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Features of process control in the structure of the nutation line for the formation of a mode for measuring flow parameters with magnetization inversion at the noise level

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The problems that arise when conducting experiments using flows of liquid media, as well as during technical measurements of their parameters in various fields of human activity, are considered. The need for new research in the field of nuclear magnetic resonance is substantiated, which involves the use of liquid media flows to solve complex scientific and technical problems in which the use of measuring instruments operating on other physical phenomena is impractical. A new method for forming the structure of the nutation line at the noise level from the flow of a liquid medium with magnetization inversion has been developed and the features of controlling the processes of formation of this structure have been established. Experimental studies were carried out and the adequacy of using this mode for measuring liquid flow q was proven. New coefficients are proposed in the Bloch equations, which describe the movement of three magnetization components (Mx', My' and Mz') in a nutation coil in a fluid flow in a strong inhomogeneous field. For various parameters B0 and q, the structures of nutation lines were calculated. The minimum value of magnetic field inhomogeneity has been established, taking into account q and the parameters of the current medium, which must be ensured in the nutation coil location sector to form the line structure at the noise level. Theoretical calculations are compared with experimental data.

Keywords: fluid flow, magnetic field, nuclear magnetic resonance, nutation line, magnetization inversion, relaxation, magnetic field inhomogeneity, resonant frequency, line width, signal-to-noise ratio.

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Introduction

These days some new challenges appear all the time that must be resolved within the context of technical physics [1–5]. Their successful resolution requires development of new research methods and instruments for their implementation [3–7]. On the other hand, some new tasks may be solved by upgrade of the existing equipment, where newly developed measurement modes may be implemented. To develop these modes and to upgrade the design of existing instruments, it is necessary to do additional research for collecting new data [4–9].

One of the sections of technical physics, where such challenges arise, is nuclear magnetic resonance (NMR). NMR in flowing fluid is of special importance therein, where flow meters-relaxometers, magnetometers, variometers are used for various studies [5–7,10–12]. Use of these instruments makes it possible to resolve various challenges, when it is extremely complicated to use other instruments for the necessary measurements. Besides, in some cases, measurements using other instruments prevent from collecting complete information about the flow parameters to make an adequate decision on the study results. Such situations include studies in fluid media flows, when it is necessary to both monitor the flow rate of the fluid q and its state (for example, in cooling systems of accelerators, tokamaks, nuclear power plants etc.) with quick variation of flow speed.

In experimental units and industrial NMR-instruments (flow meters-relaxometers and flow spectrometers), to register an NMR signal, a pulse method CPMG is used (Carr−Purrcell−Melboom−Gill impulse) or a sequence of spin echo pulses. Spin echo for NMR signal recording is mainly used only in small diameters of the pipeline. However, use of the specified methods under the conditions of quick variation of flow speed during measurements faces a series of challenges that may not be overcome at this time, which arise both in measurement of time of longitudinal T_1 and transverse T_2 relaxations, and in detuning of the NMR signal recording frequency to resonant frequencies of other nuclei. The primary NMR signal recording is carried out at the resonance frequency of protons. The classic spectrum, which is recorded in NMR-spectrometer with a fixed specimen, is absent in the flow NMR-spectrometer.

Besides, to ensure the measurements of value q, which varies in the range of more than two orders, in case of fast variation of flow speed the large dimensions of magnetic systems are required. The length of the entire instrument structure may reach up to 8−10 m, and weight — up to 4000 kg and more. This creates great problems with installation, repair etc. Practical examples of such challenges are considered in [4,5,13–16].

Analysis of operation of industrial NMR-flow meters-relaxometers (for example, M-PHASE 5000 model) demonstrated that they include a function for retuning the pulse sequence parameters. Parameters for the pulse sequence vary until the connection of the instrument by the operator in case of fluid medium variation as it flows along the pipeline. Mainly it is true for fuel at petroleum refineries (PRs). In other cases the pulse sequence is selected with account of the potential changes of values T_1 and T_2 in the studied medium, which does not vary in process of operation of the instrument.

Under significant variations of T flowing fluid temperature, values T_1 and T_2 vary. This causes termination of the measurement process (there is no automatic switching with valid selection of sequence parameters) — the medium did not change in process of instrument operation. Therefore, mostly the models of industrial NMR-instruments are designed for measurements of parameters of certain flowing fluid class, which substantially limits the experiment capabilities with their use.

A significant problem arises in the experiments, when the flowing fluid flow rate changes fast greatly, which causes reaching beyond the measurement range q (measurements will stop, and it will be necessary to restart the instrument). Experiments will have to be restarted.

Use of the modulation method to register the NMR signal in the flow meters-relaxometers and mode of „magnetic" labeling for the measurement q [13,16,17] makes it possible to solve the noted problems. The magnetic mark was implemented using modulation of constant magnetic field in the sector of nutation coil placement [13,16,17]. Long-term operation of NMR flow meters-relaxometers with the magnetic labeling method made it possible to identify some problems that influence the validity of experimental studies results.

