

Analysis of the Principle, Facility and State-of-art Applications of Different Types Inductive Sensor

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Abstract. As a matter of fact, different types of inductive sensor are widely used in various aspects. In this case, this study introduces the development history and current status of electromagnetic sensors, as well as the basic principles and future trends of different types of electromagnetic sensors. It provides a detailed introduction to the principles, structures, and measurement specifications of self-inductive sensors, differential air gap self-inductive sensors, mutual inductance sensors, and helical coil mutual inductance electromagnetic sensors. The characteristics and application scenarios of each sensor are analyzed. A comparison of the advantages and disadvantages of various electromagnetic sensors is presented. Furthermore, predictions are made regarding the future research directions and application trends of electromagnetic sensors. This study has gained a good understanding of the basic principles of various electromagnetic sensors and has learned about the selection of electromagnetic sensors for different scenarios, providing guidance for the study of new electromagnetic sensors and their practical applications.

Keywords: Electromagnetic induction, electromagnetic sensors, differential electromagnetic sensors.

1. Introduction

The history of sensors can be traced back to 5000 years ago, with the compass being one of the representatives. This phase of development, known as the first generation of sensors or mechanical sensors, witnessed the invention of notable sensors such as the compass, seismometer, and the first gas thermometer. With the maturity of Faraday's law of electromagnetic induction and Lenz's law, it became possible to convert changes in magnetic fields into electrical signals for data collection and expression. This phase of sensors is known as electrical sensors, capable of converting pressure, temperature, humidity, and displacement into changes in magnetic flux, and then converting the magnetic flux into electrical signals based on the principles of electromagnetic induction. By analyzing the changes in the electrical signals [1], the variations in the source data signals can be calculated. The third generation of electromagnetic sensors is known as smart sensors. With the development of the Internet of Things (IoT) and new materials, sensor technology has been combined with intelligent technology, IoT, semiconductors, and integrated circuits [2]. As a result, an increasing number of smart sensors have been applied in various aspects of life and production [3].

Smart sensors embody characteristics such as intelligence, networking, scalability, and miniaturization. With the advancement of wireless transmission and the maturation of 5G technology, wireless sensors have made significant progress in replacing contact sensors with non-contact sensors, facilitating data collection and storage [4]. Examples of wireless sensors include those found in mobile phones, Bluetooth devices, and microwave sensors. The development of integration technology has also promoted the advancement of sensor technology. MEMS sensors, which integrate regulation circuits, microcomputers, memory, and interfaces onto a single chip, represent the combination of microcomputer technology and detection technology. Inertial measurement units (IMUs) have found wide applications in consumer products [5], automobile manufacturing, and aerospace. Miniaturized sensors have begun to be applied in fields such as bionics and brain-computer interfaces [6, 7].

This paper will discuss the characteristics and basic principles of different categories of magnetic sensors, analyze their respective application scenarios and fields, and discuss their limitations and

urgent technical issues that need to be addressed. Furthermore, predictions and prospects for sensor technology and application fields will be provided.

2. Principle and Applications

Electromagnetic sensors are devices that utilize the principle of electromagnetic induction to convert the collected analog signals into the self-inductance or mutual inductance coefficients of electromagnetic coils, and then convert the analog information into digital data. The basic principle is based on Faraday's law of electromagnetic induction. Depending on the induction quantities of the electromagnetic coils, electromagnetic sensors can be divided into self-inductance sensors, mutual inductance sensors, and eddy current sensors. The composition of a self-inductance sensor includes a core, yoke, and an inductive coil [8] as shown in Fig. 1.

