11

Research of nutation kinetic in a strong inhomogeneous field

© V.V. Davydov,[1] A.A. Goldberg,[1] R.V. Davydov,[1,2,3] V.I. Dudkin[3]

[1]Peter the Great Saint-Petersburg Polytechnic University,
195251 St. Petersburg, Russia
[2]Alferov University,
194021 St. Petersburg, Russia
[3]Bonch-Bruevich St. Petersburg State University of Telecommunications,
193232 St. Petersburg, Russia
e-mail: davydov_vadim66@mail.ru

Received October 28, 2023
Revised December 25, 2023
Accepted February 12, 2024

The necessity of describing the mechanism for the formation of a nutation line in a flowing liquid is substantiated. The shortcomings that are inherent in the equations used to describe the motion of the longitudinal and transverse components of the magnetization vector in a nutation coil with a flowing liquid are noted. New equations of motion of the longitudinal and transverse components of the magnetization vector in a nutation coil with a flowing liquid are developed, in which the inhomogeneity of the magnetic ΔB_0 in the zone of action of the radio-frequency field H1 on the flowing liquid is taken into account. The developed equations take into account the nature of the change in the value of the inhomogeneity of the magnetic field ΔB_0 when the magnetized liquid moves along the length of the nutation coil. Nutation lines were calculated for various parameters of the magnetic field and flowing fluid. The results of experimental studies of the shape of the nutation line are presented. Theoretical calculations are compared with experimental data.

Keywords: nuclear magnetic resonance, magnetic field, flowing liquid, nutation line, magnetization inversion, relaxation, inhomogeneity, resonant frequency, linewidth, signal-to-noise ratio.

DOI: 10.61011/JTF.2024.04.57540.273-23

Introduction

Currently in many cases during studies and measurements we prefer noncontact instruments measuring systems [1–6]. There are many operated such devices and instruments operating based on different physical principles. Specific place is occupied by NMR (nuclear magnetic resonance), especially for studies with fluid flows [1,7,8]. This is because NMR-meters (nuclear magnetic flowmeters-relaxometers, and spectrometers, magnetometers and variometers of flowing fluid) have wide functional abilities [1,4,9–12]. Note that some objectives of monitoring all flow parameters, for example, when working with aggressive mediums and their mixtures (concentrated sulfuric or nitric acid, benzene and others) without NMR-meters use are difficult for solution [9–13]. The same relates to the cases when during work we need to follow the sterility conditions (biological solutions and suspensions) [9–12]. Besides the nuclear magnetic flowmeter-relaxometer is one of the main meters in the monitoring systems operating in complex conditions, for example, as part of nuclear power unit — in cooling system of the nuclear power plant or on mobile object [13–15].

If for fluid medium flow q measurement in NMR flowmeter-relaxometer a nutation coil is used, then by updating of the instrument electronic part we can ensure with its use the parameters monitoring of the magnetic field (induction and homogeneity) [16–18]. In this case in the industrial enterprise or scientific laboratory we can easily implement transformation in NMR-meters of one instrument into another one (e.g., flowmeter-relaxometer into magnetometer (teslameter)). The advantages of NMR-magnetometers use as compared to other types of magnetometers are discussed in detail in [16,19,20]. The main advantage is absence of the necessity to calibrate the instrument during its operation. All measurements of physical values are made in real time. Opposite to other types of magnetometers this instrument is also simple in operation [16–18]. So, based on the nutation NMR-magnetometer a primary [19] and secondary [20] induction meter was developed and is successfully operated. Specific feature of this magnetometer design is complete decoupling between its functional elements [16]. This unique property ensures development and put into operation of the specific state reference (units of magnetic field induction) [17].

The main characteristic in the previously discussed NMR instruments with flowing fluid for measurements is the nutation line. There are some definitions of the nutation line, but mainly dependence U_s on f_n is used, where f_n — field frequency B_1, U_s — amplitude of NMR-signal [1,16,19,20–22]. Note that definition corresponds to the case when the nutation coil is positioned in the pipeline section between the magnetic systems of polarizer magnet and analyzer magnet [15–23].

Upon scientific and technical progress worldwide there are more and more various objectives on monitoring structure and characteristics of the magnetic fields both permanent, and variable, in which induction exceeds 1 T with homogeneity over $0.1\,cm^1$ in different conditions (strong electromagnetic interference, increased radiation exposure, etc.), where the use of optical sensors [24–26] and other types of magnetometers [27] is difficult — e.g., in the area of particle accelerator or high-resolution spectrometer, near voltage converters of a power plant at offshore facilities with a nuclear reactor, etc. In such conditions the field parameters measurements with error about 2% are sufficient to monitor the field.