As a result of the study it was found that substantial change of temperature T impacts the formation of magnetic labeling structure. It should be noted that for various flowing fluids and their mixes the dependences of T_1 and T_2 change on T differ. All of it together with the change of q flow rate when the flowing fluid changes, or impurities get into its composition, causes increased measurement error q, T_1 and T_2 up to 3.0% and higher, which is unacceptable for scientific research and industrial measurements.

For the cases of experimental studies with the flowing fluid at values q, which are close to the upper limit of the measured flow rate (this mode is often used in tokamaks and cooling systems of experimental reactors), the failure in the formation of magnetic labeling with fast variation of q (upwards) causes termination of measurements q. Experimental studies after instrument restart will have to be restarted. This causes loss of time and expenditure of resources. Besides, if the studies are long-time, it is possible that such a situation recurs.

The laws established by us as a result of the studies substantially limit the functional capabilities of using NMR flow meter-relaxometer with the modulation magnetic labeling for experimental studies and other technical applications. Therefore, the objective of this paper is development of a new method to form the nutation line structure with magnetization inversion at the noise level, using which does not presume the noted limitations and makes it possible to obtain the valid results in the large range of measurement q and composition of the fluid flow at quick changes of its speed.

1. Features of nutation line formation at noise level and experimental unit to research the processes of its structure management

Our previous studies [12,13,16–18] demonstrated that as magnetic field homogeneity ΔB_0 increased in the sector of nutation coil location, the width of the nutation line Δf_n increases. Besides, increase of value ΔB_0 causes decrease of amplitude of the recorded NMR signal with magnetization inversion, which is used for measurements q in NMR flow meters-relaxometers [6,7,10,13,16]. The data obtained on the previously designed experimental unit [17,18] made it possible to find that changes T of fluid flow impact the amplitude of the recorded NMR signal with magnetization inversion for the reason of change of T_1 from T. In this case the fluid magnetization processes in the magnet-polarizer and its demagnetization processes at the expense of relaxation processes in the scattered magnetic fields change, when the fluid flows from the magnet-polarizer to the NMR signal recording coil. Fig. 1 presents the results of the studies of nutation line structure changes from T for running water. Analysis of the obtained data (Fig. 1) demonstrates that the nutation line structure will not change, contrary to the mode of „magnetic" labeling, which is formed using modulation of constant magnetic field in the sector of nutation line placement [13,16].

Fig. 2 presents the results of the nutation line structure change study depending on the change of value ΔB_0 in the sector of nutation coil placement. Analysis of these dependences shows substantial impact of magnetic field ΔB_0 heterogeneity on value Δf_n (nutation line width). It is also necessary to note that change of ΔB_0 changes the time t_n, when the field B_1 interaction occurs with the magnetized fluid in the vicinity of resonance frequency $f_0 = \gamma B_0$ (in this case protons, since they have higher sensitivity to NMR method compared to other nuclei) in the nutation coil. This creates difficulties with generation of an NMR signal with magnetization inversion and maximum signal-to-noise ratio, the amplitude of which is maximum 72–75% of the NMR signal amplitude registered with the nutation coil off. Measurement error in experiments increases, the validity of the obtained results decreases.

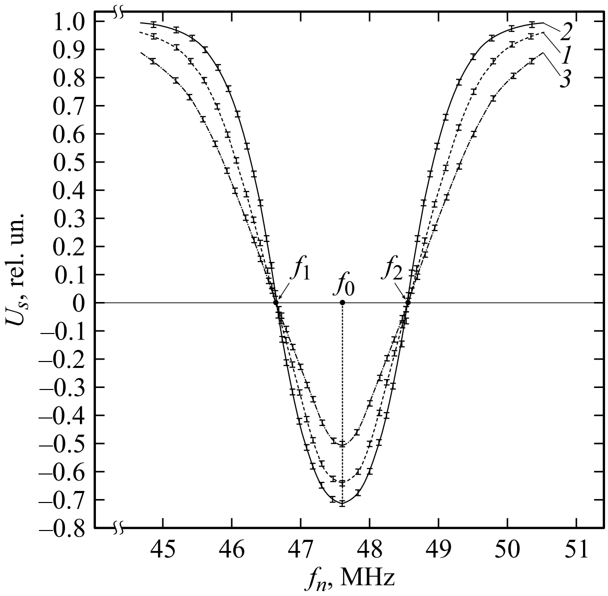

Figure 1. Dependence of change in amplitude of NMR signal U_s on f_n (nutation line) for running water flow at different temperatures T. Water flow rate $q_{\text{opt}} = 2.59$ ml/s. Field induction $B_1 = 32.16\,\mu$T. Curves *1–3* comply with temperatures 288.2, 293.1, 308.6 K.

