Design of a Digital Gauss Meter for Precision Magnetic Field Measurements

James Sedgwick, William R. Michalson, and Reinhold Ludwig

Abstract—**The design of a precision gauss meter for measuring magnetic fields is presented. The instrument utilizes a Hall element probe as a transducer and features an analog front end capable of amplifying dc and ac signals. A 16-bit analog-to-digital converter interfaces the analog section to a microcontroller-based digital section which corrects nonlinearities in the Hall element probe as well as gain errors in the amplifiers. The specifications called for 0.25% dc accuracy and an ac bandwidth of 10 kHz. SPICE models were used to determine the frequency response, noise characteristics, and temperature effects of the Hall element probe and the analog section. Finally, the analog section and the Hall element probe were calibrated separately and configuration information was created for storage in EEPROM memory.**

Index Terms—**Analog systems, circuit noise, electric variables measurement, electromagnetic measurements, Hall effect devices, measurement.**

I. Introduction

The MEASUREMENT of magnetic fields has become an important concern in industry over the past several years. The need to design precision electric motors, coils for magnetic resonance imaging (MRI), actuators, and magnetic switches require instrumentation capable of accurately measuring magnetic flux densities with a resolution of often less than 1 G over a large frequency range. Recent biomedical interest in low-frequency magnetic field influences on humans has only accelerated the demand for such equipment. The challenge is therefore to construct magnetic field recording devices, or gauss meters, with high measurement precision and a wide bandwidth, which are economically feasible. Conventional analog instruments can no longer achieve the field recording precision demanded by industry, especially when dealing with high-frequency signals, since errors introduced by the nonlinearity and temperature dependency of the magnetic sensor cannot be adequately taken into account.

The objective of this paper is to present a unique instrumentation approach that combines high measurement accuracy with wide signal bandwidth as part of a portable system. The magnetic field sensor relies on using Hall effect sensors to cover a measurement range from 0.3 G to 30 kG. Since Hall effect sensors are inherently nonlinear and are affected by field strength and temperature, each must be individually configured with probe compensation data stored in an EEPROM within the probe. The probe also contains a thermistor so that the instrument can ensure accuracy over the desired measurement range.

The paper is organized as follows. Section II discusses the analog subsystem which incorporates amplification and analog-to-digital conversion. This includes a brief description of what error sources are dominant and how they manifest themselves. A SPICE simulation of the analog circuit is presented in Section III, and Section IV discusses calibration.

II. Analog Circuit Design

The goal in building this instrument was to achieve 0.25% dc accuracy with a bandwidth of 10 kHz and a measurement range of 0.3 G–30 kG, as discussed in subsequent sections of the paper. Measurements had to be repeatable, with low drift and temperature dependence. Economic concerns dictated low parts count and also efficient design. The analog front end required particular attention with regard to component selection and the error budget.

A. Analog Front-End Design

A block diagram of the analog front-end is provided in Fig. 1. The heart of the analog section is comprised of three programmable amplifiers. The first stage interfaces to the Hall element probe and provides gains of 1, 10, 100, and 1000. Voltage offsets are compensated by a reference input driven by a digital-to-analog converter (DAC). In addition, a guard shield amplifier helps to improve common mode rejection. The front-end amplifier drives a low-pass filter intended to reduce the noise bandwidth of the system. The filtered signal is amplified by two additional programmable amplifiers with gains of 1, 10, and 100. These stages drive both an rms to dc converter and a peak hold detector. An analog multiplexer allows selection of which signal the analog-to-digital converter (ADC) will monitor.

The maximum required overall gain is 10 000. However, the need for an ac bandwidth of 10 kHz complicates instrument amplifier selection because of the characteristic roll-off of some programmable instrumentation amplifiers. The second- and third-stage amplifiers permit high bandwidth, but do not have the same precision as the first stage device. Fortunately, the ac specifications are less stringent (5%) than the dc specifications. So, for high-bandwidth ac measurements, the first-stage gain can be reduced to unity, and the second- and third-stage gains may be increased to an overall gain of 10 000.

