Ultra low noise induction magnetometer for variable temperature operation

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Abstract

In recent publications, the authors have reported on the performance of compact broadband induction magnetometer systems with an operating bandwidth from 100 μHz to 1 MHz. The best room temperature noise performance achieved was ~ 500 fT/√Hz from 10 kHz to 1 MHz. In this paper, we describe improvements to the coil design and signal processing electronics, which result in a further reduction of the noise (~ 50 fT/√Hz in the range 1–30 kHz). In addition, we have chosen a magnetic material with a very small temperature dependence allowing us to investigate whether a reduction in noise may be achieved by operating the system at a reduced temperature (77 K). © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

Using compact solenoidal sensing coils with high permeability cores [1,7–9], the authors have demonstrated previously that an induction magnetometer system may be constructed with a noise performance ~ 500 fT/√Hz at 1 kHz. Improvements have been implemented to the coil design, core material and the signal processing electronics, which have resulted in a significant reduction in the level of noise. These improvements have been so successful that the magnetometer described here approaches the theoretical limit for the noise performance of an induction system (> 1 kHz) operating at room temperature. The magnetometer is constructed using a magnetic material, which is compatible with cryogenic operation. This will also allow us to investigate the origin of the noise by operating the system at a reduced temperature (liquid nitrogen, 77 K) in a heavily shielded environment. This choice of magnetic material also produces a magnetometer capable of operating over a wide range of temperatures.

2. Coil design

Using published data on the performance of magnetic materials at low temperatures [2], we have chosen Metglas [3] as a suitable temperature-independent low loss amorphous core material. The amorphous nature of the tape is significant since the associated resistivity is much higher than would be the case for magnetic alloy materials such as supermumetal [4], resulting in lower eddy current core losses. A Metglas toroid was tested using a B–H loop curve tracer based on a published design [5], but adapted to allow measurements over a range of temperatures from 293 to 4.2 K. Using this, we have been able to verify the temperature-independent performance of the material from 293 to 77 K. A core 5 mm² and 150 mm in length (l), consisting of ~ 250 laminations, was fabricated from 0.018 mm thick Metglas 2714AF tape. The coil was wound using...
0.15 mm diameter wire and 10,000 turns, as for the previous ferrite and supermumetal cored magnetometers [9]. The theoretical maximum rod permeability ($\mu_{\text{eff}}$) for this geometry is 250 based on the finite aspect ratio of the rod [6]. This ratio would need to be infinite (the toroidal limit) in order to obtain an effective permeability close to the initial permeability of the material ($\mu_0 \approx 90,000$). Compared with the previous systems, the Metglas cored coil is clearly exhibiting a much higher $\mu_{\text{eff}}$, as illustrated by the following measurements:

<table>
<thead>
<tr>
<th></th>
<th>Ferrite F14</th>
<th>Supermumetal core</th>
<th>Metglas 2714AF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance ($L$)</td>
<td>4.7 H</td>
<td>5.4 H</td>
<td>7.1 H</td>
</tr>
<tr>
<td>Resistance ($R$)</td>
<td>320 $\Omega$</td>
<td>285 $\Omega$</td>
<td>315 $\Omega$</td>
</tr>
<tr>
<td>$R/L$</td>
<td>68 Hz</td>
<td>53 Hz</td>
<td>44 Hz</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>26.3</td>
<td>26.6</td>
<td>26.8</td>
</tr>
</tbody>
</table>

The significant increase in coil inductance for the Metglas cored coil may be attributed entirely to the effective rod permeability of the core, since all other parameters were constant. The frequency below, which the coil may no longer be regarded as a pure inductor is given by $R/L$ for each coil and is an important parameter. Below this frequency, any induced signal will be significantly attenuated by the resistance of the coil when a current is drawn. This results in a first-order high pass filter characteristic in the frequency response of the magnetometer.

