Electric Power Steering (EPS)

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1. Introduction

The effects of global warming are becoming increasingly apparent. As a result, we product engineers are being asked to develop products that are more friendly to the earth's environment. Electric power steering (EPS) is such a product. By using power only when the steering wheel is turned by the driver, it consumes approximately one-twentieth the energy of conventional hydraulic power steering systems and, as it does not contain any oil, it does not pollute the environment both when it is produced and discarded. While offering these environmental benefits now, in the future EPS is expected to facilitate automatic steering—user-friendly technology that should ultimately reduce traffic accidents. Additionally, the software built into the EPS controller results in high performance and easy tuning during the development of prototypes of EPS systems. Because of these advantages, EPS has drawn the attention of automobile manufacturers all over the world. The EPS systems we produce have the highest market share not only in Japan but in Europe as well. This report outlines the construction of the column-type and pinion-type EPS systems produced by our company, as well as gives a technical profile of their main components: electronic control unit (ECU), sensor and motor.

2. EPS System

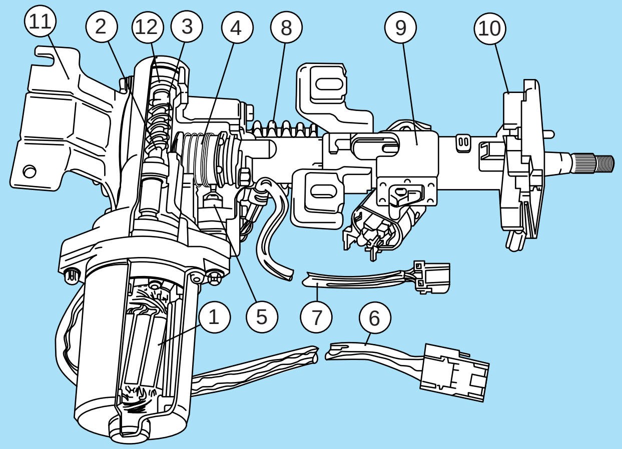
The EPS system consists of a torque sensor, which senses the driver's movements of the steering wheel as well as the movement of the vehicle; an ECU, which performs calculations on assisting force based on signals from the torque sensor; a motor, which produces turning force according to output from the ECU; and a reduction gear, which increases the turning force from the motor and transfers it to the steering mechanism. EPS is available in two types: a column type in which the reduction gear is located directly under the steering wheel, and a pinion type in which the reduction gear is attached to the pinion of the rack and pinion assembly. Each type of EPS system is speed-sensitive—vehicle speed and engine rotation signals are input from the vehicle into the ECU. Fig. 1 shows a vehicle with column-type EPS.

Fig. 1 A vehicle with column-type EPS

3. General Description of Column-Type EPS System

3.1 Construction of column-type EPS

Fig. 2 shows the construction of the column-type EPS system. Collapsible safety columns are usually used. The unit is contained in the dashboard.



1. Motor
2. Worm gear
3. Worm wheel
4. Torque sensor mechanism
5. Potentiometer
6. Motor harness
7. Torque sensor harness
8. Energy-absorbing convoluted tube
9. Keylock assembly
10. Switch bracket
11. Lower bracket
12. Rubber damper

Fig. 2 Construction of column-type EPS system

3.2 Column-type EPS series

Already ten years have passed since our column-type EPS systems were introduced in mini-cars (<0.66ℓ engine capacity). During this period, we have worked to increase their applications in mini-cars and to expand their range of applications into small vehicles (approximately 0.66 to 1.5ℓ engine capacity). As a result, our series of column-type EPS systems is now being used by automobile manufacturers in Japan and overseas. Table 1 lists four column-type EPS systems.