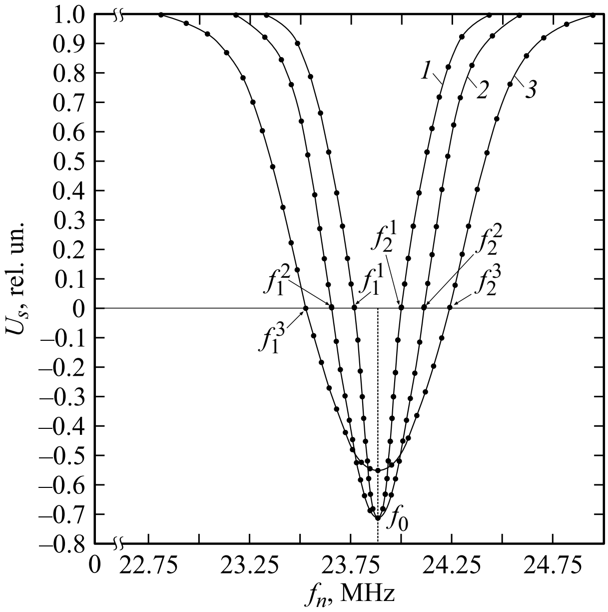

Figure 2. Dependence of NMR signal amplitude variation U_s for magnetized fluid flow (running water) on variation f_n (nutation line) at induction $B_0 = 0.56071$ T, $q_{\text{opt}} = 2.59$ ml/s. Curves *1–3* comply with heterogeneity ΔB_0 in mT·cm^{-1} and induction B_1 in μT: 5.58, 2.69; 11.45, 2.69 and 17.01, 4.06.

Based on conducted research [12,13,16–18] and analysis of developments by other scientistis [2–7,10,11,19,20], we propose a new method to control the nutation line structure using impact of the strong heterogeneous magnetic field at magnetization vector in nutation coil with account of the established features for mutation line formation in strong heterogeneous fields. Controlling the direction of the magnetization vector in the nutation coil at the expense of change of ΔB_0, you may obtain a flow rate measurement mode resistant to quick change of flow rate q, which is similar to mode using magnetic labeling, where amplitude of NMR signal is generated at the noise level.

Fig. 3 presents a laboratory bench designed by us with NMR function of a flow meter-relaxometer and the possibility too control heterogeneity of the field within the wide limits in the sector of nutation coil placement. This design of the bench provides for the possibility to study the features of nutation line structure formation with magnetization inversion at the level of noise and implementation of the new measurement mode q of the fluid flow on the basis of this phenomenon.

Processes of magnetization creation in the flowing fluid are discussed in detail in many papers [4–7,10–17,19,20]. It should be noted that structures of systems (*2* and *3*, Fig. 3) to form magnetized flowing fluid differ from each other by induction of magnetic field, dimensions and configuration *2*, and the range of times for the fluid flow presence in the field B_p, which provides for signal-to-noise ratio (S/N)> 2.5 in the scheme of NMR signal recording [13,16,19,20]. In the developed experimental plant for performance of the studies, field with $B_p = 1.272$ T at $d_p = 22$ mm with field homogeneity 0.0104 cm^{-1} was used. Inner diameter of the pipeline d_t, where the nutation coil is located *9*, was 3.0 mm. Therein the fluid from *2* arrives to the nutation coil *9*.

The principle new element in the developed design of the laboratory bench, by contrast with previously used ones in the experimental plants, is a special electromagnet, (Fig. 3), where value B_0 varies from 0 to 1.427 T, homogeneity — from 0.0001 to 0.1 cm^{-1}. The field homogeneity is controlled using secondary coils *7* and regulating screws *5* (Fig. 3). The magnetic field is created between the pole tips with a diameter of 150 mm, the distance d_e between them can be adjusted from 2 to 58 mm. Wide functional opportunities created by us make it possible to control the field heterogeneity with various speed, including using pulse voltage, which is supplied to coils *7*. The magnetization vector M_p in the nutation coil *9* is rotated under field B_1 action on the flowing magnetized fluid. Under field B_1 action in *9* the magnetization vector M_p turns by angle ϕ_{n}. Value ϕ_{n} depends on the magnetic field parameters in sector with located coil *9*. A feature of nutation line structure control is that the adiabatic theorem condition is in effect between coils *9* and *14* for fluid flow with magnetization (orientation of vector M_p does not change). This makes it possible to maintain the structure of the nutation line with amplitude at noise level to the moment of NMR signal recording in *14*, where fluid flow is supplied along *13* from *9* (Fig. 3).

