Development of Planetary Reduction Motor with Mechanical Power Monitoring and Network Capability

In-hun Jang and Kwee-Bo Sim*

Abstract: This article describes the useful way to measure the torque and RPM of the geared motor. For this we have made the planetary geared reduction motor including 2 Hall sensors in it and the monitoring system. The monitoring system displays the sensing values (torque, rpm) and the calculated value (power) and it also has the network capability using the Bluetooth protocol. We will show that our solution is much more inexpensive and simple method to measure torque and rpm than before.

Keywords: Hall sensor, planetary reduction motor, remote monitor, torque.

1. INTRODUCTION

When the motor is rotating, the torque and rpm are varying as the loads or the driving status connecting through reduction units are changing. On the contrary, one can monitor changes of the loads or the driving status in the manner of measuring motor torque and rpm. Applications for torque and rpm measurements include determining the amount of power an engine, motor, turbine, or other rotating device generates or consumes. In the industrial world, ISO 9000 and other quality control specifications are now requiring companies to measure torque during manufacturing, especially when fasteners are applied [1].

Sensors make the required torque and rpm measurements automatically on screw and assembly machines, and can be added to hand tools. In both cases, the collected data can be accumulated on data loggers for quality control and reporting purposes.

Other industrial applications of torque sensors include measuring metal removal rates in machine tools; the calibration of torque tools and sensors; measuring peel forces, friction, and bottle cap torque; testing springs; and making bio-dynamic measurements.

There is a torque measuring method using the strain gauge and bridge circuit. A strain gage can be installed directly on a shaft. Because the shaft is rotating, the torque sensor can be connected to its power source and signal conditioning electronics via a slip ring. The strain gage also can be connected via a transformer, eliminating the need for high maintenance slip rings. Strain gages used for torque measurements include foil, diffused semiconductor, and thin film types. These can be attached directly to the shaft by soldering or adhesives [1].

But, because this is a contact method, it has the life time which is dependent on rotating velocity and used time. So this system demands on replacement of some parts or whole system itself for maintenance. And this system is also relatively big and expensive, requiring preceding annoying process.

The measuring method in rpm measurement can be divided into 3 main groups; mechanical, optical and stroboscopic measuring methods [4].

The mechanical method is the contact method and has the some disadvantage, but this method is still frequently used for low revolutions between 20 and 20,000 rpm.

The optical rpm measurement is the most popular and has the measuring range of 0 to 100,000rpm. The rotation is transmitted to the measuring instrument via infrared light beam coming from the instrument which is then reflected by a reflective tape on the object.

The stroboscopic measuring method uses the stroboscopic principle and has clear advantages over other measuring methods using mechanical or optical sensors; using this method it is possible to measure the rpm of very small objects or in inaccessible places. It has the measuring range of 100 to 20,000rpm.

In this paper, we are going to propose another non-contact method to measure torque and rpm using the *Hall effects sensor*. We have made reduction motor using planetary gear trains and put the Hall effects sensor in it. This motor unit also has the monitoring system that can measure the torque and rpm through the Hall effects sensors. This monitoring system includes the function of wireless communication with

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a remote server using Bluetooth protocol. It gives a motor unit to have the remote access point.

2. TORQUE AND RPM MEASURMENT

2.1. The special feature about planetary gear train

Most motor has a reduction unit on its center shaft to increase torque or to decrease velocity that can not be realized in a motor alone. In many applications, one gets desired torque and velocity using various gearboxes with adjusting reduction ratio.

There are many kinds of gearboxes, but the role of planetary gear trains is becoming more and more important nowadays. The method proposed by this study is the case with planetary gearboxes.

The obvious advantages of the planetary gear trains are the higher torque capacity, smaller size, lower weight and improved efficiency characteristics of a planetary design. The small size and modular construction of planetary gear trains also means that they can be assembled in several stages, providing high reduction capability from a highly compact package. As such, planetary gear trains are the preferred solution in many areas such as wheel and winch drives and also slewing drives for turning large diameter cogged items that require slow movement at very high loads [3].

Fig. 1 shows the general structure of planetary gear train. The special feature about planetary gear train is that they can produce different gear ratios depending on which gear you use as the input, which gear you use as the output, and which one you hold still.

In the method proposed by this study, we consider the case that the input is the sun gear, and we hold the ring gear stationary and attach the output shaft to the planet carrier. Of course, it is possible to apply our method to other cases; sun gear stationary or planet carrier stationary.

