Application Notes for GMR Sensors

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If application questions or concerns exist, please contact NVE prior to use of the products.

General Comments

NVE GMR sensors are designed to measure or sense magnetic field strength over a wide range of fields. GMR sensors directly detect magnetic field rather than the rate of change in magnetic field; therefore, they are useful as DC field sensors. NVE's GMR sensors are sensitive to small changes in magnetic fields. This allows for accurate measurement of position or displacement in linear or rotational systems. The extremely small size of the sensing element enhances the position sensitivity, especially in applications incorporating small magnets and large field gradients. Magnetic fields produced by current carrying conductors make our devices usable as current sensors or detectors.

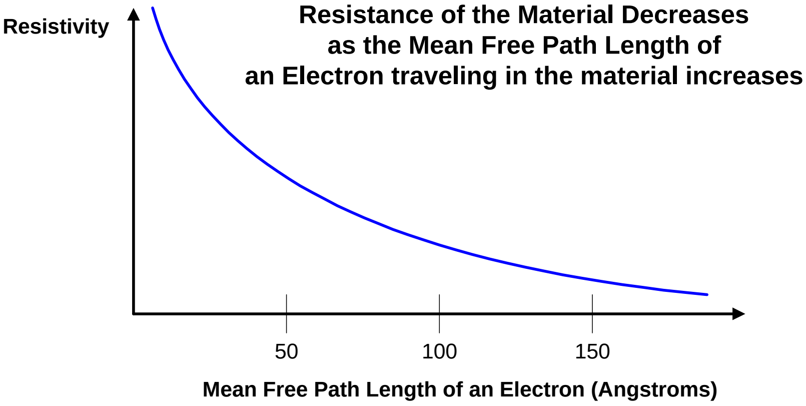
Competitive Technologies

GMR sensors have greater output than conventional anisotropic magnetoresistive (AMR) sensors or Hall effect sensors, and are able to operate at fields well above the range of AMR sensors. In addition, high fields will not "flip" GMR sensors or reverse their output as is possible with AMR sensors. High fields will also not cause damage to NVE GMR sensors, as is the case with some competing GMR sensor products.

The output of GMR sensors is frequency insensitive up to 1 MHz. GMR sensors produce an output with a constant field. This sets them apart from inductive (variable reluctance) field sensors, which respond only to changes in magnetic field. High resistivity GMR material enables the fabrication of sensors with high resistance. Sensors with 5 kΩ resistance is standard. Special low power devices can be manufactured with 30 kΩ or higher resistance. Sensors can also be fabricated with built-in offset at zero field that provide for a zero crossing in output at a specified field value.

GMR Material Physics

The giant magnetoresistive phenomenon, discovered in 1988, is an effect found in metallic thin films consisting of magnetic layers a few nanometers thick separated by equally thin nonmagnetic layers. Researchers observed a large decrease in the resistance with a magnetic field applied to the films. This effect is based partly on the increasing resistivity of conductors as their thickness decreases to a few atomic layers. In bulk material form, conduction electrons in these materials can travel a long distance before "scattering," or changing direction, due to a collision with another atomic particle. The average length that the electron travels before being scattered is called the mean free path length. However, in materials that are very thin, an electron cannot travel the maximum mean free path length; it is more likely that the electron will reach the boundary of the material and scatter there, rather than scatter off another atomic particle. This results in a lower mean free path length for very thin materials. It is therefore more difficult for conduction electrons to travel in this material, and the result is higher electrical resistivity. The chart below shows the relationship between resistivity of a magnetic material such as iron or nickel, and the thickness of the material at very small dimensions. For purposes of scale, one nanometer equals ten Angstroms; a copper atom has a diameter of about 3 Angstroms:



In order to take advantage of this effect, GMR films are manufactured with very thin layers of alternating magnetic and non-magnetic materials. This is done to allow magnetic modulation of the electron spin in the materials. The spin dependence of conduction electrons in magnetic materials, along with the increasing resistivity at very small material thicknesses, combine to make the GMR effect possible.

The figure below shows a simplified structure of a typical GMR sensor film, as manufactured by NVE:

Cross Sectional Structure of Basic GMR Material

Top Film (Magnetic Material, 20-50 Angstroms Thick)

Conductive Interlayer (Non-Magnetic Material, 15-40 Angstroms Thick)

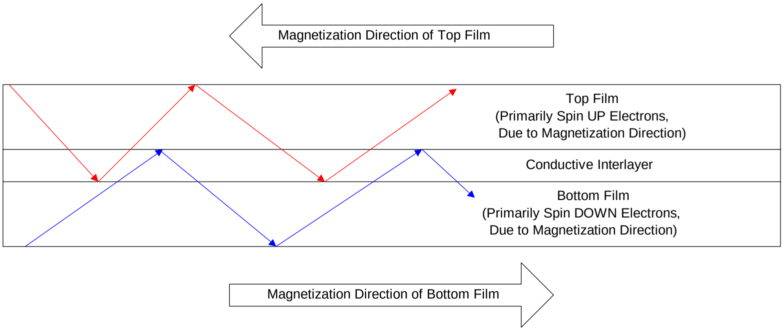
Bottom Film (Magnetic Material, 20-50 Angstroms Thick)

The diagram shows two magnetic material layers, sandwiching a non-magnetic interlayer. The magnetic layers are designed to have anti-ferromagnetic coupling. This means that the magnetization of these layers is opposite to each other when there is no external magnetic field applied to the material. Antiferromagnetic coupling can be visualized by imagining two bar magnets on either side of a thin sheet of plastic. The magnets couple head to tail (north pole to south pole) across the boundary formed by the plastic. In a similar fashion, the magnetization direction of the magnetic layers in the GMR film couple head to tail across the non-magnetic interlayer of the film.

The conduction electrons in magnetic materials have a spin characteristic. The electrons are normally referred to as spin up electrons when the material is magnetized in one direction, and spin down electrons when the material is magnetized in the opposite direction.

The diagram below shows some electron paths inside the GMR material structure. The two arrows indicate the antiferromagnetic coupling. Notice that the electrons tend to scatter off the two GMR material interfaces. This is because the electrons from the spin up layer are trying to enter the spin down layer, and vice versa. Because of the differences in the electron spins, it is more likely that the electrons will scatter at these interfaces:

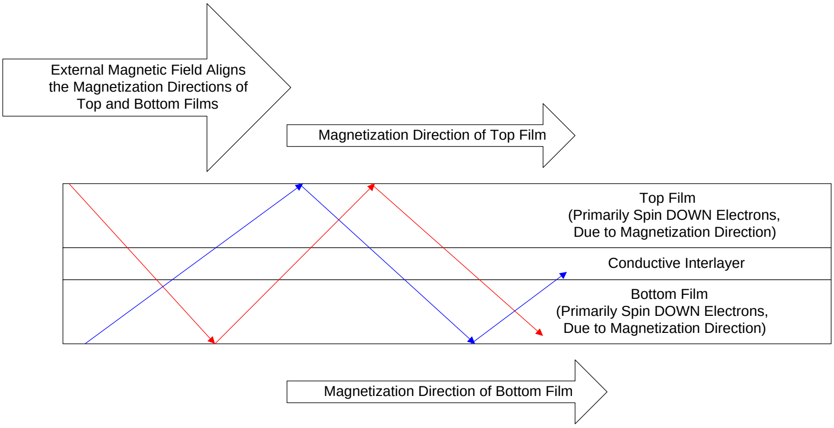
Spin UP Electrons Scatter at Interface with Spin DOWN Layer; Spin DOWN Electrons Scatter at Interface with Spin UP Layer Average Mean Free Path of the Electrons is Short



The end result in this case is that the mean free path length of the conduction electrons is fairly short, resulting in a relatively high electrical resistance.

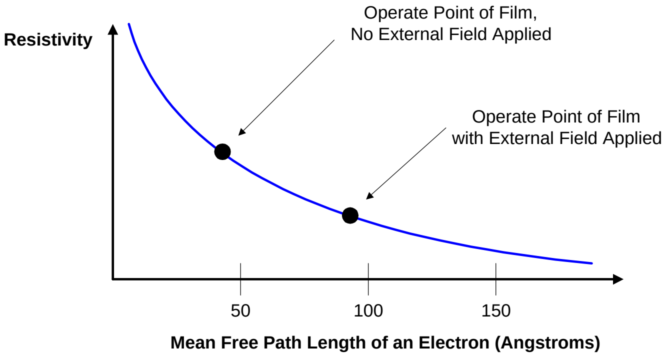
If an external magnetic field of sufficient magnitude is applied to this GMR material, it will overcome the antiferromagnet coupling of the magnetizations between the two magnetic layers. At this point all the electrons in both films will have the same spin. It will then become easier for the electrons two move between the layers:

**Spin States of the Magnetic Layers are the same;
Electrons Travel More Readily Through Entire Stack of GMR Material.
Average Mean Free Path of the Electrons is Long**



Note that the mean free path length of the electrons has now increased. This results in an overall lower electrical resistance for the GMR material. The change in resistivity of the material is shown on the path length diagram below:

**Resistivity Plot Showing Operate Points of GMR Material
With and Without an External Magnetic Field Applied;
Applying the External Field Results in Lower Device Resistance**



This change in resistance is the GMR effect.

The size of the resistance decrease is typically 4% to over 20%, depending on the material structure of the GMR films. Most of NVE's sensor products rely on a GMR material which exhibits 14% to 16% decrease in resistance. The "percent GMR" of a given material is calculated using the following formula:

% GMR = Change in Resistance / Minimum Resistance

For example, assume an electrical resistor is implemented with GMR material, and it shows a nominal resistance of 5000 Ohms. Then a magnetic field is applied and with this field a minimum resistance of 4400 Ohms is achieved. The percent GMR is then 600/4400, or about 13.6%.

Not all GMR materials operate in the manner described above. All GMR materials rely on modulating the difference between the magnetization directions of adjacent layers in the GMR film structure, but some achieve this modulation in different ways. The other most common type of GMR material is referred to as a "spin valve" GMR material. This type of material does not necessarily rely on anti-ferromagnetic coupling of the adjacent magnetic layers in the GMR film. In this case one of the magnetic layers is "pinned," or fixed with respect to its magnetization direction. The magnetization direction of the pinned layer will not move when exposed to normal operating magnetic fields. Therefore, the externally applied magnetic field will modulate the direction of the other magnetic layer, referred to as the "free" layer. As the angle between the free layer and the pinned layer varies, the mean free path length of the electrons in the GMR film also varies, and therefore the electrical resistance will change.

Fixing the magnetization direction of the pinned layer in spin valve GMR materials can be done in a variety of ways. However, it is important that the layer is pinned in a robust manner; otherwise, the pinning can be undone by application of a large magnetic field. This will destroy the operation of the sensor. NVE uses the application of large magnetic fields and high anneal temperatures (over 240°C) to set the pinned layer of the film. This layer ***cannot*** be unpinned with the application of any magnetic field in the normal temperature range of operation. Therefore, the sensor cannot be damaged by large magnetic fields. This is also true of NVE's other GMR sensors; no damage to any NVE GMR sensor product can result due to the application of extremely large magnetic fields.

One of NVE's competitors in Europe introduced a GMR sensor in 1997 that could be damaged by magnetic fields in the 250 Gauss range. This product has since been discontinued.

GMR Materials Types Manufactured by NVE

NVE manufactures four different types of GMR materials for use in our sensor products. These GMR materials are described below:

Standard Multilayer (ML) – This GMR material has AF (antiferromagnet) coupling, % GMR in the range of 12% to 16%, magnetic saturation fields of about 300 Oersteds, stable temperature characteristics for operation up to 150°C, and moderate hysteresis.

High Temperature Multilayer (HTM) – This GMR material has AF coupling, % GMR in the 8% - 10% range, magnetic saturation fields of about 80 Oersteds, stable temperature characteristics for operation up to 200°C, and high hysteresis.

Low Hysteresis High Temperature Multilayer (LHHTM) – This GMR material is AF coupled, has % GMR in the range of 8% - 10%, magnetic saturation fields of about 180 Oersteds, stable temperature characteristics for operation up to 200°C, and low hysteresis.

Spin Valve (SV) – This GMR material has one pinned layer, has % GMR in the range of 4% - 5%, magnetic saturation fields of about 25 Oersteds, stable temperature characteristics for operation up to 200°C, and nearly zero hysteresis when operated in saturation mode.

The following table gives a brief comparison of these different GMR materials, and indicates in which product prefix they are used:

GMR Material	% GMR	Saturation Field (Oe)	Temperature Range	Hysteresis	Product Prefixes
ML	12%-16%	250 - 450	-40 - +150	Medium	AA, AB, AD
HTM	8%-10%	60 - 100	-40 - +200	High	AAH, ABH, ADH
LHHTM	8%-10%	160 - 200	-40 - +200	Low	ABL
SV	4%-5%	20-30	-40 - +200	Low	AAV

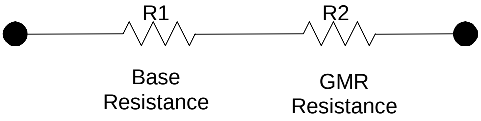
In addition to these materials, NVE is currently developing more specialized GMR materials for various sensor applications, including a bipolar output low hysteresis material and a spin dependent tunneling material. Please check our web site for new product releases based on these new GMR materials.

Temperature Characteristics of GMR Sensors

Temperature excursions cause several changes to the characteristics of GMR sensors. The changes are described below:

1. Changes to base resistance of the sensor element [TCR] – This is a temperature coefficient of resistance of the sensor element with no applied magnetic field to the sensor. The TCR is normally given in %/ºC.
2. Changes to the % GMR of the sensor element [TCGMR] – When a magnetic field is applied, the % GMR exhibited by the sensor element will change. Generally as temperature increases, % GMR decreases. TCGMR is normally given in %/ºC.
3. Changes to the saturation field of the sensor element [TCHsat] – The magnetic field at which the sensor will provide its maximum output will also change with temperature. The saturation field (Hsat) will decrease as temperature increases. TCHsat is normally given in %/ºC.

