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FREQUENCY MODULATION IN NUCLEAR MAGNETOMETER

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Ивашкевич С. А. Д13-2006-161
Частотная модуляция в ядерном магнитометре

На базе конкретной схемы ядерного магнитометра с полевой модуляцией предлагается вариант магнитометра с частотной модуляцией. Указаны недостатки полевой и достоинства частотной модуляции.

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Frequency Modulation in Nuclear Magnetometer

A version of the frequency-modulation magnetometer based on a particular design of the field-modulation nuclear magnetometer is proposed. Disadvantages of field modulation and advantages of frequency modulation are pointed out.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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The year 2006 sees the 60th anniversary of the discovery of a remarkable physical phenomenon — nuclear magnetic resonance (NMR), which has found wide application in many branches of science and technology, including magnetometry [1–3].

The main advantage of NMR-based magnetometers (nuclear magnetometers) is a high measurement accuracy for the magnetic field induction B. The explanation is simple.

If a working material inserted in the field to be measured is affected by another radiofrequency (RF) field of frequency ω, which is perpendicular to the former field, an abrupt transition of the material nuclei from one energy state to another may occur if $\omega = \gamma B$ (NMR condition). Here γ is the gyromagnetic ratio of working material nuclei. The results of the transitions may be observed and used by radioengineering means.

Materials containing hydrogen nuclei (protons) are normally used in nuclear magnetometers. The proton resonance allows one to get the most intense NMR signal and thus to provide the best characteristics for the instrument.

The gyromagnetic ratio of hydrogen nuclei is known to an accuracy of about $5 \cdot 10^{-6}$. Frequency can be measured even more accurately by present-day techniques. Therefore, fixing the resonance with quite a high accuracy, measuring ω, and knowing γ, one can calculate B with a high accuracy.

There are several versions of the NMR method. In magnetometers used to measure B higher than hundredths of a tesla, the RF field is most often generated by the inductance coil L connected in the tuned circuit of the self-excited oscillator. The working material is located inside the coil. The NMR affects the generated voltage through the coil, decreasing its amplitude, which is indicated by readings. This is the so-called resonant absorption signal separation mode. It is this version of the NMR method that the further discussion concerns.

To have an NMR signal convenient to use, the resonance condition is periodically produced in the magnetometer, which results in a periodic sequence of pulsed absorption signals. This may be done by varying (modulating) either B or ω. In the former case, the field to be measured is modulated by imposing on it a modulating field B_{m} generated by a coil L_{m} energized, for example, by sinusoidal current. The simplest way to modulate ω is to add sinusoidal voltage U_{m} to voltage U used to retune ω for producing resonance conditions. Capacitance C of varicaps connected in the tuned circuit of the self-excited oscillator is used for this retuning. Thus, a sum of two voltages U and U_m should be applied to the varicaps. The method is detailed elsewhere.

In most of the known magnetometers field modulation is used. Frequency modulation is used very rarely, probably because it is accompanied by amplitude modulation of the voltage generated by the self-excited oscillator. The latter modulation should be treated as spurious, unlike the working amplitude modulation resulting from the NMR. Spurious modulation is actually several times higher than the working one.

Despite the above disadvantage of frequency modulation (and it is not the single one), the field modulation was abandoned in favor of the frequency modulation while seeking to eliminate all its disadvantages. The main reason for abandoning field modulation was an intention to raise the RF property of the self-excited oscillator to the highest possible level in order to use the proton resonance in measurements of high-induction fields without switching to nuclei with lower resonance frequencies and accordingly lower intensities of NMR signals, as is often done. In addition, the RF property of the self-excited oscillator is urgently needed for the magnetometer described in [4], where it was shown that a device with wide continuous range of measured fields, which uses NMR to measure high fields and ESR (electron spin resonance) to measure low fields, could be created.

In field-modulation magnetometers the coil L is located inside the coil L_m. Long connections of the coil L with the rest of the oscillator limits its RF property. Frequency modulation allows the shortest possible connections.

Before describing how field modulation can be implemented, we would like to point to a number of other drawbacks of field modulation. Presence of L_m increases overall dimensions of the probe, which makes the magnetometer less convenient for measuring fields in narrow-gap flat magnets and solenoids with small inner diameters. This coil requires a rather powerful power supply which, in addition, should comply with special requirements [5]. Also, a particular direction should be observed between the modulating and measured fields — a requirement difficult to meet in some instrument designs. In the case of frequency modulation this problem never arises.

