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Wideband precision phase detection for magnetic induction spectroscopy

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A R T I C L E I N F O

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A B S T R A C T

Magnetic induction spectroscopy (MIS) has many potential applications in medical engineering as well as industrial and food manufacturing process applications, providing a contact-less impedance measurement. However, the applications of MIS is currently limited due to the high precision of phase detection required over a wide band of frequencies. This paper focuses on phase detection aspect of the MIS. The chosen phase detection method is investigated in depth and a prototype hardware and software is developed. The phase detection system is then tested and compared to other recent MIS system design. The prototype hardware is able to measure the phase difference of signals from 200 kHz to 20 MHz with milli-radian precision which will significantly enhance the MIS systems.

1. Introduction

Magnetic Induction Spectroscopy (MIS) is one of the bio-electrical impedance spectroscopy (BIS) technique that can be used to determine the electrical conductivity of materials as a function of frequency [2]. It is known that for biological tissues, the conductivity property is frequency dependent because of the cellular structure, e.g. intracellular fluid (ICF) and extracellular fluid (ECF). There is a great potential for MIS based technology for biomedical engineering applications in particular for its non-contact measurement nature. Extensive work is done in both contact and non-contact impedance spectroscopy for medical and industrial applications [13,11,12,8,10,7,6,5,9]. When a low frequency electric signal is passed through biological tissues, the highly resistive cell membranes act as barriers so the field can only react with the ECF phase. At radio-frequencies, the field can penetrate through both the ICF and ECF phases. By applying electrical fields using different frequencies, a complete dielectric dispersion properties of the sample can be obtained. Based on these concept, MIS can be applied into many applications including: Medical, such as tumour and stroke detection [1]. Although the main interest area for MIS is in biological field, it can also be used in industrial areas, such as detection of pipe blockages; and land mine detection. The traditional BIS techniques require a direct contact between electrodes and measuring samples, so the electric signal can be directly induced into the measuring sample. It creates a number of difficulties such as electrode positioning, intrusive contamination and electrode-sample interface consistency. In some industries like food manufacturing, direct contact is not allowed as it increase the contamination risk. To overcome these problems, an inductive spectroscopy methods were proposed so the direct contact of the samples is no longer required. MIS technique generally utilises two coils: one transmitting coil and one receiving coil. By injecting an alternative current into the transmitting coil, the primary magnetic field will be generated and induce eddy current on the testing sample. This stimulated eddy current will generate the secondary magnetic field which contains the conductivity information of the sample itself [3]. By sensing this secondary magnetic field using the receiving coil over a wide frequency range, the full BIS information can be obtained. Conductivity detection using MIS is challenging because of the small magnitudes of the induced currents, which results in a small phase shift signal on the receiving coil. Hence the performance of an MIS system is limited due to the high precision of phase detection required over a wide band of frequencies. The phase change caused by a biological variation is generally very small [1], therefore milli-radian measurement accuracy is required. Here we define a number of important parameters in performance of phase detector. Phase drift is also critical as it shows how much the measured phase changes over a long period of time [3]. Noise in the phase measurement is a measure of how much the measured phase changes over multiple measurements taken over a short period of time [3], also an important consideration. Phase skew is how much the measured phase changes when the input signal amplitude is changed was considered in [3]. The aim of this paper is to present a novel MIS electronic design and experimental validation; results from a precision phase detector suitable for MIS working in a wide range of frequencies. The conductivity, over a range of frequencies, of biological material contains information about the structure of the cells, making the MIS a potentially attractive bio-impedance device [1]. MIS

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has the advantage that it does not require contact with the material being tested, bio-electrical impedance spectroscopy (BIS) requires contact to be made with the material being tested. Following section shows the system implementation and experimental results.

2. Phase detection methods

Digital phase detection by sampling signal and mixing is proposed a phase detection method. The signal is digitally sampled, once sampled, the phase difference between the received signals can be determined by using a discrete Fourier or Hilbert transform. Phase can be measured by mixing the signals to an intermediate frequency before sampling and determining the phase using digital signal processing. Unlike the systems that mix down to base-band, this system needs to be able to sample the inputs very fast, therefore the use of a micro-controller instead of an FPGA would be less suitable. Multiplying with an offset signal also results in noise ($y(t)$) at an image frequency also being mixed down to the same lower frequency. Any noise at $(2\omega_{LO}-\omega)$ will also be mixed down to ω_{IF}.

$$y(t) = C\cos((2\omega_{LO}-\omega)t-\Phi_i) = C\cos(-(2\omega_{LO}-\omega)t + \Phi_i) \tag{1}$$

$$\omega_{IF} = -(2\omega_{LO}-\omega) + \omega_{LO} = \omega-\omega_{LO} \tag{2}$$

Wei et al. [2] found that the odd harmonics from mixing with a square wave not to be an issue, therefore the noise at the single image frequency is not likely to be a problem. If the noise at the image frequency is an issue it is possible to use the Hartley architecture to image reject. This is our chosen method in this study.

