

## SQUID sensor with additional compensation module for operation in an AC applied field

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**Abstract.** A possible implementation of an in-vivo SQUID susceptometer able to estimate the liver iron concentration of humans uses a low frequency applied field together with a lock-in detection. The room-temperature magnetising coils and the detection coils are designed to minimize their mutual coupling. Nevertheless, deviation from ideal behaviour causes a residual signal in the detection coil, with an amplitude significantly larger than the patient's. In addition low frequency noise is added by any relative displacement of the magnetising and sensing coils. Thus, we designed a SQUID sensor using a compact compensating module to be used in a multichannel SQUID susceptometer. The sensor consists of two second order axial gradiometers, wounded one inside the other on the same support. The sensing channel is larger than the compensation channel which is only sensitive to the residual signal. Each gradiometer is coupled to a dc SQUID with parallel washer configuration. The output of the compensation channel is A/D converted and is processed by an adaptive algorithm running on a real time unit. The compensation signal is coupled to the sensing channel by an additional feedback loop. The performances of a prototype module will be presented.

### 1. Introduction

Instrumentation based on SQUID sensors operating in an applied field can be used to measure the liver iron concentration which is a useful parameter for the diagnosis of haematological diseases implying iron overload [1]. A possible implementation of an in-vivo SQUID susceptometer uses a low frequency applied field, generated by large coils external to the dewar containing the superconductive devices, together with a lock-in detection. With this kind of design is possible to operate the SQUID sensor well above the 1/f corner of the device and environmental noise, and to achieve a high signal to noise ratio [2].

The magnetizing and the detection coils are designed to minimize their mutual coupling. Nevertheless, deviation from ideal behavior causes a residual signal in the detection coil. The amplitude of this signal could be so large as making the measurement of the patient signal a hard work. In addition, low frequency noise is added by any relative displacement of the magnetizing and

sensing coils since the amplitude of the residual signal is a function of the sensor position in the applied field. To overcome these problems, we designed a SQUID sensor using a compact compensating module, to be used in a multichannel architecture for in vivo measurement [3]. The sensor is equipped with an additional second order axial gradiometer (compensation channel) that is mounted on the same support of the sensing gradiometer. The compensation gradiometer is placed far from the object under study and it is only sensitive to the residual signal. The signals detected by two dc SQUIDs coupled to these gradiometers are A/D converted at high sampling frequency and then processed by an adaptive algorithm running on a real time unit. The output of this process is the signal used as additional feedback for the compensation of the residual on the sensing channel.

In the following sections we will give some details about the components of the SQUID sensor and the compensating module together with preliminary results obtained with a prototypal unit.

## 2. The sensor

The sensor consists of two second order axial gradiometers, wound one inside the other on the same support. The sensing gradiometer is made of Nb wire wound around a MACOR support and is coupled to a dc SQUID. The gradiometer is 25 mm in diameter with a 60 mm baseline, and has an inductance of about 1.8  $\mu\text{H}$ . The compensation channel consists of a second order gradiometer coupled to a dc SQUID, with the same design as the one coupled to the sensing channel. As for the primary sensing gradiometer, the compensation gradiometer is made of Nb wire wound around a MACOR support. The compensation gradiometer is 4 mm in diameter, has a 10 mm baseline, and has an inductance of about 0.2  $\mu\text{H}$ . Both units are shown in Figure 1. The compensation gradiometer is inserted in the center of the sensing one, far from patient position. It is therefore not sensitive to signal generated by magnetized sample, but only to the magnetizing field residual and to its variations.

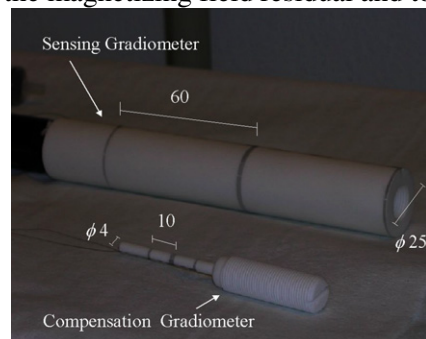


Figure 1. The sensing and the compensation gradiometers. Distances are expressed in mm

