Approach for sub pT, Room Temperature Magnetic Sensors

Alan S. Edelstein, Greg A. Fischer, Jonathan E. Fine,
US Army Research Laboratory
Adelphi, MD 20783, USA
alan.edelstein@us.army.mil

Dwight Viehland
Virginia Tech University
Blacksburg, VA 24061, USA

Abstract— Some of the major contributions to noise in magnetic sensors can only be reduced by increasing the size of the sensor. Here we present an approach for reducing 1/f noise in large magnetic sensors. The approach is based on modulating the field by rotating a disc containing permalloy flux concentrators or flux guides. The disc rotation is driven by an air turbine. Modulation frequencies as high as 76 Hz have been achieved, but higher modulation frequencies will be achieved in our new design. Low frequency signals appear as sidebands around the modulation frequency. The magnetic sensor used is a magnetoelectric sensor. Magnetoelectric sensors have achieved sensitivities of 2nT at 1 Hz. By using modulation to operate at the mechanical resonance frequency of magnetoelectric sensors it should be possible to achieve sub pT/Hz^{1/2} at 1 Hz. Here we discuss the progress and problems in achieving this goal.

I. INTRODUCTION

There has been considerable recent progress in magnetic sensors. Examples of this progress are: (1) The discovery[1,2] that using MgO barriers in magnetic tunnel junctions leads to magnetoresistance values as large as several hundred percent and (2) the invention[3] of magnetoelectric sensors. Magnetoelectric sensors are composed of a piezoelectric material sandwiched between slabs of a magnetostrictive material. In a magnetic field the magnetostrictive material stresses the piezoelectric material which in turn generates a voltage. Thus, an output is generated without using any input power.

The sensitivity of magnetic sensors is limited by the magnitude of their response to a magnetic field and their noise. Sensors with large responses to magnetic fields also tend to have larger 1/f noise. Fig. 1 shows an example of 1/f noise in a magnetoelectric sensor. Even though anisotropic magnetic sensors only have magnetoresistance values less than 3.5 % they are still widely used because their 1/f noise is small. The large 1/f noise in magnetic tunnel junctions with MgO barriers has limited their use at low frequencies. This led to research[4] on a device, the MEMS flux concentrator, that modulates the field and thus increases the operating frequency to a region where 1/f noise is less important. The MEMS flux concentrator is a viable solution for essentially solving the problem of 1/f noise in small magnetic sensors.

Besides the 1/f noise term there are other contributions to the noise. Both shot noise and thermal magnetic noise[5] that depend on the size of the sensor are also important. Thus, to achieve sub pT sensitivities it is probably necessary to use larger sensors. Since the MEMS flux concentrator was designed to be used with small sensors, a different approach is needed to achieve sub pT sensitivities with large magnetic sensors. Here we describe a new approach, based on using a rotating disk, which allows us to modulate the field for sensors occupying a volume of about a cubic cm.

II. APPROACH FOR MODULATING THE MAGNETIC FIELD OF LARGE MAGNETIC SENSORS AND ACHIEVING SUB PT SENSITIVITY

Magnetoelectric sensors were chosen for this approach because their sensitivity is already about one nT and magnetoelectric sensors must have dimensions of several cm to maintain good sensitivity. The magnetoelectric coefficient, which is a measure of the response of a magnetoelectric sensor to a magnetic field, is shown in Fig. 2. Note that this coefficient has a sharp peak that occurs at the mechanical resonant frequency of the sensor. It also should be pointed out that the data shown was taken in a constant 240 Oe magnetic field. A biasing field like this is required because the magnetostriction is an even function of the field and approaches $H=0$ with zero slope

Figure 1. Example of 1/f noise in a magnetoelectric sensor.

Fig. 3 shows a picture of the apparatus used for modulating the field. The sensor is positioned about 1 mm above the rotating disc. The rotation rate is monitored by using a photo cell and holes in the disc. Thin pieces of sheet permalloy on the disc act either as flux concentrators or as flux guides that shield the sensor from magnetic flux. Originally an electric motor was used to drive the rotation, but the motor generated too much electrical noise. This led us to switch to using an air turbine and air bearing to drive the motion.

III. RESULTS, ISSUES, AND METHODS FOR RESOLVING THESE ISSUES

The results reported here were made with a spin valve from NVE Corporation. Spin valves are thin, four layer structures composed of an antiferromagnetic layer that “pins” the magnetization of the next layer, a metallic ferromagnetic. The next layer is a nonmagnetic conductor such as Cu. The last layer is another ferromagnetic layer called the free layer because its magnetization is unconstrained from rotating. The resistance of a spin valve has its minimum value when the magnetizations of the two ferromagnetic layers are parallel to one another. The room temperature magnetoresistance of our

Figure 2. Transverse magnetoelectric coefficient of a magnetoelectric

Figure 3. Rotating flux concentrator apparatus.

spin valve was 4 %. The test results using a 10 Hz field are shown in Fig. 4. One sees the expected sidebands at 66 and 86 Hz around the modulation frequency of 76 Hz. This result proves the validity of the concept of using rotating flux concentrators and guides to shift the operating frequency. To make practical application of this concept several changes have to be made and certain technical difficulties have to be overcome. The rest of the paper discusses these modifications, difficulties, and possible solutions.