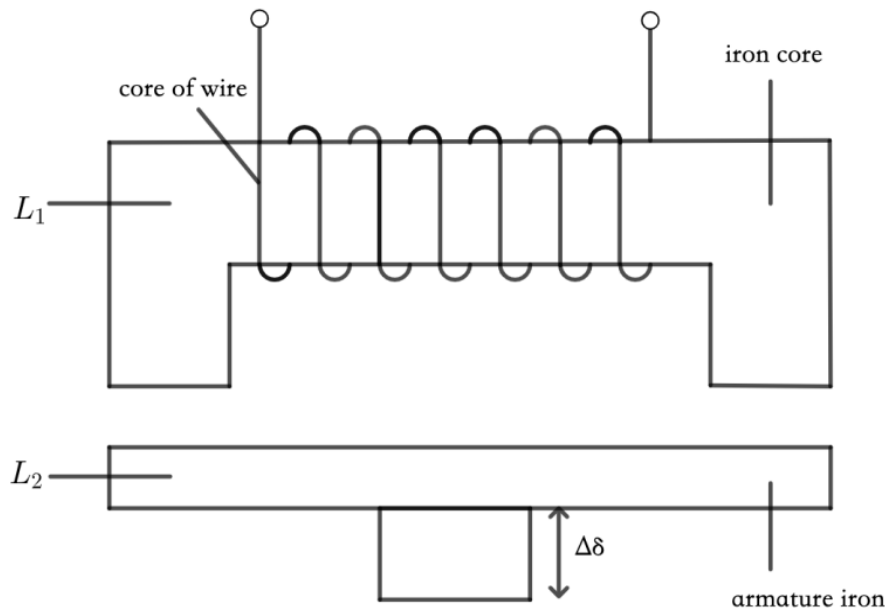


Figure 1. Self-inductive electromagnetic sensor.

According to the definition of inductor, there is

$$L = \frac{W\phi}{I} \quad (1)$$

Where L is the inductance of the magnetic field, W is the number of turns of the coil, I is the current of the coil, and ϕ , the magnetic flux of the coil. According to Magnetic Ohm's law, the value of magnetic flux ϕ can be obtained as

$$\phi = \frac{IW}{R_m} \quad (2)$$

Where is the total magnetic resistance R_m of the coil. If the sensor air gap δ small, the magnetic loss can be ignored, and the total magnetic loss of the magnetic circuit is

$$R_m = \frac{L1}{\mu_1 S_1} + \frac{L2}{\mu_2 S_2} + \frac{2\delta}{\mu_0 S_0} \quad (3)$$

Where $L1$ is the inductance of the core, $L2$: the inductance of the armature, μ_1 , the magnetic permeability of the core, μ_2 , the permeability of the armature, $S1$ is the cross-sectional area of the core, $S2$ is the cross-sectional area of the armature, $S0$ is the cross-sectional area of the air gap, and the height of the air gap δ . As

$$\frac{2\delta}{\mu_0 S_0} \gg \frac{L_i}{\mu_i S_i}, i = 1, 2, \quad (4)$$

So

$$R_m \approx \frac{2\delta}{\mu_0 S_0} \quad (5)$$

From the above formule:

$$L = \frac{W^2}{R_m} = \frac{W^2 \mu_0 S_0}{2\delta} \quad (6)$$

Therefore, when a sensor with a constant cross-sectional area S_0 is called a self-inductance variable gap sensor [8], similarly, when a sensor with a constant gap is called a self-inductance variable area sensor [9]. In practical applications, given the initial inductance of the electromagnetic coil as L_0 and the initial gap as δ_0 , when a varying gap $\Delta\delta$ is introduced, the new inductance L can be measured. There is a non-linear relationship between inductance L and gap δ . This is due to the measurement range and sensitivity of the inductance. Therefore, this type of self-inductance sensor is more effective in measuring small changes in analog quantities. In order to reduce this non-linear error, a differential variable gap electromagnetic sensor with two inductances connected in reverse has been developed [10]. The structure is shown in Fig. 2.

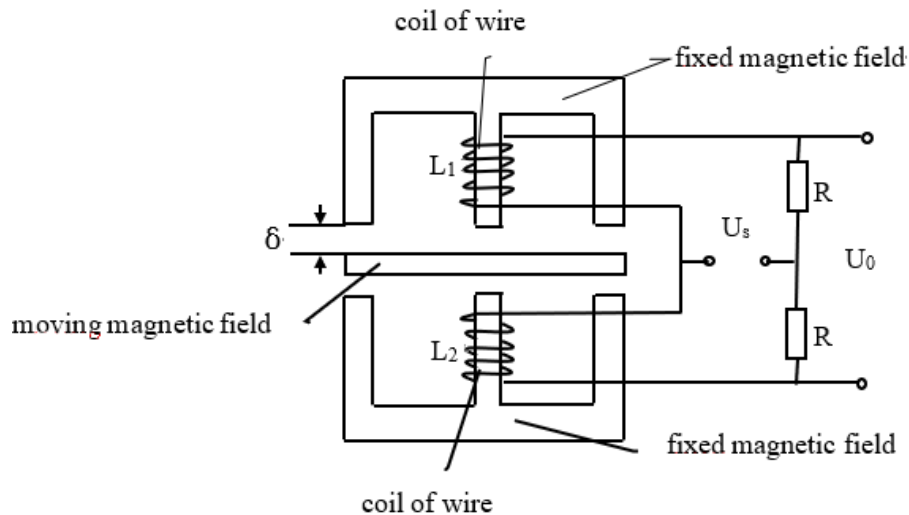


Figure 2. Schematic diagram of a differential variable gap electromagnetic sensor.

