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Development of Electric Power Steering

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ABSTRACT

A new electric power steering (EPS) was developed which uses an electric motor to provide assistance. It is a system combinning the latest in power electronics and high power motor technologies. The development was aimed at enhancing the existing hydraulic power steering's energy efficiency, driver comfort as well as increasing active stability.

This paper describibes the overall concept of EPS and outlines the components and control strategies using electronics. The EPS was tested on a front wheel drive vehicle weighing 1000kg in front axle load. The results showed a 5.5% improvement in fuel economy. The EPS has also achieved returnability that gives the driver more moderate feelings matching the vehicle in action as well as the active stability control strategy for high speed driving.

1.INTRODUCTION

Recently, electronics application to automobile technology is remarkably spreading. This means that the electronics are going to be used for the following objectives which the automobile technology inherently demands :

(1) Improvement in efficiency;
(2) Improvement in comfortability; and
(3) Improvement in safety.

The electronics application allows us to obtain very desirable effects in relation to those 3 objectives.

For example, the electronic fuel injection systems have given engines high output and remarkably less fuel consumption. Shift shock in the automatic transmissions has been very much reduced. The anti-lock brake systems allow us to brake easily the vehicles running on snow covered slippery roads.

Concerning the power steering system, the hydraulic steering system is now the main steering system and widely used even in small cars. The hydraulic steering system has about a half century history and thought to be a completed technology. However, considering the objectives above mentioned, it is thought that a time has come to restudy the existing system.

This paper describes thorough solution of negative points owned inherently by the hydraulic power steering system, and outlines effects of the electric power steering system (EPS) developed newly to eliminate those negative points and further to add merits to the steering system.

2.DEVELOPMENT CONCEPT OF EPS

Considering the points described above, requirements for the next generation power steering which will take the place of the hydraulic power steering are thought to be as follows: the new technology shall make improvements over the hydraulic power steering, create new merits to be added to the existing system, and establish the technology as a basis of the steering system in future. We studied concretely on the new steering system to be applied to a front drive passenger car weighing 1000 kg in front axle load. Our targets were as follows:

* Improvement in actual fuel efficiency could be obtained.
* Driver's feeling on steering should be the same or better compared with that on the existing hydraulic power steering, and the new power steering should match easily dynamic performance of the car.
* The new system should have the same or higher drive safety compared with that of the existing system.

Further, design concept of the system and component were as follows:

* To enhance productivity, the system had to be composed simply.
* As the system had the most important components in view of drive safety, highly reliable design was required.
* The system should have high serviceability and maintenability.

3.SYSTEM OUTLINE

3.1 Construction and operation description

(1) System composition

As Fig.1 shows, EPS system consists of the following components:

* Gear box containing rack and pinion mechanism and generating assist force based on signal issued by input from steering wheel operation and signal from vehicle speed sensor.
* Two vehicle speed sensors to detect vehicle speed.
* Relay to shut off power supply.
* Fuse box containing fuse to be fused to shut off overcurrent.
* Indicator light to issue failure warning and show kind of failure.

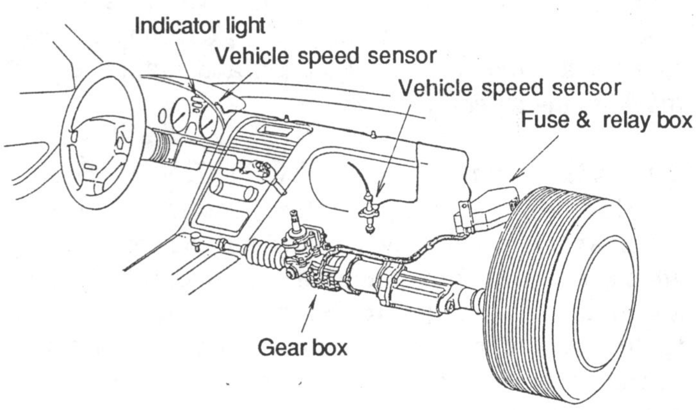


Fig.1 System composition drawing

(2) Component

(2.1) Gear box

As shown in Fig.2, the followings are added to the traditional rack and pinion steering mechanism:

* Steering sensor to detect steering input.
* Control unit to calculate optimum assist force based upon main input including signal from the sensor described above and the vehicle speed sensor, to output the calculation results to a power unit and at the same time to diagnose condition of each function parts and the control unit itself.
* Power unit to drive a motor according to signal issued by the control unit.
* Assisting mechanism to reciprocate the rack shaft by thrust force to which motor torque is converted through a ball screw.

During the system design, the following two layout plans had to be examined in view of reliability of the electric system:

a) The electric parts such as the control unit and power unit were installed in the cabin to protect them from being exposed to outside circumstances directly.

b) The electric system parts were placed in the gear box to simplify the system and further, the box could serve as a container having enough strength to protect the electric parts from the outside condition.

As a conclusion the plan b) was selected and both control unit and power unit were placed in the gear box. This construction is called "mechatronic combined construction". Adoption of this construction forced us to study how to design both the units in small size. However, the following greater merits could be obtained that made our study efforts worthwhile.

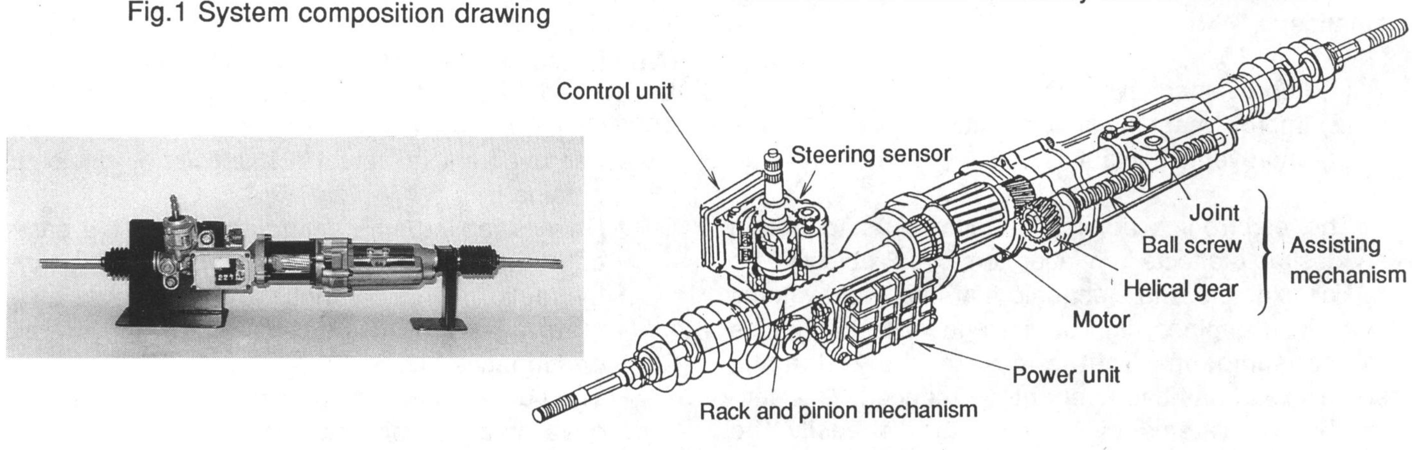


Fig.2 Gear box

* Simple system composition allowed us not only to reduce its weight, but also to control the assist characteristics which included performance variation of the control unit and power unit. As a result, steady characteristics of the system could be obtained.
* As the plan b) did not require to lay lines of the power unit inside or outside of the cabin, signal lines were less affected by outer noise, and power line issued noise reduced.
* As heat generated by the power unit could be transferred to the gear box, no cooling fin was required for the power unit.
* Automatic assembly of the EPS and further, automatic attaching of the complete EPS to a car can be expected.

Now, explanation on each component is given.