For purposes of temperature compensation, a single resistor sensor element made from GMR material can be modeled as two resistors in series. The first resistor is the base resistive element, and is a constant resistance at a given temperature, regardless of the applied magnetic field. The second resistor represents the changing resistance of the single resistor sensor element made from GMR material, as magnetic field is applied. This model is shown in the following diagram:



The base resistance of R1 is the resistance of the sensor element at 25°C when the saturating magnetic field is applied and R2 has dropped to 0 resistance; in other words, the minimum resistance of the sensor element as described in the GMR Material Physics section. The following formula can be used to compute R1 at various temperatures:

R1 = R1 Base Resistance * [1 + (TCR * (Temperature - 25°C))]

The resistance of R2 in the diagram varies both with the temperature and the applied magnetic field. The base resistance of R2 is defined as its maximum resistance at 25°C. This is the resistance with zero applied magnetic field. The base resistance of R2 will vary with temperature (at zero applied field) as described by the following formula:

$R2_{\text{Zero Field}}$ = R2 Base Resistance * [1 + (TCGMR * (Temperature - 25°C))]

When a magnetic field is applied to R2, its resistance will vary in a generally linear fashion with the applied field, from zero up to the saturation field (Hsat). After the GMR material's saturation field is reached, applying additional magnetic field will not result in changes to the resistance of the device.

The complete equation for R2, taking into account both the changes in % GMR with temperature and the changes in Hsat with temperature, and assuming operation of the sensor element at magnetic fields less than the Hsat value, is given below:

$R2 = R2_{\text{Zero Field}} * [1 - (AF / HsatT)]$

Where:

AF = Applied Magnetic Field

HsatT = Hsat@25°C * [1 - (TCHsat * (Temperature - 25°C)]

Please note that although the equations provided above result in linear results, the actual GMR devices are not perfectly linear. In particular, the transition of the output characteristic as it enters magnetic saturation is rounded, and can be seen in the temperature performance graphs of the various GMR materials shown at the end of this section. In addition, non-linearities also exist in some cases near the zero field range of the devices. The best fit for the formulas provided above is in the linear operating range of each sensor element as defined in the product specifications.

In addition, the effects of flux concentration and shielding in the sensor element are not reflected in these equations, nor is any effect from hysteresis included.

In many cases, an analysis of the complete temperature characteristic of the device is not required; the only important parameter is how the output of the sensor device itself changes with temperature. In this case, it is important to know if the sensor is being supplied with a constant voltage source or a constant current source. If a constant current source is used, the voltage across the sensor can increase as the resistance of R1 increases with temperature, thus mitigating some of the signal loss effects with temperature.

NVE has defined the following two terms to describe the change in signal output with temperature:

TCOV: Temperature Coefficient of the Output with a constant Voltage (V) source; given in %/°C.

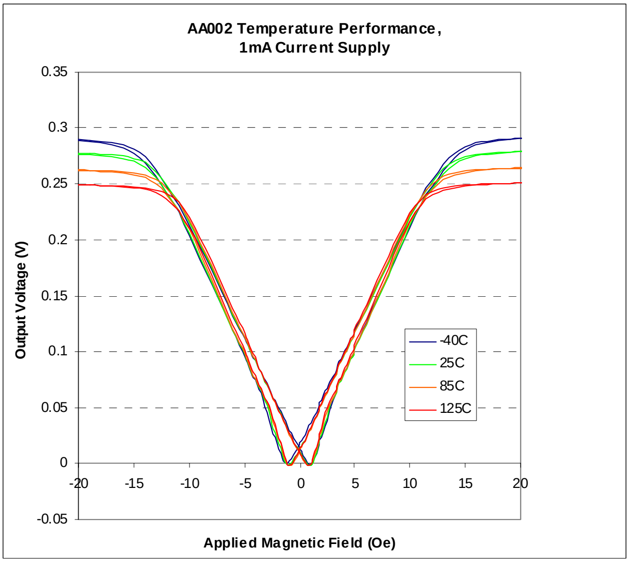
TCOI: Temperature Coefficient of the Output with a constant Current (I) source; given in %/°C.

These numbers will provide an accurate indication of the change in the output of the parts over temperature in the linear operating range. Note that this data is provided for NVE's AA and AB type parts but not for any of the parts that include a signal processing IC in the package. This is because NVE typically builds temperature compensation circuitry into the signal processing IC.

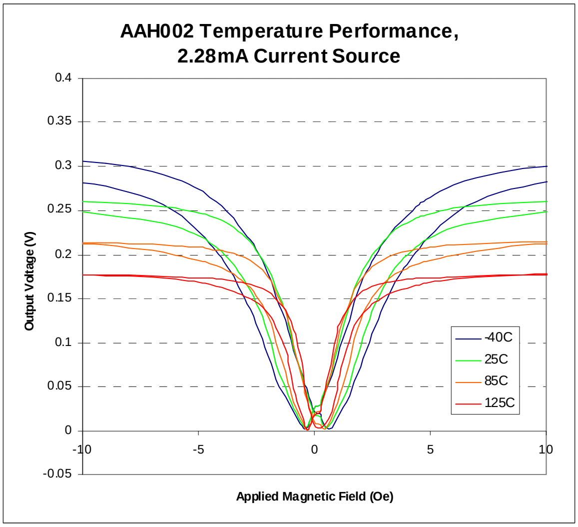
The following table summarizes the temperature coefficients described in the preceding paragraphs for the GMR materials used in most of NVE's products:

GMR Material Type	ML	HTM	LHHTM
Product Series	AA, AB, AD	AAH, ABH	AAL, ABL, AKL
TCR (%/C)	+0.14	+0.11	+0.11
TCGMR (%/C)	-0.10	-0.38	-0.38
TCHsat (%/C)	-0.10	-0.45	-0.25
TCOI (%/C)	+0.03	+0.10	-0.28
TCOV (%/C)	-0.10	0.0	-0.40

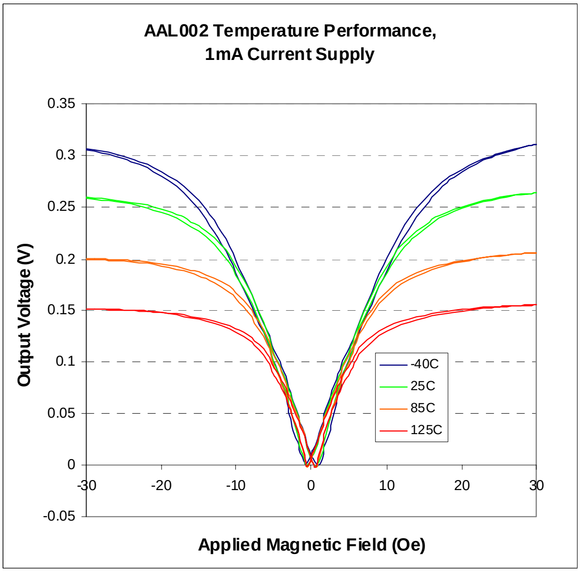
The following graphs show the basic temperature behavior of the three most common types of GMR materials used in NVE's products. The first graph shows the temperature behavior of an AA002-02 sensor, which is representative of the GMR material used in NVE's AA, AB, and AD-Series products:



The next graph shows the temperature behavior of an AAH002-02 sensor, which is representative of the GMR material used in NVE’s AAH and ABH-Series products:



The next graph shows the temperature behavior of an AAL002-02 sensor, which is representative of the GMR material used in NVE’s AAL, ABL, and AKL-Series products:



Hysteresis in GMR Sensors

All magnets and magnetic materials (iron, nickel, etc.) have magnetic hysteresis. Hysteresis refers to the history of the magnetic field applied to the material and how it affects the material properties and performance. NVE's GMR sensors are made of magnetic materials, so they are subject to hysteresis effects.

Hysteresis can make GMR sensors easier or harder to use, depending on the application. In nearly all digital applications, hysteresis is desirable because it prevents "jitter" at the sensor operate point. With sensor elements that do not have hysteresis, electrical hysteresis is normally built into the signal processing electronics.

In a linear application, hysteresis can be problematic, but this depends on the application. For example, if a GMR sensor is used as a current sensor, and it is detecting the magnetic field from a repetitive current such as a sinusoidal waveform, then the recent magnetic history at sensor will always be the same. This will result in repeatable output from the sensor at each current level. In this case, hysteresis is not an issue. Another important point is that time is not a factor, only the magnitude of the fields that the sensor is exposed to. For example, if the frequency of the current's sinusoidal waveform changes, or if the current stops at a given level for some period of time, and then restarts in the same sinusoidal pattern, there will be no hysteresis effects at the sensor.

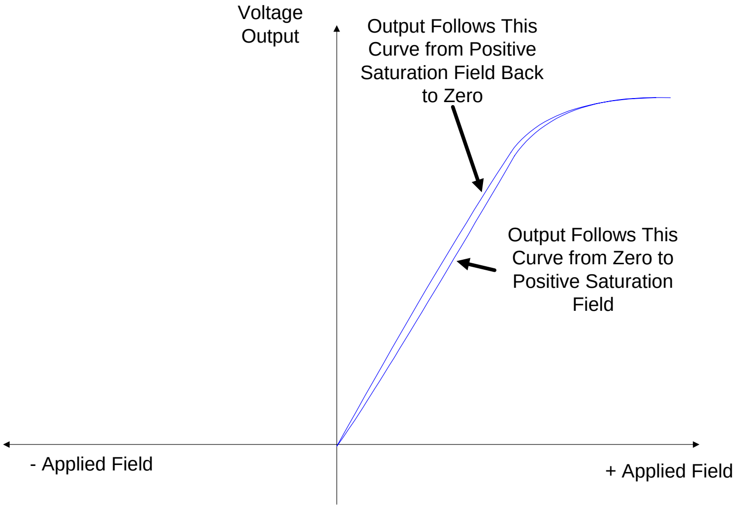
On the other hand, if the magnetic field to be detected is not repetitive in magnitude, but more random in nature, then an error can result in the sensor output reading. The size of this error will depend on the amount of hysteresis in the sensor element and the difference in the polarity and magnitudes of the applied fields that the sensor was recently exposed to. The error will take the form of a voltage offset change in the sensor element.

Because the error is essentially an offset change, it can be eliminated in cases where the signal is high in frequency by AC coupling the output of the sensor to an amplifier. This is a common solution in applications such as currency detection where a very small signal that can be random in nature must be detected from a moving object. AC coupling and a high gain amplifier are employed to see this small signal with GMR sensors.

If DC coupling the sensor to an amplifier or output stage is required, and the magnetic field will not be repeatable, then the hysteresis in the sensor element must be taken into account as a potential error in the reading. For NVE's AA-Series sensors, this potential error can be as high as 4% if the sensor is exposed to one polarity of magnetic field (unipolar mode of operation), and as high as 20% if the sensor is exposed to a bipolar field. However, even in these cases the large output signal of the GMR sensor elements can provide advantages over other technologies.

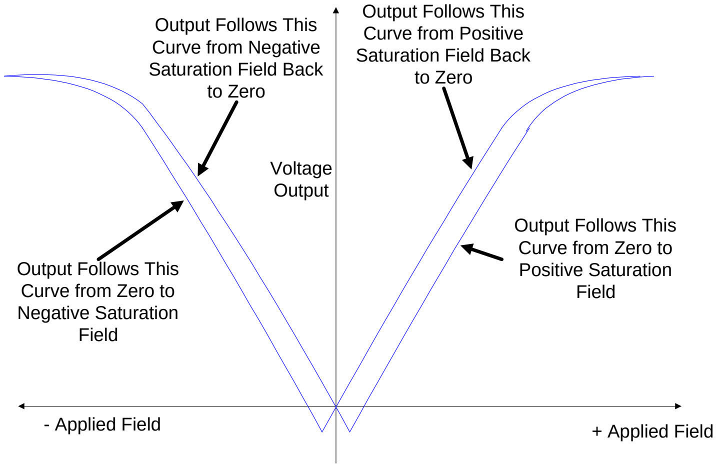
The polarity of the magnetic field that is applied to the sensor has a strong effect on the amount of hysteresis. Unipolar operation is when the applied magnetic field at the sensor is always in the same polarity, or direction. Bipolar operation is when the magnetic field at the sensor changes direction. Hysteresis is much more exaggerated in the sensor element when a bipolar magnetic field is applied to the sensor.

The following chart shows the output of an AA-Series sensor when it is exposed to a saturating unipolar field:



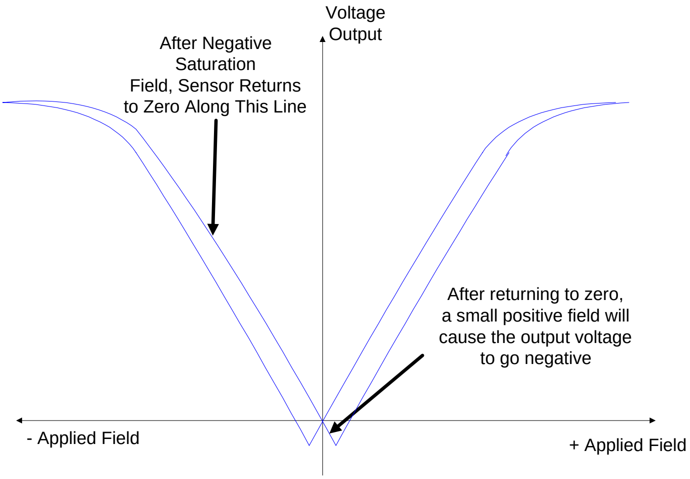
In the case of a unipolar field, the sensor is operating on the minor hysteresis loop. The hysteresis in this case is relatively small.

The following chart shows the output of the same sensor when it is exposed to a saturating bipolar field:

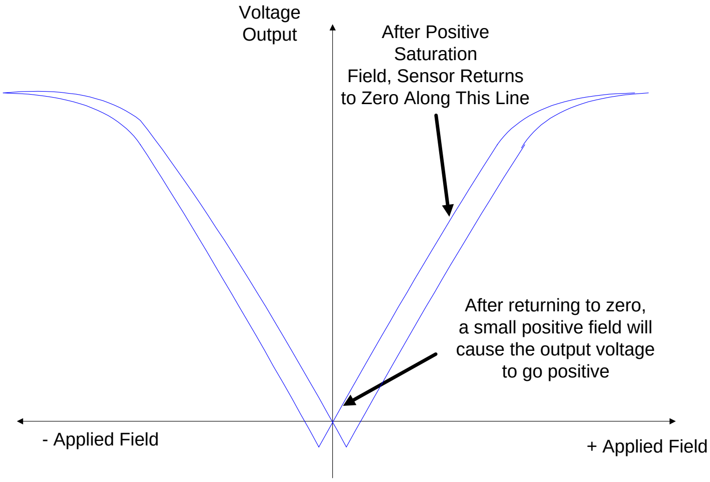


In this case the sensor is operating on the major hysteresis loop, so the hysteresis shown by the output characteristic of the sensor is relatively large. This is the worst-case hysteresis exhibited by the sensor element.

