FLUXGATE MAGNETOMETER FOR TEMPERATURES UP TO 180°C

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For applications in geothermal drilling fluxgate magnetometers in Vacquier geometry are investigated. The high operation temperatures in these applications require new selection of materials, especially for the core where Vitroperm 800R from Vaccumschmelze is employed here. The apparent permeability of the Vitroperm core at 260°C was found to be 6% lower than at room temperature. We characterize the fluxgate sensor by its closed loop sensitivity in dependence of temperature up to 180 °C. At room temperature, the sensor exhibits a closed-loop sensitivity of 130.000 V/T, a linearity of better than 40 ppm in the range ± 50 μT and a noise at 100 Hz of 15 pT/Hz^{½}. The sensitivity of the sensor operated in a current-compensation loop at 180°C is only 0.6% higher than the room temperature value, mainly caused by the temperature coefficient of the resistance of the copper wire of the secondary coil.

Keywords: Fluxgate sensor, Vacquier geometry, high temperature operation

1 INTRODUCTION

Classical drilling processes in geology use the earth's magnetic field to navigate their tools. Generally, vector fluxgate magnetometers are applied as sensitive magnetic field sensors due to their robustness, accuracy and temperature stability. The exploration of new energy sources, i.e., geothermal energy, implicates even higher requirements of the sensors. Drilling depth up to 5000 m, correlating with ambient temperatures up to 250°C, requires sensors with extremely reliable behaviour under these operating conditions. For the operation at such high temperatures, materials have to be investigated that can be used for the realization of fluxgate magnetometers.

2 EXPERIMENTAL

2.1 Materials

To investigate various core materials, coils with a length of $l = 40$ mm and diameter $d = 1.94$ mm were fabricated from thin enamelled copper wire and a bobbin made of ceramic Alsint™ 99.7 [1]. They were bonded using special high temperature silicone. As core material, nanocrystalline Vitroperm VP800R stripes from Vacuumschmelze [2] with a length of 45 mm were employed. Vitroperm VP800R has a nominal Curie temperature of 600°C and it was thermally treated to have a R-shaped magnetization loop. It should therefore be suitable as core material for fluxgates operating up to at least 250°C.

2.2 Temperature dependence of effective permeability of Vitroperm core

Using a precision impedance analyzer (Agilent 4294A), the spectral impedance of coreless coils as well as of coils with Vitroperm core were studied in dependence of temperature. Fig. 1 depicts the magnitude of the impedance in dependence of temperature. Measurements were performed in a tube oven. The measured impedance spectra were analyzed with the equivalent circuit diagram depicted in Fig. 2. The values of the resistance R_s and the capacity C_p were extracted from measurements on the coreless coil. We found an increase of R_s originating from the temperature coefficient of the copper wire resistivity. The inductance of the air coil was found to rise with temperature with about 30 ppm/°C. The inductance of the coil with Vitroperm

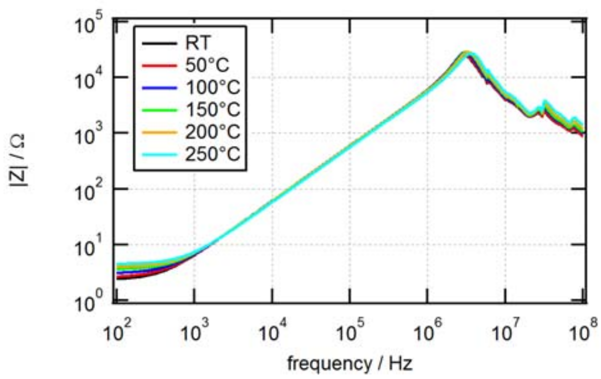

Fig. 1. Measured dependence of magnitude of impedance of coil with Vitroperm core on frequency for different temperatures (RT – room temperature).

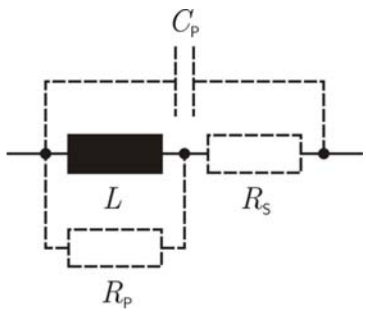

Fig. 2. Equivalent circuit diagram used to analyze the impedance spectra shown in Fig. 1.

core decreased with a temperature coefficient that was only ten times higher. The apparent permeability of the core μ_a was estimated with [3]

$$\mu_a = \frac{L_{core} - L_{air}}{L_{air}} \cdot \frac{A_{coil}}{A_{core}} + 1$$

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where L_{core} and L_{air} are the inductances of the coil with and without core, respectively. A_{coil} and A_{core} are the cross-sectional areas of the coil and the core, respectively. The temperature dependence of the apparent permeability is shown in Fig. 3. As can be seen it decreases by only 6% when increasing the temperature from room temperature to 250°C. For comparison, the apparent permeability of a Vitrovac 6025Z core at 240°C is already close to zero.

