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Geomagnetic Field NMR Relaxometer to Monitor the Working Substance, Sensor and Electronics of the POS-1 Overhauser Magnetometer

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Abstract. This paper presents a hardware-software solution to the problem of studying and controlling the amplitude-time characteristics of the nuclear precession signal of the working substance of the Overhauser sensors of POS-1 magnetometers. The aspects of development are considered: the technical task for the test bench, the hardware design of the device, its general functionality and its software components. Also presented are some results of studies conducted on the stand, demonstrating its efficiency and accuracy.

INTRODUCTION

The research laboratory of Quantum Magnetometry of the Ural Federal University is the leading developer of high-precision magnetometers of a weak field, for various purposes, based on the Overhauser effect. In particular, the laboratory is a manufacturer of serial magnetometers of the POS (Processor Overhauser Sensor) line, including POS-1, which is widely represented in ground geological exploration, observatory and metrological practice, in seismic and volcanic monitoring systems.

Proton Overhauser magnetometers measure the magnitude of the magnetic field induction with high accuracy based on the fundamental connection between the proton gyromagnetic ratio and the frequency of free precession of the total vector of nuclear magnetization:

$$\omega_0 = \gamma B_0, \tag{1}$$

where ω_0 – is the Larmor precession frequency, $\gamma = 2.67515255 \cdot 10^8$ rad/(nT·s) – is the gyromagnetic ratio of the proton, B_0 is the modulus of the external magnetic field. Measuring the frequency of proton precession, the POS-1 calculates and provides the user with the magnitude of the field modulus with a high degree of accuracy, of the order of 10^{-6}.

The ideal signal of the free precession of the nuclear moments of the working substance is:

$$S(t) = A \cdot \exp\left(-\frac{t}{T_2}\right) \cdot \cos(\omega_0 t + \theta_0), \quad A > 0, \tag{2}$$

where T_2 is the transverse relaxation time. The initial amplitude A is determined by the parameters of the working substance, the design parameters of the sensor, the magnitude of the polarizing field or the effective polarizing field

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(depending on the type of sensor), the polarization time and the measurement mode. After digitization, in order to calculate the frequency as precisely as possible, the essential information for the hardware developer is actually the characteristics of the signal envelope that are hidden for the average consumer: its amplitude and decay time. Knowledge of these characteristics is especially important at the stages of development, production and performance monitoring during long-term operation.

In addition to the initial amplitude, the key parameter that actually determines the duration of signal digitization is the transverse relaxation time T_2. In the Overhauser technology, relaxation essentially depends on the type and content of the radical added to the working substance. Accordingly, highlighting the key contributions, we can present the relaxation rate of the sensor working substance in the form:

$$\frac{1}{T_2} = \frac{1}{T_{20}} + \frac{1}{\tau_g} + const \cdot c, \tag{3}$$

where T_{20} – is the relaxation time of the pure solvent, τ_g – is the decay time due to the gradient of the external field, and c – is the radical concentration. In the case of measurements in a shielded magnetic system, the gradient component is directly proportional to the field [1]:

$$\frac{1}{\tau_g} = const \cdot B_0. \tag{4}$$

When investigating the relaxation rate in Overhauser sensors, it is necessary to take into account that connection between T2 and the temperature of the working substance is significant, and sensor heats up during operation by an average of 10 degrees. This connection is described by expression:

$$\frac{T_2 \eta}{T} = const, \tag{5}$$

where T – is the temperature in kelvins, η – is the viscosity of the solvent [2]. Using this formula, it is possible to calibrate temperature effects, when measuring the relaxation rate.

When designing and producing Overhauser sensors, in particular, POS-1 magnetometers, it is necessary to monitor the NMR signal, namely, its amplitude and attenuation, in fact, the relaxation time (2). Automation of this process - the creation of a specialized stand, makes it possible to quickly monitor the quality of the Overhauser sensor, in particular, its key part - the working substance. The availability of information on the signal characteristics allows the selection and study of the properties of various solvents and radicals, the selection of their percentage ratios, and the synthesis of the radical to determine its percentage (efficiency of chemical synthesis).

The purpose of this work was to create and test the functionality of a software and hardware test bench to study the amplitude-temporal characteristics of the nuclear precession signal of working substances of POS-1 Overhauser sensors.

THE IMPLEMENTATION OF THE TEST BENCH FOR STUDYING AND TESTING OVERHAUSER SENSORS OF POS-1 MAGNETOMETERS

Based on the characteristics of the POS-1 sensor, we will establish operating ranges of values within which the stand should have the best accuracy indicators:

1. concentration of the radical 0.001 - 0.01 mmol/l;
2. optimal relaxation times are 0.3–3 s;
3. correlation time of noise 1 - 10 ms;
4. range of measured fields is from 20,000 to 100,000 nT, which according to (1) corresponds to frequencies of about 0.8 to 4 kHz;
5. from the previous paragraph and the Kotelnikov-Nyquist theorem, the digitization frequency should be at least 8 kHz (in actual practice, more than 15 kHz).

