To the question of constructing measuring devices based on fluxgate sensors

Anatolij Nikishechkin^{1,*}

¹Department of Computer Control Systems of «MSTU «STANKIN», 127055 Moscow, Russia

Abstract. The article discusses the issues of feeding fluxgates from compact, low-power generators built on AND-NOT logic elements. The frequency of such generators depends on the magnitude of the measured magnetic field strength. This gives reason to consider the possibility of using frequency as a useful signal. The article discusses the issues of feeding fluxgates from compact, low-power generators built on AND-NOT logic elements. The frequency of such generators depends on the magnitude of the measured magnetic field strength. This gives reason to consider the possibility of using frequency as a useful signal. The article proposes to use modulated rectangular voltage pulses, that is, pulses with high-frequency filling, to power a fluxgate. Then, under the influence of the measured magnetic field, the filling frequency changes, according to which the magnitude of the intensity is determined, and the frequency of the modulating voltage corresponding to the passport frequency of the fluxgate remains constant. In this case, it becomes possible to increase the deviation of the filling frequency due to the use of the released output winding of the fluxgate as an additional element of the generator. It was also experimentally established that in order to increase the voltage on the excitation winding of the fluxgate and, as a consequence, to increase its sensitivity, it is advisable to power through the D-trigger, which makes it possible to obtain bipolar voltage on the excitation winding. In addition, it is necessary to use resonance phenomena (at the frequency of the modeling voltage) in the serial circuit “connecting capacitors - excitation coil of a fluxgate”, which allows increasing the voltage on the excitation winding without increasing the voltage of the power source.

1 Introduction

The magnetic field generated by the DC motor carries information about the load on the motor shaft and can be used as a diagnostic parameter in various control and monitoring devices [1, 12]. The mass of the cargo transported by the lifting and transport device, the mass of the train, the cutting force during processing on a metal cutting machine can be estimated by the magnitude of the magnetic field [2, 3, 4, 13].

Therefore, of particular interest are devices for measuring the magnitude of the magnetic field. In order to measure the magnetic field strength, various sensitive elements

* : Corresponding author: anatolij-petrovich@yandex.ru

can be used: magnetodiodes, magnetoresistive sensors, Hall sensors, Josephson's superconducting quantum interferometers, NMR sensors (quantum devices based on nuclear magnetic resonance) [6, 10].

Widely used as sensitive elements in devices for measuring magnetic field parameters are fluxgate sensors. They provide high measurement accuracy [6–8, 11]. In this regard, of particular interest is the possibility of their use for measuring the cutting force, for assessing the wear of the cutting tool and in adaptive control systems of the metalworking process [3, 13].

Unlike supersensitive (up to 10^{-13} T) and high-precision from Josephson's superconducting quantum interferometers and NRM sensors, which are complex and expensive devices, fluxgate converters are simple and cheap devices, but inferior to them in sensitivity and accuracy. However, in comparison with magnetodiodes and magnetotransistors, the sensitivity and accuracy of flux-gate transducers are significantly higher [6, 9, 10, 14–20].

Fluxgate sensors are characterized by low power consumption, the ability to work in a wide temperature range (–50 ... 200), are resistant to interference, and (unlike magnetoresistive sensors and Hall sensors) do not require signal amplification and careful tuning of the switching circuit [5, 6].

Thus, fluxgate sensors in comparison with other sensitive elements in many respects have undoubted advantages. However, the task of increasing the sensitivity of measuring devices based on fluxgate sensors remains relevant.

2 Problem Status and Problem Setting

The sensitivity of the fluxgate sensor is largely determined by the supply voltage of its field winding. The supply voltage is characterized by three parameters: shape, frequency and amplitude.

Typically, the fluxgate sensors are fed according to the standard scheme from a generator with a sinusoidal, sawtooth, or pulsed voltage of a rectangular shape [7, 8, 11]. It has been found that a rectangular shape is preferable.

