Optical Reflective Gear Tooth Sensor with Application to Rotational Speed Measurement

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Abstract:

An optical reflective gear tooth sensor is described in this paper. Mathematical models of optical and electrical signals are derived after theoretical analysis and calculation, and the waveforms are plotted as a reference of design by MATLAB programming. The test results show that the optical reflective gear tooth sensor with collimation LED can work well in a wide range of sensing distance, and the optical reflective sensor can detect a longer distance than Hall-effect sensor with high measuring accuracy. The developed optical reflective gear tooth sensor can be applied to various kinds of rotary speed measurement, especially where the electromagnetic interference or a wide sensing distance of sensor is required.

1. Introduction

Speed control is an important operation in mechanical systems, since the performances of these systems are closely related to the quality of measured rotary speed [1]. Rotational speed sensors are widely used in industrial automation, production lines, intelligent robots, wind power stations, and automotive industry for testing, controlling and monitoring engines, motors, generators, spindles of different rotating machines [2]. There are lots of methods to measure the rotary speed, and the most widely used is rotational impulse counting method with inductive, capacitive, magnetic or optoelectronic proximity switches, sensors or encoders [3-4].

However, proximity switches have a low resolution because they only output one impulse per revolution. Although encoders have high revolution, they are so expensive that they are suitable for some circumstances where precision measurements are needed. Hall-effect sensors are based on magnetoelectric effect, thus they are susceptible to electromagnetic interference. And optical interrupter sensors are not convenient to install and adjust since they detect signal with LEDs and detectors on opposite side of the target [6-8]. Therefore, this paper proposes a method to measure rotary speed with optical reflective gear tooth sensors, which can solve the above-mentioned issues.

2. Measuring System

An optical reflective gear tooth sensor consists of four basic components: a light source, a photo detector, a gear tooth on the shaft and a signal processing circuit. Figure 1 shows the structure of optical reflective gear tooth sensor. Light beams emitted from the light source strike on the gear tooth that is covered with a regularly-spaced radial pattern of reflective and non-reflective elements. With the shaft rotating, light beams are modulated by the periodic sequence of reflection and non-reflection zones generated by gear teeth, and the modulated light beams are sensed by a photo detector and processed by electronic circuits [9].

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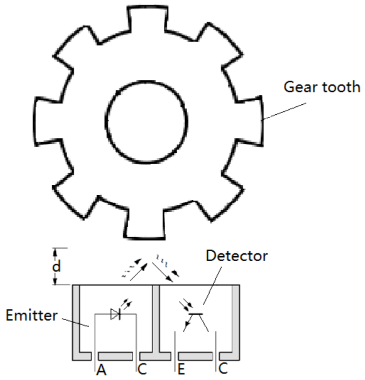

Fig. 1 Structure of optical reflective sensor

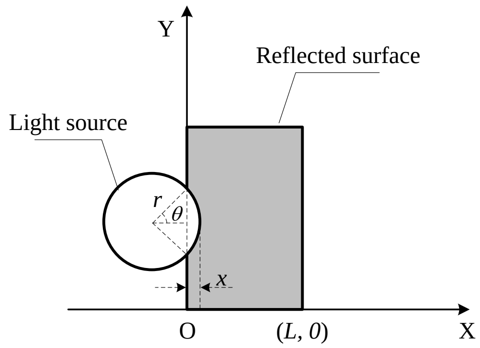

Fig.2 Relative motion between light and teeth

2.1 Mathematical Model of Optical Signal

Figure 2 shows the relative motion between light source and gear tooth. The light source has a circular light spot with a radius r and the teeth, with a rectangle surface of width L, are covered with white surface that can reflect light beams. When the relative motion between light source and teeth is happened on axis X, photo detector can receive a period analog signal which contains speed information. Supposing the addendum arc width L_1 is the same as the teeth gap L_2.