3. Signal processing

Since the current drawn from an induction coil is proportional to the applied magnetic field, and is independent of frequency above $R/L$, we choose to amplify this rather than the coil voltage. The signal from the coil is fed to a current-to-voltage converter circuit in order to produce an output voltage proportional to the applied magnetic flux. In Fig. 1, we show the frequency response for the magnetometer with a simple current-to-voltage converter using a 100-k$\Omega$ feedback resistor. The effect of the $R/L$ roll off may be seen at low frequency producing the expected high pass filter response. To allow signals lower in frequency than $R/L$ to be processed, it is necessary to introduce a compensation network into the feedback loop of the current-to-voltage converter. In Fig. 2, we show the final design for the converter circuit. Here, we have two time constants, $1/RC$ and $1/R_r C$. The shorter time constant $1/RC$ is set to the $R/L$ frequency of the coil and determines the frequency at which the compensation network will start to act. Below this frequency, the impedance of the combination of $R$ and $C$ will act as an integrator to produce a gain, which increases as the frequency decreases. The second, and longer time constant 1/$R_r C$ prevents the gain in becoming too large at very low frequency, which would generate drift and instability. The use of extremely long time constant feedback networks is essential if the drift and instability problems usually associated with integrator circuits are to be avoided. For this magnetometer, $1/R_r C$ is set to 10 mHz, although this could easily be lowered to 100 $\mu$Hz if required. Fig. 3 shows the frequency response for the compensated current-to-voltage converter circuit when driven by a current source. At high frequency, the conversion gain is set to 1.
V/10 μA. This is a factor of 10 higher than in previous versions [1], and was implemented after preliminary results indicated that the limiting noise contribution may be due to the converter circuit. The gain at low frequency is limited to ~1 V/30 nA at ~10 mHz.

4. Results

The induction coil was placed at the centre of a Helmholtz pair driven by the tracking generator output of a spectrum analyser (Hewlett Packard HP3562A). In this way, we obtained the frequency response for the magnetometer system. The result is shown in Fig. 4, with an essentially flat response from ~10 mHz to 30 kHz. Since these measurements were conducted in a magnetically unshielded environment, it seems likely that the apparent noise between 10 and 100 mHz was due to external pickup. The system was then calibrated with a known fixed frequency (200 Hz) field applied using the Helmholtz coils, and a calibration factor of 1 V output for 50 nT applied field was measured. To measure the noise response of the magnetometer, the coil was placed inside a pair of nested mu-metal cans insulated from each other, each with a tightly fitting lid. These were located inside a screened room facility to minimise the effect of external noise as much as possible. Considerable care was exercised in obtaining this data to ensure that DC offsets and drift did not produce spurious results. Discrepancies between the linear and log resolution modes of data acquisition with this instrument are common, and are symptomatic of measurement problems. It was therefore necessary to compare the magnitude of the noise in both data acquisition modes to ensure consistent results. In addition, the measured noise was at least a factor of 30 above the intrinsic noise floor of the instrument for all frequencies. In Fig. 5, we show the noise response with the lowest noise ~50 fT/√Hz at the high frequency end of the spectrum, above 1 kHz. By comparison with earlier versions of the magnetometer, we can clearly see that both the high frequency noise floor and the 1/f noise level at 1 Hz are reduced:

Perhaps the most significant result, however, is that the Metglas cored coil has performed better at room temperature (293 K) than the supermumetal cored coil at reduced temperature (77 K). Preliminary data indicated that for low frequency operation, significant benefits may be gained by cooling induction magnetometers to 77 K, and at first sight, the present data appear to be consistent with that. The thermal noise current ($I_N$ in a 1 Hz bandwidth) is given by:

$$I_N = \sqrt{(4k_B T/R)}$$

where $k_B$ is the Boltzmann constant, $T$ is the absolute temperature (K), $R$ is the coil resistance. For our system parameters: $I_N = 7.2$ pA/√Hz. By combining the measured field calibration factor (1 V/50 nT) and the conversion factor of the current-to-voltage converter (1 V/10 μA), we are able to obtain a relationship between the magnetic field and the input current. Hence, (1 V/10 μA)/(1 V/50 nT) = 50 nT/10 μA or 50 fT/10 pA. Using this to convert our theoretical current noise into an equivalent magnetic field noise produces a theoretical minimum noise floor of ~36 fT/√Hz. The measured value of 50 fT/√Hz is reasonably close to the predicted one, but on cooling to 77 K, no measurable reduction in the high frequency noise was seen. This suggests that above 1 kHz,
the present system is limited by current noise in the current-to-voltage converter circuit.

