Receive Coil for Low-field NMR Scanner Optimized Using Inductive Coupling

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Abstract. *The paper describes a receive coil system for low-field NMR scanner intended for cardio measurements. The coil system is based on good qualities of surface coils accommodating them to volume measurements. The active volume of the coil is widened using two inductively coupled resonators. Signal from the coil system is amplified using a high-impedance preamplifier thus no special matching is necessary. The coil can be utilized for larger samples measurements. Thanks to inductive coupling the coil system need not be retuned before every new measurement. Performed experiments confirmed good agreement between the theory and the practice but should be verified by more experiments.*

Keywords: Receive Coil, Low-Field NMR, Inductive Coupling

1. Introduction

One of the first uses of inductive coupling for nuclear magnetic resonance (NMR) receive coil systems solved balancing surface coils [1]. The purpose was reducing losses due to parasitic capacitances and increasing sensitivity in this way. Widening the frequency bandwidth in over-coupled mode motivated to experiments with coil systems not needing fine tuning before every measurement [2]. Moreover the authors used preamplifier with high input impedance and matched the coil system to receiver in the manner. The subsequent step should have been a receive system with universal coupling coil and several receive coils changed at need. The first experiments and deeper analysis showed that fulfilling the theoretical assumptions in [2] is not a simple thing. The further experiments therefore were aimed at a receive coil system with one passive and one active receive coils widening the frequency bandwidth, preserving proper tuning in sufficiently wide span. Purpose of the paper is to describe some interesting parts of the designed system.

2. Subject and Methods

Older studies revealed that surface coils can operate in smaller volume compared to volume coils but their signal-to-noise ratio (SNR) in the volume is higher than SNR of volume coils in their volume. The fact motivated to design of receive systems consisting of several surface coils. The way has been selected for solving the studied problems. Fig. 1 depicts a circuit diagram of the investigated system. The difference to usual use of such circuit and also to [2] is the fact that the signal from the excited sample is induced into both coils of the circuit. It changes behaviour of the circuit compared to known uses. The coil system can be described by the equation system

$$\begin{bmatrix} \mathrm{V}_{s1} \\ \mathrm{V}_{s2} \end{bmatrix} = \begin{bmatrix} R_1 + \mathrm{i}\left(\omega L_1 - \frac{1}{\omega C_1}\right) & \mathrm{i}\omega M \\ \mathrm{i}\omega M & R_2 + \mathrm{i}\left(\omega L_2 - \frac{1}{\omega C_2}\right) \end{bmatrix} \cdot \begin{bmatrix} \mathrm{I}_1 \\ \mathrm{I}_2 \end{bmatrix}, \tag{1}$$

where V_{s1} and V_{s2} are voltages induced into the both coils from the excited sample,

M is the mutual inductance and the other quantities are obvious from the circuit diagram.

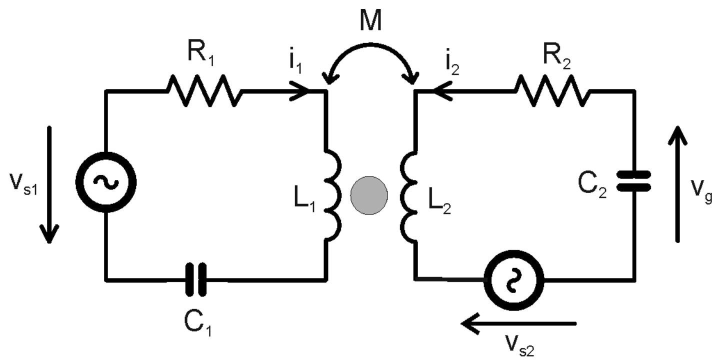

Fig. 1. Circuit diagram of the receive coil system. Voltages V_{s1} and V_{s2} are induced into the both coils from the excited sample.

The output voltage v_g is amplified using a preamplifier with high input impedance. Fig. 2 depicts a real configuration of the coil system.

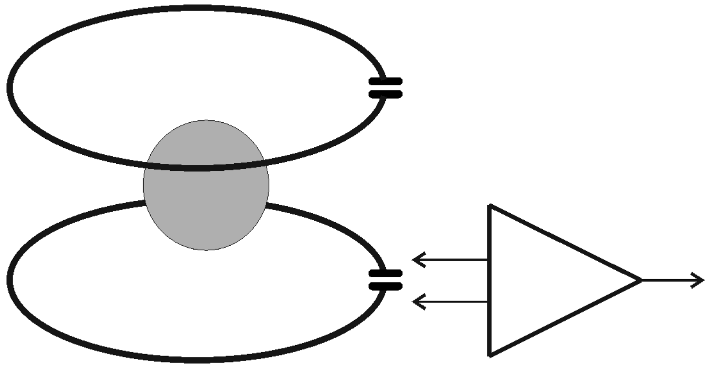

Fig. 2. A real configuration of the experiment. One of the both coils is active and its voltage is amplified using a preamplifier with high input impedance. The second coil is passive and serves to widening the active volume.

