

Application Note 37

Basic Introduction to the use of Magnetoresistive Sensors

Howard Mason, September 2003

This application note provides an introduction to the rudiments of anisotropic magnetoresistive (AMR) sensors for those users who may be unfamiliar with their characteristics and modes of operation and goes on to describe some applications, with guidelines to getting the best use out of the sensors.

Magnetic field sensor principle

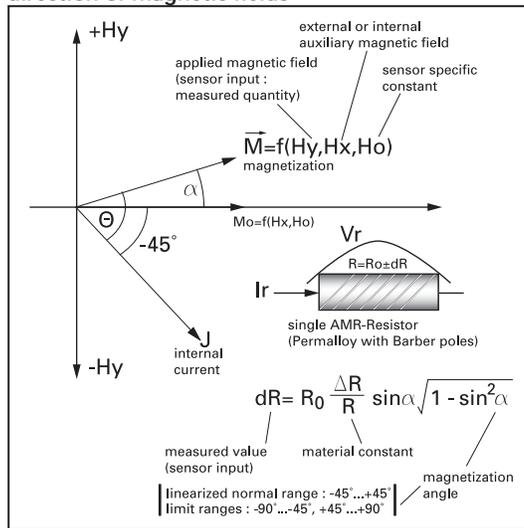
An AMR sensor is made by depositing a very thin film of Permalloy. When a magnetic field is applied, the magnetic domains "swing" round and the electrical resistance changes by around 2-3%.

The physical origin of the magnetoresistive effect in the transition metals lies in the dependence on the direction of the magnetization of the scattering of electrons. In the transition metals, the predominant carriers of current are the 4s electrons since they have a higher mobility than the 3d electrons. The scattering of electrons from the s to the d bands is found to be highest when the electrons are traveling parallel to the magnetization.

Lord Kelvin, formerly William Thompson, discovered the magnetoresistive effect. He first observed this effect in ferromagnetic metals in 1856 when he noticed the slight change in the electrical resistance of a piece of iron when he placed it in a magnetic field. But it took more than 100 years before thin film technology could make it into a practical sensor, which was when the Hunt element was invented in 1971.

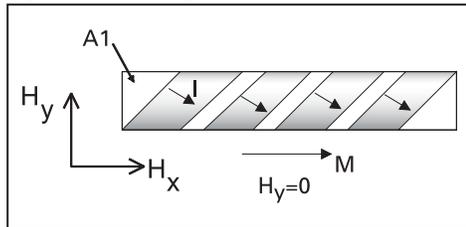
Applying low magnetic fields to a Hunt element will lead only to small changes of the magnetization. A Hunt element is not sensitive to small field strengths. In order to make the MR sensor sensitive for low magnetic fields, the MR transfer curve has to be modified. The most common way to achieve this is by the use of what are called "barber poles". The geometry of a Hunt element with barber pole structure (a single AMR-Resistor) is depicted in Figure 1.

Figure 1. Barber pole construction showing direction of magnetic fields



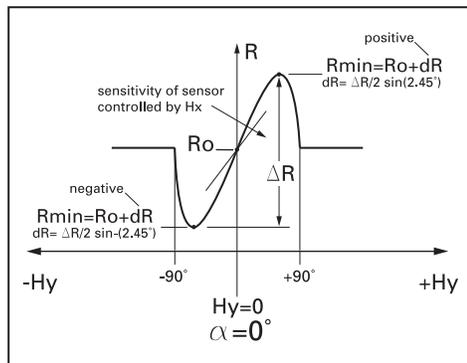
A magnetic field H_y coupled into the soft magnetic sensor material will change the resistivity of the stripe, which is measured by passing a sense current through the element. The linear behavior of the AMR-Resistor is achieved by the use of these barber pole structures. The stripes are covered with aluminum bars having an inclination of $|45^\circ|$ to the stripe axis (for example -45° between current and H_x -axis). Aluminum has a resistivity about 5 times lower than permalloy, so the barber poles cause a change of the direction of current. Figure 2 shows the construction of the barber poles and how the current direction is changed by them.

Figure 2. Barber pole construction



The characteristic of the AMR sensor after the barber poles have been added is represented in Figure 3.

Figure 3. Characteristic of an Anisotropic Magnetoresistive Sensor



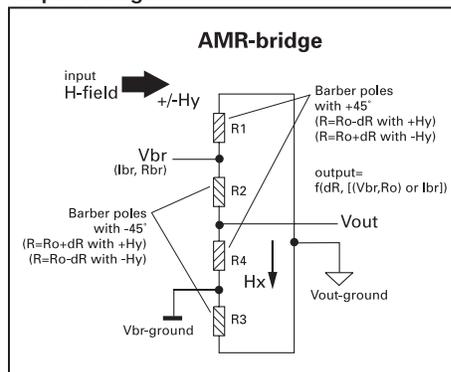
Predictable operation of the sensor is achieved by applying an auxiliary field H_x . This stabilizing H_x -field is usually generated by an external or internal permanent magnet.

This field defines the value and direction of the magnetization M_s . The range of H_y for safe sensor operation is determined by the strength of the H_x -field. In addition, the sensitivity of the sensor can be controlled by the strength of this auxiliary field, making it very versatile.

In most applications, the single AMR-Resistor is not suited as it does not provide a zero reference as well as having an absolute resistance tolerance of $\pm 30\%$ and a temperature coefficient of $+0.3\%/K$. These disadvantages can be avoided by using a Wheatstone bridge (AMR-Bridge). Furthermore the output signal of an AMR-Bridge is twice as high as with the single AMR-Resistor.

The overall size is $1.3\text{mm} \times 1.9\text{mm}$. The stripes are arranged into a Wheatstone bridge wired so that 2 of the 4 resistors increase in resistance when a field is applied and the other 2 decrease in resistance. The bridge is balanced by laser trimming. By comparing the mid-point voltages, absolute resistor tolerances are canceled and an extremely sensitive field detector can be made. The circuit of a AMR-Bridge with four AMR-Resistors as used in the sensor chip is shown in Figure 4.