1) Steering sensor

As Fig.3 shows, the steering sensor detects steering condition, and consists of a torque sensor, which senses rotation torque of a steering wheel, and a rotation speed sensor, which senses rotation speed of the steering wheel.

a) Torque sensor

The torque sensor consists of an input shaft, connected to the steering wheel, a pinion shaft, with pinion gear of the rack and pinion mechanism, a torsion bar, connecting the input shaft and the pinion shaft, a slider, with a movable iron core, a cam mechanism, converting relative torsional displacement between the input shaft and pinion shaft to axial displacement of the slider, and a linear variable differential transformer, converting displacement of the slider to electric signal. As Fig.4 shows, amount and direction of the steering wheel torque can be detected based on displacement and direction of the slider. In Fig.4, S3 shows output signal of torque and S1 and S2 show outputs for diagnosis use.

The differential transformer type torque sensor has a high sensing accuracy and also good temperature characteristics since the output is obtained differentially. Further, as its electric system is composed in duplication, system failure can be detected easily and the system has high reliability.

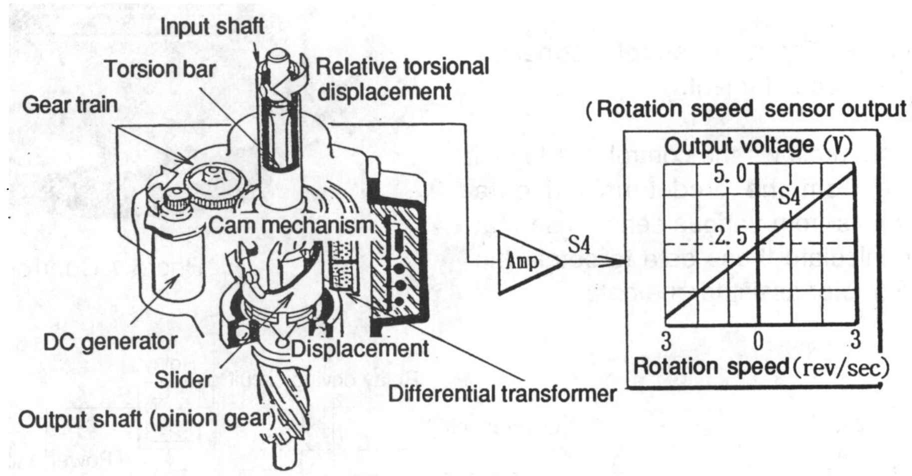


Fig.3 Steering sensor

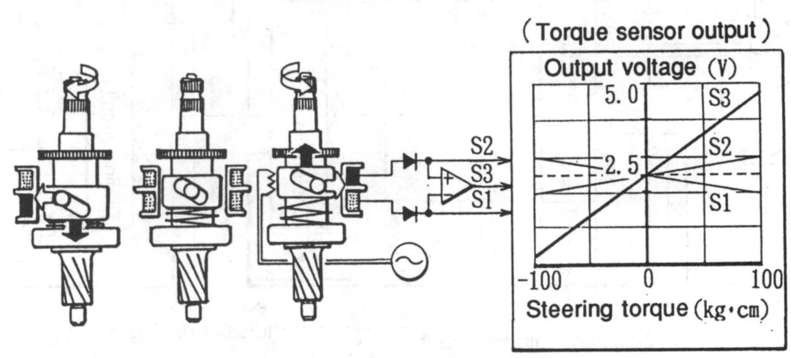


Fig.4 Working diagram of torque sensor

b) Rotation speed sensor

The rotation speed sensor consists of a gear train equipped on input shaft and a DC generator whose speed is raised by the gear train. This sensor senses rotation speed and rotation direction of the generator to know rotation speed and direction of the steering wheel. The signals indicating rotation speed and direction of the generator are issued to the control unit. S4 in Fig.3 is the rotation speed output.

2) Control unit

As Fig.5 shows, the control unit consists of the following major circuits:

* One chip, 8-bit microcomputer with built-in A/D converter and PWM unit.
* Interface circuit to adjust signals from various sensors.
* Driving circuit to drive the power unit(described later) through the PWM unit.
* Torque check circuit to check torque signal.
* Watch dog timer (WDT) circuit to check operation of the one chip microcomputer.
* Relay driving circuit to drive relays.
* Indicator lamp driving circuit to drive the indicator lamp on/flashing.
* Constant voltage circuit to supply constant voltage current to each element.

Table look up system allows the control unit to call instantaneously data from the predetermined data table based upon signals from various sensors so that the control unit can calculate those data to obtain the optimum assist force (motor assist torque data).

Further, failure diagnosis is performed on each sensor and the 1 chip microcomputer. If there should be any failure in them, the relay driving circuit stops to shut off the relay and consequently the motor power stops. At the same time, the indicator light turns to on and failure mode is stored, and the light can be flashed to indicate failure if necessary. Then, the EPS system can be operated only manually.

Reliability design had to be given to the control unit as the mechatronic combined construction, as mentioned before, required the unit to be small in size and further to have a high resistance against environmental stress. During the development, discrete circuits were used for the control unit. However, after its specification had been determined, high density design using LSI was done. As a result, the LSI whose size is a little smaller than of a tobacco case was obtained. Considering vibration resistance, water proof and heat resistance, the control unit construction is epoxy resin molded one. Photo 1 shows its appearance (the mold treatment is omitted to show its circuit).

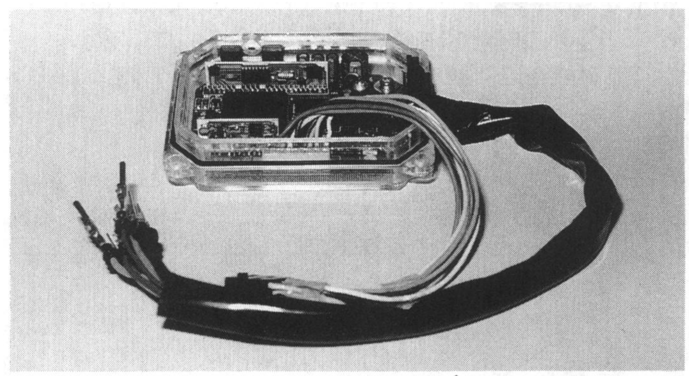


Photo 1 Control unit

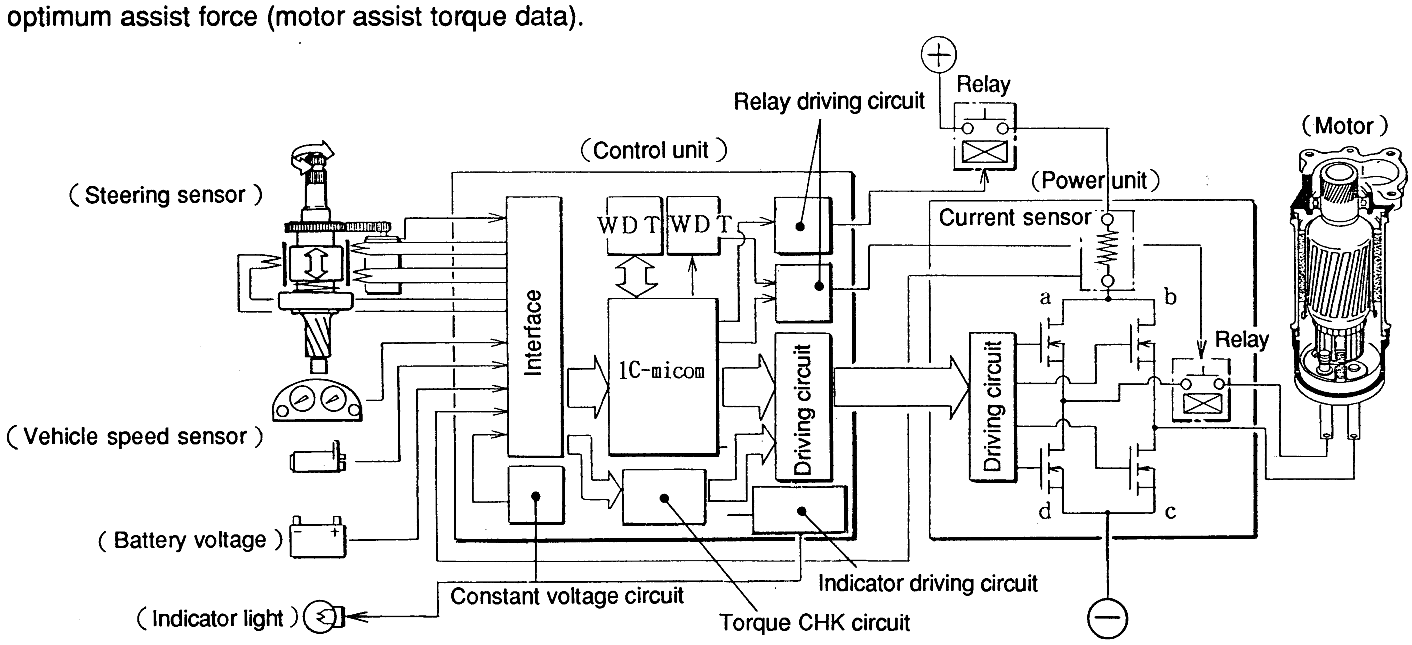


Fig.5 System block diagram

3) Power unit

The power unit consists of the following major components as shown in Fig.5:

* FET bridge circuit to drive the motor.
* Circuit to drive the bridge circuit based on signal from the control unit.
* Current sensor to detect current supplied to the power unit.
* Relay to turn on/off motor current.

