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Citation for published version (APA):

Jonker, R. J. W., Briaire, J., & Vandamme, L. K. J. (1999). Automated system for noise-measurements on low-ohmic samples and magnetic sensors. *IEEE Transactions on Instrumentation and Measurement*, 48(3), 730-735. <https://doi.org/10.1109/19.772210>

DOI:

[10.1109/19.772210](https://doi.org/10.1109/19.772210)

Document status and date:

Published: 01/01/1999

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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- The final published version features the final layout of the paper including the volume, issue and page numbers.

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Automated System for Noise-Measurements on Low-Ohmic Samples and Magnetic Sensors

R. J. W. Jonker, J. Briaire, and L. K. J. Vandamme

Abstract—An automated system for electronic noise measurements on metal films is presented. This new system, controlled by a personal computer which utilizes National Instruments' LabVIEW software, is designed to measure low frequency noise as a function of an externally imposed magnetic field and as a function of a dc bias current in low-ohmic samples and magnetic sensors. With this system we are able to measure continuously for several days, during which the measured spectra are collected, processed and stored for further analysis.

Index Terms—Automatic test equipment, digital control, electric variables measurement, noise measurement.

I. INTRODUCTION

WE ARE investigating the low-frequency noise in metal layers as a function of a dc bias current, in metal-lines, and as a function of an externally imposed magnetic field in magnetic resistors.

In a conventional noise measurement system, a constant dc current, obtained by the use of batteries and a metal film bias resistor, is applied to the sample. For ohmic samples, the measured spectrum $S_V(f)$ is proportional to the applied bias current squared [1]. Recently, Yassine and Chen [2] discussed the limitations of this dc noise measurement system and introduced a novel ac/dc noise measurement system for electromigration studies. Another ac excitation approach for measuring noise on low-ohmic samples was introduced by Verbruggen *et al.* [3]. Their system uses a single carrier frequency in a balanced bridge and two phase-sensitive detectors which operate in quadrature. With this system it is possible to measure the spectral density of the resistance fluctuations with strongly reduced background noise. In our system, we only use dc bias currents and the system noise is strongly reduced by using an ultralow-noise amplifier and cross correlation techniques.

Ciofi *et al.* [4] presented a measurement system based on a personal computer (PC) and a data acquisition system. In addition, others have used a PC to automate their measuring system [5], [6]. Although we also use a PC, in our system the data acquisition and Fourier analysis are performed by a separate spectrum analyzer. Besides automating the measurements, we would also like to automate the variation of the bias conditions and the amplitude and orientation of the externally applied magnetic field.

Sherry and Lord [7] demonstrated the applicability of National Instruments' LabVIEW in an educational environment. They describe the advantages of LabVIEW's graphical programming language over the traditional text based languages in automating a laboratory measurement setup. We also use LabVIEW to drive and control the system and to collect the data.

This paper describes an automated system for low frequency noise measurements on low-ohmic samples and magnetic sensors as a function of an externally imposed magnetic field and a dc bias current. The paper is structured as follows. Section II presents the system specifications and requirements. In Section III, the measurement setup and system control are presented. The custom made, ultralow-noise amplifier is also introduced in this section. Finally, in Section IV, conclusions are drawn.

II. SYSTEM SPECIFICATIONS

The samples under study are low-ohmic ($\leq 100 \Omega$) magneto-resistors and metal-lines, known to have low-noise levels. Investigating these samples requires a very sensitive measuring set-up, which makes the measuring system susceptible to disturbance. Therefore, special attention has to be paid to the design of the set-up in order to cope with the disturbance.

The resistivity of both metal-lines and magnetic sensors are a function of temperature. Accordingly, measures have to be taken to guarantee temperature stability.

Noise in magnetic sensors depends on the imposed magnetic field [8]. The investigation of this relationship demands the ability to manipulate the imposed magnetic field. For magnetic field sensors, special precautions have to be taken with respect to the pick up of spurious magnetic fields.