Table 1 Column-type EPS

	Reduction gear ratio	Electric current (A)	Assist torque (N·m)
A	16.5	25	17.3
B	16.5	30	19.8
C	17	30	25.0
D	18	45	33.5

3.3 Output improvement and energy-absorbing mechanism

a. Response to output improvement

In response to the improved output of EPS, we reviewed current design standards with a focus on improving endurance and impact strength. As a result, new design standards compatible with the higher output of today's EPS systems are now in place for the following components:

- worm and worm wheel gears
- output shaft
- bearing
- joints and connections
- mounting bracket

In addition, we achieved the serialized production of plastic worm wheel gears and, through the use of cold forging, reduced the cost of producing sensor system components such as the output shaft.

b. Energy-absorbing mechanism

Generally, with column-type EPS systems, there is less space available for the steering column to absorb energy in the event of an accident because the EPS system is located on the column. However, based on the safety column technology we have cultivated, we have developed an EPS equipped with an energy-absorbing mechanism, motor, gears, torque sensor system, key lock housing, and switch bracket, in spite of the fact that the overall length from the input shaft end to the output shaft end is restricted by the layout of vehicles (see Fig. 2). The column assembly of this EPS system has inner and outer column sections like a conventional EPS. In addition, for added safety in accidents, it has a mechanism to soften its collapse, a convoluted tube to absorb the driver's energy, and a device that allows the lower bracket to absorb energy.

3.4 Reduction gear and rattling noise

Because the steering wheel and reduction gear in a column-type EPS are located close to each other, sound produced in the reduction gear is directly transferred to the vehicle interior, to the detriment of driving comfort. To reduce this noise, our worm wheel gear is made of plastic. Moderate backlash is generally necessary for the meshing of gears, but the rattling noise of the gear teeth caused by backlash can be particularly troublesome when the vehicle is running on a bad road. As today's vehicles are required to be increasingly quiet, column-type EPS systems, which are located in vehicle interiors, must operate with minimum noise.

3.5 Reducing rattling noise

The rattling noise is caused by the teeth of the worm and worm wheel gears colliding as a vehicle is running on a bumpy irregular road. The noise, which may sometimes be perceived as self-excited vibration, becomes more noticeable as backlash increases. As backlash is unavoidable with reduction gears, we developed an impact absorption system that considerably reduces the rattling noise backlash generates.

A) Measures for reducing rattling noise
Elimination or reduction of teeth noise

- Lower backlash value
- Impact absorption by elastic material
- Review of gear specifications to reduce teeth noise

B) Optimum specifications for significant reduction of rattling noise
To absorb impact effectively

- Determine appropriate rigidity of rubber damper (Fig. 3)
- Determine sufficient volume of rubber for impact absorption

C) Reliability (endurance and strength)
To achieve high reliability

- Ensure rubber's resistance to deterioration (deformation from heat and repeated use)

D) Utilization of rubber damper characteristics
Rubber damper applications:

a. Impact damping
Cushioning impacts of stopper by utilizing the low impact resilience of rubber

b. Vibration absorption
Vibration attenuation in resonance region by utilizing the energy-absorbing property of rubber

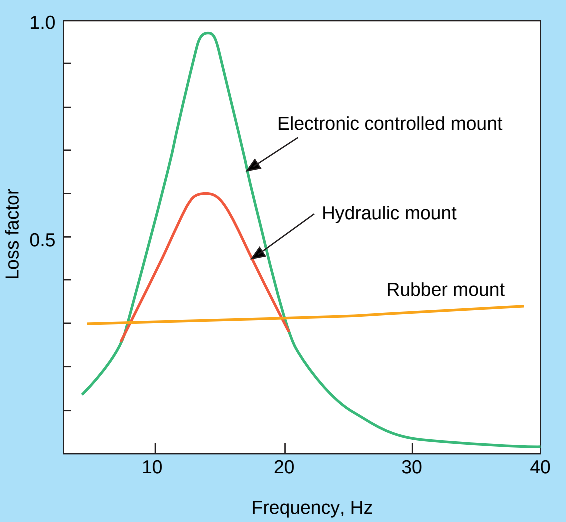


Fig. 3 Characteristics of impact-damping rubber mounts

Rubber characteristics required for impact damping:

a. Large loss factor (Fig. 3)
- Rubber material (physical properties)
- Volume of rubber
- Shape of rubber mass

b. Resistance to surrounding factors
- Heat resistance
- Resistance to deterioration from aging (deformation from fatigue)
- Resistance to year-round weather conditions
- Resistance to oils