A software controlled source provides the necessary drive current for the Hall element probe. Since the Hall voltage

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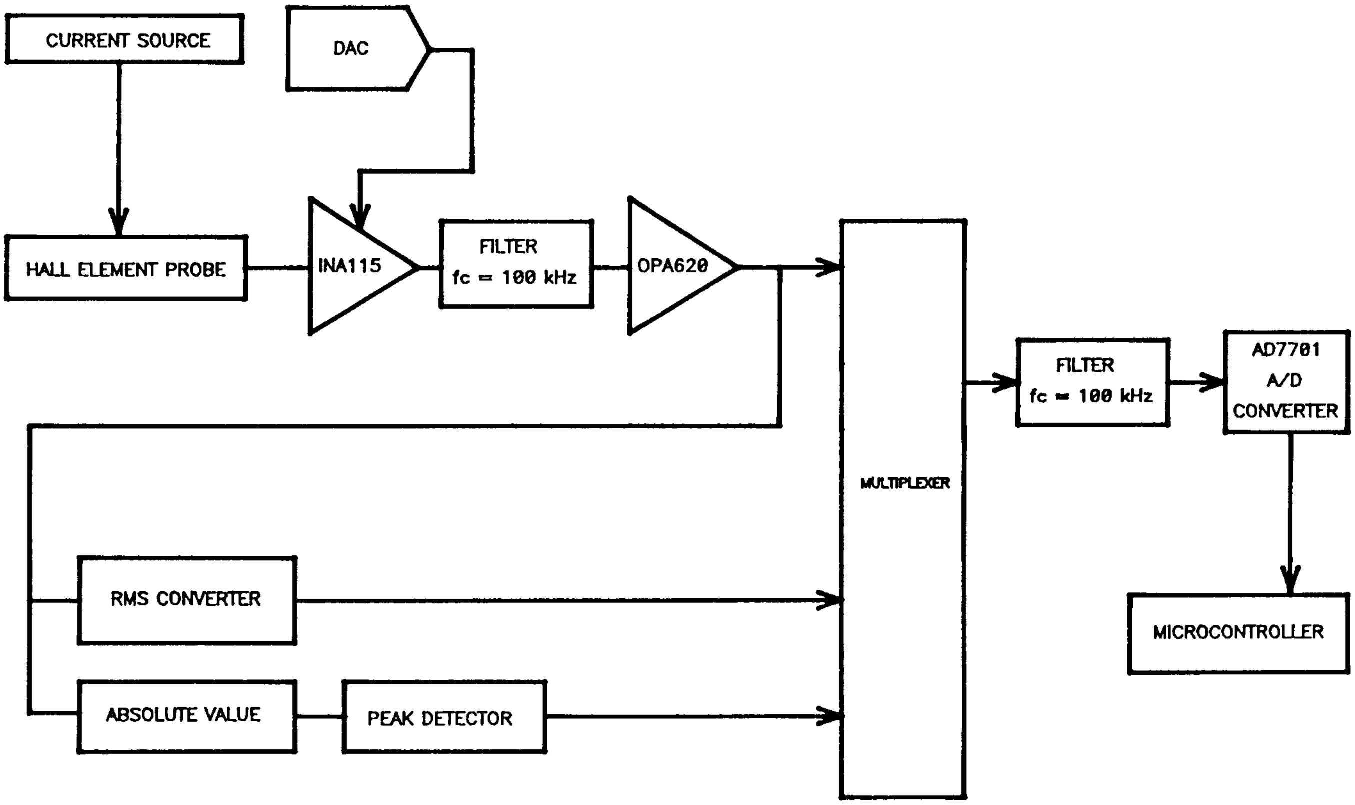

Fig. 1. Block diagram of a Gauss meter.

is directly proportional to the current, a tightly regulated low-noise current source is essential. The current source is comprised of a PNP transistor driven by an operational amplifier which monitors the Hall current through a 0.01% shunt resistor and compares it to a programmable reference voltage.

B. The Analog-to-Digital Converter

An analog device's AD7701 16-bit sigma–delta converter was chosen because of its unique filtering and calibration features, as well as its upgrade path to a 20-bit device. The AD7701 has a built-in low-pass digital filter with a 10-Hz cutoff frequency, making it ideal for dc measurements. Since ac measurements utilize an rms converter with a dc output, the ADC need only process dc signals. It also has calibration modes, which permit gain and offset errors to be corrected automatically.

