Tomáš KŘÍŽ
Karel BARTUŠEK
Radim KOŘÍNEK

NMR MAGNETIC FIELD MEASUREMENT FOR EIT

ABSTRACT *The possibility of magnetic flux density measurement by nuclear magnetic resonance is presented in the paper. The current source is connected to a specimen. This direct current creates magnetic field around the specimen. All three components of magnetic flux density have been measured. The processing and evaluation of data measured are described. Measured values of magnetic flux density were compared to theoretical values calculated according to the Biot-Savart's law. These data will be used as input data for conductivity reconstruction based on electrical impedance tomography.*

Keywords: *measurement, magnetic flux density, nuclear magnetic resonance, conductivity reconstruction, electrical impendance tomography*

1. INTRODUCTION

The measurement was assembled to obtain magnetic field values in the neighbourhood of a specimen connected to a current source. The measured values will be used for reconstruction of specimen conductivity. The reconstruction of specimen conductivity from magnetic field values is on inverse

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Tomáš KŘÍŽ, Ph.D.[1]; **Radim KOŘÍNEK, Ph.D.**[1]
e-mail: krizt@feec.vutbr.cz; xkorin06@stud.feec.vutbr.cz
Karel BARTUŠEK, Prof.[1], [2]
e-mail: bartusek@feec.vutbr.cz, bar@isibrno.cz

[1] Department of Theoretical and Experimental Electrical Engineering
Brno University of Technology
[2] Institute of Scientific Instruments, Academy of Sciences of the Czech Republic

problem. For this purpose the EIT regularization methods are used. Details can be found in [1]. All magnetic flux density components must be measured in case of a conductivity reconstruction task.

There is a lot of different ways for magnetic field measurement. Most of these methods are based on the Hall effect. The magnetic field components were measured in three different times but it is very difficult to move the measuring head precisely to measuring points. It is better to use nuclear magnetic resonance (NMR) to measure magnetic field because one component of magnetic flux density $\mathbf{B}$ is measured in whole specimen at the same time.

There is one very important condition – to use low levels of direct current. The level of source current has to be established taking into account the possibility of changes in specimen material properties.

The NMR approach was chosen to measure the magnetic field. It is possible to measure small values of magnetic field by NMR. Gradient echo method (GE) or unsymmetrical spin echo method (SE) can be used for magnetic field measurement. Both methods have advantages and disadvantages. The GE is very sensitive to basic magnetic field $\mathbf{B}_0$ changes but it is necessary to unwrap the image phase. The phase unwrapping is very difficult and it is multivalent in the case of neighbouring pixels with phase change higher than 2π. Disadvantage of the SE method is smaller sensitivity to changes in basic magnetic field $\mathbf{B}_0$. It is not necessary to unwrap the phase of image obtained by this method. The values of phase shift are between $\pm\pi$.

2. MEASUREMENT ASSEMBLY

Several specimens have been prepared for experimental measurements. Two basic shapes of specimens were chosen. The first shape is a circle and second shape is a ring. Both types of specimens were prepared with and without defects. The specimens diameter is d = 34 mm. These specimens were created on printed circuit board (PCB) with copper thickness of 35 µm. Direct current source was connected to the specimens. The current value was adjusted to I = 100 mA.

To obtain magnetic field map it is necessary to place suitable material over a specimen. Distilled water of 2 mm level was used as measured medium. Magnetic field distribution has been measured only in this layer. In order to measure the distribution of magnetic flux components the specimen was placed into the working place of NMR tomography. Specimen arrangement for measurement of the B_y component of the magnetic field by tomography is shown in Figure 1a). In order to measure the B_x component the specimen was rotated perpendicularly with respect to the previous position.