The output signal corresponding to the magnitude of the measured magnetic field is removed from the output winding of the fluxgate, that is, the current value of the output winding or the magnitude of the voltage across it is measured. In this case, the measuring device (ammeter or voltmeter) is calibrated in units of magnetic field strength.

In fig. 1 shows a traditional scheme for switching on fluxgate windings. Winding L1, consisting of two counter-wound windings L'1 and L"1 - excitation coil of a fluxgate, L2 - output winding of a fluxgate, L3 - compensation winding.

Fig. 1. The inclusion circuit of the fluxgate windings

The compensation winding of the L3 fluxgate is designed to compensate for extraneous magnetic fields and to set the value of the recording device to zero in the absence of a measured magnetic field. Zero value is set by variable resistance R2.

In measuring devices based on fluxgate sensors, a square-wave generator based on logical elements NOT or AND-NOT can be used to power the field winding [2–5]. For example, in fig. 2 shows a diagram of such a generator on the chip K561JH2.

Fig. 2. Generator circuit built on three elements NOT

The scheme is simple, low energy consumption and allows for the compactness of the measuring device; the frequency of the generator can be set over a wide range (using the variable resistance R1).

Using the generator on the elements NOT (or AND-NOT) shown in Fig. 2, for feeding a flux gate it has the following feature. The excitation coil of the fluxgate becomes an element of the generator, and the measured magnetic field through the excitation winding affects the frequency of the generator by changing it. The fact of the influence of the measured magnetic field on the frequency of the flux gate is well known and was already mentioned in the works of Yu. V. Afanasyev [7, 8]. Moreover, an increase in the measured magnetic field leads to an increase in the frequency of the generator. This gives reason to talk about the possibility of a frequency-measuring approach to building devices for measuring magnetic field strength and to use the generator frequency as a useful signal that carries information about the magnitude of the magnetic field.

The use of frequency as a useful signal has its well-known advantages [21]. Modern digital frequency meters provide the highest metrological characteristics among all measuring instruments (accuracy and resolution); they operate in a wide range of measured frequencies, have high speed, reliable and easy to operate.

In this case, the frequency meter becomes the recording device, and there is no need for the output winding of the fluxgate.

Given the fact that a bipolar rectangular waveform is preferable in the sense of increasing sensitivity and reducing power consumption, it is advisable to power the field coil through a D-trigger. Then a bipolar signal is formed with a doubled effective voltage value, which is supplied to the field winding through connecting capacitors.

In addition, studies have shown that with increasing voltage on the field winding (both amplitude and current values), the sensitivity of the flux gate increases [5, 6]. Therefore, it is of interest to use resonance phenomena in the series circuit “connecting capacitors - field winding”.

A possible variant of the circuit is shown in Fig. 3.

Fig. 3. The generator circuit, combined with a D-trigger, to power the excitation coil of the fluxgate

The circuit shown in fig. 3, contains a rectangular pulse generator, made on three elements of the AND-NOT chip 564JIA7 (IC1.1 - IC1.3). The field winding is fed through a D-flip-flop made on three AND-NOT elements (IC1.2, IC1.3, IC1.4) of the same microcircuit; while the elements IC1.2 and IC1.3 are simultaneously elements of the generator.

The excitation winding L1 of the fluxgate, consisting of two counter-wound windings L'1 and L"1, is connected to the outputs of the D-flip-flop (outputs of circuits IC1.3 and IC1.4) through isolation capacitors C2 and C3. Thus, a double amplitude of the generator voltage is applied to the excitation winding of the flux gate. In addition, by energizing the field winding through the D-flip-flop, it is possible to reduce distortion of rectangular pulses supplied to the excitation winding of the fluxgate.

The frequency meter in the circuit in Fig. 3 can be connected directly to one of the outputs of the D-trigger or to the output of the element IC1.2. Using the frequency as a useful signal makes the output winding L2 unnecessary, and the compensation winding L3 can be connected in the same way as in Fig. one.

