Application of Anisotropic Magnetoresistive sesnsors for detection of changes in organ activity

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***Abstract* – This paper addresses the measurements of biomagnetic fields that occur in the vicinity of biological tissues using AMR (Anisotropic magnetoresistance) technology based magnetic sensors. Throughout the years of research new technologies have emerged in the field of sensorics. In biomedicine, the most commonly used and the most precise, but at the same time the most complex and expensive is the SQUID magnetometer (Superconducting Quantum Interference Device). In recent years, less costly versions of magnetometer technologies have been perfected in the form of microelectromechanical systems. The latter offer a vast variety of sensors, which work on the basis of different principles (AMR, GMR, GMI, Hall effect). The amount of academic efforts on this subject indicates a relative lack of research concerning the usage of AMR technology for measurement of biomagnetic fields, which - caused by electrical properties of magnetically unexposed human body - ranges from approximately 0.1 nT in the vicinity of human heart, and around 1 pT near human brain. On the other hand magnetically exposed human body with devices such as MRI, reflects several times higher values of magnetic field. Top resolution of commercially available anisotropic magnetoresistive sensors touches the bottom level of biomagnetic field's spectrum, therefore we have investigated possibilities for its improvements. The main goal of research presented in this paper is to determine whether realization of AMR based biomagnetometer and its usage for such measurements is really possible.**

1 INTRODUCTION

Information about actions of human body is transfered via nervous system which connects center of human activity - brain - with all the other parts of the body. Nervous cells forming the nervous system are called neurons. It formation consist of body - axon - covered by myelin layer which is in equal intervals disconnected inside of Ranvier nodes, and axon terminal ending the synapse which connects neuron with other nerve cells. In a process of information being transfered, the chemical and electrical pulses are exchanging. Due to chemical signal (also known as neurotransmitter) release in a synaptic cleft connecting the chain of neurons, the receiving neuron's electrical potential is changed. [1]

Potential of neuron in an inactive state values approximately -70 mV. Its highest action potential on the other hand, values 50 mV. If neurotransmitter received by a neuron is strong enough to adequately increase its potential, the electrical pulse is being generated. Frequency of the generated pulses is in linear correlation with the value of the achieved neuron potential. The electrical pulses (short flow of a electrical current) in nerve tissue are present due to chemical changes (concentration of ions) in body. Even a short flow of current in (generally speaking) biological tissue contributes to magnetic field in its vicinity. Due to neuron's anatomy and way of pulse's transfer procedure, there can be imagined an infinitesimally short wire carrying a current $I\vec{dl}$ which represents a basic physical resource in era of magnetism. [2]

Therefore, nerve impulses being carried through the neurons are causing instantaneous magnetic fields directions of which are circular around axon of conducting neuron. If we can, in such a moment, measure all of the persisting magnetic fields in vicinity of biological tissue, we can actually measure the sum of all fields of currently affected neurons. Therefore we can determine the strength of impulses (the amount of affected cells) and by that measure the biological activity in a given moment (magnetogram). These procedures are commonly used in medicine to determine human organ activity: magnetoencefalography, magnetocardiography and others. Typical values of magnetic flux density in vicinity of magnetically unexposed human body are approximately from 0.1 nT to 1 pT [3]. Magnetically polarized biological tissue reflects different magnetic fields, especially in area of so called ultra-low-field MRI's. Its general idea is to polarize the biological tissue with harmless magnetic field (in range of 10 mT) and for needs of tissue's imaging, measure the field's reflection (in range of 10 μT) [4]. The technology mainly used for both types of biomagnetic observations is called Super-conducting Quantum Interference Device (SQUID), developed by David Cohen in early seventies. Its resolution is high enough to detect even the smallest biomagnetic fields, but its complexity and therefore the price is high. Some alternatives have also been used, such as SERF (Self-relaxation free) based atomic magnetometer or Fluxgate, but not in clinical environment. The field of our interest was to explore the possibilities of low cost sensors being used for such observations. We chose the anisotropic magnetoresistance (AMR) technology based microelectromechanical device, with promising resolution of 10^{-9} T and price in a range of several 10$ [5]. With given characteristics of Honeywell's AMR sensors HMC 1001 and HMC 1002, we have assumed that we will touch the bottom biomagnetic range of unpolarized biological tissue and on the other hand, whole range needed for implementation in new age ultra-low-field MRI's.

2 METHODS

Magnetoresistance is the property of a material or system of materials that results in a change of resistance when exposed to a magnetic field. Anisotropic magnetoresistance, discovered in late 19 century by William Thomson (Lord Kelvin) occurs in ferromagnetic materials. It is called anisotropic because, in contrast to ordinary magnetoresistance, it depends on the angle between the electric current and the magnetization direction. [6]

The AMR effect is described as a change in the scattering cross section of atomic orbitals distorted by the magnetic field. The resistance produced by scattering is maximal when the magnetization direction is parallel to the current direction and minimal when the magnetization is perpendicular to the current. In general, the resistance is given as a function of the angle φ, between the magnetization and current. [6]

$$R = R_0 + \Delta R \, \cos(\varphi)^2$$

The linearity of the equation and corresponding maximum sensitivity is when the magnetization is at the angle 45° with respect to the current in the material.

