Three-Axis Teslameter With Integrated Hall Probe

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***Abstract*—The first commercially available teslameter with a fully integrated three-axis Hall probe is described. The Hall probe chip contains horizontal and vertical Hall elements, analog electronics, and a synchronization circuit. A horizontal Hall element measures the perpendicular component, and two vertical Hall devices measure the two in-plane components of a magnetic flux density vector. Current spinning in the Hall devices cancels offset, 1/f noise, and the planar Hall voltage. The analog electronic module of the teslameter cancels the residual offset and compensates temperature dependence and nonlinearity of the Hall voltages. The digital module provides analog-to-digital conversion and communication to a computer.**

***Index Terms*—Gaussmeter, Hall probe, magnetic measurement, planar Hall effect, teslameter, three-axis Hall.**

I. Introduction

FOR THE measurement of nonhomogeneous magnetic flux densities that are produced by electromagnets and permanent magnets ranging from 10^{-6} to 10^{2} T, one usually uses teslameters with Hall probes. To simultaneously measure the three orthogonal components of magnetic flux density, a three-axis Hall probe is applied. According to the present state of the art, a three-axis Hall probe consists of three Hall plates that are positioned at the three mutually orthogonal faces of a small cube [1]. The size of the individual Hall plates and the tolerances in their positioning severely limit the achievable spatial resolution and the angular accuracy of the measured magnetic flux density vector. In addition, the electromagnetic induction in the wires connecting the Hall devices limits the useful bandwidth of such a Hall probe. Moreover, the planar Hall effect [2] usually produces additional errors [3]. In the Hall plates, based on the quantum well, the planar Hall effect is weak [4], but the problem persists.

In this paper, a novel teslameter is presented with a three-axis integrated Hall probe. The new Hall probe is the optimized version of the first fully integrated three-axis Hall magnetic sensor [5]. Compared to the former version [5], the present one has lower noise and improved output buffers. The integrated three-axis Hall probe allows a spatial resolution of magnetic measurement of about 0.1 mm, a mutual orthogonality of the three sensitivity axis that is better than 0.5°, a bandwidth from dc up to 25 kHz, and virtually no errors due to the planar Hall effect.

Both analog teslameters (magnetic flux density to voltage transducers) and digital teslameters have been developed [6]. Applications of these instruments include mapping of magnetic fields [7], characterization and testing of magnets [8], and monitoring of electrical machines [9].

Some parts of the present paper were presented at recent conferences [10]–[12].

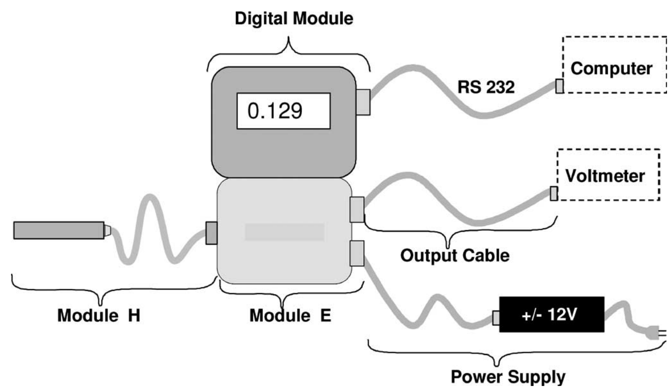

Fig. 1. Structure of the teslameter. An analog teslameter (transducer) consists of the modules H (Hall) and E (electronics), which are connected to an external power supply and voltmeter. The digital version includes an RS232 interface.

II. Structure of the Teslameter

Fig. 1 shows the structural block diagram of the three-axis teslameter. The central part of the system is an analog section, i.e., magnetic flux density to voltage transducer. It consists of two modules: 1) module H (Hall), which includes a three-axis Hall probe with the input cable, and 2) module E (electronics), which incorporates three-channel analog electronics for signal conditioning. This teslameter includes the cancellation of the residual offset and compensation of temperature cross sensitivity and nonlinearity.

In order to operate, the transducer must be connected to a power supply. In order to display the measurement results, all three analog output voltages of the transducer can be fed to three voltmeters.

Fig. 2 is a photograph of the analog version of the instrument.