The used preamplifier must, besides the high impedance input, have also low own noise. Whereas the coil system was intended for a low-field scanner, also an appropriate operational amplifier (OA) can be used as a base for the preamplifier design. Preamplifiers using an operational amplifier are rather simple. There is a basic circuit diagram in Fig. 3 of a voltage amplifier with voltage and current noise sources. In practice the circuit diagram must be completed with protection circuits, protecting the semiconductor device from too strong signal during the excitation of the sample. The circuit with back-to-back diodes and detuning circuits are utilized. Many equations for calculation of the output noise of the OAs can be found in publications of the manufacturers, but they consider infinity voltage gain of the used operational amplifier. It can be fulfilled at acoustic frequencies, nevertheless at frequencies of MHz an infinity gain cannot be considered. The analysis of the circuit in Fig. 3 yielded the following equation for the spectral density corresponding to noise, added to output voltage V_2

$$S(\mathrm{V}_2) = \left(\frac{A \cdot (R_1 + R_2)}{R_1 + R_2 + A \cdot R_2}\right)^2 \cdot [\left(I_{n2} \cdot R_g\right)^2 + 4kTR_g + e_n^2 + \left(\frac{R_2}{R_1 + R_2}\right)^2 4kTR_1 +$$

$$+ \left(\frac{I_{n1} R_1 R_2}{R_1 + R_2}\right)^2 + \left(\frac{R_1}{R_1 + R_2}\right)^2 4kTR_2] \qquad (2)$$

RMS value of the noise voltage is given by

$$V_{2n} = \sqrt{\int_{f_0-\Delta f}^{f_0+\Delta f} S(V_2)df}, \tag{3}$$

where f_0 and Δf determine the noise bandwidth of the receiver, A is voltage gain of the used operational amplifier at the working frequency. Resistor R_g represents the real part of the coil system impedance. Sources of noise voltage e_n and noise currents I_{n1} and I_{n2} together with a noiseless operational amplifier simulate noise in the real preamplifier. The expression

$$G_v = \frac{V_2}{V_g} = \frac{A \cdot (R_1 + R_2)}{R_1 + R_2 + A \cdot R_2} \tag{4}$$

represents voltage gain of the preamplifier.

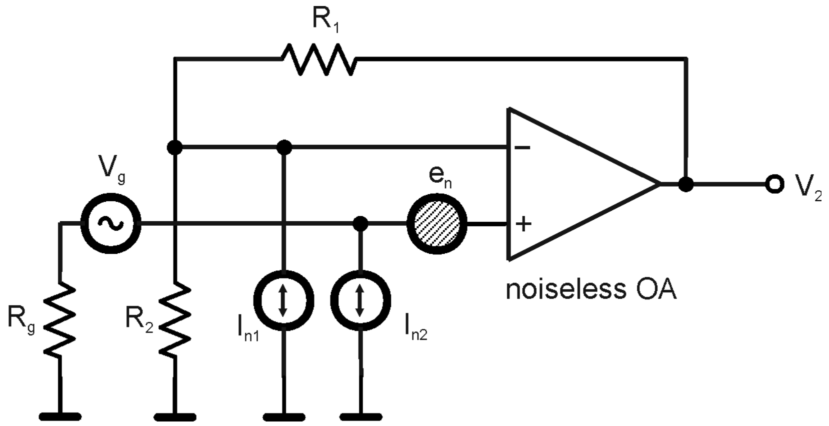

Fig. 3. Circuit diagram of the preamplifier with an operational amplifier. A noiseless operational amplifier together with voltage and current noise sources simulate the real circuit.

The amplifier is connected to the receiver using a cable, therefore output of the preamplifier must be matched to its impedance. All necessary calculations were performed using the program package Mathematica (Wolfram Research Inc., Champain IL). Verification experiments have been performed using the experimental scanner with home-made resistive magnet, equipped with the Apollo (Tecmag Inc., Houston, TX) console.

3. Results

The two one-turn square-shaped coils of the described coil system has been manufactured of copper tube with diameter of 6 mm. Dimensions of one coil is 30 cm × 30 cm. Each coil, including non-magnetic ceramic tuning capacitors is encapsulated in PVC shell. The active coil is connected to the preamplifier and the passive coil is in changeable distance from it to widen the active volume of the system. The operational amplifier for the preamplifier is ADA4817 (Analog Devices Inc., Norwood, MA, U.S.A.). It is a FET IC with very low voltage and current sources of noise. The ability of widening the volume of the coil was verified in the following experiment: the coil system was tuned to 4.45 MHz, the working frequency of the scanner and a beaker (more than 1 liter) filled with water solution of 5 nM of $NiCl_2$ and 55 nM of NaCl was measured using the spin echo measuring sequence. First the both coils were used to measurement and the SNR was calculated (Fig 4(a)) within the pixels of the sample. Subsequently only the active coil was used and the same measurement was repeated and the SNR calculated (Fig. 4(b)). Widening the active volume is evident when used the both coils in this experiment, though the SNR has been decreased. The result needs to be verified in more, different experiments.

