Air-core Coil Gradiometer for Biomagnetic Sensing in Non-shielded Environments

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***Abstract*—Magnetic fields emitted from the human body can serve as indicators of diverse health conditions. However, such fields are very small, making it hard to detect. Devices used to date for capturing these fields are bulky, expensive, and require additional equipment such as heaters, coolers, lasers, and/or shielding rooms. In this work, we report a lightweight miniature air-core coil gradiometer that is combined with advanced Digital Signal Processing (DSP) to capture biomagnetic fields in non-shielded environments. *In vitro* experimental results show that our gradiometer can pick up 50-Hz signals as low as 76 fT by averaging 5 min of raw data. Notably, the gradiometer's coil has an outer diameter of only 14.5 mm, height of 10 mm and weight of 1.64 g. In the future, this design can be modified to detect *in vivo* biomagnetic signals including: magnetomyography (MMG), magnetocardiography (MCG), magnetoencephalography (MEG), and magnetospinography (MSG).**

I. Introduction

Electromagnetic fields emitted by the human body have been widely used in clinical practice to diagnose various conditions. Traditionally, electric signals are collected as they can be easily captured via intrusive electrodes or via electrode pads adhered on the skin. However, electric signals suffer from various challenges. These include, but are not limited to, human tissue attenuation, intrusive procedures, and limited ability to provide three-dimensional views of the target organ/area.

Magnetic signals radiated by the human body overcome the aforementioned challenges, but their level is extremely low (order of 10^{-15} to 10^{-10} T) [1] [2]. In fact, the strongest human biomagnetic signal is 10^6 times lower than the earth's magnetic field. For this reason, devices used to detect these naturally emanated magnetic fields necessitate extremely high sensitivity. As such, they are bulky, expensive, and typically require additional equipment, such as heaters, coolers, lasers, and/or shielding rooms. For example, the current clinical standard, namely Superconducting Quantum Interference Device (SQUID), needs to be cooled to 77K or 4K in order to maintain a superconductive state [3] [4]. This increases the size of the device and the cost per use. Added to the above, SQUIDs must operate in shielded spaces; this further increase the cost and complicates the procedure.

In this work, we provide proof-of-concept results for an induction coil gradiometer that is miniaturized, lightweight, low-cost, and can operate in non-shielded environments, as inspired by [5]. Our *in vitro* results show that our device can detect 50 Hz sinusoidal signals as small as 76 fT by averaging 5 min of raw data. In the future, more realistic signals and higher sensitivity coils can be designed to detect human biomagnetic signals for diverse applications, including magnetomyography (MMG), magnetocardiography (MCG), magnetoencephalography (MEG), and magnetospinography (MSG).

Parameters	Value
Outer diameter [mm]	14.5
Inner diameter [mm]	13
Coil height/length [mm]	10
Wire diameter [mm]	0.2

(a)

(b)

Fig. 1. (a) Relevant coil parameters. (b) Fabricated air-core coil sensor.

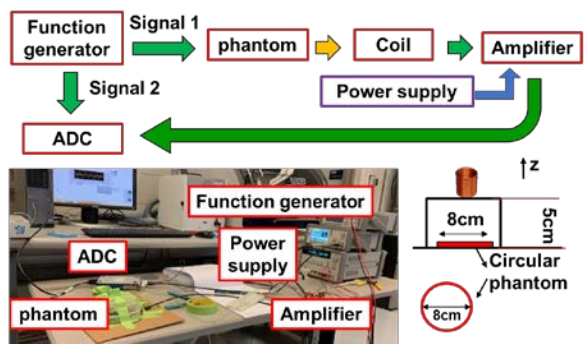

Fig. 2. Overall procedure and experimental set-up.

II. Operation Principle

Our detection system consists of an induction coil sensor, an amplifier, and an Analog to Digital Convertor (ADC). It is further combined with advanced Digital Signal Processing (DSP). The induction coil operates based on Faraday's law: magnetic fields emitted by the human body are picked up by the coil and generate time-varying voltage. In turn, voltage readouts upon the coil correlate to the magnetic field being picked up. However, since human biomagnetic fields are weak, the collected voltage falls under the noise floor and cannot be retrieved straight from the raw data. As such, an amplifier board is connected to the coil to amplify the received signal by 1000 times. The amplified signal is further connected to an ADC, with digital signals undergoing advanced DSP to retrieve the target voltage. In particular, window averaging and bandpass filtering are used to clear up the raw data, bringing up the actual biomagnetic signal from the noise floor.

