Analysis of NMR Signal for Static Magnetic Field Standard

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This article describes the analysis of the NMR (Nuclear Magnetic Resonance) stabilizer signal. Magnetic field of the standard is created using an electromagnet. Sufficiently high stability of the magnetic field is achieved with the help of a stabilizer with an NMR probe. The NMR phenomenon makes possible very accurate measurements of the static magnetic field, but the resulting stability depends also on supporting electronics. An analysis has been done and tolerances of the measured quantities have been estimated. The calculated tolerances indicate the needed features of the material. First the probe excites the FID (Free Induction Decay) signal in the water sample and acquires the signal answer. It is Fourier transformed and its spectrum is investigated. The actual magnetic field corresponds to the strongest frequency sample. It is utilized for the magnetic field strength correction and stabilization of it. The article brings many equations for such calculation.

Keywords: Nuclear magnetic resonance, NMR, static magnetic field standard, NMR signal.

1. INTRODUCTION

A static magnetic field standard is an effective tool for studies of magnetic field features. It consists of several parts; a very important part is the stabilizer of the static magnetic field. Reference [1], [2] analyzes features of the Fourier transform. The transform is the main tool for the NMR (Nuclear Magnetic Resonance) stabilizer analysis. Theory for the utilization of the NMR technology is briefly explained in [3], [4]. Authors [5], [6] suggested some modifications of the NMR working place equipment with the endeavor to get the best sensitivity in the experiment. Significant part of the NMR equipment are the RF coils. Many authors studied arrangements of coils to improve the resulting sensitivity [7], [8]. Authors [9]-[11] present different experiments based on the NMR technique. Some articles solve technical problems of the NMR instrumentation, e.g. [12]-[14]. The processing of the measured data is discussed elsewhere [15], [16].

Stabilization of the magnetic field is not a simple thing. The NMR technique provides high accuracy of the magnetic field measurement. However, if the accuracy is utilized in full degree, also the supported electronics must be of high quality. This article offers the analysis which should help in making the decision what equipment is suitable for achieving the resulting goal and what budget is necessary for it.

The NMR is not the only physical phenomenon suitable for a magnetometer design. For solving special problems also Electron-spin resonance (ESR) can be utilized. Instead of protons it utilizes the resonance of electrons and the circuit diagram of the supporting electronics is very similar to that operating with the NMR. Only the values of the devices are different. A design of such magnetometer is described in [17]. Reference [18] brings a lot of useful information on magnetometers and is suitable either for a designer who wants to build a self-made instrument or for a user of a purchased magnetometer who wants to utilize his/her instrument in full degree.

2. SUBJECT & METHODS

A standard of static magnetic field is an instrument utilized for different measurements. Its significant part is a magnet with a stable field. Many times the stability of the magnet is not sufficient, and it must be improved using a stabilizer. The stabilizers differ in the principle of measuring the stabilized magnetic field. At present, the measurements using the Hall probes and the NMR probes are utilized. The most accurate results provide magnetometers using the NMR probes. The phenomenon of NMR makes possible measurements with accuracy of parts per million [18]. However, a magnetometer with an NMR probe needs besides the NMR probe also electronics which help in its operations. The electronics influence the quality of the result as well. The first step is excitation of protons in the water sample of the probe. It is done using an RF pulse. The excited protons returning into their quiescent condition emit the FID (Free Induction Decay) signal. Spectrum of the FID contains all information about the static magnetic field within the sample. The FID is in the RF domain, it must be detected. It can be done using the quadrature detector. It provides FID in a complex form (Fig.1.). The complex FID is digitized, the subsequent data has the form of a series of time samples. They are processed using the Fourier transform, it provides a series of frequency samples. Frequency of the k-th sample is given by (1).
\[ \omega_k = 2\pi \frac{k}{NT}, \]  

(1)

where \(N\) is the number of all samples  
\(T\) is the sampling interval.

\[ B_k = \frac{\omega_k}{\gamma}, \]  

(2)

where \(\gamma\) is the gyromagnetic ratio for hydrogen.

The desired frequency \(\omega_0\) is used for the detection. The stabilized magnetic field should have the strength \(B_0\). After the detection it is operated with deviations from the desired values. In practice the quantities are only with finite accuracy. \(\Delta\omega_0\) is the deviation between the desired \(\omega_0\) and the actual value. It depends on the actual values, but for a very small dispersion may be considered constant. The \(T\) can also differ from the desired value by \(\Delta T\). The deviation from the desired angular frequency can be calculated from (1) using the derivation. It is given by (3)

\[ \Delta\omega_{0,T} = -2\pi \frac{\Delta T}{NT^2} k, \]  

(3)

where \(\Delta\omega_{0,T}\) is a deviation of \(\omega_0\) due to \(\Delta T\) for \(k\)-th frequency sample.