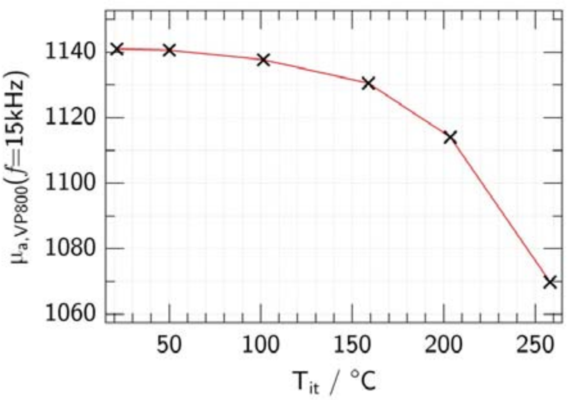

Fig. 3. Temperature dependence of effective permeability of Vitroperm core.

2.2 Vacquier-type fluxgate magnetometer at room temperature

Based on two identical coils with Vitroperm core, a Vacquier-type fluxgate magnetometer was built. A schematic drawing is depicted in Fig. 4. To build the sensor, two of various Vitroperm-core coils with identical properties were selected. The sensor was operated with our standard readout electronics [4] which is based on the second-harmonic detection principle and which was developed for operation of our highly sensitive room temperature fluxgate sensors [5]. To increase the linearity, these sensors are generally operated with field compensation, i.e., besides the excitation and detection coils an additional compensation coil is required. In order to reduce complexity of the sensor this extra compensation coil is omitted and the high-temperature fluxgates is operated in a current-feedback mode (Fig. 5).

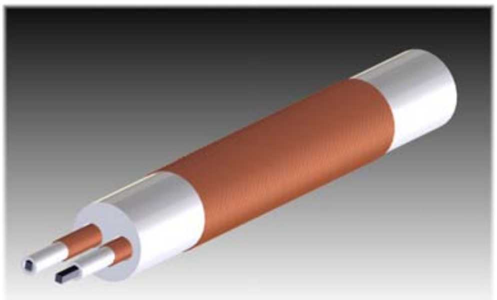

Fig. 4. Drawing of Vacquier-type high-temperature fluxgate

Furthermore, since the main application area of the developed sensor is navigation using the earth's magnetic field, the readout electronics were laid out to provide only a sensor bandwidth of 300 Hz.

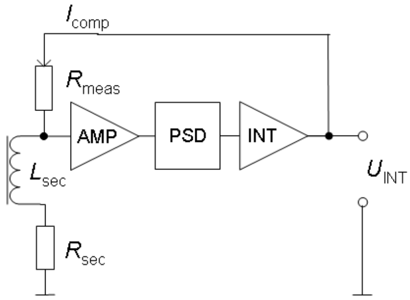

Fig. 5. Current feedback scheme.

The room temperature characterization was carried out in a triple mu-metal shield. The sensor exhibits a closed-loop sensitivity of $S = 130000$ V/T. The linearity of the system, measured in the range of ±50 μT, amounts to < 40 ppm and – for the given experimental setup – was found to be comparable to that of the commercial sensor MAG-03MCL 100 from Bartington [6]. The magnetic field noise measured with a dynamic spectrum analyzer 35670A from Agilent is shown in Fig. 6.

The magnetic field noise in the white region was determined to 15 pT/Hz$^{1/2}$ with a $1/f$ corner at 10 Hz. This value can presumably be further reduced by a better adjustment of the readout electronics.

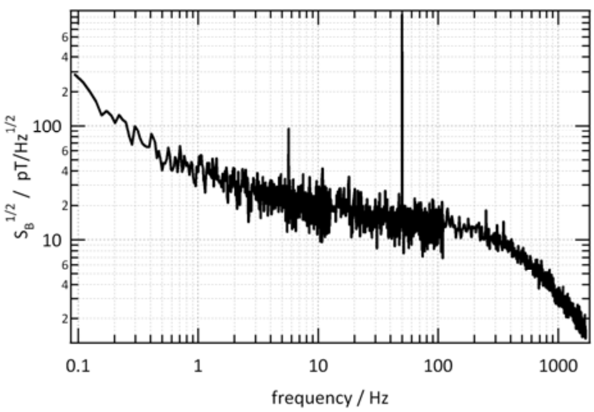

Fig. 6. Magnetic field noise measured at room temperature in triple mu-metal shield.

2.2 Vacquier-type fluxgate magnetometer at temperatures up to 180°C

Temperature dependent measurements of the sensitivity of the high-temperature fluxgate sensor were carried out in the test lab "Magnetsrode" of the Institute for Geophysics and Extraterrestrial Physics of TU Braunschweig. The background magnetic fields were compensated with a special compensation coil system. For the temperature dependent measurements, the temperature was increased from room temperature to 180°C – the maximum realizable temperature with this set-up – and then gradually ramped down. At each temperature point, the field was varied from -50 μT to +50 μT in 5 μT steps to determine the fluxgate sensitivity and linearity.

