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Open-loop linear differential current sensor based on dual-mode Hall effect

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ABSTRACT

This study proposes a novel double Hall linear differential sensor and investigates its output and temperature characteristics in detail. Finite element method is used to confirm the effectiveness of the proposed method. A practical, open-loop current sensor circuit is designed and constructed based on dual-mode Hall effect theory. Results show that the quiescent output voltage is significantly reduced, and that the signal amplitude is increased by 99.5%. Moreover, sensitivity is more than 40 mV/mT, linearity is 1.2% full scale, and the zero drift coefficient is 0.033 mV/°C. The differential output model can suppress common mode interference and zero drift. The sensor also exhibits temperature self-compensation and non-linear correction functions.

1. Introduction

The signal voltage of a linear Hall-integrated device is commonly used in single-ended output modes. Although necessary compensations have been made for this device, its output voltage still produces superimposed ripple signals caused by power fluctuations [1]. Moreover zero drift remains affected by temperature [2], and common mode interference is still subjected to environmental electromagnetic effects. Therefore, signal filtering, temperature compensation, and linearity correction are necessary for the application circuit [3]. Calibration at various temperature values requires an expensive and time-consuming trimming cycle [4]. Imbalances caused by offsetting the orthogonal coupling of different Hall devices are assumed to be similar; thus, offsetting is minimized [5]. This method strongly depends on sensor matching. Reducing the spinning current offset requires complex signal processing, moreover, this process is slow because of switching [6,7]. Several studies have proposed the following approaches investigate the micro-tension measurement model: (1) a combination of switch-type Hall element application methods with expanded switch-type Hall elements [8], (2) a bridge structure for the Hall-voltage generator that improves the temperature characteristics of the magnetic sensor [9], and (3) a symmetrical complementary application to obtain a differential output of Hall elements [10]. A dual-Hall sensor scheme can reduce temperature drift, static output, and position errors [11]. However, this design only partially solves the external interference problem because the external interferences at two points may be different; thus, any position variation in the conductor or the Hall chip can lead to inaccurate measurement results. The two Hall chips also overlap, thus resulting in increased thickness. Consequently, the magnetic gathering properties of the Hall element, particularly for a current less than 100 A, are affected. Therefore, an improved packaging scheme for the dual-Hall current sensor is proposed.

A complementary model combined with the linear differential Hall, which is composed of two linear Hall element components in the design of the differential Hall-current sensor, can maximize the output characteristics of the elements. A novel linear differential dual-Hall

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sensor model is proposed in the present study based on previous research. The output and temperature characteristics of the proposed sensor are also experimentally investigated.

2. Design of the dual-Hall sensor model

2.1. Basic principle of the dual-Hall differential sensor

The dual-Hall model is composed of two Hall components, H_1 and H_2, which are placed side by side and have the same power. The output voltages of H_1 and H_2 are U_1 and U_2, respectively. The Hall voltage coefficient K_H and the role of the magnetic induction intensity on $H_1$and H_2 are assumed to be the same. The signal voltage output equations of U_1 and U_2 can be expressed as [8]:

$$U_1 = U_{01}(t) + K_H B, \tag{1}$$

$$U_2 = U_{02}(t) - K_H B, \tag{2}$$

where $U_{01}(t)$ and $U_{02}(t)$ are the quiescent output voltages of H_1 and H_2, respectively, at temperature t. The Hall devices demonstrate the same process in an ideal state: $U_{01}(t) \approx U_{02}(t)$.

The output voltage difference between H_1 and H_2 is used as the sensor signal output, that is, the component model is based on differential outputs. The signal output is given by:

$$U = U_{01}(t) - U_{02}(t) + 2K_H B.$$

$\Delta u(t) = U_{01}(t) - U_{02}(t)$ is set.

Then,

$$U = \Delta u(t) + 2K_h B, \tag{3}$$

where $\Delta u(t)$ is the static output difference of the two Hall elements and $\Delta u(t) \ll 3000$ mV. The differential results show that such complementary component model reduces DC voltage component and increases signal voltage amplitude. The differential voltage output can suppress common mode interference and temperature drift. The dual-Hall model can improve output stability and linearity.