A digital teslameter is built by attaching a digital module to the analog module E. The digital module provides A/D conversion, some additional error correction, a little display,

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Fig. 2. SENIS analog three-axis Hall magnetic field transducer. With reference to Fig. 1, module E (the box) and module H (the cable with the Hall probe) are visible. The front end of the cable is very thin and flexible to allow easy positioning of the probe.

and communication to a computer. A dedicated software package provides to the computer further signal processing and visualization of the measurement results.

III. Three-Axis Integrated Hall Probe

The Hall probe contains an integrated circuit, which is similar to the one that is described in [5]. Briefly, the integrated circuit consists of a sensing part, analog section, and a digital synchronization circuit. A horizontal Hall element measures the perpendicular component, and two vertical Hall devices [13] measure the two in-plane components of a magnetic field. The probe has a sensitive volume of 0.15 mm $\times$ 0.15 mm $\times$ 0.01 mm and a mutual orthogonality of the three sensitive axes better than 0.5°.

The electronic on chip provides current supply, cancellation of offset and of 1/f noise, and amplification. The cancellation of offset and of 1/f noise is realized using the spinning-current method [13], which is described in Appendix A. As explained here, this method also cancels the planar Hall voltage. The switching frequency in the spinning-current circuit is 600 kHz. This is well outside the measurement bandwidth, so the switching noise can be completely filtered out. The on-chip amplification of the small Hall voltages makes the output signal of the probe immune to electromagnetic disturbances. The gain of the on-chip amplifier depends on the measurement range, e.g., for the range $\pm$2T, the gain is about 20. A temperature sensor is also integrated on the chip.

The integrated circuit is realized in a conventional complimentary metal–oxide–semiconductor 0.8-μm technology. The chip dimensions are 4.45 mm (length), 0.5 mm (width), and 0.55 mm (thickness). The integrated Hall sensor chip is encapsulated in a package that is connected with a long cable to an external electronics module.

Several probe packages have been developed. Figs. 3 and 4 show two examples of probes. Fig. 5 shows a detail of the probe that is illustrated in Fig. 3, and Fig. 6 shows the probe that is mounted on a holder.

IV. Canceling the Planar Hall Voltage

If a Hall device is exposed to a nonorthogonal magnetic field, as illustrated in Fig. 7, then its output appears to be the sum of

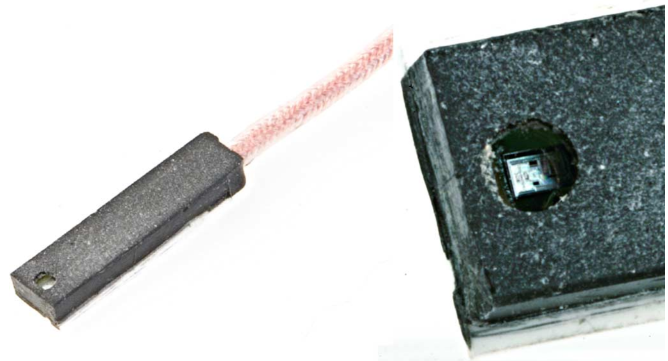

Fig. 3. Thee-axis Hall probe with a window. The magnetic-sensitive region of the integrated Hall sensor is visible through the window, which allows for precise positioning of the probe. The dimensions of the probe are 4 mm $\times$ 2 mm $\times$ 16 mm.

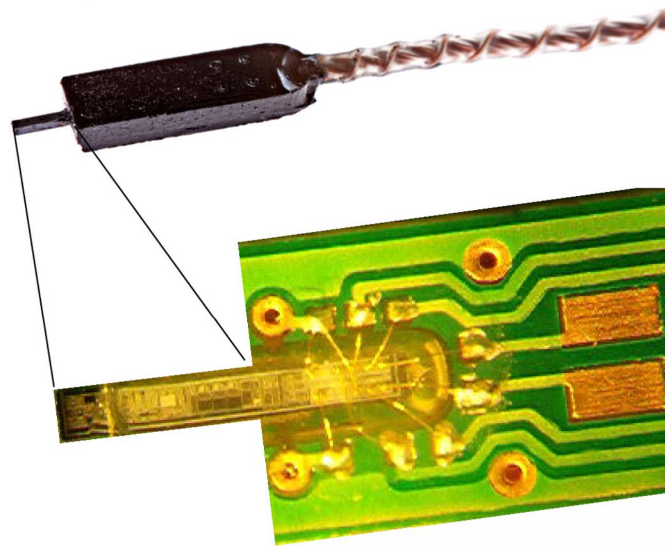

Fig. 4. World's smallest three-axis Hall probe. The thin tip of the probe is a part of the silicon integrated Hall sensor chip, which is not encapsulated. The dimensions of the naked silicon tip are 0.5 mm $\times$ 0.55 mm $\times$ 3 mm. The magnetic-sensitive point is only 0.15 mm away from the tip end.