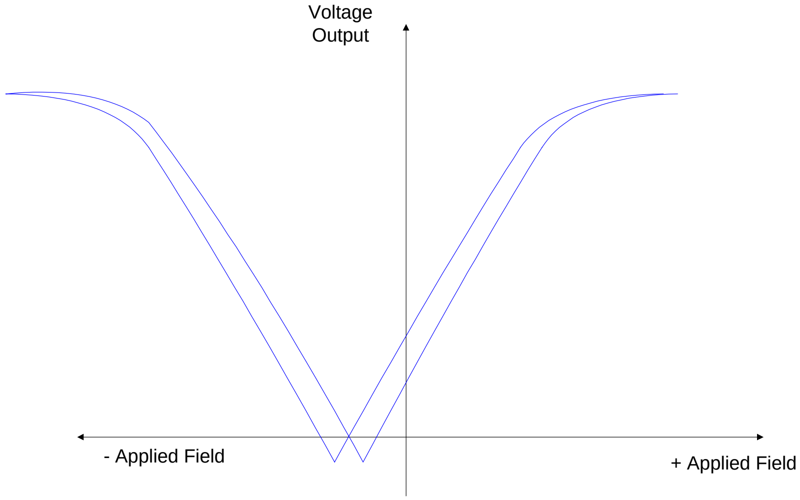
After-saturation effects are important in understanding how the sensor behaves. It is important to note that after the sensor is saturated by a magnetic field, either in the positive or negative direction, it returns to zero field along the inside curve of the major loop characteristic. As shown in the diagram below, a negative saturating field applied to the sensor, followed by a small positive field, will result in a negative voltage output:



The same small positive field, applied after a positive saturating field, will result in a positive voltage output:

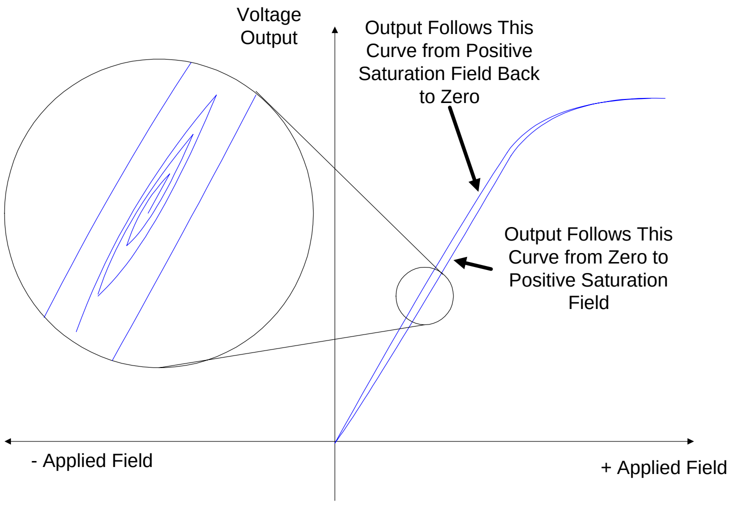


This confusing result is often seen when trying to detect very small magnetic fields such as the earth's field in magnetic compass applications or currency detection applications. The solution to this problem is to bias the sensor element with an external magnetic field, so that the operating point of the sensor is on the linear portion of the characteristic curve. This can be done either with an external permanent magnet, or a current running near the sensor. Biasing the sensor with a positive external field from a magnet or current will shift the sensor's output characteristic as shown below:



With this approach, a small applied field to the sensor will result in a bipolar output signal. Furthermore, the slope of the signal characteristic will be the same no matter which curve the sensor is operating on. So, the magnetic sensitivity of the device is the same, no matter how much hysteresis the sensor has.

Also important to note regarding hysteresis is that it scales with the applied magnetic field. For applications where the magnetic field variations are small, hysteresis is small. The following diagram illustrates this point:



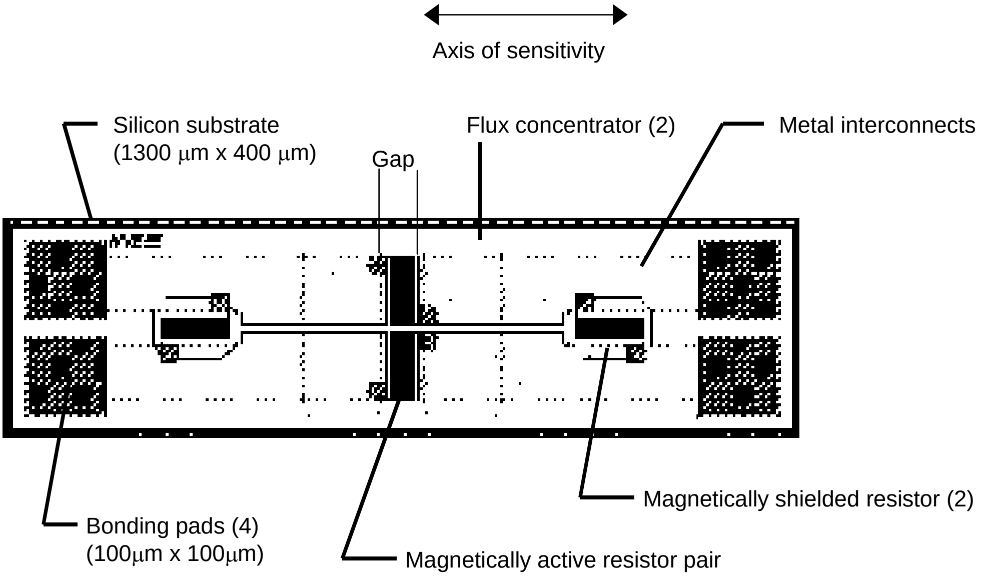
The enlarged area on the left shows the outer boundaries of the sensor hysteresis loop when it is operated in unipolar mode (positive magnetic fields only). Inside the outer boundaries is the sensor behavior if it is exposed to small but increasing magnetic fields. For example, if this was the characteristic of an AA002-02 sensor, the magnetic field history for the characteristic between the boundaries might start at 6 Gauss, then go to 6.5, then 5.5, then 7, then 7.5, and so forth. The curvature of the lines between the boundaries is exaggerated for clarity. The diagram shows that for small variations of the magnetic field, the hysteresis is also small, and as the variations in field increase, so does the hysteresis.

Sensor hysteresis presents challenges in some applications, but in most cases the sensor elements can be used to advantage despite the hysteresis characteristics.

GMR Magnetic Field Sensors (Magnetometers)

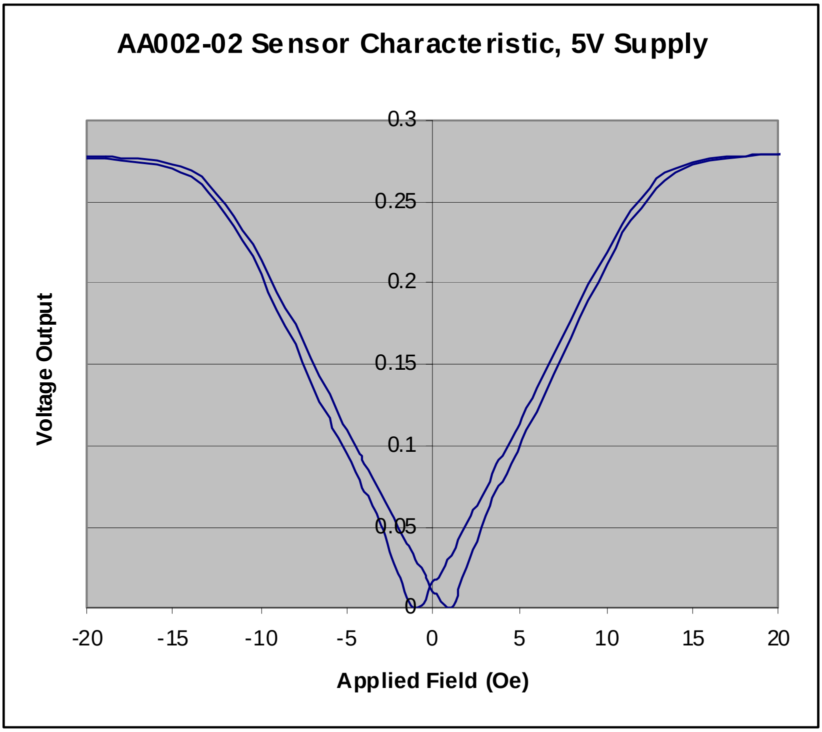
The NVE standard line of magnetic field sensors use a unique configuration employing a Wheatstone bridge of resistors and various forms of flux shields and concentrators. Using magnetic materials for shielding eliminates the need for a bias field with GMR sensors. NVE has developed a process to plates a thick layer of magnetic material on the sensor substrate. This layer forms a shield over the GMR resistors underneath, essentially conducting any applied magnetic field away from the shielded resistors. The configuration allows two resistors (opposite legs of the bridge) to be exposed to the magnetic field. The other two resistors are located under the plated magnetic material, effectively shielding them from the external applied magnetic field. When the external field is applied, the exposed resistors decrease in electrical resistance while the other resistor pair remain unchanged, causing a signal output at the bridge terminals.

The plating process developed by NVE for use in GMR sensor applications has another benefit: it allows flux concentrators to be deposited on the substrate. These flux concentrators increase the sensitivity of the raw GMR material by a factor of 2 to 100. The flux concentration factor is roughly equivalent to the length of one shield divided by the length of the gap. This allows use of GMR materials that saturate at higher fields. For example, to sense a field from 0 to 100 Oersteds, NVE deposits a GMR sensor that saturates at a nominal 300 Oersteds and flux concentrators with a magnification factor of three. The figure below shows the basic layout of the device:



TYPICAL GMR MAGNETIC FIELD SENSOR LAYOUT

The magnetic characteristic of a shielded bridge device is shown below. This characteristic was taken from an actual production device with 5V supplied to the bridge power terminals (5 kΩ bridge).



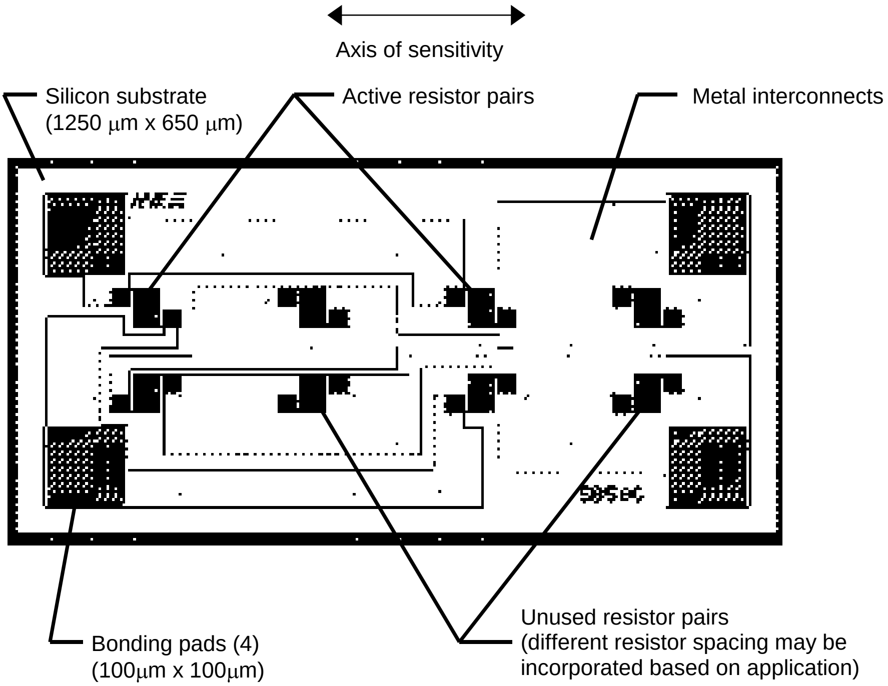
GMR MAGNETIC FIELD SENSOR OUTPUT CHARACTERISTIC

This signal output can be coupled directly into a linear amplifier or a comparator to generate a high level electrical signal proportional to the strength of the magnetic field seen by the sensor.

GMR Magnetic Gradient Sensors (Gradiometers)

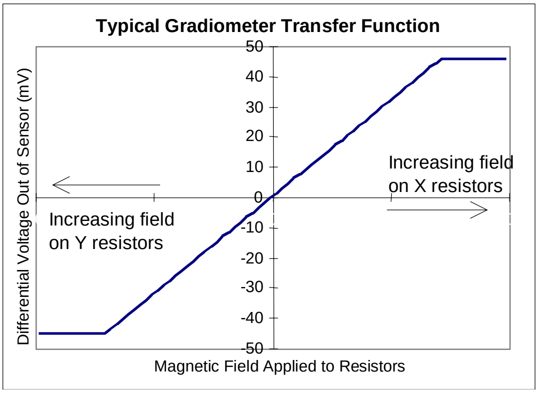
The NVE gradiometer is a GMR magnetic field sensor used to detect field gradients between Wheatstone bridge configured resistors. This device is "unshielded" (*i.e.*, it does not employ resistor shields) therefore all four (4) legs of the Wheatstone bridge are active (they respond to changes in field level). Gradiometers can be used to detect either magnetic or ferrous targets. To detect gradient changes caused by the proximity to a moving ferrous target, a biasing magnet is required. Refer to the Magnetic Biasing section and the GT Sensor application notes for gradiometer biasing guidelines.

