Development of High-Sensitivity Fluxgate Magnetometer Using Single-Crystal Yttrium-Iron Garnet Thick Film as the Core Material

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Contract Number: N00014-00-C-0093

Thrust Category: Sensitive Fluxgate Sensor, Coherent Detection, Insulator Core

LONG-TERM GOALS

Traditionally, a fluxgate sensor is made of metallic magnetic ribbons by which the second-order harmonics is characterized in relation to an imposed dc field. Resolution of the sensor device is limited by Barkhausen noise generated in the core region. In contrast to the conventional approach we propose to perform fluxgate operation coherently involving detection of the generated harmonics of all orders. As such, noise influence is minimized, since noise can only add to the detection scheme incoherently. In order to achieve this goal we choose to work with insulator cores, such as single-crystal yttrium-iron-garnet (YIG) thick films. In the absence of eddy-current damping, high-order harmonics are not attenuated in the core region, allowing them to be effectively included as coherent detection. Our long-term goals are to fabricate efficient fluxgate sensors using YIG films as the core material providing the following advantages: reliability, ruggedness, and economy. Most importantly, we expect our new sensor devices would result in a sensitivity one or two orders superior to the existing devices.

OBJECTIVES

The objectives of the research are to develop a new class of fluxgate magnetometers using insulator YIG as the core material measuring and analyzing the gated signal in the coherent scheme. As such, noise content is reduced and the sensitivity of the device increased. We expect that our research products can ultimately compete with the more complicated and costly SQUID fluxmeter operating at liquid helium temperatures.

APPROACH

We will first fabricate prototype fluxgate magnetometers using insulator YIG films as the sensing-core material. High-order harmonics will be measured and included in the detection scheme in a coherent manner so as to decouple noise participation. The prototype device will be further miniaturized, improving temperature stabilization, reducing power requirement, and simplifying software manipulation to allow for optimal performance. The prototype will include all necessary electronics miniaturization, improved ruggedness, reliability in performance, and lower fabrication costs.

WORK COMPLETED

We have demonstrated graphically the generation of the gated signal in the fluxgate core region. With

this graphical construction it becomes apparent how high order harmonics are included in the final form of the signal. We have experimentally characterized the high order harmonics generated in a single-crystal YIG core and in a traditional core containing a nickel foil. The measured 10th order harmonics in the YIG core has shown 30 dB more resolution power than could be possibly provided by the nickel core when they are intended for high-order harmonics detection.

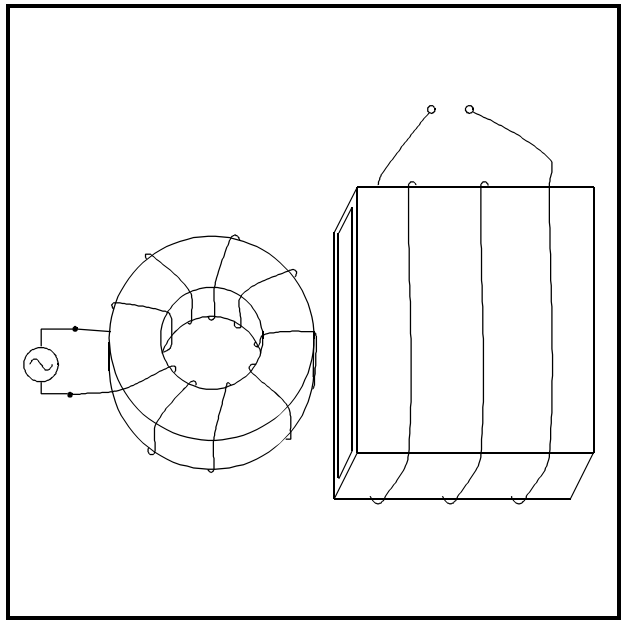

Fig.1 A traditional ring-core fluxgate magnetometer.

RESULTS

A fluxgate device employs an excitation coil winding around a ferromagnetic core shaped as a toroid, the so-called ring-core fluxgate magnetometer. The pickup coil is located outside the core and the excitation coil. To operate, an ac drive current is applied to the excitation coil producing a longitudinal magnetic field along the axial direction of the core. The drive field excites the core material encompassing the magnetized and the demagnetized states of the core material in alternation showing nonlinear variation in magnetic flux. Due to the canceling mechanism of the balanced structure only even harmonics of the drive current appear at the fluxgate terminals, and it is usually the second harmonics that is measured by the detection electronics. The schematic of a fluxgate magnetometer is shown in Fig.1. [1]

