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Design of Hall Effect Gear Tooth Speed Sensors by Using Magnetic Field Simulation

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Abstract:

In this paper design of Hall Effect Gear Tooth Speed Sensors by using Magnetic Field Simulation (MFS) is proposed for shortening development time and saving high experimental costs. The MFS is implemented with the software Ansoft Maxwell. The deviation between the simulation and measured results of magnetic flux density passed through Hall IC during rotating the target gear is corrected by a proposed calibration algorithm of adapting input parameters of the MFS. The presented methods are applied to the design and optimization of speed sensor CYGTS101DC-S and its target gear. After the optimization the duty cycle of the sensor output impulse is about 50% with relative error within ±2%, and the sensing gap reaches 3.5mm.

Key words: Hall Effect gear tooth speed sensors, rotational speed measurement, magnetic field simulation, calibration algorithm, design and optimization.

1. Introduction

Hall Effect gear tooth sensors are widely used for rotational speed measurements in industrial automation, motor drives, intelligent motion, electric bikes and automotive industry, especially electric automobile, for testing, controlling and monitoring engines, motors, generators, and spindles of different rotating machines.

A rotational speed measuring system consists of a Hall Effect gear tooth sensor (GTS) IC, a permanent magnet and a target gear (see Fig. 1). The GTS IC detects the addendum of the target gear by using peak magnetic field or differential magnetic field principles [1]. It generates a series of output impulses when the target gear rotates. The goal of developing such a measuring system is to get duty cycle 50% of output signal and a large sensing gap for most applications.

In [1] parameter optimization of Hall Effect gear tooth speed sensors is presented, based on experimental results. In order to optimize the sensor, time-consuming experiments must be done by selecting magnetic field detection methods, changing the magnet sizes and modifying the target gear etc. This optimization process costs enormous development time and materials.

The solution is to use Magnetic Field Simulation (MFS) to calculate the magnetic flux density passed through the Hall GTS IC during rotating the target gear. According to the operating and release points of the Hall GTS IC, the output impulse waves of the gear tooth sensor can be determined by a digital detection algorithm under using the MFS results. The duty cycle and the sensing gap of Hall Effect gear tooth sensors can be optimized after the simulation. As results one can obtain the optimized relevant parameters of the target gear, the permanent magnet and sensor configuration.

The MFS accuracy plays an important role for approximating simulation output impulse waves to the measured output impulse waves. Thus a calibration algorithm for adapting simulation input parameters is proposed to reduce the deviation of the MFS. The calibrated simulation input parameters can be then used for the design and optimization of Hall Effect gear tooth speed sensors.

After the optimization the duty cycle of the output impulse of a developed speed sensor CYGTS101DC-S is about 50% with relative error within ±2%, and the sensing gap reaches 3.5mm. This sensor is used for the speed measurement of motor rotor and other rotational machines etc.

2. Magnetic Field Simulation MFS

According to [1] the sensing distance of a Hall Effect gear tooth sensor can be improved by using a Hall GTS IC based on differential magnetic field detection. The sensing distance is nearly doubled in comparison with that of sensor based the peak magnetic field detection. A large sensing distance is more convenient for applications. Therefore this type of gear tooth sensor was used as example for the magnetic field simulation.

The differential gear tooth sensor model is shown in Fig.1. Two Hall Effect elements, which are positioned in distance *a,* and built in the GTS IC, are used for detecting the magnetic field change during the rotation of the target wheel. The GTS IC generates output impulses by using the difference between the output voltages of the two Hall Effect elements caused by differential magnetic field.

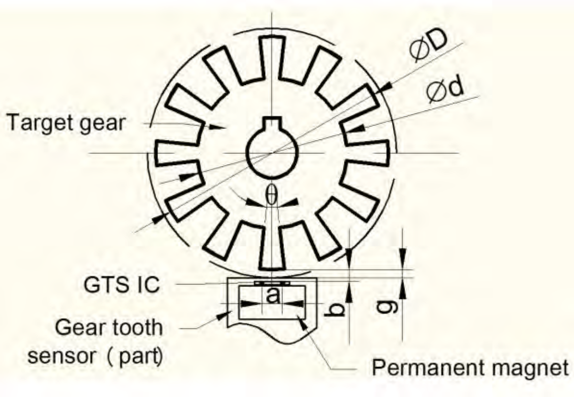

Fig.1. Configuration of a Hall Effect gear tooth rotational speed measuring system based on differential magnetic field detection

Ansoft Maxwell is commercial software, which is developed for electromagnetic field simulation used for the design and analysis of 3D/2D structures, such as motors, actuators, transformers and other electric and electro-mechanical devices and sensors. It is based on the Finite Element Method (FEM) and Maxwell magnetic field theory, and can be used for calculating static, frequency-domain and time-varying electromagnetic field. Therefore this software was used for the magnetic field simulation of Hall Effect gear tooth sensors.