In figure 2, light beams are reflected where the light source and reflected surface overlap, the width of which is x on the axis X. When x is between 0 and r, we have

$$\cos\theta = \frac{r-x}{r} \tag{1}$$

The area of triangle and sector in figure 2 are

$$S_T = r\sin\theta(r-x) \tag{2}$$

$$S_S = \frac{\pi r^2\theta}{180} \tag{3}$$

So the area of reflected light is

$$S(x) = S_S - S_T = \frac{\pi r^2 \arccos(\frac{r-x}{r})}{180} - (r-x)\sqrt{r^2-(r-x)^2} \tag{4}$$

When the light source passes through a tooth, $S(x)$ can be represented as

$$S(x) = \begin{cases} \dfrac{\pi r^2 \arccos(\frac{m}{r})}{180} - m\sqrt{r^2-m^2}, 0 < x \le r \\ \pi r^2 - \dfrac{\pi r^2 \arccos(\frac{-m}{r})}{180} - m\sqrt{r^2-m^2}, r < x \le 2r \\ \pi r^2, 2r < x < L_1 \\ \pi r^2 - \dfrac{\pi r^2 \arccos(\frac{n}{r})}{180} + n\sqrt{r^2-n^2}, L_1 < x \le L_1 + r \\ \dfrac{\pi r^2 \arccos(\frac{p}{r})}{180} - p\sqrt{r^2-p^2}, L_1 + r < x \le L_1 + 2r \\ 0, L_1 + 2r < x \le 2L_1 \end{cases} \tag{5}$$

where $m=x-r$, $n=r-x+L_1$, and $p=x-L_1$. If the rotary speed of gear tooth is v, x is

$$x = vt \tag{6}$$

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where t is the relative motion time. The phototransistor receives light reflected by target and transforms it into photocurrent, the magnitude of which is related to the energy of reflected light. The current in the diode is

$$i = i_p + i_{sat}(e^{\frac{eV_a}{kT}} - 1) = \frac{-\eta eP}{h\nu} + i_{sat}(e^{\frac{eV_a}{kT}} - 1) \tag{7}$$

where i_P is the photocurrent, i_{sat} is the dark current (leakage current), P is the light power falling on the detector, η is the quantum efficiency, e is the charge of an electron, k is Boltzmann's constant, and T is the temperature in degrees Kelvin[7]. Since the optical power is proportional to the luminous flux, which is $d_E d_S$, when the illuminance is constant, the luminous flux is proportional to the area. Therefore, the light power is related to the area of light reflected on detector.

$$P \propto S \tag{8}$$

2.2 Electronic Circuit Design

The optical signal received by a detector is converted into a sequence of photocurrent signal, which is so weak that cannot be used for generating speed impulses directly. Therefore, the photocurrent should be converted into voltage signal by adding an external load resistance R_L.

If there is no reflected light detected, the output U_L equals to the supply voltage V, otherwise, the voltage U_L is calculated by formula (9). Suppose that the supply voltage is $5V$. With the rotating of gear tooth, the output voltage U_L is a periodic signal, shown as Figure 3.

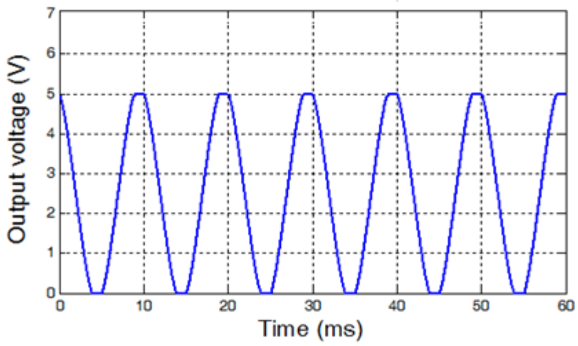

Fig. 3 Waveform of output voltage U_L calculated by MATLAB

The output voltage U_L has a same frequency as photocurrent, but a reversed phase. This analog signal will be converted into a square wave with constant amplitude through a comparator.

