ISSN 1392 – 1215 ELECTRONICS AND ELECTRICAL ENGINEERING 2008. No. 2(82)
ELEKTRONIKA IR ELEKTROTECHNIKA

T191 HIGH FREQUENCY TECHNOLOGY, MICROWAVES
AUKŠTŲJŲ DAŽNIŲ TECHNOLOGIJA, MIKROBANGOS

Elimination of Distortions in Static Magnetic Field Distribution Measurements

P. Andris, I. Frollo
Institute of Measurement Science, Slovak Academy of Sciences,
Dúbravská cesta 9, SK-841 04 Bratislava, Slovakia, phone: +4212 5910 4541, e-mail: umerandr@savba.sk

Introduction

Measurement of magnetic field distribution of the basic magnet is rather frequent measurement in Nuclear Magnetic Resonance (NMR). It can be useful for maintenance of the NMR scanner as well as for measurement of quantities calculated from magnetic field [1, 2].

Methods of static magnetic field distribution are based on phase of NMR data measurement frequently. NMR data is set of complex numbers and their phases are directly proportional to static magnetic field inhomogeneity. Nevertheless calculating phases of complex numbers periodicity of the exponential function of imaginary variable must be considered. The periodicity is within 2π and can distort result of the measurement. The distortion can be removed using an appropriate unwrapping algorithm [3-5]. Sometimes unwrapping is not appropriate or result of measurement must be absolute (magnetic field distribution $\Delta B = 0$ corresponds to B_O of the scanner). Therefore several NMR sequences were developed shortening the echo time and eliminating the phase distortion in such manner [6-8].

The presented approach is different. The NMR signal from the gradient-echo (GE) sequence is double acquired with different echo times and after the Fourier transform ratio of the both data for each voxel is performed. The distortion due to phase periodicity was removed similarly to sequences shortening the echo time. The experiments revealed that also further distortion due to magnetic field background and gradients influence was removed.

Several methods were published using double acquisition but the purpose of it was different or acquired data were processed in different manner [5, 9]. The way of calculation was direct subtraction of the measured images arguments [9] thus the solving problems of unwrapping were limited. The absolute results of inhomogeneities measurement can be acquired by methods based on spectral line of water investigation [9-13]. They are not wrapped and do not include inhomogeneities of RF coils into the whole result. They are nevertheless much more time consuming. That’s why methods based on phase processing are still interesting. The described method can be utilized for phase and inhomogeneity measurement on almost every NMR scanner.

Theory and results

Our method has been tested on the NMR data generated by the 0.1 Tesla experimental whole-body NMR imager TMR-96. This device is controlled by S.M.I.S. console (Surrey Medical Imaging Systems Limited, Guildford, UK).

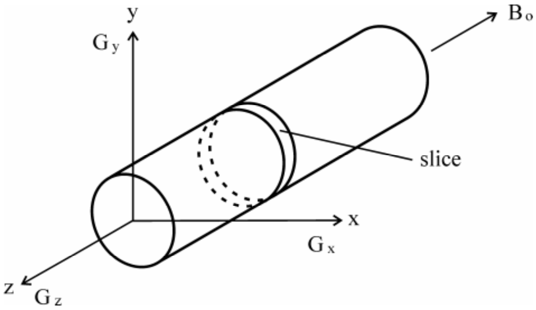

Fig. 1. Arrangement of the experiment

In our NMR scan experiments a circular plastic vessel (diameter of 110 mm) filled with 0.1 % solution of $CuSO_4$ in distilled water (applied for relaxation time shortening) was used (Fig. 1). Measuring parameters: GE sequence (program sequence supplied by SMIS), eight averages, $TE_1 = 15\,ms$, $TE_2 = 16\,ms$ or $TE_2 = 20\,ms$, repetition time TR=300 *ms*, transversal slice thickness = 5 *mm*.