The power unit drives the motor based on instruction from the control unit. The current at that time is monitored by the control unit via the current sensor and if an abnormal condition is found, the relay shuts off motor current.

In our initial development concept, a vehicle weighing 1000 kg in front axle load was supposed. Then, the max. current of 90 A had to be driven by the FET bridge circuit. On the other hand, to meet requirements of the mechatronic combined construction, the power unit had to be small in size and have a high reliability as mentioned above. To satisfy the requirements, FET chip is installed on a ceramics base plate and they are sealed with gel to be a module type (see Photo 2). This design allows the power unit to have a high capacity, but still its size is a little smaller than that of a tobacco case.

Progress of heat analysis technology permitted the chip surface temperature to be visible, and the optimized junction temperature could be achieved. The power unit was integrated to the aluminum casted gear box as one body, and it was confirmed that heat from the unit was dissipated effectively by this method.

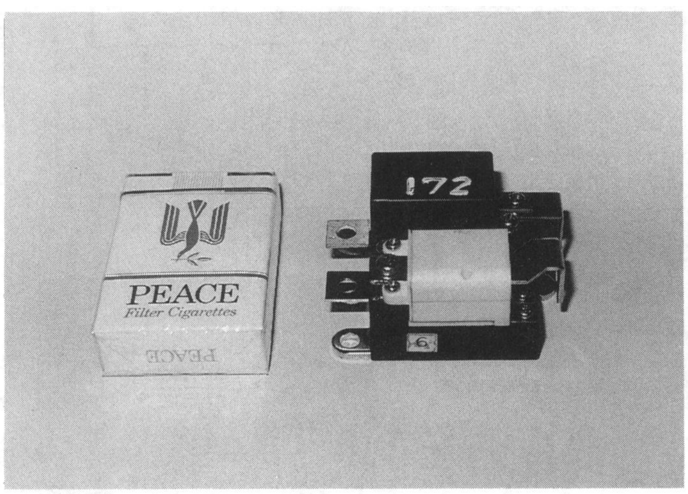


Photo 2 Power unit

4) Assisting mechanism

As Fig.2 shows, the assisting mechanism consists of the following components and rotation torque is converted smoothly and effectively to reciprocating movement of the rack shaft.

* Motor arranged coaxially with the rack shafts to generate rotation torque.
* Helical gear to transmit rotation torque to the ball screw.
* Ball screw to convert rotation torque to thrust force through the helical gear.
* Joint giving thrust force obtained from the ball screw to the rack shaft.

As equation (1) shows, when a thrust conversion ratio i/ℓ is large, or motor torque T_M is high, strong thrust force can be achieved.

$$P = 2\cdot\pi\cdot i\cdot\eta\cdot T_M/\ell \qquad (1)$$

where, P : thrust force $\quad$ i : gear ratio
η : efficiency $\quad$ T_M : motor torque
ℓ : lead of ball screw

Considering degree of freedom in steering feeling setting, smaller conversion ratio is desirable. To make motor torque as high as possible,a large motor as far as the layout permits is used, i.e., the motor has an outer diameter of 94mm and 6-pole ferrite magnet. At first brushless motor was planned in view of maintenance free, but as torque of the same size brushless motor was about 2/3 of that of brush motor, we were forced to give up the brushless motor at that stage . The motor was designed to satisfy the following 3 items according to required performance of the EPS:

* High torque output at low rotation speed.
* Low torque ripple.
* Low friction.

Motor torque is determined by outer diameter of its rotor. Therefore, a rotor center part is needed only to have an enough thickness to form magnetic circuit.
The hollow rotor through which the rack shaft was placed was designed to reduce rotor weight.

As the ball screw was required to convert torque to thrust force and vice versa smoothly and efficiently, it was designed considering the following two points:

* Nut should be moment free.
* To make lead angle larger.

To reduce deflection influence on the rack resulting from bending moment given by tie rod, the rack and ball screw were arranged in parallel and the joint was designed to absorb deflection of the rack.The design allowed us to have the minimum screw diameter and to make the lead angle larger.

(2.2) Vehicle speed sensor

The vehicle speed sensor senses vehicle speed and issues pulse rows with frequency proportional to the vehicle speed to the control unit. Two vehicle speed sensors are used to diagnose failure of them.

(3) Operation description

As Fig.6 shows, assisting operation (shown with black arrows) is added to manual steering (shown with white arrows) to reduce steering effort.

(3.1) Manual steering operation

Steering wheel input is transmitted to the pinion shaft of the rack and pinion mechanism via the universal joint. Rotation displacement of the pinion shaft is converted to axial displacement of the rack, and thrust arises. The axial thrust is transmitted via the tie rods to the knucles which support rotating tyres and the thrust is converted to oscillating displacement of tyres. Therefore, steering wheel input can finally make the tyres to oscillate to turn vehicle direction.

(3.2) Assisting operation

Other than the manual operation mentioned above, steering wheel input (torque and speed) is sensed by the steering sensor and signal is issued to the control unit. The control unit receives the signals along with vehicle speed signal from the vehicle speed sensor. The unit determines assisting force from predetermined table so that the optimum steering characteristics can be obtained and calculates output data. At the same time, the unit detects steering condition based on signals from various sensors and decided modes (normal, return and damper). The output data and the modes switching signals are output to the power unit. The power unit drives the motor based on those signals. Motor torque generated is transmitted to the ball screw via the gear. Then, motor torque is converted smoothly and efficiently through the ball screw to assisting force working along axis of the rack shaft. As a result, the thrust acts on the rack shaft and reduce another thrust obtained by the rack and pinion mechanism as mentioned above, i.e., the thrust generated by the motor is fed back to the steering sensor to reduce driver's effort on the steering wheel.

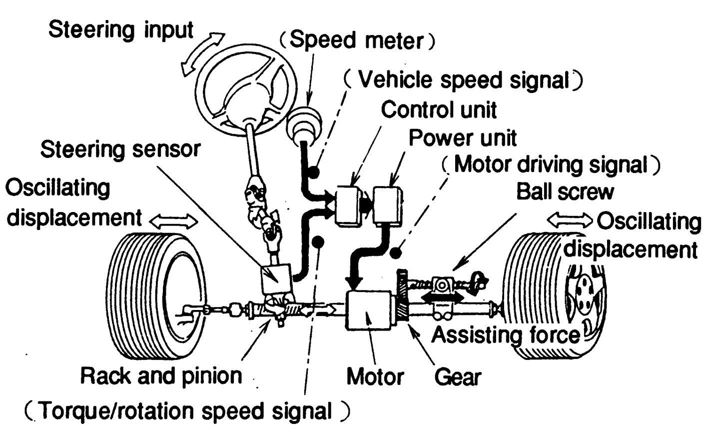


Fig.6 System process diagram

3.2 Control principle and basic control

(1) Control principle

Fig.7 shows equivalent circuit of the motor. Where, motor terminal voltage is V_M, inductance is L, resistance is R, induction voltage constant is k, rotation speed is N, current is i, and time is t, the following equation is obtained:

$$V_M = L\,(di/dt) + R \cdot i + K \cdot N \fallingdotseq R \cdot i + K \cdot N \qquad (2)$$

Current i is proportional to motor torque T_M and when Kt is a proportional constant, the following equation is obtained:

$$V_M = K_T \cdot T_M + K \cdot N \qquad (3)$$

Signal issued by the torque sensor sensing steering torque and signal issued by the rotation speed sensor sensing steering wheel rotation speed are input to the control unit as shown in Fig.8. In the control unit, motor torque data and its rotation speed data are determined respectively responding to the data table being predetermined so that the optimum steering characteristics can be achieved. As a result, the motor can be controlled directly by adding both data.