Figure 7 depicts the measured inverse sensitivity versus temperature. A nearly linear increase of the sensitivity was found which can be described by

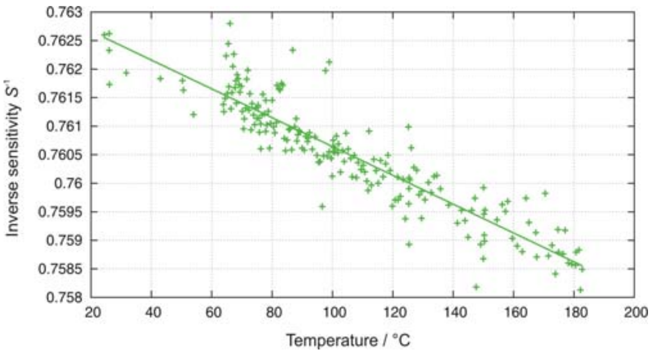

Fig. 7. Inverse sensitivity versus temperature

$$S(T) = S_{20^\circ\mathrm{C}}\left(1 + \frac{33.17\times10^{-6}(T-20^\circ C)}{^\circ\mathrm{C}}\right),$$

where T is the temperature in °C. The sensitivity at 180°C was less than 0.6 % higher than the value of $S \approx 130000$ V/T measured at room temperature.

To understand the slight increase of the closed-loop sensitivity with temperature – note that the apparent permeability showed decay with a temperature coefficient of 6% – the realized readout scheme must be taken into account. The current feedback is schematically depicted in Fig. 5. The external magnetic field H_{ext} determines the feedback current via the coil constant k_{sec} of the secondary coil resulting in [7]

$$\mu_0 H_{\mathrm{meas}} = k_{\mathrm{sec}} I_{\mathrm{comp}} = \frac{k_{\mathrm{sec}} U_{\mathrm{INT}}}{R_{\mathrm{meas}} + R_{\mathrm{sec}}}$$

where R_{sec} is the ohmic resistance of the secondary coil. Taking the temperature derivative and taking into account of

$$\frac{\mathrm{d}\mu_0 H_{\mathrm{meas}}}{\mathrm{d}T} = 0$$

one obtains for the temperature coefficient of the closed-loop sensitivity

$$\alpha_{\mathrm{FG}} = \frac{1}{U_{\mathrm{INT}}}\frac{\mathrm{d}U_{\mathrm{INT}}}{\mathrm{d}T} = \frac{1}{R_{\mathrm{meas}} + R_{\mathrm{sec}}}\left(\frac{\mathrm{d}R_{\mathrm{meas}}}{\mathrm{d}T} + \frac{\mathrm{d}R_{\mathrm{sec}}}{\mathrm{d}T}\right) - \frac{1}{k_{\mathrm{sec}}}\frac{\mathrm{d}k_{\mathrm{sec}}}{\mathrm{d}T}$$

With the experimentally chosen values $R_{meas} = 5.36$ kΩ and $R_{coil} = 55.8$ Ω, with $\mathrm{d}R_{meas}/\mathrm{d}T = 0$ for the room temperature electronics and using the temperature coefficient of copper for $(\mathrm{d}R_{sec}/\mathrm{d}T)/R_{sec}$ one obtains for the first term on the right-hand side 40.5×10^{-6} K^{-1} which is slightly larger than the measured value $\alpha_{FG} = 33.2\times10^{-6}$ K^{-1}. Thus, the temperature dependence of the closed-loop sensitivity is dominated by the temperature coefficient of the resistance of the secondary coil wire. The remaining difference must be attributed to the temperature coefficient of the coil constant k_{sec} which amounts to 7.3×10^{-6} K^{-1}. Measurements of the temperature coefficient of the inductance of an air coil of identical geometry provided a temperature coefficient of 35×10^{-6} K^{-1} which is only about a factor of two higher than the thermal expansion coefficient of the copper wire. Consequently, it is most probable that the measured temperature coefficient of the coil constant k_{sec} is caused by an increase of the coil cross-sectional area due to thermal expansion of the wire. Also, the temperature coefficient of the closed-loop sensitivity of the fluxgate sensor can be further minimized by choosing a proper value of the resistance R_{meas}. In contrast, in open-loop operation the temperature dependence of the sensitivity would be dominated by the temperature dependence of the apparent permeability μ_a.

3 CONCLUSIONS

In conclusion we prepared a fluxgate sensor for operation at high temperatures and investigated its properties up to 180°C. At this highest temperature the closed-loop sensitivity was 0.6% higher than the room temperature value when the sensor was operated in a current-compensation mode. The noise measured at room temperature was found to be 15 pT/Hz$^{1/2}$ in the white noise region above 10 Hz. Noise measurements at higher temperatures up to 250°C are in preparation.

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