3.6 Construction of column-type EPS system with rubber damper

Fig. 4 shows the section of an EPS system with a rubber damper. The rubber damper effectively reduces the amount of external force transferred from the tires to the worm wheel and worm gears. Taking into consideration the results of past studies, the rubber damper is mounted on the worm gear shaft, and a bush is used between the bearing and the worm gear shaft. This arrangement allows the rubber damper to absorb the external force by sliding along the worm gear shaft.

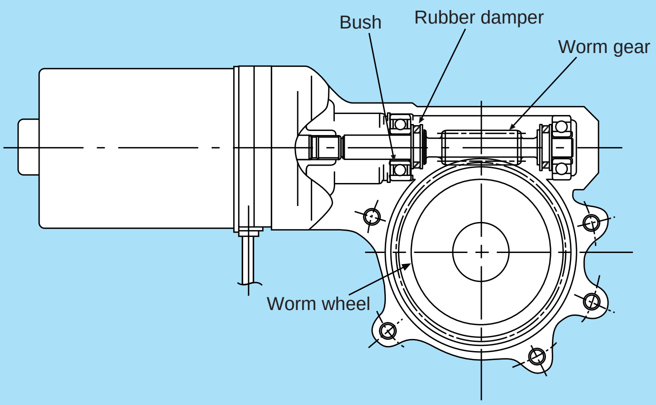


Fig. 4 Section of EPS system with rubber damper

3.7 Evaluation of rubber damper

Figs. 5 and 6 present frequency analysis results from a bench test on the effectiveness of the rubber damper.

In an endurance test of an EPS system without a rubber damper in an actual vehicle, the backlash naturally increased. When the backlash exceeded a certain level, the rattling noise began to be audible to the driver. However, in an endurance test of an EPS system with a rubber damper in an actual vehicle, the rubber damper system was found to suppress the rattling noise even when excessive backlash was produced.

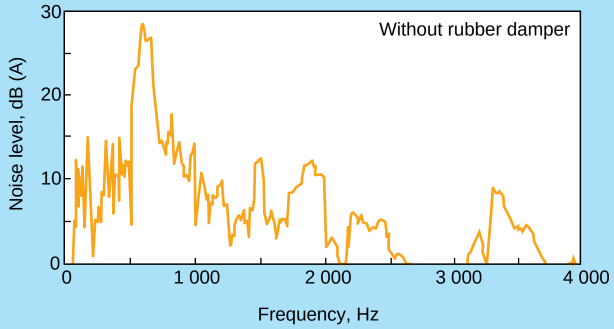


Fig. 5 Frequency analysis results from bench test without rubber damper

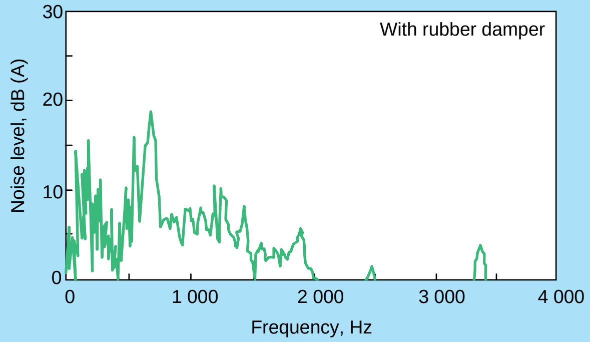


Fig. 6 Frequency analysis results from bench test with rubber damper

4. General Description of Pinion-Type EPS System

4.1 Construction of pinion-type EPS

Fig. 7 shows the construction of the pinion-type EPS system. In terms of the ability to withstand crashes (particularly secondary impacts), pinion-type EPS has an advantage over the column-type in that the impact-absorbing columns currently in use can be used as they