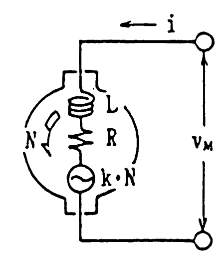


Fig.7 Motor equivalent circuit

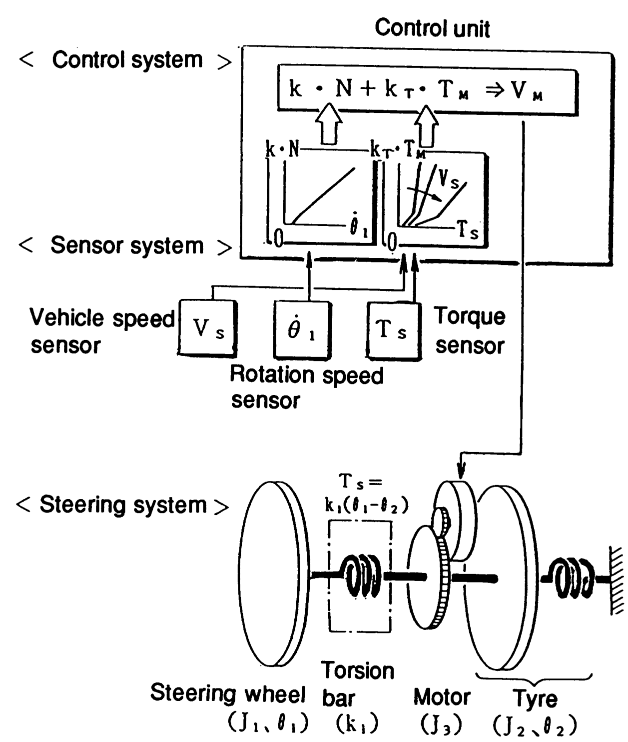


Fig.8 Control principle diagram

When signal issued by the vehicle speed sensor sensing vehicle speed is input to the control unit to reduce motor torque data, steering torque can be increased with vehicle speed increase to be able to give driver reaction feeling of the steering wheel.

(2) Basic control

This description covers an important technology to determine steering feeling. As steering is controlled directly by driver, its feeling requires smoothness instead of on-off like. For this purpose, the following technology was developed by us.

* Operation time for one loop was 1 msec or less.
* Driving the motor with PWM (Pulse width modulation) method of 20 KHz or more.

The first item was achieved by adopting the table looking up system that could process data instantaneously instead of complicated data processing with software. The second item was achieved using the enhancement type power MOS FET which could drive the motor with a high current and had extremely high switching speed.

Then, the control method following the control block diagram shown in Fig.9 is described. The basic control consists of 3 controls, normal control, return control and damper control.

A) Normal control

This control method is to make motor torque act on the rack shaft of the rack and pinion mechanism via the ball screw to reduce force to be exerted on the steering wheel.

In the control unit, the following operations are carried out:

1. Input signal from the vehicle speed sensor is measured and processed to obtain vehicle speed data (V_s).
2. Input signal in relation to torque and its direction from the torque sensor are measured and processed to obtain torque data (T) and torque direction data respectively.
3. Input signal in relation to rotation speed and direction from the rotation speed sensor are measured and processed to obtain rotation speed data (N) and rotation direction data respectively.
4. Based on vehicle speed data (V_s) and torque data (T), basic torque data (T_M), torque gain data, and torque offset data (T_O) are retrieved from respective tables and finally motor torque (T_M) is calculated.
5. Based on rotation speed data, rotation speed data of the motor (N_M) is retrieved using the table.
6. The rotation speed data of the motor (N_M) is added to the motor torque data (T_M) to obtain motor output data.
7. To determine motor rotation direction (right/left) based on torque direction data (right/left), output data is output to the power unit with modes being switched. However, if output data is zero, the modes shall be switched to the neutral to make motor torque zero.

Then, in the power unit:

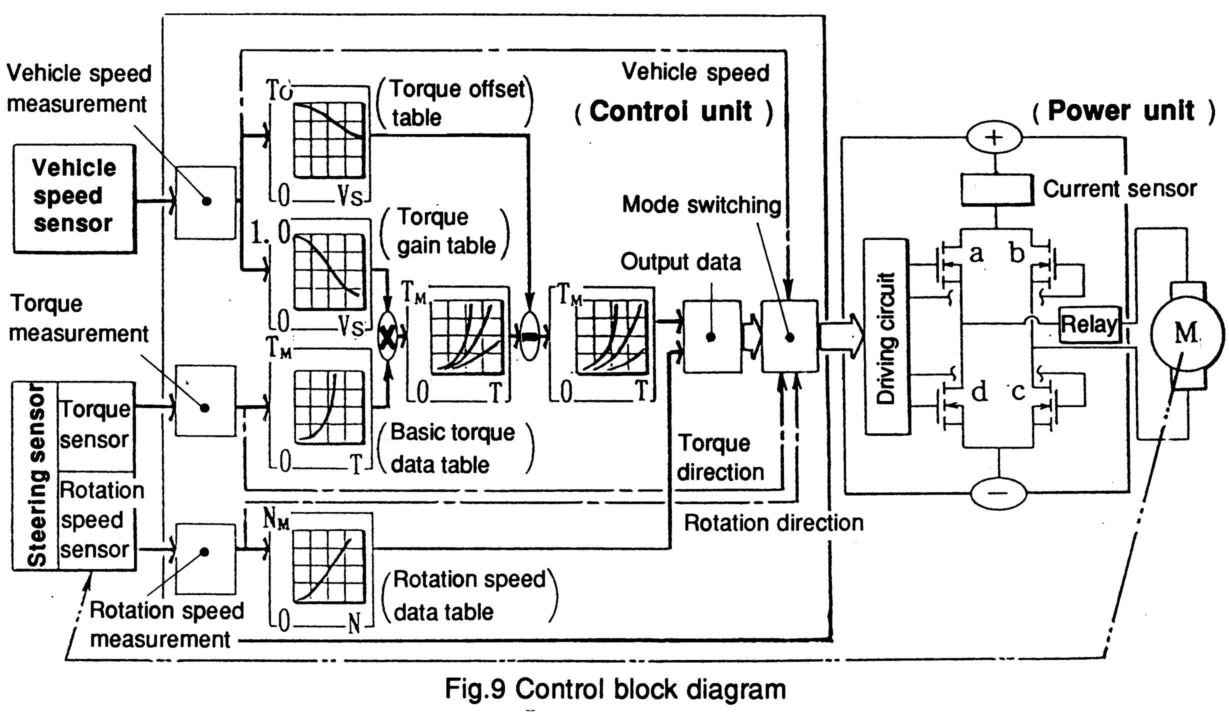


Fig.9 Control block diagram

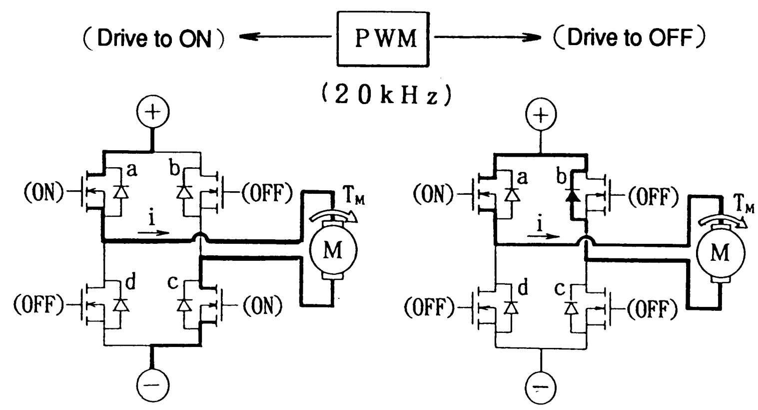


Fig.10 FET bridge working diagram

8. When mode switching signal indicates right, FET(a) is driven to ON, and at the same time, FET(c) is driven through PWM driving signal based on output data. When mode switching signal indicates left, FET (b) is driven to ON and at the same time, FET (d) is driven through PWM driving signal based on output data. When mode switching signal indicates the neutral, all FET from (a) to (b) become OFF.

