Automotive power assisted steering

using optical torque monitoring

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Over the last decade, power-assisted steering has become standard on virtually all passenger cars and light vans, as customers demand ever increasing levels of comfort, performance, safety, reliability and economy. Features such as variable assistance with road speed and extra assistance whilst parking are also becoming widely available. To meet these market needs, Tier 1 automotive suppliers have developed a range of different power steering technologies optimised for particular applications.

Electric Power Steering (EPS) systems are now in production with a number of major vehicle manufacturers world-wide and are capturing an increasing share of the market. Demand is expected to continue to boom for this technology, eventually increasing to an estimated one out of every two cars built by the year 2010.

Optical torque sensors offer a number of advantages over competing technologies for EPS systems, being non-contacting and with excellent fault detection capability.

Hydraulic Power Assisted Steering (HYPAS)

Hydraulic Power Assisted Steering (HYPAS) is still the most common system, fitted to larger new vehicles as well as older vehicles both small and large. A hydraulic pump is driven by a belt from the engine. This pumps fluid to a rotary spool valve which provides a differential pressure output depending on the driver applied torque. The differential pressure drives a hydraulic ram mounted on the steering rack, which provides the power assistance.

Because maximum assistance is required when the vehicle is stationary, e.g. during parking, the pump has to be sized to accommodate this with the engine idling. This means that during normal driving (when little or no assistance is needed), the pump is grossly oversized for the requirement and therefore wastes several kilowatts in pumping fluid around the system to no effect. The system is also mechanically complex and there are many parts which must be assembled to the vehicle on the production line. It must then be filled with fluid and tested once the air has been bled out. It is also complex to incorporate features such as speed dependence, which requires extra valves and additional electronic systems.

Electrically Powered Hydraulic Steering (EPHS)

To address some of the disadvantages of HYPAS, many vehicles now use Electrically Powered Hydraulic Steering (EPHS). These systems retain the hydraulic control valve and actuation system, but instead of being mechanically driven from the engine, the pump is driven by an electric motor.

The EPHS system consists of a conventional rack and pinion power gear and a compact "Power Pack". The "Power Pack" combines a motor, a pump, a tank for the hydraulic fluid and an electronic control unit (ECU) with the control electronics and the power electronics in one housing. The pump speed is controlled electronically independent of engine speed to give the appropriate output relative to the power assistance required.

Unlike ordinary hydraulic steering systems, EPHS is delivered to the vehicle manufacturer as a fully tested, ready-to-install unit filled with fluid. EPHS technology enables the vehicle manufacturer to acheive cost savings in terms of reduced installation time, and also offers fuel consumption benefits to the vehicle user as the pump only operates when required.

Electric Power Steering (EPS)

An Electric Power Steering (EPS) system has no hydraulic parts at all. The steering assistance is provided directly by an electric motor, either driving the steering rack or the steering column. An electronic torque sensor measures the driver input, this signal is then processed by an ECU to drive the motor to provide the assistance. EPS systems are even easier than EPHS systems to install, and as there is no hydraulic fluid, there is no possibility of leakage and no environmental concerns over the disposal of used fluid.

Due to the limitations of the power available from a conventional 12V vehicle electrical system, current EPS systems are limited to a peak motor power of about 600W, which corresponds to an actual peak current consumption of around 85A. This means that such systems are only powerful enough for small and medium-size cars. Future developments such as higher voltage electrical systems will enable the deployment of more powerful EPS systems on larger vehicles.

EPS system overview

The advantages of EPS include reduced size and weight (particularly for small cars), easier installation and, above all, reduced fuel consumption. A number of studies have shown that for a variety of driving cycles, fuel consumption savings of between 5% and 8% can be achieved relative to the same vehicle fitted with a HYPAS system. This

Figure 1: Column-drive EPS system (TRW).

Parameter	Typical Specification
Full-scale torque range	+/- 8 Nm to +/- 10 Nm
Max rotation speed	up to +/- 1800 °/s (300 rpm)
Overload torque without damage	+/- 200 Nm
Temperature range	-40°C to +85°C (cabin mount) -40°C to +125°C (engine compartment mount)

Table 1: Basic EPS torque sensor specification.

is because the EPS system only draws power for assistance when it is actually needed, rather than continuously.