C. The Error Budget

For the first gain stages, nullable dc errors include gain error and input offset error. Nonnullable errors include noise, gain, and offset drift, as well as common mode rejection limitations. Offset errors can pose the most serious threat to accuracy.

Traditional analog instrumentation often employs manual zero adjustments for nulling drifts. An intelligent system which can automatically check for drifts would substantially ease use and reduce nullable errors to a very low order. Gain drift errors could be nearly eliminated with an auto-calibration circuit if a reference voltage were switched into the input stage. However, an accurate low-impedance low-drift 0.3-mV reference would be necessary for evaluating a gain of 10 000. Since it was undesirable to encumber the analog section, gain autocalibration was ruled out for this implementation.

In order to compensate for dc drift components, the AD7701 converter can be programmed to calibrate out the offset. To facilitate this, a shorting relay was placed at the system input to short both inputs of the first stage to ground. In addition, two DAC's provide coarse and fine adjustment of the reference input to the first stage. These DAC inputs are active filtered to keep noise out of the instrumentation amplifier. A binary search algorithm is employed to zero the probe when the user selects nulling mode. As long as such drifts occur gradually, they can be calibrated out. However, rapid or erratic offset drifts may be difficult to null, and gain drifts cannot be calibrated out during operation. Therefore, an instrumentation amplifier was chosen for its low drift properties.

Drift must also be considered in the current source. A DAC4815 with an output drift between 5 and 30 ppm/°C is used for setting a reference voltage. This is compared to the voltage measured across a shunt resistor in series with the Hall element probe, and the error voltage controls the Hall current. A 0.01% resistor with a 20 ppm/°C coefficient was chosen for the shunt. The Hall element probe measurements may consequently exhibit errors of up to 0.003%/°C due to current variation.

The strategy for gain error correction may incorporate the use of calibration constants stored in memory. However, this assumes linearity over the field range and low gain drift. The INA115 instrumentation amplifier was chosen for the first stage because of its high accuracy and low nonlinearity: a

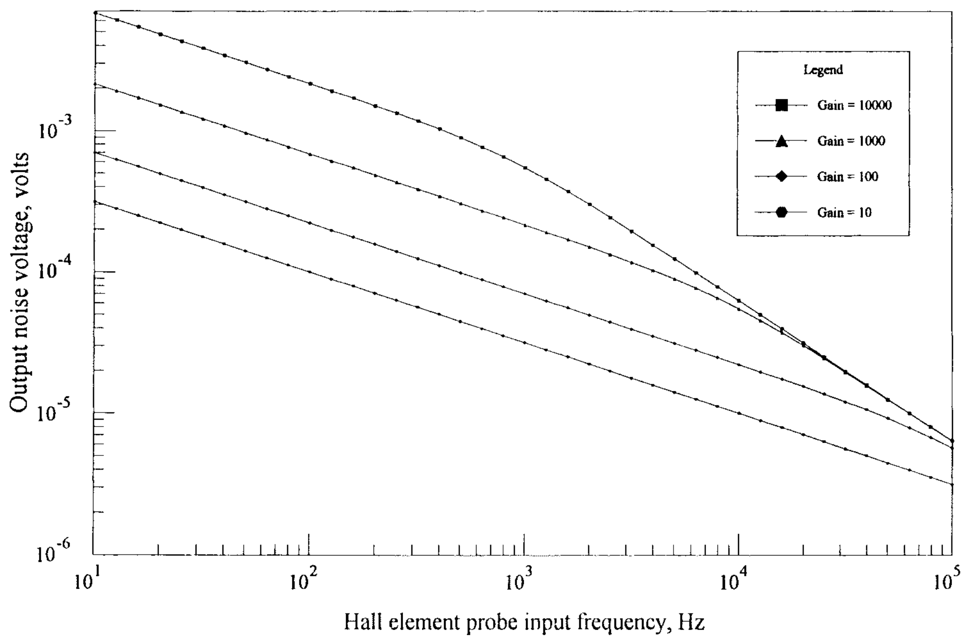

Fig. 2. Effect of amplifier gain on noise voltage at ADC input.

worst-case gain drift of 10 ppm/°C and nonlinearity of 0.01% of full scale. More importantly, the INA115 input voltage offset has a low drift component of only 0.25 μV/°C. The second-stage operational amplifier is an OPA620, chosen for its wide bandwidth. The voltage offset is 8 μV/°C; however, this is only amplified by 10 for dc measurements. For high bandwidth measurements, this is amplified by 10 000, so a potential drift of 80 mV/°C must be considered for the ac case.