The laboratory bench uses electromagnet as analyzer magnet *16*, because detuning to various resonant frequencies is necessary (by change in field induction B_a) for NMR signals recording, where the external interference

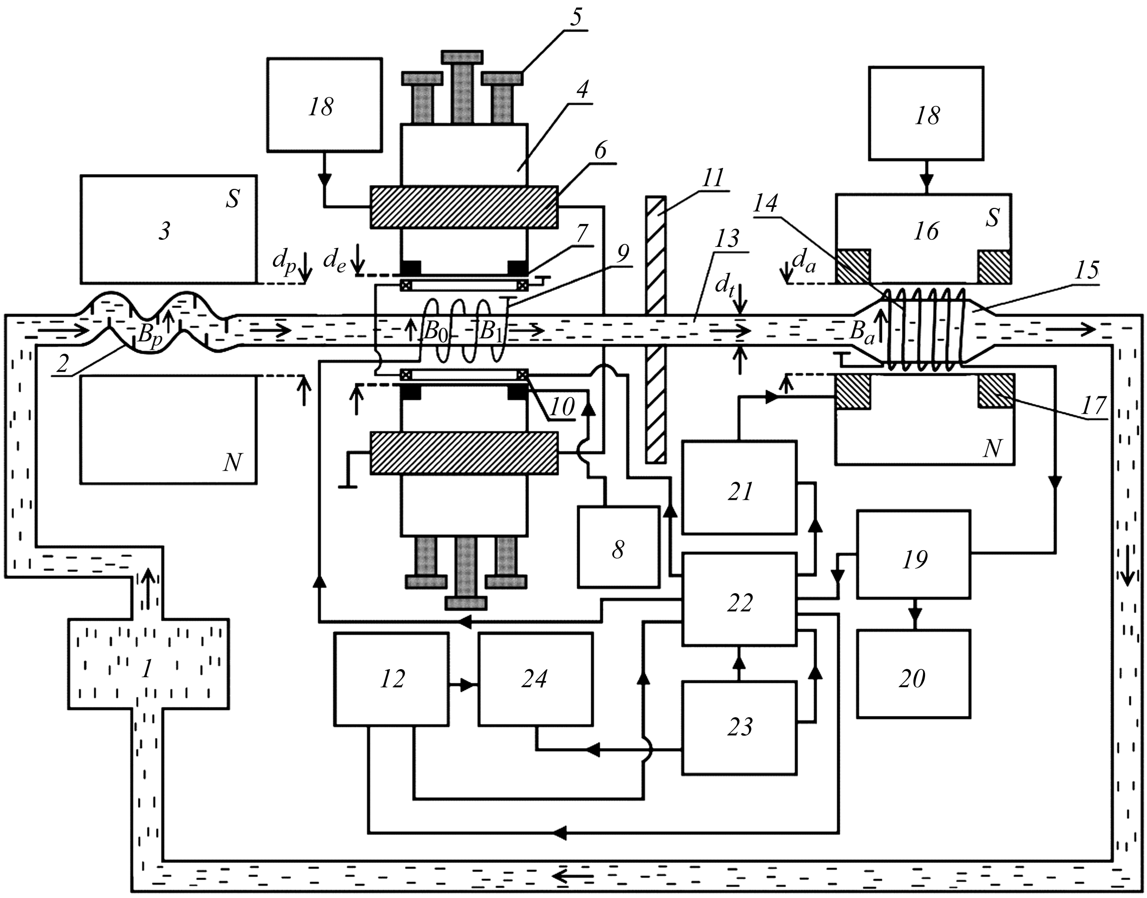

Figure 3. Experimental bench for research of fluid media flows in various conditions with function of nuclear-magnetic flow meter-relaxometer: *1* — circulator, *2* — vessel of special shape from non-magnetic material, *3* — magnet-polarizer, *4* — pole tips of electromagnet, *5* — regulating screws of electromagnet poles position, *6* — magnetic field poles for pole tips, *7* — correction coils, *8* — special power supply unit of correction coils, *9* — nutation coil, *10* — field modulation coil B_0, *11* — magnetic screen, *12* — nutation generator, *13* — connecting section of the pipeline, *14* — NMR signal recording coil, 15 — analyzer vessel, *16* — electromagnet with field value control B_a, *17* — field modulation coils B_a, *18* — multifunctional power supply unit of electromagnets *6* and *16*, *19* — NMR signal recording device, *20* — oscilloscope, *21* — radio frequency generator, *22* — control and processing device, *23* — radio frequency generator, *24* — two-channel frequency meter.

level is minimum. Under the laboratory conditions the minimum noise level complied with the resonant frequency of induction field $B_a = 0.354\,\mathrm{T}$, which was set between poles of the magnet *16* (Fig. 3) in the sector of recording coil location *14*. Field homogeneity in the *14* placement area at $d_a = 1.8\,\mathrm{cm}$ was $0.0001\,\mathrm{cm}^{-1}$. For NMR signal recording the laboratory bench uses a generator of low oscillations (autodyne) [5–7,12,13,17–20], to which the recording coil was connected *14*. By design the generator of low oscillations is part of recording circuit *19* (Fig. 3).

To make it possible to compare our experimental data and results of studies by other scientists, all studies in the laboratory bench were carried out using a running water flow at temperature T, which varied in the range from 288 to 308 K (basic fluid temperature in the studies $T = 293.1\,\mathrm{K}$). At $T = 293.1\,\mathrm{K}$ the times of running water relaxation have the following values: $T_1 = 1.27\,\mathrm{s}$, $T_2 = 0.89\,\mathrm{ms}$. The NMR signal was recorded from protons.

