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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)

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$$\omega_k = 2\pi\frac{k}{NT}, \tag{1}$$

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

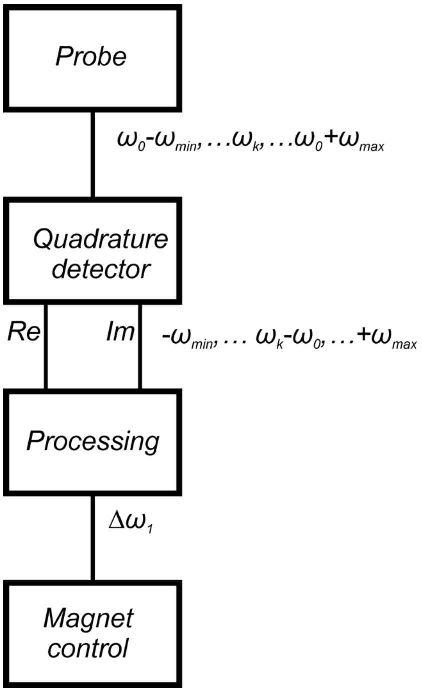

Fig.1. Simplified circuit diagram of the supporting electronics for the magnetic field stabilizer.

The static magnetic field in the space of the k-th sample is given by (2)

$$B_k = \frac{\omega_k}{\gamma}, \tag{2}$$

where γ is the gyromagnetic ratio for hydrogen.

The desired frequency ω_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 ω_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 ΔT. The deviation from the desired angular frequency can be calculated from (1) using the derivation. It is given by (3)

$$\Delta\omega_{0\_T} = -2\pi\frac{\Delta T}{NT^2}k, \tag{3}$$

where $\Delta\omega_{0\_T}$ is a deviation of ω_0 due to ΔT 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)

$$\frac{\pi}{NT}. \tag{4}$$

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

$$\omega_0 - \omega_{min} \dots \omega_k \dots \omega_0 + \omega_{max}. \tag{5}$$

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

$$-\omega_{min} \dots \omega_k - \omega_0 \dots \omega_{max}. \tag{6}$$

The detected angular frequency ω_k is given by (7).

$$\begin{gathered}\omega_k - \omega_0 = \left(2\pi\frac{k}{NT} - \omega_0 + out + off\right) + \\ \pm\left(\begin{gathered}\lfloor -\Delta\omega_0 \rfloor + \left|-2\pi\frac{\Delta T}{NT^2}k\right| + \left|\frac{\pi}{NT}\right| + \\ +|\Delta out| + |\Delta off|\end{gathered}\right).\end{gathered} \tag{7}$$

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; *off* = *off*. 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).

$$\begin{gathered}\Delta B_0 = \frac{(B_k\gamma - \omega_0 + out + off)}{\gamma} \pm \\ +\frac{1}{\gamma}\left(\begin{gathered}|-\Delta\omega_0| + \\ +\left|-2\pi\frac{\Delta T}{NT^2}k\right| + \left|\frac{\pi}{NT}\right| + \\ +|\Delta out| + |\Delta off|\end{gathered}\right).\end{gathered} \tag{8}$$

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).

$$\Delta B_0 = \frac{(B_k\gamma - \omega_0 + out + off)}{\gamma} \pm C, \tag{9}$$

$$C = \frac{1}{\gamma}\left(\begin{gathered}|-\Delta\omega_0| + \left|-2\pi\frac{\Delta T}{NT^2}k\right| + \left|\frac{\pi}{NT}\right| + \\ +|\Delta out| + |\Delta off|\end{gathered}\right). \tag{10}$$

Calibration of the standard is obvious from (11).

$$\Delta\omega_1 = \left(B_{k\_known}\gamma - \omega_0 + out + off\right), \tag{11}$$

where B_{k_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)

$$K = \Delta\omega_1 - B_{k_{known}}\gamma, \tag{12}$$

is a correction constant used for the magnetic field stabilization.

The off expresses offset due to the difference between the probe of the magnetometer space and the space where the resulting magnetic field is measured. The Δoff 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*.