The AD7701 converter was chosen in part for its excellent integral linearity—0.0007%—and low gain drift: 1.2 LSB's or less than 0.002%. The specified 0.25% dc accuracy can be achieved if the drifts and nonlinearities are in accordance with these rated values.

D. Resolution

The resolution for this system was specified as one part in 2999. Some of the above-mentioned accuracy errors may also effect resolution. A 0.001% error in gain is reflected as a 0.001% reduction in resolution. Similar effects can be seen from common-mode rejection errors and noise.

E. Noise Considerations

At the end of the signal path, less than 1-mV noise should be present at the ADC input when the overall gain is 10 000. If a resolution of one part in 3000 is required for a maximum voltage of ±3 V, then this corresponds to a noise voltage of a maximum of 1 mV.

When set for a gain of 1000, the INA115 output begins to roll off at 1 kHz, reducing the noise bandwidth of the system somewhat. At this gain, the noise amplitude at the output is approximately 17 mV. However, the *RLC* filter placed before the ADC reduces this significantly. In addition, the AD7701 digital filter in combination with software filtering keeps the noise for dc measurements to within an acceptable level. For the ac case, the 17-mV noise signal is present at the input of the rms converter and has to be considered when evaluating the ac accuracy.

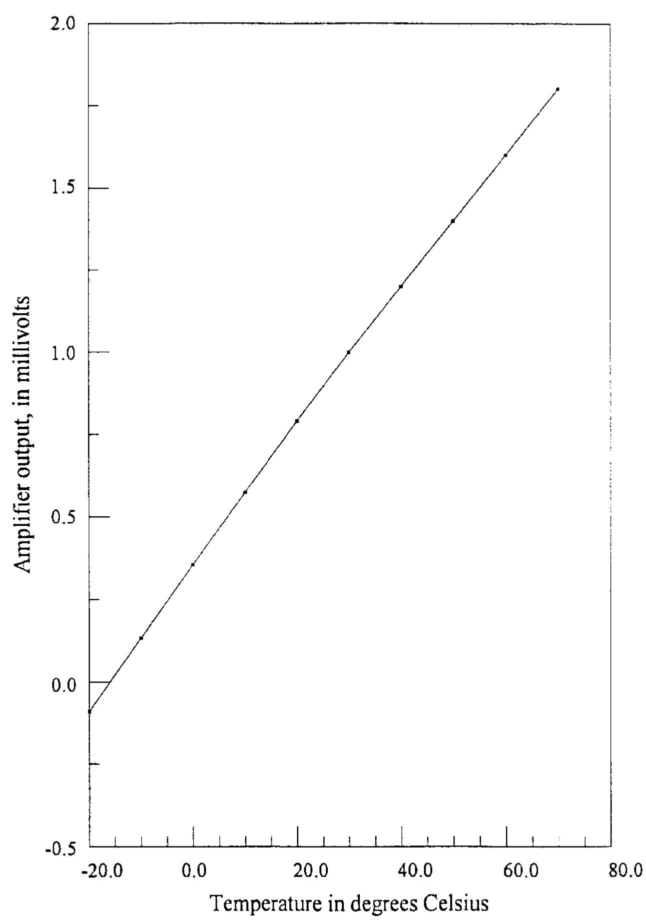

Fig. 3. Effect of temperature on offset voltage, referred to output.