The task of the magnetic field simulation is to calculate the magnetic flux density passed through the two Hall Effect elements on the GTS IC during rotating the target gear. The main procedures of the simulation are described as follows:

1) Target Gear Model

Taking a gear with addendum diameter 28mm, dedendum diameter 18mm, thickness 8mm and number of teeth 12 as example, a target gear model can be drawn directly with the Ansoft Maxwell. Fig. 2 shows the target gear under simulation. The material of the gear, for instance Steel1010, should be given for the simulation.

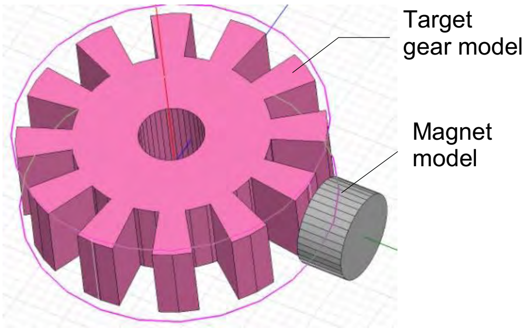

Fig.2. Target gear and permanent magnet under simulation

2) Permanent Magnet Model

A SmCo disc magnet is used for building the gear tooth sensor under simulation. The magnet has a diameter of 8mm and thickness of 4.5mm. The material grade is S240 with remanence Br=0.98T~1.08T and intrinsic coercivity Hc=1432 kA/m. These parameters should be given before the simulation.

3) Hall GTS IC Model

The Hall GTS IC has two Hall Effect elements, which are positioned at distance of 2.5mm in the rotating direction. The GTS IC is put near to the disc magnet. The distance between the IC and the target gear is presented with *b*, see Fig. 1 and Fig. 3.

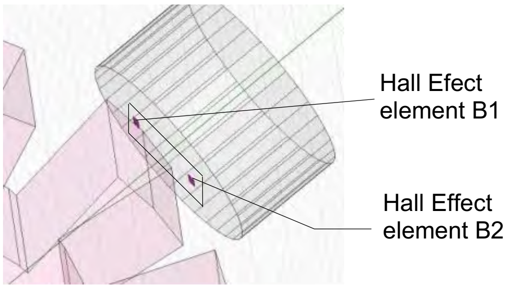

Fig.3. Hall Effect GTS IC under simulation

4) Transient Band Definition

The magnetic flux density should be calculated when the target gear rotates. Therefore, the gear model is also needed to rotate for the simulation. Maxwell software offers a method using “Band” to make the gear to move. The Band needs to cover the whole moving model. The Band must be defined before simulation. The motion of the gear should be also defined by using Motion Setup Box. Normally the rotation axis is Z-axis. One can input the angular velocity of 360°/s as example.

5) Mesh Definition

Mesh number of all elements must be defined before the simulation by using FEM. Tab. 1 shows an example of mesh number of all elements used in the simulation.

Tab. 1. Mesh number of elements under simulation

Element	Name	Number of mesh elements
Magnet	magnet	8000
Gear	gear	10000
B1	B1	8000
B2	B2	8000
Region	region	12000

6) Simulation

After defining all necessary parameters the MFS can be started to calculate the magnetic flux density passing through the two Hall elements during rotating the target gear. One can get magnetic flux density as function of rotating angle of the target gear under different air gap. The differential magnetic flux density between the two Hall elements is approximate to a sinusoid function. The output impulse of the GTS IC can be generated by using a digital detection algorithm according to the operating point and releasing point of Hall GTS IC. The duty cycle and maximum sensing distance can be determined after simulation.

3. Calibration Algorithm

The accuracy of the simulation mentioned above cannot be satisfied with the design of Hall Effect gear tooth sensors because the simulation system is not calibrated. The uncertainty of the simulation comes mainly from the input parameters of the target gear and permanent magnet. Therefore the input parameters of the MFS must be calibrated by approximating the magnetic flux density calculated by the Ansoft Maxwell simulation to the corresponding value measured with a Gaussmeter.

Fig. 4 shows the calibration algorithm of the simulation input parameters. Firstly, initial input parameters {V} are given, and input to the simulation system. The magnetic flux density values at assigned points are calculated by the Ansoft Maxwell Algorithm. The results are compared with the real measured data. If the difference Δ between them is larger than the given maximum error ε, the input parameters will be modified with parametric correction matrix {ΔV}. The calibrated input parameters will be assigned for the design and optimization of the speed sensors when the difference Δ is not higher than the maximum error ε.

