The development of three-tip fluxgate magnetometer applied on ship magnetic field measure

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Abstract

A proposed new three-tip fluxgate sensor is developed that is structured of a racetrack loop iron core and a couple of symmetric inverse-parallel windings. The second harmonic of the output signal is twice proportional to the measured external magnetic field intensity. The magnetic measuring resolution reaches 1nT, and the dynamic measuring range reaches 100μT. The multi-channel magnetic measuring system, which is made up of three-component and three-tip fluxgate sensors, can satisfy the requirement of the space magnetic measuring on large warship.

Keywords: Ship magnetic measure, three-tip fluxgate, second harmonic

1. Introduction

In the early of 1930s, a type of fluxgate sensor was created that measures the Earth magnetic field by itself magnetizing saturation characteristics. Because it is of simple structure, of steady performance and of low power loss, now it is still one of the most sensors applied for weak magnetic field measuring [1-2]. According to the differences of the structure of fluxgate sensors, there are basic kinds of fluxgate magnetometer which measures magnetic field utilizing high magnetic materials, such as single winding fluxgate, dual-winding fluxgate, and loop-typed fluxgate and so on [3-4]. To improve the measure precision and stability, there arise short-circuit-typed fluxgate, digital-typed fluxgate, fast Fourier transform fluxgate, current-output-typed fluxgate and so on [5-7]. The key is how to process errors of magnetic measurement and to generate a corresponding feedback field; the aim is for higher precision, far less noise, lower cost, lower power, smaller size, lighter weight and larger dynamic measure range.

Warships sailing in the sea will generate permanent magnetic field around after magnetized by the geomagnetism field, and will generate induction magnetic field after excited by the current-loop of shipborne equipments. In order to demagnetize a warship purposefully, we must test magnetic field and its space distribution of the warship termly. The measure range of warship magnetic field is about 1~10⁶nT, which is a slow variational medium intensity magnetic field [8], and it can be measured using the fluxgate magnetometer. However, it needs multi-point and multi-component measurement at the same time to the space magnetic field distribution of warship; this is unable for the general single-channel fluxgate magnetometer.

The fluxgate magnetometer and its multi-channel measuring system with the three-tip fluxgate sensor studied in this paper. The three-tip fluxgate sensor is a single winding fluxgate with a loop-typed core, and the winding is as the exciting coil, the inductive coil and the feedback coli. Its signal regulating circuit that is made of a frequency-selecting amplifier, a phase-sensitive detector and an integrating filter can improve the linearity, stability and measure range of the magnetic measure, and enhance the dynamic performance of measuring system.
2. Structure and principle of the three-tip fluxgate

The proposed three-tip fluxgate is shown in Fig. 1. The winding on the racetrack loop core is separated into two semi-windings, an up coil $N_1$ and a down coil $N_2$, which are symmetric. The exciting source enters from the tip $L_1$ and the tip $L_2$, the centre tip $L_3$ is not only the signal port, but also the feedback port. It is called the three-tip fluxgate because the whole sensor only has three tips.

![Fig. 1. Three-tip fluxgate.](image1)

![Fig. 2. Three-component fluxgate sensor.](image2)

Without considering the magnetic leakage effect of the core and in the condition of the exciting magnetic field intensity $H_{e}=H_{m}\cos \omega t$, the magnetizing field paralleled with the core axis is $H_{e}=H_{e1}+H_{e2}=2H_{m}\cos \omega t$. The resultant magnetic field $H$ of the magnetizing field $H_{e}$ and the measured external magnetic field $H_0$ is $H=H_{e}+H_0$ (up $N_1$ core) and $H=H_{e}-H_0$ (down $N_2$ core). Supposing the permeability of the core is $\mu$ and considering the demagnetization effect, the magnetic flux density of core should be

$$B=B_{e}+B_{0} = \mu \frac{H_{e}+H_0}{1+D(\mu -1)/4\pi} = \mu' H$$

(1)

There, $D$ is the demagnetization coefficient; $\mu'$ is the permeability of the core within the demagnetization effect. We can use a cubic polynomial $B_e=aH_e-bH_e^3$ to approach the actual magnetization characteristic (hysteresis curve). According to the Faraday law of electromagnetic induction, when the exciting magnetic field is changing with time, the $N_1$ will generate an induced electromotive force $e_1$ as follows

$$e_1 = -10^{-8} N_1 S \frac{dB}{dt}$$

(2)

Where, $S$ is the section area of the core, $N_1$ is the turns of the up coil. In common, the variation of the ship magnetic field change is slow, so regard $dH_0/dt=0$ and put (1) into (2), we will get the induced electromotive force on the $N_1$ as follows

$$e_1 = 2 \times 10^{-8} NS\omega H_m \left(3bH_0^2 + 3bH_m^2 - a\right) \sin \alpha t + 6bH_0 H_m \sin 2\alpha t + 3bH_m^2 \sin 3\alpha t$$

(3)

Similarly, the induced electromotive force on the $N_2$ is

$$e_2 = -2 \times 10^{-8} NS\omega H_m \left(3bH_0^2 + 3bH_m^2 - a\right) \sin \alpha t - 6bH_0 H_m \sin 2\alpha t + 3bH_m^2 \sin 3\alpha t$$

(4)

Hence, the total induced electromotive force can be gained as

$$e = e_1 + e_2 = 24 \times 10^{-8} NS\omega H_m^2 H_0 \sin 2\alpha t$$

(5)

Make sure the exciting source, the signal value is

$$E = K_H H_0$$

(6)

In the formula (6), $K_H=24 \times 10^{-8} NS\omega BH_m^2$ is the sensitivity parameter of the three-tip fluxgate sensor, which is proportional to the square of the exciting field intensity and is proportional to the frequency. Therefore, it can improve the sensitivity of the three-tip fluxgate sensor by increasing the exciting field intensity or its frequency.
It is can be seen from the above formula (6), the output signal $E$ of the fluxgate is proportional to the second harmonic of the measured external magnetic field $H_0$, and the odd harmonic component (including the fundamental component) can be inhibited effectively. The output signal intensity of the three-tip fluxgate is two times of the measured magnetic field intensity. Square wave is as an exciting source in the actual application, so the exciting source can be simplified.