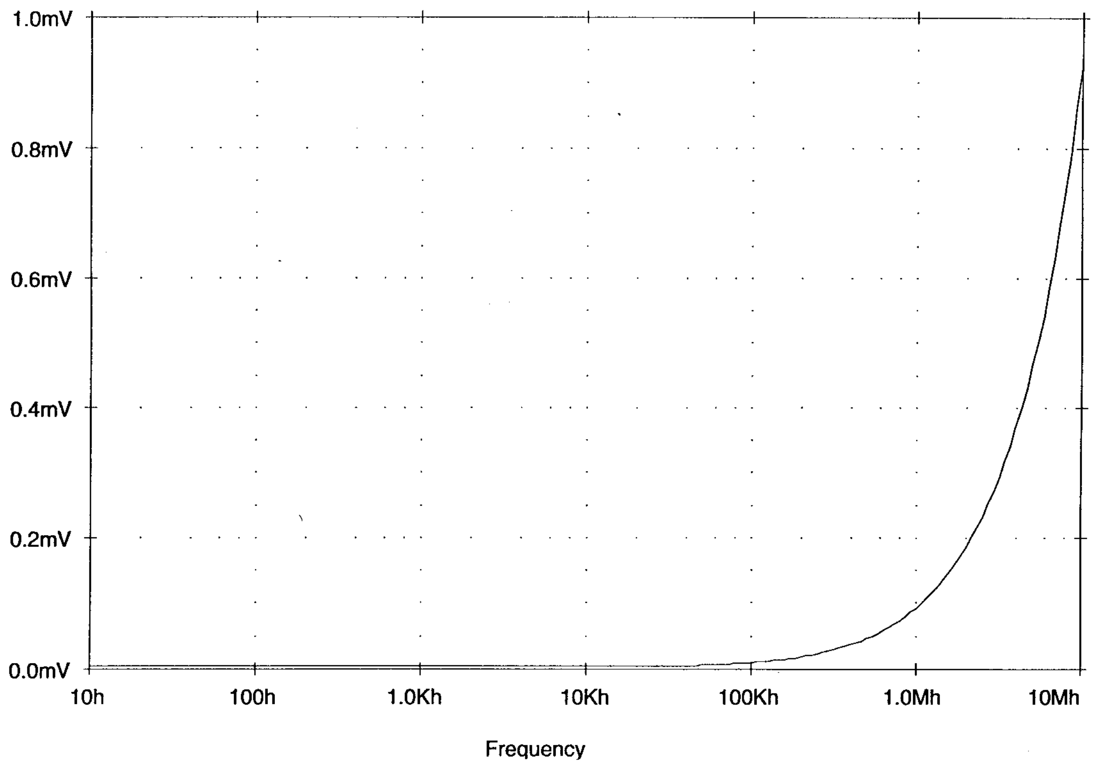

Fig. 4. Frequency response of Hall probe element, with 1-MΩ resistive load.

III. SPICE MODELING

A SPICE model of the analog amplifier section was created to evaluate the frequency response and study the noise floor more closely, so that an acceptable system bandwidth could be determined. SPICE models for the Hall element probes permitted evaluation of temperature effects in addition to accumulated noise in the signal path.

Fig. 2 shows the results of the noise analysis for each of the four gains. The higher accuracy dc circuit was used for this case. The worst case gain of 10 000 was achieved using the SPICE model of the input instrument amplifier set to a gain of 1000, and the lower accuracy second stage was set to a gain of 10. To simulate the dc noise floor, the SPICE model was run using the NOISE command, which requires that the input circuit be swept with an ac signal at a range of frequencies, within the bandwidth of interest. To accomplish this, the SPICE model of the Hall element probe was excited by a simulated ac field swept from 10 Hz to 100 kHz. At a gain of 1000, the output noise voltage reached 2 mV, and at a gain of 10 000, it reached 6.7 mV. Therefore, the original goal of achieving 1-mV resolution appears unrealistic for the two highest gains. However, additional digital filtering may be performed by the software, although this may slow the system response time.

This model also revealed that the offset voltage drift was within a millivolt for temperature fluctuations of ±20 °C. Fig. 3 shows the result of a SPICE simulation of the same dc circuit with the instrument amplifier inputs shorted to ground. The simulated system temperature was varied from −20 °C to 70 °C, and the output dc voltage for a gain of 10 000 was plotted. This suggests that offset drift would not pose a problem for normal use in a laboratory environment.