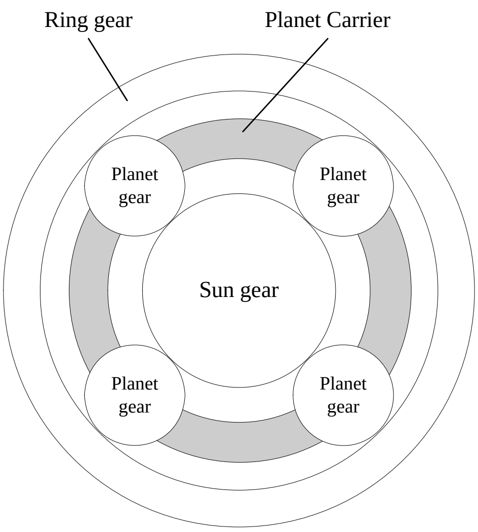

Fig. 1. The general structure of planetary gear.

2.2. Basic idea for measuring torque

In the gear train, the ring gear is fixed to the housing by an elastic material.

When the motor is rotating, the loads make some strain between the stationary element (the ring gear) and the rotating elements (the sun gear and planet carrier) by the action-reaction force. This strain pushes out the elastic material and then it makes some displacement corresponding to its torque.

Compare with ordinary method measuring the strain itself, we try to detect the displacement caused by the strain and the structural characteristic of the planetary gear train. We can measure this displacement by using the hall sensor and magnet pair.

2.3. Measurement of the torque

In many applications, the linear Hall effects sensors are used in conjunction with a permanent magnet. To maximize linearity, a large change in field strength vs. the required displacement is desired. Careful selection of the magnets, and the way of placement of that magnet, will pay large dividends.

High-quality, high field-strength magnets are generally required in most linear sensing applications.

Table 1 shows some basic magnet characteristics on particular magnet types and *Samarium-cobalt* or *Alnico 8* magnets are recommended [6].

There are some methods to combine the magnet with Hall sensor.

Fig. 2 shows slide-by sensing method using single magnet that is a non-complex method of obtaining a linear output voltage vs. slide-by movement.

As shown in Fig. 2, depending upon the location of the sensor relative to the zero-field center of the magnet, both negative and positive outputs can be produced and the center portion of the output is very linear. For our Hall sensor, the sensor output voltage at the center of magnet is Vcc/2.

As shown in Fig. 3, a proper magnet in the size and

Table 1. Properties of magnetic materials.

Material	BH*	Temp. Stability (Tc in %/ºC)	Cost
Alnico	5 to 10	Excellent thru +150ºC(-0.02)	Moderate
Ceramic	2 to 4	Moderate thru +150ºC(-0.2)	Low
Flexible	0.6to 1.5	Typ. Limitation of 100ºC(-0.2)	Lowest
Neodymium	30 to 40	Typ. Limitation of 125ºC(-0.12)	High
Samarium	20 to 30	Excellent thru +150ºC(-0.04)	Highest

BH* is the product of flux density and field strength. In general, this value represents the energy density of the magnet and is used to grade permanent magnets. The higher the value is, the stronger the magnet is.

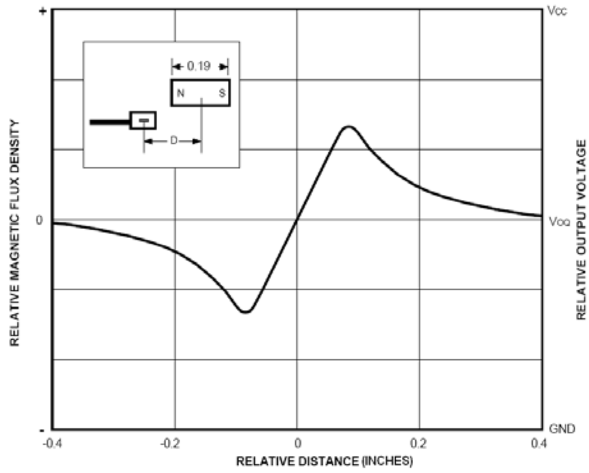

Fig. 2. Hall output voltage in slide-by sensing [6].