Commercial AMR sensors are realized in different manners to achieve optimal angle for optimal sensitivity. Honeywell HMC1001 sensor that was used in laboratory for investigation of low magnetic fields has a so called ``barber-pole'' structure of conductive electrodes between magnetoresistive ferromagnetic material as shown on Fig. 1.

Four AMR sensitive micromachined sensors form a Wheatstone bridge. Two pairs of AMR sensors are coupled with their sensitive axis at the angle of 180 degrees to each other.

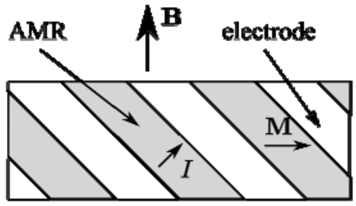

Figure 1: Barber pole structure of the magnetic sensor.

All electronic components have intrinsic 1/f noise, which is largest at low frequencies (near 1 Hz) which are of particular interest in biomagnetic field measurements. At higher frequencies thermal noise prevails (also called Johnson or shot noise). Minimization of the noise of the amplifiers and other electronics, not only the sensor is also critical in obtaining accurate measurements [7].

Noise of commercial samples that limit resolution of the sensor was investigated in [7]. It was determined that one axis sensor HMC1001 made by Honeywell excelled in lowest noise between tested integrated AMR sensor, where magnetic fields of around 0.2 - 1 nT can be measured using HMC1001 sensor in the low frequency range from 1--100 Hz.

The signal from our AMR sensor HMC 1001 is being transformed by the instrumentation amplifier INA 129 which amplified the difference of signals from the resistive bridge for a factor of 10^3 [8]. The offset value of the input, that corresponds to static magnetic field in the vicinity of the AMR sensor (such as Earth's magnetic field) must be compensated at this stage, thus voltage reference was connected to the offset input of the instrumentation amplifier.

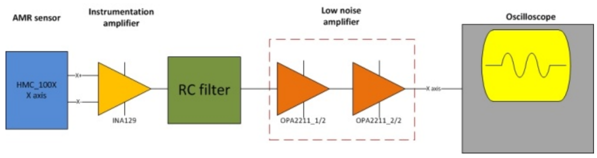

Figure 2: A block diagram of a built magnetometer.

The output signal's amplitude came in order of mV. The signal was noticeably affected by 50 Hz line noise (including its higher harmonic) due to industrial environment's electromagnetical influence - therefore, we have added an active first-order low-pass filter with cutoff frequency of 15 Hz to each subsequent amplification stage to reduce the amplitude of the line noise by -30 dB in total. Further on, signal from instrumentation amplifier was amplified with two stage inverting amplifiers based on OPA 211 low noise operation amplifiers, amplifying signal by 20 and 10 dB respectively [9].

The total signal's amplification was therefore a factor of 10^6 (120 dB).

Addressing possible power supply noise, the circuit was battery powered. This also allowed experimental work on the field, where ambient magnetic field noise is lessened. Whole electronics was electrically shielded by aluminum enclosure to avoid exposure to electromagnetic interference from other electrical devices.

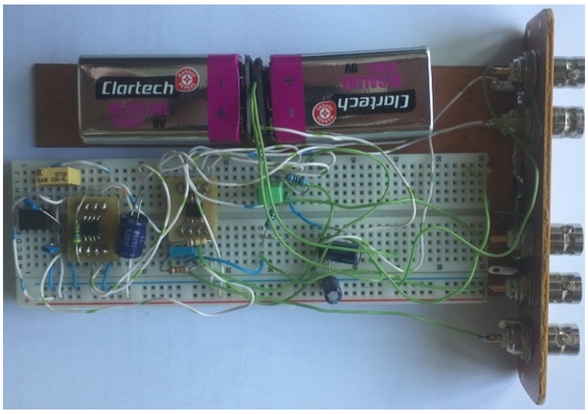

Figure 3: A prototype circuit for detection, filtration and amplification of the AMR sensor output.

3 RESULTS

Simulation of the circuit was made with LT Spice simulator using equivalent elements used in the experimental work. Although we made a couple of simplifications to the circuit, the circuit functionality itself remained the same.

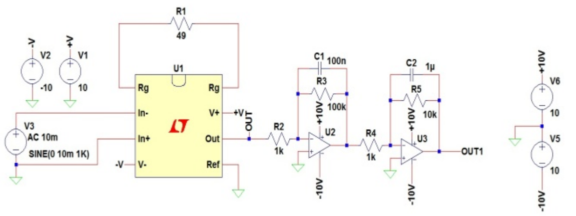

Figure 4: Simulated circuit with basic setup.