Measurement using GE sequence yielded set of complex numbers, the phases of which are proportional to basic magnetic field inhomogeneity and echo time. Measurement by gradient-echo method was repeated two times with different echo times *TE*. Subsequently, ratio of the both measured and Fourier transformed results were computed and the basic magnetic field from its phase inhomogeneity was calculated. A term of data matrix obtained by gradient-echo sequence measurement and subsequent Fourier transform can be described by

$$I = \rho \exp(-\mathrm{i}\,\gamma\,\Delta B\,TE) = I_{re} + \mathrm{i}\,I_{im}\,, \tag{1}$$

where ρ – proton density, γ – the gyromagnetic ratio, ΔB – average inhomogeneity of the basic magnetic field within a voxel, TE – the echo time of the gradient echo sequence and $\mathrm{i} = \sqrt{-1}$. Influence of measuring gradient was omitted.

Phase can be calculated as an argument of the complex data

$$\Phi = \arg(I)\,. \tag{2}$$

The exponential function of imaginary variable is periodic, for only one period depicted, the condition must be valid

$$-\pi \le -\gamma\,\Delta B\,TE \le \pi\,. \tag{3}$$

If inhomogeneity is higher or echo time longer the periodicity distorts the result. The distortion can be excluded by shortening the echo time but this is limited by the parameters of the signal sampling. For almost arbitrary shortening the echo time, the following procedure can be used.

In the first step the sample is scanned with the echo time TE_1. After the Fourier transform, the following values of data are obtained

$$I_1 = \rho_1 \exp(-\mathrm{i}\,\gamma\,\Delta B\,TE_1) = I_{1re} + \mathrm{i}\,I_{1im}\,. \tag{4}$$

Subsequently the same sample is scanned in the second step with longer echo time TE_2 and Fourier transformed values of data are given by

$$I_2 = \rho_2 \exp(-\mathrm{i}\,\gamma\,\Delta B\,TE_2) = I_{2re} + \mathrm{i}\,I_{2im}\,. \tag{5}$$

Ratio of the both values is calculated using the third form of the expression:

$$\begin{aligned}\frac{I_1}{I_2} &= \frac{\rho_1}{\rho_2}\exp(\mathrm{i}\,\gamma\,\Delta B\,(TE_2 - TE_1)) = \\ &= \frac{\rho_1}{\rho_2}\exp\mathrm{i}(\varphi_1 - \varphi_2) = \\ &= \frac{I_{1re}\cdot I_{2re} + I_{1im}\cdot I_{2im}}{I_{2re}^2 + I_{2im}^2} + \mathrm{i}\,\frac{I_{1im}\cdot I_{2re} - I_{1re}\cdot I_{2im}}{I_{2\mathrm{re}}^2 + I_{2im}^2}\,,\end{aligned} \tag{6}$$

or

$$\begin{aligned}\frac{I_2}{I_1} &= \frac{\rho_2}{\rho_1}\exp(\mathrm{i}\,\gamma\,\Delta B\,(TE_1 - TE_2)) = \\ &= \frac{\rho_2}{\rho_1}\exp\mathrm{i}(\varphi_2 - \varphi_1) = \\ &= \frac{I_{1re}\cdot I_{2re} + I_{1im}\cdot I_{2im}}{I_{1re}^2 + I_{1im}^2} + \mathrm{i}\,\frac{I_{1re}\cdot I_{2im} - I_{1im}\cdot I_{2re}}{I_{1\mathrm{re}}^2 + I_{1im}^2}\,.\end{aligned} \tag{7}$$

For the whole span of the phase the following condition must be achieved:

$$-\pi \le \arg\left(\frac{I_1}{I_2}\right) \le \pi\,, \tag{8}$$

or

$$-\pi \le \arg\left(\frac{I_2}{I_1}\right) \le \pi\,. \tag{9}$$

This can be easily fulfilled for the difference of the both echo times can be made very short.

Magnetic field distribution or inhomogeneity (in ppm) related to the working magnetic field of the scanner is calculated as:

$$\Delta B = \frac{\arg\left(\frac{I_1}{I_2}\right)10^6}{2\pi\, f_o\,(TE_2 - TE_1)} \tag{10}$$

or

$$\Delta B = \frac{\arg\left(\frac{I_2}{I_1}\right)10^6}{2\pi\, f_o\,(TE_1 - TE_2)} \quad \text{[ppm]}, \tag{11}$$

where f_o is working frequency of the scanner.