Operation of a fluxgate magnetometer is shown graphically in Figs.2, 3, and 4. In Fig.2 M denotes the magnetization and H the internal magnetic field, and a hysteresis loop is shown in the M-H plane whose coercive field is H_c and saturation field is H_s. The saturation magnetization is M_S. Fig.2 assumes the external field H_0 is zero. The drive field H_D then includes only the field generated by the excitation coil, which is connected with a current source as shown in Fig.1. Let H_D be a triangular wave whose waveform is shown at the lower left of Fig.2. Other waveforms may be equally considered. In Fig.2 t_c and t_s denote the time that H_D reaches H_c and H_s, respectively

In Fig.2 M_1 and M_2 denote the magnetization at two corresponding points located at the upper and the lower halves of the sensor core, respectively. Waveform for M_1, shown at the upper right of Fig.2, is derived as the output curve using the M-H plot, the upper left of Fig.2, as the transfer curve, and the H_D-t plot, the lower left of Fig.2, as the input curve. Waveform for M_2, shown at the lower right of Fig.3 is derived in a similar manner, but using the negative of H_D as the input curve, since the magnetization

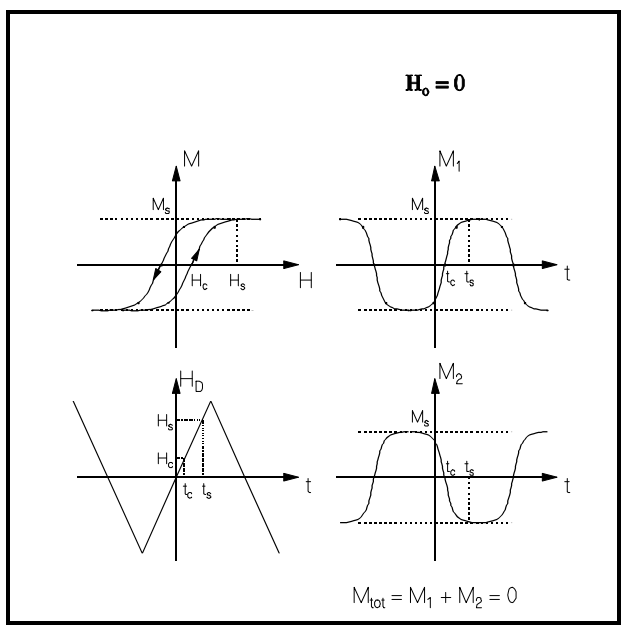

Fig.2 Graphical construction of output waveform when H_0 = 0 Oe.

direction changes from the upper half to the lower half of the core. The net magnetization from these two points is $M_{tot} = M_1 + M_2$, which is zero due to the symmetry of the ring-core geometry and the manner in which the drive field is excited. Thus, by including all the points contained within the core material the induced electromotive force at the two terminals of the pickup coil of Fig.1 is zero, if the external field $H_0 = 0$.

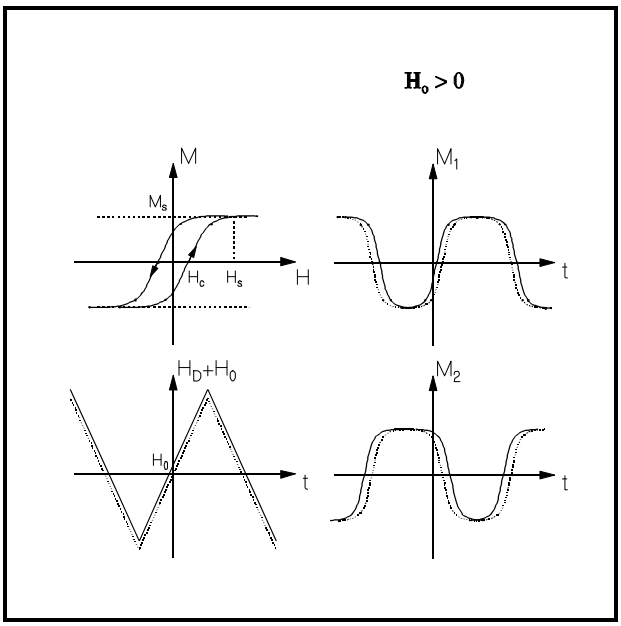

Fig.3 Graphic construction of output waveform $_o$ when H > 0 Oe.

