Hall Effect Gear Tooth Magnetic Encoder

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***Keywords*—Hall-Effect, Gear Tooth, Position Sensor, Magnetic Encoder.**

***Abstract*—Encoders are the most common speed/position sensors in industrial applications. The commercial encoders are divided into two groups: optical and magnetic types. From accuracy point of view, the first one has distinguished performance. While, the next has superior performance in harsh environments. The accuracy of the magnetic encoders is influenced by geometrical dimensions of different parts and the quality of their employed materials. In this paper, the effect of the air-gap length, slot depth, the number of gear's teeth, the employed material for the ferromagnetic gear and the used permanent magnet on the performance of the Hall effect gear tooth magnetic encoder is discussed.**

I. Introduction

Closed-loop control of electrical machines needs the information of rotor's position. Therefore, position sensors are widely used in different industrial applications such as automotive industry, robot arms, electric bicycles, wind turbine stations and closed loop control of different inverter driven electrical machines [1]- [2]. The most common position sensors are optical encoders and magnetic sensors [3]. Optical encoders due to high accuracy, low cost and digital output are frequently employed in different applications [4]. However, they suffer from accuracy deterioration in harsh environments, where magnetic sensors attract more attentions [5]-[6]. Magnetic position sensors are divided into two groups. In the first group a high frequency input voltage is applied to the excitation winding and the induced voltage in the signal windings are used for calculating the rotating position. The commercial position sensors of the first group are Resolvers, Inductosyns, and Synchros. This group of sensors have high accuracy and reliability, robustness and low-noise effects in the price of heavy weight, large volume relatively high cost [3]. The next group, so-called Magnetic Encoder, use permanent magnets for the excitation. Two common types of magnetic encoders are gear tooth type and permanent magnet disk type. In the first type, a gear tooth, a small permanent magnet, and usually two Hall-Effect sensor are used as the sensor. The second type is consisted of a disk that is magnetized, with a number of poles around its circumference, and Hall-Effect sensors. Both types of the magnetic encoder need a conditioning circuit. There are other types of magnetic encoders that are called PM resolvers [7]-[9]. In PM resolvers there are more than two Hall-effect sensors that are designed to have a two-phase sinusoidal voltage as the output of the sensor. Among different types of magnetic encoders, gear tooth type attracts more attentions due to its simple structure and wide industrial applications. However, mathematical calculations are necessary for this type of magnetic encoder in order to have the proper duty cycle, phase shift, and frequency. Authors of [10] proposed some ideas for determining the dimensions of the Gear tooth target wheel. In [11] the influence of changing the hall effect sensors is discussed. However, the influence of wheel's geometrical dimensions, the distance between the wheel and the sensors, and the quality of the ferromagnetic materials on the sensors performance is not discussed in literature. Therefore, in this paper time stepping finite element analysis is employed to determine the influence of different design parameters on the sensor's output.

II. The studied Encoder

The studied magnetic encoder is made up of two Hall Effect sensors, a permanent magnet and a target wheel as illustrated in the Fig.1. The target wheel is rotated by the rotating shaft and the other components are fixed to the stationary part. When facing the target wheel's tooth, the hall effect sensor experiences a stronger magnetic field; When facing the target wheel's slot, a weaker magnetic field is experienced. The output voltage of each Hall Effect sensor will be correlated to the magnetic field it detects. The diameter of the target wheel (D), the gap (g), the slot depth (ds), the size of the magnet (wpm), the material of the permanent magnet and the target wheel, and of course the gain of the sensor all affect the output voltage of the sensor.
Hall Effect sensors typically have relatively low output voltage amplitudes in the range of 15 to 20 mV. The signal is more vulnerable to noise due to its low voltage amplitude. Therefore increasing the voltage amplitude by adjusting the aforementioned parameters is considered in this paper.