Below a way of implementing frequency modulation in a formerly field-modulation magnetometer is proposed. The magnetometer in question is described in [6], therefore only the changes caused by its conversion to the frequency-modulation type will be mentioned. The circuit diagram of the new instrument is shown in the figure. A list of microcircuits, transistors, and diodes used is given at the end of the paper.

There arises a question of whether the frequency modulation introduces a noticeable error in measurement of the resonance frequency. With the amounts of modulation used, the answer is negative, as follows from comparison of the frequency meter readings with frequency modulation switched on and off. The constituent frequency meter [7] of the magnetometer was used. In this frequency meter, measured frequencies ω were automatically converted to the corresponding values of the field B. The values of the measured field in teslas are displayed on the digital indicator and can be transmitted to a computer through the circuit [8] which is also a part of the magnetometer.

Frequency modulation requires a «pure» sinusoid, i.e., without any distortions and interferences. Therefore, the voltage from the supply-line transformer winding used as an initial one for modulation is first filtered. The sufficient quality of filtration is ensured by the simplest low-frequency RC filter.

The primary task on switching to frequency modulation is neutralization of spurious modulation. In the proposed circuit this problem is solved by passing the signal from the amplitude detector (T4) in the magnetometer probe through the rejection filter with a double T-shaped bridge. Filter elements should be stable while the filter itself should be carefully tuned to the maximum suppression of spurious modulation. Circuits of such a filter are described in many text-books and other books on electronics.

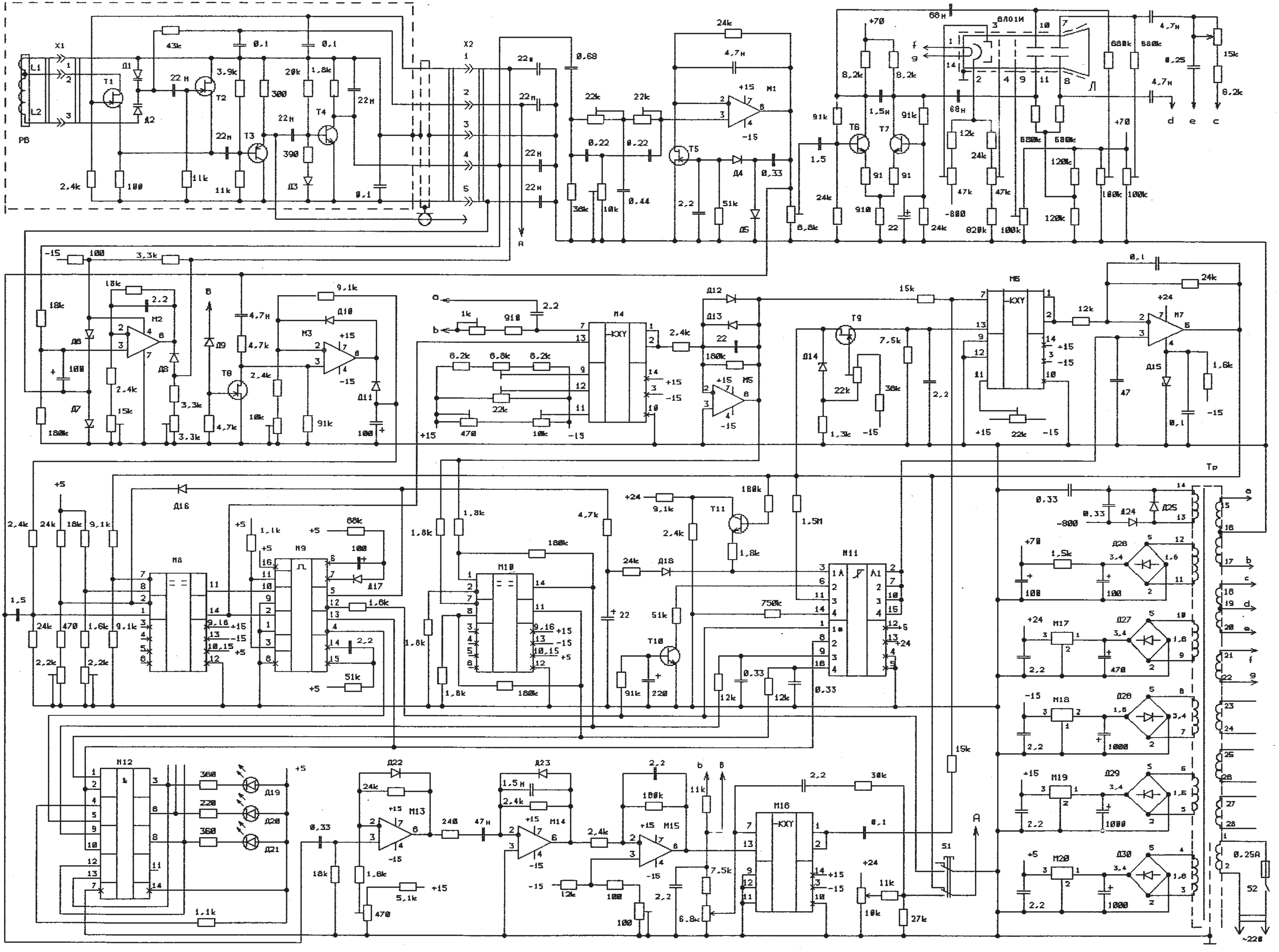
The next task is to eliminate troubles associated with nonlinear dependence of the capacitance of varicaps upon their voltage. It is clear that at a constant amplitude U_{m} modulation will vary with C, i.e., with U. Therefore, when U varies in a wide range, U_{m} must be adjustable with respect to U.