The nuclear magnetic magnetometers with the nutation line to measure the magnetic fields [14–23,28,29] ensure successful solution of these complex problems. This is possible as the nutation coil, considering instrument design features, can be positioned at the required distance (e.g., 80, 100 m and more) from units for magnetization formation and signal recording of NMR-nutation magnetometer [22,23,28–30]. Fluid flow with magnetization inversion ensures decoupling between the zone of parameters measurement of magnetic field and NMR-signal registration systems. Pay special attention to the fact that decoupling is complete (NMR-signal from fluid flow is registered without any contact).

In fluid flow changes in the magnetization direction (its turn by some angle) in the nutation coil are determined by the magnetic field parameters in zone of its positioning. All information about these changes enters the NMR signal recording system with the flowing liquid [14–23,28–30]. This permits the NMR signal recording device positioning in zone where the influence of electromagnetic interference is minimal, and there is no radiation exposure.

To ensure error of parameters measurement of magnetic field below 2% in case of the updating the operated nutation NMR-magnetometers the specific attention is paid to the selection of optimal parameters of the nutation coil (both its geometric dimensions, and wire characteristics). This, in turn, ensures stable operation of electronic circuits, which control current during field formation B_1 to create magnetization inversion in the flowing fluid. The studies performed by us using the discussed NMR-meters (flowmeters and magnetometers) of various purpose showed that the geometric dimensions and shape of the nutation coil affect the error in measuring induction and field inhomogeneity [1,4,13,15–17,21–23,28–30]. In strong inhomogeneous fields the dependence of these parameters measurement error only increases, so, additional studies are necessary to determine directions for this problem solution.

Note that mathematical relations based on Bloch equations [31–34], and obtained for calculations in homogeneous fields, can not be used in these cases. Experimental data obtained by us confirmed this. This significantly limits the possibilities of systems design to measure field parameters in nutation NMR-magnetometers.

Solution of these complex problems is the objective of present paper, its implementation requires new experimental theoretical studies. These studies are necessary to understand how effect of change in field heterogeneity in sector of nutation coil positioning can be considered properly by formation of new coefficients in Bloch equations. During operation in strong inhomogeneous magnetic field it is very important o determine B_1 optimal values for various values of induction and inhomogeneity of the magnetic field in sectors where the nutation coil will be positioned, depending on fluid flow q, fluid relaxation time, and geometric dimensions of the nutation coil.

1. Experimental set-up and results of study of magnetization vector in strong magnetic fields with various inhomogeneity

In present paper we set a new complex problem which solution required development and manufacturing of the special experimental set-up (Fig. 1) combining functions of NMR-magnetometer and flowmeter-relaxometer. Processes of magnetization creation in the flowing fluid from the circulating pump *1* are discussed in detail in many papers [21–23,27–30,33,34]. Note that in the experimental set-up using field with $B_p = 1.023\,T$ at inner diameter of pipeline $d_p = 15\,mm$, the field heterogeneity is $0.0044\,cm^{-1}$. In our case the inner diameter of pipeline in which the nutation coil is positioned *9*, d_p, is 2.5 mm. The fluid via this pipeline from *3* enters the nutation coil *9*.

The principle new component of the developed design of the experimental set-up by contrast with previously used ones is a special electromagnet, in which B_0 varies from 0 to 1.246 T, field heterogeneity — from 0.0001 to $0.1\,cm^{-1}$. The field heterogeneity is controlled using secondary coils *6* and regulating screws *7* (Fig. 1). The magnetic field is created between the pole tips with a diameter of 150 mm, the distance between them can be adjusted from 2 to 36 mm. These electromagnet functionalities make it possible to create the conditions in which the nutation coil is located during actual measurements with nutation NMR-magnetometer.

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 coil *9* the magnetization vector M_p turns by angle φ_n. φ_n value depends on the magnetic field parameters in sector with located coil *9*. Feature of developed experimental set-up is as follows. Between coils *9* and *14* for the fluid flow with magnetization the adiabatic theorem condition is valid (orientation of vector M_p does not changes). Further the flowing medium enters the recording coil *14*. The experimental set-up uses electromagnet as analyzer magnet *16*, because detuning to resonant frequencies is necessary (by change in field induction B_a) during NMR