Fig.3 shows the case that $H_0 > 0$. The same hysteresis curve is assumed, as shown at the upper left of Fig.3. However, M_1 is now derived by using $H_D + H_0$ as the input curve, which is shown as the solid triangular waveform at the lower left of Fig.3; the dashed waveform there denotes H_D only. The resultant waveform for M_1 is shown solid at the upper right of Fig.3. Analogously, M_2 is derived by using $-H_D + H_0$ as the input curve, whose waveform is shown solid at the lower right of Fig.3. The dashed curves shown for both the M_1 and M_2 plots duplicate the original curves shown in Fig.2 for the case of $H_0 = 0$ for the purpose of comparison. The total magnetization from these two points is $M_{tot} = M_1 + M_2$, which is shown solid at the top of Fig.4; the dashed curves in Fig.4 denote the original M_1 and M_2 curves shown in Fig.3. The resultant electromotive force at the fluxgate terminals is proportional to the time-derivative of M_{tot}, which is plotted at the bottom of Fig.4. In Fig.4 it is seen that, when $H_0 > 0$, the output waveform shows a non-vanishing amplitude whose frequency has been doubled when comparing to the waveform of the input drive field shown at the lower left of Fig.2.

As shown in Fig.4 the excited flux in the sensor core consists of a full spectrum of even-order harmonics of the drive current. Unfortunately, the conventional fluxgate measurements involve only the lowest order harmonics, whose operation could be adversely influenced by noise. By including harmonics of all orders, the detection sensitivity can be therefore improved, since noise can only add to the detection scheme incoherently. In fact, by including the second, fourth, and sixth order harmonics, Vetishko et al have successfully characterized weak signals in human body with improved sensitivity, as reported in Refs.[2,3].

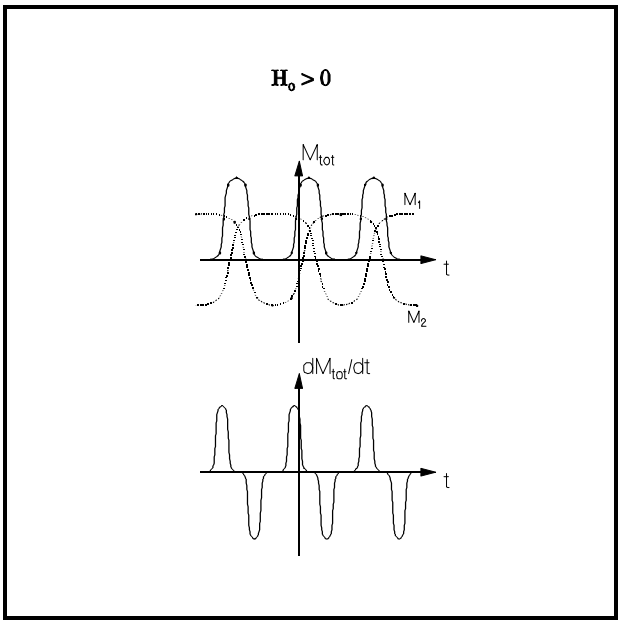

Fig.4 The resultant output waveform at the pickup coil of the magnetometer when H $_o$> 0 Oe.

Fig.5 shows the measured spectrum of the flux excited in a YIG core. The core was cut from a YIG/GGG/YIG sample purchased from Airtron, Charlotte, NC. The YIG films are of a nominal thickness of 100 µm, which were epitaxially grown along the <111> direction on both sides of a crystal GGG substrate (thickness 20 mil). The core was

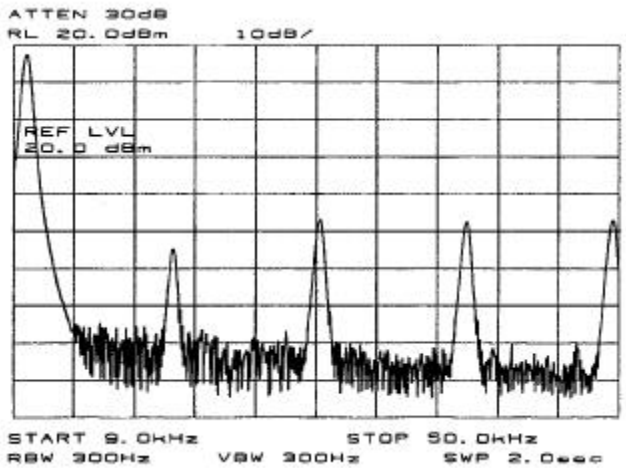

Fig.5 Measured high order harmonics in a YIG insulator core at 10 KHz.

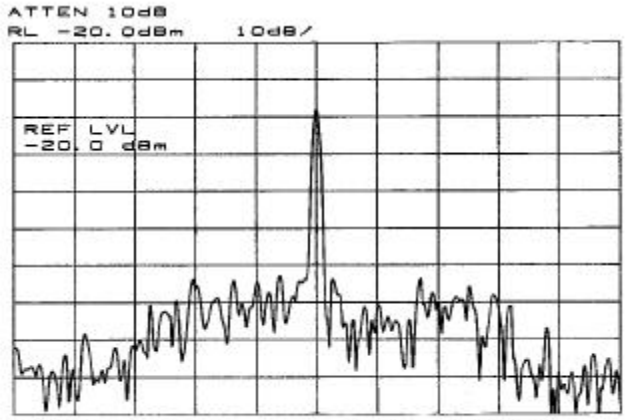

Fig.6 Measured 10th order harmonics shown in Fig.5.

driven by a sinusoidal current at 10 KHz encompassing the magnetic saturation states in both directions. High order harmonics, as well as noise, are seen in Fig.5, and the harmonics show little attenuation at high frequencies, since eddy-current damping is not important. Fig.6 shows the same plot of Fig.5 but centered at the 10th order harmonics at 100 KHz. It is seen in Fig.6 that the generated 10th order harmonics is 45 dB above the noise level, providing a sufficient resolution power for the detection of a weak signal.