For very small dispersion it may be considered constant. Digital signal changes with steps. It brings a small tolerance of (4) (a half of the resolution)

\[ \frac{\pi}{NT}. \]  

(4)

The series of the frequency samples determines the series of the angular frequencies, given by (5).

\[ \omega_0 - \omega_{\min} \ldots \omega_k \ldots \omega_{\max} + \omega_{max}. \]  

(5)

After the detection, the series has been changed as given by (6).

\[ -\omega_{\min} \ldots \omega_k - \omega_0 \ldots \omega_{\max}. \]  

(6)

The detected angular frequency \(\omega_k\) is given by (7).

\[ \omega_k - \omega_0 = \left(2\pi \frac{k}{NT} - \omega_0 + out + offset\right) + \pm \left(|\Delta\omega_0| + \left|\frac{2\pi\Delta T}{NT^2} k\right| + \frac{\pi}{NT} + \right) + |out| + |offset|. \]  

(7)

The tolerances have been calculated using the total differential of the detected \(k\)-th angular frequency in the point: \(\omega_0 = \omega_0\), \(T = T\); \(out = out\); \(offset = offset\). The detected frequencies are the deviations to the frequencies of the frequency samples. The highest frequency sample corresponds to the resulting frequency of the series. Let it be the \(k\)-th sample. It is given by (8).

\[ \Delta B_0 = \frac{\left(B_k\gamma - \omega_0 + out + offset\right)}{\gamma} \pm \left(\frac{|\Delta\omega_0|}{\gamma} + \left|\frac{2\pi\Delta T}{NT^2} k\right| + \frac{\pi}{NT} + \right) + |out| + |offset|. \]  

(8)

Power supply for the electromagnet has the accuracy \(out\). All tolerances create the resulting tolerance, which is expressed with the constant \(C\) as shown in (9) and (10).

\[ \Delta B_0 = \frac{\left(B_k\gamma - \omega_0 + out + offset\right)}{\gamma} \pm C, \]  

(9)

\[ C = \frac{1}{\gamma} \left(|\Delta\omega_0| + \left|\frac{2\pi\Delta T}{NT^2} k\right| + \frac{\pi}{NT} + \right) + |out| + |offset|. \]  

(10)

Calibration of the standard is obvious from (11).

\[ \Delta\omega_1 = \left(B_{k,\text{known}}\gamma - \omega_0 + out + offset\right), \]  

(11)

where \(B_{k,\text{known}}\) (close to \(B_0\)) is a known magnetic field in the active space of the standard, measured with an accurate external magnetometer. The expression (12)

\[ K = \Delta\omega_1 - B_{k,\text{known}}\gamma, \]  

(12)

is a correction constant used for the magnetic field stabilization.

The \(offset\) expresses offset due to the difference between the probe of the magnetometer space and the space where the resulting magnetic field is measured. The \(Delta\) is a tolerance of the offset.
3. RESULTS

Verification experiments were done with the electromagnet DXWD-50 (Xiamen Dexing Magnet Tech. Co., Ltd, Xiamen, China) (Fig.2.), Programmable Controlled Power Supply DX-F2031 (Xiamen Dexing Magnet Tech. Co., Ltd, Xiamen, China) (Fig.3.), and a control arrangement Red Pitaya STEMlab 125-14 Starter Kit (Red Pitaya, Solkan, Slovenia) (Fig.4.). The power supply is the unipolar version with maximal output current of 5.00 A. It is important to know the ratio $B/I$. It depends on the adjustment of the magnet. In the experiments the ratio was 0.0679 T/A. The $B = 0.1 \, T$ was reached with $I = 1.4717 \, A$.

Therefore, the resulting tolerance must be only estimated, the accurate calculation is impossible.

![Fig.2. Electromagnet DXWD-50.](image)

![Fig.3. Programmable Controlled Power Supply DX-F2031 for the electromagnet.](image)

Example:
Consider stabilization of the magnetic field at the value of 0.1 T.
\[
\omega_0 = \gamma B_0 = 2.675153268 \times 10^7 \text{rad/s}.
\]
Signals from standard quartz oscillators have relative tolerance of $10^{-4}$.
\[
\Delta \omega_0 = 10^{-4} \times \omega_0 = 2.675153268 \times 10^3 \text{rad/s}.
\]
The arrangement Red Pitaya can operate also as a two-channel digital oscilloscope. It is utilized for digitization of the complex FID signal. Assume the sampling of the oscilloscope as 1 Gsample/s.
\[
T = 10^{-9} \text{s}.
\]
The sampling interval is also derived from a quartz oscillator.
\[
\Delta T = 10^{-4} \times T = 10^{-13} \text{s}.
\]
Assume that 0.2 s of FID is digitized.
\[
N = \frac{0.2}{10^{-9}} = 2 \times 10^8.
\]
The $k$-th component of the stabilized field is of value approximately $N/2$. The second component of the expression $C$ is given by
\[
2\pi \frac{k}{N^2} \Delta T = \pi \times 10^5 \text{rad/s}.
\]
The third component of $C$ has its value of $\frac{\pi}{N^2}$ \, rad/s.

The fourth component of $C$ is given by
\[
\Delta out = 2 \times 10^{-3} \times 0.1 \times \gamma = 53503.06536 \, \text{rad/s}.
\]
The component $\Delta off$ cannot be determined in this moment, it depends on mechanical arrangement.
The expression $C$ has been estimated as follows

$$C > \frac{370337.4856}{2.675153268 \times 10^8} = 138.4359885 \times 10^{-5} \text{T}.$$ 

The calculation has been approximate.

4. DISCUSSION / CONCLUSIONS

The purpose of this study was to analyze conditions for the static magnetic field standard design. The standard should be utilized for different measurements. The analysis showed that it is not possible to achieve the desired parameters directly. The available budget makes possible purchase only of standard devices, but the result with such devices does not provide an excellent parameter. The way out is improvement of the construction with standard devices. An analysis of the error’s sources must be carried out and the errors must be compensated using suitable calculation. Such way can provide significant improvement of the resulting parameters. Self-made standards of the magnetic field are rather frequent, but they are very seldom described in journals. This article wants to be a contribution to that problem. The derived analysis can help in future endeavors.

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