The AMR sensor was replaced by two different electrical sources. The offset input value of the instrumental amplifier was set to zero and signal input had zero offset as well. This mode corresponds to compensated sensor operation (no external time invariant magnetic field on the sensor).

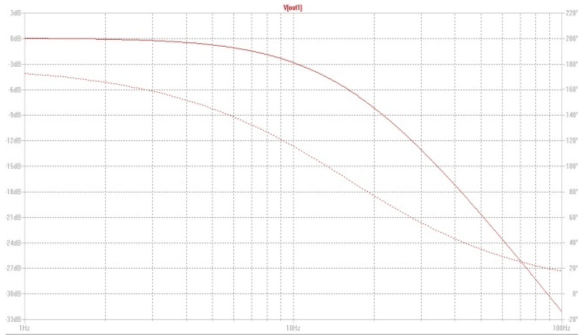

Figure 5: Simulation of a circuit with basic setup.

Considering the results of simulations and measurements of the noise at 50 Hz, the -30 dB attenuation of signal at 50 Hz is not enough to inhibit line noise to the level of thermal noise (there should be -80 dB attenuation), therefore we have made a simulation of modified active filter with Sallen Key topology using Butterworth's coefficients, that can be easily modified to provide required amplification of the signal.

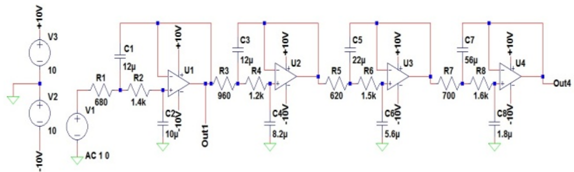

Figure 6: Simulated circuit with modified setup.

The examination showed that for total elimination of 50 Hz noise, we would need a filter of eighth order.

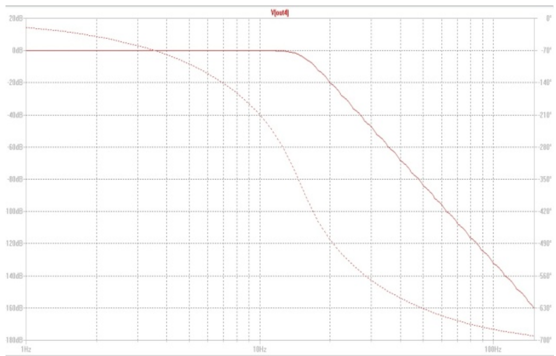

Figure 7: Simulation of a circuit with modified setup.

The main results (presented in Figure 8) of real-time examination were made in an industrial environment and showed that the measured peak-to-peak voltage was 28.125 mV. Examination's main goal was to measure the environmental noise, declaring the highest resolution our sensor is capable of. Transforming the graph's data, maximum resolution of HMC 1001 was 28 nT.

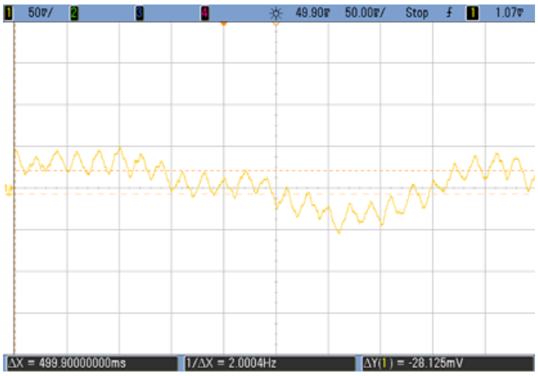

Figure 8: Real-time environmental noise measurements.

4 DISCUSSION

Due to results shown in previous section, the biomagnetic signal range of unpolarised biological tissue is evidently unreachable with the method presented in this paper. We even reach the theoretical detectability limit of chosen AMR sensor set by thermal and 1/f noise simply because the noise of the environment was an order of magnitude larger even after filtration. Improved filter stage will allow to reach the thermal noise limit of the sensor, but the sensitivity will still be to coarse to get meaningful results. Sensor used in our observation has the lack of higher resolution at least by factor of 10 for purposes of unexposed tissues studies. However, results showed that the highest resolution of our device is 10^{-8} T, so there exists a justified assumption of AMR sensor being capable enough for application in technology of ultra-low-field MRI, which requires measurements of reflected magnetic flux density in range of μT [4]. With given circumstances, implementation of AMR would significantly lower the price of MRI's usual build based on SQUID's. Despite the plausibility of the previously discussed hypothesis, we have some doubts about potential problems we would encounter. First subject worth of a research is stability of the sensor right after polarizing the tissue. The manufacturer's datasheet states that the period of so called “set/reset” pulse is 65 μs [5]. As declared in [4], the time, for SQUID based device, between polarizing the tissue and measuring its reflected magnetic field is 33 ms, theoretically coinciding with our sensor’s characteristic.

Acknowledgments

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