However, questions immediately arise. How painless for the fluxgate are the changes in the frequency of the generator feeding its field winding? Does this change in frequency lead to a loss in the efficiency of the fluxgate? What is the magnitude of these frequency changes?

Indeed, on the one hand, in the proposed frequency-measuring method, it is necessary to increase the frequency range under the influence of the measured magnetic field in order to increase the information content of the frequency, which is defined as the ratio $\frac{\Delta f}{\Delta H}$, where: Δf is the magnitude of the change in the frequency of the generator; ΔH - the

magnitude of the change in the intensity of the measured magnetic field that caused this change in frequency Δf .

But, on the other hand, it is impossible to go far from the passport frequency, which is determined by the capabilities of the core of the fluxgate, since this can lead to a decrease in the efficiency of its operation. The authors even proposed measures to reduce the influence of the measured magnetic field on the frequency of the generator [5].

The problem arises of finding a compromise between these two conflicting requirements. How to make sure that, on the one hand, the frequency of the generator could vary significantly depending on the magnitude of the measured magnetic field, but, on the other hand, would not go far from the passport frequency, since this can lead to a decrease in the efficiency of the fluxgate?

The circuit shown in Fig. 3 is an attempt to find a compromise between two conflicting requirements. However, experimental studies with fluxgate sensors led to another solution and gave encouraging results.

3 Proposed solution

The essence of the proposed solution is as follows.

1. The excitation winding is energized (as in the circuit shown in Fig. 3) by rectangular pulses through the D-trigger in such a way that a bipolar signal is generated with a doubled effective voltage value, which is supplied to the excitation winding through the connecting capacitors.
2. The rectangular pulses by which the power is supplied are modulated, that is, filled with rectangular pulses; the filling frequency is significantly higher than the frequency of the modulating voltage.
3. Significant changes in the filling frequency under the influence of an external measured magnetic field are painless for the fluxgate, since the fluxgate operates at a frequency of modulating voltage, which corresponds to the operating frequency of the fluxgate and does not change under the influence of the measured magnetic field.
4. Since the frequency of the modulating voltage becomes independent of the external magnetic field, it becomes possible to effectively use the voltage resonance at this frequency to increase the voltage on the field winding and, ultimately, to increase the sensitivity of the fluxgate. An increase in voltage due to resonance does not require an increase in the voltage of the power source.
5. To increase the range of frequency changes when changing the magnitude of the measured magnetic field strength (that is, to increase the information content of the frequency), the output winding of the fluxgate is used as an element of the fill pulse generator.

In fig. 4 presents a non-standard scheme for powering the excitation coil of a fluxgate, built on the above principles.

Fig. 4. The proposed scheme for powering the excitation coil of a fluxgate

The circuit (Fig. 4) contains the following components.

1. The excitation winding of the flux gate, consisting of two counter-wound halves L1' and L1''.
2. Connecting capacitors C3, C4, through which the excitation winding of the fluxgate is fed. Capacitors of capacitors are determined from the condition of providing a resonance of voltages in the series circuit "connecting capacitors - excitation winding of a fluxgate" at the frequency of the modulating voltage.
3. Generator 1 (made on three elements 2AND-NOT IC1.1 - IC1.3 of the 564JIA7 chip) is a generator of unipolar modulating rectangular voltage pulses, the frequency of which is tuned using the resistor R1 to the operating (passport) frequency indicated in the documentation for the fluxgate.
4. Generator 2 (made on three elements 2AND-NOT IC2.1 - IC2.3 of the 564JIA7 chip) is a generator of unipolar rectangular pulses, the frequency of which exceeds the passport frequency of the flux gate by orders of magnitude and is set using resistor R2. The generator 2 generates voltage pulses, which fill the voltage pulses of the generator 1. The pulse frequency of the generator 2 (filling frequency) depends on the measured magnetic field strength and is used as a useful signal. To increase the information content of the filling frequency, a released output winding of the fluxgate is used, which becomes an element of the generator 2.
5. D-trigger made on three elements 2AND-NOT IC2.2, IC2.3, IC2.4 of the 564JIA7 chip (while the elements IC2.2 and IC2.3 are also elements of a generator 2).

