

Biological and medical applications of a new electric field sensor

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Abstract— We describe the biological and medical applications of a new electric field sensor technology developed at Sussex. It provides an ultra-high impedance alternative to conventional low impedance Ag/AgCl electrodes used in electrophysiology and may even be used to acquire nuclear magnetic resonance signals via the electric field component of the free induction decay. Results are reported for both of these application areas.

I. INTRODUCTION

Bioelectric measurements are usually made by detecting ionic current flow. Major advances in electronic instrumentation, software development and in the understanding of the physiology have occurred, but have not been matched by equivalent advances in detection techniques. For example, the detection of ionic current is still routinely used for monitoring of the clinical electrocardiogram (ECG) and electroencephalogram (EEG) and is achieved either by using invasive subcutaneous techniques, or from the surface of the body using Ag/AgCl electrodes attached to the skin, acting as transducers [1]. Attempts have been made to use dry electrode techniques [2], but they lacked the accuracy of the conventional measurements. In this article we report on the development of a new sensor technology which allows high quality bioelectric signals to be acquired via capacitive coupling, or remotely at a distance from the source. This is achieved using the electric potential sensor developed at Sussex, and operates by measuring the spatial potential (or electric field) created by the source. Clearly this technology has many possible applications including security sensing and biometrics.

Electromagnetic measurements up to radio frequency usually utilise magnetometers to measure the magnetic field. There is a large range of such devices, with a wide variety of performances. By contrast, the use of electric field sensors or electrometers to measure electric field is less common. Indeed, the choice is restricted to either insensitive portable instruments or laboratory-based electrometers [3], which are not user friendly. This is simply because to date there has been no suitable sensor technology available. The electric potential sensor fills this gap in the portfolio of measurement tools by enabling non-contact measurement of electric fields or voltages to be made with high precision. In fact, the electric potential sensor may be regarded as a non-contact voltmeter with extremely

high input impedance. As recognized by other workers, this allows impedance matching to be achieved at the measurement electrode [4], thus enabling the highest signal to noise ratio [5] to be attained. The EPS is truly generic, scalable in size, non-invasive and completely biocompatible. The technology is ideal for integration into array formats for real-time imaging applications, since the capacitive cross coupling between EPS is less of a problem than the inductive cross coupling with arrays of magnetic sensors [6].

As would be expected from a generic measurement tool, EPS applications are many and varied. We have demonstrated proof of principle of non-contact electric potential sensing in many areas including; body electrophysiology [7] (electrocardiogram, electroencephalogram), non-destructive testing of composite materials [8], imaging electrical activity of integrated circuits [9], following the propagation of pulses in saline solutions [10], novel nuclear magnetic resonance (NMR or MRI) sensing probes [11] and real-time array imaging [12]. For the purposes of this article we shall concentrate on two areas of interest namely, remote monitoring of electrophysiological signals and NMR.

II. ELECTRIC POTENTIAL SENSOR

Details of the design of the sensor have been previously published by the authors [13]. The EPS consists of an electrometer grade operational amplifier with external bias circuitry designed so that it does not compromise the input impedance of the sensor. In addition, associated feedback systems provide the functions of guarding, bootstrap and neutralisation. The net effect of this combination of positive feedback techniques is to produce a broadband sensor in the range 100 μHz to 100 MHz with extremely high input impedance ($\sim 10^{18} \Omega$) and low effective input capacitance ($\sim 10^{-15} \text{F}$). The actual operating bandwidth is dependent on the application and determined both by the choice of amplifier and by the coupling capacitance between the sensor and the source. The EPS is capable of monitoring, via the displacement current only, through weak capacitive coupling, changes in spatial potential or electric field due to currents flowing within a source, even through an insulating surface layer. This capacitive coupling may take the form of either an air gap or a dielectric spacer. When an air gap is used this is termed remote mode as opposed to contact mode when a dielectric spacer is present. The use of a dielectric spacer is beneficial in most circumstances, since it maintains a constant distance between the sensor and the source and therefore a constant coupling capacitance. Any variation in coupling capacitance may lead to a variation in the apparent gain of the sensor and is therefore undesirable. In addition it also increases the coupling capacitance and hence the signal amplitude, since the relative dielectric constant is usually greater than 2.