The bandwidth for the ac mode of the instrument was also evaluated. The frequency response of the SPICE model for the Hall probe element is shown in Fig. 4. The Hall Probe elements modeled here exhibit a marked upswing in output amplitude at 10 kHz, as shown. This effect, however, may be offset by the roll-off of the amplifiers. The frequency response of the amplifiers as predicted by SPICE models with a Hall element probe input is shown in Fig. 5. As mentioned previously, the roll off of the first-stage instrument amplifier does not meet the 10-kHz specification, so the less accurate second- and third-stage gains were increased, while the first stage was reduced to a gain of 10. Since the signal at the rms converter input must be allowed maximum bandwidth, minimal RC filters are placed in that signal path, after the first and third stages. The OPA620 operational amplifiers can easily permit a 10-kHz bandwidth. The SPICE model demonstrated that RC filters with cutoff frequencies of 100 kHz yield less than 1% attenuation at 10 kHz.

IV. CALIBRATION

The need for an accurate low-impedance reference for calibration at the time of manufacture still poses a problem when attempting to evaluate the accuracy of the high gain ranges. External voltage sources were extremely susceptible to 60-Hz noise. A precision voltage source as well as the voltmeter used for measurements injected sufficient noise and common-mode errors into the amplifiers to make it difficult to determine the performance of the amplifier at a gain of 10 000. The current source is calibrated at manufacturing time and the actual measured current for each probe type is

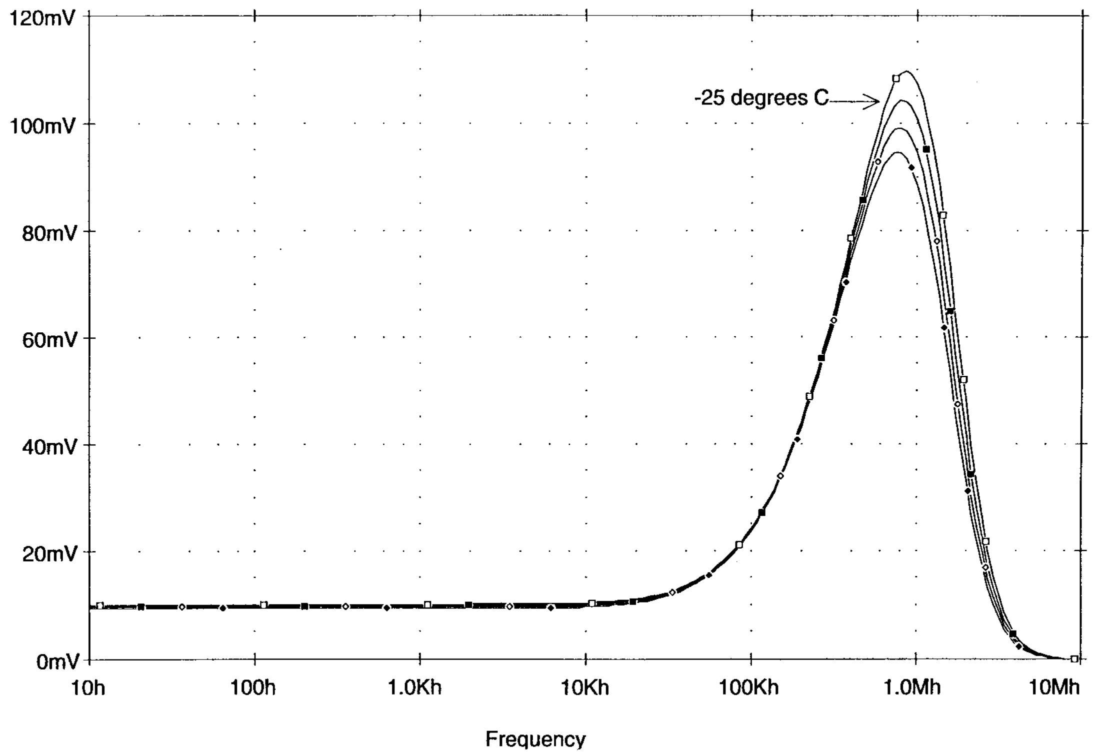

Fig. 5. Frequency response of ac amplifier with Hall probe element at input.

stored in EEPROM. Calibration constants for each of the four gains are determined by averaging the overall measured gain errors and storing the correction factors. Finally, the reference voltage for the AD7701 is also checked and recorded in memory.