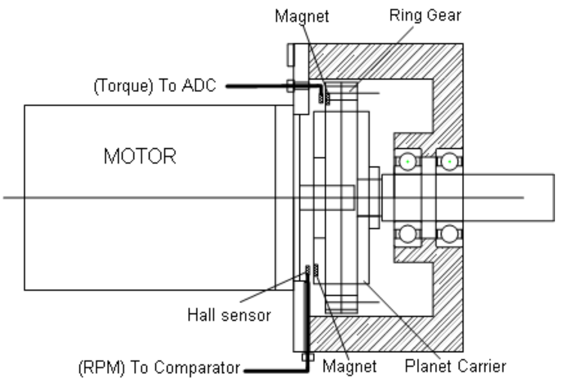

Fig. 3. Attachment of the hall sensors and magnets.

the magnetic force can be mounted directly on the ring gear. We make a hole on the ring gear supporter (elastic material) and simply attach the Hall sensor.

The air gap between the sensor and the magnet is another important factor for good sensitivity.

In general terms, the weakest magnets (flexible) would typically operate in a 0.25 mm to 2 mm range, while the strongest (neodymium or samarium cobalt) could allow an air gap of 4 mm to 6 mm.

The Hall sensor output voltage becomes the ADC input through the amplifier of the monitoring system.

The relations between the displacement and the torque also vary with the motor size, capacitance and types etc. So we should derive the relational equation or LUT (Look Up Table) measuring the each mechanical displacement from the various reference dummy torque. We consider LUT for compensating nonlinear characteristic of Hall sensor and other unknown factor.

2.4. Measurement of the RPM

As shown in Fig. 3, we have attached a proper magnet on the Planet Carrier and set the other Hall sensor on the opposite side of the magnet.

As the motor is rotating, the magnet attached on the planet carrier is also rotating and it is passing by on the fixed hall sensor every rotation.

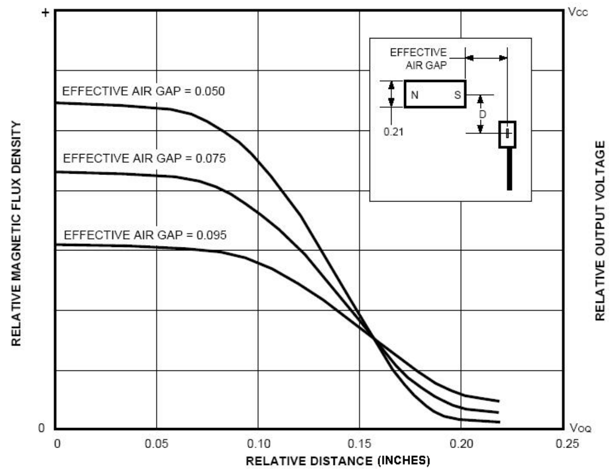

Fig. 4. Hall output voltage for RPM measurement [6].

Output hall voltage of this Hall sensor becomes the comparator input of the monitoring system.

Fig. 4 shows another slide-by sensing method for measuring RPM.

Comparing with Fig. 2, the hall sensor in Fig. 4 is sliding on *the South Pole* of the magnet.

If the comparator input value exceeds the reference value, a counting flag will be set; on dropping below the reference value, a counting flag will be cleared. We can calculate the RPM with the time interval of this counting flag's period.

We can also replace the Hall effects sensor with *Hall Effect switch* or *Hall IC* [5,7]. Hall switches have an integrated comparator with predefined switching points and a digital output which can be adapted to different logic systems. All Hall switches include an open-drain output transistor and require an external pull-up resistor to the supply voltage. A standard Hall switch has a single Hall plate and responds to the absolute value of the magnetic field perpendicular to the plate.

The Hall switch is characterized by the magnetic switching points B_{ON} (or B_{OP}) and B_{OFF} (or B_{RPN}). If the magnetic flux exceeds B_{ON}, the output transistor is switched on; on dropping below B_{OFF}, the transistor is switched off. The magnetic hysteresis B_{HYS} is the

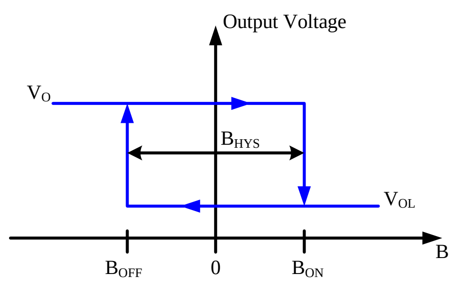

Fig. 5. Definition of switching points [5].

difference between the switching points B_{ON} and B_{OFF}. Fig. 5 shows this definition [5,7].

