Development of Magnetoelectric Speed Sensor for Engine with High Environment Adaptability

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Abstract. The high reliable environment adaptive magnetoelectric speed sensor developed by this project is mainly used in the field of engine measurement and control. This project can effectively improve the accuracy and reliability of sensor measurement by adopting a new output design of redundancy synchronous coil and transformer secondary amplification design. By optimizing the induction coil, magnetic steel and internal structure, the sensor has outstanding performance such as low speed work, high sensitivity and low noise; At the same time, the project also through the overall structure of the sensor, material design, packaging technology and other optimization design, to ensure that the sensor meets the wide temperature zone, vibration resistance, impact resistance and full seal protection and a series of high reliable environmental adaptability technical requirements.

Keywords: High Reliable Environmental Adaptability, Magnetoelectric Speed Sensor, Dual Redundancy Synchronous Coil Output, Transformer Secondary Amplification

1. Introduction
In recent years, electronic measurement and control technology has made rapid development, and the application in the field of engine measurement and control is becoming more and more popular. This technology has a series of advantages, such as high control precision, many control functions, strong adaptability, convenient debugging and so on. Therefore, electronic measurement and control technology has become an important symbol to measure the development level of modern engines. All kinds of sensors, such as temperature, pressure, flow rate and speed [1], are essential in the engine centralized control system, and the speed signal is one of the most basic and important parameters in the engine control system. Therefore, it is very important to realize the accurate and effective control of the engine operation system by accurately and reliably measuring the engine speed signal. The sensors used for speed measurement mainly include photoelectric type, capacitive type, Hall type, magnetoelectric type and so on. The magnetoelectric speed sensor is the most important speed sensor type in engine speed measurement [2].

For the magnetoelectric wheel speed sensor, the accuracy and reliability of the measurement are the most important technical characteristics of the sensor, and the design of the double residual coil is an effective means to realize the above key technical characteristics. At present, there are two main structural forms of double residual magnetoelectric speed sensor. One is that the two groups of
induction coils are divided into two layers on the same skeleton. Because of the different circumference of each coil in the inner and outer layer, the resistance and the number of turns of the two groups cannot be guaranteed to be exactly the same. Second, two groups of induction coils in the sensor shell using parallel installation structure. Since the measuring end face of the sensor is unique to the area corresponding to the external tangent point of the measuring gear convex tooth, that is, the measuring end face of the speed sensor should be in the area where the cutting point of the gear convex tooth is measured. Therefore, the two sets of coils can only adopt a common skeleton, iron core and magnetic steel. Because of the parallel winding of the two coils, the number of turns wound is limited, and the signal amplitude of the speed output is low, especially under the condition of low speed, the problem of low signal amplitude will be more prominent. Therefore, the two speed signals need to be effectively amplified to meet the needs of stable and reliable measurement of speed sensors.

When the magnetoelectric wheel speed sensor is low in speed, because the amplitude of the effective output signal is too small and the noise content is high, the anti-interference ability of the whole sensor is poor, so the related measurement and control system cannot be accurately identified and measured. Therefore, the speed sensor should have low speed working, high sensitivity, low noise and other outstanding performance. Because the speed sensor of this project is in the engine running environment and the working conditions are extremely bad, it is required that the speed sensor should have good temperature resistance, oil resistance, corrosion resistance, vibration shock resistance and other protective.

2. Principle of Magnetoelectric Speed Sensor

2.1. Main Characteristics of Magnetoelectric Sensors

Using the principle of electromagnetic induction, magnetoelectric sensor converts the change of measured physical quantity into inductive electromotive force [3]. It is a kind of machine-electric energy conversion sensor, which belongs to passive sensor [4]. Magnetoelectric induction sensor, also called electric sensor, is only suitable for dynamic measurement. This type does not need external power supply, the circuit is simple, the performance is stable, the output impedance is small, but also has a certain frequency response range (generally 10~2000 Hz), which is mainly suitable for the measurement of vibration, speed, torque and other signals.

2.2. Working Principle

Under Faraday's law of electromagnetic induction, the magnitude of the induced electromotive force E (V) generated in the coil is determined by the rate of change the magnetic flux passing through the coil when the magnetic field of the turn coil moves to cut the magnetic field line of force or the magnetic field in which the coil is located, N is:

\[ E = -N \frac{\text{d} \Phi}{\text{d}t} \]  

In the formula: The N is the number of turns of the coil, and \( \Phi \) is the magnetic flux through the coil.

The magnetoelectric induction sensor can be divided into two types: constant flux type and variable flux type. The constant flux magnetoelectric induction sensor can be divided into moving ring type and moving iron type according to the different moving parts. The center coil of the movable coil magnetoelectric sensor is a moving component; the basic form is the velocity sensor, which can directly measure the linear velocity or angular velocity. If an integral circuit or differential circuit is connected to its measuring circuit, it can also be used to measure displacement or acceleration.

