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Nonlinear amplification of the magnetic induction signal in a magnetomodulation sensor with an amorphous ferromagnetic core

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Abstract. The *purpose* of this work is to show the possibility of using a magnetic field-controlled nonlinearity of the amplitude change in an oscillatory *LC*-circuit containing a core made of an amorphous ferromagnetic alloy with compensated longitudinal magnetostriction, which makes it possible to obtain a high conversion coefficient of weak magnetic field sensors operating at room temperature. *Methods.* A practical method for constructing magnetomodulation sensors of magnetic induction with a fixed magnetic displacement field, which corresponds to the maximum steepness of the nonlinear characteristic of an oscillatory circuit with an amorphous ferromagnetic core in the region of autoparametric resonance, is considered. *Results.* It has been shown that the stable conversion factor of a 35 mm long sensor based on an oscillatory circuit with autoparametric amplification at a modulation frequency of 256 kHz can reach 10 mV/nT, which allows, with the available element base, to record signals of a weak alternating magnetic field with an amplitude of 0.03 pT/Hz$^{1/2}$ in the frequency range 10...1000 Hz. It is noted that the excitation of the sensor by a weak harmonic magnetic field of a high frequency and the constant presence of the amorphous ferromagnetic core near the state of technical saturation significantly reduces the level of intrinsic magnetic noise of the magnetomodulation sensor. *Conclusion.* Magnetomodulation sensors with autoparametric amplification of the magnetic induction signal can find application in geophysics, magnetobiology and biomedicine.

Keywords: magnetomodulation sensor, autoparametric resonance, magnetization nonlinearity, weak magnetic field measurement.

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Introduction

Measurements of a weak magnetic field of low frequencies with an amplitude of less than 1 pTl remains one of the most popular areas of modern applied research in geophysics, magnetobiology and biomedicine. Despite the large number of available magnetic field sensors, their improvement continues and new methods of measuring magnetic induction are being developed. This is due both to the technical features of the developed devices and to the conditions and methods of their operation. Induction sensors are reliable and easy to manufacture, but they are large enough to work at low frequencies, they do not measure magnetic induction, but its time derivative, which makes them practically unsuitable for measuring broadband signals and low-frequency magnetic field signals of objects located close to them [1]. Ferrosonde devices have a relatively high level of their own magnetic noise (5...10 pTl/Hz $^{1/2}$). But recently there have been reports of ferrosondes with orthogonal excitation having a sensitivity threshold of 2 pTl/Hz$^{1/2}$ [2]. Quantum magnetometers with optical pumping measure the magnetic induction module and require constant heating of the vapors of the working substance. The use of a solid-state sensor in the form of a diamond crystal in quantum magnetometers with optical pumping with the substitution of a part of carbon atoms with nitrogen atoms makes it possible to obtain high sensitivity only when using a ferrite magnetic flux concentrator [3]. The most advanced vector magnetometers are considered to be low-temperature superconducting quantum interference detectors (SQUIDs), which have a sensitivity threshold of 1 fTl/Hz$^{1/2}$ [4]. However, they operate at a temperature of about 4 K, which sharply limits their wide application. The high-temperature superconducting quantum interference detectors developed later approach the sensitivity threshold of low-temperature superconducting quantum interference detectors, but also require the use of cryogenic technology, since they operate at the temperature of liquid nitrogen [5].

1. Magnetomodulation sensors with auto-parametric amplification

The creation of highly sensitive magnetic field sensors with autoparametric amplification of the magnetic induction signal became possible with the appearance of amorphous ferromagnetic alloys with compensated longitudinal magnetostriction obtained by rapid quenching from a melt. The absence of a crystal lattice in amorphous ferromagnetic alloys leads to the fact that mechanical stress is an acting factor of the first order, as well as an external magnetic field [6]. As a result, mechanical stress can reversibly bring an amorphous ferromagnet into a state similar to saturation with an external magnetic field. At the same time, an effective forward and reverse magnetically elastic interaction occurs in amorphous ferromagnets obtained by rapid quenching from a melt. It is observed even in amorphous ferromagnetic alloys with compensated longitudinal magnetostriction. When amorphous ferromagnets are excited by an external magnetic field, due to the parity of magnetically elastic effects, after the reverse magnetoelastic transformation, in addition to the primary excitation signal, magnetic field signals of even harmonics of the excitation frequency appear in them. In this case, the amplitude of a number of harmonics can be comparable to the amplitude of the excitation signal. In an LC circuit with an amorphous ferromagnetic core, at a certain ratio of frequency and amplitude of modulation, an autoparametric resonance occurs in an external magnetic field directed along an amorphous ferromagnetic core, leading to an abrupt change in the voltage amplitude on the LC circuit.