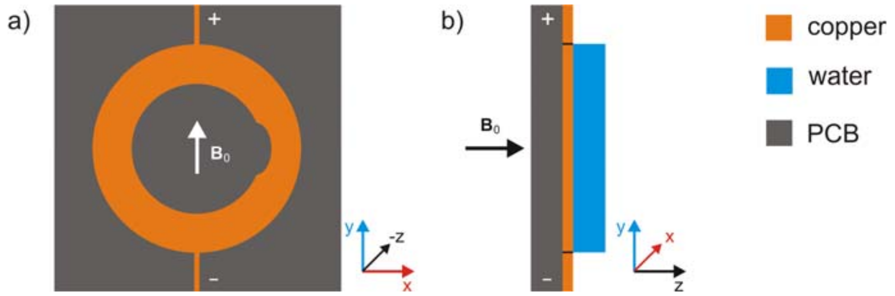

Fig. 1. Specimen arrangement: a) *y*-component, b) *z*-component

The GE method was chosen for magnetic field measurement because this method is sensitive to $\mathbf{B}_0$ changes. Basic principle of GE method: basic field $\mathbf{B}_0$ has z-component only. After the specimen is inserted into the basic field the magnetization vector $\mathbf{M}_0$ is parallel to the z-component of $\mathbf{B}_0$. When the radiofrequency pulse (RF) is excited, $\mathbf{M}_0$ is dropped into xy plane. Energy of RF pulse makes phase matching magnetic dipole possible. Magnetization vector is moving in transversal plane with Larmor's frequency and generates the GE. Gradient G_s is generated with RF pulse. G_s choose layer in z-direction. The G_s value changes the Larmor's frequency which depends on the magnetic field value. Repeated phasing makes the G_r gradient. This gradient excitation is used for frequency encoding in x direction. Gradient excitation G_p is used for phase encoding in y direction [2].

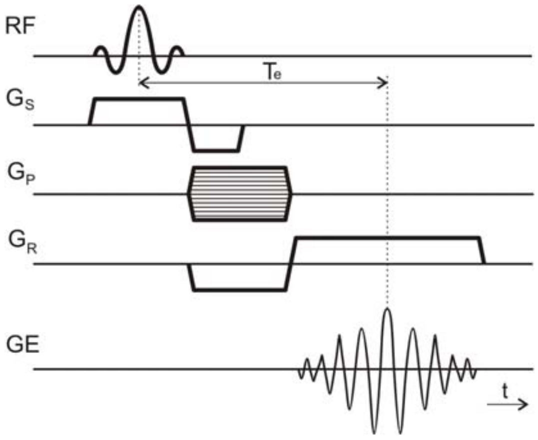

Fig. 2. Basic impulses for GE

Frequency encoded image represents the result of NMR measurement. Using inverse Fourier transformation one obtaines a complex image. The phase and module image is necessary to calculate the magnetic field.

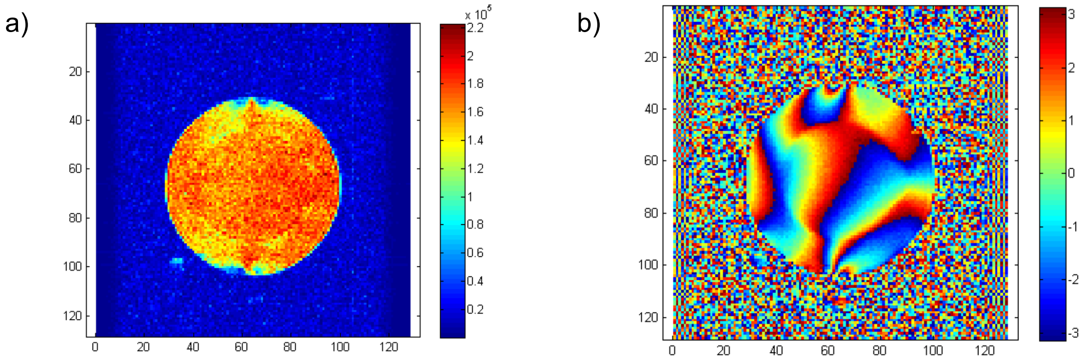

Fig. 3: Example of a) module image and b) phase image

The main information about magnetic field distribution is encoded in the phase image. The interval of phase is <π; -π). It is necessary to unwrap the phase image. The initial point for phase unwrapping is identified by the module image. A differential measurement has been used for background signal suppression and to obtain a magnetic field map around the specimen. There were made two measurements for different current direction. Changes in values of magnetic field with respect to the static magnetic field $\mathbf{B}_0$ are given by the following equation (1):

$$\Delta B = 0.5\left(\frac{\Delta\varphi}{\gamma\cdot T_{\mathrm{E}}}\right)^{+} - 0.5\left(\frac{\Delta\varphi}{\gamma\cdot T_{\mathrm{E}}}\right)^{-}, \qquad (1)$$

where ΔB is change in $\mathbf{B}_0$, T_{E} is the time echo, $\Delta\varphi$ is the coded phase and γ is the gyro-magnetic spin ratio.