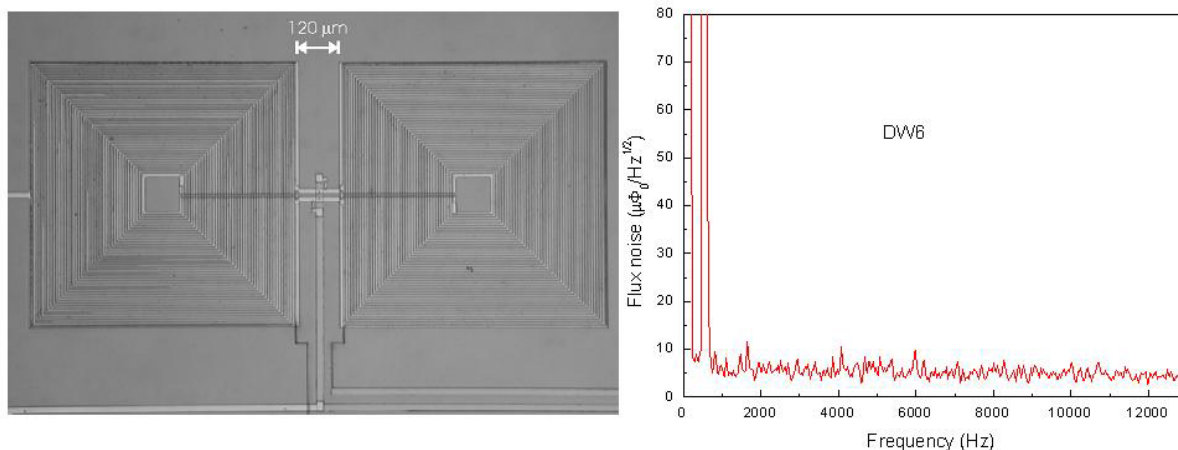


Figure 2 *Left*) The dc SQUID in the double washer configuration, comprising a 80 turns input coil. *Right*) Noise spectrum with the input coil connected to a Nb single loop

Each gradiometer is coupled to a dc SQUID (see Figure 2) fabricated with high quality Nb/AlO<sub>x</sub>/Nb junctions [4]. The SQUID design is suitable for operation in an applied field, since it is based on a double washer parallel configuration with a gradiometric layout which rejects any background field. The sensing gradiometer signal is connected, by means of a superconducting contact using a Nb screw, to a Ketchen type input coil, inductively coupled to the SQUID loop. This design of the input coil provides a good match to the inductance of the sensing gradiometer and to the compensation gradiometer. The SQUID is designed to have a high intrinsic responsivity (about 1 mV/ $\Phi_0$ ). This feature allows to couple the device directly to the read-out electronic, without the use of standard modulated electronic scheme. The SQUID flux noise is about  $2 \mu\Phi_0/\sqrt{\text{Hz}}$ .

### 3. The compensation electronics and the algorithm

The sensing and compensation unit outputs are simultaneously A/D converted at a sampling rate of about 4 kHz by a National Instruments apparatus, with PXI6031E A/D conversion boards. Then, the compensation signals is calculated by means of an embedded controller (PXI8176), based on a 1.2 GHz Pentium III running a real time operating system. A scheme is shown in Figure 3. The compensating procedure is based on a classical adaptive noise cancellation scheme [5]: the reference signal from the compensation channel is processed by a classical FIR filter whereas the signal from the sensing channel is used as error signal for the compensating algorithm that updates the coefficients of the filter. The parameters of the compensating algorithm are determined without the sample being present and then frozen during the measurement, so that the sample signal is not compensated.

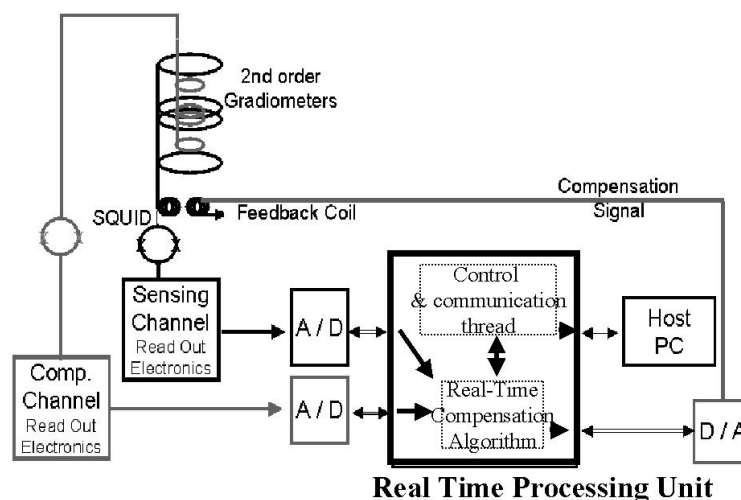


Figure 3. The digital processing and data acquisition and system. The compensation signal, after D/A conversion, is coupled to the sensor by means of an additional feedback path

### 4. Performances of the compensation module

We here report on some tests for the compensation of the residual generated by a homogeneous field produced by a couple of large magnetizing coils (138 cm in diameter) in Helmholtz configuration. In these preliminary tests we used a prototypal realization of the sensor supports featuring an intrinsic balancing factor of 50 for the sensing gradiometer and only 10 for the compensation gradiometer.