Figure 4. Arrangement of four AMR elements with barber poles into a Wheatstone bridge, showing how resistance changes to give the output voltage



Let us assume that there is a field H_X as shown in figure 4 above and no field H_Y to begin with. Bearing in mind that the resistance is lowest when the current is flowing parallel to the magnetic field, it can be seen that with no H_Y field it starts with the current at 45° to the field in all four resistors and the bridge is balanced.

Applying an H_Y field pushes the resultant field in two of the resistors more into line with the current (angle $<45^\circ$), thus reducing their resistances and the field in the other two resistors more out of line (angle $>45^\circ$), this increasing their resistances. This unbalances the bridge and gives an output. Applying an H_Y field in the opposite direction (but keeping the H_X field unchanged) unbalances the bridge in the opposite direction. We can therefore detect both amplitude and polarity of the H_Y field.

The basic resistance of the bridge R_0 is $1.7k\Omega$ and it will change by an amount dR which is:

$$R_0 \frac{\Delta R}{R} \sin \alpha \sqrt{1 - \sin^2 \alpha}$$

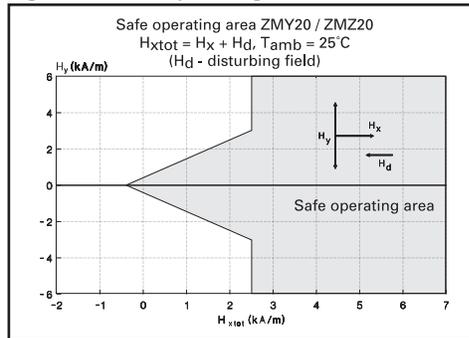
where $\Delta R/R$ is set by the properties of the material and α is the angle between the current flow and the resultant field as shown back in Figure 1. The resultant field is the vector sum of H_Y (the applied field), H_X (the auxiliary field) and H_0 (the initial magnetization of the permalloy).

Because the domains can have random orientation without a field, there is an inherent magnetism in the permalloy H_0 , but the resistance is not stable and predictable, so the auxiliary field H_X should be provided to line up the domains to be at 45° as explained to make the barber poles work. This can be done using a small external magnet or a coil, however Zetex offer the sensors with built-in magnets for this purpose. The suffix "M" after the part number signifies that a magnet is included. By aligning the domains first, the change in resistance due to the field at right angles H_Y will be much more linear. Fields perpendicular to the chip face (H_Z) do not affect the operation.

Safe Operating Area

It is necessary to explain in some detail the "Safe Area" of operation. The following explanation applied to the MR sensors which do not have internal magnets fitted. If an excessive field is applied in the Y (measuring) direction with little field in the X direction, the domains will line up with Y, almost regardless of the magnitude of H_Y , and the change in resistance will not be proportional to the field we wish to measure. Not only that, but they can get permanently magnetized in this direction and need "resetting" by a strong H_X field. Figure 5 explains the area in which the sensor should be operated.

Figure 5. Safe Operating Area



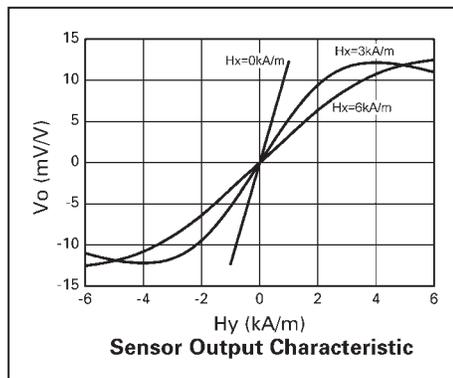
An H_X field of greater than $2.5kA/m$ will guarantee that the domains are always reset after the H_Y field is removed and cannot be "flipped" into the Y direction and cause false readings.

The ZMY20M and ZMZ20M have internal magnets fitted under the chips and these provide an adequate field to ensure that the devices remain in a safe operating area. This also means the user does not have to provide an auxiliary field and the sensitivity is defined at manufacture.

Sensitivity and Polarity

To use the devices effectively, some sensitivity and polarity issues should be understood. For the reason as explained above, a strong field in the H_x direction will try to keep the domains aligned in X and, as the orientation of the domains is the resultant of H_x and H_y , it now needs a larger H_y field before the domains get pulled into the Y direction. Hence the sensitivity is reduced in the presence of a strong H_x field, but the range of H_y is increased. The user can therefore choose the measurable range by choosing H_x . Bear in mind that, whether the 2 fields are weak or strong, the domains are only really doing the same thing by lining up with the resultant direction of the two fields, so the maximum change of resistance is still the same. This means that the maximum output in volts per volt is always limited at around 15mV/V and sensitivity will be reduced for large H_x fields. This makes the device very versatile. Figure 6 shows the graphs of sensitivity versus applied fields in H_x and H_y .

Figure 6. Sensitivity of Output voltage to H_y field for different values of H_x field.



It is clear from this that no H_x field results in the highest sensitivity, but the device will "saturate" with an output of 15mV/V when H_y is only 1kA/m. An H_x field of 6kA/m makes the device capable of measuring H_y up to 6kA/m, but now the output voltage will still only be 15mV/V at this higher field. The device spec gives a sensitivity which reflects the middle curve above with an H_x field of 3kA/m. As an example of a sensor with internal magnet, the ZMZ20M magnet provides a field of 2.5kA/m, so the sensitivity is slightly higher than this middle curve. The ZMY20M magnet only provides 2.0kA/m, so the sensitivity is higher still, but still not as high as the devices with no magnet and therefore no intrinsic H_x field.