In the variable flux magnetoelectric induction sensor, the coil and magnet are stationary, and the rotation of the object causes the change of magnetoresistive and magnetic flux, which is often used to measure the angular velocity of the rotating object.
The speed sensor of this project adopts variable flux working principle. The measuring gear is mounted on the measured shaft and rotates with the shaft. The induction coil of the sensor is built into a soft magnet core, and the inductive end face of the sensor is encapsulated, corresponding to the direction of gear convex and concave teeth. When the convex tooth of the measuring gear is aligned with the sensor inductive end face, the air gap of the magnetic circuit is the smallest, the magnetoresistive is the lowest, and the magnetic flux is the largest. The magnetic flux is the smallest. In the process of gear rotation, the gap between the inductive end face of the sensor and the convex teeth of the measuring gear changes periodically, which causes the change of the magnetic resistance of the magnetic circuit, and then makes the magnetic flux change periodically. The frequency is equal to the product of tooth number and rotational speed. As shown in figure 1, the induction coil and the permanent magnet are stationary. For each tooth transferred from the measuring gear (made of magnetic conductive material), the magnetic resistance of the sensor changes once, thus causing the change of AC induction electromotive force in the induction coil.

**Figure 1.** Measuring principle of magnetoelectric speed sensor

For the cam magnetoelectric speed sensor [5, 6], the sensor output waveform is shown in figure 2, and for the crankshaft magnetoelectric speed sensor, the sensor output waveform is shown in figure 3.

**Figure 2.** Typical Cam Speed Sensor Wave
2.3. Output Characteristics

According to the working principle of magnetoelectric sensor, the frequency of AC voltage signal is proportional to gear speed and tooth number. The relationship is:

\[
f = \frac{Z \times n}{60}
\]  

(2)

In the formula: The \( z \) represents the number of teeth of the gear, \( n \) represents the speed of the measured shaft per minute (r/min), and the \( f \) represents the frequency of the induction signal (Hz).

When the number of gear teeth is certain, the output signal frequency of the sensor depends on the speed of the gear, while the voltage amplitude is related to the speed and clearance. The higher the gear speed, the higher the frequency and amplitude of the output signal, and the smaller the gap between the sensor and the gear, the stronger the output signal and the greater the amplitude. as shown in Figure 3.

![Figure 3. Typical Waveform of RPM Sensor](image)

Figure 3. Typical Waveform of RPM Sensor

According to the above analysis, it can be concluded that the relationship between the output amplitude voltage of the sensor signal and the installation obtained as follows:
The Um represents the output peak voltage of the sensor; the K represents the coefficient of the speed sensor; the n represents the engine speed; and the d represents the gap between the sensor and the gear.

3. Optimal Design Technique of Magnetoelectric Speed Sensor

The magnetoelectric speed sensor for engine is different from other applications. It has the outstanding characteristics of poor working environment, complex test conditions and high reliability requirements. Therefore, the temperature resistance and output performance of the sensor are analyzed. Protection performance and other technical indicators put forward more stringent requirements. In order to make the speed sensor fully meet the requirements of all kinds of engine speed measurement, this project has carried out a special technical research on synchronous output design of double redundancy coil, widening the working temperature range, increasing the amplitude of low speed output signal and enhancing the reliability and protection performance of the sensor, and achieved good results. The internal structure of the speed sensor is shown in figure 5.

![Figure 5. Structure diagram of magnetoelectric speed sensor](image)

3.1. Output Design of Dual Residual Synchronous Coil

In this project, a kind of speed magnetic sensor with double redundancy synchronous output is designed, which solves the problem that the original double redundancy speed magnetic sensor is not synchronized because of the asymmetry of coil structure [7]. The original double residual coil is divided into two layers on the same skeleton. Because of the different circumference of each coil in the inner and outer layer, the resistance and the number of turns of the two groups of coils cannot be guaranteed to be exactly the same. In this project, in the same speed sensing shell, two speed signal induction coils are designed. The two induction coils share skeleton, iron core and magnetic steel, and the two sets of coils are wound in parallel and synchronously. Therefore, the two induction coils are completely symmetrical and the speed signals output by the two induction coils can be completely synchronized. When the two speed signals are output synchronously, it can be determined that the sensor is in normal working state at this time, and once a certain speed signal is short-circuited or broken, the other way can still work independently.