2.2. Position of the dual-Hall components in the magnetic core

In the most common dual-Hall model, the two Hall chips are overlapping [8,10,11], thus resulting in increased in thickness [the thickness of the overlapped dual-Hall will exceed 3 mm if the size of a single Hall chip is approximately 1.5 mm, such as CS49E (ZHONGXU China)]. The increased thickness will undoubtedly affect the magnetism-gathering properties of the Hall element, particularly in the case of a current less than 100 A. The suitable size of the air gap is 1.2–2.0 mm for the magnetic characteristic of the Hall chip if the current is below 100 A. Therefore, an improved packaging scheme for the dual-Hall current sensor is proposed.

The Biot–Savart law is used to compute the resultant magnetic field B at position r generated by a steady current I. The Biot–Savart law can be expressed as

$$dB = \mu I d \sin\theta / 4\pi r^2 \tag{4}$$

where dB is the infinitesimal contribution of B, μ is the permeability of free space and θ is the polar angle.

Based on Eq. (4), the magnetic flux density generated by the conductor is inversely proportional to the distance square. In this study, distance is calculated from the wire to a certain point. Each Hall sensor measures the magnetic flux density generated by the flowing current and generates an output voltage. The magnetic flux density in the air gap will be different if the size between the bus bar and the air gap is variable quantity.

A scheme featuring two Hall parts in the same air gap is shown in Fig. 1. This scheme is selected based on two aspects. On one hand, a small air gap in the magnetic core is known to generate large magnetic flux density in the air gap [12]. On the other hand, the measuring range of the focused current sensor is below 100 A, which requires the air gap in the iron core to be less than 2 mm. The air gap will be larger than 2 mm if the iron core is designed with two gaps or if the dual-Hall chips are stacked.

The Ohm's law formula for the Hall electric current sensor is as follows [13]:

$$NI = \phi R = \phi\left[\frac{l_t}{\mu_r S_t} + \frac{l_\delta}{\mu_0 S_\delta}\right] = B_t\frac{l_t}{\mu_r} + B_\delta\frac{l_\delta}{\mu_0}, \tag{5}$$

where B_t, l_t, μ_r are the magnetic flux density, magnetic circuit length, and relative permeability of ferrite core, respectively; and B_δ, l_δ, μ_0 are the magnetic flux density of the air gap, the width of the air gap, and the relative permeability of air, respectively. When ferrite core is not saturated, $\mu_r \gg \mu_0$, then the formula will be:

$NI \approx B_\delta \frac{l_\delta}{\mu_0}$, and then, $B_\delta \approx \frac{NI\mu_0}{l_\delta}$. Therefore, as the width of the air gap increases, the magnetic flux density in the air gap decreases.

The simulation result in Fig. 2 shows that the magnetic flux density in the air gap decreases when the width of the air gap increases.

The parameters of the sensor core are provided based on relevant parameters (refer to LA55-P from LEM) and experience data to facilitate the simulation. The primary current is 50 A. The cross-sectional area of the bus bar is 8 mm × 6 mm. The width of the air gap is 2 mm. The magnetic core with a cross-sectional area of 6.0 mm × 2.1 mm has the following dimensions: 40 mm × 34 mm × 2.1 mm.

The magnetic flux density distribution in air gap is shown in Figs. 3 and 4. The two Hall elements are placed

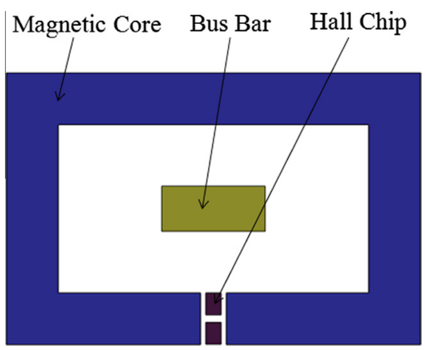

Fig. 1. Double Hall element under the same air gap induction intensity.