If using the device with no H_x field to obtain maximum sensitivity, the domains may have "flipped" round the opposite way if the sensor has previously been subjected to a large field and the measurement will be incorrect. To overcome this, the sensor should be "flipped" into the correct H_x direction using a pulse of current in a coil of 2.5kA/m, which is then switched off just before the sensitive measurement is made. This is necessary for compassing applications for example. After the coil is switched off, the field should be limited to 0.5kA/m to avoid flipping the sensor. It must be said that compassing applications of AMR devices require some very sophisticated electronics.

Although the internal magnet on the ZMY20M and ZMZ20M guarantees the sensor can not be flipped, there is still a maximum allowable flux of 40kA/m with the devices with internal magnets. Above this, the internal magnet will be damaged and the sensor will no longer work correctly.

Temperature Coefficients

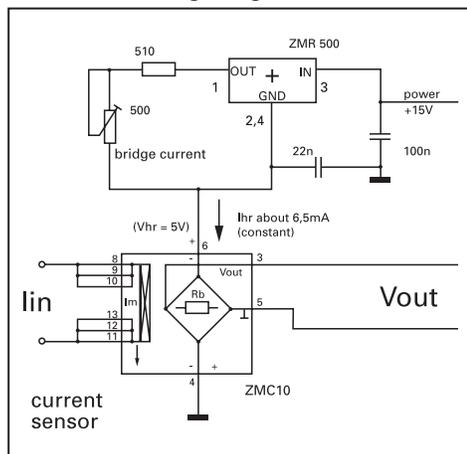
If the user wishes to measure fields accurately over a wide temperature range, bear in mind that the sensitivity in mV/V itself has a temperature coefficient of minus 0.3%/K. The bridge resistors themselves have a temperature coefficient of resistance of plus 0.3%/K. There are two ways to cancel out the temperature effects, either via temperature-dependent circuitry in the external amplifier or by using constant current drive to the bridge.

Using constant current drive, the +0.3%/K coefficient of the bridge resistance results in the bridge voltage rising at +0.3%/K which cancels out the -0.3%/K decrease in the sensitivity. This is because the output is in mV/V, so a 0.3% greater bridge voltage results in 0.3% more mV for the same field. One problem here is that the absolute bridge resistance has a tolerance of $\pm 30\%$, so the current must be set up for the particular bridge, otherwise the output voltage would be excessively low for low resistance bridges and vice versa. Figure 7 shows a way of using the Zetex ZMR500 to force constant current through a bridge to obtain reasonably temperature independent sensitivity to the H_Y field. In this case it is actually used with the ZMC10 10 amp current sensor, so it will obtain a temperature independent sensitivity to current being measured.

It can be preferable to supply the bridge with a regulated voltage and design an amplifier with a temperature coefficient of gain of +0.3%/K. This way the bridge resistance tolerance does not affect the circuit and it is not necessary to set up the current for each bridge.

Another important parameter is the temperature coefficient of the sensor offset TCOFF. This effect is caused by small differences in the temperature behavior of the four sensor bridge resistors. In practice, it leads to a drift in the output voltage which can not easily be separated from the output signal caused by the magnetic field H_Y which is being measured. In applications using DC-signal coupling the TCOFF will limit the measurement accuracy. If the offset voltage is nulled out by external adjustment at one temperature changes of temperature will result in the offset changing, limiting accuracy.

Figure 7. Constant Current Drive to ZMC10 Current Measuring Bridge



Frequency Response

It is useful to know the two effects which limit the frequency response of MR sensors. One is the "magnetic inertia" of the permalloy, which means that the magnetic domains take a finite time to align themselves with the external field.

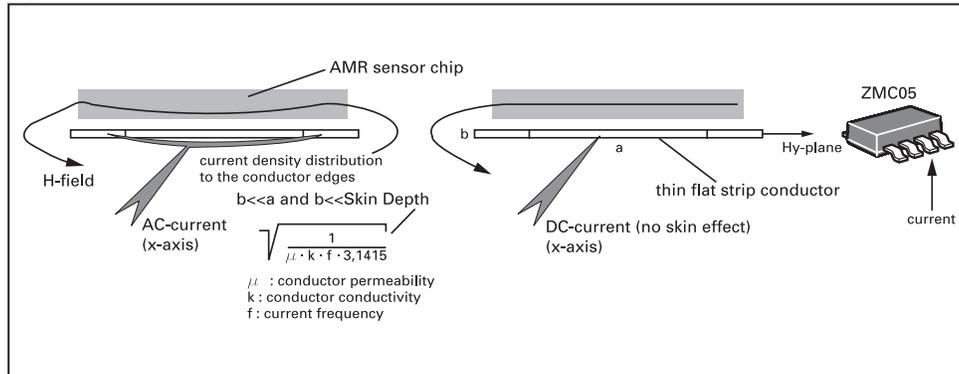
In addition, eddy current reduces the permeability of magnetic materials such as $\text{Ni}_{81}\text{Fe}_{19}$ at higher frequencies. This means that, when the sensitivity is plotted in mV/V/kA/m versus frequency, it rolls off at 1MHz and the devices can not be used above this. This limiting frequency applies to the AMR sensor itself and therefore affects the whole range of devices.

However, in the case of the current measuring devices (ZMC range), there is another limitation. The conductor carrying the current is subject to the "skin effect" which means that the field is not proportional to the current above 100kHz. The AMR chip measuring this field will therefore give erroneous readings and so the ZMC series can not be used above 100kHz.

Figure 8 shows the current path being altered and a formula to explain this effect.

If the field sensors are used to measure the current in a conductor (as explained later in this article) the skin effect will have to be calculated for that particular conductor, unless the frequency is low, for example when measuring mains currents.