2.1. Complete system

The prototype circuit is constructed and assembled based on this design. Both hardware and software development are required for controlling the phase detector effectively. Fig. 1 shows the DDS signal generator, the Arduino and the final prototype design connected for automated testing with MIS coil system. Two coils of 12 turns each with radius of 2 cm is used for transmitting and receiving coil and a current of 0.1 (A) was used in transmitting coil.

2.1.1. Description of hardware operation

The system consists of two analog multipliers (AD835), which mix the input signals with a locally generated signal. Both of these are voltage signals. The locally generated signal is generated by a 10 bit, 400 MHz DDS (AD9859) which is controlled via a digital serial interface (SPI). The DDS is controlled to output a signal which has a frequency offset from the input signals by approximately a couple of hundred Hz. The output of the DDS is filtered using a third order balanced LC low pass ladder filter. The DDS control is implemented by using a FPGA to measure the frequency of the input signal, subtract a offset, and then set the local oscillator frequency by setting the frequency control register in the DDS via a SPI interface. The FPGA measures frequency of the input signal by counting the number of edges over a known period of time. Before the signal is input to the FPGA for frequency measurement, the signal is converted to a square wave by a comparator (TLV3501) with hysteresis. The signals output from the mixers contain a frequency component at the difference in frequency between the local oscillator frequency and the input signals, this is a couple of hundred Hz. Before sampling of the signals, frequency components of more than half of the sampling frequency need to be removed to prevent aliasing. It is important that the anti-aliasing filters have a very small affect on the phase of the signals because it is not possible to have exactly identical analog filters due to real component value variations. In order to achieve a small affect on phase of the wanted signal, a high cutoff frequency is chosen. A RC filter for each channel is used. Because of the high cutoff frequency, a high sampling rate is required. The signals are sampled using two 12 bit, 10 MHz ADCs (AD9220). The parallel digital outputs from the ADCs are input to the FPGA where a large amount of the redundant data resulting from the poor analog anti-aliasing filter and the oversampling is removed using a 10th order CIC filter and decimator. This decimator is implemented in the FPGA's configurable logic. The lower rate data, $\left(\frac{10\text{ MHz}}{1024}\right)$ is stored to an external SDRAM which is on the FPGA development board (Altera DE0-Nano). After a number of samples have been written to memory, they can be read and copied to a PC via a USB interface. The PC does further digital signal processing in order to determine the phase difference between the two signals.

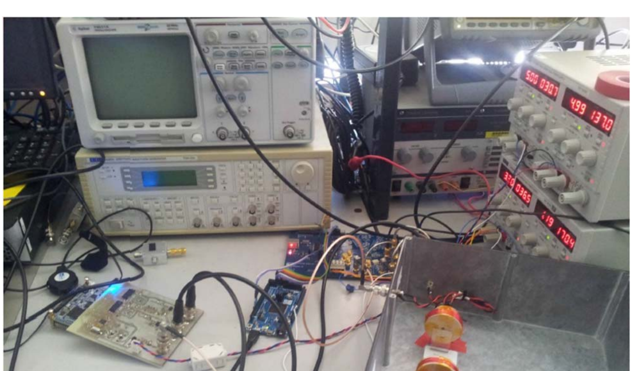

Fig. 1. Test set up with the MIS coil set up.

2.2. Automated test implementation

It is decided that in order to characterise the performance of the prototype a automated test system to be assembled. An automated test system has the major advantage that data can be collected over many combinations of the 4 dimensions of independent variables: These are; input phase difference, input amplitude, input frequency, and time. The test system needs to be based around a signal generator that is capable of generating a wide range of signals with a known and adjustable phase, amplitude and frequency. Suitable signal generators are selected: A 40 MHz sample rate TTI TGA1242 dual output arbitrary waveform generator, and a dual output 10-Bit, 500 MHz sample rate, Analog Devices DDS (AD9958) evaluation board. The Analog Devices DDS evaluation board is chosen due to its use of SPI interface, and the higher sample rate.

3. Experimental results

The results from the automated testing of the final prototype design are shown here. The difference between the measured phase difference and the input phase difference is shown against the input phase difference and the input amplitude in Fig. 2. The noise in the phase measurement is calculated as the standard deviation of 32 measurements each sampled for 52 ms and is plotted against input amplitude and input phase difference in Fig. 3. The phase drift and the noise in the phase measurement is shown over 12 h by Figs. 4 and 5. In ideal case the colormap should show zero difference between true phase difference and recovered phase difference, but small error in this phase detection shown in Figs. 2 and 3.

Table 1 shows the peak to peak drift and Table 2 shows the mean noise in the phase measurement. Figs. 6 and 7 show the prototype is very linear. The linear regression is calculated for the prototype for 16 data points between 0 m rad and 5.75 m rad and shown in Table 3. The measured phase is plotted against frequency for a number of input phase differences and shown in Fig. 8. The noise in the phase measurement plotted against input signal amplitude is shown in Fig. 9. Fig. 10 shows the variation in the measured phase as the input signal amplitude is varied (see Tabel 4).