2. Results of experimental studies of nutation line structure formation and discussion

In the laboratory bench that we designed with the implementation of the function of the nuclear-magnetic flow meter-relaxometer the structure of the nutation line, which is formed in the nutation coil *9* (Fig. 3) between poles *4* in the electromagnet, was controlled using regulating screws *5* and correction coils *7* by changing the field heterogeneity ΔB_0. The heterogeneity value ΔB_0 is controlled by width of the nutation line $\Delta f_n = f_2 - f_1$, where f_2 and f_1 — frequencies, at which the amplitude of the recorded NMR signal after exposure to field B_1 is zero (Fig. 1).

Fig. 4 shows the results of the study on impact of heterogeneity of magnetic field ΔB_0 on the change of the nutation line structure. It should be noted that

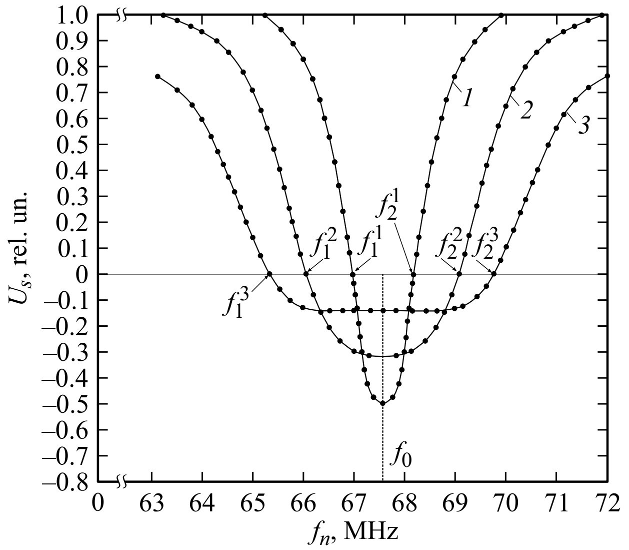

Figure 4. Structure of the nutation line of running water flow with magnetization at $q_{\text{opt}} = 2.59$ ml/s in the field $B_0 = 1.5871$ T (central area between pole tips of the magnetic system). Curves *1–3* comply with the irregularities of the magnetic field ΔB_0 in the area of nutation coil placement in mT·cm^{-1} and values B_1 in μT: 29.36, 2.69; 70.93, 3.42 and 98.88, 5.45.

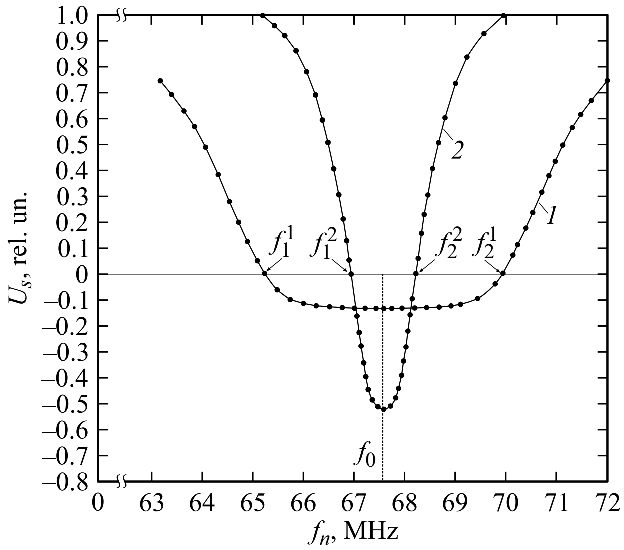

Figure 5. Structure of the nutation line of running water flow with magnetization at $q_{\text{opt}} = 2.59$ ml/s in the field $B_0 = 1.5871$ T (central area between pole tips of the magnetic system). Curves *1* and *2* comply with the irregularities of the magnetic field ΔB_0 in the area of nutation coil placement in mT·cm^{-1} and values B_1 in μT: 27.62, 2.69 and 114.43, 5.67

amplitude of the recorded NMR signal with the inversion of magnetization varies with the change of ΔB_0.

For one of the versions of the formed nutation line (Fig. 4, curve *1*) the heterogeneity of the magnetic field was measured in the sector of the nutation coil location in the electromagnet that made 29.01 ± 0.29 mT·cm^{-1}. This results matches (within the measurement error limits) the value of heterogeneity of 29.09 ± 0.29 mT·cm^{-1}, obtained using a magnetic induction meter „Sh1−1“, and also value 28.96 ± 0.29 mT·cm^{-1}, measured using a multifunctional tesla meter Measure ac & dc magnetic field DX−160 (by Xiamen Dexing Magnet Tech. Co., Ltd, China).