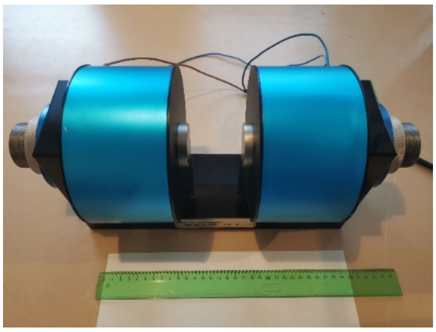

Fig.2. Electromagnet DXWD-50.

Fig.3. Programmable Controlled Power Supply DX-F2031 for the electromagnet.

The resolution of the power supply is 0.1 mA. It must be checked so that the accuracy of the result is ensured. The accuracy of the power supply is 0.2 %. It is the ground for the tolerance $\Delta \boldsymbol{out}$ calculation. Stability of the power supply is 0.1 %@10A. The resulting stability depends on the whole stabilizer. The magnet should provide a sufficiently homogeneous static magnetic field allowing utilization of the NMR technique. The control arrangement should organize the whole operation of the stabilizer, besides others, the sampling interval should be produced. Its inaccuracy is another significant source of the tolerances. All the considered sources of the tolerances are assumed as accuracies, though in practice they are also precisions. Therefore, the resulting tolerance must be only estimated, the accurate calculation is impossible.

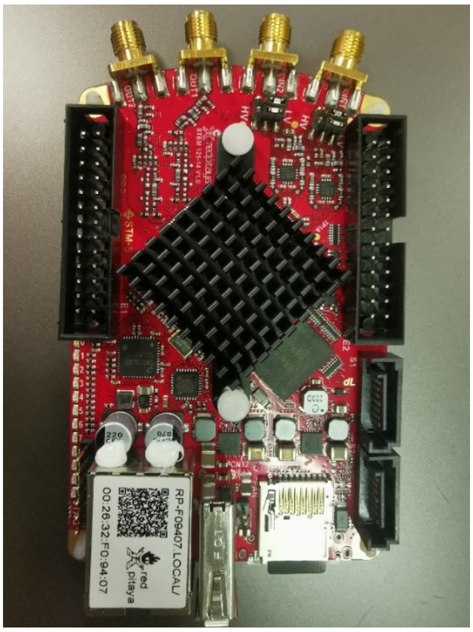

Fig.4. Control arrangement Red Pitaya STEMlab 125-14.

Example:

Consider stabilization of the magnetic field at the value of 0.1 *T*.

$\omega_0 = \gamma B_0 = 2.675153268 \times 10^7 \mathrm{rad/s}.$

Signals from standard quartz oscillators have relative tolerance of 10^{-4}.

$\Delta\omega_0 = 10^{-4} \times \omega_0 = 2.675153268 \times 10^3 \mathrm{rad/s}.$

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.

$T = 10^{-9}\mathrm{s}.$

The sampling interval is also derived from a quartz oscillator.

$\Delta T = 10^{-4} \times T = 10^{-13}\mathrm{s}.$

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

$$2\pi \frac{k}{NT^2}\Delta T = \pi \times 10^5 \mathrm{rad/s}.$$

The third component of *C* has its value of

$$\frac{\pi}{NT} = \frac{\pi}{0.2}\mathrm{rad/s}.$$

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 Δoff cannot be determined in this moment, it depends on mechanical arrangement.

The expression C has been estimated as follows

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

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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REFERENCES

[1] Brigham, E.O. (1974). *The Fast Fourier Transform.* Prentice-Hall.

[2] Čížek, V. (1981). *Discrete Fourier Transform and Its Application*. Praha, Czech Republic: SNTL. (in Czech)

[3] Hoult, D.I., Richards, R.E. (1976). The signal-to-noise ratio of the nuclear magnetic resonance experiment. *Journal of Magnetic Resonance*, 24 (1), 71-85. https://doi.org/10.1016/0022-2364(76)90233-X.

[4] Hoult, D.I., Lauterbur, P.C. (1979). The sensitivity of the zeugmatographic experiment involving human samples. *Journal of Magnetic Resonance*, 34 (2), 425-433. https://doi.org/10.1016/0022-2364(79)90019-2.