Comparators have very high open-loop gain, and without any type of positive feedback. For open-loop operational amplifiers, which are often used as comparators, a small amount of noise or interference mixed with the input signal can cause undesirable rapid changes between the two output states. It can generally be cured by introducing hysteresis. Hysteresis is a positive feedback that pulls the input signal through the threshold when the output switches, thus preventing multiple switching. Figure 4 shows the hysteresis circuit of a comparator.

In Figure 4, the switching voltages of comparator are

$$V_{sl} = V_+ - i_1 R_1 = V_+ - \frac{V_+}{R_1 + \frac{R_2 + R_3}{R_2 R_3}} R_1 \tag{9}$$

$$V_{sh} = i_2 R_2 = \frac{V_+}{R_2 + \frac{R_1 + R_3}{R_1 R_3}} R_2 \tag{10}$$

where V_{sl} is the low switching voltage and V_{sh} is the high switching voltage. Hysteresis voltage is the difference between the two voltages,

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$$V_{hys} = \frac{V_+}{R_1 + \frac{R_2 + R_3}{R_2 R_3}} R_1 + \frac{V_+}{R_2 + \frac{R_1 + R_3}{R_1 R_3}} R_2 - V_+ \quad (11)$$

The comparator with hysteresis has only two output states: low output (V_{ol}) which is zero or high output (V_{oh}) which equals to the supply voltage. Figure 5 is the simulation results of comparator with hysteresis in MULTISIM.

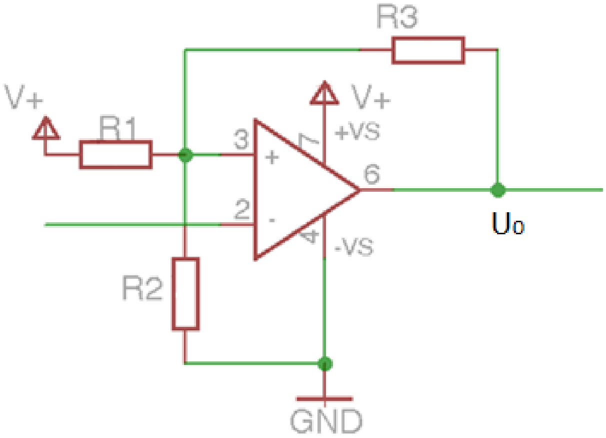


Fig. 4 Hysteresis circuit of a comparator

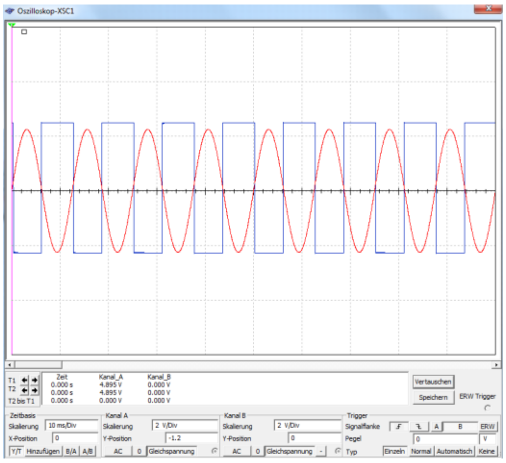


Fig. 5 Input and output of comparator

When the input voltage increases from $0V$, the output is V_{CC} and remains there until the input passes the high threshold. At that point, the output changes drastically from V_{CC} to $0V$, because the inverting input is more positive than the non-inverting input for V_{hys}. Then the output remains low until the input passes the low threshold. In this case, the output switches immediately to V_{CC}, because the non-inverting input is more positive than the inverting input for V_{hys}.

3. Experiment results

To evaluate the performance of optical reflective gear tooth sensor, the following experiment is implemented.