The feature of the nutation line structure control in our experimental bench is use of two modes for control of the heterogeneity value ΔB_0. Implementation of this feature made it possible to obtain two options of the nutation line for two modes of magnetic field heterogeneity formation in the area of the nutation coil placement (Fig. 5), which are of further interest for measurement q. Curve *1* (Fig. 5) complies with the mode of formation of ΔB_0 using regulating screws *5* and specially made correction coils *7* (heterogeneity of the magnetic field in the area of the nutation coil placement is set at maximum). Curve *2* (Fig. 5) complies with the conversion of the nutation line structure when the correction coils are switched off *7*.

Analysis of the collected data demonstrated that at these values of magnetic field heterogeneity ΔB_0 from 10^{-4} to 0.1271 T/cm in our design of the experimental bench with inner diameter of the pipeline of 2 mm, outer diameter of the pipeline of 4 mm, diameter of the nutation coil frame 8 mm, nutation coil length 10 mm, distance between the poles of 14 mm and more, it will not be possible to form the nutation line structure with the magnetization inversion. It is necessary to note that increased distance between the poles causes increased heterogeneity of magnetic field ΔB_0 in relative units, by absolute value ΔB_0 may decrease, since as d_e increases, B_0 decreases. Therefore, control of the nutation line structure by changing value ΔB_0 at the expense of changing d_e is an irrational method that may create uncertainty in measurements. It is very difficult to implement such a method in automatic mode in instrumental version.

On the other hand it is found that the reduction of NMR signal amplitude with inversion of magnetization and increase of ΔB_0 is a pronounced function tending towards zero. At the same time it is necessary to adjust value B_1, since change of ΔB_0 reduces the area of field B_1 interaction with magnetized fluid at resonant frequency of field B_0. Besides, as fluid low rate increases, time t_n decreases, when the magnetized fluid in the nutation coil is exposed to field B_1:

$$t_n = V_n/q, \tag{1}$$

where V_n — volume of the nutation coil that depends on the diameter of pipeline d_t.

Change of t_n causes violation of the condition of π-pulse, which provides for inversion of magnetization [3,4,6,7,12–14,16–20]. This circumstance should also be taken into account to develop a magnetic system to control the nutation line shape.

As a result of the experimental studies it was found that our laboratory bench, which is essentially an NMR flow meter-relaxometer (it includes q, T_1 and T_2 measurement functions), may implement a new mode for measurement of the flow rate q using the magnetic labeling principle, which was previously implemented in modulation of field B_0 [13,16]. Measurements in this mode are implemented in digital code 0 and 1. A meander is formed, which excludes the impact of many factors at the result of the pulse duration measurements and, accordingly, at the error of definition of q.

In our design of the laboratory bench with function of NMR flow meter-relaxometer (Fig. 3) the measurement mode q in the digital code 0 and 1 may be formed as follows. The difference between amplitudes of NMR signals with inversion of magnetization (Fig. 5, curve *1* with a wide site at level (-0.13 in relative units) and curve *2* — close to the classic non-widened nutation line) is more than 3.5 times.

The feature of nutation line structure control in the designed laboratory bench is the fact that whenever ΔB_0 changes with the help of *4* pole position adjustment using regulating screws *5* the difference between the amplitudes of NMR signals on curves *1* and *2* (Fig. 5) is 3.5 times and will remain nearly uncharged at change of ΔB_0 in the interval from 0.056 to 0.127 T/cm. This will make it possible to further form a structure of the nutation with inversion of magnetization at the noise level for realization of the stable measurement mode q in respect to the fast variations of flow speed, as it is implemented in the magnetic labeling mode using modulation of magnetic field B_0 [16–18]. The NMR signal (curve *1*, Fig. 5) after achievement of the noise level after the inverted operational amplifier with gain ratio $4-5$ will be close to zero. This signal will comply with logical zero for a digital code. Maximum amplitude $U_{\max}$ of NMR signal (curve *2*) after amplification will be equal to 1.0, which corresponds to the logical one. As a result, a signal is generated to measure the time for fluid medium flow in the form of a meander, which makes it possible to compensate many negative factors, as in [13,16], which impact the measurement of the pulse duration and accordingly the measurement error q. To form such a mode, it is necessary to determine the ratios between ΔB_0, B_1 and t_n with account of the fluid flow q, nutation coil dimensions and dependence of ΔB_0 on d_e.

Another feature in the research of the nutation line structure that will provide for the possibility to adequately use these dependences for the line structure management is ensuring the compliance with the condition of the adiabatic theorem in the connecting pipeline *13* (Fig. 3) for the flow of the magnetized fluid.

It should also be noted that in the flowing medium that is used in technological processes, temperature T may vary, especially in the cooling systems of nuclear reactors, spectrometers, powerful electromagnets, tokamaks and accelerators [16–19]. Temperature variation causes change of values T_1 and T_2, which impact the mode of magnetic labeling formation, since they are included in the Bloch equations [21,22]. Our previous studies for the magnetic labeling formation mode using modulation of magnetic field B_0 confirm this [16–19]. All of it demonstrates that it is very complicated and expensive to experimentally determine the noted ratios, therefore it is more feasible to solve this task using mathematical modeling.