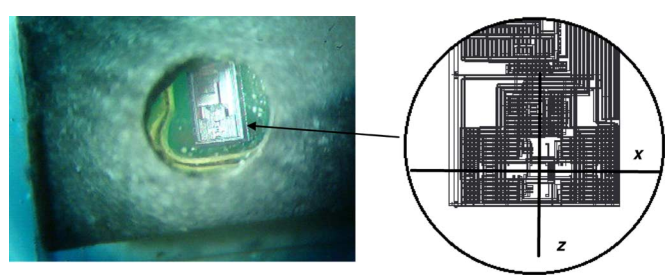

Fig. 5. Photo of the window of the probe that was shown in Fig. 3. The inset shows the magnetic-sensitive part of the integrated Hall probe. The field-sensitive point is located at the crossing point of the axes x and z.

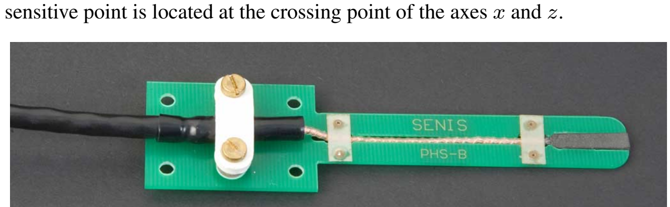

Fig. 6. For easy handling, the probe can be mounted on a holder. The holder is as thin as the probe.

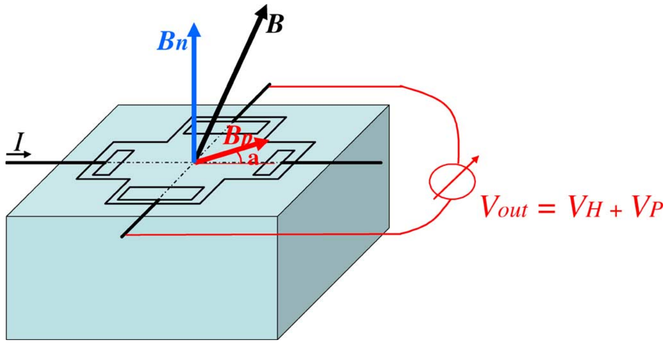

Fig. 7. Planar Hall effect. A magnetic flux density vector $\boldsymbol{B}$ acting on a Hall device can be decomposed into a normal component $\boldsymbol{B}_n$ and a planar component $\boldsymbol{B}_p$. The normal component $\boldsymbol{B}_n$ produces a "normal" Hall voltage V_H. The planar component $\boldsymbol{B}_p$ produces the planar Hall voltage V_P. The total output voltage is the sum of the normal and the planar Hall voltages.

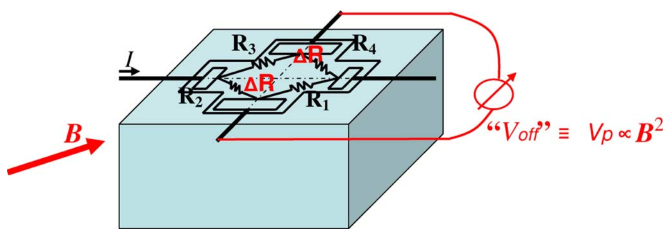

Fig. 8. Magnetoresistance model of the planar Hall effect. A planar magnetic flux density $\boldsymbol{B}_p$ produces an increase ΔR in the resistances R_2 and R_4 due to the strong transversal magnetoresistance effect. Resistances R_1 and R_3 remain practically unchanged because the longitudinal magnetoresistance effect is weak. As a result, at the output appears as an offset voltage. Since $\Delta R \sim B_p^2$, $V_{\mathrm{off}} \sim B_p^2$. This is the planar Hall voltage.

