

Vector fluxgate magnetometer for high operation temperatures up to 250 °C



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ABSTRACT

Vector fluxgate sensors have to operate at high temperatures for various applications. In drilling processes with greater drilling depths fluxgate sensors and corresponding electronic circuits are required to operate in a high temperature environment of up to 250 °C for a prolonged period of time. We present an accordant three-axis vector fluxgate system consisting of three single Vacquier-type fluxgate sensors and the signal processing electronics. The high temperature stability is achieved by selecting appropriate materials, mainly for the fluxgate core. The electronic circuits are built using commercially available silicon-on-insulator processed active and appropriate passive devices. The sensor system was characterized in a high temperature environment (up to 250 °C) by evaluating sensitivity, noise, crosstalk, excitation current amplitude and bandwidth. We found a system sensitivity of 28 kV/T (at room temperature) with an acceptably low temperature coefficient of $6.8 \times 10^{-4} \text{ °C}^{-1}$ and a room temperature flux density noise of 43 pT/(Hz)^{1/2} at 1 kHz. At 250 °C the noise values decrease by approximately 50%.

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1. Introduction

Fluxgate sensors are known for their robustness, low noise and their ability to measure weak dc and low frequency ac magnetic fields [1–4]. They have a broad application field including space exploration [5–7], non-destructive evaluation [8,9] and detection of biomagnetic markers [10,11]. They are also applied in drilling processes in geology to navigate the drilling head and to survey drilling holes [12–14]. To explore new energy sources, i.e., geothermal energy, drilling depths up to 5000 m are necessary, where ambient temperatures can rise up to 250 °C. The sensors and the electronic parts have to withstand these temperatures. This demanding task requires careful selection and matching of electronic and sensor components.

2. Sensors

The choice of suitable materials for high temperature operation is important. Regarding the core material, magnetic characteristics must be stable over a broad temperature range, especially a high Curie temperature is crucial. We recently demonstrated that nanocrystalline high permeability Vitroperm VP 800R made by

Vacuumschmelze GmbH is a promising core material for temperatures above 180 °C [15].

For our new fluxgate sensors we used a similar approach. Our wirewound sensors are of Vacquier-type geometry. This set-up features two identical excitation coils with inversely oriented current flow allowing magnetic filtering of the excitation signal in a common detection coil.

Each of the two excitation coils (number of turns 200, length 28 mm) is wound on a tube (length 30 mm, diameter 2 mm) made of ceramic Alsint material obtained from Morgan Technical Ceramics Haldenwanger [16] which also provides mechanical support. The core is again made out of nanocrystalline high permeability Vitroperm VP 800R material obtained from Vacuumschmelze GmbH [17]. Due to its high Curie temperature of 600 °C, Vitroperm is useable in a high temperature environment and therein advantageous over Vacuumschmelze's Vitrovac 6025 material, which is well suited for room temperature sensors [18,19], but limited to a Curie temperature of 240 °C. Porous Vitroperm material strips of 30 mm length were thermally treated to possess an R-Shaped magnetization loop. The core cross-sectional area amounts to 0.6 mm × 0.6 mm. The thermal expansion coefficients α of Vitroperm ($8 \times 10^{-6} \text{ °C}^{-1}$) and the Alsint ceramic ($7.8 \times 10^{-6} \text{ °C}^{-1}$) match reasonably well. Thus, thermally induced mechanical stress is limited.

The coils consist of a specially coated copper wire of 125 µm in diameter, which is obtained from Elektrisola GmbH [20]. Its solderable coating called Estersol E180 consists of polyester imide and can withstand temperatures of 250 °C for several hundred hours.

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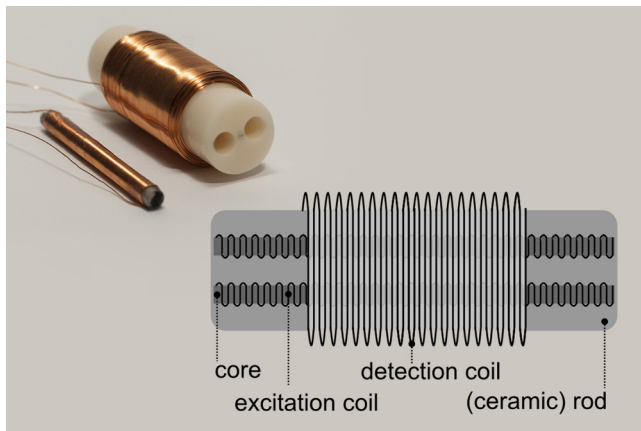


Fig. 1. Individual components of the presented Vacquier-type fluxgate (upper left side showing one excitation coil wound on a ceramic rod including the core material and the detection coil wound on a ceramic rod that gives support for the excitation coils) and schematic drawing of Vacquier-type fluxgate elements (lower right side).

Providing two identical excitation coils is crucial to achieve a high magnetic filtering of the excitation signal. For each of the three fluxgates we chose two coils which preferably were nearly identical in their electric specifications, mainly their inductance measured at 1 kHz (value of approx. 270 μH) and their Ohmic resistance (around 2.5 Ω).

The detection coil (24 mm in length) is wirewound on a ceramic Alsint rod (length 30 mm, diameter 8 mm) with two through borings that provide mechanical support for the excitation coils and the included core material. The number of wire layers was chosen to be eight which is a compromise between size and sensitivity. The number of turns in total is 1000. All coils have been glued on the respective ceramic rods using acetoxysilicone Loctite 5398. The individual components of such a fluxgate sensor are shown in Fig. 1.