Figure 6 shows the experimental system and elements. It includes: (1) Power supply, (2) red LED and photo transistor, (3) Displacement platform, (4) gear tooth, (5) motor, (6) circuit, and (7) oscilloscope.

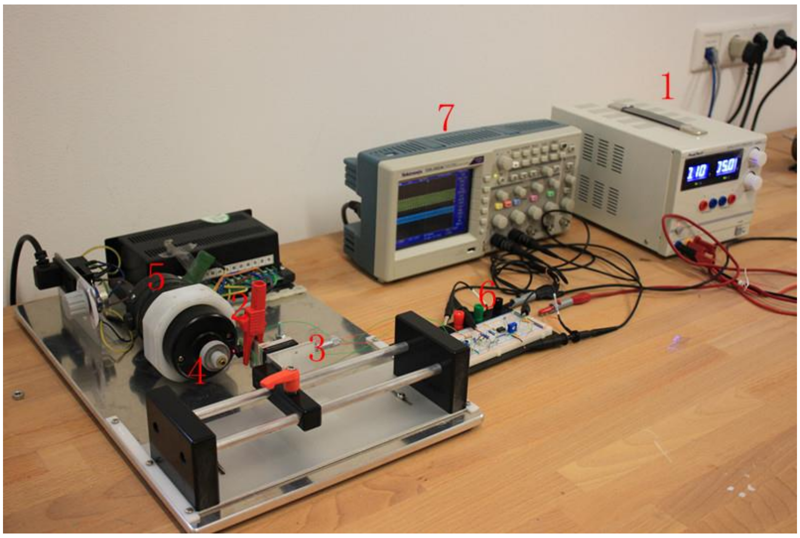


Fig.6 Experimental devices and system

In figure 6, the gear tooth is installed on the shaft of motor and the optical reflective sensor is on the side of gear tooth. The LED and detector are placed on the axial direction of gear tooth, the addendums of which are painted with white color to reflect light. Figure 7 shows the basic characteristics of optical reflective sensor. The output of the photo detector depends on the wavelength of incident light. Unless optical filters are used, the peak spectral response of a photo diode is in the near IR at approximately 840 nm. The peak response of a phototransistor is at a somewhat shorter wavelength than that of a typical photodiode, because the diffused junctions of a phototransistor are formed in epitaxial rather than crystal grown silicon wafers. In this paper, a red LED is chosen as light source. It should be noted that LED and transistor are packed in a surface mount package to block visible light. The voltage U_L is connected to the inverting input of comparator after a filter. Channel A and channel B of oscilloscope are connected to the inverting terminal and the output of comparator respectively.

Parameter	Value	Condition
Forward voltage of LED	1.2V typ., 1.5 V max.	I_F=50 mA
Radiant intensity	7 mW/sr typ., 75 mW/s max.	
Virtual source diameter	1.2mm	63% encircled energy
Reverse dark current	1 nA typ., 10 nA max.	V_R=10V, E=0 lx

Fig.7 Basic characteristics of Sensor 1

The experiments are carried out to measure the speed with four kinds of target gears, shown in figure 8. From left to right, the first one has 5 teeth (L_1= 12.16mm, L_2= 5.82mm, r=14.01mm), and the width of addendums are much larger than tooth gaps. The second one has 12 teeth (L_1= 3.04 mm, L_2= 3.32mm, r=14.01mm), and the width of addendums are almost same as tooth gaps. The third one has 22 teeth (L_1= L_2=1.96mm, r=14.01mm) and the last one has 64 teeth (L_1= L_2= 1.96mm, r=40.89mm), of which the addendums width are the same as the tooth gaps. Where L_1 is the addendum arc width, L_2 is the width of tooth gap and r is the radius of gear tooth.
Figure 9 shows the inverted input signal and output signal of comparator. It can be seen that the output signal is of high stability and low noise.

