PHILIPS
Electronic components and materials
Technical publication
REVISED EDITION
102

The KMZ10 magnetoresistive sensor

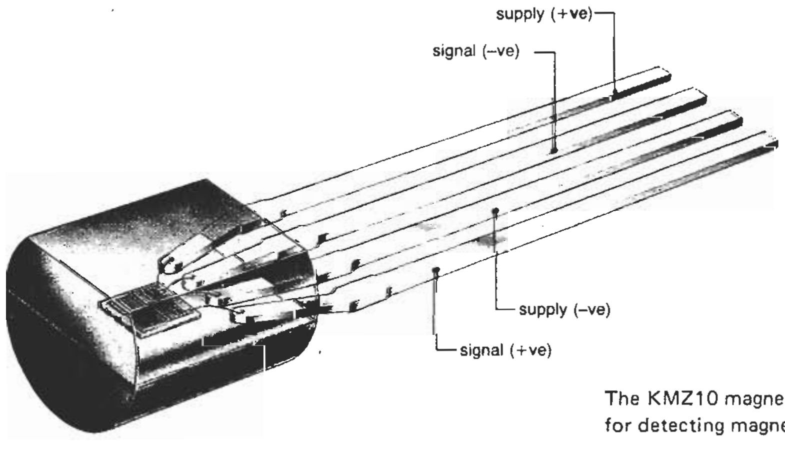
a sensitive device for detecting magnetic-field variations

Magnetic-field sensors provide a highly effective means of measuring both linear and angular displacement. This is because even quite small movement of actuating components in machinery (metal rods, cogs, cams etc.) can create measurable changes in magnetic field. Examples where this property is put to good effect can be found in instrumentation and control equipment, which often require position sensors capable of detecting displacements in the region of tenths of a millimetre, and in electronic ignition systems, which must be able to determine the angular position of an internal combustion engine with great accuracy.

The KMZ10 magnetosistive sensor (MRS) is one of the more recent developments for detecting magnetic field variations, and in many applications provides an attractive alternative to the conventional Hall-effect sensor. For example, the MRS is more sensitive than the Hall-effect sensor and can operate over a much wider temperature range. Moreover, its frequency range is much wider – from d.c. up to several megahertz.

The device makes use of the well-known property of a magnetic material to change its resistivity in the presence of an external magnetic field. This change is brought about by rotation of the magnetization relative to the current direction. In the case of permalloy for example (a ferromagnetic alloy containing 20% iron and 80% nickel), a 90° rotation of the magnetization (due to the application of a magnetic field normal to the current direction) will result in a 2 to 3% change in resistivity.

The MRS consists of four permalloy strips arranged in a meander pattern (Fig.1) on a silicon substrate, and connected to form the four arms of a Wheatstone bridge configuration. The degree of bridge imbalance is then used to indicate the magnetic field strength, or more precisely, the variation in magnetic field normal to the permalloy strips. As detailed below, the device characteristic (resistivity versus magnetic-field) is linearized using a special set-up known as a 'barber-pole' configuration.



The KMZ10 magnetoresistive sensor – a recent development for detecting magnetic-field variations.

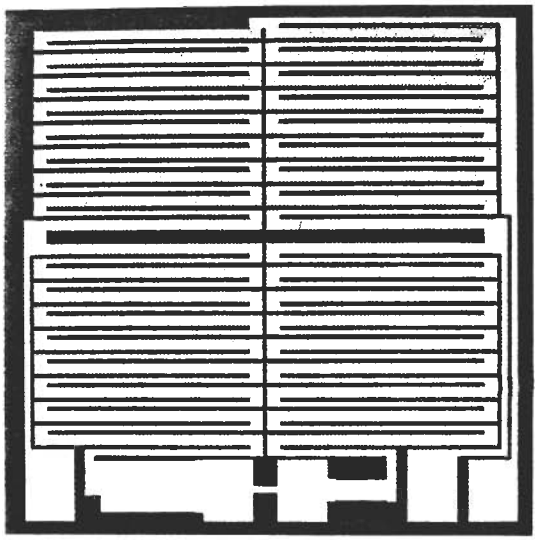


Fig.1 The MRS chip is made up of four permalloy strips arranged in a meander pattern and connected to form the four arms of a Wheatstone bridge. The chip incorporates special resistors that are trimmed during manufacture to give zero offset at 25 °C

LINEARISING SENSOR CHARACTERISTICS – THE 'BARBER-POLE' CONFIGURATION

The resistivity of a polycrystalline ferromagnetic alloy such as permalloy is related to the angle θ that the magnetization makes with the current direction by

$$\rho = \rho_0 + \Delta\rho_{max} \cos^2\theta \qquad (1)$$

where ρ_0 is the isotropic resistivity, and $\Delta\rho_{max}$ is the change in resistivity resulting from a 90° rotation of the magnetization (from the direction of current flow).