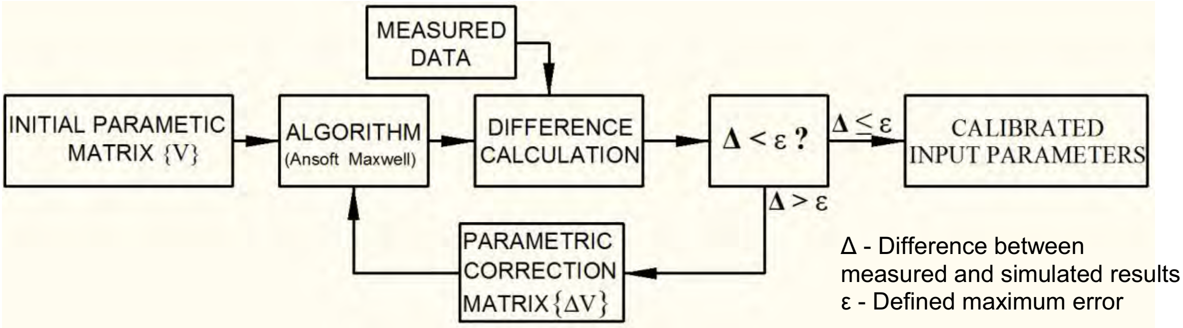

Fig. 4. Calibration algorithm of simulation input parameters

Taking the Hall Effect gear tooth sensor CYGTS101DC-S as example, the maximum B_{max} and minimum B_{min} values of the magnetic flux density on the front end of the sensor were measured with Gaussmeter CYHT201 under coupling with target gear. The corresponding flux density values were calculated by the calibrated simulation.

Fig. 5 gives the comparison between the simulation and measured results of the maximum and minimum flux density in the air gap range from 1.5mm to 4mm. The simulation results are approximately to the measured results.

Tab. 2 shows the relative errors of maximum and minimum flux density between simulation and measured results in air gap range from 1.5mm to 3.5mm. The relative errors are limited within ±2.0%

Tab. 2. Relative error between simulation and measured flux density (CYGTS101DC-S)

Air gap *g* (mm)	1.5	2	2.5	3	3.5
Error of B_{max} (%)	-1.95	-0.58	0.19	0.50	0.78
Error of B_{min} (%)	2.00	1.42	1.09	0.73	0.85

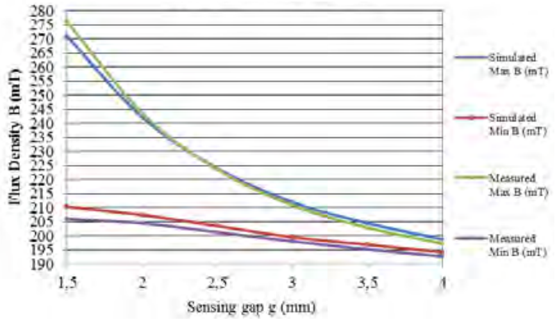

Fig. 5. Simulation and measured magnetic flux density as function of air gap

4. Design with Simulation

The methods mentioned above are applied to the design and optimization of rotational speed measuring systems. The design has two tasks. One of them is to design a Hall Effect gear tooth sensor according to an existed target gear. Another task is design a custom made target gear under using a developed sensor.

In the first task a suitable sensor should be designed by simulation under optimizing the magnet parameters (sizes, material and grade) and Hall GTS IC. In this case the target gear is existed and cannot be changed. The Hall gear tooth speed sensor CYGTS101DC-S is designed in this way. It uses SmCo disc magnet and optimized sizes. The sensor is optimized by using a target gear with 12 teeth shown in Fig. 2. After the optimization the duty cycle of the output impulse of the sensor is about 50% with relative error within ±2%, and the sensing gap reaches 3.5mm (see Tab. 3 and Fig. 6).

Tab. 3. Comparison between simulation and measured duty cycle of sensor CYGTS101DC-S

Sensing gap (mm)	1.5	2	2.5	3	3.5
Duty cycle η_m(%)	49.2	49.5	50.2	50.3	50.8
Duty cycle η_s(%)	49.4	49.7	49.2	49.3	48.9
$(\eta_s - \eta_m)/\eta_m$ (%)	0.4	0.4	-2.0	-2.0	-3.8
$(\eta_m$-50)/50 (%)	-1.6	-1.0	0.4	0.6	1.6

The developed sensor CYGTS101DC-S is used for the speed measurement of motor rotor (see Fig. 7 and Tab. 4) and other rotational machines etc.