As described above, force to be exerted on the steering wheel can be varied freely according to vehicle speed and rotation speed of the steering wheel.

B) Return control

With force reduction on the steering wheel, the steering wheel is liable to be returned by self-aligning torque. Therefore, it is required that motor torque is smoothly reduced according to reduction of force exerted on the steering wheel. However, if the force on the steering wheel is reduced under the normal control, motor inductance forces motor current i to continue to flow via diode of the FET (b) with OFF drive of PWM, as Fig.10 shows. As a result, return characteristic has a damping tendency and lacks response ability sometimes. Therefore, items 6 and 8 of the normal control have to be modified as follows;

At first, in the control unit:

6. Considering torque direction data and rotation direction data, the return control is required when their directions are different. Otherwise, the normal control is required. For this reason, the modes must be switched to the return mode under this condition.
7. This item is the same as that of the normal control.

Next, in the power unit:

8. When mode switching signal indicates right, FET (a) is driven through PWM driving signal based on rotation speed data of the motor (N_M) and at the same time, FET (c) is driven through PWM unit based on motor torque data (T_M). On the contrary, when mode switching signal indicates left, FET (b) is driven through PWM driving signal based on number of rotation data of the motor (N_M) and at the same time, FET (d) is driven through PWM driving signal based on motor torque data (T_M).

As described above, in the case shown by Fig.10 as well, speed of the motor can be decreased according to rotation speed of the steering wheel. Further, when the motor rotation speed table under normal control and that table under return control are prepared separately, return characteristic of the steering wheel can be varied freely by modifying the motor rotation speed table under the return control.

C) Damper control

In Fig. 7, if between both terminals are short circuited, the equation (4) is obtained from the equation (3).

$$T_M = -(K / K_T) \qquad (4)$$

This means that damper torque, which is proportional to motor rotation speed and direction is contrary to rotation direction of the motor, arises. Based on this principle, this control method intends to improve actively steering convergency.

In the EPS system, its inertia of steering system is greater than that of traditional steering system due to inertia of its motor. This is a demerit of the EPS in view of steering convergency. Therefore, the damper control is an effective method when inertia of the motor is set at a comparatively large value (this is the same when the thrust conversion ratio is high).

The damper control can be achieved when the item 6 and 7 of the normal control are modified as in the return control.

At first, in the control unit:

6. When motor torque data is less than the specified value and rotation speed data is larger than the damper control table data retrieved from vehicle speed data, i.e., steering wheel rotation speed is high with no action being given to the steering wheel, the modes have to be switched to the damper mode.

Next, in the power unit:

7. As mode switching signal indicates the damper mode, both FET (c) and FET (d) are driven to ON at the same time.

As described above, the motor can generate torque proportional to rotation speed of the steering wheel and counter-direction to the wheel. When damper control table is modified, effectiveness of the damper control can be varied.

4. RELIABILITY DESIGN

4.1 High reliability concept

The EPS system requires high reliability since the system is the important one that steers the vehicle. Especially, the EPS is the assist system which generates electric motor power, when required, under electronic control, to drive directly the steering system to reduce driver's effort to be exerted on the steering wheel. Considering its role, it is essential that the EPS has to be inactive and not to fall active when the EPS is unnecessary. Therefore, the first point to consider on design is that the EPS shall be free of failure, and then fail safe against any failure.

(1) Failure free design

(1.1) Design based on actual data

Important EPS parts such as rack and pinion mechanism, ball screw and steering sensor mechanism must be designed so that they can have the same time-tested concept and design as the hydraulic power steering.

(1.2) Strength guarantee

The strength of steering parts such as input/output shafts for rack and pinion mechanism, ball screw and steering sensor mechanism, must be made to comply with the strength specification of our steering system.

(1.3) De-rating

Highly stressed parts such as power MOS-FET of the power unit and the motor shall be specified to have higher safety factor than usual parts.

(1.4) Aging

Electronic parts of the control unit shall be tested by giving the same stress as estimated in actual use before shipment to reduce chance failure while they are actually used.

(1.5) Foolproof

When the EPS is misoperated or required to assist steering operation excessively, its control shall be specified to have a capacity to control by itself heat generated from the power unit and motor.

(2) Safety design against failure (Faile safe)

(2.1) No single failure point

Even if its any single part should fail, the system must be designed to aboid serious trouble.

(2.2) Manual steering on failure of the EPS system

On failure of the EPS system, manual steering has to be substituted and functioned.

a) Sure diagnosis of failure

Failure of any part which might lead to a serious failure of the system, must be surely diagnosed.

b) Sure power shut off

Motor power shall be shut off in a specified time after a failure has been detected as a result of diagnosis.

(2.3) Indicator lamp lighting

The indicator lamp shall be on when any one part fails to warn against a failure of any more part thus forewarning a potentially serious system failure.

4.2 Technique establishing highly reliable design

(1) Component

(1.1) Steering sensor

The torque sensor mechanism, input/output shafts, converting mechanism are designed with the same design concept as that of the traditional hydraulic power steering. The differential transformer, whose output side, i.e., the secondary coil consisted of double circuits, including electric circuit, is used to sense displacement of the slider core. This design allows us to diagnose and detect failure without mechanical contact.

(1.2) Control unit

An one chip microcomputer, whose peripheral circuit is integrated so that CPU data bus is unexposed on top surface of substrate, is used to avoid the highest difficulty in diagnosing failure of the data bus.
As far as possible, LSIs are used to compose the simple system. This unit has epoxy resin moulded construction to be vibration proof, water proof and heat proof.

(1.3) Power unit

The power unit is of simple construction by installing FET chip on ceramic base material to reduce chip temperature. Because of poor heat dissipation of bonding wire, parallel wires are used to lower current per wire for improved toughness.

(1.4) Motor

As motor yoke has also housing function of the steering gear box, its strong and tough construction was made to offer an enough resistance against hit from flying pebbles. Improved toughness caused by magnet mould and magnet cover assure the motor reliability against a rare possibility of magnet breakage.

(1.5) Vehicle speed sensor

Diagnosing sensor failure is difficult because of its pulse input. Using two sensors enables us to diagnose sensor failure by making comparison between them. As vehicle speed signal is generally unsteady, if the diagnose system indicates sensor failure, an immediate judgement cannot be made. Under such circumstances,the higher speed data from one sensor is used for control.

(2) System

(2.1) Foolproof design

In addition to basic control, foolproof control is incorporated to protect the system from failure even when excessively loaded operation or misoperation is given to the system.

* Unloading control

  When the rack and pinion mechanism stays at either end of stroke or tyres are fixed, furthermore turning effort on steering wheel generates overcurrent in the system. If the condition lasts for a long time, the system may result in failure. Sensed rotation speed data and torque data provide a signal to protect the system from overcurrent attack.

* Moving average value control

  When steering operation is repeated incessantly on parking, especially on a hot summer day, power element such as FET is liable to fail. This control method intends to prevent such a failure by restricting current in the power unit.

  Using sensor signals from the current sensor sensing current flowing in the power unit, moving average current value, to instantaneously figure out average current value at a specified time can be obtained. When the data thus obtained becomes higher than the specified data, the control system reduces allowable maximum motor current. Thus, the average current value saturates finally to a low value. As moving average current value is almost proportional to exoergic quantity of the power elements such as FET in the power unit, the exoergic temperature can be restricted to a set value.

* Motor current control on excessive power source voltage.