In order to avoid uncontrolled changes of the domain wall pattern, the orientation of the magnetic field should not be changed instantaneously. Noise in magneto-resistors is very sensitive to the disturbance of domain walls. The manipulation of the magnetic field should be controlled automatically.

The resistance and the noise of the magnetic-sensors is a function of the imposed magnetic field. Hence, each measurement should be preceded by an accurate resistance measurement. There is a relationship between the derivative, $\frac{\partial R}{\partial H}$, and the low-frequency noise [8], [9]. Although it is possible to calculate the derivative of the magneto-resistor, it is preferable to measure this derivative directly with a small ac field.

Another parameter is the bias current, which should therefore be adjustable.

There are two reasons why we do not use a Faraday cage to suppress the pickup of 50 Hz parasitic fields. First, a too

Manuscript received August 26, 1998.

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Publisher Item Identifier S 0018-9456(99)04989-X.

Fig. 1. Diagram of the bias circuit. Dashed line indicates sample, in this case a balanced Wheatstone bridge configuration.

close shielding disturbs the imposed magnetic field at the sample. Secondly, the large currents (up to 1.5 A), through the resistance ($10\ \Omega$) of the Helmholtz coils introduce a dissipation and a temperature drift in the cage and the sample.

In order to guarantee amplifier stability, we have to use a stabilized power supply. Since the measurements extend over several days, it is not possible to use a battery power supply.

It is necessary to average the noise spectra in order to collect data with smaller errors. In addition, measuring metal-lines, in order to investigate degradation in time by electromigration, requires repeated noise measurements over longer time spans. Consequently, measuring conditions should be stable for a long period (hours or even days). A high degree of automation is required, not only because the measurements are time-consuming, but also because measuring an entire magneto-resistance curve requires many measurements.

In order to measure automatically, software is needed to control the measurement setup. A PC has to be used to drive the instrumentation and to control the sample and magnetic field biasing. All data should be directed to the PC, where it can be processed and stored for data analysis.

The system requirements can be summarized as follows:

- ability to measure low-ohmic ($\leq 100\ \Omega$) magneto-resistors and metal-lines;
- stability of the sample temperature;
- capability of manipulating both orientation and amplitude of imposed magnetic field in case of magnetic sensors;
- magnetic field should be stabilized to guarantee stationary conditions;
- measure the derivative $\frac{\partial R}{\partial H}$ of the magnetic-sensor directly by ac technique;
- high degree of automation, i.e., the system should be able to measure continuously for several days;

- drive/control instrumentation (spectrum analyzer, lock-in amplifier and function generator) via GPIB;
- capability to control the bias circuitry (bias current through sample, magnetic field orientation and amplitude);
- data processing and storage facilities;
- additional noise introduced by instrumentation and circuitry should be negligible.

III. SYSTEM DESIGN

A. Measurement Setup

Of the problems indicated above, three can be solved by selecting an appropriate sample configuration. By using a Wheatstone bridge configuration (see Fig. 1), the introduced current noise, e.g., from the batteries, the noise due to temperature fluctuations common to all elements of the bridge and the noise introduced by a varying magnetic field, are common to all bridge components and therefore, can be regarded as common mode signals. Common mode signals have no influence on the measurements if the bridge is in perfect balance [10].

Suppose a dc current I is applied to the bridge (see Fig. 1). If we assume that $R_a \approx R_b \approx R_c \approx R_d$ and $\langle(\Delta R_a)^2\rangle = \langle(\Delta R_b)^2\rangle = \langle(\Delta R_c)^2\rangle = \langle(\Delta R_d)^2\rangle$ we will find expression (1) [11]

$$S_{V_{CD}} = \frac{1}{4} I^2 S_R. \quad (1)$$

The bias circuitry for the samples consists of a battery power supply ($\pm 24\ \text{V}$), providing a clean voltage source, and a set of metal film resistors in parallel which can be switched independently. In our set-up we use five metal film resistors (see Fig. 1) which can be selected individually, by means of

Fig. 2. Block diagram of measurement setup.

relays. This provides the selection of 32 (2^5) different bias currents, determined by the resistor range (516 Ω upto 16 k Ω and ∞ , i.e., all relays switched off). To measure the current through, and the voltage across the bridge, two meters have been included. During the noise measurements these meters are automatically disconnected. The obtained values are stored for analysis.