Result of the measurement is a matrix of values which can be depicted as an image. Magnetic field distribution of the experimental NMR scanner ($f_o = 4.45 MHz$) with purposely caused inhomogeneity using the 1st order shim coil correcting inhomogeneity in x-direction was measured and is depicted in Fig. 2(a). The program package Mathematica (Wolfram Research Inc., Champaign, IL) was used for the data processing and the figures creating. The echo time $TE_1 = 15\,ms$ was used for the first measurement. The same sample measurement with $TE_2 = 16\,ms$ is depicted in Fig. 2(b). It is evident that the difference between the both figures is not significant though there are differences not only in number of 2π periods but also in gradients of the measured distributions. Effect of wrapping is apparent in the both Fig. 2(a) and 2(b). To acquire the absolute values of the measured magnetic field the whole measured span within the sample must be depicted in one period. It can be easily fulfilled with the procedure described above. Fig. 2(c) shows the magnetic field distribution measured by the described method. The improvement in suppressing the distortion due to wrapping is evident. The whole measured span of magnetic field is within one period and the measured values can be considered as absolute ($\Delta B = 0$ corresponds to B_o of the scanner). Nevertheless not only distortion due to periodicity was removed. Direction of the magnetic field gradient in Fig. 2(c) is consonant with the x-axis while directions of gradients in Fig. 2(a) and (b) is different and depending on echo time. The effect is more apparent in Fig. 3. where the same magnetic field distribution measured at $TE_1 = 15\,ms$ (a) is compared with measurement at $TE_2 = 20\,ms$ (b). The echo times difference $TE_2 - TE_1 = 5\,ms$ is too long to depict the measured magnetic field distribution within the sample in one period.

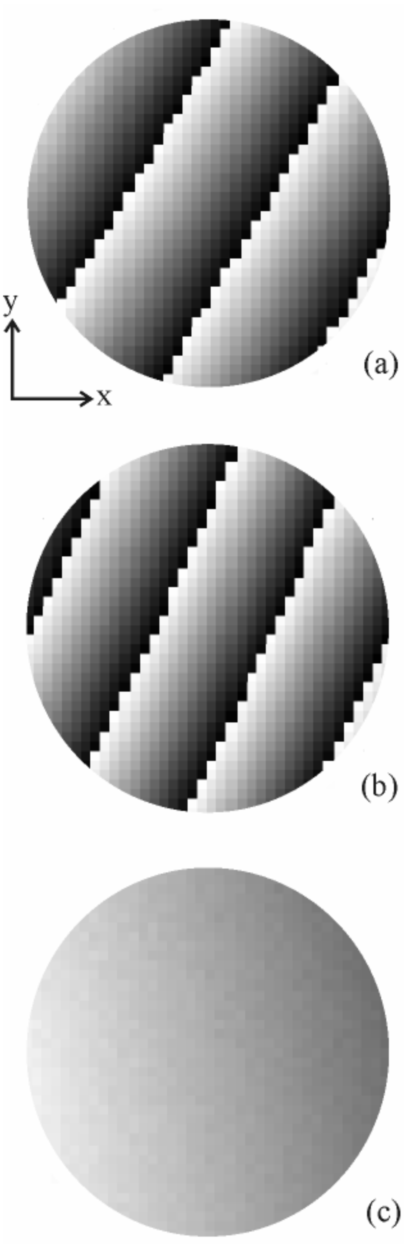

Fig. 2. Magnetic field distribution of the experimental scanner with apparent artefacts due to periodicity (a) for $TE_1 = 15\,ms$, (b) for $TE_2 = 16\,ms$. Resulting magnetic field distribution measured by the proposed method (c). The magnetic field distribution was caused by the 1st order shim coil, correcting inhomogeneities in x-direction. The original matrices were reduced to the points of the sample