  Sometimes two 12 V batteries are connected in series on to start the engine in the extreme cold. As twice the usual current will flow to the motor and otherwise, current level must be regulated to the normal current.

  Using voltage signal obtained by input battery voltage, the specified table is retrieved to obtain output correction data which makes output data smaller than increased battery voltage. This method restricts increase of current by correcting output data.

(2.2) Fail safe design

The design techniques to assure manual steering function in case system failure is detected by failure diagnosis will be outlined.

1) Failure diagnosis

a) Diagnosis method

Failure in the steering sensor, vehicle speed sensor, control unit, power unit, etc. is diagnosed by the computer. The diagnosis methods are classified roughly into the following 3 :

* Comparison between two
  - Comparison with a standard value—— Torque sensor /Constant voltage circuit,etc.
  - Comparison between equivalent properties——vehicle speed sensor /torque sensor, etc.
* Checking input/output——auxiliary circuit of control unit (interface/driving circuit etc.)/ power unit, etc.
* Identifying unusual—— rotation speed sensor, torque sensor, power unit, etc.

As almost all failure diagnises are performed using judgement function of the computer, it is required to diagnose surely the computer itself. For this purpose, an internal self-check program combined with 2 kinds of attached watch dog timer circuits are built in to secure accurate diagnosis function.

b) Action on sensed failure

When a failure is detected by the diagnosis function, basically the following actions are taken by the system:

* Motor power is shut off by the relay so only manual steering operation is available.
* Indicator light is on.
* Coded failure is stored in the one chip microcomputer. The stored code can be shown by flashing of the indicator light triggered by outside behaviors.

2) Responding technologies

Required technologies to respond to failure diagnosis is mainly as follows:

* Doubled relays to ensure shutting off motor power.
* As a result of the reliability verification test (described later), it is confirmed that there is no danger when motor power is shut off within 20 msec of a failure. So 1 msec is set for failure diagnosis control time within which to diagnose failure, but the final judgement of failure is not intended to be made untill more than one such diagnosis control time that failure is detected are repeated. Thus the objective of preventing the misjudged failure has been achieved.

4.3 Reliability verification test

The verification test steps were divided into the following 3 steps according to development levels, and the steps advanced in the order of component, system and actual vehicle.

* Various tests on performance and durability of components by applying various stress to them to verify achived levels in comparision with the design targets.
* Various breaking tests for component or system to verify strength limit and life limit to confirm their allowance for reliability.
* To study and confirm driving safety, drive test of actual vehicle under the worst possible conditions.

Tests on component and system were carried out on the benches. As the final confirmation, the system was installed in a 2.5-ℓ FF vehicle, and the various tests including a long distance running test were performed in Alaska to give the vehicle stresses such as extreme coldness, vibration and dust. And also to give various stresses under extremely hot condition to the vehicle, various tests including a long distance running test were carried out in Australia.

Among those tests described above, one of the drive safety confirmation tests which seems to be especially important to the fail safe design will be introduced here.

In this test,on the assumption that the maximum power of the motor was exerted on the steering system during driving, the allowable time from failure diagnosis and failure detection to shutting off motor power was set and its effects studied.

(1) Test method

The EPS systems were installed in a 2.5-ℓ front-engine, front-drive(FF) vehicle and 3.0-ℓ mid-engine, rear-drive(MR) vehicle as the NSX respectively. The vehicles had totally different dynamic characteristics to each other. As shown in Fig.11, they were equipped with outer system with a motor to feed the maximum power with a manually operated trigger to the vehicle running straight at high speed. As shown in Fig.12, yaw of the vehicle was measured and deviation length from the original straight line was calculated.

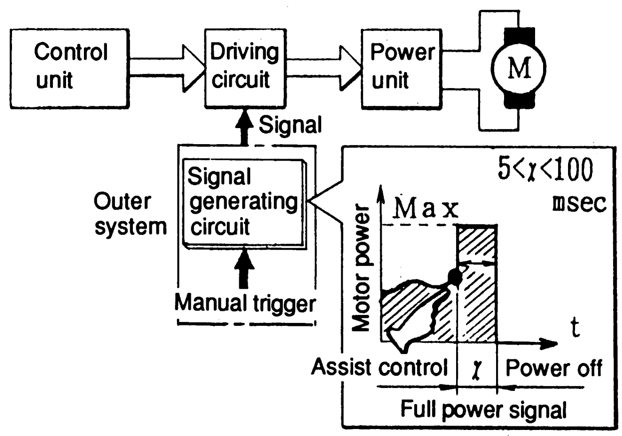
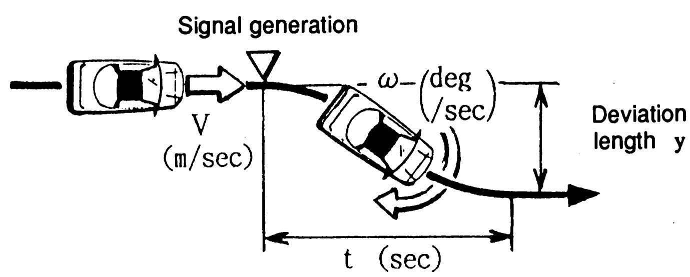


Fig.11 Test method



Yaw	:	$\omega = f(t)$
Angle	:	$\theta = \int f(t)\, dt$
Deviation length	:	$y = V \cdot t \cdot \sin\theta$

Fig 12 Calculation method for deviation length

(2) Test result

The results of the test is shown in Fig.13. The standard deviation on design was fixed considering our stability standard value aganist cross wind. The deviation length of the MR vehicle having smaller yaw inertia than the FF vehicle is larger than that of the FF vehicle. As a result, the allowable time for the MR vehicle was lowered in comparison with the FF vehicle to 20 msec.

Physical feeling given by both the MR and FF vehicles was like passing over a low step when set

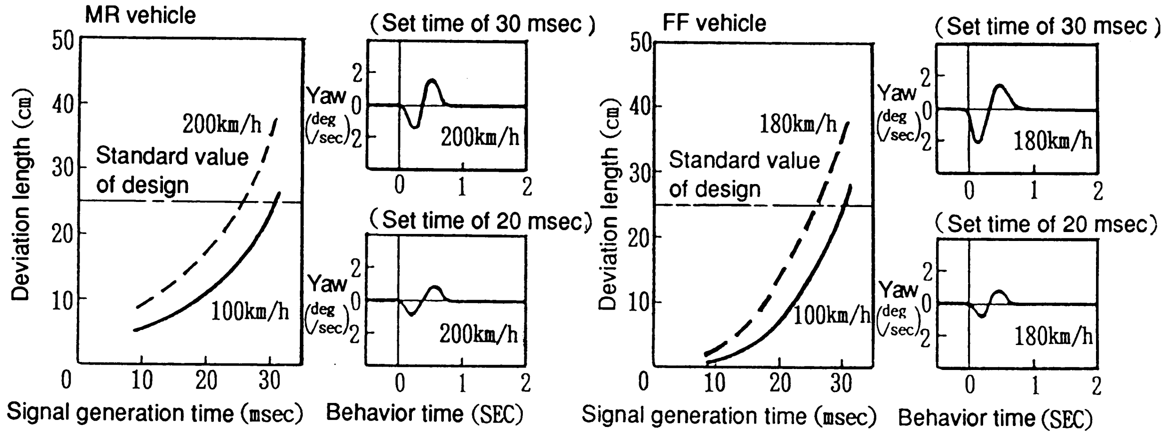


Fig 13 Test results

time was 20 msec or less, and even when it was raised to 30 msec, no more than the usual kick back feeling was given on the steering wheel.

5. EFFECT

5.1 Improvement in fuel consumption

A hydraulic steering system requires an engine to keep driving a hydraulic pump. By contrast, the EPS requires power only when steering operation is needed and power is consumed according to the rotation speed of the steering wheel. Hence the "Power on Demand" system as the EPS system is called. As Fig. 14 shows, at the same motor current, battery current increases as the rotation speed of the steering wheel becomes higher. This is attributable to the PWM driving signal.