The calibration of the sensing channel was  $4 \times 10^{-3} \text{ V}/\Phi_0$ , whereas the reduced sensitivity of the compensation channel was  $1.4 \times 10^{-4} \text{ V}/\Phi_0$ . The power spectrum density of both channels are shown in Figure 4.

We used different amplitudes of the applied field measuring the residual signal after activating the compensation algorithm. In Figure 5 (left) an example of the effect of the activation of the compensation algorithm is presented. This recording has been done with a very low amplitude (20 mG) of the applied field to avoid the saturation of the SQUID read out electronics. We reached a value

of 105 dB for the rejection of the residual signal.

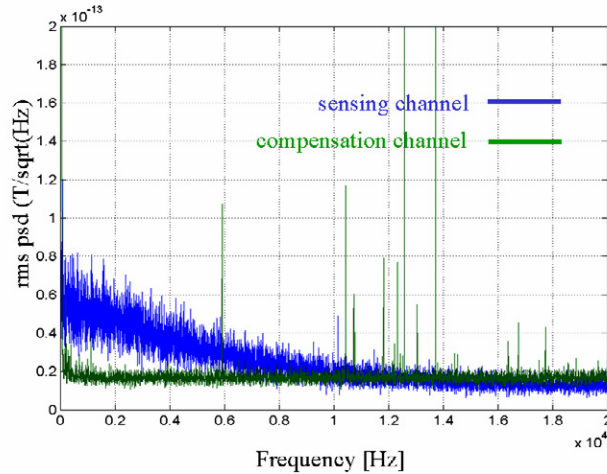


Figure 4 The power spectrum density (rms) of the sensing channel and the compensation channel

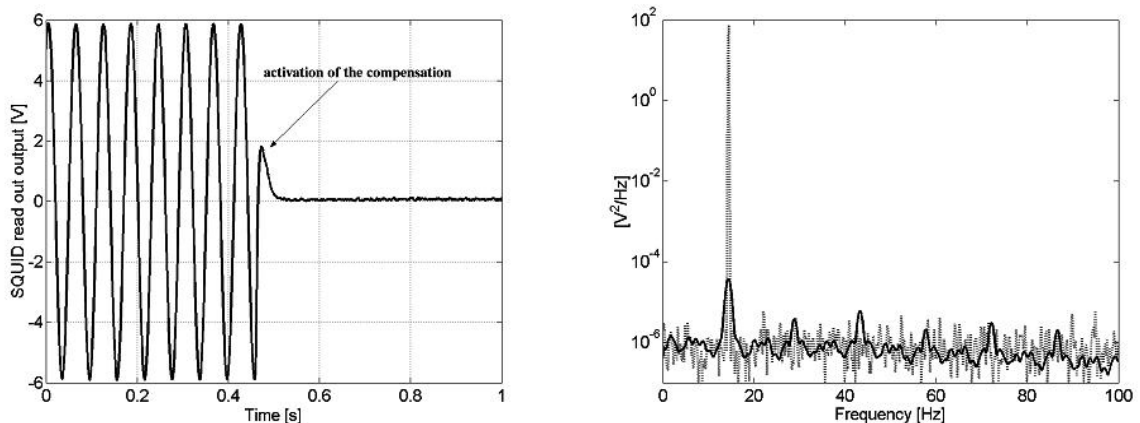


Figure 5 *Left*) Example of the activation of the compensating strategy with an applied field of 20 mG; *Right*) Power spectrum of the signal on the sensing channel after the cancellation of the residual with an applied field of 300 mG (solid line); estimated power spectrum before the activation of the cancellation process (dotted line)

In Figure 5 (right) we show also the power spectrum of the signal on the sensing channel after the cancellation of the residual with an applied field of 300 mG. On this graph we superimpose the estimated power spectrum (it is not a real signal) before the activation of the cancellation process. Higher order harmonics are generated by the algorithm. However they do not affect the detected signal because of the narrow bandwidth applied by the lock-in detection technique. We obtained a rejection of the applied field better than 70 dB. Our final goal will be making this module effective to reject applied fields larger than 1 G.

## References

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