From the hardware point of view, the stand represents the development of an existing laboratory measure of the magnetic field. An external ADC module was added to it for communication between the electronics unit of the magnetometer and the computer. An L-Card model E20-10 was chosen, which has the following characteristics: digitization frequency up to 10 MHz, 14 bits, a voltage measurement range of ± 5 V, limits of permissible reduced basic error of voltage measurements of ± 0.25%, limits of permissible relative basic error frequency conversion ADC ± 0.005% [3].

The general block diagram of the device is shown in Fig. 1.

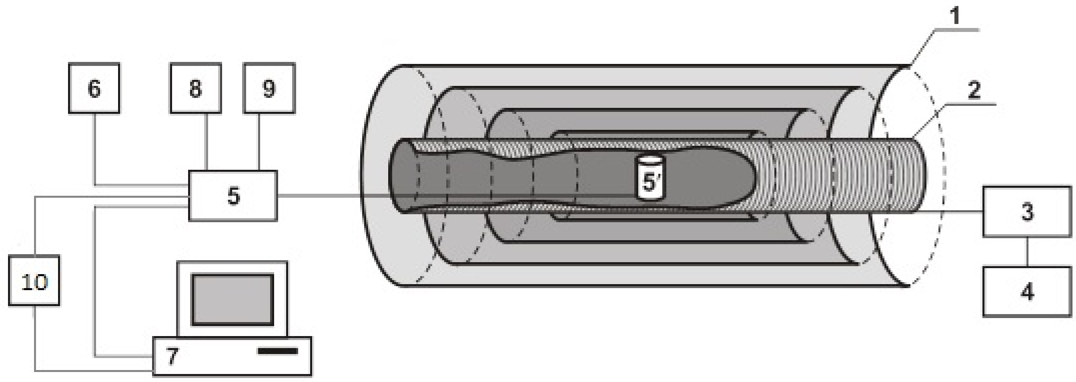

FIGURE 1. Installation block diagram (1 - magnetic screen consisting of four coaxial layers of permalloy alloy; 2 - two-layer solenoid; 3 - power supply source of the solenoid; 4 - power supply unit of the current source of the solenoid; 5 - a magnetometer consisting of an electronics unit (5) and an Overhauzer proton sensor (5'); 6 - battery for powering the magnetometer; 7 - a computer equipped with developed software; 8 - oscilloscope; 9 - voltmeter; 10 - ADC.)

The LabView environment was chosen for the development of the software part of the complex, because it allows visualizing each development stage of the program, and also has specialized libraries for the selected ADC.

The program is a sequential conversion of a digitized signal. The first step is the digitization of the nuclear precession signal. In accordance with the specification, at the beginning of the signal there are transients that must be excluded from processing (cut off 10-20 ms).

The second stage highlights the signal envelope with the help of a software-implemented quadrature detector (6, 7). To find the envelope of the signal (2), it is convenient to use the Hilbert transform, thus obtaining the quadrature component Q (t), orthogonal to the component S (t):

$$\mathrm{Q(t)} = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{S(t')}{t-t'}, \qquad (6)$$

the improper integral being understood in the principal value sense. To perform this operation in the LabView libraries there is a virtual instrument HHT. Accordingly, conducting quadrature detection, we select the signal envelope [4]:

$$\mathrm{E(t)} = \sqrt{S(t)^2 + Q(t)^2}. \qquad (7)$$

The third step is decimation of the signal using averaging to reduce the frequency of the signal to 1 kHz. This frequency is selected based on the time correlation of the noise presented in the technical task.

At the fourth stage, a regression analysis is performed (8, 9). In our case, based on (2), it should be assumed that the model has the form:

$$\mathrm{f(t)} = a \cdot \exp(bt) + c. \qquad (8)$$

The function of this type is obtained using the generalization of the iterative least squares method and the Levenberg-Marquardt steepest descent method, for which the LabView library has a special virtual instrument «Exponential fit».

Comparing expressions (2) and (8), we obtain that A = a, and the relaxation time:

$$T_2 = -\frac{1}{b}. \tag{9}$$

To find the errors of the parameters found, use the virtual instrument Exponential Fit Intervals from the standard LabView libraries.

As a result, the received signal of nuclear precession of the working substance of the sensor under study, its smoothed envelope, amplitude and relaxation time with errors are displayed on the front interface of the program. The program interface is shown in Fig. 2.