Figure 8. The Skin Effect in conductors



Stress, Anisotropy and Hysteresis

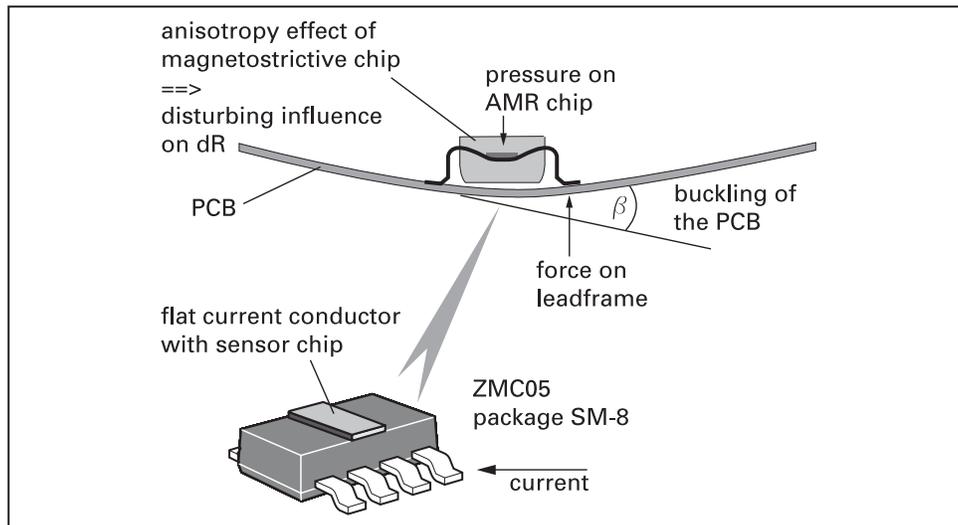
The user should be aware of three effects if the MR sensor is used for very accurate measurements, especially if these are around its zero field point.

Package Stress

Firstly, stress applied to the package of an AMR sensor can cause bending of the permalloy structure. This causes magnetostriction effects which can cause the bridge to become unbalanced even when the H_y field is zero. Figure 9 shows how mounting a package on a PCB badly will induce stress and zero offsets:

The package stress may be reduced by the use of a small carrier if the MR sensor is being mounted on a very large PCB where stress may be expected.

Figure 9. Package stressed by PCB distorting AMR sense element

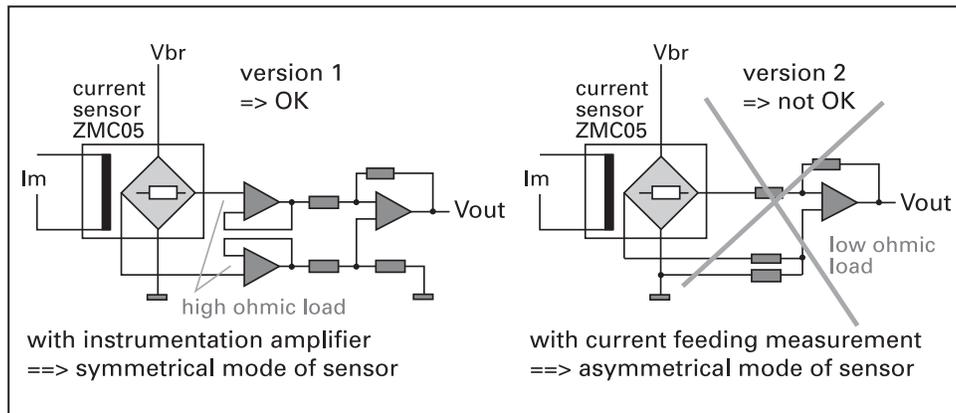


Anisotropy caused by Asymmetrical Electrical Loads on Bridge

The bridge will need an amplifier to amplify the small signals and this will present a finite electrical load to the bridge. For large field operation, such as proximity detector giving a rail to rail output voltage, it does not matter if the two outputs of the bridge are loaded asymmetrically. However for accurate measurement of fields the amplifier should present a symmetrical load. The two examples are shown in Figure 10 for the 5 amp current sensor ZMC05. Version 1 is recommended and version 2 is not recommended.

The asymmetrical current load for the sensor would increase the anisotropy effect of the magnetostrictive sensor and lead to offsets, making it impossible to measure very low field strengths accurately.

Figure 10. Symmetrical and Asymmetrical Loading of Bridge



Hysteresis

Another characteristic of the AMR sensors which should be noted is that of hysteresis. The accuracy of the magnetoresistive sensors during low field measurements is affected by hysteresis. The magnetization of the permalloy strips is not always completely homogenous, and an effect called "pinning" can occur, where some magnetic domains in the permalloy can swing other domains into line with them, causing hysteresis.

If the output must be measured accurately around the zero field point, it is possible to determine the amount of hysteresis and cancel it out electronically, in a manner similar to Op-Amp offset voltage cancellation.