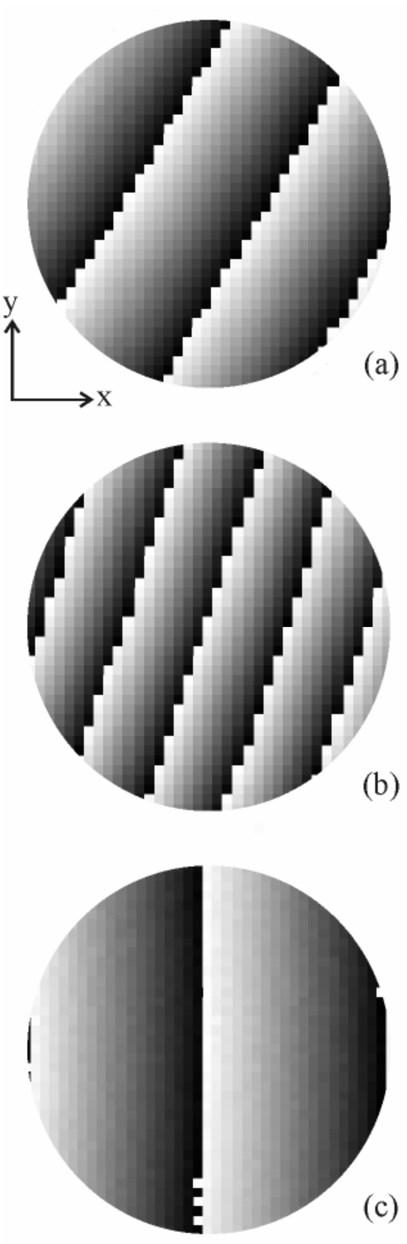

Fig. 3. The same magnetic field distribution measured with different echo times: (a) again $TE_1 = 15\,ms$; (b) $TE_2 = 20\,ms$. The difference between gradients in the both images is apparent. The resulting magnetic field distribution (c). The difference $TE_2 - TE_1 = 5\,ms$ is too long to depict the field within the sample in one period

The image can be processed by an appropriate unwrapping algorithm but it is not obvious which point $\Delta B = 0$ corresponds to B_o of the scanner. To avoid similar distortions caused by wrapping and measuring gradient influence the static magnetic field distribution or phase should be measured with double acquisition and ratio processing the measured data.

Conclusion

The presented method allows removing distortions due to periodicity of the phase and due to measuring method and environment. Although the method is not the only sole it has some advantages. It can be simply implemented on almost every NMR scanner without writing a new program sequence and the results of the magnetic field distribution measurement are absolute. The measured static magnetic field distribution can be used for shim coils setting or for magnetic susceptibility mapping or as a base for other dimensions calculation.

Acknowledgment

The research was sponsored by the Grant Agency of the Slovak Academy of Sciences, grant number 2/0142/08.