If this rotation is caused by a magnetic field H normal to the direction of current, and if the field tending to align the magnetization with the current is H_0 (comprising the demagnetizing and anisotropic fields), then $\sin\theta = H/H_0$, and

$$\rho = \rho_0 + \Delta\rho_{max}\,[1 - H^2/H_0^2] \qquad \text{for } H < H_0$$

and (2)

$$\rho = \rho_0 \qquad \text{for } H \geqslant H_0$$

It's obvious from this quadratic expression that the resistivity/magnetic-field characteristic is non-linear, and moreover, that the set-up will not furnish a unique value for H.

There are, however, several ways of linearizing the characteristic. One is to provide a uniform biasing field H_{bias} in the direction of the field H. Then, provided $H \ll H_{bias}$, ρ will be proportional to H. The MRS employs another method that uses gold stripes secured to the top of each permalloy strip at an angle of 45° to its axis (Fig.2). This has been termed the 'barber-pole' configuration owing to its resemblance to the poles commonly seen outside barber shops.

Since gold has a much higher conductivity than permalloy, the effect of these stripes is to rotate the net current direction through 45° (Fig.2), i.e. to reduce θ to $\theta - 45°$. Relation (1) then becomes

$$\rho = \rho_0 + \Delta\rho_{max}/2 + \Delta\rho_{max}\, H/H_0\sqrt{[1 - H^2/H_0^2]} \qquad (3)$$

As Fig.3 illustrates, for small values of H (relative to H_0) ρ increases linearly with H.

With the complementary barber-pole configuration to that shown in Fig.2, i.e. with the gold stripes inclined at

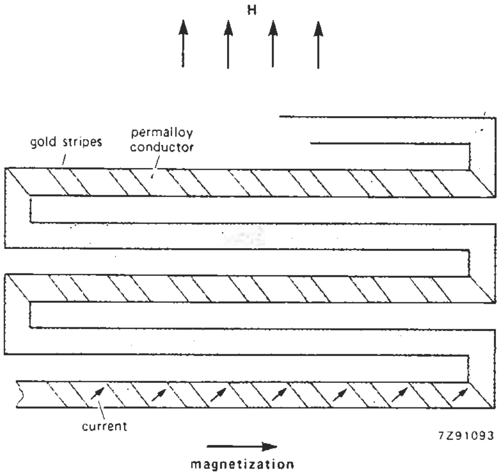


Fig.2 Gold stripes on the permalloy surface rotate the current direction through 45°. This linearizes the resistivity/magnetic-field characteristics of the MRS

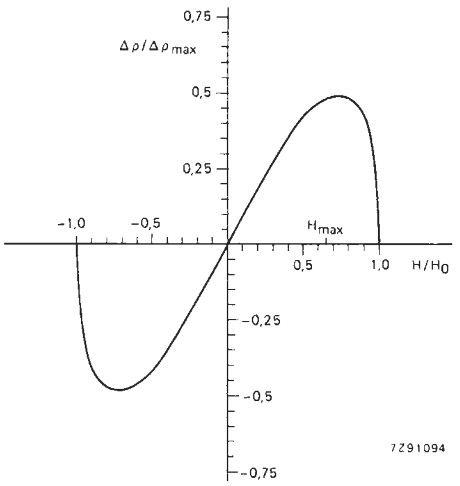


Fig.3 In a barber-pole MRS, resistivity varies linearly with H ($H \ll H_0$). The figure shows the normalized change $\Delta\rho/\Delta\rho_{max}$ in resistivity as a function of H/H_0 ($\Delta\rho = \rho - \rho_0 - \Delta\rho_{max}/2$)

-45° to the axis of the permalloy strip, θ increases to $\theta + 45^\circ$ and (1) becomes

$$\rho = \rho_0 + \Delta\rho_{max}/2 - \Delta\rho_{max}\, H/H_0 \surd[1 - H^2/H_0^2]$$

i.e. ρ decreases linearly with H.