[5] Raad, A., Darrasse, L. (1992). Optimization of NMR bandwidth by inductive coupling. *Magnetic Resonance Imaging*, 10 (1), 55-65. https://doi.org/10.1016/0730-725x(92)90373-8.

[6] Décorps, M., Blondet, P., Reutenauer, H., Albrand, J.P., Remy, C. (1985). An inductively coupled, series-tuned NMR probe. *Journal of Magnetic Resonance*, 65 (1), 100-109. https://doi.org/10.1016/0022-2364(85)90378-6.

[7] Vergara Gomez, T.S., Dubois, M., Glybovski, S., Larrat, B., De Rosny, J., Rockstuhl, C., Bernard, M., Abdeddaim, R., Enoch, S., Kober, F. (2019). Wireless coils based on resonant and nonresonant coupled- wire structure for small animal multinuclear imaging. *NMR in Biomedicine*, 32 (5), e4079. https://doi.org/10.1002/nbm.4079.

[8] Qian, Ch., Duan, Q., Dodd, S., Koretsky, A., Murphy-Boesch, J. (2016). Sensitivity enhancement of an inductively coupled local detector using a HEMT-based current amplifier. *Magnetic Resonance in Medicine*, 75 (6), 2573-2578. https://doi.org/10.1002/mrm.25850.

[9] Weis, J., Ericsson, A., Hemmingsson, A. (1999). Chemical shift artifact-free microscopy: Spectroscopic microimaging of the human skin. *Magnetic Resonance in Medicine*, 41 (5), 904-908. https://doi.org/10.1002/(sici)1522-2594(199905)41:5%3C904::aid-mrm8%3E3.0.co;2-4.

[10] Marcon, P., Bartusek, K., Dokoupil, Z., Gescheidtova, E. (2012). Diffusion MRI: Mitigation of magnetic field inhomogeneities. *Measurement Science Review*, 12 (5), 205-212. https://doi.org/10.2478/v10048-012-0031-8.

[11] Bartusek, K., Dokoupil, Z., Gescheidtova, E. (2007). Mapping of magnetic field around small coil using the magnetic resonance method. *Measurement Science and Technology*, 18 (7), 2223-2230. https://doi.org/10.1088/0957-0233/18/7/056.

[12] Nespor, D., Bartusek, K., Dokoupil, Z. (2014). Comparing saddle, slotted-tube and parallel-plate coils for Magnetic Resonance Imaging. *Measurement Science Review*, 14 (3), 171-176. https://doi.org/10.2478/msr-2014-0023.

[13] Latta, P., Gruwel, M.L., Volotovskyy, V., Weber, M.H., Tomanek, B. (2007). Simple phase method for measurement of magnetic field gradient waveforms. *Magnetic Resonance Imaging*, 25 (9), 1272-1276. https://doi.org/10.1016/j.mri.2007.02.002.

[14] Latta, P., Gruwel, M.L., Volotovskyy, V., Weber, M.H., Tomanek, B. (2008). Single-point imaging with a variable phase encoding interval. *Magnetic Resonance Imaging*, 26 (1), 109-116. https://doi.org/10.1016/j.mri.2007.05.004.

[15] Wimmer, G., Witkovský, V., Duby, T. (2000). Proper rounding of the measurement results under normality assumptions. *Measurement Science and Technology*, 11 (12), 1659-1665. https://doi.org/10.1088/0957-0233/11/12/302.

[16] Witkovsky, V., Frollo, I. (2020). Measurement science is the science of sciences - there is no science without measurement. *Measurement Science Review*, 20 (1), 1-5. https://doi.org/10.2478/msr-2020-0001.

[17] Sundramoorthy, S.V., Epel, B., Halpern, H.J. (2017). A Pulse EPR 25 mT magnetometer with 10ppm resolution. *Applied Magnetic Resonance*, 48 (8), 805-811. https://doi.org/10.1007/s00723-017-0902-0.

[18] Keller, P. (2011). NMR magnetometers. *Magnetics Technology International*, 2011, 68-71.

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