III. The Required Amplification Circuit

As was already indicated, sensor output voltage typically has a limited amplitude. For the calculation of an encoder, a digital circuit is typically employed as well. These factors necessitate the use of an amplification circuit and schmitt trigger. The magnetic encoder's output circuit is shown in

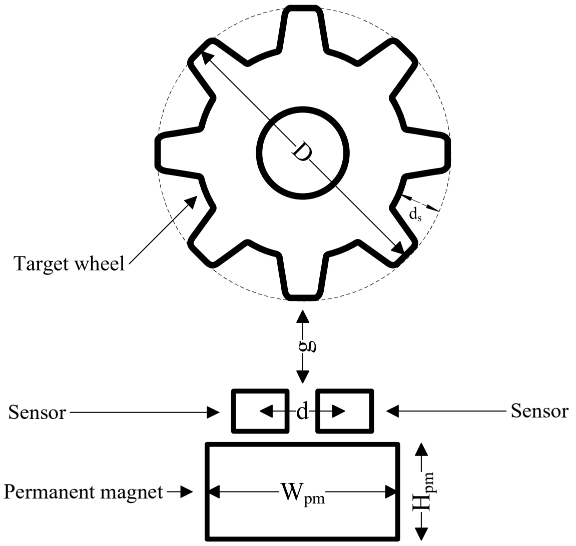


Fig. 1: The studied Hall Effect Gear Tooth Encoder

Fig.2. The DC component of the output voltage is eliminated using the capacitor C and the resistor R. In an amplifier, the AC voltage is then compared to Gnd to increase its amplitude and create a pulse voltage. The lowest frequency to be eliminated determines which values for R and C should be used. In addition the circuit's time constant grows with the multiplication of R and C. Therefore, these two elements should be chosen in accordance with those two constraints.

IV. Finite Element Results

Three-dimensional (3D) time stepping finite element method is used for performance evaluation of the studied magnetic encoder. The target wheel is rotated with 1500 rpm and the magnetic flux density on the sensors is calculated. Total number of mesh elements are 512000, and the simulation's time step is set equal to 10 µs . In the next sections, the influence of different design parameters on the measured magnetic flux density is studied.

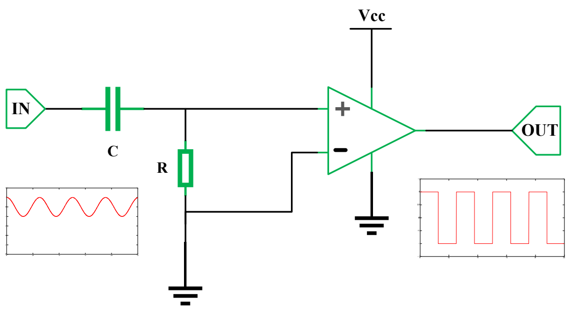


Fig. 2: Magnetic encoder output circuit

A. The distance between the sensor and the target wheel

The magnetic field is significantly impacted by the distance between the sensor and the target wheel. Fig.3 illustrates the influence of increasing g, on the measured magnetic field strength by hall effect sensors. Due to the vacuum's high reluctance, when the gap is widened, the magnetic field that the sensor is exposed to will weaken. The output voltage decreases as the magnetic field weakens. The average value (B_{av}) and the amplitude of the measured B, for different value of airgap length is presented in table I. When the air gap increases from 1mm to 2mm, the amplitude is reduced by less than half. For the best output voltage amplitude, it is crucial to maintain a low airgap length.

B. The slot depth

The depth of a slot is one of the factors that impacts the output amplitude, as shown in Fig.4 Due to an increase in the magnetic reluctance difference between the slot and the tooth, the measured magnetic field strength will rise as the slot deepens. The average value (B_{av}) and the amplitude of the measured B, for different value of d_s is presented in table II. The amplitude is increased by more than twice when d_s is raised from 3mm to 10mm. More magnetic field amplitude is produced as d_s increases, but the target wheel's toughness is reduced as well.