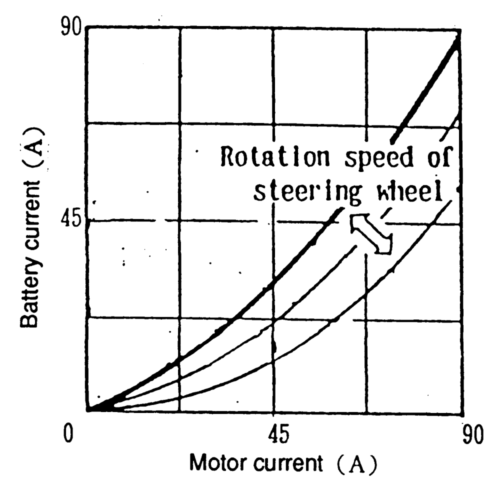


Fig.14 Current characteristic on driving through PWM driving signal

Actual improvement of fuel consumption ratio is described below.

(1) Mode fuel consumption

Measured results for the EPS on mode fuel consumption using a 2.5-ℓ FF vehicle is shown in TABLE 1. Both LA-4 and High Way modes show improvement by about 2.5%. Under fuel consumption measuring process of the mode (steering wheel was kept at straight running without using power assisting), the EPS and hydraulic steering were compared. The results shows that the EPS outscored the hydraulic steering. For the hydraulic steering's demerit results mainly from oil kept flowing in the system by the oil pump driven by the engine.

Table 1 Measurement results on mode fuel consumption

	EPS (MPG)	Hydraulic power sreering (MPG)	Improvement in fuel consumption	
			Fuel consumption difference (MPG)	Improved rate (%)
LA-4	20.51	20.01	0.50	2.50
High Way	28.88	28.18	0.71	2.52

(2) Fuel consumption on actual running

The result of measurement of fuel consumption in actual running of 1.6-ℓ FF car is shown in Fig.15. The data were obtained through a half year period of running of the same car with the same driver, but with the two different steering systems were changed. The running course was mainly suburban roads with some urburn roads, freeways and mountain roads added. To avoid possible data discrepancy arising from volatile driving ways, moderate running way was kept as far as possible.

As this was an actual running test, the data ranged somewhat. But, at this average normal speed of around 25 MPH (40 km/h), improvement of the fuel consumption ratio by about 1.6 MPG (5.5%) was achieved.

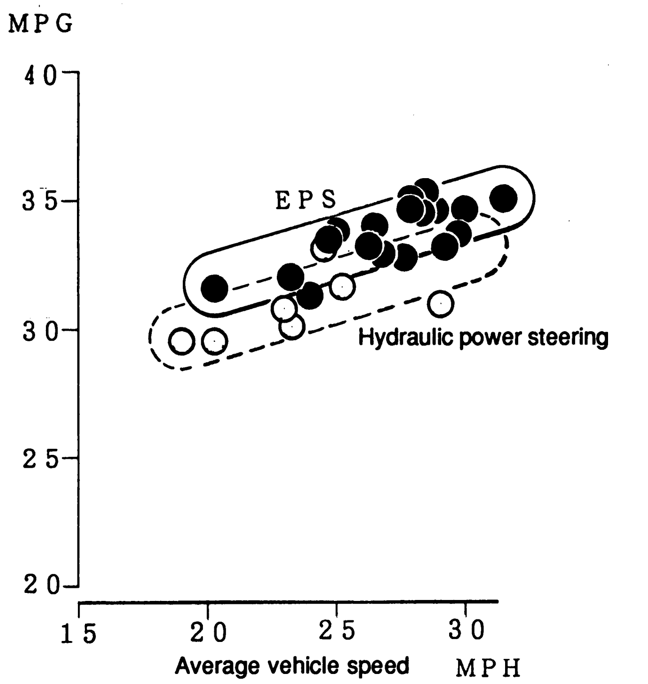


Fig.15 Fuel consumption comparison on actual running

5.2 Improvement in steering feeling

Direct and tough steering feeling given by the steering system having rack and pinion mechanism is preferable On the other hand, steering feeling of this type of steering system as opposed to the one having ball screw mechanism is liable to be affected by kick back from inverse input on the pot road or steering shimmy resulting from wheel imbalance.

In this type of EPS system, the motor is directly coupled so that motor power can act directly on steering. Thus, as the system can use inertia mass damper effect, kick back and steering shimmy mentioned above can be greatly reduced. Another advantage of this system is its enhanced steering wheel follow up ability for stationary swing on parking over the hydraulic power steering system. Because the motor torque shows the maximum value at starting of the motor and then reduces. This torque characteristic allows the system to have remarkably improved steering ability due to load reduction after start of normal running.

As described before, steering input is sensed using steering torque and rotation speed of steering wheel, and both signals are added to vehicle speed signal to calculate the optimum assisting force. At the same time, modes are switched according to steering conditions to control the motor directly. This control allows us not only to have smooth steering feeling, but also enables us to set optimum steering force according to vehicle speed and rotation speed of steering wheel as well as giving steering return characteristic matching dynamic performance of the vehicle. Further more, such performance can be easily realized by modifying data on a table in the program of the control unit. The effectiveness is summerized as follows:

(1) Toughness improvement against disturbance

Fig.16 shows kick back on steering wheel, represented by steering torque and enmeshed steering angle, arising from inverse input from uneven concrete road on which a 2.5-ℓFF vehicle equipped with the EPS or hydraulic steering ran at a speed of 30km/h (18.6M/H). Both steering torque and steering angle enmeshed with the EPS were about 1/2.4 of those with hydraulic steering.

Fig.17 shows steering shimmy data arising from imbalanced wheel using measurements of G exerting on the steering wheel to compare between the EPS and hydraulic power steering. The EPS was installed

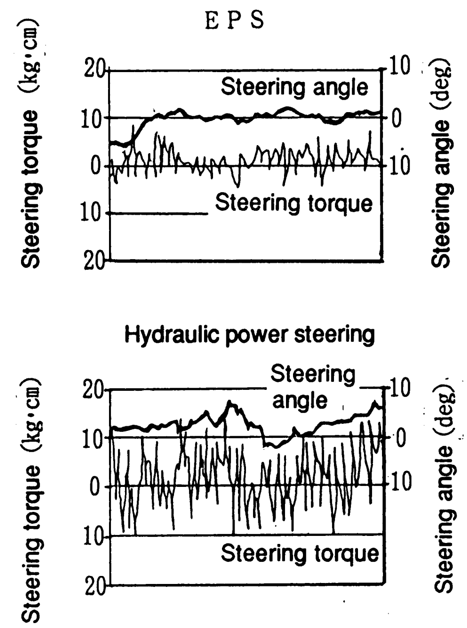


Fig.16 Comparison of kick back between steering systems

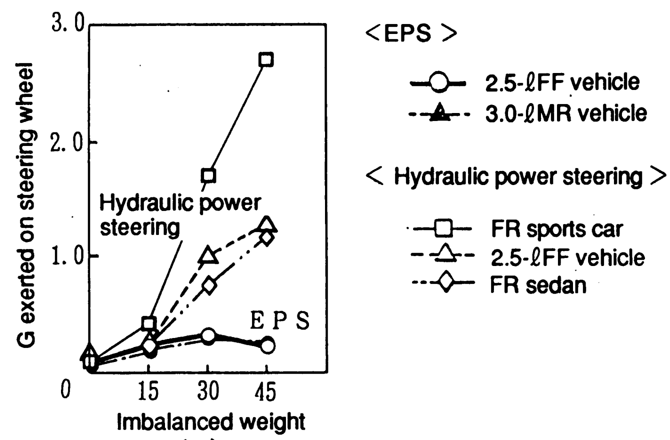


Fig.17 Comparison of steering shimmy between steering systems

in 2.5-ℓ FF vehicle and 3.0-ℓ MR vehicle. The hydraulic power steering was installed in 2.5-ℓ FF vehicle, FR sedan and FR sports car. The results show that EPS vehicles are little affected by the difference in driving method of FF or MR. With the EPS, both FF and MR vehicles have small G increase on the steering wheel regardless of increased imbalanced weight on wheel. This means the EPS has higher toughness than that of the hydraulic power steering.

