Dependence of NMR Spin Echo Form on Liquid Flow Structures

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Abstract. *The influence of the flow structure on a NMR spin echo form is discussed. The form of spin echo signals is considered for flow under acoustic pressure (acoustic flow) without any magnetic field gradient and for laminar and turbulent flow in the presence of a magnetic field gradient. The reason for discussion this theme is caused by the influence of the echo form on measurement errors in flow velocity measurements. Spin echo signals can have in some cases from one to four peaks. It is known that intensive acoustic waves can induce in a liquid high pressure and produce two symmetrical circular streams flowing in opposite directions at frequencies* $\pm\Delta\omega$. *These circular streams cause the kinematic frequency shift from resonance at* ω_0 *and, consequently, produce corresponding time shifts* $\mp\Delta t$ *of the echo peaks from the central position at* $t = 2\tau$. *Unexpected time shift to higher times* $t > 4\tau_1$ *of the position of the second echo peaks is also discussed and explained by presence of spiral trajectories of flowing liquid particles.*

Keywords: NMR, Spin Echo Form, Flowing Liquid, Structure, Acoustic Flow, Frequency Shift

1. Introduction

Various properties of flowing liquids can be studied by using NMR spin echo technique in the presence of a constant or pulse field gradient along the direction of flow [1].
It is known that a flow structure can change with increasing of velocity and Reynolds number. The basic theory [2, 3] gives good description for the form of spin echo signals in the laminar flow region. Some researchers [2, 3, 4] have observed the "anomalous" spin echo signals in turbulent flows, but they did not obtain any good explanation about the form of the signals. The form of an echo signal has great importance in flow velocity measurements because it influences on the measurement errors. Here the short explanation of the results of the papers will be proposed. The reason for discussion this theme is caused by the influence of the echo form on measurement errors in flow velocity measurements.

2. Subject and Methods

Four peaks of spin echo signals in NMR flow measurements

Flow measurements are usually carried out by using spin echo or Carr-Purcell-Meiboom-Gill (CPMG) pulse sequences. Usually first and odd number echo amplitudes are measured in the Carr-Purcell-Meiboom-Gill sequence with rf phase sensitive detection. The stimulated spin echo pulse sequence is also used frequently for flow measurements of high viscous liquids.
Four peaks in the spin echo signal have been observed and the phenomenon explained by Volkov *et al* [3]. For simplicity authors have considered the case when the length L of a transmitter coil of a NMR spectrometer is much greater than the length of a receiver coil l. According to the publication [3], the complex amplitude of a stimulated spin echo signal for flowing at a velocity υ liquid can be described by

$$S(a,t) = A(T_1,T_2,D,t)\ K(g_0,l,t) \int_{-\infty}^{\infty} f(\upsilon)\exp(ia\upsilon)d\upsilon, \quad (1)$$

where $A(T_1, T_2, D, t)$ is a function describing relaxation and diffusion damping of an NMR signal, T_1 and T_2 are relaxation times, D is a diffusion coefficient, g_0 and g_p are the amplitudes of constant and pulse magnetic field gradients.

$$K(g_0, l, t) = \frac{\sin[0.5\gamma g_0 l(t - \tau_1 - \tau_2)]}{0.5\gamma g_0 l(t - \tau_1 - \tau_2)}, \tag{2}$$

$$a = \gamma g_0 \left[\frac{t^2}{2} - t(\tau_1 + \tau_2) + \frac{\tau_1^2 + \tau_2^2}{2} \right] + \gamma g_p \Delta\delta, \tag{3}$$

τ_1 and τ_2 are time intervals between the first and second and the first and third 90° rf pulses, respectively. The formula (2) represents an echo form in the absence of the relaxation and diffusion for an immobile cylinder sample. The amplitude of a spin echo represents itself the oscillating function of time. The form of an echo has usually three peaks for diode detection. The formula (3) describes the total effect of the constant g_0 and g_p gradients on the phase shift of a spin echo signal. Δ and δ are a time interval between the gradient pulses and width of these pulses.

The phase of a spin moving with a velocity V at a moment $2\tau_1$ is $\varphi = \gamma g_0 V \tau_1^2$ for a steady gradient and $\varphi = \gamma g_p V \delta\Delta$ for a pulse gradient. In case of laminar flow of viscous liquid in the round pipe, a profile of velocities can be described by a parabola $V = 2V_0\left(1 - r^2 / R^2\right)$, where V_0 is an average velocity, R is a pipe radius. After integrating accounting the distribution of the velocities in the pipe, the amplitudes of echo signals are described by

$$R_x(t) = \frac{\sin 2\gamma V_0\left(g\tau_1^2 + g_1\delta\Delta\right)}{2\gamma V_0\left(g\tau_1^2 + g_1\delta\Delta\right)}. \tag{4}$$

Therefore, laminar flow results in a $(\sin x)/x$ behavior and the doubled frequency of oscillation of the echoes compared to a cosine behavior and oscillations for plug flow. But the spin echo changes its form near the zeroes of the function (4). The reason is that the signal function (1) is the product of the functions (2) and (4). As a result the spin echo form obtains an additional minimum at its center and has four peaks in this case [3].