The output of the gradiometer differs from that of a standard GMR Magnetic Field Sensor. The gradiometer's output can be bipolar versus unipolar and can be shaped by the use of magnetic biasing and the application of external flux shaping devices (flux guides). The figure below shows an example design:



BASIC GRADIOMETER BRIDGE SENSOR LAYOUT

The following graph shows the output characteristic from a gradiometer as the field gradient is varied across the sensor IC:



GRADIOMETER BRIDGE SENSOR OUTPUT CHARACTERISTIC

Magnetic Reference Information

Permanent Magnets

The Magnetic Materials Producers Association (MMPA) publishes two reference booklets with valuable reference information on basic magnetic theory, permanent magnet materials and their practical application. They are:

MMPA Standard no. 0100-96
Standard Specifications for Permanent Magnet Materials
MMPA PMG-88
Permanent Magnet Guidelines

These booklets can be obtained from the MMPA:

Magnetic Materials Producers Association
8 South Michigan Ave., Suite 1000
Chicago, IL 60603
(312) 456-5590
(312) 580-0165 (fax)

Measurement Systems

Unit	Symbol	cgs System	SI System	English System
Length	L	centimeter (cm)	meter (m)	inch (in)
Flux	ϕ	maxwell	weber (Wb)	maxwell
Flux density	B	gauss (G)	tesla (T)	lines/in^2
Magnetizing force	H	oersted (Oe)	ampere turns/m (At/m)	ampere turns/in (At/in)
Magnetomotive force	F	gilbert (Gb)	ampere turn (At)	ampere turn (At)
Permeability in air	μ_0	1	$4\pi \times 10^{-7}$	3.192

Conversion factors for between measurement systems can be found in the appendix to this catalog.

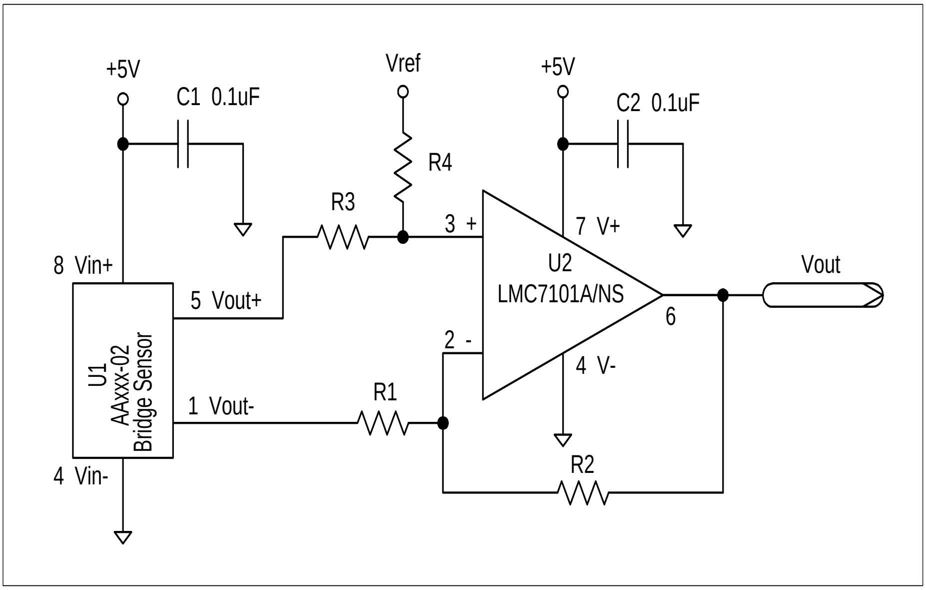
Signal Conditioning Circuits

A number of methods exist for pre-amplification of an NVE GMR bridge sensor output. This section shows some representative circuits and compares the relative advantages and disadvantages of some common configurations. The circuits shown were designed for low power and 5V operation. Low noise or high performance applications should be designed with lower noise, higher performance components.

Operational Amplifier (Op Amp) Bridge Preamplifier Circuits

Single Op Amp Bridge Amplifier

The figure below shows a simple circuit for amplifying an NVE AAxxx-02 GMR Magnetic Field Sensor's bridge output using a single 5V supply. The advantages of this configuration are simplicity, low component count, and low cost.



SINGLE OP AMP PREAMPLIFIER CIRCUIT

The equation for the amplified voltage is:

$$V_{out} = \left((V_{out+}) \left(\frac{R_2}{R_1 + R_2} \right) \left(\frac{R_3 + R_4}{R_3} \right) - (V_{out-}) \left(\frac{R_4}{R_3} \right) \right) + V_{ref}$$

Assuming $R_1 + R_2 = R_3 + R_4 >> 5K$

This type of amplifier has two significant limitations in that;

1) the feedback resistors load the output of the NVE bridge sense resistors,

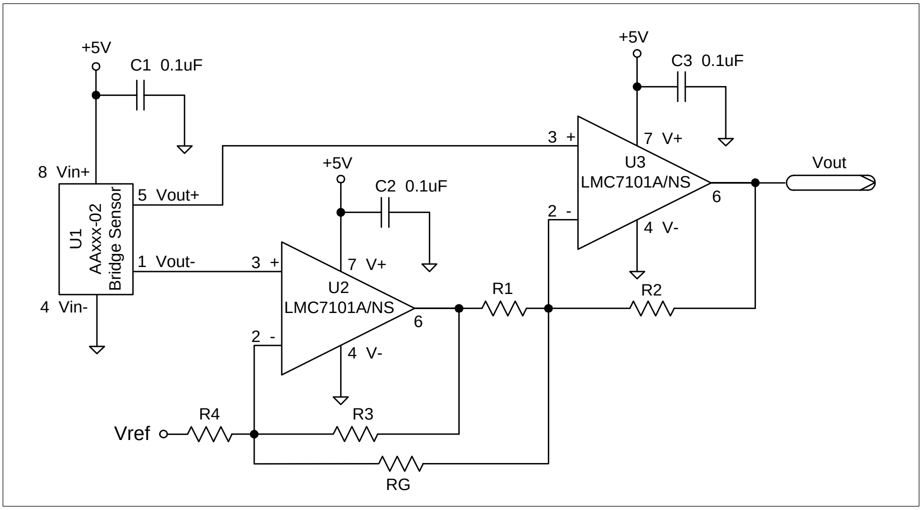
and

2) the circuit has a poor common mode rejection (CMRR) if the resistor ratios are not ideally matched.

Users of this circuit should be aware of the deficiencies and ensure that the feedback resistors are large compared to the bridge resistor values and that the bridge supply is stable and free from noise and ripple. Any pickup on the bridge leads should be minimized through proper layout, filter capacitors, and/or shielding.

Two Op Amp Bridge Amplifier

The two op amp circuit shown below reduces the loading of the preamplifier on the NVE bridge outputs but still has a CMRR that is dependent on the ratio of resistor matching. The AC CMRR is also poor in that any delay of the common mode signal through op amp U2 provides a mismatch in the signals being delivered to op amp U3 for cancellation. Its advantages are simplicity and low cost.



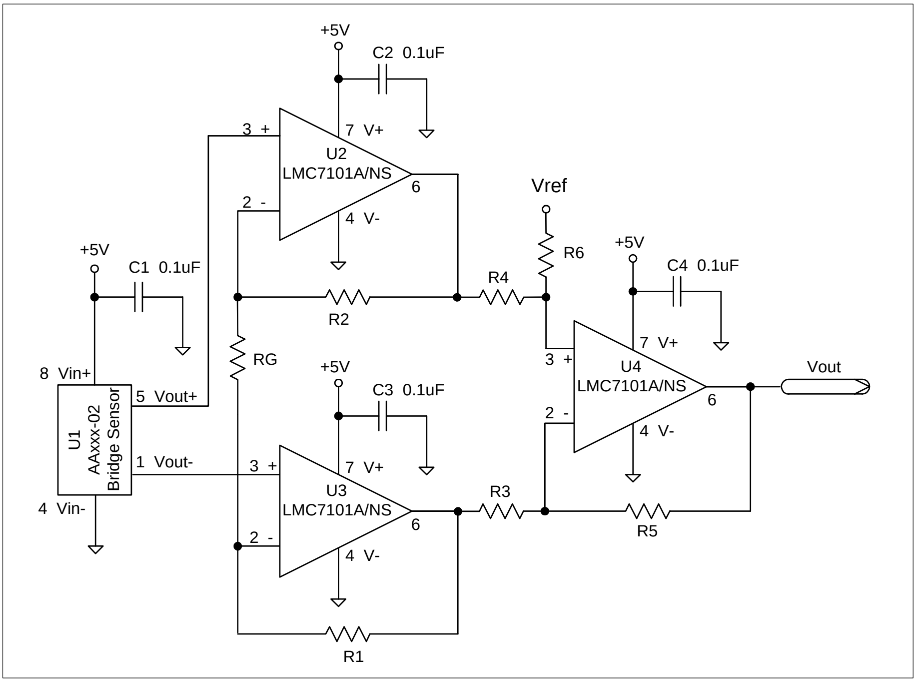
TWO OP AMP PREAMPLIFIER CIRCUIT

The equation for DC gain of the two op amp circuit (assuming infinite input impedance of the op amps) is:

$$\mathrm{Vout} = V_{ref} + V_{IN}\left(1 + \left(\frac{R_2}{R_1}\right) + \left(\frac{2R_2}{R_G}\right)\right) \quad \text{for} \quad \left(\frac{R_2}{R_1}\right) = \left(\frac{R_4}{R_3}\right) \quad \text{and } V_{IN} = (V_{out+}) - (V_{out-})$$

Three Op Amp Bridge Amplifier

The three op-amp circuit shown in the figure below is the most robust version of an op amp implementation. In this circuit the CMRR still depends on the resistor ratios of the differential amplifier (U4) but is not dependent on the resistors R1, RG, and R2. Therefore to minimize common mode errors the gain of the first stage should be made large compared to the gain of the second stage. The minimum gain of the second stage is dependent on amplifiers U2 and U3 output voltage range and Op Amp U4's common-mode input range, which for the LMC7101, is rail-to-rail allowing a gain of one (1) in the second stage.



THREE OP AMP PREAMPLIFIER CIRCUIT

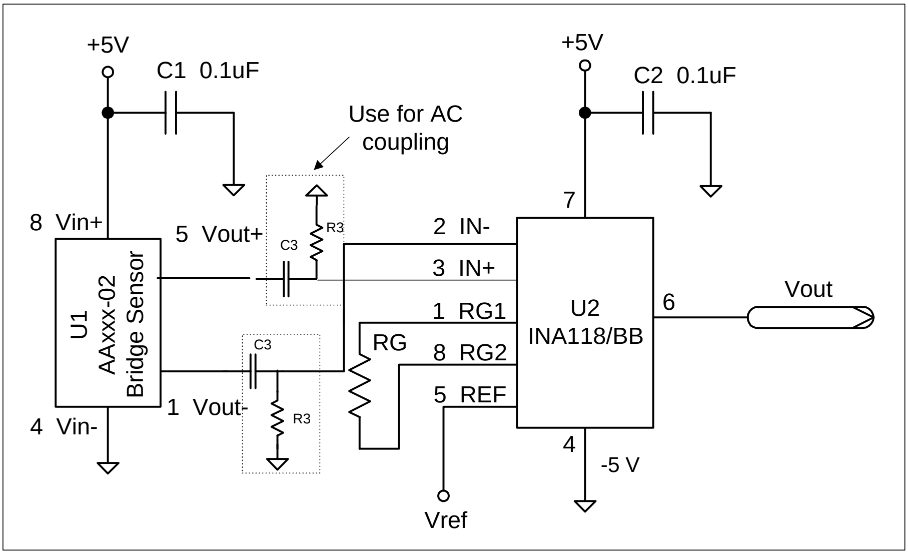
The DC transfer function of the circuit is:

$$\mathrm{Vout} = V_{\mathrm{ref}} + \left(1 + \frac{2R_1}{R_G}\right)\left(\frac{R_4}{R_3}\right)V_{IN} \quad \text{for } R_1 = R_2,\ R_3 = R_5,\ R_4 = R_6 \text{ and } V_{IN} = (V_{out+}) - (V_{out-})$$

The symmetrical nature of this configuration also allows for cancellation of common mode errors in amplifiers U2 and U3 if the errors track.

Instrumentation Amplifier Bridge Preamplifier

The advent of low-cost, high-performance Instrumentation Amplifier (IAs) such as the Analog Devices AD620 and the Burr Brown INA118 have greatly simplified the design of bridge preamplifiers while adding significant advantages in noise, size, and performance over op amp implementations. The figure below shows the design of a bridge amplifier circuit using an INA118 (the Analog Devices AD620 is pin-for-pin compatible with the INA118).



INSTRUMENTATION AMPLIFIER PREAMPLIFIER CIRCUIT

The gain of this circuit is:

$$V_{OUT} = \left(1 + \frac{50K}{R_G}\right) V_{IN} + V_{ref}$$

with $V_{IN} = (V_{out+}) - (V_{out-})$ and the frequency 3dB point is given by $f = \frac{1}{2\pi R_3 C_3}$

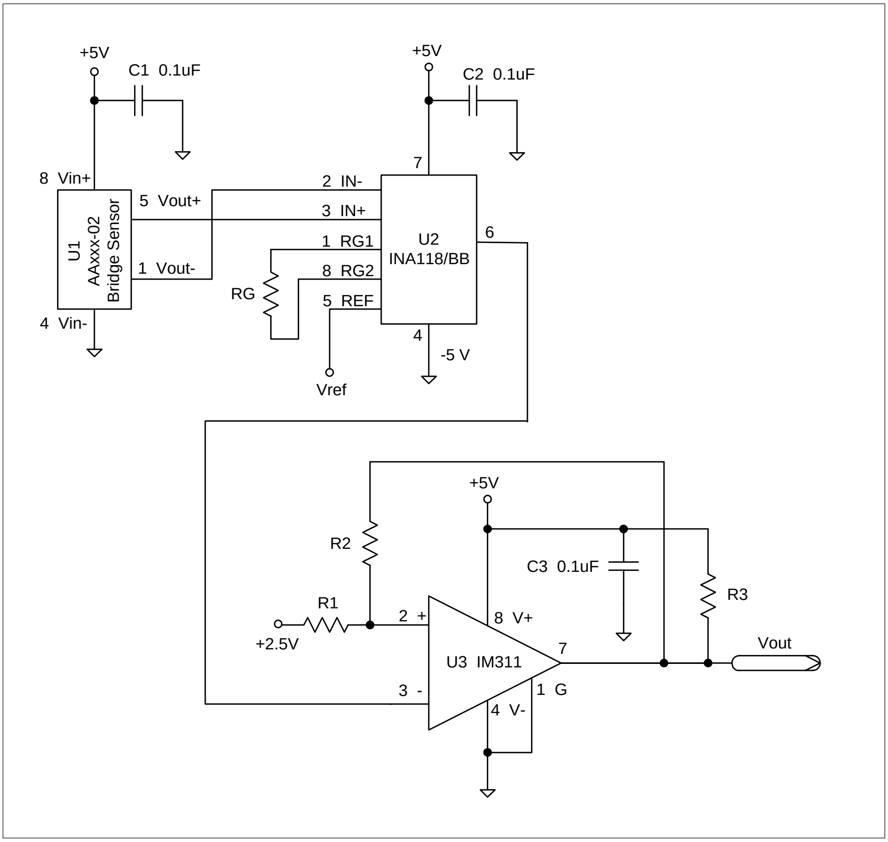
Integrated circuit instrumentation amplifiers utilize circuit techniques where resistor matching is not as critical to the CMRR as active device matching. Active device matching can be easily controlled on integrated circuits allowing for greatly improved CMRR of instrumentation amplifiers over op amp implementations. Also, the gain-bandwidth product of instrumentation amplifier circuits can be higher than op amp circuits.