The figure shows a typical experimental dependence of the voltage amplitude U on an oscillatory LC circuit with an amorphous ferromagnetic core on the magnitude of an external constant magnetic field H directed along the longitudinal axis of an amorphous ferromagnetic core in the region of parametric resonance. When the core excitation level is exceeded, an abrupt change in the voltage amplitude occurs on the LC circuit (fig. a). The direction of magnetization is indicated by arrows. Dotted lines show discontinuities of dependence and correspond to voltage amplitude jumps. As the excitation amplitude of the LC circuit decreases, the distance between jumps (hysteresis) decreases and, starting from a certain excitation amplitude, the nonlinear resonance dependence of the voltage amplitude on the LC circuit becomes continuous (рис. b). Here, the area of maximum steepness of the transformation is marked with an oval, and the dotted line shows the non-resonant dependence of the voltage amplitude on the LC circuit.

With a constant frequency and amplitude of the modulation magnetic field, the amplitude of the voltage on the LC circuit depends only on the magnitude of the component of the external magnetic field coinciding with the longitudinal axis of the amorphous ferromagnetic core. Since the dependence «voltage amplitude – magnetic induction» on the LC circuit is

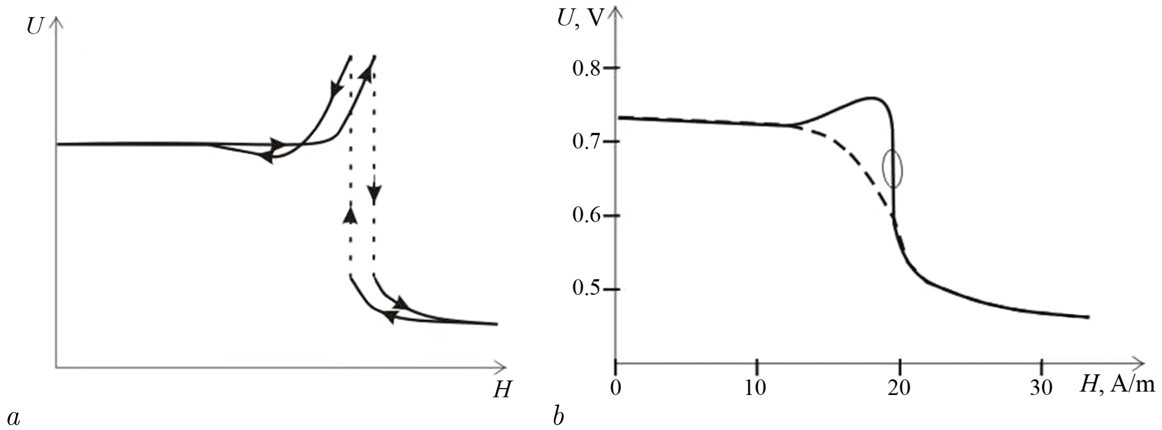

Fig. 0. Рисунок. Амплитуда напряжения на LC-контуре с сердечником из аморфного ферромагнитного сплава при автопараметрическом резонансе в зависимости от внешнего магнитного поля H: *a* — при сильном возбуждении, *b* — при слабом возбуждении

Figure. Voltage amplitude across the LC-circuit with an amorphous ferromagnetic alloy core at autoparametric resonance depending on the external magnetic field H: *a* — with strong arousal, *b* — with weak arousal

nonlinear and ambiguous, then for measuring purposes it must be converted to linear and made unambiguous. The linearization of this dependence is technically achieved by the fact that the displacement magnetic field corresponding to the selected conversion coefficient is supported by a negative feedback system along the magnetic field, and the measured signal is removed from the feedback coil covering the amorphous ferromagnetic core. In this case, a constant magnetic field of displacement is continuously maintained by comparing it with the corresponding voltage of a precision reference voltage source. The capture of the working point on the dependence «voltage amplitude – magnetic induction» is carried out by short-term disconnection of the power supply of the negative polarity of the operational amplifier, which performs proportional-integrating current regulation in the feedback coil. As a result, the capture of the working point area always occurs on one side of the resonance curve. The schematic diagram of one of the variants of the magnetomodulation converter is published in [7].