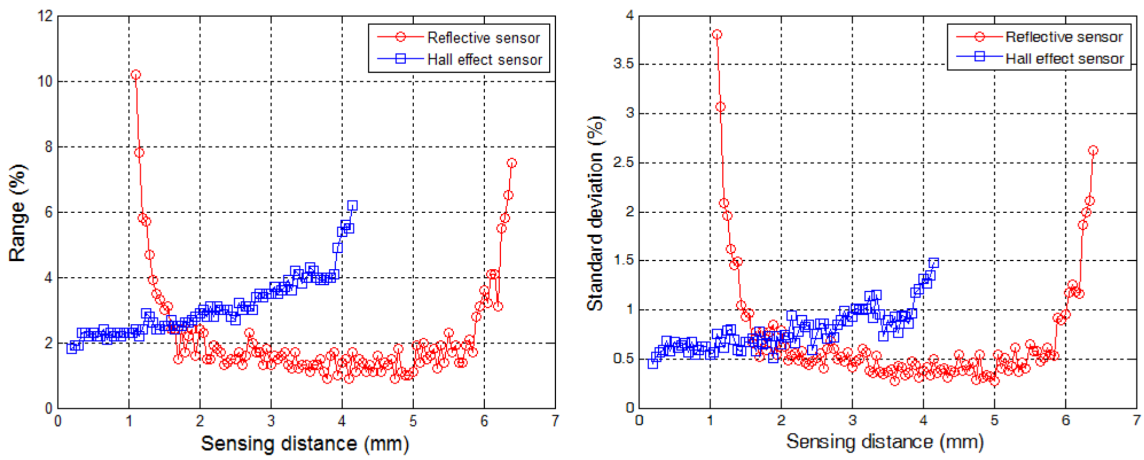
Fig.8 Four kinds of target gears

Fig.9 Input and output voltage on oscilloscope

The maximum output of U_L where no photons are reflected on the phototransistor is always below *5V* for the existence of dark current and ambient light. Therefore, in order to get accurate results, it will be better if the light in experiment condition is constant. Each pulse of square wave corresponds to a tooth and is used for speed calculation. It can be seen that the minimum output is *0V*, but the maximum output is not the supply voltage *5V*, since the maximum output U_m of the operational amplifier LM358 here used as comparator is

$$U_m = V - 1.5 \tag{12}$$

Figure 10 gives a comparison of optical reflective gear tooth sensor and Hall-effect gear tooth sensor (CYGTS101DC-S) [10] in different sensing distance. It is measured with gear tooth 2 at the rotary speed of *10 r/s*.