5. Conclusions

It has been demonstrated that with careful choice of magnetic core material and coil design, the theoretical noise limit for an induction magnetometer operating at room temperature may be approached. The measured noise response approaches 50 fT/√Hz at the high frequency end of the spectrum (1–30 kHz), significantly lower than previous compact induction magnetometer systems. The magnetometer is capable of operating over a wide range of temperatures from room temperature to 77 K, although no improvement in noise performance has been seen on cooling the magnetometer coil. This leads us to the conclusion that the principle source of noise is the converter circuit. Two routes seem to exist for reducing the contribution from the current-to-voltage converter and these require further investigation. If the noise is inherent to the operational amplifier used then a commutating auto zero amplifier may be the best route in reducing the 1/f noise. If on the other hand, the 1/f dependence arises because of the frequency-dependent impedance presented to the electronics by the coil, then an improvement may be produced by matching the coil to the converter, possibly using a transformer [10].

References

[6] Fair-Rite Products, PO Box J, One Commercial Row, Wallkill, NY 12589, USA.

Biographies

Dr. Robert J. Prance received his B.Sc. in Physics from the University of Liverpool in 1976 and his M.Sc. in Applied Cryophysics, with a research on high frequency SQUID magnetometers, from the University of Lancaster in 1977. He joined the “Quantum Circuits Group”, University of Sussex working on improving the performance of SQUID magnetometers. He was a CASE graduate student supported by Mullard Laboratory, Redhill. In 1983, he got his D.Phil in Physics with a research on the behaviour of a UHF SQUID in a low noise environment from the University of Sussex. He was appointed SERC Research Associate to work on the spectroscopy of weak link ring devices, viewed as macroscopic quantum objects. In 1985–1991, he was a Research Fellow in the British Petroleum Venture Research Unit, working on experimental investigations of macroscopic quantum objects. He collaborated with B.P. Research Centre, Sunbury on the application of non-invasive sensors to non-destructive testing in the oil industry. In 1991, he was promoted to Senior Research Fellow at the University of Sussex. In 1995, he was appointed Lecturer in Electronic Engineering, School of Engineering, University of Sussex, and a member of the “Physical Electronics and Instrumentation Group”. In 1994–1997, he was a consultant in D.E.R.A. Fort Halstead and McCorquadale Card Technology, Lewes. In 1998, he was promoted to Senior Lecturer, and in 1999, promoted to Reader in Electronic Engineering.

Professor Terry D. Clark received his B.Sc. in Special Chemistry from the University of London in 1961. He worked for Mullard Laboratories, Redhill, on electron tunnelling phenomena in superconductivity. In 1967, he seconded to Philips Laboratory, Eindhoven, to work on two and three dimensional arrays of Josephson weak links. In 1971, he received his PhD in Physics from the University of London. He was appointed Senior Research Associate at the School of Applied and Engineering Physics, Cornell University, USA to work on the operation of SQUID devices. In 1974, he was a visiting Professor in Physics, University of Copenhagen, Denmark, with a research on non-linear problems in superconductivity. In 1975, he was appointed Senior Research Fellow at the Physics Department, University of Sussex. He established the “Quantum Circuits Group”. In 1985–1991, he was a Senior Research Fellow in the British Petroleum Venture Research Unit, working on macroscopic quantum phenomena in superconducting weak link rings. He collaborated with B.P. Research Centre, Sunbury on the application of non-invasive sensors to non-destructive testing in the oil industry. In 1990, he was appointed Reader in Physics, University of Sussex, and in 1995, appointed Professor of Physical Electronics, School of Engineering, University of Sussex. He is the Director of the Physical Electronics and Instrumentation Group.

Dr. Helen Prance received her B.Sc. in Physics from the University of Birmingham in 1977 and her M.Sc. in Medical Physics and Biomedical Engineering, with a research on ultrasound scanning of bone healing, from the University of Aberdeen in 1978. She joined the “Biomedical Engineering Group”, University of Sussex, to work on dynamics of blood flow. In 1979, she transferred to the “Quantum Circuits Group” to develop SQUID magnetometers for human body measurements. In 1985, she received her D.Phil in Physics on quantum electrodynamic duality in superconducting weak link circuits. In 1985–1991, she was a Research Fellow in the British Petroleum Venture Research Unit, working on ultra low noise cryogenic electronics and duality in macroscopic quantum objects. She collaborated with B.P. Research Centre, Sunbury on the use of cryogenic electronics in NMR spectroscopy. In 1994, she was appointed EPSRC Advanced Research Fellow to work on investigations of the energy band structure of macroscopic quantum objects with Professor Clark and Dr. Prance in the “Physical Electronics and Instrumentation Group”, University of Sussex. In 1999, she was appointed Lecturer in Electronic Engineering at the School of Engineering, University of Sussex.