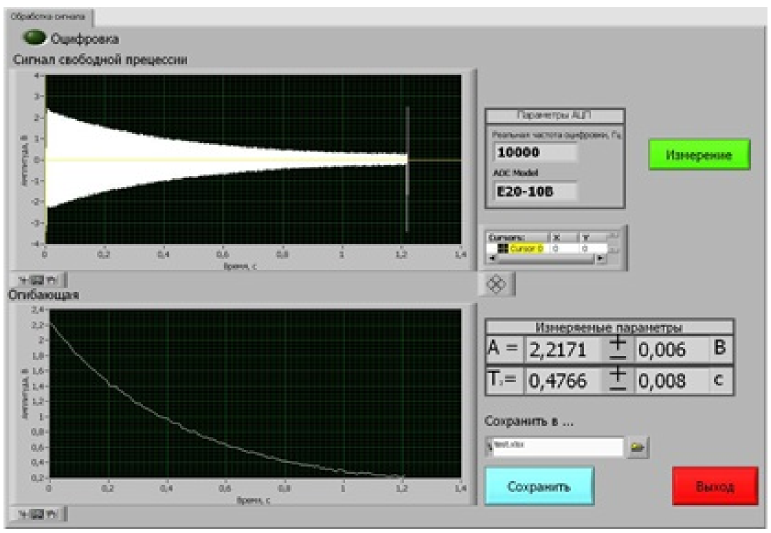

FIGURE 2. Program panel with the display of the signal and its main characteristics

STAND TESTS

Experiments were carried out to check for compliance of the measured characteristics with theoretical dependencies. The relaxation times are measured for three sensors with a known concentration of the radical to verify the law (3). The experiment was performed with a minimum field of 20,000 nT to minimize the gradient component. As can be seen from the graph in Fig. 3, the law (3) is fulfilled.

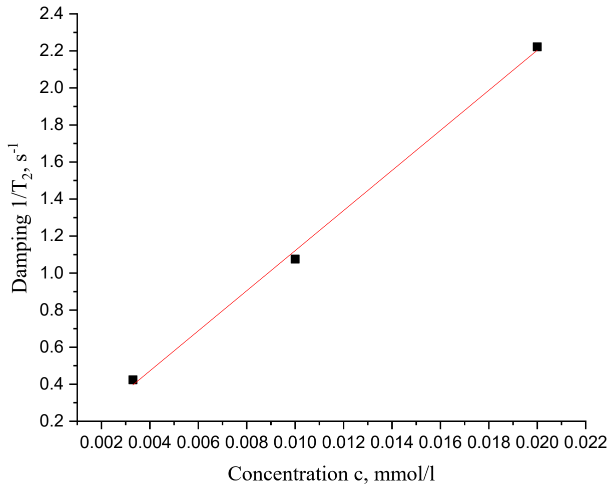

FIGURE 3. The dependence of the attenuation rate of the signal on the radical concentration

Next, relaxation times were measured for a single sensor in different fields in the range of 20000–80000 nT, to verify the law (4). The graph in Fig. 4 has the form described by expression (4).

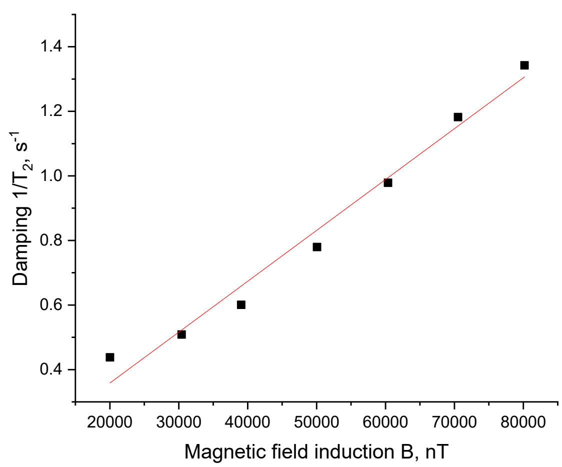

FIGURE 4. The dependence of the attenuation rate of the signal from the magnetic field

Thus, from the presented experiments, it can be concluded that the developed installation can be used for monitoring and research of POS-1 Overhauser sensors of magnetometers.

CONCLUSION

A testbed has been developed for analyzing the amplitude-time characteristics of the nuclear precession signal of the working substance of the Overhauser magnetometers. The hardware and software algorithms used in it are described. Experiments confirming the correspondence of the measured parameters to theoretical dependencies were carried out.

It is planned to further develop the system with the expansion of its functionality. In particular, the development of a system up to a spectrometer for dynamic polarization of nuclei will make it possible to study solutions of stable radicals, which are the working substances of Overhausier magnetometers.

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