Table 2 Main specifications of pinion-type EPS

Maximum rack thrust		> 4.48 kN
Gear specifications	Stroke ratio	39 mm/rev
	Rack ratio	126 mm
	Lock to lock	3.23 rev
Reduction gear	Type	Plastic worm and worm wheel
	Reduction ratio	17
Motor	Type	DC brush motor
	Rated current	35A
	Rated speed	1210 rpm
	Rated torque	1.76 Nm
Torque sensor	Type	Non-contact self-induction
	Rated voltage	DC 12V
Controller	Rated voltage	DC 12V
	Control range of motor current	0 – 35A
	Control items	1) Differential compensation 2) Friction compensation 3) Astringent control

are. Pinion-type EPS, like the column-type EPS, consists of a torque sensor, reduction gear, motor, rack and pinion. The auxiliary power of the motor is directly transferred to the pinion shaft. The pinion-type gear assembly is located in the engine compartment so it is made very durable to enable it to endure the heat from the engine as well as water from outside the vehicle. The ECU, on the other hand, is located in the vehicle interior and is therefore free from the influence of heat and water. To help make the system lightweight and compact, the motor is small and the reduction gear has only one stage. Pinion-type EPS is available in various sizes for different motor outputs from 25A to 60A. The pinion-type EPS system was developed for small cars. Its main specifications are listed in Table 2.

4.2 Construction and characteristics of steering gear assembly

1) Comprising a worm and worm wheel gear, the reduction gear has reliable performance already proven on the market. The worm and worm wheel gear are made of glass fiber-reinforced plastic resin with improved strength at high temperatures. For the protection of the plastic gear, a torque sensor is incorporated on the motor shaft to prevent the application of torque higher than a certain level.

2) For application to the EPS, we developed a non-contact self-induction torque sensor with improved performance and endurance. The sensor circuit is contained in the gear assembly and therefore protected from extreme temperatures, radio waves and exposure to water. The principle of operation and the construction of this torque sensor are detailed in a following section.

3) Based on accumulated technology for manual steering mechanisms, the rack and pinion combination is designed to have high wheel-end impact strength and high endurance, with the effects of motor inertia peculiar to EPS taken into consideration.

4) To prevent the rattling noise generated by the tires, the design of the support yoke employs both a coned disk spring that applies pressure around the circumference of the support yoke and a center spring. To reduce the sliding resistance and wear of the rack, a sheet of specially formulated PTFE (polytetrafluorethylene) is employed.

5. ECU

Photo 1 shows the ECU. The three primary roles and corresponding functions of the ECU in EPS systems are:

1. Assurance of comfort
   Power steering functions
   (Motor current control function)
2. Assurance of safety
   Self-diagnosis and fail-safe functions
3. Assurance of convenience
   Communication functions

Table 3 details the functions of the ECU.