The three-tip fluxgate shown in Fig. 1 is of a stronger directionality, only the component $H_0$ which is at the length direction of the fluxgate magnetic core is detected and the components at its orthogonal directions are not detected. The independent three-component fluxgate sensor making up of the three mutually orthogonal three-tip fluxgates is shown in Fig. 2. By this, the space magnetic field distribution of the warship can be measured.

Every component probe in the three-component fluxgate sensor is excited by exciting sources uncorrelated with each other. So the output of the three-component fluxgate sensor is a three-dimensional signal vector

$$E = \begin{pmatrix} E_X \\ E_Y \\ E_Z \end{pmatrix} = K_H \begin{pmatrix} H_X \\ H_Y \\ H_Z \end{pmatrix} = K_H H_0$$

Further more, multi-channel measuring system can be structured up by using some three-component fluxgate sensors, and we can detect the space magnetic field distribution of the whole warship at the same time.

3. Signal regulating circuit

The signal regulating circuit mainly consists of a frequency-selecting amplifier, a phase-sensitive detector, an integrating filter and a feedback unit, which is shown in Fig. 3. Because of the special structure of the three-tip fluxgate and the symmetry complementarity of the $N_1$ and $N_2$, the odd harmonic component in the output signal is eliminated mostly, but the useful even harmonic component is enhanced, in other words, the signal-to-noise ratio (SNR) of the fluxgate is improved greatly.

The frequency-selecting amplifier is used to amplify the second harmonic component (the frequency is $2f_1$) of the fluxgate output signal, and to filter out the noise signal, so the frequency-selecting amplifier is a band-pass filter amplifier.

The phase-sensitive detector adopts analog switches, every signal with the frequency $2f_1$ (the second harmonic component) can pass when the exciting source is at the cycle of $\pi/2 - \pi$ and $3\pi/2 - 2\pi$, other harmonic components are hindered. The noise without the frequency of $2f_1$ is restrained greatly.

The integrating filter transforms the output signal from the phase-sensitive detector into the stable direct current signal proportional with the measured outer magnetic field.
4. Testing

In Fig. 4 (a), Curve 1 is the original square wave of the exciting voltage source with 5.4KHZ. Curve 2 is the exciting square wave after power amplifying. The exciting square wave is not obviously phase-drift after power amplifying, so the signal regulating circuit of the three-tip fluxgate can’t need a phase-drift circuit.

In Fig. 4 (b), Curve 1 is the original signal wave of the three-tip fluxgate output. Adopting a square wave exciting, although the sensor uses symmetric difference complementary structure ($N_1$ and $N_2$), there are higher harmonic components with more than $2f_1$ in the fluxgate output signal, and the expected signal amplitude with $2f_1$ isn’t too high.

Figure 4 (c) shows that Curve 1 is the signal wave after frequency-selecting amplifying, the frequency of which is mainly $2f_1$, and the phrase keeps the same with the exciting signal. However, seen from the waveform, there are basic wave and thrice harmonic component, and the frequency-selecting amplifier can’t eliminate the odd harmonic components completely.

The signal waveform after the phase-sensitive detecting is Curve 1 shown in Fig. 4 (d). Obviously, the signal is hindered and the output is zero when the exciting square wave is in the cycle of $0$-$\pi/2$, $\pi$-$3\pi/2$; when the exciting square wave is in $\pi/2$-$\pi$, $3\pi/2$-$2\pi$, other harmonic components are hindered while the second harmonic component can pass.

The signal wave after integrating and filtering is shown in Fig. 4 (e), it is seen that the output signal of the phase-sensitive detector has been integral into a smoothing signal. When joining a RC low-pass filter at the end of the integrating and filtering, the output signal wave is shown in Fig. 4 (f), the glitch has been eliminated.

5. Multi-channel magnetic measuring system based on Ethernet

In order to measure the 3-D space description of more precise warship magnetic field. The multi-channel dynamic magnetic field measuring system is shown in Fig. 5.

In Fig. 5, every measuring box (MB) main contain two parts: the signal regulating board (SRB) and the micro control unit (MCU). The MCU can send the measuring signal to a professional computer (PC) through Ethernet of the system, and the PC processes comprehensively the multi-channel magnetic measuring data. One MCU can manage seven SRB and one SRB contains six fluxgate signal channel, so one MB can connect forty-two measuring channels or connect fourteen three-component fluxgate sensors. When one MB
isn’t enough to measure, we can expand more MB to satisfy the requirement of the space magnetic field measuring on large warship.

Fig. 5. The principle structure of the multi-channel magnetism measuring system.

6. Conclusion
The three-tip fluxgate proposed in this paper is a single winding fluxgate with a loop-typed core, and the winding is as the exciting coil, the inductive coil and the feedback coil. This three-tip fluxgate sensor is small and light. Its resolving power of magnetic measure can reach 1nT, the dynamic measure range is 0~±100μT, the measure error≤1%, the measure fluctuation (stability) ≤2nT/2h. The multi-channel magnetic measuring system, which is made up of three-component and three-tip fluxgate sensors, can satisfy the requirement of the space magnetic measuring on large warship.

7. Acknowledgements
This work is supported by Science and Technology Development Fund of Shanghai Education Committee, No. 07ZZ100.

References