EPS also enables extra features such as road-speed dependence, active yaw damping and active self-centring to be achieved relatively simply. The additional hardware requirements are minimal compared with HYPAS and the extra functions along with the tuning of the system "feel" can be achieved by altering the software in the ECU. To tune a HYPAS system during development is time-consuming and expensive as it involves mechanical changes to the valve assembly, whereas with an EPS system the appropriate parameters can be adjusted using a laptop computer in the vehicle on the test track.

The easiest way to position the EPS power unit is often at the steering column right behind the dashboard. With this type of system, the assist torque from the motor is transmitted through a worm gear to the steering column (*Figure 1*). The Column-drive EPS configuration is an attractive option particularly when under-bonnet space is at a premium.

It is a very cost-effective solution, in part due to its location in the passenger compartment which enables less stringent requirements for temperature range and environmental sealing. The column system is designed to optimise Noise, Vibration and Harshness (NVH) performance as well as to incorporate reach, rake adjustment, collision collapse, and other features required by the vehicle manufacturer. It is supplied in one compact module which is fully tested and ready to be installed.

Depending on the vehicle configuration, an alternative packaging solution for EPS is to fit the system at the steering rack, this can allow a larger motor to be fitted but the environmental demands on the components of the system are greater, particularly exposure to higher temperatures, vibration and contaminants.

Torque sensing requirements for EPS

A power steering system is fundamentally a torque servo, not a position servo as might be first thought. The system must determine how much torque is being applied by the driver to the steering wheel, and add an appropriate amount of assistance to keep the driver's applied torque to the required value. The driver completes the overall position control loop, operating the steering wheel until the desired vehicle trajectory is achieved. Despite this, position sensors may also be required in an EPS system: (a) to determine steering column position ("steering angle") for active self centring and yaw damping; and (b) for control of the motor if a brushless motor topology is used. The steering angle signal can also be exported for use by other systems in the vehicle, such as slip-control systems and headlamp direction control systems.

However, it is perfectly possible to make a basic EPS system with just a torque sensor.

An important part of designing an EPS system is to choose the most appropriate torque sensor technology for the application. Although apparently simple at first sight, torque is actually one of the most difficult physical parameters to measure. Many different torque sensors have been proposed over the years, and they continue to be invented. However, only a very few have been successfully engineered into low-cost products for high-volume manufacture.

Specification

The typical basic specification for an EPS torque sensor is shown in *Table 1* (above).

It is worth noting that this specification is independent of the size or steering assistance requirements of the particular vehicle, since the input torque from the driver is similar in all cases. The torque sensor is generally mounted within the EPS unit housing next to the motor gearbox.

Whatever type of sensor is used, it is important to correctly detect faults in the sensor and avoid incorrect signals being used by the rest of the system.

Choice of sensor technology

Potential torque sensor technologies for EPS systems include optical devices, potentiometric sensors, variable inductance, magnetostrictive and strain gauges. All EPS systems currently in volume production use either a potentiometric, an inductive (in various forms) or an optical torque sensor.

All production EPS sensors are actually differential angular position sensors which measure the twist across a torsion bar (sometimes called a "quill shaft"). This is a narrow section of shaft designed to give the appropriate torsional compliance in the system. As torque is applied, there is an angular movement between the two ends of the torsion bar, and this movement is detected by the sensor. In EPS systems the torsion bar generally provides between 2° and 5° of twist for 10 Nm of applied torque.

Hydraulic power steering systems also use torsion bars as part of the torque sensing valve mechanism. Furthermore, sensors without torsion bars, such as those using strain gauges, tend to suffer from dynamic range problems. This is because the sensor must be designed to take the full overload torque of around +/- 200 Nm without damage, while only a small proportion of this (around +/- 10 Nm) is actually used for measurement. A sensor with a torsion bar, however, can be designed to use the full twist range for measurement. Care must be taken to ensure that the stresses in the materials are within safe limits to avoid plastic deformation and failure, but overload torques do not have to pass through the torsion bar since they are transmitted by an arrangement of end stops which mechanically limit the angular twist of the torsion bar.