Self-inductance sensors are commonly used to measure displacement and dimensions. They can also measure other parameters that can be converted into displacement, such as force, tension, pressure, pressure difference, strain, rotation, speed, and acceleration. Mutual inductance sensors are sensors that convert non-electrical quantities into the mutual inductance coefficients of inductance. Due to their similar working principles to transformers and the use of differential connection, they are also called differential transformer-type sensors [11]. According to different structural forms, they can be divided into variable gap type, variable area type, and helical coil type, but the most commonly used is the helical coil type [12]. Its equivalent circuit is shown in Fig. 3.

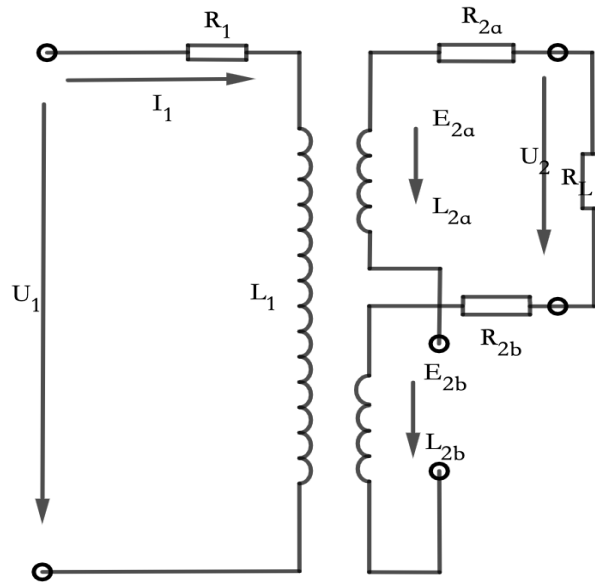


Figure 3. Equivalent circuit diagram of spiral tube mutual inductance electromagnetic sensor.

This sensor includes a primary winding W1 and two reverse-connected secondary windings W2a and W2b, with a movable yoke in between. In the initial state, an initial voltage U_1 is applied to the primary winding W1. Due to the symmetrical reverse connection of the two secondary windings, the induced voltages E_{2a} and E_{2b} produced are equal, resulting in an induced voltage $U_2 = E_{2a} - E_{2b} = 0$. When the movable yoke moves upward, E_{2a} increases and E_{2b} decreases, resulting in a positive induced voltage U_2 . Similarly, when the movable yoke moves downward, U_2 becomes negative. Therefore, the induced voltage U_2 varies with the displacement of the movable yoke, and the direction of movement determines the polarity of the voltage. When the primary winding is open, the value of the excitation current is

$$I_1 = \frac{U_1}{R_1 + j\omega L_1} \quad (7)$$

where I_1 is the excitation current, U_1 is the excitation voltage, R_1 is the fixed resistance, L_1 is the inductance of the primary winding, and the angular frequency of the excitation voltage ω . The induced potentials generated on the secondary windings at this time are respectively

$$E_{2a} = -j\omega M_1 I_1 \quad (8)$$

$$E_{2b} = -j\omega M_2 I_1 \quad (9)$$

Among them, M_1 and M_2 are the mutual inductance generated on the windings of the two stages, respectively. Since the two secondary windings are connected in reverse series, the induced voltage U_2 is

$$U_2 = E_{2a} - E_{2b} = -\frac{j\omega(M_1 - M_2)U_1}{R_1 + j\omega L_1} \quad (10)$$

Valid values for U_2 are

$$U_2 = \frac{\omega(M_1 - M_2)U_1}{\sqrt{R_1^2 + (\omega L_1)^2}} \quad (11)$$

When the movable yoke is in the center, $M_1=M_2=M$. ($U_2 = 0$). When the movable yoke moves upward, $M_1=M+\Delta M$ and $M_2=M-\Delta M$ ($U_2 > 0$). When the movable yoke moves downward, $M_1=M-\Delta M$, $M_2=M+\Delta M$ ($U_2 < 0$).