The proposed sensor and related dimensions are shown in Fig. 1. The amplifier circuit is designed based on the board used in [5] and relies on a low voltage noise instrumental amplifier (INA217) to limit the introduced electronic noise. A voltage regulator pair is used to maintain a stable voltage source (±5V) to power up the amplifier. Finally, a 24-bit ADC (NI9239) is employed to collect the data. We purposely select such high number of bits to ensure high resolution, suitable for low-level signal recording.

Our DSP approach is similar to that reported in [6]. The collected raw data first go through a bandpass filter that targets the intended frequency range. The filtered data are then cut into multiple windows via a synced guiding signal, each window containing one full wavelength of the magnetic signal. Here, the guiding signal can be any signal that is somehow synced with the target magnetic signal. For example, when capturing cardiac magnetic signals (MCG), electrocardiogram (ECG) or pulse can both be used as guiding signals. Finally, all windows are averaged to ultimately bring down the uncorrelated noise and retrieve the signal.

III. EXPERIMENTAL SET-UP AND RESULTS

A. Experimental Set-up

The overall procedure and experimental set-up are shown in Fig. 2. Signal 1 and Signal 2 represent the guiding signal and the source of the magnetic field, respectively. Specifically, Signal 2 is fed into a circular loop (8 cm in diameter) to create a magnetic field that emulates that emitted by the human body. For this proof-of-concept experiment, Signals 1 and 2 are selected as 50 Hz sinusoidal waves that are generated using a function generator. We purposely select such low frequency, as typical of human biomagnetic signals. Expectedly, other frequencies and/or multi-frequency signals can be considered in the future.

The emulated magnetic signal is picked up by the coil sensor and further amplified. To account for a typical deep-body-to-skin distance of 5 cm, our sensor is placed 5 cm away from the biomagnetic-emitting loop. Of course, the closer the coil sensor is placed to the loop, the easier it is to detect the signal. The sensor is placed vertically (see Fig. 2), picking up only the z-direction signal that has the highest strength. The collected raw data together with Signal 1 are fed into the ADC for subsequent DSP. The signal is recorded for a period of time depending on how many windows of averaging are needed for denoising. Expectedly, longer recording time implies a higher number of windows being averaged and leads to lower levels of noise.

Our goal is to identify the smallest detectable signal that can be retrieved by averaging data over a certain amount of time. By comparing this signal level to that of typical human-emitted magnetic fields, we can confirm whether the sensor is suitable for *in vivo* signal acquisition in non-shielded environments.

B. Experimental Results

Preliminary experimental results show that our coil sensor can detect 76 fT of the 50 Hz signal over 5 min of data (Fig. 3).

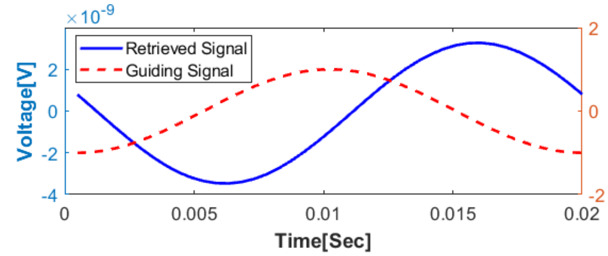

Fig. 3. Processed final averaged signal: blue solid line is the final retrieved signal, red dash line is the guiding signal (Signal 1).

We note that the lowest signal level produced by our function generator is 1mV peak-to-peak. Hence, attenuators are used to further reduce the level. Specifically, 60 dB attenuators are employed to create a 0.02 µA peak-to-peak current flowing in the biomagnetic-emitting loop. The corresponding magnetic field can be calculated using Biot-Savart's law: along the centerline of the loop and at 5 cm distance, it is 76 fT.

Remarkably, our detected signal lies in the lower spectrum of the magnetic fields radiated by the human body (10^{-15} to 10^{-10} T) [1] [2]. This provides promise for biomagnetic signal detection from within the human body in non-shielded environments. Here, it is worth noting that the latter signals are typically multi-frequency. As would be expected, the DSP reported in this work may not be as effective when removing noise for a wider bandwidth as it cannot eliminate noise inside the signal's own frequency range. To this end, more advanced DSP methods can be pursued in the future.

IV. CONCLUSION

We reported a proof-of-concept design for an air-core coil sensor that can detect 50 Hz magnetic signals as low as 76 fT in non-shielded environments over 5 min of recording. This high sensitivity provides promise for biomagnetic signal detection from within the human body, suitable for detecting and monitoring diverse health conditions. In the future, improved signal processing techniques will be pursued to validate feasibility for wider bandwidth signals, similar to those encountered in the human body.

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