(2) Improvement in follow-up ability to steering wheel

Fig. 18 shows characteristics of the motor output. In stationary swing on parking, the maximum current of the motor is set at 90 A. When the vehicle starts to run, the motor current remarkably decreases, to about 30 A, because of load reduction due to wheel rolling. As once the vehicle starts to run its motor rotation speed capacity becomes about 1.7 times that of stationary swing. Steering wheel follow up ability can be enhanced by 1.7 times. Fig.19 shows actual effect. Test results of the EPS and hydraulic power steering as installed on a 2.5-ℓ FF vehicle are shown. Both systems were set prior to testing at almost the same stationary swing ability. The results show that the EPS has much higher operability at low vehicle speed than the hydraulic power steering whose engine dependant oil pump can not increase oil flow amount delivered even with reduced load and pressure.

(3) Improvement in returnability

An example of improvement of returnability for 2.5-ℓ FF vehicle by modifying data on the table of the soft program is shown in Fig.20 (b). It shows that light feeling with a small hysteresis is obtained. By contrast, for a vehicle having strong returnability, a curve shown in Fig.20 (a) can contribute to a stable feeling. Thus EPS can give suitable returnability matching vehicles' dynamic performance.

5.3 Improvement In stability

As described in the damper control, counter torque proportional to the rotation speed of the motor can be obtained by short-circuiting between the motor terminals. This control method is intended for quickly converging hunting of characteristic resulting from excessive steering during high speed running or sudden steering wheel return while cornering.

In our evaluation, excessive steering angle input (90°) was given to a vehicle running at a high speed (100 km/h) to force the body to roll. The vehicle characteristic was measured until it converges by the vehicle itself. Convergeing in a short time shows high stability, reflecting the vehicle ability to make itself stable without driver's aid.

The effects of the damper control are shown in Fig.21.

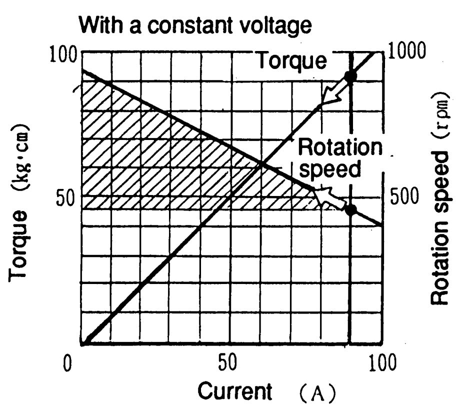


Fig.18 Motor output characteristic

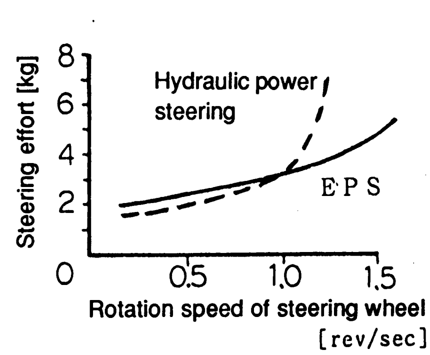


Fig.19 Comparison of follow up ability to steering wheel between steering system

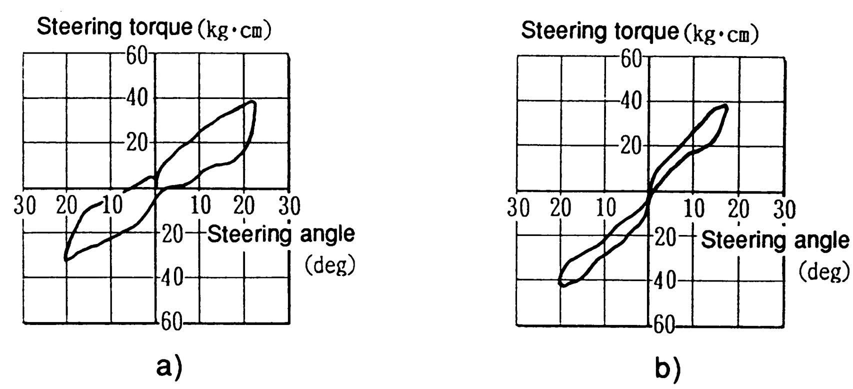


Fig.20 Comparison of steering characteristic (return characteristic)

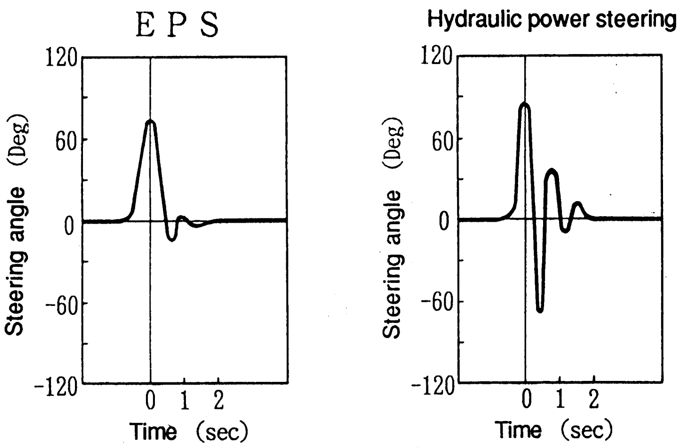


Fig.21 Effect of damper control

6. TECHNICAL CHALLENGES OF THE FUTURE

As described in the beginning of this paper, the development concept of this system was basically to make improvements over the hydraulic power steering and to serve as a basic technology for future steering system. The effects outlined in 4 above. Realization of this electronic control has provided a communication means with other systems on the vehicle laying groundwork for overall vehicle control system.

The hydraulic power steerings are now widely used because of comfortness and safety, and after a half century of mass production has achieved low cost. The EPS has yet to accumulate good records and reduce cost. Reducing the size of control unit and power unit is the major challenge of electronics, to which the EPS has a good chance of progressing, thus over coming the barrier of cost.

Smaller size motor also stands a good chance with highly magnetic material such as Nd-B magnet. An Nd-B magnet motor separately developed by us (see Photo 3) has the same output as the motor used in the EPS, and diameter of about 80 mm. However, the new motor is now remarkably expensive compared with the usual Fe magnet motor. Cost down is its major challenge. On the other hand, using the higher voltage batteries (24 V or 48V) has less technical difficulty, and has a better chance of being adopted from the viewpoint of overall vehicle electrical system.

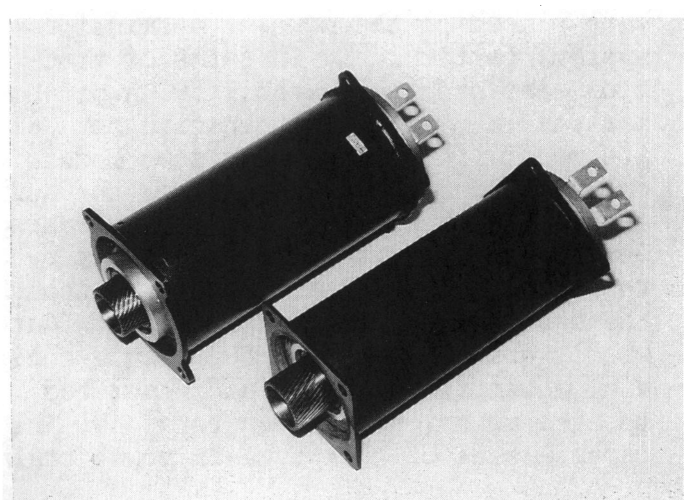


Photo-3 Fe magnet motor and Nd-B magnet motor

7.CONCLUSION

It took us 7 years to develop the EPS. Japanese midget-car manufactures have during that period sold EPS system. All of them, however are power steering systems having low assisting ratio and control range limited to low vehicle speed of midget -cars.

Our system, by contrast, is intended to be used for a front wheel drive vehicle weighing 1000 kg in front axle load, resulting from a concept different from other EPSs. That concept was to replace the hydraulic power steering system as that of the next generation. That development concept and achievement have enabled installation of the new EPS in the new sports car NSX created as a result of pursuing the best in efficiency, driveability and safety. It is electronics technology that have helped us send to the market our EPS with many advantages unprecedented in the hydraulic power steering system.