In practical applications, in order to determine the direction of movement, rectification of the output of the secondary windings is required, known as differential rectification [13]. Additionally, in order to eliminate the influence of zero residual voltage, a phase-sensitive detection circuit needs to be designed [14]. Mutual inductance sensors are suitable for measuring displacement, as well as related parameters such as vibration, acceleration, strain, tension, specific gravity, and thickness. Eddy current sensors are designed based on the eddy current effect, which refers to the induction of eddy currents in a metal conductor when it is exposed to a magnetic field. The induced eddy currents generate an alternating magnetic field, which opposes the excitation magnetic field, resulting in a change in magnetic resistance [15]. Fig. 4 shows a schematic diagram of an eddy current electromagnetic sensor.

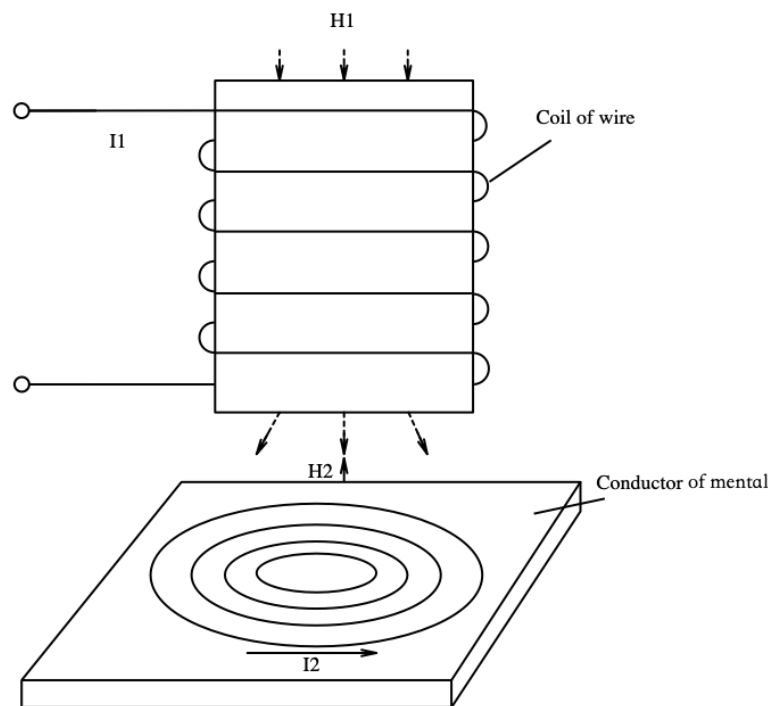


Figure 4. Schematic diagram of eddy-current electromagnetic sensor.

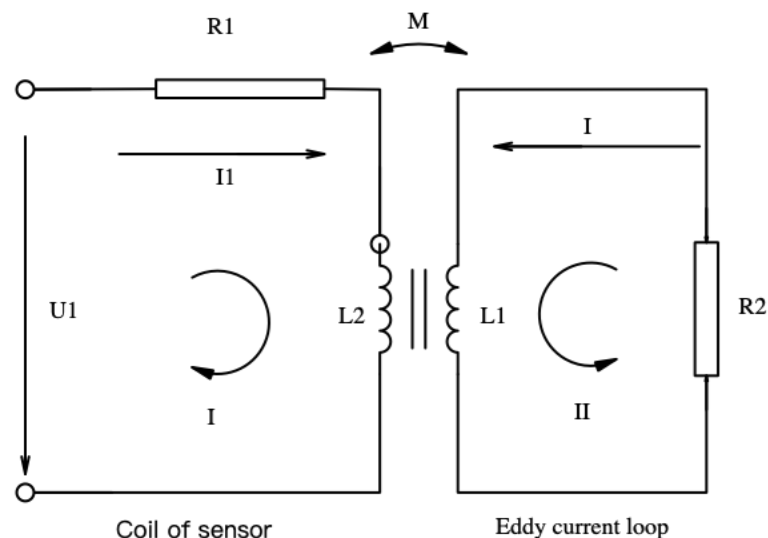


Figure 5. Equivalent circuit diagram of eddy current electromagnetic sensor.

When the excitation current I_1 flows through the winding, it generates an alternating magnetic field H_1 , which induces eddy currents in the metal conductor. The induced eddy currents then generate a magnetic field H_2 , which opposes H_1 , causing a change in the impedance of the winding [16]. The corresponding equivalent circuit is shown in Fig. 5.