3. NUMERICAL SIMULATION

In order to verify the measured values by NMR, tomography numerical models were built for each specimen. Geometrical models were discretized by linear triangle elements. The models consist of approximately 5000 elements and of 2600 nodes. The electrodes were placed on y axis outer elements. The source current was adjusted to 100 mA. The copper conductivity was adjusted to σ = 59.59 MS/m. Direction of current corresponded to the negative y axis. The electrical potential was solved by the finite element method. The current was calculated for each element. These current values were used for calculation of magnetic field components. The Biot-Savart'law [3] was used for evaluation of magnetic flux density components. Components of magnetic flux density were calculated by averaging values measured two millimetres above models. The average value was calculated from forty values for each element. Triangular meshes were used. We suppose that the surface current density $\mathbf{K}$ is constant on each element. The x- and y-component of magnetic flux density in an examined point, which is given by coordinates $[x_i, y_i, z_i]$, can be calculated by means of the superposition principle.

$$B_{ix} = \frac{\mu_0}{4\pi}\sum_{j=1}^{NE} R_{ijz}\frac{\Delta S_j}{R_{ij}^3}\,K_{jy} \quad , B_{iy} = -\frac{\mu_0}{4\pi}\sum_{j=1}^{NE} R_{ijz}\frac{\Delta S_j}{R_{ij}^3}\,K_{jx}\ , \qquad i = 1,\dots,NE \tag{2}$$

where ΔS is element area, K is surface current density component, x, y, z are element center coordinates and R is the distance between centers of elements.

4. MEASUREMENT AND SIMULATION RESULTS

The x- and y-components are shown in Figure 4. Comparing measured and simulated magnetic field distribution we can see that distribution of magnetic fields is corresponding. Diversity between measured and simulated values is due to signal phase periodicity in the measured layer.

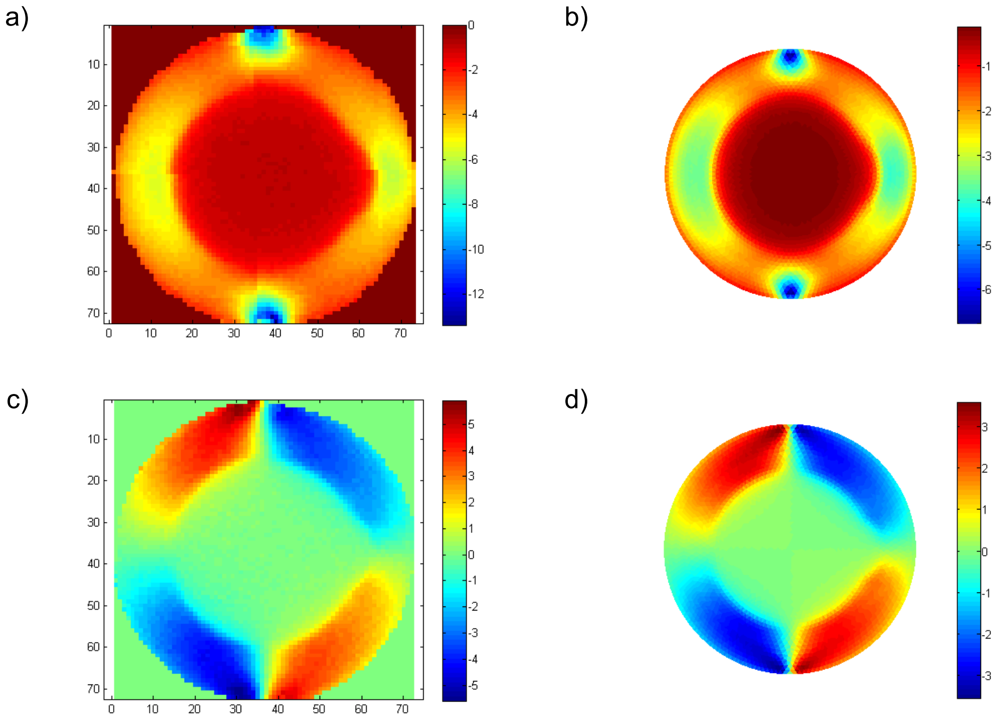

Fig. 4. Measured values are a) B_x and c) B_y, while the calculated values are b) B_x and d) B_y

5. CONCLUSION

Comparing measured and simulated results it is obvious that the measured data obtained by NMR tomography are not suitable to be used as input data for conductivity reconstruction. Our future work will be focused on improvement of magnetic field measurement by NMR tomography.

Acknowledgement

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POMIAR EIT METODĄ NMR (JĄDROWEGO REZONANSU MAGNETYCZNEGO)

Tomáš KŘÍŽ, Karel BARTUŠEK, Radim KOŘÍNEK

STRESZCZENIE *Artykuł przedstawia możliwość pomiaru indukcji magnetycznej przy użyciu jądrowego rezonansu magnetycznego. Źródło prądu jest połączone z próbką. Prąd stały wytwarza pole magnetyczne wokół próbki. Mierzono wszystkie trzy składowe indukcji magnetycznej. Opisano przetwarzanie i ocenę danych pomiarowych. Zmierzone wartości indukcji magnetycznej porównano z teoretycznymi wartościami obliczonymi w oparciu o prawo Biota-Savarta. Dane te będą użyte jako dane wejściowe do rekonstrukcji przewodności w oparciu o tomografię impendancji elektrycznej.*