In our setup we use a set of Helmholtz coils in order to vary both orientation and amplitude of the applied field in a plane (see Fig. 2). We use a programmable dc power supply (Delta E030-3) to drive the coils and we measure the actual current. By providing this information to the software, a controlled system is realized which keeps the current constant and is able to compensate for drift in the dc current due to temperature drift. The dc power supply introduces disturbance, 50 Hz and higher harmonics. Consequently, a low-ohmic low pass filter is required, and we therefore use an LC -filter ($L = 1$ H, $C = 0.15$ F) which provides a cut-off frequency of 0.4 Hz without a large dissipation.

To determine the derivative, $\frac{\partial R}{\partial H}$, of the magneto-resistance, we investigate the small signal behavior. We make use of an ultralow distortion function generator (Stanford Research System DS360) to generate the ac current in the Helmholtz coils. Typically, the frequency is chosen within the 100 Hz–1 kHz range to avoid inductive pickup of the signal. The lock-in amplifier (Stanford Research System SR830 DSP) is used to measure the change in resistance due to the change in magnetic

field. Then the sensitivity coefficient or derivative $\frac{\partial R}{\partial H}$ of the magneto-resistance is calculated. With the lock-in amplifier locked at the ac frequency, we can now measure the small signal characteristic R_{ac} without problems caused by noise and pick up of spurious magnetic fields. Each set of coils contains two separately accessible coils: an inner coil, with a slightly smaller impedance, and an outer coil. We use the inner coils, in both directions, for the dc field and the outer for the ac field.

To compensate for slow temperature changes, a separate temperature controller for the sample in the bridge is implemented in an autonomous circuit. A thermometer (Keithley 871A), with a linear Temperature-Voltage characteristic, is used to measure the temperature of the sample. In combination with a Peltier element and a custom made PI-controller, temperature stability of the sample can be obtained (± 0.1 $^{\circ}\text{C}$). The Peltier element has a very large time constant (order of minutes), so the temperature controller will not be able to compensate for fast temperature fluctuations.

In the setup we use three custom made ultralow-noise differential voltage amplifiers, based on the Burr-Brown INA103 low-noise, low distortion instrumentation amplifier (see Fig. 3). We use cross-correlation techniques to suppress the amplifier noise. The implementation of the amplifiers will be discussed below.

To measure the spectrum we use a digital spectrum analyzer (Advantest R9211E), which is based on fast Fourier transform

Fig. 3. Diagram of the custom made ultralow-noise differential voltage amplifier. The first stage provides a gain of $201\times$, the second and third stage a total gain of $561\times$, resulting in ≈ 100 dB gain. The band-pass filter limits the bandwidth to a frequency range from 160 mHz up to 16 kHz.

(FFT). The analyzer can be programmed remotely. The analyzer is equipped with a cross-correlation algorithm, has a wide frequency range (10 mHz–100 kHz) and an input sensitivity ranging from -60 dBV (1 mVrms) up to $+30$ dBV (31.6 Vrms), which makes this analyzer suitable for our application.