A. Modifications

As mentioned earlier, the electric motor gives rise to considerable electric noise. This problem is illustrated in Fig. 5 where one sees the large increase in noise that occurs when the electric motor is running. To solve this problem we substituted an air turbine and air bearing for the electric motor. As seen in Fig. 6, using the air turbine and air bearing does not add to the background noise. The noise is about the same when the disc is rotating as when it is at rest. It is not clear why the background noise is larger in these later measurements than in the earlier measurements (Fig. 5). To increase the modulation of the field, we have changed the design of the flux concentrator and the flux guide. The new

Figure 4. Sidebands at 66 and 86 Hz generated by rotating the disc

Figure 5. Comparison of the noise with a stationary disc and with the disc being rotated by an electric motor.

design is shown in Fig. 7. There are rods of permalloy that have been annealed to increase their magnetic permeability. In the position of the disc shown in Fig. 7, the field at the position of the sensor is maximum. When the disc is rotated by 90 degrees the flux guide on the disk will largely shunt the magnetic flux under and away from the sensor. Thus, rotating the disc will create a large modulation of the field.

The spin valve must be replaced with the magnetoelectric sensor. This will require several changes. First, because the piezoelectric is a high resistance material, using a voltage amplifier loads down the output. Because of this, we shall use a charge coupled amplifier, PCB Piezotronics Model 441A33. Further, the magnetostrictive material must be biased with a DC field.

B. Difficulties and Possible Solutions

If one uses permanent magnets to bias the magnetostrictive material that are not on the disc they will interact with the permalloy on the disc and affect the motion. The solution to

Figure 6. Comparison of the spin valve output when the disc is stationary but has flux concentrators attached to the disc, when it is rotating at 10.4 Hz but with no flux concentrators attached to the disc, and when it is rotating at 40 Hz and with flux concentrators attached to the disc.

Figure 7. New flux concentrator design at the orientation of the disc that maximizes the flux at the position of sensor (yellow square).

this problem is to place the permanent magnets on the disc and configure the magnets in the form of a ring so that the DC field at the position of the sensor remains constant as the disc rotates.

In order to take advantage of the increased response of the magnetoelectric sensor at its mechanical resonance frequency it is necessary to modulate the field at this frequency. This will be achieved by measuring the rotation rate with a photocell as we are currently doing and using feedback to control the air flow driving the rotation so that modulation frequency matches the mechanical resonant frequency of the sensors. Since the mechanical resonant frequencies of magnetoelectric sensors tend to be much higher than our rotation rate, it will be necessary to both increase our rotation rate, by using a new design of the air turbine and air bearing, and decrease the mechanical resonant frequency of the sensor. The possible ways of decreasing the mechanical resonant frequency of the sensor include using a different normal resonant frequency and increasing the mass. With our current design the modulation frequency is limited to about 1000 Hz because above this frequency the velocity of the outer edge of the disc will approach the speed of sound.

IV. CONCLUSION

Large magnetic sensors are needed to reach the ultimate sensitivity. We have demonstrated that one can use a spinning disc containing flux concentrators and flux guides to increase the operating frequency of large magnetic sensors. We have found that using an air turbine and air bearing we can spin the disc without increasing the noise. Though we demonstrated the concept with a spin valve sensor, our program is focused on using magnetoelectric sensors to obtain sub pT sensitivity at 1 Hz. Problems in using these sensors and solutions to these problems were discussed.

ACKNOWLEDGMENT

The assistance of Wm. Frasier in the design of the air bearing and the assistance of Peter S. Cremona-Simmons is gratefully acknowledged.

REFERENCES

- [1] W. H. Butler, X.-G. Zhang, T.C. Schulthess, J.M. MacLaren., "Spin-dependent tunneling conductance of Fe[MgO]Fe sandwiches," *Phys. Rev. B*, vol. 63, pp. 054416/1-12, 2001.
- [2] Stuart S. P. Parkin, Christian Kaiser, Alex Panchula, Philip M. Rice, Brian Hughes, Mahesh Samant, and See-Hun Yang, "Giant tunnelling magnetoresistance at room temperature with MgO (100) tunnel barriers," *Nature Materials*, vol. 3, pp. 862, 2004.
- [3] J. Das, M. Li, S. S. Kalarickal, S. Altmannshofer, K. S. Buchanan, J. F. Li, and D. Viehland, "Control of magnetic and electric responses with electric and magnetic fields in magnetoelectric heterostructures," *Applied Physics Letters*, vol. 96, pp. 222508, 2010.
- [4] A. S. Edelstein, J.E. Burnette, G.A. Fischer, K. Olver, Wm. Egelhoff, E. Nowak, and Shu-Fan Cheng, "Validation of the microelectromechanical system flux concentrator concept for minimizing the effect of 1/f noise," *J. Appl. Phys.*, vol. 105, p. 07E720, 2009.
- [5] W. F. Egelhoff, Jr., P. W. T. Pong, J. Unguris, R. D. McMichael, E. R. Nowak, A. S. Edelstein, J. E. Burnette, and G. A. Fischer, "Critical challenges for picoTesla magnetic-tunnel-junction sensors," *Sensors and Actuators A*, vol. 155, pp. 217-225, 2009.