In fig. 5 shows the timing diagrams of stresses (excluding distortions) and provides explanations for the diagrams.

The whole circuit shown in Fig. 4 is made on two 564JIA7 2AND-NOT chips.

A fundamental feature of the proposed solution is the frequency deviation of the voltage pulses generated by the generator 2 and filling the modulating pulses of the generator 1, depending on the amplitude and direction of the vector of the measured magnetic field strength. The frequency of the modulating pulses of the generator 1 remains almost unchanged and corresponds to the passport frequency of the fluxgate. This decision suggests the possibility of a frequency-meter approach to the construction of measuring devices based on fluxgate sensors without changing the passport frequency of the fluxgate.

Fig. 5. Timing diagrams of stresses

The filling frequency, which depends on the measured voltage, is recorded by a digital frequency meter, which can be connected directly to one of the outputs of the D-trigger (output of the IC2.3 element or IC2.4 element) or to the output of the IC2.2 element (similar to the circuit in Fig. 3).

The compensation winding L3 can be connected in the same way as in the circuit in Fig. one.

4 Experimental Results and Conclusions

The proposed device is tested on a prototype. The experiments were carried out with a differential fluxgate, consisting of two permalloy cores and having a passport frequency of 2 kHz, which is set by the generator 1. The number of turns of each half of the field

winding L'1 and L"1 is 200, a wire with a diameter of 0.3 mm. Winding single-layer turn to turn. Over two cores with windings L'1 and L"1, an output winding L2 is wound, the number of turns 2000, the diameter is 0.1 mm. Winding multi-layer turn to turn. The compensation winding is located on top of the first two, diameter 0.1 mm, the number of turns 500.

The capacitance of the connecting capacitors C3 and C4 at each output of the D-flip-flop is 0.68 μ F. The inductance of the field winding of the used fluxgate is of the order of 0.01 H.

The frequency of the generator is 2 - 20 kHz.

When the intensity of the measured magnetic field changes from zero to $80 \cdot 10^3 \frac{\text{A}}{\text{M}}$ (or when the magnetic field induction changes from zero to 0.1 T), the voltage frequency generated by the generator 1 changes from 20 to 40 kHz. Such a change in frequency indicates its information content and confirms the possibility of a frequency-measuring method for constructing measuring devices based on a fluxgate sensor.

To increase the sensitivity and ensure the ability of the fluxgate to frequency-differentiate magnetic field changes of order magnitude $10^{-4} - 10^{-5} \frac{\text{A}}{\text{M}}$, it is proposed to use the released output winding L2 of the fluxgate. It was experimentally established that the inclusion of the output winding in the open circuit of the generator 2 between the output of the DD2.1 element and the input of the DD2.2 element (Fig. 4) can significantly increase the frequency deviation when changing the measured magnetic field strength. The magnitude of the deviation depends on the number of turns in the output winding of the fluxgate. At the same time, the frequency of the 2 kHz modulating signals generated by the generator 1 remains unchanged.

The experimental results also showed that the proposed scheme for implementing the frequency-measuring approach allows you to effectively use resonance phenomena to increase the voltage on the excitation coil of the flux gate and thereby increase the sensitivity of the measuring device by an average of 50% (compared with the standard power supply circuit).

The conducted experimental studies indicate the effectiveness of the proposed solution. The resulting measuring device is characterized by compactness, low energy consumption, does not contain complex and expensive elements and does not require careful tuning. The increased sensitivity of the device and the convenience of measurement make it possible to use it in various control and monitoring devices, in particular, for on-line measurement of cutting force during processing on a metal-cutting machine. Measurements can be made remotely and there is no need to integrate a fluxgate into a structure containing a magnetic field source.

Moreover, as in the case of using the traditional power supply scheme, the preparation of the device for operation consists in taring the scale of the measuring device [1–4].

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