Threshold Detection Circuit

The figure below shows the implementation of a low power threshold detection circuit that utilizes the AAxxx-02 GMR Magnetic Field Sensor and the Burr Brown INA118 instrumentation amplifier. Comparator hysteresis has been added around the LM311 comparator to minimize random triggering of the circuit on potential noise sources and pickup. The gain of the instrumentation amplifier is the same as before. The hysteresis of the comparator is approximately:

$$V_h \approx 2.5\left(\frac{R_1}{R_1+R_2+R_3}-\frac{R_2}{R_1+R_2}\right)$$

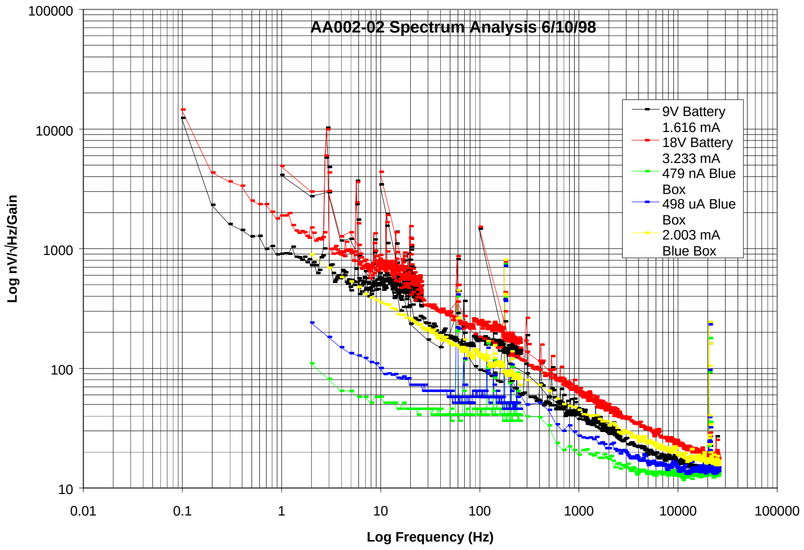
Neglecting the finite output swing of the comparator.



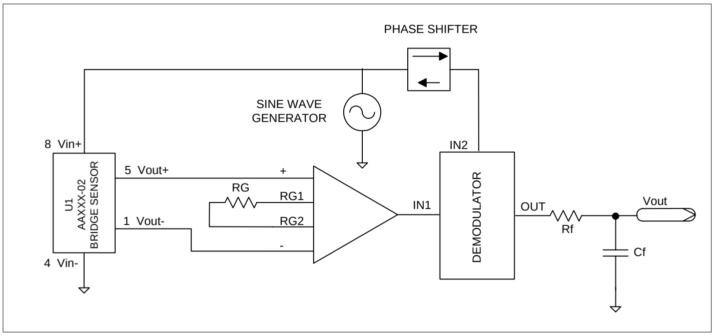
THRESHOLD DETECTION CIRCUIT

Noise In NVE Giant Magnetoresistive Sensors

The 1/f noise characteristic of NVE GMR sensors is approximately an order of magnitude higher than noise for thin film resistors. The noise has been shown to follow the usual characteristics of being proportional to the square of the current density. The figure below shows a noise plot of an AA002-02 sensor using various methods for powering the sensor:



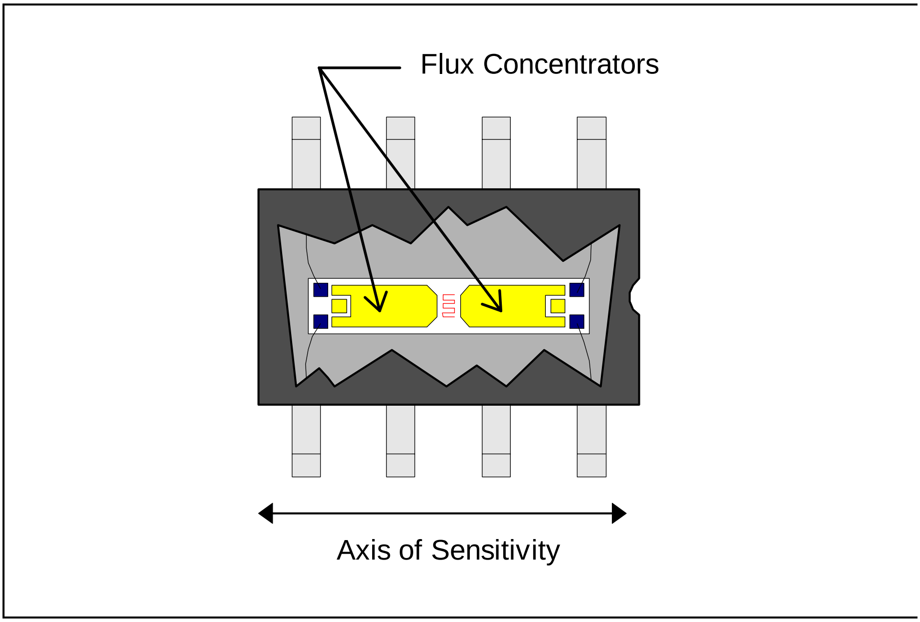
For use in low-field applications, the noise of the NVE GMR sensors limits the minimum signal detected. For measuring low fields it is recommended that an AC modulation/demodulation scheme be implemented. The figure below shows a block diagram of an AC modulation/demodulation circuit. The phase shifter block is required to account for parasitic phase shift around the loop.



Use Of GMR Magnetic Field Sensors

General Considerations

All of NVE's GMR Magnetic Field sensors have a primary axis of sensitivity. The figure below shows an AAxxx-02 Series GMR Magnetic Field Sensor with a cut away view of the die orientation (not to scale) within an SOIC8 package.

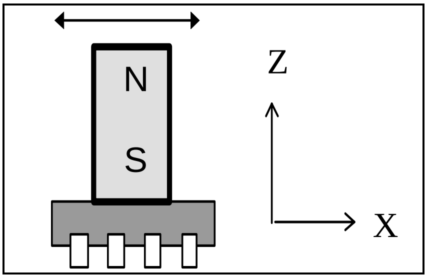


Sensitive Magnetic Axis – AA00x-02 Sensor

The flux concentrators on the sensor die gather the magnetic flux along the axis shown and focus it at the GMR bridge resistors in the center of the die. The sensor will have the largest output signal when the magnetic field of interest is parallel to the flux concentrator axis. For this reason, care should be taken when positioning the sensor to optimize performance. Although sensor position tolerance may not be critical in gross field measurement, small positional variation can introduce undesirable output signal errors in certain applications.

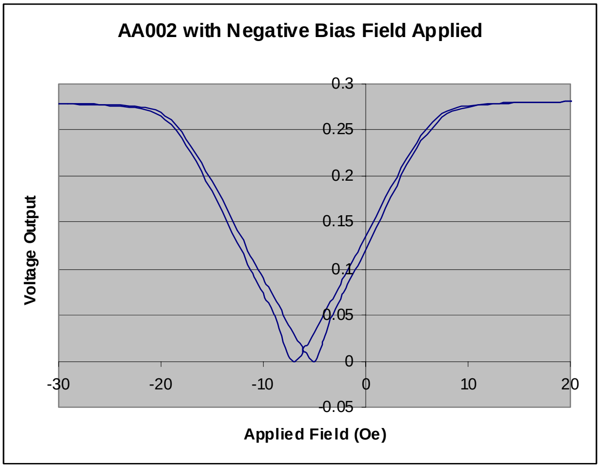
Magnetic Biasing

In many applications, GMR Magnetic Field Sensors make use of biasing magnetic fields. Biasing magnetic fields provide either a magnetic field to sense (where one is not present) or create a pseudo zero field. Back-biasing a sensor consists of applying a magnetic field through the sensor package without influencing the sensor. The purpose is to create a magnetic field that the device can sense for applications where no magnetic field is present such as ferrous material detection. The figure below shows a permanent magnet used for this purpose. The magnet adjusted in the X direction, as shown, achieves the maximum field in the Z direction and minimum field in the sensitive X direction.



MAGNETIC BIASING CONFIGURATION

Another means of biasing a GMR Magnetic Field Sensor is to provide a constant magnetic field in the sensitive direction. The result is a sensor biased part way up its output curve shown in the figure below.



This biasing technique creates a bipolar output with a DC offset. Another typical purpose for this kind of biasing is to bias the sensor away from the zero field area, where hysteresis is more pronounced.

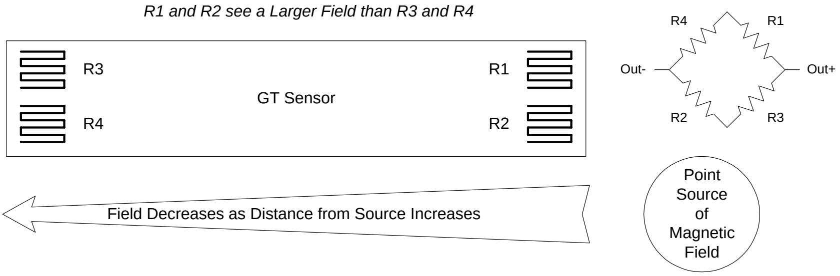
Since gradiometers respond to the flux gradient rather than the field itself, they can be biased to zero offset to work in a gear tooth sensing application. It is important not to bias a gradiometer to a high enough field to saturate the GMR resistors.

More information on biasing gradiometers for gear tooth sensor applications is found in the GT Sensor application notes section.

Application Notes for GT Sensors

General Theory of Operation of Differential Sensors (Gradiometers)

Differential sensors, or gradiometers, provide an output signal by sensing the gradient of the magnetic field across the sensor IC. For example, a typical GMR sensor of this type will have four resistive sensor elements on the IC, two on the left side of the IC, and two on the right. These resistive sensor elements will be wired together in a Wheatstone bridge configuration. When a magnetic field approaches the sensor IC from the right, the right two resistive sensor elements will decrease in resistance before the elements on the left. This leads to an imbalance condition in the bridge, providing a signal output from the bridge terminals.



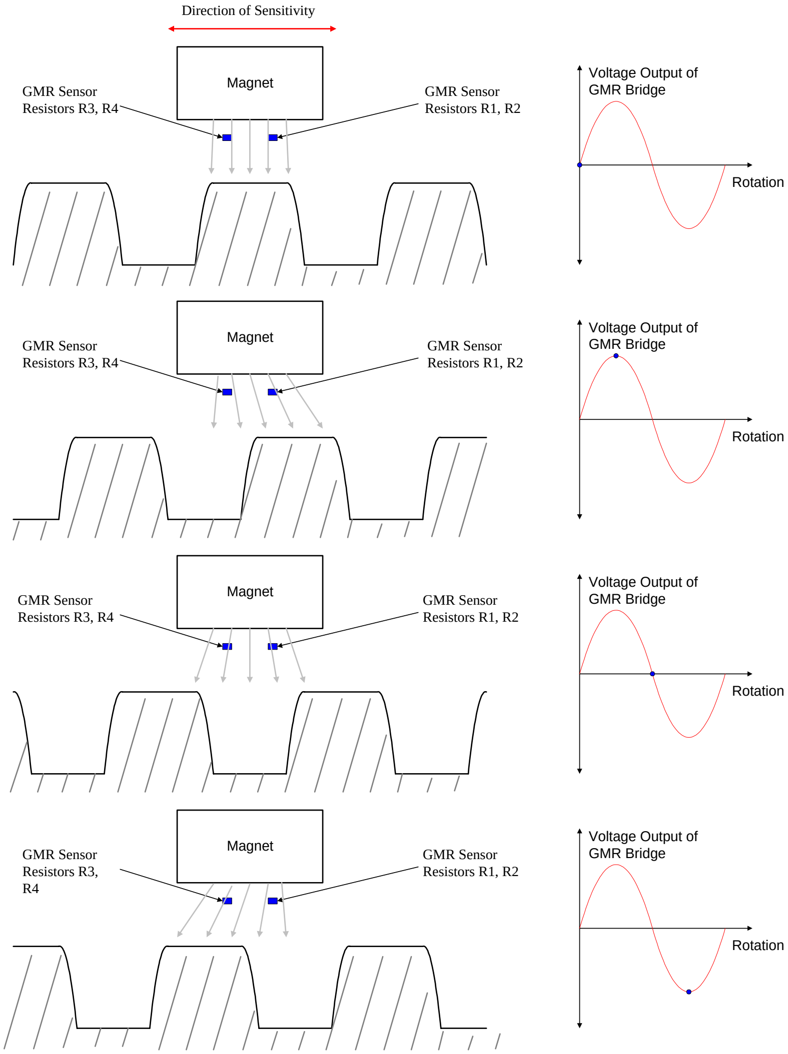
Note that if a uniform magnetic field is applied to the sensor IC, all the resistive sensor elements will change at the same time and the same amount, thus leading to no signal output from the bridge terminals. Therefore, a differential sensor cannot be used as a magnetometer or an absolute field detector; it must be used to detect the presence of a magnetic gradient field.