Applications

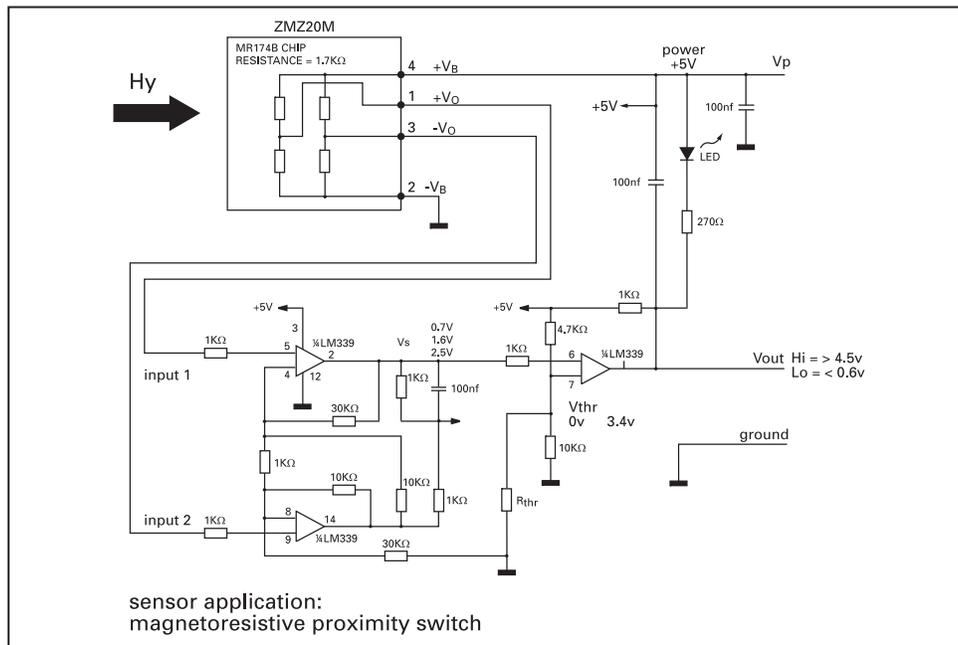
Field Sensors

It is worth describing the various types of field sensor. These all use the same AMR chip, but it is available either in a SOT223S package, with the prefix "ZMY" or in a 4 pin E-line package with the prefix "ZMZ". The number "20" signifies the bridge resistance (this used to be $2k\Omega$, but is now $1.7k\Omega$). Both these devices are available with an internal magnet to provide the auxiliary field, in which case they have the suffix "M" or without the magnet, in which case they have no suffix. Hence the ZMZ20M is a $1.7k\Omega$ bridge in a 4 pin E-line package with an internal magnet.

Some simple applications will be described, firstly a proximity switch using the ZMZ20M, the circuit of which is shown in Figure 11.

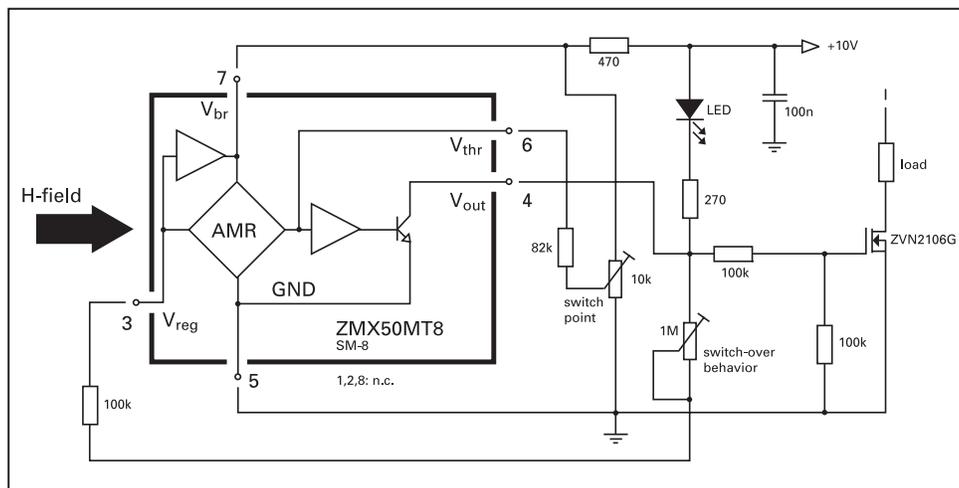
The output from the bridge is amplified using an LM339 and used to light the LED or alternatively the output can be brought out to drive other external circuits. It is advisable to include some positive feedback on circuits to provide hysteresis, otherwise if the metal object is on the threshold of the circuit, the output could jitter or oscillate.

Figure 11. Proximity Detector using ZMZ20M plus LM339.



Another circuit uses two Zetex ZR431 regulators, one of which regulates the voltage on the top of the bridge to 5 volts and the other acts as an amplifier. The power consumption can be reduced and operation from a 5 volt rail is possible if the ZR431L regulator is used instead, as this will regulate the voltage on the top of the bridge to 2.48 volts, which means the bridge will only draw 1.5mA. The circuit using two ZR431s is shown in Figure 12.

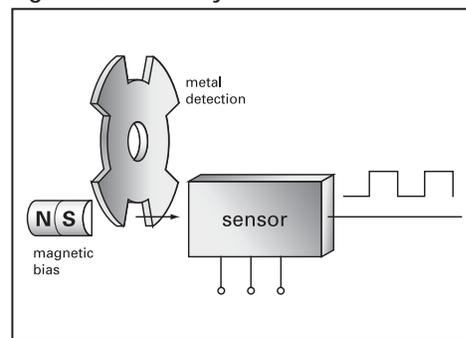
Figure 12. Proximity Detector using ZM220M



ZMX50MT8: target presentation, engineering sample

A typical application for this proximity detector (nowadays called "Proxies") could be the detection of a rotating wheel, e.g. for engine timing, shown in Figure 13.

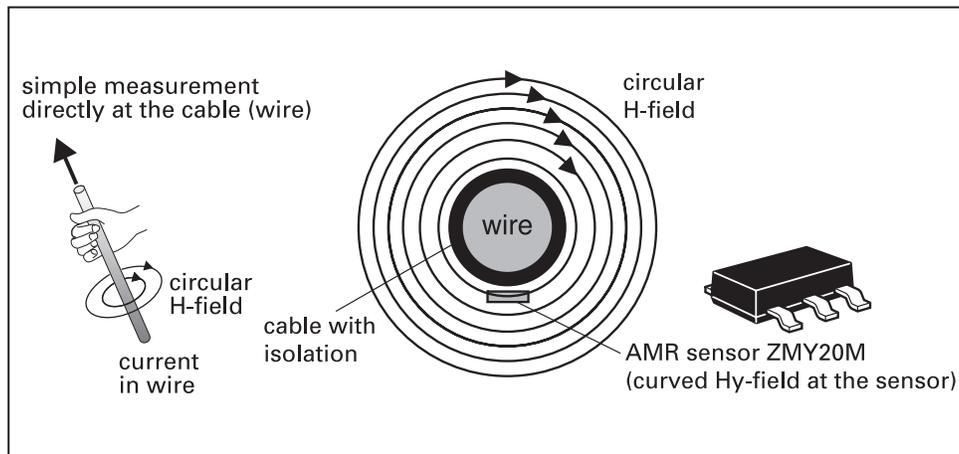
Figure 13. Proximity Detector



Current Measurement is possible using the Field Sensors, by placing them close to a conductor and suitable calibrating them in terms of bridge output versus conductor current. Two obvious advantages are that the galvanic isolation can be made as high as desired and there is no upper limit to the current to be measured, as the sensor can be positioned as near or far away as is needed. Currents of hundreds of amps in conductors at hundreds of volts can be measured. Figure 14 shows some suggestions for arranging the ZMY20M near to conductors.