III. RESULTS

Results are presented for two applications, NMR readout via electric field and detection of remote cardiac signals. Traditional NMR uses pulsed radio frequency methods. Both the input signal and the nuclear precession output signal are coupled inductively, introducing physical and electronic constraints on performance. The problem is the direct inductive coupling between the transmitter and receiver coils. A number of strategies exist to alleviate this, including; making the transmitter and receiver coils perpendicular to each

other; adding diode protection circuitry; Q damping the transmitter, and mismatching using quarter wave lines. Despite this the inherent difficulty remains i.e. a large amplitude transmitter pulse will couple to the receiver coil and hence to the amplifier, leading to saturation. By contrast, the EPS utilises the electric field associated with the precessing magnetic field of the nuclear spins. Therefore we couple in inductively and out capacitively. The upper trace in figure 1 shows a conventional inductively coupled free induction decay signal due to a sample of glycerine. The lower trace shows a preliminary result acquired using an EPS coupled capacitively through the thin wall of the sample tube. The results of figure 1 were measured simultaneously, using a solenoidal coil for the inductive signal and a small gold foil electrode (\sim few mm^2) on the outside of the tube for the EPS signal. Clearly there is a high degree of correspondence between these two.

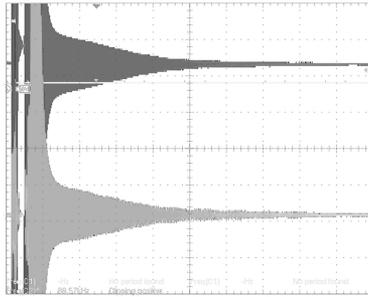


Fig. 1. The upper trace shows a conventional free induction decay signal as a function of time for a sample of glycerine. The lower trace is a preliminary result for an EPS coupled through the wall of the sample tube.

We have also developed a smart version of the EPS, with additional feedback circuitry, which has the ability to reject the four principal components of line related noise, the major constituent of electric field noise in most environments. The rejection is measured to be 50 dB at the fundamental frequency, in this case at 50 Hz. The frequency and width of these notches in the response are digitally tunable by adjusting an external clock frequency. This technique results in a sensor with barely perceptible line noise and the sensitivity required to detect a human heart signal remotely through an air gap of 10 cm using a 2.5 cm diameter sense electrode.

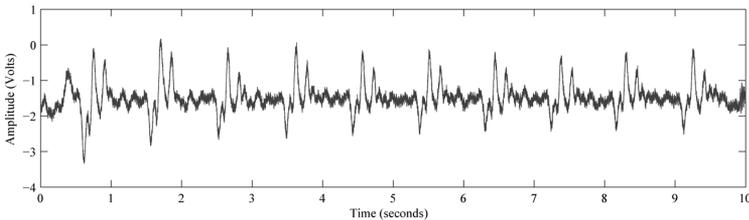


Fig. 2. Human heart signal measured remotely through an air gap using a 2.5 cm diameter sense electrode. The data was acquired with the subject seated and the sensor 10 cm behind the chair in a noisy unshielded room.

The data shown in figure 2 was acquired with the subject seated and the sensor positioned 10 cm behind the chair. The data shown is raw and was collected in an operating band-

width of 1 Hz to 300 Hz in real-time, with no digital signal processing or signal averaging techniques. This is a remarkable result which we have previously only been able to achieve within the confines of an electrically screened enclosure. The measurement was made in a laboratory which was fully cabled with line sockets and in close proximity (~0.5 m) to line operated computer equipment and other live electronics. Clearly the ability to acquire electrophysiological information so readily has many potential applications.

IV. CONCLUSION

The new mode of NMR signal acquisition could be used in a number of ways. For example, for real-time imaging without the use of magnetic field gradients, or for micro NMR where high field gradients are difficult to achieve. The ability of the smart sensor to reject noise has allowed us to measure electrophysiological data in an electrically noisy environment. This could have significant repercussions for telecare, security and biometrics.

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