the normal and the planar Hall voltages. Physically, the planar Hall effect is closely related with the magnetoresistance effect [13]. Fig. 8 shows how the planar Hall effect appears on a Hall device that is modeled as a resistor bridge. Ideally, the four resistors are exactly equal, and we expect that the output voltage is zero, i.e., there is no offset. However, if the device is exposed to a planar magnetic field B_p acting in the diagonal direction, the resistors are no longer equal: Since the magnetic field is inclined with respect to the resistors at different angles, the magnetoresistance effect in each of them is not equal. This disturbs the symmetry of the resistor bridge, and as a result, an output voltage appears. This "offset voltage" depends on the magnetic field, where it is proportional to the square of the planar field B_p.

Based on the fact that the planar Hall voltage is so closely related to the conventional offset voltage, we anticipate that some offset cancellation methods may also be used to cancel the planar Hall voltage. In the previously described three-axis Hall probe, we cancel the offset by the spinning-current method (see Appendix A). An experiment proved this method to also be very efficient as a method to cancel the planar Hall voltage (see Fig. 9).

Without a spinning current, the ratio $V_P/V_H = 1.3\%$; with a spinning current, $V_P/V_H = 0.02\%$, which is at about the resolution limit of our probe. Suppression of the planar Hall effect by the spinning current technique is equally efficient for the horizontal and vertical Hall devices.

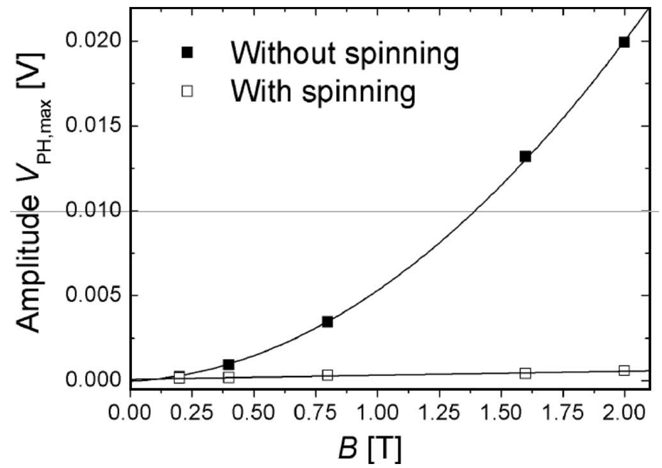

Fig. 9. Measured planar Hall voltage of the horizontal Hall plate without and with the application of the spinning-current method. A similar result is also obtained for the vertical Hall devices.

V. Additional Signal Treatment

The external electronics in module E cancels residual offset and its temperature drift, compensates temperature influence on magnetic sensitivity, and compensates nonlinearity of the Hall voltages (see Fig. 10). The roles of the dashed blocks of Fig. 10 are given as follows: The block "offset comp. 20 °C" cancels the constant part of the offset. The block "Temp. Comp. of OFFSET" makes the temperature signal suitable for compensating the offset drift with temperature. Using the same temperature signals, the block "Temp. Comp. of SENSITIV-ITY" corrects the temperature influence on the sensitivity. The block "NONLINEARITY Comp." corrects the nonlinearity of signal X = f(B). At point +, all these corrections are added to the row signal X. Finally, the block "SENSITIVITY Adjust." brings the sensitivity of channel x to the calibrated value of exactly 5 V/T.

The digital module provides fast 16-bit A/D conversions of the analog signals from module E. It allows for a calibration accuracy of up to 0.01%. The digital module also provides the interface to the data acquisition and visualization software package on an external computer.

VI. Conclusion and Performance

The analog outputs of module E consist of three differential voltages that are proportional to the three components of the measured magnetic flux density and a voltage that is proportional to the chip temperature. The performance figures here refer to the three analog "magnetic" outputs for the measurement range ±2T, with a sensitivity of 5 V/T.

The standard accuracy of the introduced teslameter is 0.1% of the measurement range. The major parts of the error budget are the residual nonlinearity error (up to 0.05%—see Appendix B) and the sensitivity error (up to 0.02%). These two errors can be eliminated by using a calibration table.