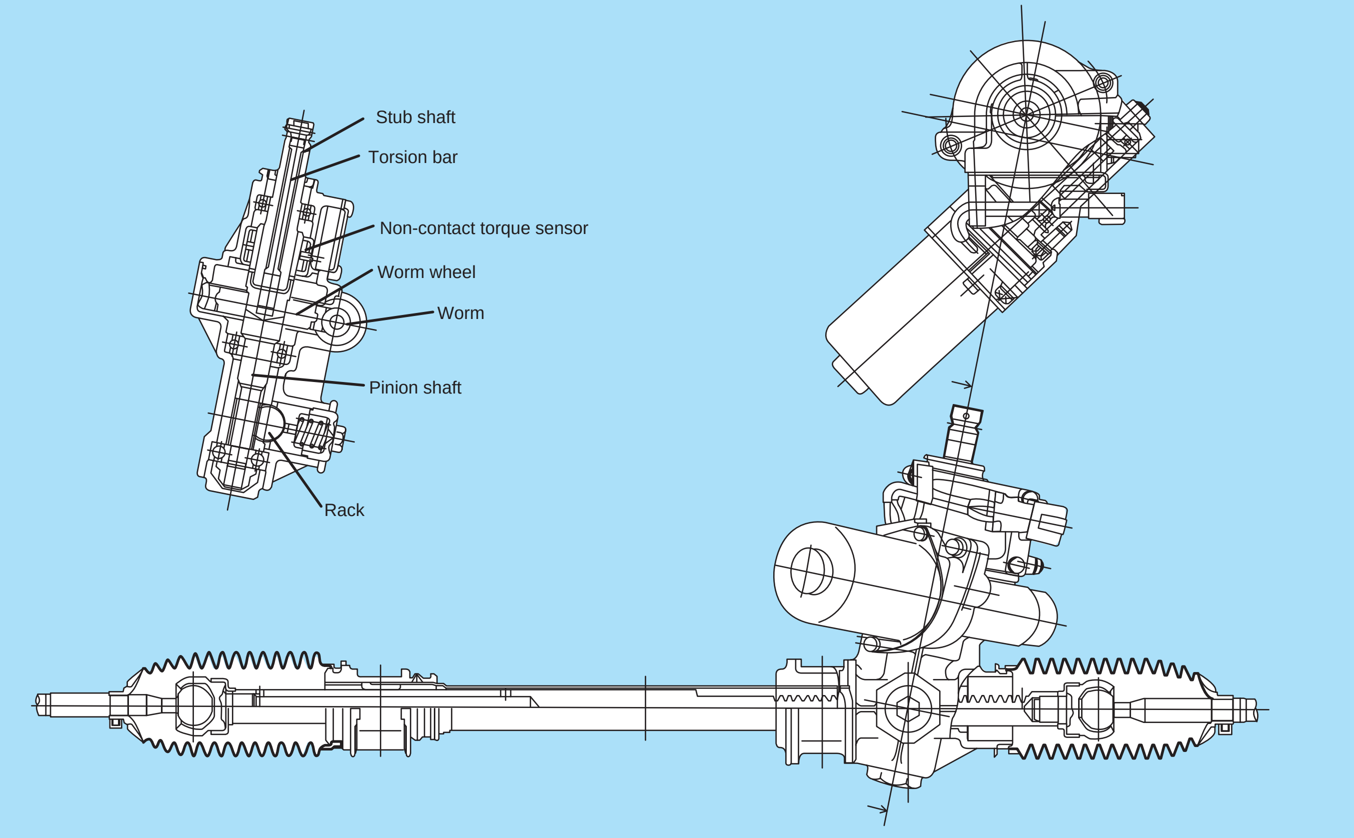


Fig. 7 Construction of pinion gear assembly

Table 3 Functions of ECU

Power steering functions The ECU controls motor current as shown in Fig. 8, Control block diagram.	
(1) Target base current operation	Generates assisting force (motor current) pursuant to vehicle speed and input torque to ensure appropriate steering power throughout vehicle speed range.
(2) Differential control	Minimizes fluctuations in steering power by compensating motor current in response to input torque fluctuations.
(3) Friction compensation	At low speeds, by compensating motor current, helps the steering wheel return to the straight position after having been turned.
(4) Convergence control	At high speeds, stabilizes the behavior of turned steering wheel (e.g., while changing lanes) by compensating motor current to make the steering wheel return to the straight position smoothly.
(5) Maximum motor current operation	Limits maximum motor current to the optimum level to protect ECU and motor from being damaged by motor's overheating.
Self-diagnosis and fail-safe functions	
Self-diagnosis function Fail-safe function	Monitor the EPS system components for failure. Upon detecting any failure, controls EPS functions depending on the influence of the failure and warns the driver. Also, stores the failure location in the ECU.
Communication functions	
Data communication function EPS testing function	Data stored in the ECU (ID code, date of manufacture, failure data, etc.) can be read and EPS system functions checked using external communication equipment.