3. COMPUTING TORQUE, RPM AND POWER

3.1. Output torque

The measuring torque is the calibrated output data from ADC using relational equation or LUT and *the output torque* is the final displaying value determined by following equation from the measuring torque.

$$T_o = T_3(z_1 + z_3)/z_3, \quad (1)$$

T_o : Output torque to display

T_3 : Measuring torque

z_1 : Number of teeth of the sun gear

z_3 : Number of teeth of the ring gear

3.2. Measuring RPM (w_o) to display

As counting output pulse of the Hall sensor or Hall switch, we can easily calculate the rpm of the motor.

Differently Hall Effect sensor, Hall Effect switch has benefit that can be connected directly on the micro-controller input port without additional circuit like comparator, because their output hall voltages are discrete pulse. But because the Hall switch is characterized by the magnetic switching points B_{ON} and B_{OFF}, we can not vary the reference value or the switching points.

The measuring RPM w_o can be representative as following equation.

$$w_o = 60 \times cntRotate, \quad (2)$$

$cntRotate$: Revolution per every second.

Infrared sensor with reflective tape is another good choice for measuring rpm, but the size of planetary gearbox and infrared sensor itself must be considered.

3.3. Transmit power (W)

The transmit power often becomes more useful and important measure than any other displaying values and can be calculated by multiplying the output torque and RPM.

$$W = T_o w_o. \quad (3)$$

4. THE MONITORING SYSTEM

4.1. Main board

Fig. 6 shows the block diagram of the monitoring system. It is simple and composed of 3 main parts; Hall sensing data input and processing part including CPU, communication part, and user interface part including LCD and keys.

Hall sensing data input part has an amplifier and ADC for measuring torque, and a comparator for measuring RPM. Especially the reference voltage for measuring RPM is needed to variable for eliminating interference noise. One of the interference noises may be magnet flux generated from motor itself when motor is rotating. We try to eliminate this noise in the manner of controlling the threshold value to set RPM counting flag. So we use a variable resistor to adjust proper reference input.

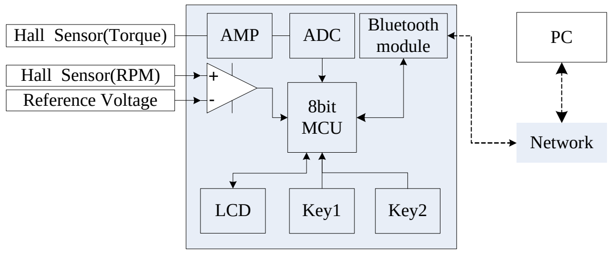

Fig. 6. Block diagram of the monitoring system.

4.2. Networking capability

It is tending that expensive measurement systems have their own communication environments whether they are cable or wireless. Among them, RS232 serial communication is the most popular and basic in many industrial applications. But the mobile systems are becoming more and more important nowadays. Especially ubiquitous environments are becoming a very big issue.

In our study, we make our monitoring system to have wireless communication ability using Bluetooth module. We make the monitoring system to attach on the motor unit as possible as compact.

This monitoring system just collects the Hall sensors output values and transmits their raw data to PC or notebook through the wireless communication. User can monitor the final processing data on PC.

It is not difficult to extend remote monitoring to on internet base with TCP/IP.

Bluetooth is a technology using short range (10m) radio links, intended to replace the cable(s) connecting portable and/or fixed electronic devices. Its key features are robustness, low complexity, low power and low cost. Designed to operate in noisy frequency environments, the Bluetooth radio uses a fast acknowledgement and frequency hopping scheme to make the link robust. Bluetooth radio modules operate at 2.4GHz, and avoid interference from other signals by hopping to a new frequency after transmitting or receiving a packet.

Bluetooth also can easily form a piconet which has a master and up to seven slaves [10]. In many industrial applications, most systems could have many motors rather than one and each motor have a correlation with other motors. On such environments, the piconet using Bluetooth will give some other advantages as well as remote monitoring function and this is the another reason that we consider Bluetooth in our study.

5. EXPERIMENTS

5.1. Experiments

We choose the ATmega128 AVR as CPU, because it has 10-bit ADC and on-chip Analog Comparator.