3. New method to calculate nutation line formation at noise level under conditions of strongly heterogeneous field

Motion of magnetization components in the flowing fluid M_x, M_y and M_z in the nutation coil is described by Bloch equations [21,22]. In the previous studies [15–20] of fluid media flows it was found that amplitude and phase of the recorded NMR signal using a modulation method was determined by value and phase of component M_z in the coil *9* (Fig. 3). Components M_x and M_y decay to NMR signal recording coil *14* in scattered magnetic fields between coils *9* and *14* (Fig. 3). To solve the task of determining the amplitude and phase of component M_z at the outlet of the nutation coil *9* we introduce a new coefficient $S(\Delta B_0)$ in Bloch equations, which takes into account the change ΔB_0 in the sector of nutation coil location, and also time t_n, for which the segment of magnetized flowing fluid is exposed to field B_1 in the coil *9*. With the new coefficient the Bloch equations transformed into a rotary system of coordinates using Vagness method [23,24] take on the following form:

$$dM"_x/dt + M"_x/T_2 = [\Delta f_n + S(\Delta B_0)]M"_y,$$

$$dM"_y/dt + M"_y/T_2 = [\Delta f_n + S(\Delta B_0)]M'_x - \gamma \cdot H_1 M'_z,$$

$$dM'_z/dt + M'_z/T_1 = \gamma \cdot H_1 M'_y + M_0/T_1. \tag{2}$$

With account of the features of magnetic field control in the electromagnet *4* (Fig. 3) we use in the nutation coil location sector *9*, several options of the function were developed, which describes change ΔB_0 as the magnetized fluid flows in the nutation coil *9*:

$$1. \quad S(\Delta B_0) = \left(\frac{\Delta B_0}{t_n}\right) \cdot \gamma \cdot t,$$

$$2. \quad S(\Delta B_0) = \left(\frac{\Delta B_0}{t_n^2}\right) \cdot \gamma \cdot t^2 + \left(\frac{\Delta B_0}{t_n}\right) \cdot \gamma \cdot t,$$

$$3. \quad S(\Delta B_0) = \left(\frac{\Delta B_0}{t_n}\right)^2 \cdot \gamma^2 \cdot t^2 + \left(\frac{\Delta B_0}{t_n}\right) \cdot \gamma \cdot t,$$

$$4. \quad S(\Delta B_0) = \left(\frac{\Delta B_0}{t_n^2}\right) \cdot \gamma \cdot t^2,$$

$$5. \quad S(\Delta B_0) = \left(\frac{\Delta B_0}{t_n^3}\right) \cdot \gamma \cdot t^3 + \left(\frac{\Delta B_0}{t_n^2}\right) \cdot \gamma \cdot t^2 + \left(\frac{\Delta B_0}{t_n}\right) \cdot \gamma \cdot t.$$

As an example, Fig. 6 shows the results of the nutation line structure calculation from detuning of frequency Δf_n of field B_1 from resonance for $S(\Delta B_0)$, which corresponds to version 1.