Gradient fields are present at the edge of magnetic encoders and magnetically biased gear teeth. As a result, differential sensor elements are ideally suited for speed and position detection in these applications.

GT Sensor Operation with Permanent Magnet Bias

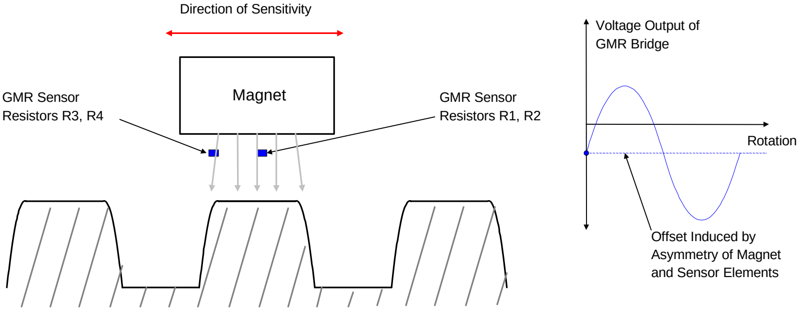
Magnetic encoders generate their own magnetic field, but a gear tooth wheel does not, so if a differential sensor is to be used to detect gear teeth, a permanent magnet is required to generate a magnetic bias field. The differential magnetic sensor will then be used to detect variations in the field of the permanent magnet as the gear tooth passes by in close proximity.

The following series of drawings shows a biased GT Sensor. The drawings show how the magnetic field generated by the bias magnet is influenced by the moving gear tooth, and how the output signal appears at four equally spaced positions between adjacent gear teeth:

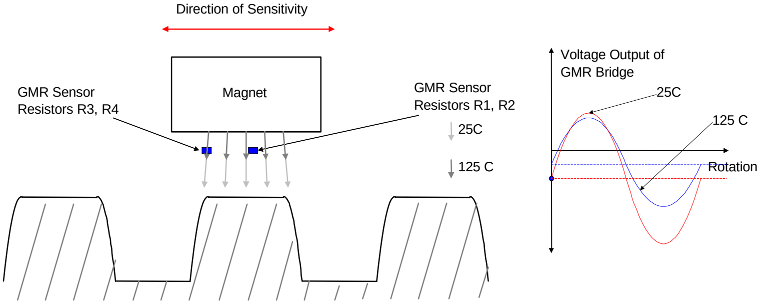


Despite the simplicity of the preceding drawings, magnetically biasing a gear tooth for a production product can be complex. Typically, the position of the sensor relative to the magnet is fixed, but there is a variation in the airgap between the sensor and the target gear tooth. This can lead to magnetic conditions that can cause an unstable output.

For example, tolerances on the placement of the magnet relative to the sensor are not perfect, and any slight variation in the placement of the magnet can lead to offset problems; see the drawing below:



Generally the magnet is glued in place; this can lead to tilting of the magnet with respect to the sensor, introducing more variations in the field at the sensor, and more offset problems, as well as potential glue joint problems. Furthermore, the composition of most inexpensive magnets is not particularly uniform, and many have cracks or other mechanical imperfections on the surface or internally that lead to a non-uniform field. Most permanent magnets have a temperature coefficient, and some can lose up to 50% of their room temperature strength at 125°C. The following drawing shows the effects of temperature added onto an imperfect bias. The offset of the sensor varies with temperature as shown:



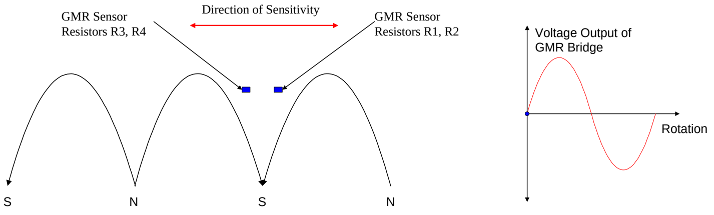
Finally, as the airgap changes, the magnetic field at the sensor also changes. So, the magnetic field at the sensor will vary from one installation to the next, and if the gear has runout, wobble, or expands with temperature, the output signal and offset of the sensor element will vary.

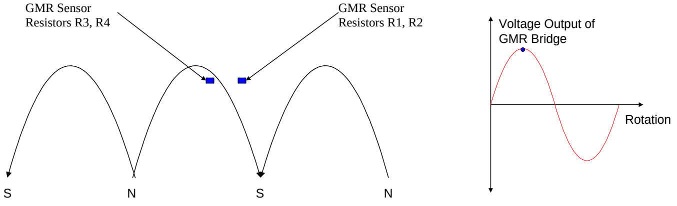
As a solution to these potential problems, NVE's AKL-Series GT Sensors offer internal signal processing which compensates for temperature variation, sensor output variation, and magnet/target variation. This results in a stable digital output signal with wide tolerance for magnet placement and quality. For analog applications, NVE offers the following guidelines for biasing GT Sensors with permanent magnets:

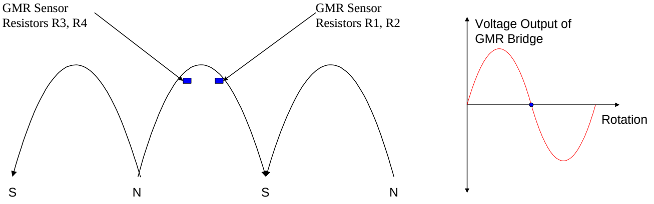
1. NVE recommends about 1.5 mm distance from the back of the sensor to the face of the magnet, in order to keep the flux lines at the sensor element "flexible" and able to follow the gear teeth with relative freedom. This distance can be achieved by putting the sensor on one side of a circuit board, and the magnet on the other.
2. To fix the position of the magnet on the circuit board more precisely, the board can be made thicker, and a pocket can be machined into it to hold the magnet. This service is readily available from most circuit board manufacturers.
3. Various high temperature epoxies can be used to glue the magnet in position; NVE recommends 3M products for this purpose.
4. If zero speed operation is not required, AC coupling the sensor to any amplifier circuitry will remove the offset induced in the sensor by the magnet.
5. If zero speed operation is required, some method of zeroing the magnet-induced offset voltage from the sensor will be required for maximum airgap performance. NVE's AKL-Series sensors have this feature built in, and NVE's DD001-12 signal conditioning IC also includes this feature.
6. GT Sensor ICs are centered in the plastic package, so placement of the permanent magnet should be symmetrical with the package.
7. Ceramic 8 magnets are a popular choice in this application, and provide good field characteristics and low cost. However, C8 magnets lose substantial magnetic strength at higher temperatures. For analog output applications where a consistent signal size over temperature is desirable, use of an Alnico 8 magnet (the most temperature stable magnet) is recommended. Samarium-Cobalt magnets and Neodymium-Iron-Boron magnets are not recommended because they are so strong that they tend to saturate the GMR sensor element.

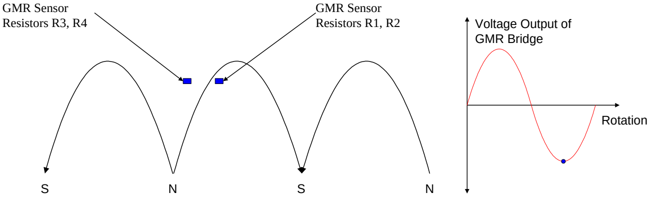
GT Sensor Operation with Magnetic Encoders

Magnetic encoders generate their own magnetic field, so they are much easier to work with than gear tooth wheels, as no bias magnet is required for the sensor. Also, magnetic encoders have alternating north and south magnetic poles on their faces. Therefore the magnetic field is generated by the moving body, and sensor offset problems are greatly reduced. The following drawing shows a GT Sensor response to a magnetic encoder:









Note that in this case, as long as the sensor is positioned symmetrically with the encoder, offset is minimized. Also note that the GT Sensor provides one full sine wave output for each magnetic pole. This is double the frequency of a Hall effect sensor, which provides one full sine wave output for each north-south pole pair. As a result, replacing a Hall sensor with a GT sensor doubles the resolution of the output signal.

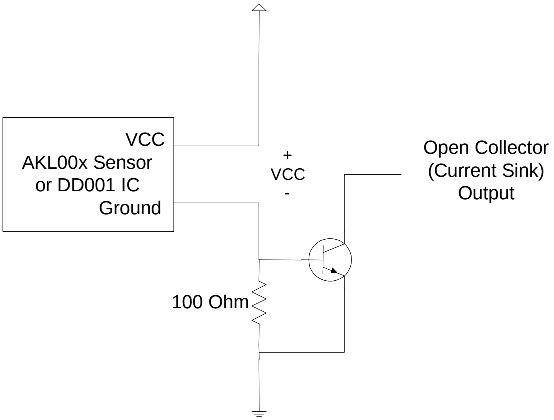
NVE offers the following guidelines for using GT Sensors in magnetic encoder applications:

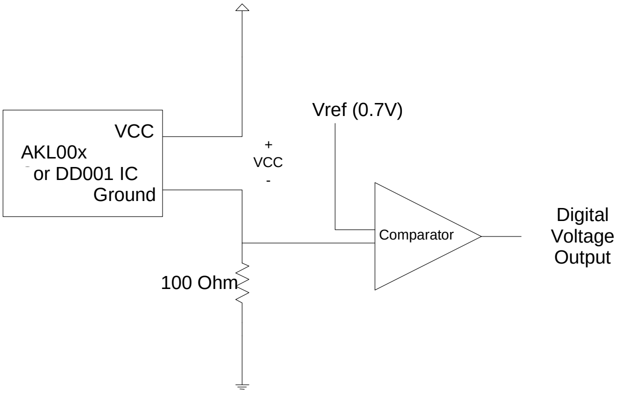
1. Position the sensor as symmetrically as possible with the encoder to minimize offset problems.
2. AC couple the sensor to an amplifier to eliminate any offset issues if zero speed operation is not required.
3. If zero speed operation is required, NVE’s AKL-Series and DD-Series parts automatically compensate for offset variations and provide a digital output signal.

Application Circuits

Signal processing circuitry for analog output sensors, such as NVE's ABL-Series products, varies widely in cost, complexity, and capability. Depending on user requirements, a single op amp design may be sufficient. For low signal level detection, a low noise instrumentation amp may be desirable. For complete control of all parameters, use of a complete signal processing IC which can tailor gain, offset calibration, and temperature compensation may be required. Please see NVE's Engineering and Application Notes bulletin for further details on the various approaches that are available.

For digital output applications, NVE's AKL-Series and DD-Series products provide the most cost effective approach. Both of these products provide two-wire, *i.e.*, current modulated output signals. For many applications, an open collector or digital voltage output signal is desirable. The following two circuits convert a two-wire current modulated signal into an open collector or digital voltage output signal:

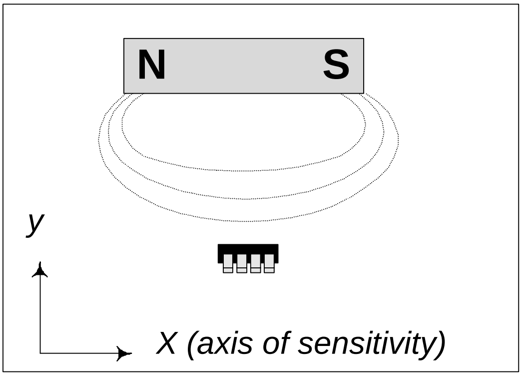


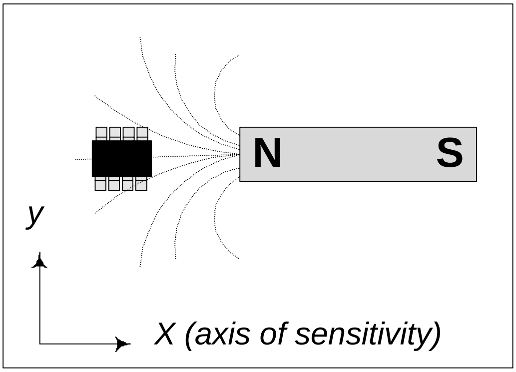


Measuring Displacement

Basic concepts

Because of their high sensitivity, GMR Magnetic Field Sensors can effectively provide positional information of actuating components in machinery, proximity detectors, and linear position transducers. The figures below illustrate two simple sensor/permanent magnet configurations used to measure linear displacement. In the first diagram, displacement along the *y*-axis varies the B*x* field magnitude detected by the sensor that has its sensitive plane lying along the *x*-axis. The second diagram has the direction of displacement and the sensitive plane along the x-axis.