In order to ensure the signal output strength of magnetoelectric speed sensor, the induction coil of the sensor should be installed near the external tangent area of measuring gear convex teeth. Because of the asymmetry of coil structure [7], the output peak voltage can be expressed as:

\[ U_m = K \times n/d \]  

(3)
of the uniqueness of the tangent area, it is determined that the two induction coils can not be installed in parallel structure. Only common skeleton, iron core and magnetic steel. Because of the parallel winding of the two coils, the number of turns wound is limited, and the signal amplitude of the speed output is low, especially under the condition of low speed, the problem of low signal amplitude will be more prominent. Therefore, the two speed signals need to be effectively amplified to meet the needs of stable and reliable measurement of speed sensors. This project uses the amplification effect of ring transformer to amplify the speed signal twice [8], so that the output amplitude of the speed signal can be greatly increased under the condition of low speed, so as to meet the requirement of the lowest output amplitude of the speed signal.

3.2. Design Technology of Sensor Wide Temperature Zone

In order to ensure that the speed sensor has a wide range of temperature operating characteristics, this project has mainly taken the following technical measures. A case of a speed sensor made of 316 L stainless steel, 316L stainless steel has good temperature resistance, Maximum operating temperature 600 °C, sensor coil is made of high temperature resistant enameled wire mm 0.04 diameter, A maximum operating temperature of 220 °C or enameled wires; The permanent magnet part of the sensor, High temperature resistant NdFeB (Nd2Fe14B) processing. At 200 °CdFeB compared to ferrite, aluminum nickel cobalt, samarium cobalt, platinum cobalt alloy and other permanent magnets, Have the best remanence, coercivity, maximum magnetic energy accumulation remanence and other magnetic properties; The sensor coil skeleton is made of polyimide material, The material has good resistance to high and low temperature test and mechanical properties, Operating tolerance temperatures can range from -200 °C to 300 °C. The core of the sensor (induction coil, permanent magnet, etc.) [9] is filled with high temperature resistant epoxy adhesive, High temperature resistant epoxy adhesive can be maintained at 240 °C for a long time, Good tensile shear strength at 240 °C can still reach more than 5 MPa; Sensor signal lead cable made of TPEE—thermoplastic polyester elastomer material, This type of cable sheath has temperature resistance, oil resistance, wear resistance, high elasticity and low temperature flexibility, Better tensile strength of signal cables than 200 N, Maximum operating temperature up to 180 °C, Each component of the speed sensor and the whole machine can work stably in 180 °G environment for a long time [10].

3.3. Design Technology of Sensor with Low Speed and High Sensitivity

Under the condition of low speed, because of the small output amplitude of the signal, the magnetoelectric speed sensor is easy to receive the interference of the external environment during the transmission process, which makes the result of the speed measurement easy to produce the phenomenon of "teeth ". Therefore, under the condition of low speed, it is necessary to improve the amplitude of the signal output of the speed sensor, enhance the anti-interference ability of the output signal, and ensure the reliability of the speed measurement. On the premise that the shape and material of the gear convex teeth and the measuring air gap between the gear and the sensor have been determined, the magnetic circuit performance can be improved by optimizing the magnetic circuit design of the sensor. In order to effectively improve the amplitude of sensor signal output. To this end, the project has adopted the following optimization, improved design.

1) Increase in coil turns
The coil diameter of sensor coil was improved from 0.05 mm to 0.04 mm, thus, the number of turns of the coil increased by about 20%, and the output amplitude of the speed sensor signal was improved effectively.

2) Optimizing high performance permanent magnets
Magnetic steel is made of high temperature resistant NdFeB (Nd2Fe14B) N52H brand permanent magnet, made by strict sintering process, to ensure that it has the best remanence, coercivity, maximum magnetic energy product and other magnetic properties are superior to the same products, its remanence Br is 15.6 KGs, coercivity is up to BHc13.8Koe, maximum magnetic energy product
(BH) MAX can reach 52.6 Mgoe. With the improvement of magnetic performance of permanent magnet, the output amplitude of sensor signal is further improved.

(3) Optimizing sensor structure design
Core of sensor coil is made of soft magnet 1 J85 Pomo alloy. The core has high permeability and low coercivity, and is sensitive to weak signal. In order to improve the cluster ability of the magnetic force line, the iron core adopts the trapezoidal cone design method, and further optimizes the sensor shell design, and controls the thickness of the sensor measuring end face within 0.15 mm, so as to effectively shorten the magnetic circuit spacing.

(4) Two-stage signal amplification
In order to further improve the output amplitude of rotational speed signal, the secondary amplification circuit of ring transformer is designed. Under the condition of low speed, the amplitude of the output signal of the sensor is on the low side. By using the amplification effect of the ring transformer, the output amplitude of the speed signal under the condition of low speed can be greatly increased. To meet the minimum output amplitude of speed signal requirements.

![Graph](image.png)

**Figure 6.** RPM Ring Transformer Secondary Amplification

3.4. Sensor Low Noise Design Technology
In the signal output link, with the help of coil internal resistance and line impedance, a low pass filter circuit is designed to effectively suppress the interference of high frequency noise signal, improve the signal-to-noise ratio of speed output signal, and ensure the output quality of speed signal. Enhance the sensor's ability to resist electromagnetic interference.