Although the torsion bar assembly (including the end stops) is a relatively complex and expensive mechanical component, there is currently no viable alternative which meets all the requirements at a lower cost.

Many EPS systems in volume production are specified with non-contacting sensors in the interests of reliability. For example, the column-drive EPS system supplied to major vehicle manufacturers by TRW Automotive uses an optical torque sensor, which was developed after exhaustive analysis of the alternatives. The optical sensor provides excellent fault diagnostics and the ability to provide extra functions such as angular position sensing as well as offering good electro-magnetic compatibility (EMC) performance.

Optical torque sensing

Optical torque sensors, in common with many other types of torque measuring devices, measure the relative angular movement between the ends of a torsion bar as torque is applied to the shaft.

Figure 2 shows a schematic drawing of one type of optical torque sensor assembly. Two concentric metal encoder discs are fitted to the shaft, each end of the torsion bar is linked to one of the discs. Each disc rotates with the shaft

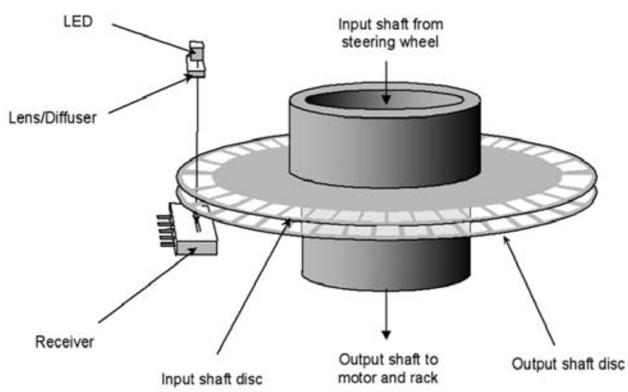

Figure 2: Schematic of optical torque sensor.

and has a pattern of spokes forming an arrangement of windows which can transmit light. One disc has wider spokes than the other, as shown in *Figure 3*.

The torque is determined by measuring the pattern of light transmitted by the varying overlap of the two discs. The discs are arranged so that at zero torque, the spokes of the "narrow spoke" disc are positioned centrally in the windows of the

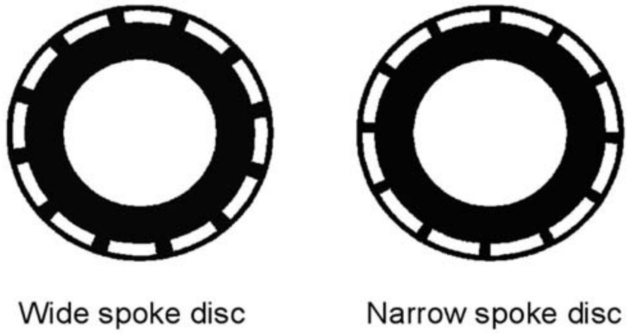

Figure 3: Discs with two tracks of slots.

"wide spoke" disc. As torque is applied in either direction, the torsion bar twists, the discs move relative to each other and the narrow spokes move within the windows as shown in *Figure 4*. This movement is detected by the optical system.

Light from an LED passes through the windows in the discs and casts a shadow of the spoke edges onto the receiver. The receiver consists of a linear array of 128 light sensitive diodes giving a 1-dimensional image of the light intensity. A cross-section through the optical components is shown in *Figure 5*.

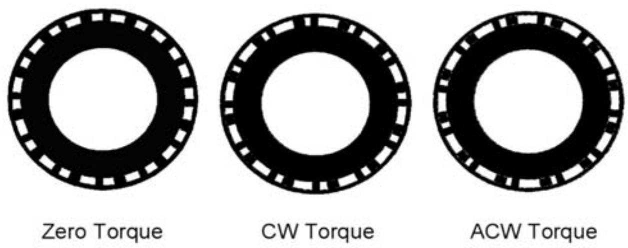

Figure 4: Disc overlap with different torques applied

The position of the narrow spokes within the windows and hence the torque can therefore be determined from the image. As the discs rotate, the pattern moves along the receiver. The system is designed so that there are always shadows from enough spokes to be able to determine the torque. The signals from the receiver are read into a microcontroller which determines the relative positions of the wide and narrow spokes from the shadows and then calculates the torque, angular position and diagnostic information.