References

1. **Suk H. O., Byung I. L., Tae S. P., Soo Y. L., Eung J. W., Min H. Ch., Seo J. K., Kwon O.** Magnetic Resonance Electrical Impedance Tomography at 3 Tesla Field Strength // Magnetic Resonance in Medicine. – 2004. – Vol. 51. – P. 1292–1296.
2. **Weis J., Ericsson A., Hemmingsson A.** Chemical Shift Artifact-Free Microscopy: Spectroscopic Microimaging of the Human Skin // Magnetic Resonance in Medicine. – 1999. – Vol. 41. – P. 904–908.
3. **Ghiglia M. D., Pritt V.** Two-Dimensional Phase Unwrapping: Theory, Algorithms and Software // Wiley. – 1998.
4. **Jenkinson M.** Fast, Automated, N-Dimensional Phase-Unwrapping Algorithm // Magnetic Resonance in Medicine – 2003. – Vol. 49. – P. 193–197.
5. **Glover G. H., Schneider E.** Three-Point Dixon Technique for True water / Fat Decomposition with B_o Inhomogeneity Correction // Magnetic Resonance in Medicine – 1991. – Vol. 18. – P. 371–383.
6. **Sekihara K., Matsui S., Kohno H.** A new method of measuring static field distribution using modified Fourier NMR imaging // J. Phys. E: Sci. Instrum – 1985. – Vol. 18. – P. 224–227.
7. **Sekihara K., Matsui S., Kohno H.** NMR Imaging for Magnets with Large Nonuniformities // IEEE Transactions on Medical Imaging M1-4. – 1985. – P. 193–199.
8. **Wen H., Jaffer F. A.** An *in Vivo* Automated Shimming Method Taking into Account Shim Current Constraints // Magnetic Resonance in Medicine – 1995. – Vol. 34 – P. 898–904.
9. **Schneider E., Glover G.** Rapid *in Vivo* Proton Shimming // Magnetic Resonance in Medicine – 1991. – Vol. 18. – P. 335–347.
10. **Pelnař J.** Measurement of the Distribution of B_1 Field in the Presence of Linear Magnetic Field Gradient // Journal of Magnetic Resonance - 1986. – Vol. 70. – P. 456–460.
11. **Weis J., Frollo I., Budinsky L.** Magnetic field distribution measurement by modified FLASH method // Zeitschrift für Naturforschung – 1989. – Vol. 44a. – P. 1151–1154.
12. **Maudsley A. A., Simon H. E., Hilal S. K.** Magnetic Field Measurement by NMR Imaging // J. Phys. E: Sci. Instrum - 1984. – Vol. 17. – P. 216–230.
13. **Kawanaka A., Takagi M.** Estimation of Static Magnetic Field and Gradient Fields from NMR Image // J. Phys. E.: Sci Instrum – 1986. – Vol. 19. – P. 871–875.

Submitted for publication 2007 08 17

P. Andris, I. Frollo. Elimination of Distortions in Static Magnetic Field Distribution Measurement // Electronics and Electrical Engineering. – Kaunas: Technologija, 2007. – No. 2(82). – P. 9–12.

A new method for magnetic field distribution measurement distortions elimination using gradient-echo double measurement is introduced. To exclude phase distortion unwrapping algorithms or methods are used shortening the echo time of the measuring sequence. In the article the measurement acquisition was double repeated with different echo times and ratio of the both acquired and Fourier transformed data matrices was performed. The distortion due to phase periodicity was suppressed and also distortion due to background influence was eliminated. Method is applicable for all NMR scanners and is suitable for magnetic field distribution measurements. Ill. 3, bibl. 13 (in English; summaries in English, Russian and Lithuanian).

П. Андрис, И. Фроло. Устранение искажений при измерении распределения статического магнитного поля // Электроника и электротехника. – Каунас: Технология, 2008. – № 2(82). – С. 9–12.

Предлагается новый метод для устранения искажений измерения распределения магнитного поля, используя двойное измерение отражения градиента. Для исключения фазовых искажений используются разворачивающее алгоритмы или методы, сокращающие время отражения последовательности измерений. Данные полученные при различных отражениях обработаны трансформацией Фуръе. Метод применим для всех сканеров NMR и подходит для измерения распределения магнитного поля. Ил. 3, библ. 13 (на английском языке; рефераты на английском, русском и литовском яз.).

P. Andris, I. Frollo. Iškreipių pašalinimas matuojant statinio magnetinio lauko pasiskirstymą // Elektronika ir Elektrotechnika. – Kaunas: Technologija, 2008. – Nr. 2(82). – P. 9–12.

Pristatytas naujas metodas iškreipiams pašalinti matuojant magnetinio lauko pasiskirstymą. Naudotas dvigubas gradientinio atspindžio matavimas. Faziniams iškreipiams pašalinti panaudoti specialūs metodai, skirti matavimo sekos atspindžio trukmei sutrumpinti. Duomenys buvo surenkami dviem atvejais, esant skirtingoms atspindžio trukmėms. Duomenys apdoroti taikant Furjė transformaciją. Buvo pašalinti iškreipiai dėl fazės periodiškumo, taip pat buvo pašalinti iškreipiai, atsirandantys dėl fono įtakos. Metodą galima taikyti visuose NMR skeneriuose. Jis tinka magnetinio lauko pasiskirstymui matuoti. Il. 3, bibl. 13 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

DOI: 10.5755/j02.eie.11046