Photo 1 ECU

6. Non-Contact Torque Sensor

6.1 Advantages of non-contact torque sensor

In our column-type EPS, primarily for reasons of reliability and cost, a potentiometer-type contact torque sensor is used. For the pinion-type EPS, we have developed a non-contact torque sensor. The position of the non-contact torque sensor is shown in Fig. 9. Compared to the conventional potentiometer-type contact torque sensor, the new non-contact torque sensor:

- is free of wear from aging
- has smaller hysteresis
- is less affected by runout and axial displacement of the shaft

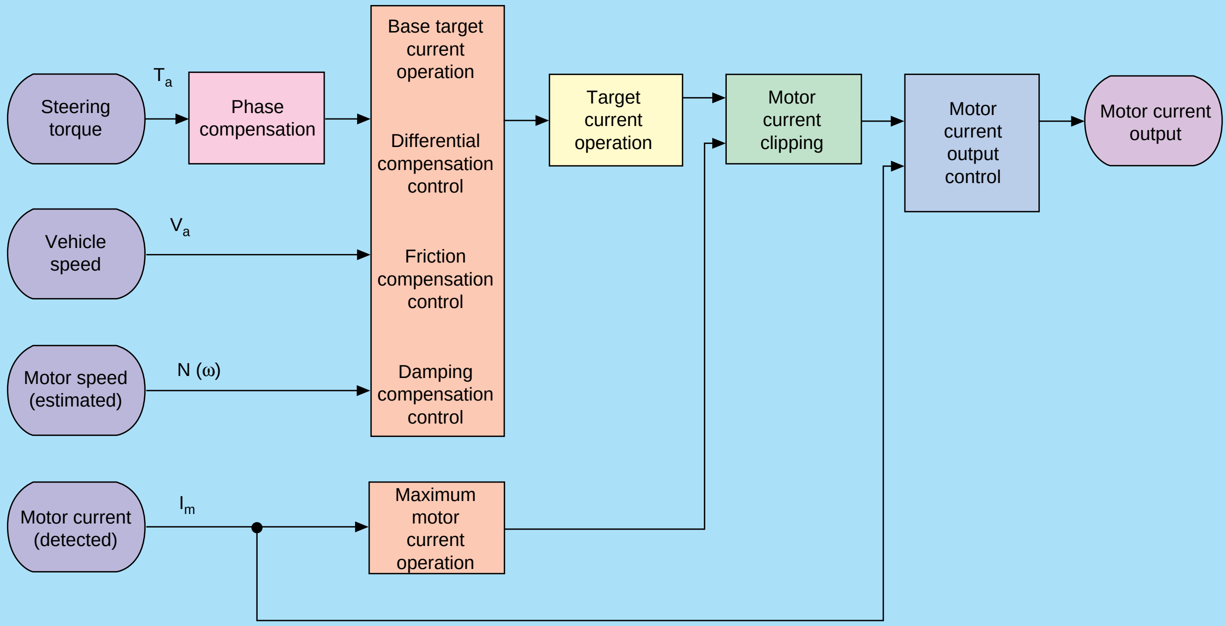


Fig. 8 Control block diagram

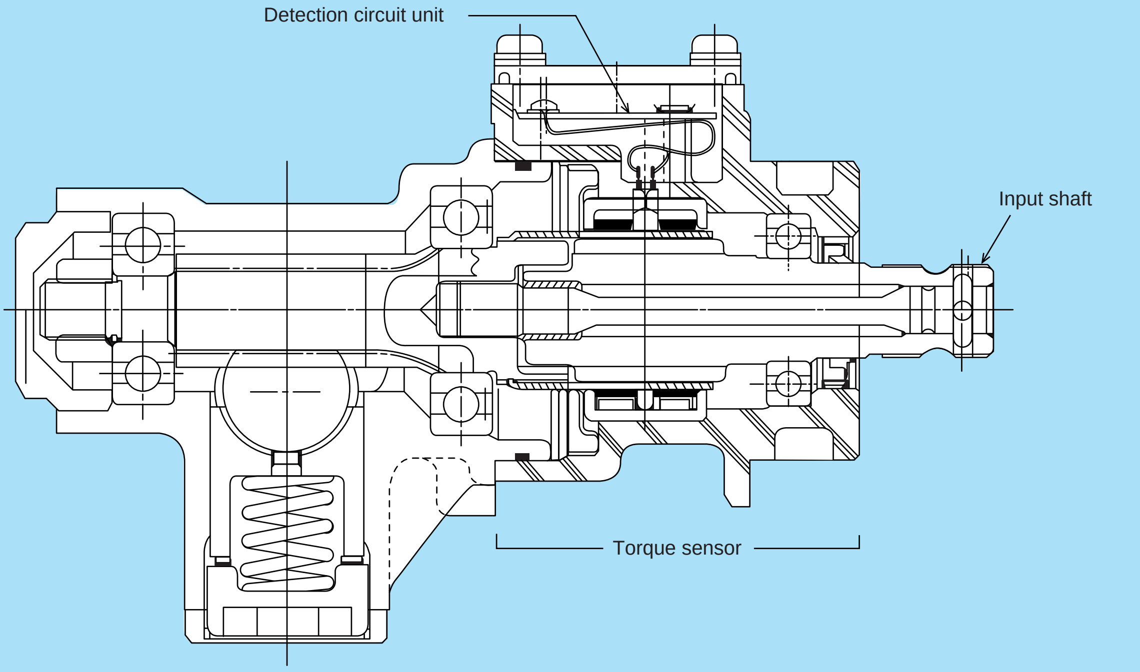


Fig. 9 Non-contact torque sensor in pinion-type EPS

6.2 Construction and principle of operation of non-contact torque sensor

Fig. 10 illustrates the construction of the non-contact torque sensor. The input shaft and output shaft are connected by a torsion bar. The input shaft has splines and the output shaft has slots. During steering, the relative displacement of the slots and splines is changed by an amount equal to the change in the torsion of the torsion bar, causing change in the amount of magnetization of the splines. If the two coils are then energized with AC, the changes in inductance of the two magnetic flux detecting coils become anti-phasic to each other because the pitches of the two rows of the slots in the metal sleeve are originally offset by an amount equal to half pitch. Differential amplification of the changes can double the output, while offsetting common mode components caused by temperature and other factors. As a result, the sensor has high sensitivity.

6.3 Basic operation of non-contact torque sensor circuit

Fig. 11 shows a block diagram of the torque sensor circuit. The current amplifier provides amplitude-constant AC to the resistor and coil bridge, but the coil terminal voltage varies depending on inductance variations caused by torque, as described in the foregoing section. Because the voltage variations are anti-phase to each other, only the difference between the changes is amplified and then the coil drive AC component is removed. In order to ensure that the ECU accurately recognizes zero torque, the circuit receives reference voltage from the ECU, corrects the voltage at zero torque, and outputs torque signals. To ensure high reliability, these two circuits are provided downstream of the coil.

The monitor checks for oscillator trouble, coil rupture and other faults and, on finding a fault, forces one signal only to output an anomaly value.