Nonlinearities in the Hall element are usually on the order of a fraction of one percent, and they follow a nonsymmetrical curve which can be approximated by a polynomial. The polynomial coefficients are stored in EEPROM so that measurement errors may be corrected in real time while making measurements.

Temperature correction is implemented using constants provided by the Hall element probe manufacturer. The element used for this paper was specified with a maximum temperature coefficient of $-0.1\%/°C$. The SPICE models permit evaluation of temperature effects. Fig. 5 shows that the variation of a 2-kG measurement sweep through a 75 °C temperature range resulted in less than 1 mV of variation after amplification.

V. Conclusions

Tradeoffs always exist when an instrumentation design must be optimized for both high precision and high bandwidth. High-frequency operational amplifiers are subject to substantial variations in drift, while high-precision amplifiers are bandwidth limited. Temperature effects and noise considerations require special techniques for calibration, since results may not be repeatable. Component manufacturers are pushing the limits of these devices to permit measurement of minute changes in small signals, but variations in component tolerances still force the designer to observe worst-case conditions.

References

[1] T. H. Wilmshurst, *Signal Recovery from Noise in Electronic Instrumentation.* Bristol, U.K.: IOP, 1990, pp. 1–68.
[2] P. Horowitz and W. Hill, *The Art of Electronics,* 2nd ed. Cambridge, U.K.: Cambridge Univ., 1993, pp. 428–440.
[3] R. S. Popovic, *Hall Effect Devices.* Bristol, U.K.: IOP, 1991, pp. 251–295.
[4] “Magnetic measurement instruments attract materials researchers,” *Res. Dev.,* vol. 37, no. 7, pp. 67–69, June 1995.
[5] V. I. Prokoshin, “Magnetic-film Hall generators,” *Meas. Tech.,* vol. 35, no. 3, pp. 335–338, Mar. 1992.
[6] R. M. Stitt, “Boost instrument-amp CMR with common-mode-driven supplies,” *EDN,* vol. 35, no. 22, p. 183, Oct. 1990.
[7] “Using noise figure to select a low-noise op-amp,” *Electron. Eng.,* vol. 69, no. 844, pp. 41–46, Apr. 1997.
[8] “Improve noise analysis with op-amp macromodel,” *Electron. Design,* vol. 40, no. 7, pp. 73–75, Apr. 1992.
[9] W. M. Frix, G. G. Kanady, and B. A. Venetz, “Comparison of calibration systems for magnetic field measurement equipment,” *IEEE Trans. Power Delivery,* vol. 9, pp. 100–106, Jan. 1994.
[10] J. Williams, “High speed amplifiers with low offset and drift,” *EDN,* vol. 36, no. 32, pp. 149–154, Oct. 1991.
[11] “Operational amplifiers—An orientation,” in *Amplifier Reference Manual,* Analog Devices, pp. 2–20, 1992.
[12] “High accuracy data acquisition instrumentation amplifier—Typical application and error budget analysis,” in *Amplifier Reference Manual,* Analog Devices, pp. 4–25, 1992.
[13] J. R. Riskin, “AN-244 application note: A user’s guide to IC instrumentation amplifiers,” *Analog Devices Applications Reference Manual,* pp. 10–13, 1993.
[14] G. H. W. Leuenberger, “Design and development of a microprocessor based Gauss meter,” M.S. thesis, Worcester Polytechnic Inst., Worcester, MA, Jan. 1995.

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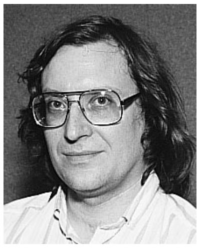

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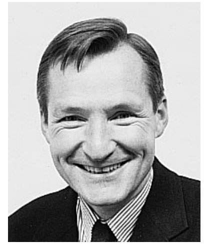

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