Position and angular velocity measurement

A significant advantage of this type of optical torque sensor is the capability to obtain incremental position and angular velocity of the steering shaft from the same sensor. This can be used in the EPS system to compensate for undesirable effects such as friction and inertia, and thus give a better steering "feel" to the driver. It can also be used to give active self-centring, where the EPS motor is used to help to return the system to the straight-ahead position rather than relying purely on the steering geometry. Another potential feature is active yaw damping, where the EPS system helps to damp out vehicle oscillations such as "fishtailing" after sudden manoeuvres in slippery road conditions.

The passage of the spokes on the discs can be counted to determine the angular position. An index feature is provided to

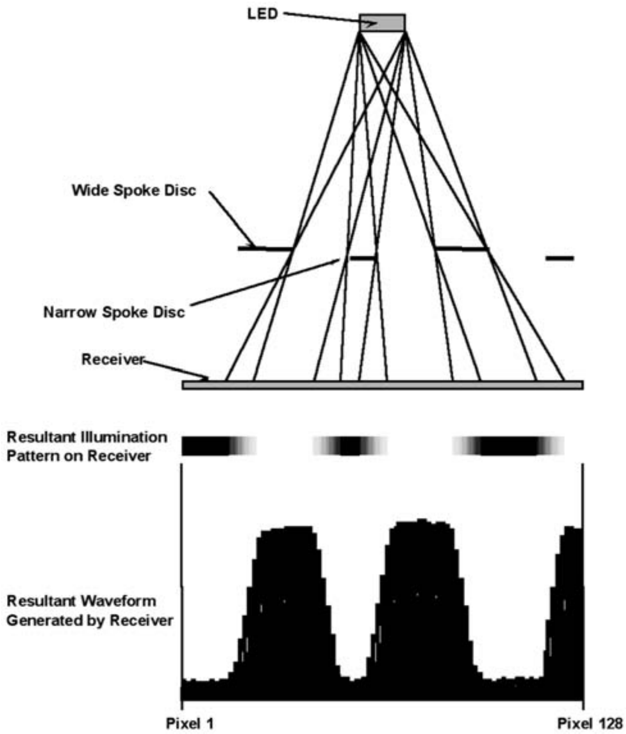

Figure 5: Cross-section of optical path.

enable the "straight ahead" position to be determined; this consists of a slot of slightly different width or an extra window. Most optical torque sensors use interpolation to increase the resolution of the angle position, at least a factor of 10 resolution improvement can be achieved over the raw slot count.

Angular velocity can be determined by differentiating the position in the usual way.

Diagnostic functions

It is essential that any system such as power steering has a high level of integrity and reliability. The optical torque sensor has been designed to meet these requirements, in particular to enable faults to be detected and appropriate action taken.

The basic philosophy adopted is that if a fault in the system is detected, the power assistance will be disabled, thus reverting the vehicle to normal, manual steering. In other words, the system is "fail-safe". The power assistance is removed if the system ECU detects a fault by interrupting the supply to the motor. The ECU tests itself and all the important system components, including the sensor at switch-on, switch-off and during operation as appropriate.

The torque sensor is one of the key components, and it is important to avoid an erroneous torque measurement being sent to the rest of the EPS system. Optical torque sensors offer a robust ability to detect sensor faults, as the sensor architecture enables a number of tests to be carried out continuously during operation. The sensor and the whole EPS system are developed using techniques such as Fault Tree Analysis (FTA) and Failure Modes & Effects Analysis (FMEA), which are widely used to formalise safety requirements in the aerospace, automotive and process industries.