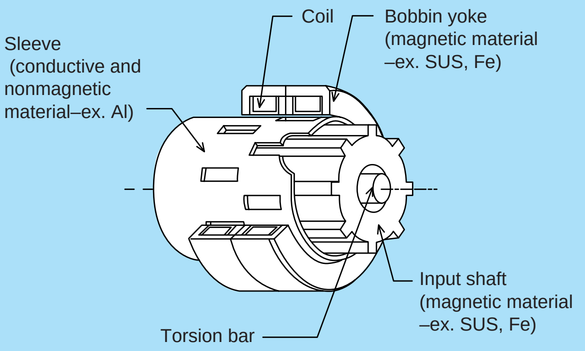


Fig. 10 Construction of torque sensor

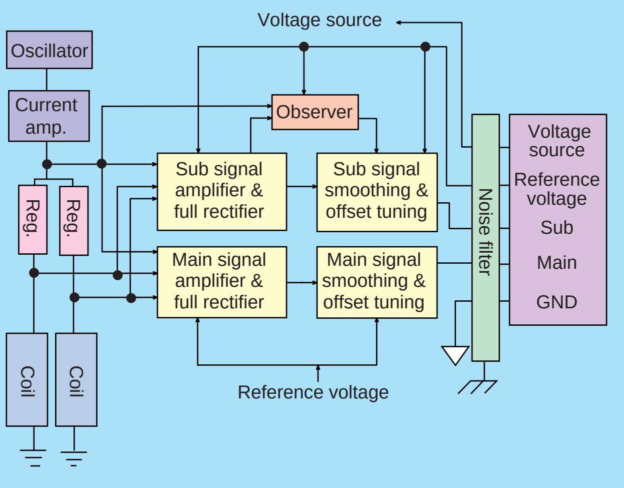


Fig. 11 Block diagram of torque sensor circuit

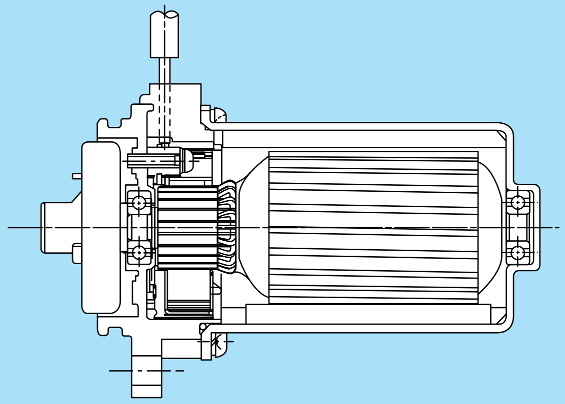


Fig. 12 Construction of new motor

7. Motor

The motor for EPS is a permanent magnetic field DC motor. Attached to the power steering gear assembly, it generates steering assisting force. This motor has the following operating requirements and features:

Operating requirements

- The motor must be able to generate torque without turning.
- The motor must be able to reverse its rotation abruptly.
- The fact that motor vibration and torque fluctuations are directly transferred through the steering wheel to the hands of the driver must be considered.

Features

- Small, lightweight and high-output
- Small fluctuations in torque during operation
- Very low vibration and noise
- Low inertia
- Low friction torque
- High reliability

We have developed a new motor with improved assisting performance and design and applied it to our EPS. Fig. 12 illustrates the construction of the motor. Compared to conventional motors, the new motor, while the same size, has approximately double the rated output torque and 43% higher rated output power. This is attributed to three factors:

- The high residual flux density of the magnet
- Multiple poles
- Increased armature coil winding density

Fig. 13 compares the rated capacities of the old and new motors.

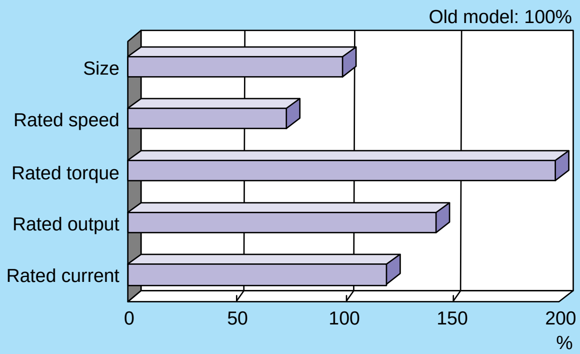


Fig. 13 Performance comparison between new and old motors

8. Conclusion

We have presented here the construction and features of our EPS systems. Just a decade old, EPS is still developing and improving, having only recently arrived at a level comparable to its predecessor, hydraulic power steering. To meet the needs of present and future users and thereby expand applications of EPS, our future efforts will be focused both on developing cost-reducing measures and on making further technical improvements such as reduced weight, higher output, and improved performance and functions.

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