Note that in both version 1 and version 2 the field is strongly curved near the sensor, so if it moves laterally, the H_y component of the field will change appreciably. The devices are not sensitive to fields vertical to the chip (we may call this the H_z field) so the sensitivity would reduce as the device moves to the side as the same resultant field from the conductor would have a smaller H_y component and a larger H_z component.

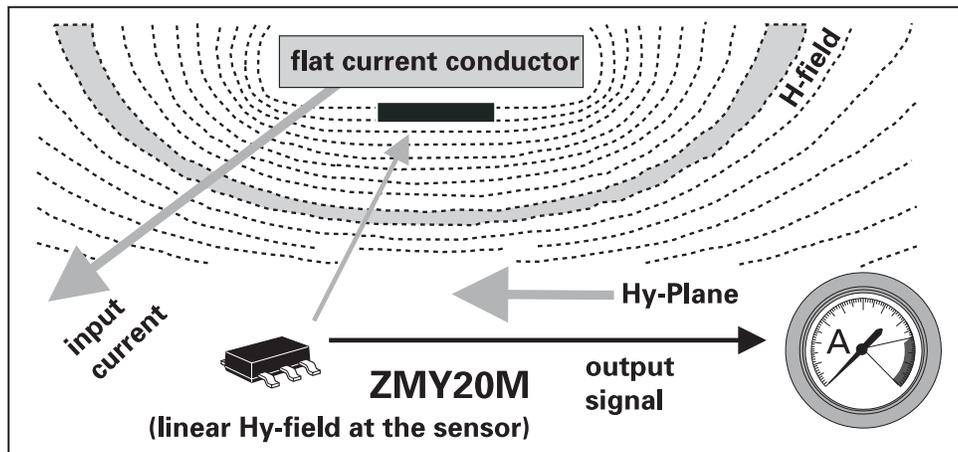
Figure 14. ZMY20M used for Current Measurement in Circular Conductors



This does not matter as long as the ZMY20M is held rigidly in a fixed position relative to the conductor.

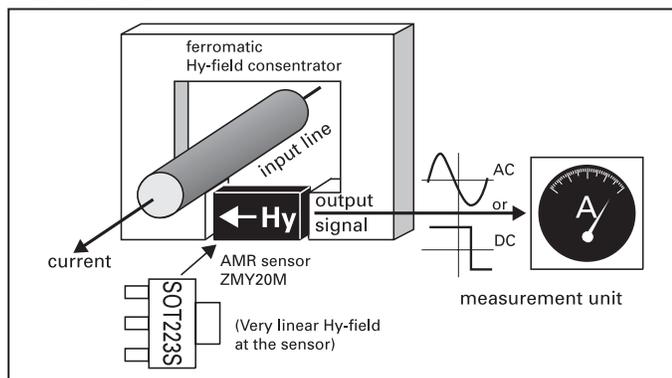
If the conductor is flat, it will give a parallel magnetic field and slight lateral movements of the ZMY20M will have less effect on the value of H_y and therefore the sensitivity. This is shown in Figure 15.

Figure 15. ZMY20M used for Current Measurement in Flat Conductors



If the expense of an iron or ferrite core can be justified, very linear current measurement is possible with this arrangement shown in Figure 16.

Figure 16. ZMY20M used for accurate proportional current measurement

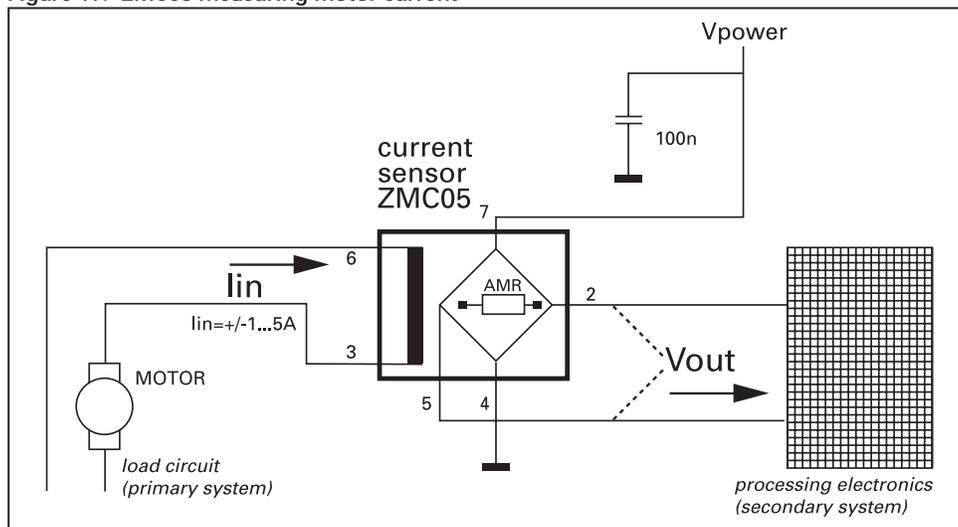


ZMC Series of Current Sensors

The next sensors to be described are the ZMC current measuring devices. These contain the same MR sensor chip, but the leadframe is shaped into a conductor running beneath the chip, so that magnetic fields produced by the current in the conductor can be measured by the sensor. The current conductor is isolated from the leadframe by a glass insert capable of withstanding 200 volts on the ZMC05 and a ceramic insert capable of withstanding 2000 volts on the ZMC10 and ZMC20. The 2000 volt types are ideal for measuring high-side currents, e.g. in mains circuits. The ZMC05 is in an SM8 package and measures currents up to 5 amps. The ZMC10 is in a modified DIL14 style package and measures up to 10 amps. The ZMC20 is also in a modified DIL14 style package and measures up to 20 amps.