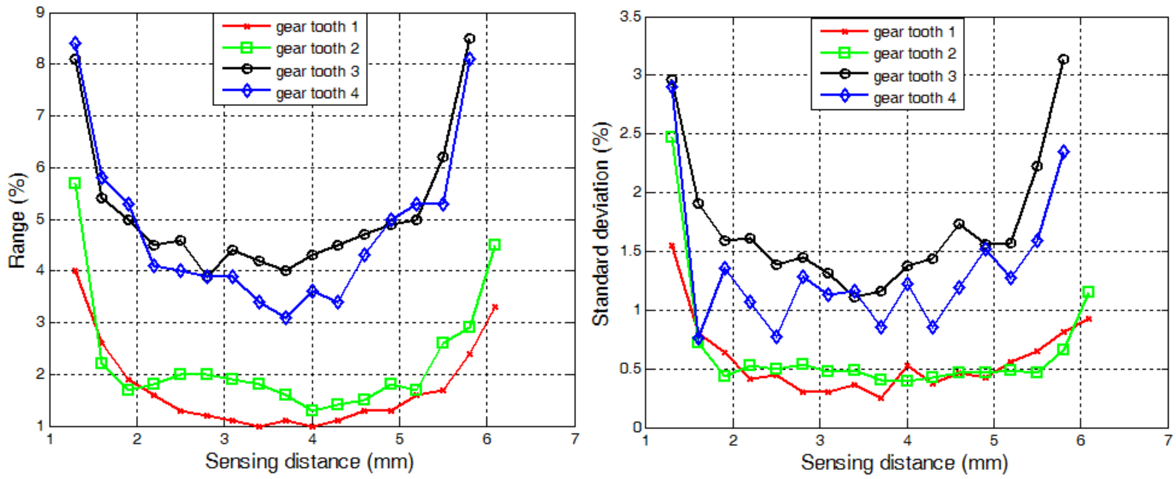


(a) Range of duty cycle (b) Standard deviation of duty cycle

Fig.10 Comparison of reflective sensor and Hall-effect sensor in different sensing distance

In figure 10, it can be seen that the Hall-effect sensor can detect rotary speed within a short distance from 0.2mm to 4.1mm, and the range is 2%-6%. The range and standard deviation of Hall-effect sensor increase as the sensing distance getting larger. If the sensing distance is longer than 4.1mm, Hall-effect sensor cannot output a square wave.

The reflective sensor can detect rotary speed within a distance from 1.1 mm to 6.4 mm, which is related to its focal length. From 1.2mm-6.2mm, the range is between 2% and 6%. And the range and standard deviation of reflective sensor increase as the sensing distance getting far away from the focal length.
Figure 11 shows the comparison of reflective sensor and Hall-effect sensor at different gear tooth with rotary speed 29.32r/s.



(a) Reflective gear tooth sensor

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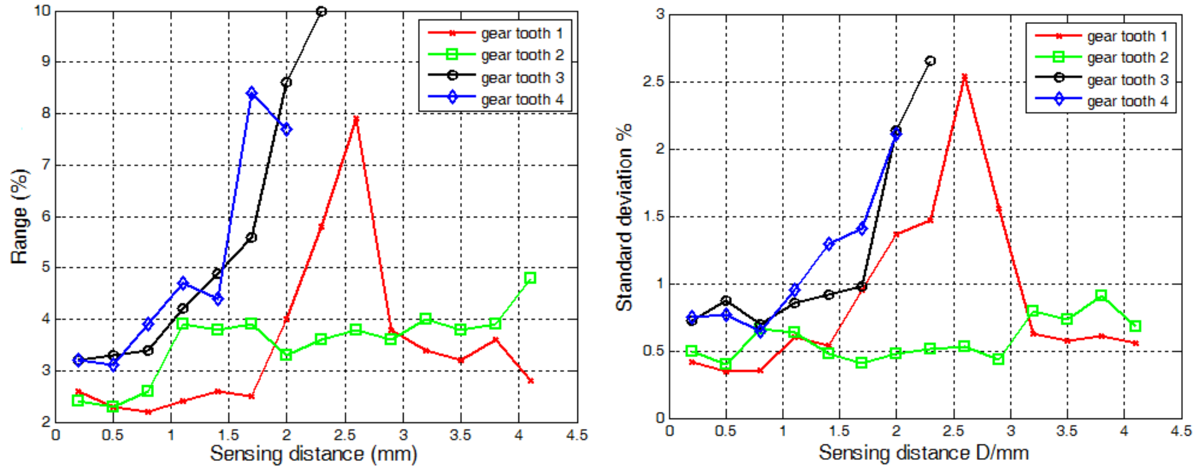

(b) Hall-effect sensor

Fig. 11 Comparison of optical reflective sensor and Hall-effect sensor with different gear tooth

We can see that the ranges and standard deviations of reflective gear tooth sensor and Hall-effect sensor increase while the tooth width decreases. It should be noted that there is a peak value of Hall-effect sensor with gear tooth 1 when the sensing distance is *2.6mm*, after which the range decreases and the duty cycle changes from *67%* to *33%*. By comparing the reflective sensor and Hall-effect sensor, it can be seen that the optical reflective sensor can detect from *1.2mm* to *6.2mm* while the Hall-effect sensor can detect from *0.2mm* to *4.1mm* at gear tooth 1 and gear tooth 2. The sensing distance of reflective sensor is from *1.2 mm* to *5.8 mm*, while the Hall-effect sensor can only detect from *0.2mm* to *2.3 mm* with gear tooth 3 and gear tooth 4. Therefore the optical reflective sensor has a longer sensing distance.
Figure 12 shows the comparison of Hall-effect sensor and optical reflective sensor with different speed. The measurement gear tooth is Nr.3 (with 22 teeth, $L_1 = L_2 = 1.96mm$, $r = 14.01mm$).