The MRS itself comprises two (diagonally opposed) elements in which ρ increases with H, and two in which it decreases. This largely eliminates the effects of ambient variations (temperature etc.) on the individual elements, and, moreover, magnifies the degree of bridge imbalance, thereby increasing the sensitivity of the device.

MANUFACTURE

The devices are manufactured in thin-film technology using established photo-lithographic processes. Major steps in the fabrication process are as follows:

- Surface oxidation of silicon substrates (dimensions 1,6 x 1,63 mm^2)
- Sputter deposition of a titanium adhesive layer (0,1 μm thick) and then of permalloy
- Formation of permalloy strips using subtractive photo-lithographic process
- Baking at high temperature and application of a strong magnetic field parallel to the strip axis. The field imparts a preferred magnetization direction to the permalloy strips
- Sputter deposition of a titanium/tungsten adhesive layer (0,1 μm thick) on the surface of the permalloy strips
- Formation of gold barber-pole pattern on the surface of the permalloy strips
- Trimming of MRS bridge to give zero offset voltage at 25 °C.

SENSITIVITY – GOVERNING FACTORS

One of the major advantages the MRS has over other devices like the Hall-effect sensor is the ease with which its sensitivity can be set during manufacture. For small field variations, the sensitivity of the MRS is, from (3), given by $\Delta\rho/H = \Delta\rho_{max}/H_0$. $\Delta\rho_{max}$ is determined by the material properties; H_0 by, among other things, the strip geometry.

Fig.4 illustrates how the strip geometry governs sensitivity. For a given field, the thicker the permalloy strip, the less the magnetization is rotated. So by using different strip geometries, it's possible to produce a range of devices with different sensitivities and measuring ranges. At present, three types are produced – designated types A to C. A comparison of these types is provided in the table below.

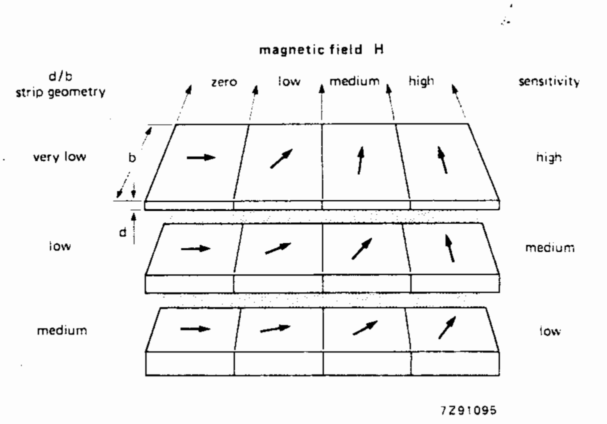


Fig.4 Factors affecting sensitivity. The higher the d/b (depth/breadth) ratio of the gold stripes, the less the magnetization will be rotated by a given magnetic field and the lower will be the sensitivity

KMZ10 characteristics (at T_{amb} = 25 °C)

	KMZ10A	KMZ10B	KMZ10C	units
H_{max}	900	2500	10000	A/m
supply voltage (max)	10	12	9	V
open-circuit sensitivity	12,0	5,0	1,1	[mV/V]/[kA/m]
temperature coefficient of sensitivity				
constant voltage	−0,4	−0,4	−0,4	%/K
constant current	−0,12	−0,12	−0,12	%/K
bridge resistance	1400	1700	1200	
temperature coefficient of bridge resistance	+0,3	+0,3	+0,3	%/K
linearity error				
full scale	⩽3	⩽3	⩽3	%
offset voltage (max)	±20	±20	±20	mV
offset drift between −40 and 120 °C	±0,001	±0,001	±0,001	[mV/V]/K

The sensitivity of the MRS falls with increasing operating temperature. This isn't a major problem, however, since it is relatively easy to incorporate effective compensating networks in the operating circuitry. In fact, as the next section shows, the linear temperature variation of bridge resistance is itself used to compensate variations of sensitivity with temperature.