The compensations of temperature drifts are very efficient due to the use of the signal that is proportional to the real probe temperature. The temperature coefficient of sensitivity is

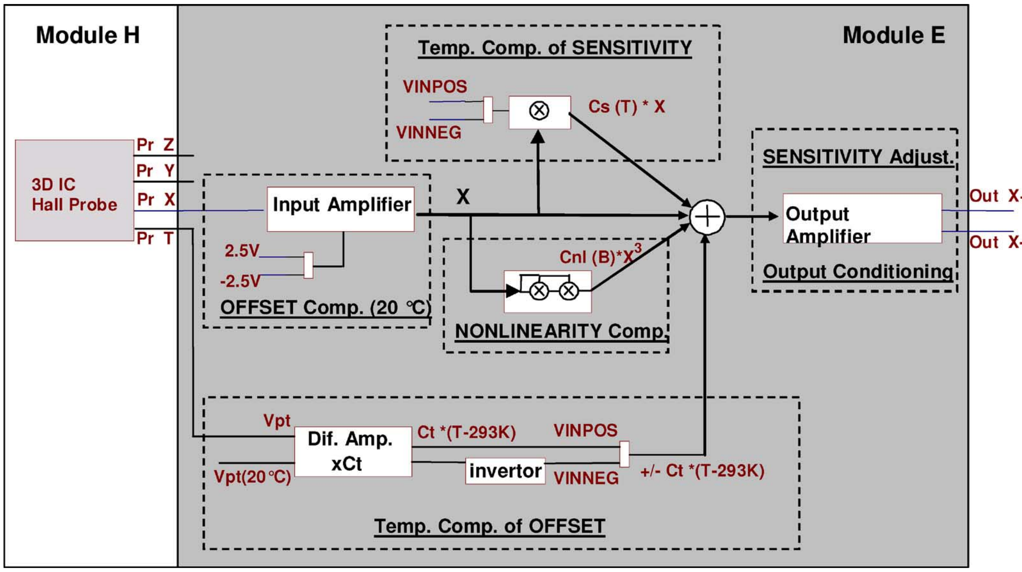

Fig. 10. Functional block diagram of the analog electronic module E. Only the signal path for channel X is shown. The same also exists for Y and Z.

smaller than 100 ppm/°C, and that of the offset is smaller than 0.05 mT/°C (±2T range).

The application of the spinning-current method in the Hall probe chip and the temperature compensation of offset help keep the offset fluctuations and drift low. The resultant dc magnetic flux density resolution is better than 0.1 mT (±2T range) for any of the three channels (see Appendix C).

The spinning-current also cancels the planar Hall voltage. Therefore, the new teslameter has virtually no crosstalk between the channels.

The on-chip amplification of the Hall voltages, the miniaturized connection part of the probe, and the tightly twisted thin cable make the probe immune to electromagnetic disturbances. Therefore, the probe can measure the magnetic fields in its whole bandwidth, from dc to 25 kHz. However, in order to improve the signal-to-noise ratio, the bandwidth of the teslameter can be limited (typically to 2.5 kHz) using a low-pass filter in module E.

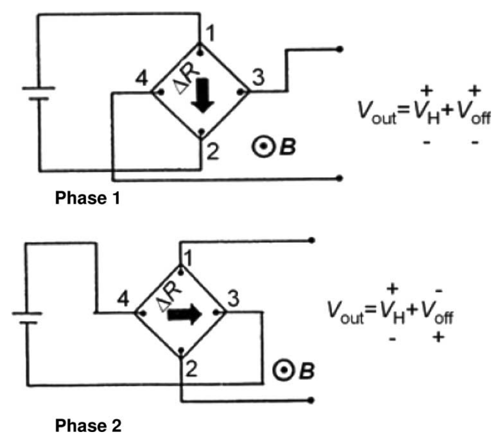

Fig. 11. Spinning-current method for the cancellation of the offset voltage of a Hall device. A Hall device is alternatively biased in two orthogonal directions. Then, the offset voltage due to the resistance asymmetry ΔR changes its sign, whereas the Hall voltage does not change. By averaging the output voltages of the two phases, one can cancel out the offset voltage.