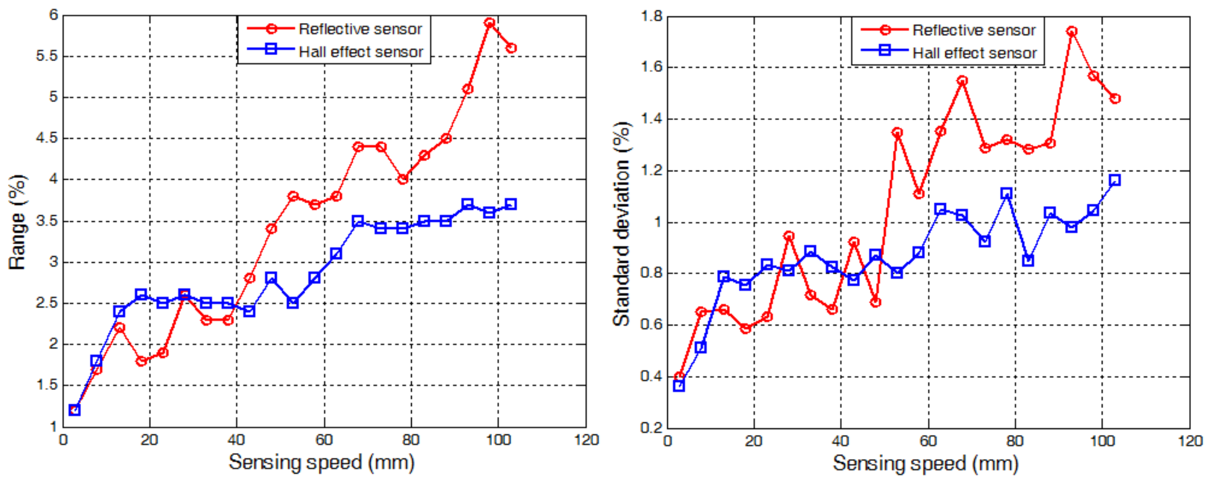

Fig. 12 Comparison of optical reflective sensor and Hall-effect sensor at different speed

It would be seemed obviously that the deviation of both reflective sensor and Hall-effect increase as the speed accelerates, but the deviation of reflective sensor varies faster than that of Hall-effect sensor, since the response speed of phototransistor has a great effect on the sensing speed of optical reflective gear tooth sensor.

4. Potential Applications

Optical reflective gear tooth sensors are designed for potential applications where large air gaps or electromagnetic interference is required. In addition, there are many options available for the material of gear tooth used in optical reflective sensors. Potential applications:

Automotive and vehicles:

- Camshaft and crankshaft speed
- Anti-skid/traction control
- Transmission speed

Industrial Areas:

- sprocket speed sensing
- Chain link conveyor speed
- Tachometers, counters

5. Conclusions

In this paper, a novel implementable speed measurement method has been developed based on the optical reflective sensor. This kind of sensor has a long sensing distance, without electromagnetic interference and no requirement for the material of gear tooth. The mathematical models of optical signal were proposed as a reference of design. The simulation and experiment results show that the designed optical reflective gear tooth sensor can be used in long distance detection and performed well in different gear tooth and different speed. Compared to Hall-effect sensor, the functionality and implementation of reflective sensor was highlighted. The work in this research has a good practical value, which is also suitable for other photoelectrical measurement systems.

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