As a comparison, Fig.7 shows the case that a nickel foil is used as the core material. In Fig.7 the core material consists of 99.5% nickel, purchased from Alfa, Ward Hill, MA. The thickness of the nickel foil is 0.025 mm. As before, the metal core was driven by a sinusoidal current at 10 KHz, encompassing the saturation states from both directions. Fig.7 shows the measured spectrum of the excited flux in the core region. From Fig.7 it is seen that the generated harmonics decrease with frequency, and at 100 KHz, the 10th order harmonic frequency, the signal is 15 dB above the noise level. Comparing Fig.6 with Fig.7 it is obvious that an insulator core provides a better resolution power for high-order harmonics detection than a metal core does, since at the 10th order harmonics frequencies, for example, the insulator core shows an intensity which is 30 dB better in signal resolution.

IMPACT/APPLICATIONS

Early development of fluxgate magnetometers was for airborne magnetic surveys and for submarine detection during World War II. They were further developed for geomagnetic studies (airborne, seaborne, and underwater), for mineral prospecting, and later for magnetic measurements in outer space. They have also been adapted and developed for various detection and surveillance devices, both for civilian and military use. Despite the advent of newer technologies for magnetic field

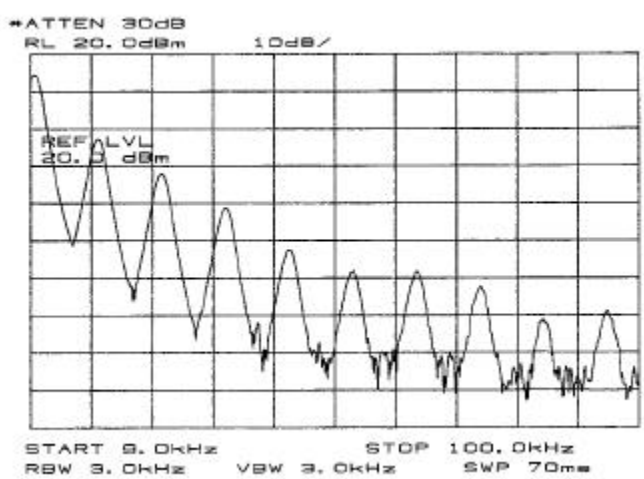

Fig.7 Measured high order harmonics in a metal nickel core at 10 KHz.

measurement, fluxgate magnetometers continue to be used successfully in all of these areas, because of their reliability, relative simplicity, economy, and ruggedness. By improving the sensitivity of a fluxgate sensor, we expect new applications in the medical field, such as for magneto-cardiogram applications.

TRANSITIONS

The fluxgate sensor continues to be the preferred transducer for magnetic field vector measurements, not only because the supporting electronics is fairly simple and reliable, but also because new developments in materials sciences continue to push the noise figure to its intrinsic quantum limit. It is now approaching the point where the fluxgate device becomes an attractive alternative to the more complicated and costly SQUID fluxmeter. Fluxgate magnetometers have been used in a variety of applications, such as magnetic air-borne detection, search and surveillance operations, nondestructive testing of materials, palaeomagnetism, and exploration of magnetic fields in space. The increased sensitivity of the proposed device can further increase its applicability, for example, in medical imaging sensor applications. Our proposed device would result in the highest sensitivity, and, hence, imply many related applications.

RELATED PROJECTS

We have analyzed for the first time a rigorous mathematical treatment of the operation of a ringcore fluxgate magnetometer. [2] Also, we have presented a theory relating the Barkhausen noises to fluxgate performance. [5] The noise performance of a fluxgate sensor have been investigated using Monte Carlo simulation in which the Preisach model was used to simulate domain wall motion. We have been involved in many linear and nonlinear studies in materials and devices. [6]

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PUBLICATIONS

Our work will present in the 8th Joint MMM-Intermag Conference, BP-11, to be held in San Antonio, Texas, January 7-11, 2001. A manuscript entitled "Generation of high-order harmonics in insulator sensor cores," has been submitted to IEEE Transactions on Magnetics, on September 18, 2000.