Appendix A
Offset Cancellation by the Spinning-Current Method

The offset voltage of a Hall device is its output voltage at a zero magnetic field. The offset is caused by an electrical asymmetry of a Hall device, which may be due to errors in geometry and nonuniformities in the chip material properties. The offset of a Hall device can be virtually eliminated by a dynamic offset cancellation technique, which is called the spinning-current method. The idea of the spinning-current method is illustrated in Fig. 11. The Hall device is connected to a biasing source and an output circuit via a group of switches (which are not shown in Fig. 11). The switches are turned on and off so that the diagonally situated terminals of the Hall device are periodically commutated and alternatively used as the current (input) and the sense (output) contacts. Thus, the bias current virtually rotates in the device for 90° back and forth (therefore, the term "spinning current"). The Hall voltage rotates with the biasing current and appears at the output with a sign that depends only on the orientation of magnetic field B. If the magnetic field does not vary much during a switching period, then the Hall voltage is quasi-dc. On the other hand, the offset voltage at the output has an opposite sign during each phase of the spinning current. Therefore, the offset voltage appears as an ac signal with the switching frequency and can be filtered out from the output voltage.

The spinning-current method is a variation of the chopping technique. Similar to the chopping, the spinning current also reduces the 1/f noise of the switched Hall device. This can be understood by imagining the 1/f noise voltage at the output terminals of a Hall device as a slowly fluctuating offset voltage. We can model the 1/f noise by a fluctuating asymmetry resistance ΔR in Fig. 11. If the biasing current of the Hall device

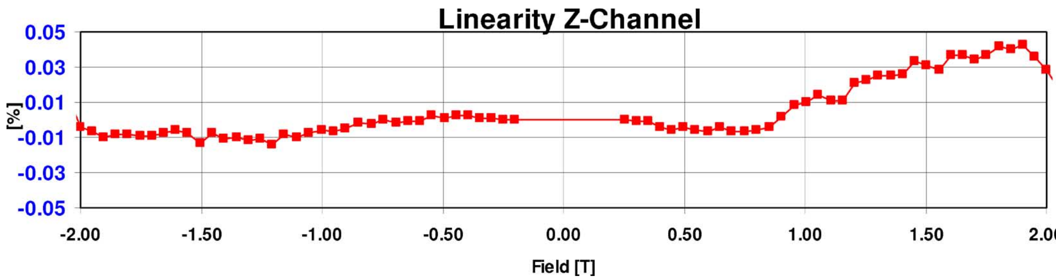

Fig. 12. Transducer nonlinearity error as a function of the measured magnetic flux density in the range ± 2T.

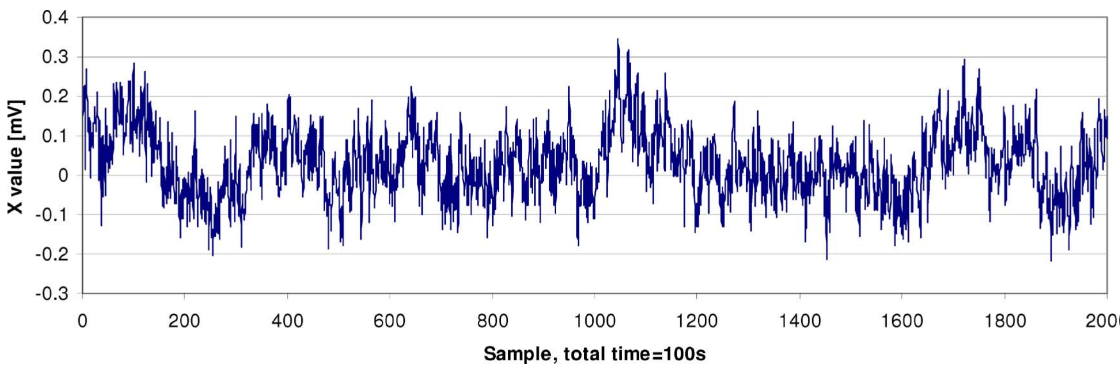

Fig. 13. Time dependence of the offset voltage of channel X. Abscissa: the order number of the samples. Ordinate: the offset voltage in millivolts.