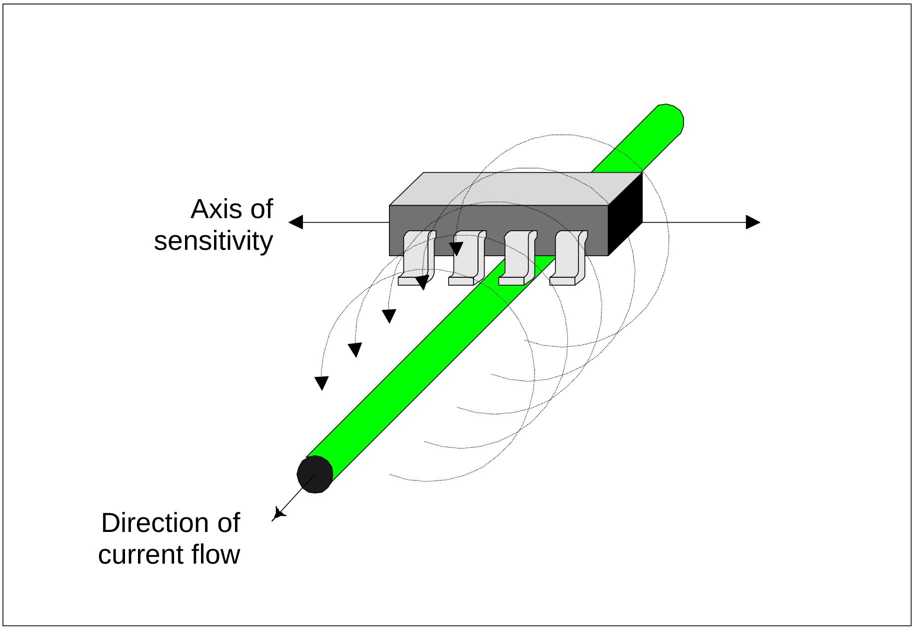
Application examples

- Hydraulic/pneumatic pressure cylinder stroke position
- Suspension position
- Fluid level
- Machine tool slide position
- Aircraft control-surface position
- Vehicle detection

Current Measurement

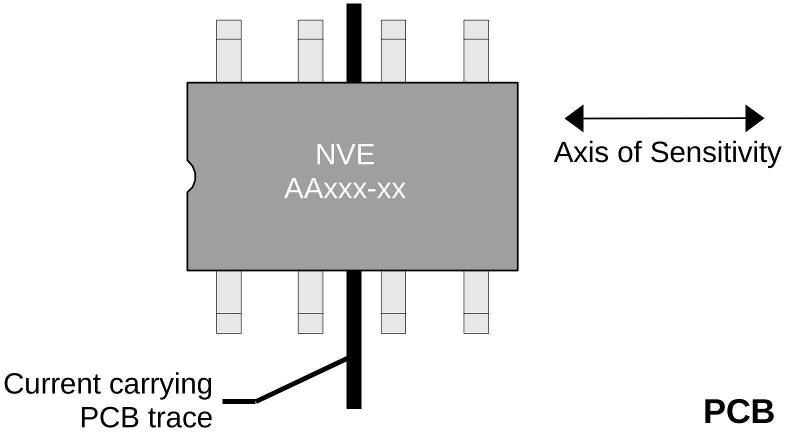
Basic concepts

GMR Magnetic Field Sensors can effectively sense the magnetic field generated by a current. The figure below illustrates the sensor package orientation for detecting the field from a current-carrying wire. This application allows for current measurement without breaking or interfering with the circuit of interest. The wire can be located above or below the chip, as long as it is oriented perpendicular to the sensitive axis.



SENSING MAGNETIC FIELD FROM A CURRENT-CARRYING WIRE

The figure below shows another configuration where a current trace on a PCB is under the board-mounted sensor.



SENSING MAGNETIC FIELD FROM A CURRENT CARRYING PCB TRACE

An Excel spreadsheet is available on NVE’s web site which helps calculate the magnetic field at the sensor from a current carrying trace on the board as shown in the diagram above.

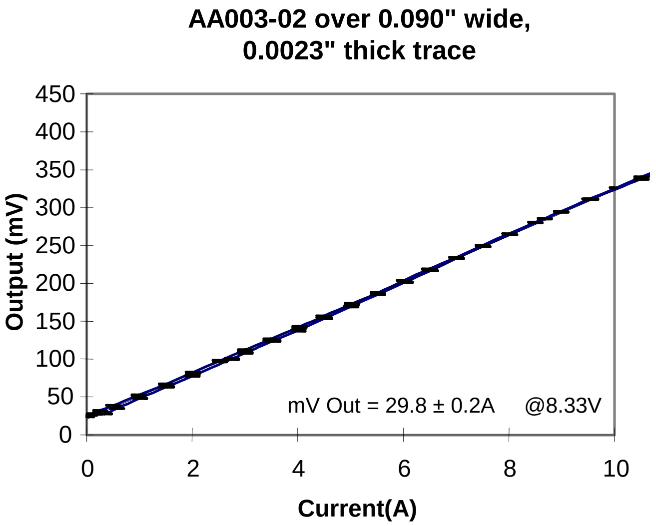
Principles of Operation

The magnetic field created by the current surrounds the conductor radially. As the magnetic field affects the GMR material in the sensor, a differential output is produced at the out pins of the sensor. The magnetic field strength is directly proportional to the current flowing through the conductor. As the current increases, the surrounding magnetic field will also increase, thus increasing the output from the sensor. Similarly, as the current decreases, the magnetic field and sensor output decrease.

Since the current is not measured directly, the sensor output must be correlated to the current. The following data and graphs are based upon analysis of NVE’s evaluation board contained in our current sensor evaluation kit, part number AG003-01. The PCB contains four traces of three different widths: 90 mils, 60 mils, and 10 mils.

DATA ANALYSIS- One To Ten Amps

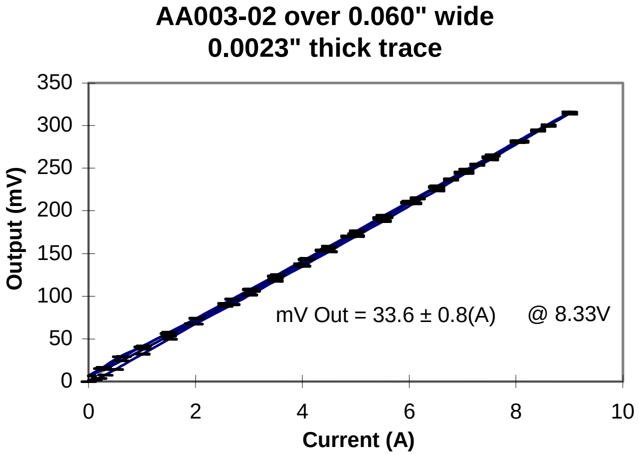
Currents (1-10 A) were run through the 90 and 60-mil traces found on the PCB in NVE's Current Sensor Evaluation Kit AG003-01. An AA003-02 sensor was placed over the 90 and 60-mil traces and different levels of DC current were run through the traces. This current and the corresponding output from the sensors are shown in the following graphs.



The sensor was supplied with 8.33V and was hand-soldered over the trace. The trace is 0.090" wide and 0.0023 ± 0.0002" thick. The marks on the graph are output error bars which cover the expected error from this part due to intrinsic hysteresis and measurement errors. The current was swept from zero to ten Amps and back to zero multiple times. The output voltage at specific current levels was analyzed and an output voltage precision was determined to have a relative error of approximately ±0.7% with errors of up to 2% possible at low currents.

A linear fit on the data above shows a 29.8 ± 0.2 mV/A correlation in this configuration. The sensor utilizes a Wheatstone bridge and thus the applied voltage across the bridge is directly related to the output. By dividing the slope by 8.33V, we get a more useful number of 3.57 ± 0.02 mV/V/A. With this number, the user can determine the expected output for any applied voltage.

The same analysis was given to a 0.060" wide trace of the same thickness. A voltage of 8.33V was applied and the resulting graph is shown below.



The current in this trace was swept from zero to nine Amps, similarly to the 90-mil analysis. The sensor output to current correlation from this graph is 4.0 ± 0.1 mV/V/A. The differences between the 90 and 60-mil traces is due to the field distribution/density differences between the two due to the difference in width.

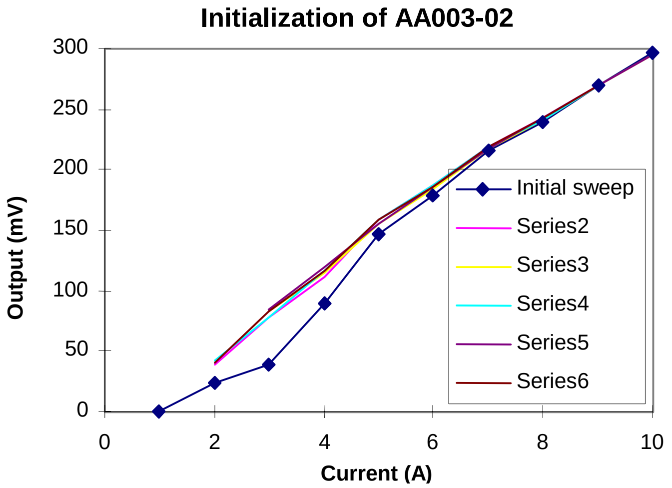
Resolution

The resolution of the sensor is a function of environmental electromagnetic noise, intrinsic noise, and hysteresis. In most applications, the environmental noise is the limiting factor in resolution. Data and information in this section are based upon non-filtered, non-amplified, non-shielded output. In this “raw” configuration, a resolution of better than 1 mA was found. With proper filtering, amplifying and shielding, the noise level can be decreased and thus the usable resolution will increase.

Hysteresis and Repeatability in GMR Current Sensors

All magnetic materials have an effect called magnetic hysteresis. This hysteresis contributes greatly to the error values given above. Hysteresis also creates a potential that the same current can produce two different voltage outputs. The hysteresis, and thus the error, is largest when the current changes direction. If the current changes direction, the precision of the output at low currents decreases significantly. The specified error of 0.7% will not be obtained again until the current goes above approximately 2A. This guideline is very rough as applications vary.

Another magnetic contribution to the error can be overcome by an initialization current. Often, depending on the magnetic history (hysteresis) of the sensor, the initial outputs are different from subsequent outputs as seen in the figure below:



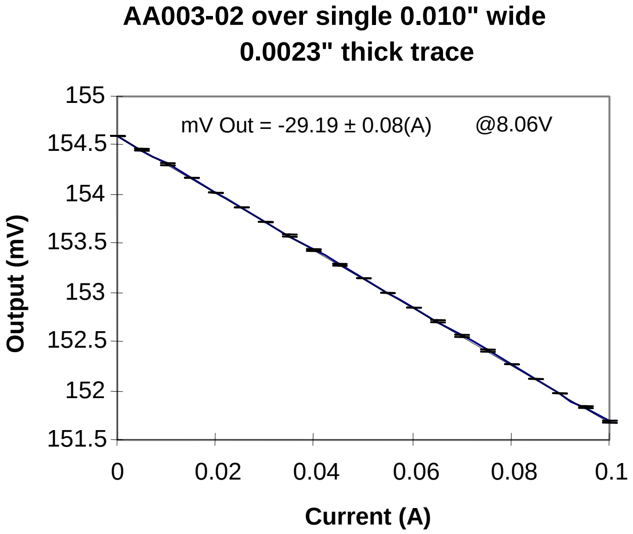
The initial sweep data has deviated from the other series of current sweeps. After the first sweep was completed, the subsequent five sweeps fell right on each other. This shows that a lower error can be obtained by "initializing" the sensor. After initialization, the error will be much lower until the working current range is exceeded in either direction. Saturation of the device (currents in the 20A range) as well as changing the applied current direction will increase the hysteresis/error.

For currents of approximately 2 Amps and smaller, the output repeatability is nominally 2% while higher currents produce output repeatability errors of less than 1%. Low current measurements of an initial current sweep may exceed 15% error in repeatability.

DATA ANALYSIS- Low Current Sensing

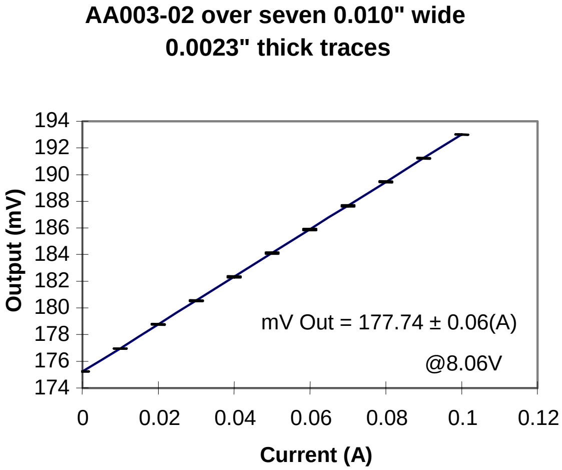
The low current analysis is handled here separately from the higher current analysis due to special considerations that must be made, although much of the same hysteresis and resolution considerations from high field sensing apply here. For low current sensing, two configurations of 0.010" wide traces were used. The first analysis will be with an AA003-02 sensor over a single 10-mil trace and the second analysis will consist of an AA003-02 sensor over seven 10-mil traces. With these traces, milliamp and sub-milliamp currents are of interest. Due to the hysteresis at low currents as discussed above, a biasing magnet was used to set the parts to approximately half of their linear range, or approximately 20 mV/V. This bias point can be seen as the Y intercept in the figures below. In this way, the output will not be near the natural zero current range, and thus, repeatability is increased. With this configuration an alternating sense current will produce a bipolar output with a DC offset in an AC application.

Note that although a permanent magnet was used for biasing in these experiments, a better method is to use a constant current. The current can be run on a trace parallel to the trace to be sensed, and will add to the current of interest. The magnetic field from the bias current can be more closely controlled than the field from a permanent magnet, which varies substantially with distance from the sensor. In addition, provided the bias current is stable over temperature, the bias field at the sensor element will also be stable over temperature. Permanent magnets often have large temperature coefficients, leading to biasing changes with temperature.



The sensor that was used to take this data was supplied with 8.06V. The marks on the graph are output error bars that cover the expected error from this part due to the part’s intrinsic hysteresis and measurement errors. The current was swept from zero to 100 mA and back to zero multiple times. In this biased state, the sensor is extremely linear and hysteresis is low. A weighed linear fit shows a -29.19 ± 0.08 mV/A correlation with 8.06V supplied which results in a sensitivity of 3.70 ± 0.01 mV/V/A.

The same analysis was performed on the seven 0.010" wide traces of the same thickness. A voltage of 8.06V was again applied and the resulting graph is shown below in the figure below.



Seven traces were run under the part so that the magnetic fields from the seven traces are additive at the sensor thus getting a much higher output with less applied current. To a first-order approximation, theory predicts that the field will be increased seven fold from just a single trace. The sensitivity from the single trace above is 3.7 mV/V/A; seven times this is 25.9 mV/V/A, which is not quite achieved. This discrepancy is due to the different current distributions. The loss would not be as extreme if seven times the current went through the single trace.

Resolution

Resolution is a function of environmental noise. By shielding, amplifying, and filtering, the low limit and usable resolution can be greatly increased. The data for the analysis done here was with a “raw” setup, no amplification or filtering. In a zero gauss chamber, single microamps were detected but the measurement equipment limited any in-depth analysis.

Effects of Biasing

For the analysis done above, a small ceramic magnet was used to supply a magnetic bias field in a direction which is parallel to the sensitive axis of the sensor. This magnetic bias “pushes” the output to a certain value, which is now a “psuedo zero” field point. The magnetic field from a current carrying conductor is also directional. If a current flows in such a direction as to add to the biasing field, the output from the sensor will increase. Likewise, if a current flows in the opposite direction, its resultant field will subtract from the biasing field, and the output will decrease. This directionality can be seen by looking at the output slopes of the previous two graphs. In the first graph, the output displayed shows the current produced a field opposite to the biasing magnetic field. Thus showing as the current increases, the output of the sensor decreases. In the same respect, the second graph shows that the field from the current was in the same direction as the biasing field.