3.5. Vibration Resistance and Impact Resistance Design Technology
To meet the requirements of high reliability, vibration resistance and impact technology, the sensor shell is made of stainless steel 316 L, the signal cable sheath is made of TPE thermoplastic elastomer material, this type of cable sheath has temperature resistance, oil resistance, wear resistance and good high elasticity and low temperature flexibility, and the cable is sealed with rubber plug to improve the fixed strength and tensile properties of the cable, and can effectively guarantee the sealing and protection performance of the sensor; The induction coil, magnetic steel and transformer coil inside the rotating speed sensor shell are all sealed with high temperature resistant epoxy resin glue, which makes the whole machine have excellent rigid strength and ensure that it meets the requirements of vibration resistance and impact protection.

3.6. Design Techniques for Full Seal Protection
To meet the environmental test requirements of underwater impregnation, salt spray and so on, the shell of the sensor is made of 316 stainless steel materials with corrosion resistance and salt spray resistance. The cable sheath is made of TPE thermoplastic elastomer material, and the oil-resistant and corrosion-resistant fluorine silicone plug is used to seal and fix the signal cable and shell, so as to ensure that the sensor has good sealing and protection performance. Characteristics of 4. Magnetoelectric Speed Sensor

The results of the speed sensor of this project are mainly reflected in the output of double redundancy synchronous signal, wide range of limit working temperature, lower limit of ultra-low speed measurement, high intensity environment adaptability and so on.

1) Output of dual redundancy synchronous signal

This project designed a new type of rotational speed magnetic sensor for the output of the dual-complexity synchronous coil, that is, in the same speed sensing shell, two speed signal induction coils are designed. The two induction coils share the skeleton, core and magnetic steel, and the two sets of coils are wound by parallel synchronization. Therefore, the two induction coils can be guaranteed to be completely symmetrical and the speed signals output by the two induction coils can be completely synchronized. At the same time, in order to improve the signal output intensity of magnetoelectric speed sensor, this project uses the amplification effect of ring transformer to amplify the speed signal twice, so that the output amplitude of speed signal under low speed condition can be greatly increased. To meet any operating conditions, speed signal minimum output amplitude requirements. By adopting the above technical scheme, the problem of output synchronization of the original double residual speed magnetic sensor due to the asymmetry of coil structure is effectively solved.

2) Wide operating temperature range

The speed sensor of this project, by optimizing the structure design of the sensor and the material design of the key components, makes the sensor meet the performance requirements of the wide amplitude working temperature zone, the minimum working temperature reaches -60℃, and the maximum working temperature reaches 180℃. Under the limit working temperature, the sensor can still maintain good working performance.

3) Lower limit for ultra-low speed measurement

By improving the structure and material design of the coil, magnetic steel and iron core of the speed sensor, and at the output end of the sensor induction coil, the secondary amplifier circuit of the transformer is designed, which effectively improves the output amplitude of the speed signal under the condition of low speed, and then expands the lower limit of the minimum speed measurement of the speed sensor. Through the actual test, the speed sensor of this project, the minimum speed frequency measurement limit is 1 Hz, and the peak value of the signal output peak is not less than 2 V, so as to ensure the accurate and reliable measurement of the speed signal under the condition of low speed.

4) High signal output sensitivity and low noise

The sensitivity of the speed signal is effectively improved by optimizing the magnetic circuit design of the speed sensor and adding the secondary amplification circuit of the ring transformer. When the speed frequency is 1 Hz, the peak value of the signal output peak can reach more than 2 V. When the speed frequency is 20 Hz, the peak value of the signal output peak can reach more than 12 V. In the signal output link, the signal-to-noise ratio of the sensor is obviously improved because the low-pass filter circuit is designed to effectively suppress the noise signal.

5) High reliability for vibration and shock protection

This project adopts a series of vibration resistance and impact resistance reliability design to make the whole machine have excellent rigid strength to ensure that the sensor machine meets the technical requirements of 50 g, impact acceleration 100 g.

6) Full seal protection

According to the requirements of full seal protection, the speed sensor is designed and made according to the requirements of temperature resistance, oil resistance and corrosion resistance in the key links of shell, signal cable and seal, so that the whole machine has good sealing and protection performance, and the protection grade meets the requirements of IP68 technical standard.
4. Conclusion

This project has developed a speed sensor with high strength environment adaptability, which has solved the key technical problems such as design and manufacture. It is innovative in the output design of double redundancy synchronous coil, wide temperature zone design, ultra-low speed measurement, high sensitivity, low noise, anti-vibration, anti-shock and full seal protection design of the sensor. It has broad market application prospect and can be widely used in the speed measurement of various vehicles, aircraft, ships and other equipment engines under all-weather environment conditions.

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