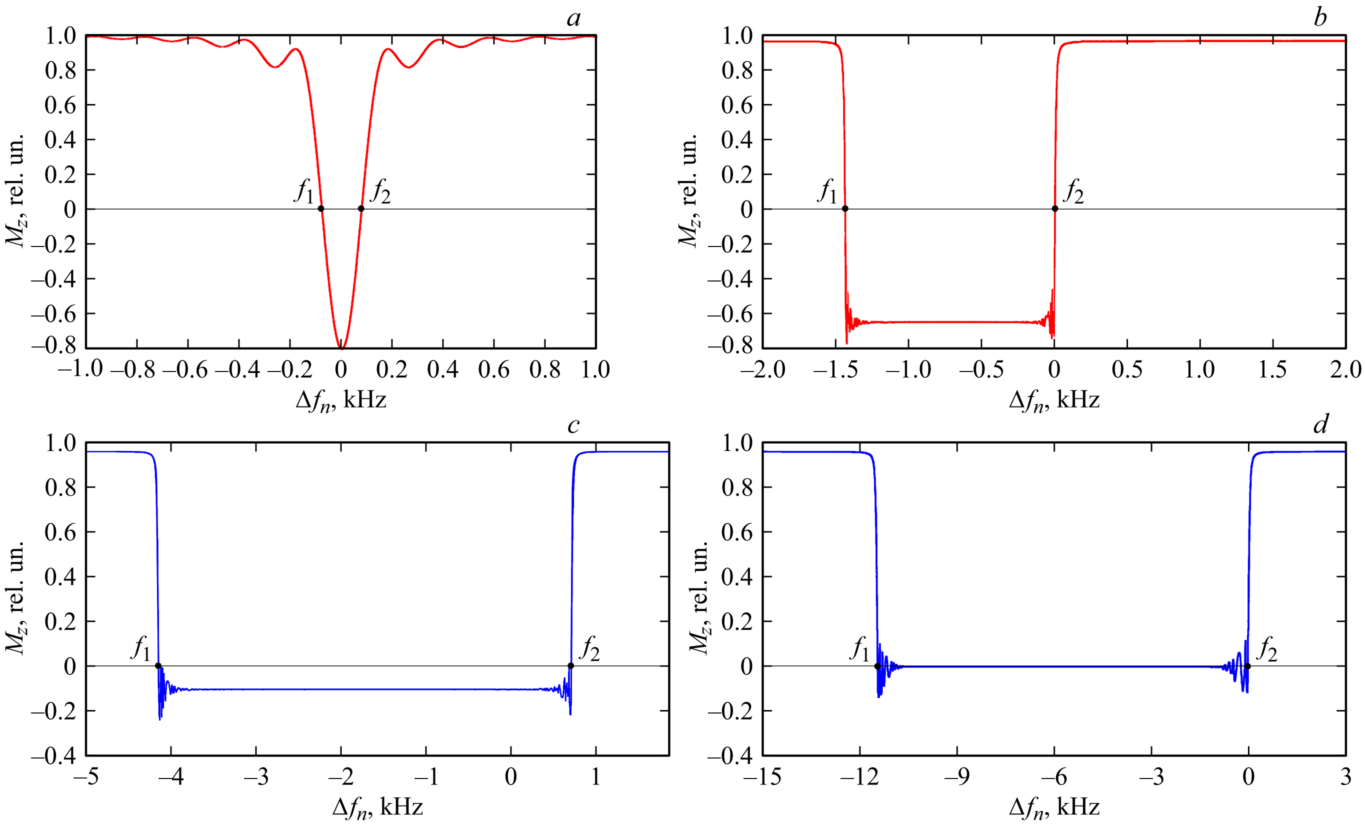

Figure 6. The nutation line structure on the basis of the calculation results for the magnetization component M_z for a running water flow at $t_n = 62$ ms, $T_1 = 1.27$ s, $T_2 = 0.89$ ms, curves *a*–*d* comply with irregularities of the magnetic field ΔB_0 in the area of nutation coil placement in mT·cm^{-1} and values B_1 in μT: 0.0047, 2.69; 34.9252, 3.11; 102.0519, 5.45 and 274.3253, 12.97.

Analysis of the produced results shows that to form the nutation line structure that reproduces the magnetic labeling mode at the noise level, it is necessary to provide value $\Delta B_0 = 0.27432$ T/cm and higher in the nutation coil placement sector *9*. This value ΔB_0 is defined via $\Delta f_n = 11.679781$ MHz, which is set by dependence in Fig. 6, *d*. This minimum value ΔB_0, which must be provided in the coil location sector *9* (Fig. 3) to obtain the nutation line structure at noise level. In the real structure of NMR flow meter-relaxometer it would be necessary to introduce 15% margin for additional change of value ΔB_0 from the determined minimum value ΔB_0 to obtain the nutation line with inversion of magnetization at noise level. This is necessary to compensate various temperature factors that may result in change of value B_0 with subsequent change of ΔB_0. This change will have to be compensated. The noted fact is another feature of formation of the nutation line structure with inversion of magnetization at noise level in strong heterogeneous fields.

Conclusion

The results that we obtained confirm the possibility, with the account of the found features, to form using the new method the nutation line structure in the flow of the fluid with inversion of magnetization at noise level, as in the previously developed magnetic labeling mode. This structure is resistant to the change of the temperature mode (within wide limits) of both the flowing fluid and the environment, which excludes the errors in research or industrial measurements in fluid media flows. In the previously developed structures of NMR flow meters-relaxometers using the mode of magnetic labeling formed using modulation of field B_0 [13,16], it was not possible to provide for such stable mode of operation in research.

It is also necessary to note that the established zone Δf_{nn} of NMR signal formation with inversion of magnetization at noise level (Fig. 5, *d*) using the control of the magnetic field heterogeneity in the sector of nutation coil placement makes by frequency around 11 MHz (with account of the noted 15% margin for change of temperature T of the flowing fluid). Analysis of data obtained by us for previously developed structures of NMR flow-meters-relaxometers used for measurement of q of the mode of magnetic labeling formed using modulation of field B_0 [13,16], demonstrated that value $\Delta f_{nn} \approx 60$ kHz is sufficient to provide for stable measurements q at sharp change of flow speed (three times). This makes it possible to conclude that the new method for formation of the nutation line structure provides for stable operation of the instrument during the studies in case of rapid change of the fluid flow speed by an order or more, which in some cases happens in an experimental reactor or in cooling systems of tokamaks and particle accelerators. This is sufficient to conduct the study for a long time.

Conflict of interest

The authors declare that they have no conflict of interest.

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