Splitted echo signals at the presence of ultrasonic irradiation

The splitted (two-maxima) echo signals have been observed at the presence of ultrasonic irradiation of the water sample containing some amount of paramagnetic salt by Zverev *et al* [4]. The time positions of the peaks were shifted from the usual position at $t = 2\tau_1$ by a small values $\mp \Delta t$. The geometry of the experiment was as follows (Fig.1). The test-tube containing a solution of paramagnetic salt has been irradiated by the strong ultrasonic waves along the long axis of the sample. The tube was placed between the poles of the electromagnet and NMR signals were observed in the homogeneous magnetic field. No gradients of the magnetic field were used. But two symmetrical circle streams flowing in the opposite directions have been seen at the photography made at one side of the tube.

Splitted and shifted to higher times spin echo signals

Koji Fukuda and Akira Hirai [2] have performed pulsed NMR experiments of Carr-Purcell-Meiboom-Gill type on water flowing through a circular pipe. The flow patterns studied were Poiseuille (laminar) flows and turbulent flows. Near the critical Reynolds number the spin echo peaks were noisy and began split into two peaks. They obtained an unexpected time shift to higher times $t > 4\tau_1$ of the position of the second echo peak with the field gradient vector along the pipe, in the case of turbulent flow. As the Reynolds number became larger than its critical number, the shift of the peak became larger.

3. Results

As to the paper of Zverev *et al.* [4], the explanation of the spin echo splitting is in the structure of the water stream in the test tube. It is known that the acoustic pumping causes the water flow. It is the phenomenon of so called “Acoustic Flow” or ‘Acoustic Wind’ [5]. The acoustic flow can be described by the equation

$$\frac{\partial \upsilon}{\partial t} + (\upsilon \nabla)\upsilon - \frac{\eta}{\rho}\Delta\upsilon = -\frac{\nabla P}{\rho} + F\,, \tag{5}$$

where P, ρ are the pressure and density of a fluid, η is the viscosity coefficient, F is the force of the acoustic radiation acting on the unit mass of a fluid and causing the flow at a velocity υ. For the acoustic radiation amplitude A in the direction x, the force equals to

$$\mathrm{F} \approx \alpha A^2 \exp(-2\alpha x), \tag{6}$$

where α is the damping coefficient.

In the experiment discussed, the acoustic radiation is focused in the central region of the test-pipe. The streams of water flow move initially along the long axis of the test pipe then are reflected from the bottom of the test-pipe to return along the inner wall of the test-pipe. The volume picture of the streams looks as a ring tore (Fig.1).

Thus there are two circular flows in the region of the central plane perpendicular to direction of the resonance magnetic field which have resonance frequencies $\omega_0 \pm \omega_r$. These flows give two signals of the spin echo shifted symmetrically relative to the position of the echo maximum for immobile water.

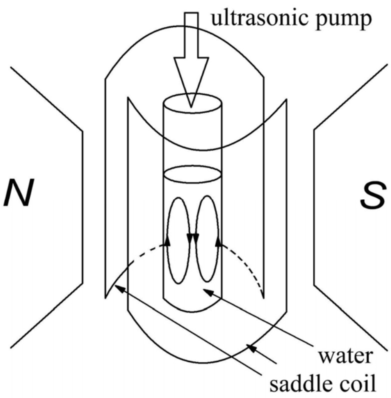

Figure 1. Scheme of the experiment [4].

It is known from the work of Vecheruchin *et al* [6], that circular motion can induce the kinematic shift of the NMR. The spin induction signal for this case can be calculated by

$$U(t) = -kB(x,y)^2 \exp\left(-\frac{t}{T_2}\right)\frac{\partial}{\partial t}\int_V \cos\left\{\left[\gamma B_0 + \upsilon(x,y)/\sqrt{x^2+y^2}\right]t\right\}dV\,. \tag{7}$$

The peculiarity of the equation (7) consists of the additional addendum $\upsilon(x,y)/\sqrt{x^2+y^2} = \Delta\omega$ which was called “the kinematic shift of the NMR”. Here $\upsilon(x,y)$ is the distribution function of the velocity in a sample. Therefore the echo signal must have two peaks shifted from the resonance frequency $\omega = \gamma B_0 \pm \Delta\omega$ at the moments $t = 2\tau \mp \Delta t$.

The observation of the splitted and displaced spin echo signals at t = 4τ [2] can be also explained by the kinematic shift. Indeed, the echo signals at t = 4τ cannot be affected by the flow. But they may be affected by the diffusion. The turbulent flow is described sometimes as the macroscopic diffusion. The macroscopic diffusion under consideration has the peculiarity that it contains a spiral motion. The spiral motion can be represented as a sum of a circular motion at a frequency ω_c and straightforward motion. The circular motion gives the observed kinematic shift of the frequency. The growth of the displacement of the second echo with the velocity and Reynolds number is the result of the growth of ω_c.

4. Discussion and conclusion

Thus it was shown here that the form of the spin echo signals is stipulated by the structure of the flow and the time at which this echo signal is detected. Usually one "high" peak and two small peaks on two sides of the first peak can be observed according to the $(\sin x)/x$ form of the spin echo.

Four peaks can be observed for the unfortunate case when the echo maximum is in the vicinity of time of the minimum of the dependence of the echo amplitude on $\tau_1 + \tau_2$ for the stimulated echo pulse sequence.

The splitted (two-peak) echo signals can be observed for the turbulent flow with the vortexes moving in opposite directions. The displacement of the second echo maximum toward higher times can be caused by spiral motion. Such signals can be explained by the kinematic frequency shift caused by the circular part of motion of flowing particles.

To minimize errors stipulated by echo forms, measurements of the flow velocity should be performed by using integral echo amplitudes instead of simple echo amplitudes.

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