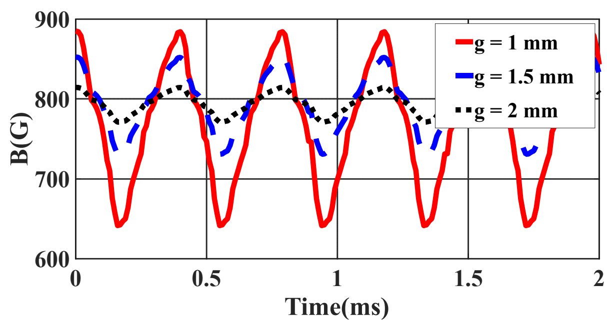


Fig. 3: The effect of air gap length on the measured magnetic field strength

TABLE I: Air gap effect

g (mm)	d_s (mm)	B_{pp} (G)	B_{av} (G)
1	10	232	762
1.5	10	129	797
2	10	56	794

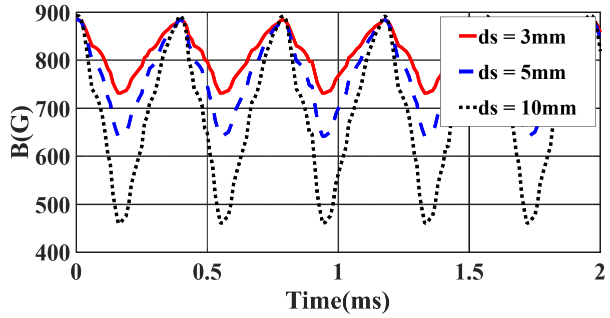


Fig. 4: The effect of slot depth on measured magnetic field by sensor

TABLE II: Slot depth effect

g (mm)	d_s (mm)	B_{pp} (G)	B_{av} (G)
1	3	148	658
1	5	256	776
1	10	432	828

C. *The influence of PM flux density*

The flux density of the PM is the other factor that directly impacts the output amplitude. The magnetic field amplitude grows linearly as the flux density of the magnet increases, as shown in Fig.5.

Three widely used materials are utilized to replicate this effect. A linear relationship between the magnet's flux density and magnetic field amplitude is seen in table III.

There is, however, a practical problem here. Nearly all hall effect sensors are capable of measuring magnetic fields with tiny amplitudes. Consequently, a magnet's flux density can be raised within a limited range. The Allegro Company's Ugn3503 hall effect sensor, which has a magnetic saturation level of 900 G, is an example of this sensor limitation. For the sensor to function properly, the average magnetic field (B_r) value must be smaller than this value.

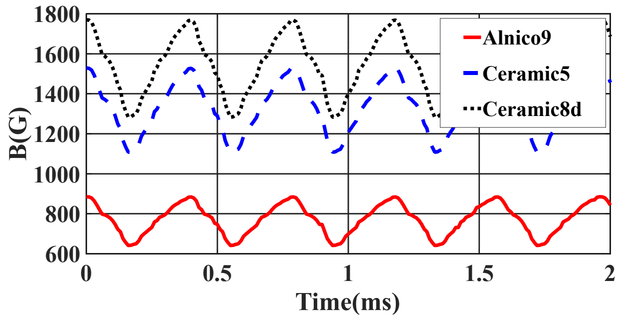


Fig. 5: The effect of magnet material on sensor output

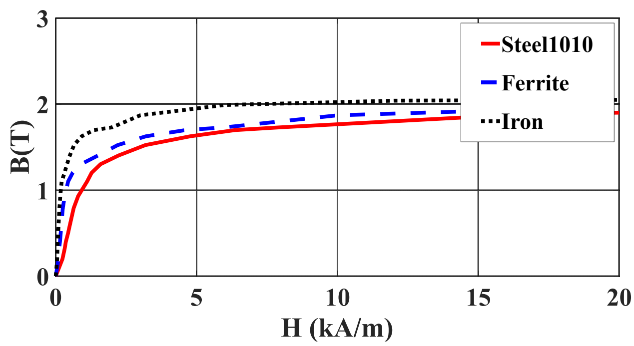
TABLE III: The influence of PM material

Material	B_r (T)	B_{pp} (G)	B_{av} (G)
Alnico	0.165	429	1541
Ceramic5	0.264	410	1326
Ceramic8d	0.368	216	778