Offset Characteristics

When using the specified sensitivity to predict the output of a sensor, remember that the sensor typically has a DC offset voltage. This is due to electrical bridge imbalance as well as external magnetic field bias (earth's field, magnets…). The output of the sensor without applying the current of interest is the base line output. The effects of the current will be added to this base line value. For the graphs shown on pages 130 and 131, the Y axis intercept is the base line offset. To determine the output of the sensor for a given field, this Y intercept number must be added to the value obtained by multiplying the current value by the slope.

AC

As mentioned previously, most information thus far has focused on DC applications. AC current detection with an AA003-02 is unique and thus deserves special attention in a separate application. Because the sensor is magnetically omni-polar, the output will be the same sign for either direction of magnetic field. As an AC current changes direction, the field surrounding the conductor will also change direction. The sensor's output will produce a fully rectified output. Low current AC is particularly laden with hysteretic errors. One method of creating both a bipolar output and a lower error is to magnetically bias the sensor. Biasing is discussed above in this Engineering and Application Notes booklet.

Part-to-Part Sensitivity

The data and evaluation thus far have focused on individual part performance. The part-to-part performance will also be briefly examined here. Each current sensor is tested and sorted to be within certain limits as given in the specification sections of this catalog. The main specification that affects the output of the sensor is the sensitivity. The AA003-02 sensors are tested to a sensitivity range of 2.0 to 3.2 mV/V/Oe. The offset specification also affects the output. The offset is the zero current or electrical imbalance of the Wheatstone bridge inside the sensor.

The magnetic field of the earth at NVE, is approximately 0.5G at a 70-degree angle to the horizon (values will vary depending on geographical location). The effects of this magnetic field should be analyzed in each application.

Care should be taken by the user to reduce the number and proximity of ferrous materials and magnetic field producers around the sensor. This typically is not a concern, but in some highly populated boards, this may be a necessity. Close proximity to such devices can increase the magnetic hysteresis or affect the output. In turn, these devices will decrease the sensor's output precision.

The output of the AA003-02 is functionally dependent on the distance between the sensor and the current. The field from a current carrying conductor is inversely proportional to the distance from the conductor. As the distance from the sensor to the conductor increases, the output from the sensor decreases. Likewise, as the sensor moves closer to the conductor, the output will increase. For the data analysis done in this report, the sensor was placed "live bug" over the current traces. In this configuration, the actual sensor element is about 0.04" from the top of the PCB trace. The output will increase with the current carrying conductor placed directly over-top of the sensor package. In this configuration, the sensing element is approximately 0.02" from the surface of the conductor. This distance change will account for an estimated doubling of sensor output.

Current Sensing - Detailed Considerations

Care must be taken in interpreting the output waveform when using GMR as current sensors. GMR sensors function as omnipolar sensors by producing positive output regardless of the magnetic field direction. In the case of AC excitation, the bipolar field created by a sinusoidal AC current will produce an output that will look like a full-wave rectified sinusoidal waveform. Biasing the sensor partway up the curve will restore a sinusoidal output with a DC component.

Although most of the examples given in this section use the AA003-02 sensor element, any of NVE's AA-Series, AAH-Series, or AAL-Series analog sensors will function as a current sensor as described above. The customer can select from a wide range of magnetic sensitivities in order to have the best sensing characteristics for the current range to be detected.

Current Sensing Application Examples

- Non-intrusive AC or DC current detection or sensing
- PCB mounted current detection or sensing (PCB trace or strap current carrier)
- Toroidal Hall effect current detector or sensor replacements
- Industrial instrumentation
- Industrial process control
- Current probes

NVE has a current sensor evaluation kit, AG003-01, which has a variety of different size traces complete with on-board sensors, available directly or through our distributors.

Magnetic Media Detection

General discussion

GMR Magnetic Field Sensors can be used for detecting different types of magnetic media. In this situation, NVE defines magnetic media as material that has a distinct magnetic signature. The media is typically a non-magnetic substrate with magnetic material placed in or on the substrate. Typically, GMR sensors are used to “read” the magnetic signature by sweeping the substrate and the sensor past each other.

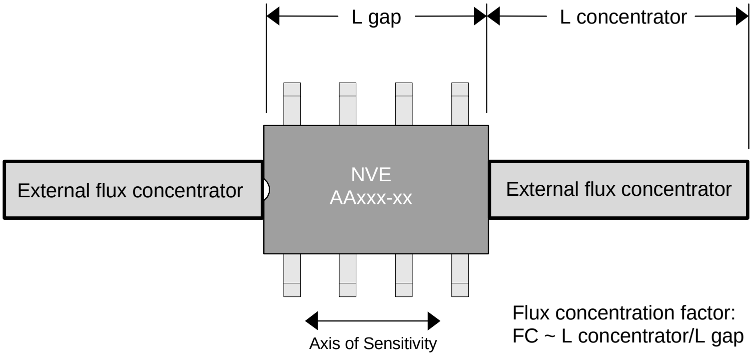
Depending upon the application, the magnetic parts of the substrate can be detected indirectly by sensing a perturbation of an externally applied field or sensed directly due to the part’s own field. The output of the sensor will be a function of: (1) the magnetic properties of the media; (2) the working gap; and (3) the type of sensor used.

Application examples

- Magnetic ink detection
- Magnetic stripe reading
- Fine magnetic particle detection
- Media magnetic signature detection
- Magnetic anomaly detection in substrates

Basic concepts

For applications in which minimum size is not critical, external flux concentrators can be used to increase sensor sensitivity. These external flux concentrators function in the same manner as the flux concentrators within the sensor.



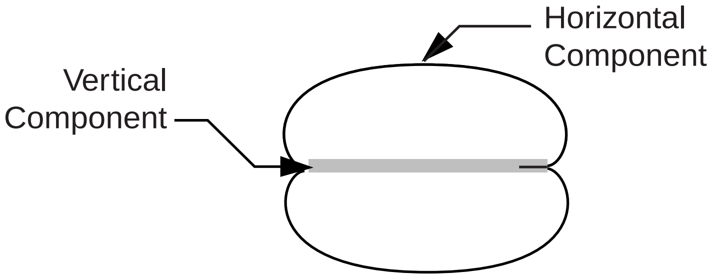
Elongated pieces of soft magnetic material gather external magnetic flux and expose the sensor to a magnetic field that is larger than the external magnetic field. For best results, two pieces of soft magnetic material of the same size are used. The concentration factor is approximately the ratio of one flux concentrator's length to the gap between the two flux concentrators. The long dimension of the flux concentrators should be aligned with the sensitive axis of the NVE sensor. To minimize the gap, the flux concentrators should butt up against the NVE sensor package.

Since the effective permeability of the flux concentrators is equal to the concentration factor, material with permeability 100 or more times the concentration factor, will be more than sufficient. Hot rolled iron wire or even cut off iron nails will work. Flux concentrators can be round or rectangular in cross section for mounting considerations. The NVE sensor must be centered within the flux concentrators' cross sectional area. The diameter of the flux concentrators should be an appreciable fraction of the gap length or flux spreading in the gap will reduce the concentration factor. The flux concentration achieved will depend on all dimensions. However, it will depend primarily on the ratio of the concentrator length to gap. The best calculation, however, is an experimental measurement made with an actual sensor and flux concentrators. For prototyping and production, the external flux concentrator can be placed down on the PCB or other substrate. The top of the metal strip must be at least as high as the sensor package to be truly effective.

It should be noted that a flux concentrator that increases the sensitivity of a GMR sensor by a factor of five will also reduce the maximum field to which the sensor can respond to one-fifth its original value.

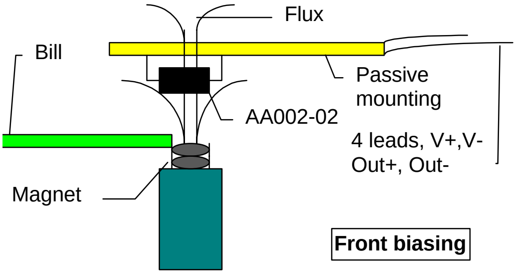
Currency Detection and Validation

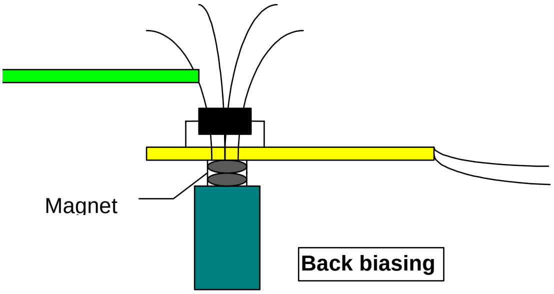
Currency detection and validation is a very important application of magnetic media detection. NVE's sensors have been used for detecting the magnetic material in paper bills. This magnetic material can be modeled as very small bar magnets. The magnetic field emitted by the bar magnets has two detectable orientations. The first is the vertical (radial) component of the field, and second is the horizontal (axial) component of the field. The sensitive axis of the sensor should be parallel with the component of field desired, *i.e.*, the horizontal axis, to pickup the horizontal component of the field.



The magnetic particles in the ink of most currencies, and also any magnetic stripes on the currency, can be magnetized and demagnetized by an external field. With only the earth's field present, the bill's magnetic properties can be seen. However, the signal increases when using an external field.

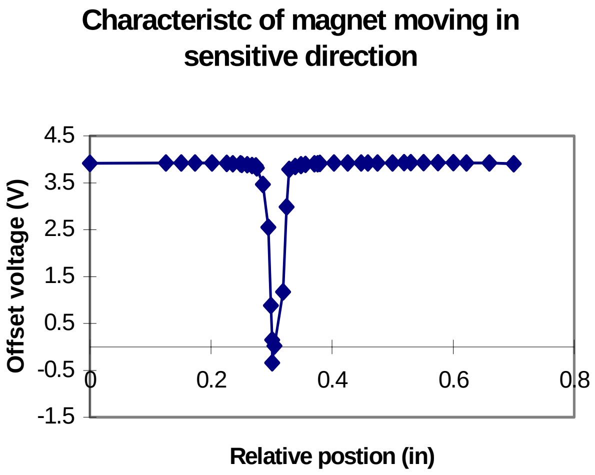
This external magnetic field can be set up in a few different orientations, either in a front/back biasing configuration or positioned "upstream" of the sensor. The back biasing configuration typically consists of an electro/permanent magnet glued to the under side of the sensor or to the under side of the PCB. The magnet should be aligned to produce the minimum output from the sensor. The ferromagnetic particles in the bill will magnetize and thus distort the field to produce a field in the sensitive direction at the sensor. Front biasing works in much the same manner except in this case the source of external field is coming from the other side of the bill.



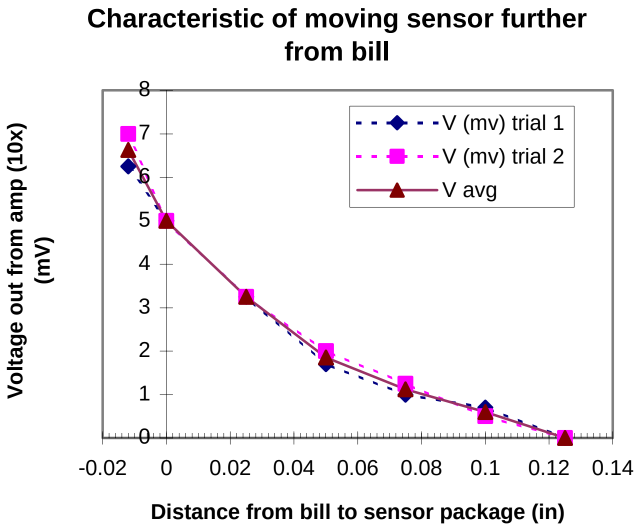


Positioning the magnet "upstream" from the sensor consists of magnetizing the bill before it reaches the sensor—this terminology comes from an application where the bills are moving past the sensor on a conveyer belt or rollers. With a magnet placed near the moving bill, the bill is magnetized before passing the sensor. The application's geometrical requirements, strength of magnet, as well as sensor-bill distance will determine which configuration works the best in each application. The following are some graphs that show the characteristics of back-biasing an AA002 sensor.

To determine the sensitivity of back biasing positioning, the magnet was moved along the sensors sensitive axis. The goal was to position the magnet so that there is minimum field in the sensitive direction. To obtain this, one pole of the magnet must be directly under the sensing resistors of the bridge. Note the steep slope around the zero output, which makes exact positioning difficult.



The graph below shows the variation in signal at the sensor as the currency is moved farther away from the GMR sensor element. Close proximity to the sensor is important in order to maximize output signal from the sensor.



In most currency detection applications, the signal from the bill is so small that it requires AC coupling the sensor to a high gain low noise amplifier in order to get usable signal levels.

In order to achieve the highest possible signal, NVE’s most sensitive sensors are necessary. NVE’s AA002-02, AAH002-02, and AAL002-02 sensors are recommended. These parts utilize large flux concentrators for high sensitivity. These flux concentrators also contribute to the magnetic hysteresis of the sensor. The hysteresis shows up mainly in a changing DC offset of the part. By AC coupling the output of the sensor, the changes in magnetic field are seen at the output rather than the DC offset. Another feature of AC coupling is a consistent output independent of the sensor’s orientation with respect to the earth’s field. The device is sensitive enough to pick up the earth’s DC field. By AC coupling, the DC offset contributed by the earth’s field, is not seen at the output.

Bipolar output signals are often very useful in currency detection and other magnetic media detection applications. As a result, NVE recommends biasing the sensors in these applications by using a current strap under the sensor to carry a bias current, and therefore bias the sensor higher, on its magnetic operating characteristic.

Magnetic media detection and validation is an important and fast-growing application for magnetic sensors. NVE’s sensors provide a reliable, non-contact, static or dynamic detection of the magnetic ink on paper currency. NVE’s AA002 sensor can resolve the distinct features printed on U.S. and other currency. NVE’s magnetic field sensors have been used for counterfeit detection, sorting, and simple bill presence detection.