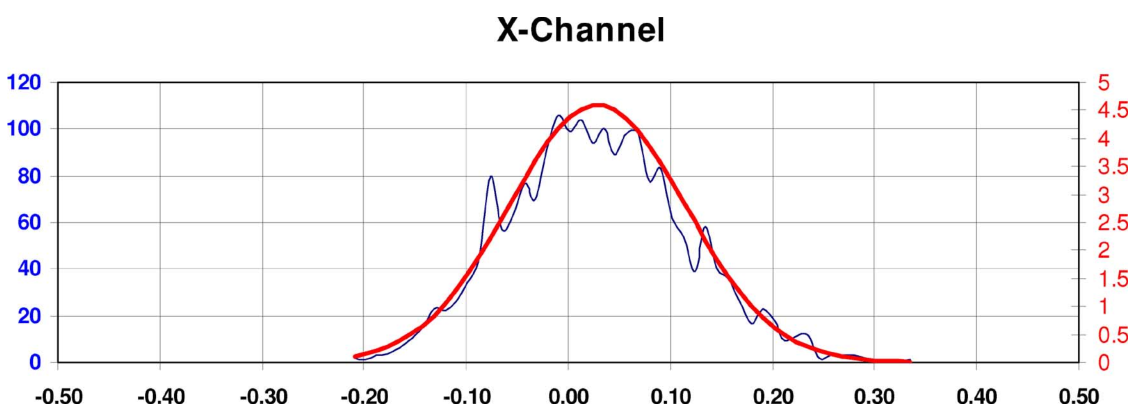

Fig. 14. Histogram of the values from Fig. 12 and the corresponding approximation by a Gaussian distribution. The standard deviation is about 83 μV, which corresponds to 17 μT.

spins fast enough, then there will be no difference between the static and the fluctuating offset, and the system will cancel both of them.

An essential condition for good operation of the spinning-current method is that the spinning frequency is significantly higher than both the highest frequency of the measured magnetic field and of the corner frequency of the 1/f noise. This allows efficient filtering of the offset voltage and the parasitic picks that are added by the switches (the switching noise), without deteriorating the spectrum of the measured magnetic signal.

Appendix B
Nonlinearity

Nonlinearity is the deviation of function $B_{\text{measured}} = f(B_{\text{actual}})$ from the best linear fit of this function. Usually, the maximum of this deviation is expressed in terms of percentage of the full-scale input. Accordingly, here, the nonlinearity error is calculated as follows:

$$NL = 100 \times \{[V_{\text{out}}(B) - V_{\text{off}}]/S' - B\}_{\max}/B_{\text{LR}}$$

$$\text{for } -B_{\text{LR}} < B < B_{\text{LR}}$$

with the following notation:

B actual testing dc magnetic flux density, which is given by a reference NMR teslameter;

$V_{\text{out}}(B) - V_{\text{off}}$ corresponding measured transducer output voltage after zeroing the offset;

S' slope of the best linear fit of function $f(B) = V_{\text{out}}(B) - V_{\text{off}}$ (i.e., the actual sensitivity);

B_{LR} linear range of magnetic flux density, here, $B_{\text{LR}} = 2$ T.

An example of the measured nonlinearity error is shown in Fig. 12.

APPENDIX C
OFFSET FLUCTUATION AND DRIFT

The fluctuation and drift of the residual offset of the "magnetic" analog outputs of a transducer with the range ± 2T were characterized as follows: The probe was kept in a zero-gauss chamber at room temperature for a few minutes to stabilize. Then, over a time period of 100 s, 2000 samples of the transducer output voltage were recorded. Thereby, each sample was averaged over the sampling time period of 0.05 s. This sampling scheme corresponds to a measurement in the frequency bandwidth from 0.01 to 10 Hz. The results are shown in Figs. 13 and 14.

By inspecting Fig. 13, we conclude that there is no visible tendency of long-term drift of offset. This corroborates with the approximately Gaussian distribution in Fig. 14, which is expected for a stationary stochastic process.

The standard deviation (sigma) of the voltage samples in the preceding diagrams is about 83 μV. This equals the rms fluctuation of the offset voltage in the preceding frequency bandwidth. The equivalent rms magnetic flux density fluctuation is about 17 μT. This is an indication of the measurement resolution for quasi-dc magnetic signals in the frequency bandwidth from 0.01 to 10 Hz. Another measure for the resolution is the peak-to-peak span of the offset fluctuations. In the present case, the six-sigma peak-to-peak offset fluctuation span is about 0.1 mT.

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Dr. Popovic is a member of the Swiss Academy of Engineering Sciences and the Serbian Academy of Engineering Sciences.