Electro magnetic compatibility (EMC)

The torque sensor in any EPS system has to operate in a hostile electro magnetic environment. For example, there is the EPS motor driven with currents of many tens of amperes nearby, along with the rest of the vehicle wiring loom. There are also magnetic fields from the motor itself as well as other vehicle fitments such as door-mounted loudspeakers. Magnetic interference can be particularly problematic, since it is difficult to screen effectively against low frequency and DC fields.

Some inductive torque sensors tend to be sensitive to interference from external magnetic fields such as those produced by the EPS motor or those encountered if the vehicle is driven near AC power lines. Optical torque sensors, however, are virtually unaffected by magnetic fields. Although very small currents are produced from the photodetectors which could be prone to electrical interference, these are converted to high-level analogue or digital signals within the receiver and so are relatively immune to interference. By taking these precautions, the optical sensor has good immunity to external electrical and magnetic interference.

Volume manufacture

The automotive industry has a well-developed process for testing and proving new products before their introduction. In order to turn the optical torque sensor from a laboratory concept into a volume manufactured and cost-competitive automotive product, a large amount of work was required in both design and validation.

An optical torque sensor is only viable for EPS because it is very closely integrated (both mechanically and electrically) into the whole system, rather than being a separate "bolt-on" sensor. For example, the sensor shares bearings and a housing with other system components. The sensor parameters and design must be tightly optimised for the EPS application, and the same sensor design could not be used in, for example, powertrain torque measurement.

Future developments

Increased market penetration of EPS

Electric Power Steering (EPS) systems will increase their penetration of the vehicle market, and could be fitted to half of all new cars by 2010. Steering equipment suppliers will continue to refine and reduce the cost of the systems. New sensor technologies may be introduced, but in the short/medium term, systems will continue to use variations on the existing sensor technologies, including optical.

Steer-By-Wire (SBW)

Most major vehicle manufacturers and Tier 1 system suppliers are now working on Steer-by-wire systems which are likely to be introduced in the next 5 to 10 years. Analogous to the "Fly-By-Wire" systems used in both civil and military aircraft, SBW has no mechanical link between the steering wheel and the steering rack; instead the steering is operated entirely electrically, in contrast to EPS which provides assistance to a basically mechanical system. This gives considerable extra freedom to the vehicle design team and offers a number of benefits, for example:

- Passive safety – no steering column
- Active safety – highly reactive avoidance manoeuvres - "Collision Avoidance".
- Advanced vehicle dynamic systems to improve handing under extreme conditions.
- Parking manoeuvres – variable ratio.
- Simple packaging – no steering column.
- Vehicle design & aesthetics – new vehicle geometries.

Prototype SBW systems currently under development generally have a Hand Wheel Actuator (HWA) connected to the steering wheel, and a Front Axle Actuator (FAA) to drive the steering rack. The HWA measures the driver steering demand, and sends an electronic signal to the FAA which uses a motor to move the steering rack appropriately. The HWA is likely to require torque and angular position sensors, and also contains a motor to provide force ("haptic") feedback to the driver, this replicates the "road feel" experienced with a conventional steering system.

SBW systems will make great demands on the sensors and other components, since integrity, safety and fault detection capability will be even more important. SBW systems will only reach the market when it can be shown that the safety and reliability of the vehicle will not be compromised. The proven capability of optical sensors in EPS means that the technology is well positioned for application to SBW systems. The challenge for the industry will be to achieve aerospace levels of system integrity at automotive costs.

Conclusions

Electric Power Steering (EPS) systems have become well established, and are now being fitted to more and more small and medium sized cars. Half of all cars sold could be equipped with EPS by 2010. EPS offers fuel consumption savings over conventional hydraulic systems, is easier to install on the production line and also gives the vehicle manufacturers a wider choice of packaging options. Optical technology offers an excellent way to meet the torque sensing requirements of EPS systems. Optical torque sensors are non-contacting to give excellent reliability, have robust fault detection and can offer angular position sensing in the same package. Careful design and close integration with the rest of the EPS package enables the optical sensor to compete cost-effectively with other technologies in a volume-manufactured product.