 18 shows energy saving ability in each H-EPS control mode compared with conventional NPS.

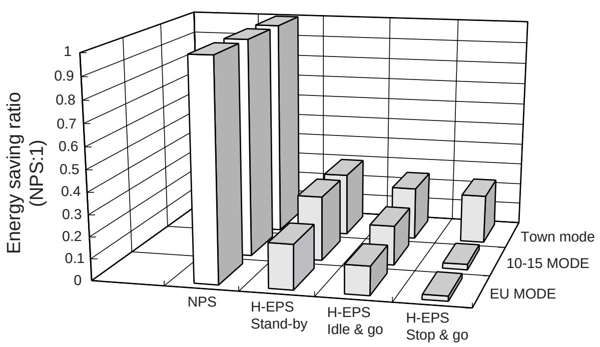


Fig. 18 Energy saving ratio for each H-EPS control method versus NPS

8. Conclusion

Koyo has worked ahead of all others on developing energy-efficient power steering systems which the company rank as the products designed to preserve the global environment, and has succeeded in developing H-EPS for passenger vehicles that has dramatically improved fuel saving ability compared to conventional NPS.

In addition, there are demands to equip small truck classes with the same system, but it requires motor increased output. With a system that uses a 12-volt battery as its power source, however, a lot of current is consumed and the design (e.g. increasing output load of the battery and alternator on vehicle, increasing thermal load on connectors, increasing voltage drop by harness, and increasing thermal load on controller) is limited.

It is therefore indispensable to raise battery voltage from the current 12 volts to 42 volts, and to develop a high-voltage system to lower current consumption of the motor.

Koyo will develop an energy-efficient H-EPS system that can handle high voltage, to make it available for so many types of vehicles.