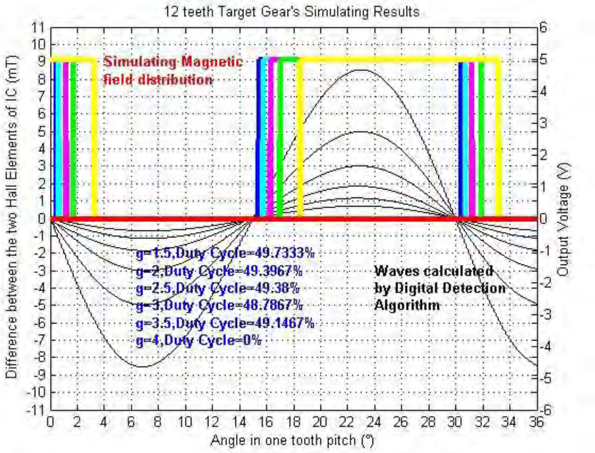

Fig. 6. Simulation results with 12 teeth gear

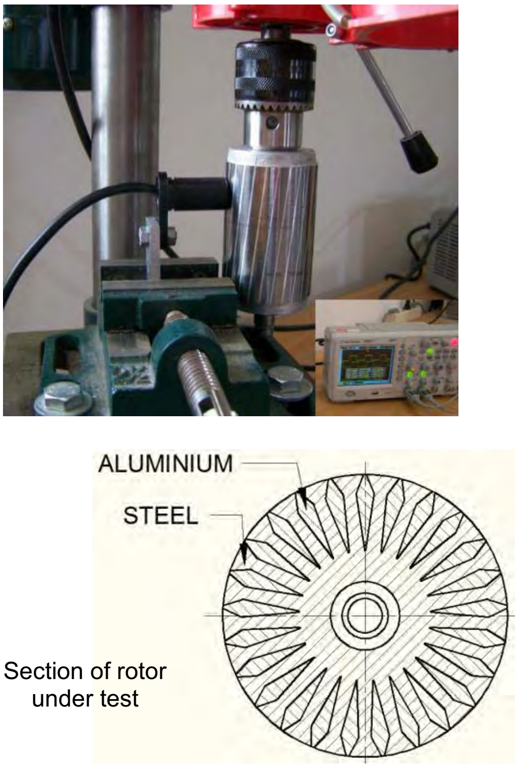

Fig. 7. Speed Measurement of rotor with Hall Effect Gear Tooth Sensor CYGTS101DC-S

Tab. 4. Results measured with CYGTS101DC-S

Air gap (mm)	0.5	1	1.3	1.5
Measured duty cycle η_m(%)	56.5	54.6	53.0	50.3

The duty cycle of output impulse is about 50.3% at air gap of 1.5mm. By using other sensors the speed of the motor rotor cannot be measured at an air gap ≥0.5mm.

In the second task the sensor used under simulation is already optimized. In this case the target wheel (teeth number, tooth shape and height) should be optimized by simulation for special applications.

Tab. 5 shows 4 target gears under simulation. These gears have the same outer diameter, tooth shape and height, and different teeth number and tooth width. Tab. 6 gives the simulation values of the duty cycle of the sensor CYGTS101DC-S under using the gears at different air gap. The target gear 2 has a duty cycle of about 50% and larger air gap of 3.5mm. Therefore the optimized teeth number for gear with an outer diameter of 28mm is 12. The teeth number will change correspondingly when the outer diameter changes.

Tab. 5. Target gears under simulation

Gear No.	Teeth Number	θ (°)	Outer diameter
Target Gear 1	6	30	28mm
Target Gear 2	12	12	
Target Gear 3	18	10	
Target Gear 4	20	9	

Tab. 6. Duty cycle of sensor CYGTS101DC-S under using different target gears

Air gap(mm)	1.5	2.0	2.5	3.0	3.5	4.0
Gear 1	46.1	43.8	42.5	42.1	41.7	40.6
Gear 2	49.4	49.7	49.2	49.3	48.9	x
Gear 3	49.4	48.8	51.5	x		
Gear 4	52.4	50.0	x			

(x means that the sensor doesn’t have output signal)

5. Conclusions

Magnetic field simulation and design of Hall Effect gear tooth sensors are discussed above. From the results one can draw the following conclusions:

- The magnetic flux density passed through the Hall elements in a Hall Effect gear tooth sensor can be calculated by magnetic field simulation effectively.
- The sensor output impulse can be generated by a digital detection algorithm under using the simulation magnetic field density and according to the operating and release points of the Hall GTS IC.
- In order to improve the accuracy of the magnetic field simulation, the simulation algorithm must be calibrated by using reference measuring value. The accuracy of the magnetic field simulation can be improved by using the proposed calibration algorithm of simulation input parameters. It can be controlled within ±2.0%.
- The proposed methods are applied to the design and optimization of speed sensor CYGTS101DC-S and its target gear. After the optimization the duty cycle of the sensor output impulse is about 50% with relative error within ±2%, and the sensing gap reaches 3.5mm.
- The developed Hall Effect gear tooth sensor is applied to measure the speed of motor rotors and other rotational machines with good results.

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