The experimental dependence shown in Fig. *b*, was obtained on the core in the form of a ribbon of an amorphous ferromagnetic alloy of the basic composition $\mathrm{Fe_5Co_{70}Si_{15}B_{10}}$ with dimensions of 35×0.6×0.02 mm. The coil of the oscillating *LC* circuit contained about 600 turns of copper wire with a diameter of 0.071 mm. The excitation frequency of the *LC* circuit was 256 kHz, and the amplitude of the excitation current was less than 0.45 mA. The conversion coefficient of a magnetomodulation sensor with a *LC* circuit in the working area marked in Fig. *b* oval, can be set in the range from 1 mV/NT to 10 mV/nt. At the same time, the excitation power of the *LC* circuit at the highest sensitivity does not exceed 0.3 MW. If, after detecting a high-frequency voltage on the *LC* circuit, the conversion coefficient will be only 1 mV/NT, then when using an OP-27 operational amplifier at the input of the electrical circuit, having an input noise of 3 nV/Hz $^{1/2}$ in the frequency range from 10 Hz and above, in On a magnetomodulation sensor with autoparametric amplification, it is possible to obtain a magnetic field resolution of about 0.03 pTl/Hz$^{1/2}$.

The sensitivity threshold of the sensor depends on the intrinsic magnetic noise of the amorphous ferromagnetic core and the noise of the active and passive elements of the electronic circuit. The thermal noise of the inductor of the *LC* circuit can be neglected, since its active resistance is only about 20 ohms. As follows from the experience of working with induction sensors, the intrinsic magnetic noise of ferromagnetic cores in the passive state in a weak magnetic field is quite small [1]. In active sensors based on ferromagnetic cores, the energy loss during their excitation consists of eddy current losses and remagnetization losses, which are characterized by the area of the hysteresis loop. There are practically no eddy current losses in amorphous ferromagnets. This follows both from their relatively high electrical resistivity and from the geometry of the core in the form of a narrow thin strip of an amorphous ferromagnetic alloy. As for magnetomodulation sensors with autoparametric amplification based on amorphous alloys with compensated longitudinal magnetostriction, unlike ferrosondes, their excitation is carried out by a weak high-frequency magnetic field along a private loop occupying an infinitesimally small part of the full hysteresis loop. In addition, a significant part of the energy of the high-frequency remagnetization of the core along a particular loop is not irretrievably lost, and with autoparametric resonance it returns to the energy of the oscillatory LC circuit in the form of the energy of even harmonics resulting from the magnetoelastic interaction. Therefore, real energy losses and random magnetic noise during high-frequency remagnetization of amorphous ferromagnets in the region of autoparametric resonance can be significantly less.

The calculated magnetic permeability of the core shape from the applied amorphous ferromagnetic alloy with compensated longitudinal magnetostriction is approximately equal to 18600. Since the magnetic permeability of the core material from this amorphous ferromagnetic alloy is close to 500,000, the magnetic permeability of the core itself turns out to be equal to 18,000. As follows from Fig. *b*, the strength of the external magnetic field at the operating point corresponding to the region of maximum resonance steepness, $H = 20$ A/m. In this case, the magnetic induction in an amorphous ferromagnetic core in the region of the working point is 0.36 Tl. This value is close enough to the saturation induction of this amorphous ferromagnetic alloy, $B_s = 0.43$ Tl. That is, the amorphous ferromagnetic core is constantly in a semi-saturated state during operation, which helps to reduce its own magnetic noise caused by the process of remagnetization and thermal fluctuations of magnetization.

Conclusion

1. *Sensor sensitivity.* The use of a nonlinear dependence section «magnetic induction —voltage in an oscillatory LC circuit with an amorphous ferromagnetic core» in the region of maximum steepness of the characteristic of the autoparametric resonance allows to obtain a conversion coefficient in a magnetomodulation sensor with an amorphous ferromagnetic core reaching 10 mV/Nt.
2. *Sensor sensitivity threshold.* The excitation of an oscillatory LC circuit with an amorphous ferromagnetic core by a weak harmonic magnetic field of high frequency and the displacement of the working line of the amorphous ferromagnetic core into the area of its technical saturation ensures a low level of intrinsic noise.
3. *Scope of application of the sensor.* Magnetomodulation sensors with autoparametric amplification of the magnetic induction signal can be used in various fields of science and technology when measuring a weak alternating magnetic field of low frequencies.

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