In our setup we use the general purpose interface bus (GPIB) to control the instruments and exchange data (spectrum analyzer, lock-in amplifier and the function generator). We control the interface by using a special GPIB PC add-on board (National Instruments AT-GPIB/TNT). In addition to this, we have a second PC add-on board (National Instruments AT-MIO-16E-10) which provides us with both digital and analog I/O. This interface is used to control the bias current. The relays, used to control the bias current, are separately controlled by five digital outputs. We use two analog inputs to measure the sample current and the voltage across the bridge. A sixth digital output controls a relay which disconnects the voltage and current meters and the lock-in amplifier, see Fig. 2—①. To control the dc magnetic field, we use two analog outputs, one for the X and Y direction respectively, to provide the correct power supply voltage. Two additional digital outputs are used to control the polarity of the magnetic field, because the power supply is not able to generate an inverse (negative) current. Negative currents are necessary to provide 360° field manipulation instead of 90° . Finally, two analog inputs are used to measure the bias current in the field biasing circuit, see Fig. 2—②.

In Fig. 2 a block scheme of the measurement setup is depicted.

B. System Control and Data-Analysis

The easy access to the GPIB-bus, as well as the extended analysis features, make LabVIEW suitable for the type of application under discussion. To increase the resolution, the spectrum is measured in successive frequency spans. In the first stage we collect the data in the frequency range 1 Hz–100

Hz. In each successive stage we measure an additional decade. If the process is stationary, it is allowed to combine the spectra.

After a spectrum is collected it should be processed before storing it on disk. Although the setup is differential configured and a Wheatstone bridge is used, the environment introduces peaks in the spectrum, e.g. 50 Hz and higher harmonics. So, the data consists of the spectral components measured by the FFT analyzer, but is also afflicted with disturbance. To eliminate the peaks in the spectrum, an algorithm is implemented.

The data processing consists of two steps: In the first step we exclude all unwanted peaks in the frequency spectrum and in the second step we reduce the number of data points.

In the first step, we have to filter out all spectral components that can be regarded as man made noise, e.g., peaks in the spectrum due to 50 Hz. Manually, these peaks are easy to detect, but in order to automate the filtering of the data, a criterion has to be defined to distinguish the disturbance peaks from the signal. We have implemented this criterion as follows.

First we use the analysis package of LabVIEW to fit a curve through the measurement points. Then, we define the *deviation* of the obtained curve as our relative error. If the relative error of a spectral component is larger than a threshold value, this component will be excluded from further analysis. The threshold value depends mainly on the number of averages, since the relative variance ($((\frac{\Delta x}{x})^2)$) of a spectral value is inversely proportional to the number of averages, and on the power of the uncorrelated background noise relative to the correlated noise since we are measuring in cross correlation [12]. Increasing the number of averages will result in a more accurate approximation of the spectral value. This allows a more stringent threshold value. With this algorithm we are able to eliminate all disturbance peaks in our measured spectra.

The second data processing step comprises the reduction of the number of data points. The FFT spectrum analyzer measures spectral values, equidistant on a linear frequency scale. However, we prefer a reduced number of equidistant points on a logarithmic scale. This is obtained by averaging

Fig. 4. Spectra (800 lines, 100 averages reduced to $k = 6$ per decade) of the equivalent input noise voltage of a shorted input (1) Brookdeal 5004 (2) Burr-Brown. Curve (3) is the equivalent input noise voltage of two Burr-Brown based preamplifiers in parallel, using cross-correlation techniques.

all frequency components in a sub-band and assigning this sub-band to a single central frequency in the chosen band. Suppose we would like to have k points per decade, we therefore define k sub-bands in the n th decade, defined by 10^n up to 10^{n+1} . The values of the low and high frequency of the sub-bands are denoted by $10^{(n+\frac{i}{k})}$, $10^{(n+\frac{i+1}{k})}$ upto 10^{n+1} , with k the number of points per decade, $1 \leq i \leq k$ indicating the i th sub-band of the n th decade. Then we average (power sum) all power spectral values in the sub-band, and assign this average value to a specific central frequency: the average $(10^{(\frac{1}{k} \sum_j \log f_j)})$ of all frequencies in the sub-band. We now have a reduced set of spectral value estimates.