The ATmega128 also supports differential input channels with a programmable gain of 10x and 200x, so we can amplify the hall sensor output for torque 10x before the A/D conversion.

The main features of experiment board are;

CPU : ATmega128,
ADC : 10-bit resolution with gain 10x on CPU,
LCD : character LCD type,
KEY : 2 keys,
COMM.: 422MHz RF Module.

We want to use Bluetooth Module, but for easy to use, the RF module is tested first in our experiments. The implementation of Bluetooth is leaved for next step.

On our experiments, we have developed the torque sensor module that consists of Hall sensor and 2 magnets pair. The basic idea of our torque sensor takes from the photoelectric sensor that consists of emitters and receivers pair.

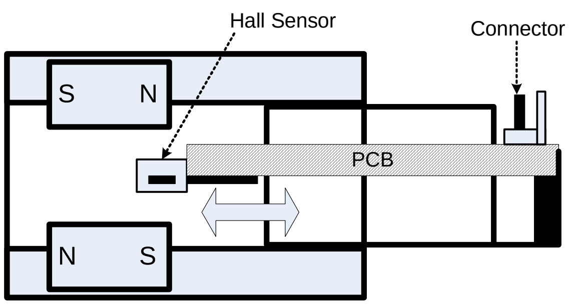

Fig. 7. Torque sensor module.

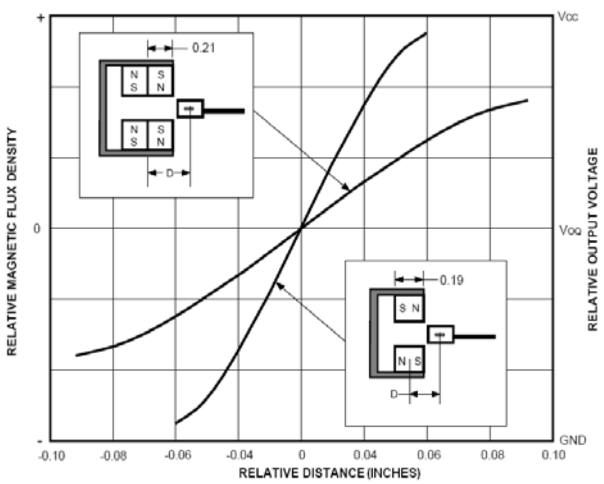

Fig. 8. Hall output voltage in push-pull approach.

Fig. 7 shows the structure our torque sensor and Fig. 8 shows the characteristic of Hall output voltage in *Push-Pull approach* [6].

In the case of the Push-Pull approach, the sensor moves between two magnets. Complementary fields provide a linear, steep-sloped output. The output is nearly rail-to-rail (GND to Vcc) with polarity dependent upon magnet orientation.

In our experiments, the displacement by torque is about 0.25mm at 29.4 N·m.

6. CONCLUSIONS

A method to measure the mechanical torque developed by an electrical motor is suggested.

The torque measuring method experimented by this study is the reduction case when the input is the sun gear, and we hold the ring gear stationary and attach the output shaft to the planet carrier.

Other is the overdrive case when the input is the planet carrier, and we hold the ring gear stationary and attach the output shaft to the sun gear.

We can apply our method not to the ring gear stationary case, but also to other cases; sun gear stationary and planet carrier stationary.

The suggested method is very simple, very small and very inexpensive in measuring the power including the torque and RPM of the motor. And this method does not need additive maintenance, because this is the non-contact method. Furthermore, on experiments, our non-contact method reduces the vibration and noise of the motor much more than we supposed to. This is caused by using elastic material and it also means that we can measure the torque more exactly and we can extend our application scope more widely.

In the case the measuring the torque or power is important, our solution is not only simple and cheap but also can give an instance in monitoring such values. Instant monitoring power, torque and rpm through the wireless communication are very useful and have many applications. Indeed we can make a motor unit smaller to wide our application like robot finger to control force.

In general, Planetary Gear Train is relatively more expensive than usual multistage spur gear box. But it deserves to replace usual multistage spur gear box by our Planetary Gear Train, having remote monitoring ability and more additive advantages.

In conclusion, our solution has a strong point in size, cost and wireless communication. So it can give many applications on industrial field and the extension of the application is dependent on user's imagination. Moreover, the usage of piconet or scatter net of our motor units will make other applications.

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