The sensors themselves can be characterized via the sideband sensitivity [18] which does not take the signal processing electronics into account. For its evaluation, we applied an excitation current of about 0.25 A_p. A sinusoidal calibration field of about 100 nT_p in amplitude was provided by a Helmholtz coil setup. Sideband amplitudes of the modulated tuned detection coil signal (due to the nonlinear magnetization curve) were referred to the calibration field. The resulting sideband sensitivity of all sensors is in the range of 24.5 kV/T with deviations of about 3%, which can result from the sensors position in the calibration field.

Three of these fluxgates form a three-axis fluxgate sensor. A ceramic rod of Macor material (30 mm in diameter, 110 mm in length) is used as an outer support. Since the intended installation space is limited to a diameter of 30 mm, the sensors could not be mounted in orthogonal positions. Hence, two sensors were placed at angles of 37° (in XY as well as in YZ plane) while the third one was mounted parallel to the length axis of the Macor rod. The orthogonal magnetic field components can be obtained e.g. via digital signal processing [21]. This setup is depicted in Fig. 2. Again, all sensors were encapsulated with high temperature acetoxysilicone Loctite 5398 that once dried stays elastic, thereby absorbing thermal strain.

Electrical connections were made via crimping copper ferrules to a high temperature resistant polyimide coaxial cable. These ferrules have the same temperature coefficient as the copper wires which prevents electrical connection problems due to different thermal expansion.

3. High temperature readout electronics

The output signal is provided via phase sensitive demodulation of the second harmonic sideband signal contained in the

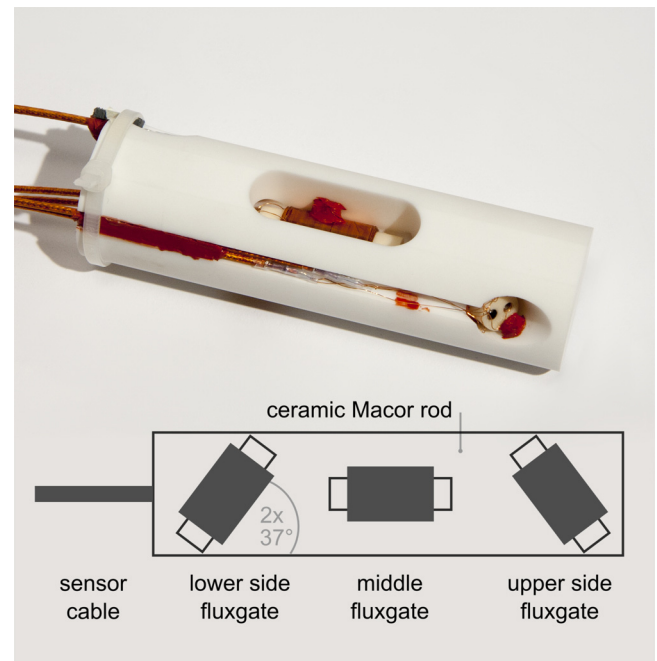


Fig. 2. Three individual fluxgate sensors are located in a ceramic Macor rod that gives outer support. Upper half: photograph of real set-up, lower half: schematic drawing.

induction voltage of the detection coil [1]. The corresponding electrical circuit consists of temperature resistant active and passive components in SMD and traditional THT packages. Active components like operational amplifiers, FET transistors or logic circuit components were obtained from Cissoid S.A. [22] and Honeywell Inc. [23]. They were realized in silicon-on-insulator (SOI) technology. This process decreases the effective cross-section area of pn-junctions by means of isolation layers [24,25]. Hence, leakage currents to the back contact are reduced. These leakage currents are a major problem in semiconductors at higher temperatures. The number of used components was chosen to be preferably small to keep the complexity of the electronics low.

Regarding the passive components, we used wirewound resistors Sfernice MSP and WSN/WSC Precision Power series made by Vishay [26] having a low temperature coefficient in the range of $\alpha_R = 10^{-7}$ – $10^{-6} \text{ } ^\circ\text{C}^{-1}$ which are preferable over metal oxide or carbon composition types with a temperature coefficient α_R of approx. $\pm 10^{-4} \text{ } ^\circ\text{C}^{-1}$, mainly arising from diffusion processes at high temperatures (see Fig. 3).

In contrast to other types, ceramic capacitors can withstand high temperatures. Certain multilayer types from Kemet [27] with C0G dielectric characteristics can have low temperature coefficients in the range of $\alpha_C = 10^{-5} \text{ } ^\circ\text{C}^{-1}$. C0G dielectrics are advertised to possess small aging effects. While different compositions are available, mostly rare earth oxides (especially neodymium and samarium) are used. Details on different compositions are not published by the manufactures. Commonly, C0G dielectrics possess a Q-factor >1000 and a small dielectric absorption. In high temperature applications they are much more suitable than standard X7R or X8R dielectric types (see Fig. 4).

The printed circuit board consists of fiberglass enhanced Teflon material RT/duroid 5880 obtained from Rogers Corporation [28]. It is copper plated (thickness 35 μm) and once accordingly coated it can be photochemically processed. The electrical connections were made by soldering with high melting point solder (composition Sn₅Pb_{93.5}Ag_{1.5}) obtained from MBO UK Ltd [29]. It has a melting temperature of around 300 $^\circ\text{C}$.

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