Figure 17 shows how the ZMC05 can be used for measuring the current in a motor with complete galvanic isolation between the motor circuit and the measuring electronics.

Figure 17. ZMC05 measuring motor current

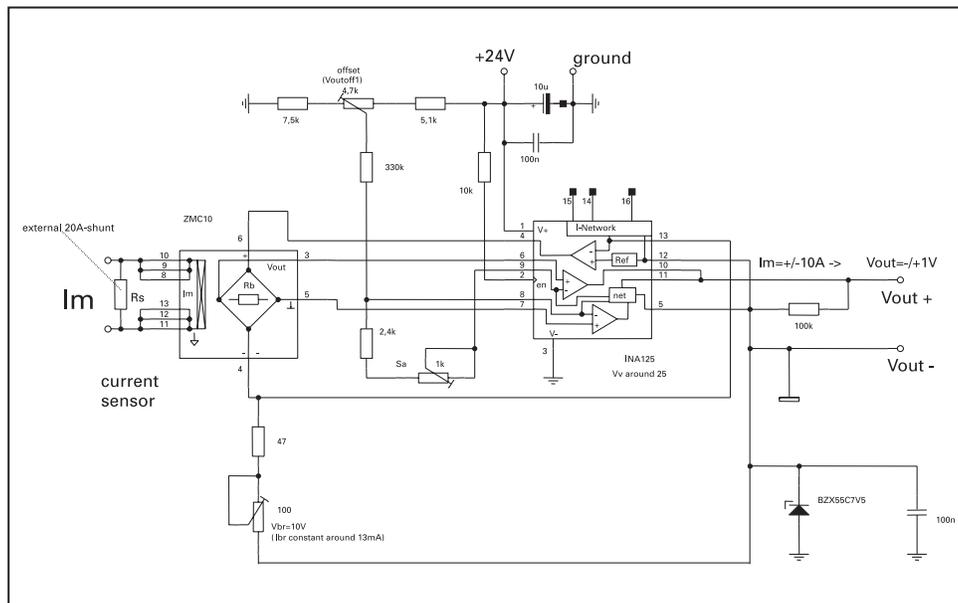


ZMC10 Current Measurement using Burr Brown INA125

Another application circuit is shown here in Figure 18 which uses the ZMC10 in conjunction with a Burr Brown INA125 instrumentation amplifier. The bridge is fed by constant current set to about 6mA. As explained earlier under "Temperature Coefficients" this enables the negative tempco of sensitivity to be canceled out by the positive tempco of the bridge resistance, hence bridge operating voltage.

There are also analog test points to look at the various voltages, enabling the user to understand the operation of MR sensors as current measuring devices. The sensor constant current can be set by links, enabling the user to understand how the operating conditions affect the accuracy of the measurements.

Figure 18. ZMC10 used with Burr Brown INA125 Instrumentation Amplifier



An evaluation board for the ZMC10 and ZMC20 is available which has 2 devices and so can measure and compare 2 currents. It has comparators and 6 LEDs which give an indication of various current measurements being performed.

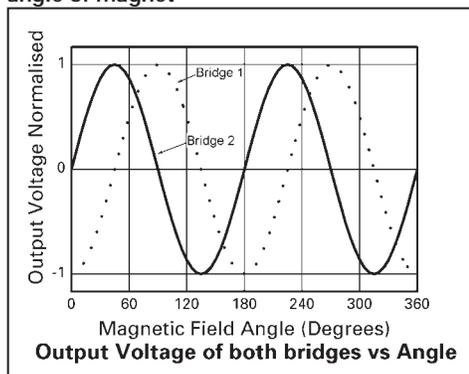
ZMT31 Rotational Measurement

Although the ZMY20M and ZMZ20M can be used for the measurement of shaft rotation or accurate positioning of a shaft at a single point (e.g. top dead center) they are sensing the presence or absence of teeth on a wheel. A magnet could be mounted on the shaft, but this sensor would only give a one-dimensional measurement of the field. This would be symmetrical as the shaft moved either side of a centerline through the sensor and would not give full positional information.

The ZMT31 contains 2 bridges at 45° to each other in an SM8 package. If a magnet is placed above the device and rotated, the sensors will give two sinusoidal outputs versus magnet angle, phase shifted by 45° as shown in Figure 19.

An important point to consider is that this device is designed to give a sinusoidal variation of resistance varying with the ANGLE of the field, not its intensity. The field should be very strong (>50,000 Amps/meter) to ensure that ALL the magnetic domains line up with it. If a low field strength is used, there would be some domains not lined up, as with the linear field sensors, and the output voltage would not be exactly proportional to the sine of the angle.

Figure 19. Outputs of the ZMT31 versus angle of magnet



Please note that there is NO internal magnet as this would interfere with the measurement of the external field. This means that, as explained in the section on "Sensitivity and Polarity" earlier, the bridge will go out of balance in the same way when it sees either a north or south pole. This is the reason it gives a complete cycle for 180° rotation of the magnet as can be seen in Figure 20 above.