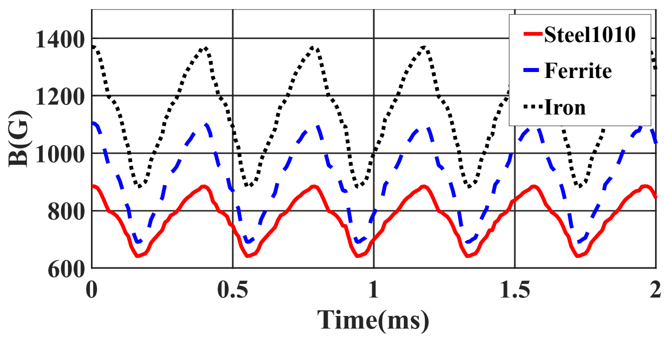
D. *The influence of ferromagnetic material*

The magnetic field that the sensor is facing is impacted by the target wheel's reluctance. three different materials are used for the target wheel. The magnetization curve of the examined materials is given in Fig. 6-a. The measured magnetic field considering different materials is shown in Fig.6-b.

Table IV presents the average value (B_{av}) and amplitude of the measured B for various target wheel's material. The magnetic field amplitude grows with increasing relative permeability of the target wheel. However, the B_{av} grows larger, which could lead to the saturation issue already discussed.



(a) The B-H curve of three materials



(b) Magnetic field

Fig. 6: Effect of target wheel‘s material on sensor output

TABLE IV: Target wheel effect

Material	μ_r (mm)	B_{pp} (G)	B_{av} (G)
Steel1010	823	206	779
Ferrite	2000	396	894
Iron	4000	458	1172

V. Resolution

Any encoder's resolution is one of its most crucial features. The resolution of a gear tooth magnetic encoder is equal to the number of output pulses in one rotation for absolute rotary encoders. Higher resolution is needed for practically all applications, increasing the target wheel's tooth count in the process. However, as the number of teeth increases, the width of each tooth decreases. Therefore, magnetic encoder resolution has a limit.The magnetic encoder's resolution can be increased, per the equation, by increasing the target wheel's diameter, although doing so makes the wheel heavier and more expensive. The sensor could also be made smaller in order to make the tooth smaller.

Resolution of a magnetic encoder is calculated by multiplying the slot number by the rotational speed, as shown in Fig.7. The impact of increasing the number of slots on the magnetic field frequency is shown in Table V. The output frequency grows linearly with the number of slots. Therefore, adding more slots improves resolution, but there is an issue with this from a practical standpoint. The target wheel's endurance decreases as the number of slots increases, which makes it more difficult to manufacture.

VI. Conclusion

Simulations demonstrate that the characteristics of the permanent magnet, target wheel's material,number of sluts,slot width and sensor's distance have a direct impact on the magnetic field of the sensors and, consequently, the sensor output voltage. The sensor magnetic field weakens and the output voltage amplitude diminishes as the distance between the sensors and the target wheel widens. The target wheel and magnet's material choice also has an impact on the output voltage. The output voltage amplitude grows linearly with the flux density of the PM. Additionally, the peak and amplitude of the output voltage rise as the relative permeability of the target wheel increases. The target wheel's slot depth grows together with the output voltage's amplitude.

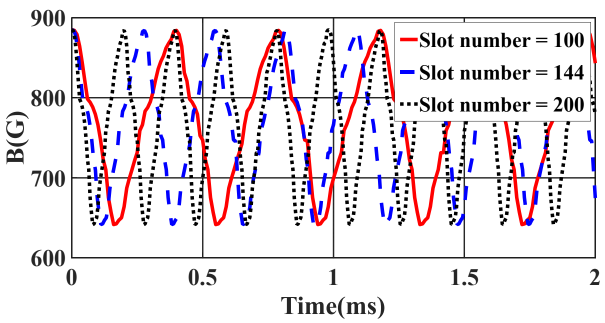


Fig. 7: Effect of slot number on resolution

TABLE V: Effect of slot number on resolution

Slot number (mm)	d_s (T)	rotational speed (rpm)	Frequency (Hz)
100	2502	1500	2496
144	3606	1500	3598
200	5003	1500	5003

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