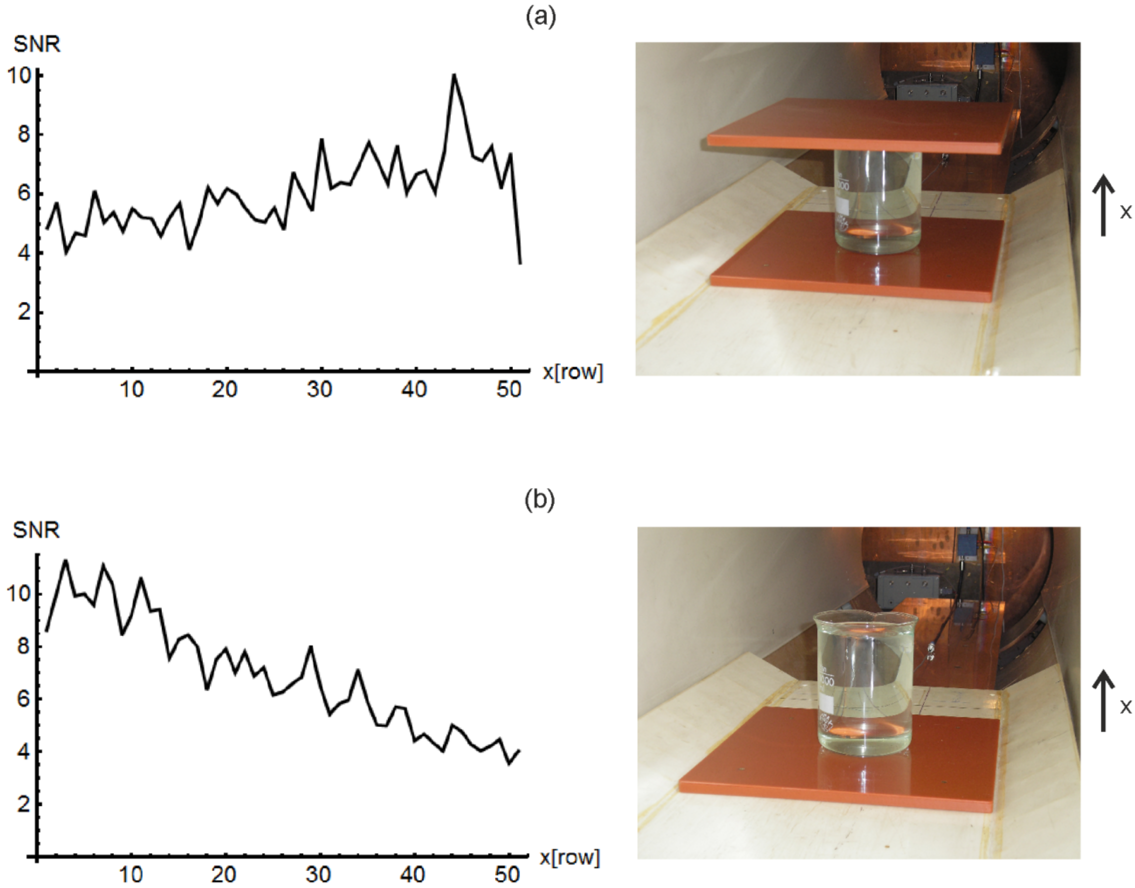

Fig. 4. Signal-to-noise ratio for experiments with double-coil system (a) or single-coil system (b). The active volume is more wide for the double-coil system. The value of the SNR depends also on parameters of the measurement and on qualities of the static magnetic field (stability, homogeneity, noise).

4. Discussion and Conclusions

Planes of the both coils are considered to be parallel. Nevertheless using the equations (1) it can be easily calculated that phase shifts between the signals induced from the sample into the both coils can change the shape of the output signal curve significantly. The best situation seems to be with the phase shift of $\pi/2$ but using such result in practice can be problematic. The width of the double-coil system active volume is larger, although its SNR is rather low. It can be increased using better filling the coil volume with the sample and also homogeneity of the static magnetic field within the coil and noise of the static magnetic field are very significant. The studies will continue in more, different experiments.

Acknowledgements

The research was sponsored by the Grant Agency of the Slovak Academy of Sciences, under Grant Number 2/0090/11 and by the Slovak Research and Development Agency, project number APVV-0513-10.

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