The output voltages of both Wheatstone bridges versus angle (α) of the magnetic field direction is as follows:

Bridge 1 output voltage 1 = $\sin 2(\alpha+45^\circ)$

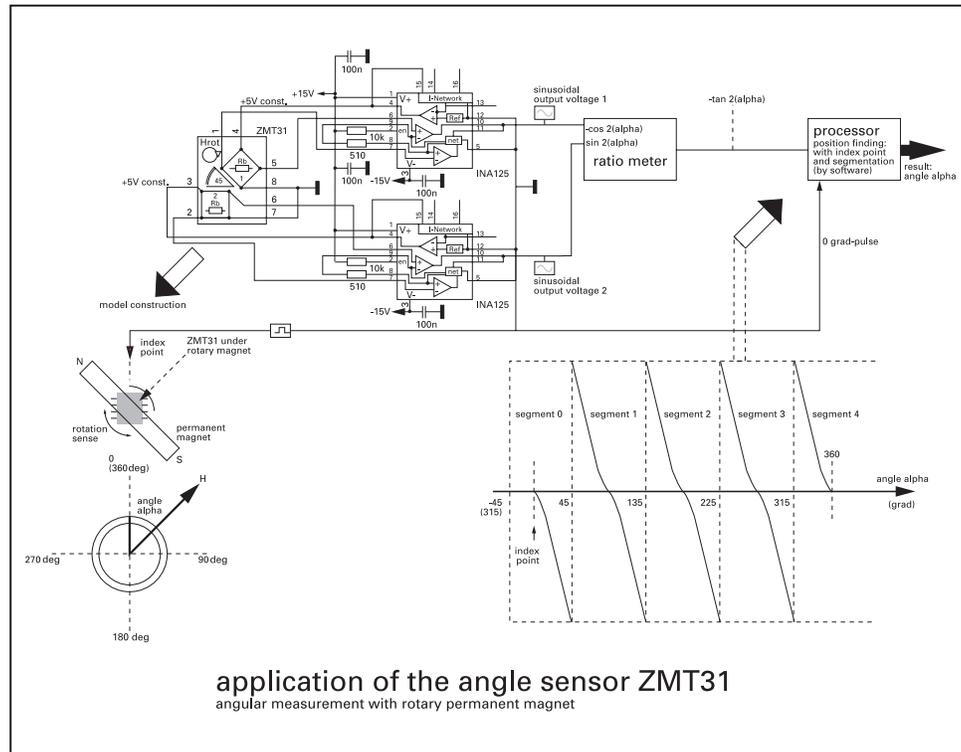
Bridge 2 output voltage 2 = $\sin 2(\alpha)$

$\sin 2(\alpha+45^\circ) = -\sin -2(\alpha+45^\circ) = -\sin 2(45^\circ-\alpha) = -\sin (90^\circ-2\alpha) = -\cos 2(\alpha)$

output voltage 2 / output voltage 1 = $\sin 2(\alpha) / -\cos 2(\alpha) = -\tan 2(\alpha)$

A circuit for processing the outputs of the ZMT31 is shown in Figure 20.

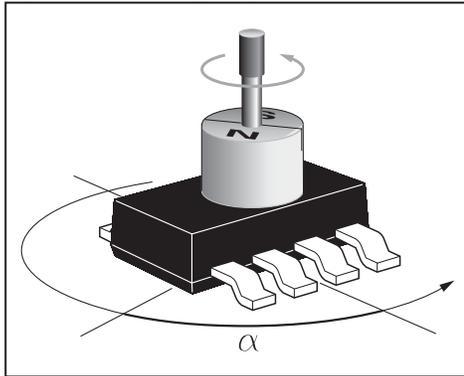
Figure 20. ZMT31 Applications Circuit



This device is ideal for designing a contactless, completely smooth potentiometer as well as for shaft encoders, machine tool control and sensing of actuating levers in automotive applications.

Figure 21 shows a pictorial representation the construction of a contactless potentiometer.

Figure 21. Rotating magnet above ZMT31



ZMX40M Dual Sensor

The ZMX40M contains two sensor chips, mounted parallel to each other in an SM8 package. In addition an internal magnet is included to bias the sensors into the linear region. The number "40" is because there are 2 bridges inside, each bridge is still $1.7k\Omega$.

The spacing between the chips is exactly 3mm. If a magnet travels horizontally above the sensor, each chip will give an output which will peak as the magnet passes above it and the two peaks will be spatially separated by 3mm.

When the 2 peaks are the same amplitude, the magnet must be mid-way between the two chips. This sensor can be used to measure the position of, for example, a wheel tooth very accurately for automotive and machine-tool applications. With calibration to allow for the tolerances on the bridge outputs being slightly different, the ZMX40M has been used in machine tool applications to resolve distances down to $30\mu\text{m}$. By comparing the two outputs and adding some hysteresis, a large-geometry magnetic tape reader can be made.

Conclusion

The Zetex range of Linear Field Magnetoresistive Sensors have applications in linear position sensing for process control, used for counting devices, door interlocks, proximity detectors, engine position and speed measurement, the sensing of a rotating impeller inside a pipe for fluid metering, vehicle sensing and traffic counting and measurement of current in a conductor with complete galvanic isolation up to very high voltages.

The Angle Sensor applications include pedal and gear lever sensing, speed and angle sensing of shafts in machine tools or engines and the construction of a contactless, high resolution potentiometer.

The Current Sensor range can be used in automotive, motor control, power tools, audio amplifier overload protection, traffic lamp bulb sensing and high intensity discharge lamp ballast circuits.

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Europe		Americas	Asia Pacific
Zetex plc Fields New Road Chadderton Oldham, OL9 8NP United Kingdom Telephone (44) 161 622 4444 Fax: (44) 161 622 4446 hq@zetex.com	Zetex GmbH Streitfeldstraße 19 D-81673 München Germany Telefon: (49) 89 45 49 49 0 Fax: (49) 89 45 49 49 49 europe.sales@zetex.com	Zetex Inc 700 Veterans Memorial Hwy Hauppauge, NY 11788 USA Telephone: (1) 631 360 2222 Fax: (1) 631 360 8222 usa.sales@zetex.com	Zetex (Asia) Ltd 3701-04 Metroplaza Tower 1 Hing Fong Road Kwai Fong Hong Kong Telephone: (852) 26100 611 Fax: (852) 24250 494 asia.sales@zetex.com

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