When the measured object is far away from the inductance coil, the impedance value of the coil is

$$Z_1 = R_1 + j\omega L_1 \quad (12)$$

When the measured object approaches the inductance coil, the two coils produce mutual inductance, and the loop equation is

$$\begin{cases} R_1 I_1 + j\omega L_1 I_1 - j\omega M I_2 = U_1 \\ -j\omega M I_1 + R_2 I_2 + j\omega L_2 I_2 = 0 \end{cases} \quad (13)$$

So the equivalent impedance is

$$Z_1 = \frac{U_1}{I_1} = R_1 + \frac{\omega^2 M^2 R_2}{R_2^2 + (\omega L_2)^2} + j\omega \left[L_1 - \frac{\omega^2 M^2 L_2}{R_2^2 + (\omega L_2)^2} \right] \quad (14)$$

The resistivity of the measured object is ρ , the magnetic permeability is μ , the frequency of the excitation current is f , the distance between the coil and the conductor is x , and the size factor of the coil and the measured object is r will cause impedance changes, and impedance Z is a function of the above parameters.

$$Z = F(\rho, \mu, r, f, x) \quad (15)$$

If certain parameters in the above-mentioned quintuples are controlled to remain unchanged, the values of the specified parameters can be measured. For example, the resistivity ρ and permeability μ can be used to measure materials, flaw detection, etc., and the distance x can be used to measure thickness and displacement.

3. Limitations and Prospects

In the decades of development, the research on electromagnetic sensors has mainly focused on three aspects. Firstly, improving the technical specifications of the sensors, including increasing accuracy, expanding measurement range, and enhancing environmental adaptability. Secondly, integrating new technologies, new materials, and new processes. Thirdly, exploring applications in other fields. Traditional electromagnetic sensors suffer from nonlinearity errors and zero residual voltage [17]. To reduce the impact of these factors, differential design and low-frequency design are commonly used, along with minimizing interference from temperature and other noise sources to improve data accuracy. Electromagnetic sensors perform well in measuring micro variations but have limitations in large-scale measurements. Some researchers have proposed using a medium with a large weight and length for the fixed magnetic core, and a medium with small mass and size for the movable yoke, along with a magnetic shield, to enhance the measurement range and maintain sensor maintainability. To improve sampling speed, a half-bridge inductance sensor has been proposed, combining high-speed oversampling with average filtering [18]. In terms of technological advancements, a planar hollow coil current transformer based on PCB has been developed. The application of new materials in electromagnetic sensors, such as magnetostrictive pressure sensors designed with amorphous alloys, has been explored [19].

The research on electromagnetic sensors has made significant progress. With the development of new technologies, new processes, and new materials, the future of electromagnetic sensors lies in miniaturization, flexibility, wireless communication, and intelligence. The improvement in new

materials and semiconductor integration enables the miniaturization of sensors. The development of flexible electronics technology enables sensors to be portable, biomimetic, and integrated into various applications such as electronic skin, brain-machine interfaces, and medical devices. Wireless communication utilizes bioelectricity and frictional electricity as energy sources for electromagnetic sensors, and data transmission can be achieved through Bluetooth or WiFi, although this is still in the laboratory research stage. The integration of electromagnetic sensors with intelligent systems enables autonomous functionality, mainly achieved through sensor fusion and sensor integration, with MEMS integrated sensors being a typical example [20].

4. Conclusion

To sum up, this paper analyzes the principles, structural designs, and application scenarios of three types of electromagnetic sensors. Self-inductive sensors utilize the principle of electromagnetic induction to convert displacement and dimensions into electrical signals, and the structure of differential air gap sensors is discussed. Mutual inductance sensors utilize the principle of mutual inductance in winding to measure data related to displacement, such as vibration, acceleration, and tension, with a focus on the principle and construction of helical coil inductance sensors. Eddy current sensors measure parameters such as resistivity and displacement thickness based on the principle of opposing electromagnetic fields generated by induced currents. Finally, the paper describes the current changes in measurement specifications of electromagnetic sensors, their integration with new technologies and materials, and their practical applications. It also provides predictions for the future research on miniaturization, flexibility, wireless communication, and intelligence of electromagnetic sensors. This paper serves as a theoretical basis and provides directions for the technological research and application of electromagnetic sensors.

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