Due to the above nonlinearity, the magnetometer circuit intended for the search for the resonance and sharp tuning to it has automatic adjustment of tuning control voltage. Now the modulating voltage adjustment is added. Both voltages are summed at an input of the analogue multiplier M6. At another (adjusting) output of M6 two nonlinear elements (T9, D14) tuned in agreement with characteristics of the varicaps used and the U range adopted are used to improve adjustment.

Finally, one more important problem of adjusting U_{m} with respect to B had to be solved. In the field-modulation magnetometer, in addition to automatic adjustment of B_{m} with respect to nonuniformity of B, stepped variation of B_{m} with B is used to optimize sharp tuning to the resonance. In each replaceable head of the probe L_{m} are different. It was shown in [5] that fields B_{m} generated by coils L_{m} should increase with increasing B.

Using calculated relations and reasoning from [5] and [9] one may show that stepped or other additional adjustment of U_{m} with respect to B is desirable at frequency modulation. Yet, we have a different situation: the modulating signal should be decreased with increasing B and, with identical ranges of measured B, the required variation range of this signal is appreciably smaller than at field modulation.

To avoid additional manual controls (e.g., a switch) in the circuit, continuous adjustment of U_{m} with a variable resistor is used; positions of its slider are marked in accordance with ranges of fields B measured by replaceable heads with L. This resistor is also used to adjust U_{m} in the manual mode of tuning to the resonance.



PB
X1
X2
L1
L2
T1
T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
M1
M2
M3
M4
M5
M6
M7
M8
M9
M10
M11
M12
M13
M14
M15
M16
M17
M18
M19
M20
8ЛО1И
Tp
S1
S2
0,25A
~220
+70
-800
+24
+15
-15
+5

Though the instrument under discussion may operate in a fully automatic mode, manual tuning is retained as it may sometimes be helpful (see [3] for details).

Automatic adjustment of U_{m} with respect to nonuniformity of B was kept unchanged in the new magnetometer circuit except for the powerful operational amplifier supplying power to L_{m}, which was rejected as unnecessary.

To sum up, considering the advantages of frequency modulation, simplicity of solutions to the problems that arose in this particular magnetometer circuit, and the above-mentioned disadvantages of field modulation, it can be concluded that frequency modulation is preferable in nuclear magnetometers of the type described.

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The list of microcircuits, transistors, and diodes used in the circuit diagram: M1-M3, M5, M13-M15 – КР140УД708; M4, M6, M16 – 525ПС2; M7 – КР140УД22; M8, M10 – КР597СА3; M9 – К155АГ3; M11 – КР590Н5; M12 – К155ЛИ1; M17 – 7824; M18 – 7915; M19 – 7815; M20 – 7805; T1,T2 – J309; T3 – КТ363БМ; T4 – КТ355АМ; T5 – КП307Б; T6,T7 – КТ503Е; T8 – КП303Б; T9 – КП303Е; T10, T11 – КТ315Д; Д1, Д2 – КВ121А; Д3 – КД512Б; Д4, Д5, Д8, Д9 – ГД508Б; Д6, Д15 – КС133А; Д7 – Д814А; Д10-Д13, Д16-Д18, Д22, Д23 – КД503А; Д14 – КС211Ц; Д19, Д21 – АЛ336Б; Д20 – АЛ336И; Д24, Д25 – КЦ106Г; Д26-Д30 – КЦ407А.

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