C. Ultralow-Noise Amplifier

In order to measure noise on low-ohmic samples we have to use an ultralow-noise pre-amplifier. The Brookdeal 5004 ultralow-noise pre-amplifier is a frequently used, commercially available amplifier, capable of measuring in a wide frequency range (0.5 Hz–1 MHz). In order to make a comparison with our (and other pre-amplifiers) we qualify the amplifier with two parameters: f_c and R_{eq} . When measuring the equivalent input noise spectrum S_V (1 Hz–10 kHz), the spectrum will show a flat part at higher frequencies, and an increasing spectrum below a certain corner frequency (f_c). From the flat part we can extract the R_{eq}

$$R_{eq} = \frac{S_V}{4k_B T} \quad (2)$$

with k_B Boltzmann's constant and T the temperature in Kelvin. The Brookdeal amplifier (60 dB) we use has a $R_{eq} \approx 45 \Omega$ and a corner frequency $f_c \approx 1$ kHz [see Fig. 4, curve (1)]. Considering the fact that our samples are low-ohmic, typically 20Ω for the metal-lines, the background noise of the amplifier is dominant. It is possible to use a matching transformer, e.g. a Brookdeal 9433, to overcome this problem, as shown in Fig. 5 curve (2). However, using a transformer will drastically reduce the bandwidth of our amplifier stage, 1 Hz–1 kHz for a 20Ω sample. If the resistance of the sample

Fig. 5. Spectra (800 lines, 100 averages reduced to $k = 6$ per decade) of the equivalent input noise voltage of low-ohmic sample (metal-line $\approx 20 \Omega$) with (1) our system (2) Brookdeal 5004 with matching transformer Brookdeal 9433.

is larger than 100Ω , this approach cannot be used due to bandwidth limitations.

To overcome this problem we implemented a low-cost, ultralow-noise preamplifier for measuring noise on low-ohmic ($<100 \Omega$) samples, with a wide frequency range (1 Hz–10 kHz). Our 100 dB amplifier has a $R_{eq} \approx 100 \Omega$ and a $f_c \approx 10$ Hz [see Fig. 4, curve (2)]. Obviously, a single amplifier with these specifications is not capable of measuring our low-ohmic samples. However, if we use two amplifiers and cross-correlation techniques we obtain a measurement system with a 100 dB gain, a wide frequency range (1 Hz–10 kHz), a low corner frequency (<10 Hz), capable of measuring noise on low-ohmic samples [see Fig. 4 curve (3)].

IV. CONCLUSION

Using LabVIEW for the implementation of an automated noise measurement system reduces the development time considerably, compared to traditional text based programming languages, such as C or C++. By using this system we are able to measure low frequency noise on magnetic sensors and metal-lines in a frequency range from 1 Hz–10 kHz as a function of bias current and applied magnetic field.

By using a bridge configuration we reduced the influence of

- 1) introduced current noise in the bias circuit;
- 2) noise due to coherent temperature fluctuations;
- 3) noise introduced by the varying coherent magnetic field.

We introduced a way to vary the dc bias current by means of a set of relays and bias resistors. This approach is also applicable in measurements on packaged devices, e.g. an L-array of resistors in a DIL package. With a switch-box, based on a set of relays, it is possible to select different resistors (samples) in successive measurements.

We have demonstrated that it is possible to use a custom made amplifier, based on a low-cost Burr-Brown INA103, to measure noise on low-ohmic samples using cross-correlation techniques. We have also illustrated that it is possible to measure noise on low-ohmic samples using a Brookdeal

5004 amplifier in addition to a Brookdeal 9433 matching transformer, although the bandwidth of this configuration is limited.

ACKNOWLEDGMENT

The authors wish to thank M. El Haddouchi for his contribution in the hardware implementation and R. R. M Vermeulen and P. N. Wouters for the development of the LabVIEW device driver for the Advantest R9211E spectrum analyzer.

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