USING THE KMZ10

The MRS in circuit

For some applications it's not necessary to compensate for temperature dependence of the bridge characteristics, and it's sufficient to operate the MRS from a simple constant-voltage source. A constant-current source could also be used, at the cost, however, of lower sensitivity.

For many applications, however, temperature compensation is essential, and Fig.5 shows a simple set-up in which this can be realized.

The output of the bridge, which indicates the degree of imbalance, is amplified by opamp A_0 – common-mode rejection being provided by a feedback network incorporating opamp A_1.

A negative-impedance converter (NIC) incorporating opamp A_2 provides a temperature dependent voltage source for the bridge. This set-up has the advantage of providing a ready means of correcting for temperature effects using the bridge resistance itself as the controlling parameter. Any change in bridge resistance (caused by a change in operating temperature) will affect the voltage across the bridge. The output signal of A_2 then acts to restore this voltage to its original value (V_{ref}).

Figure 6 shows a more extensive circuit, embodying the functions of Fig.5 and including an output comparator stage to provide a step-function output (e.g. for counting purposes). This circuit is designed to operate from a single 12 V d.c. supply.

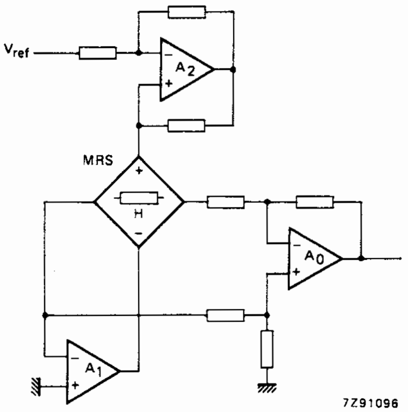
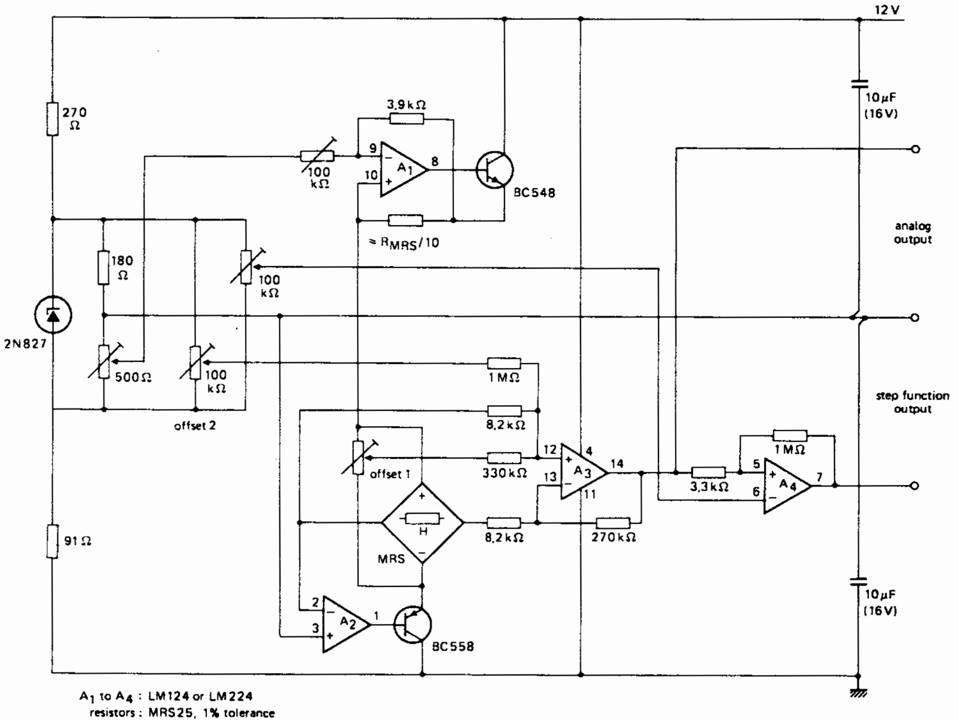


Fig.5 Simple drive circuitry for the MRS incorporating common-mode suppression and temperature-compensation



A1 to A4 : LM124 or LM224
resistors : MRS25, 1% tolerance
potentiometers : Cermet trimpot, 19 mm, type 8035

Fig.6 MRS drive circuitry designed to operate from a single 12 V d.c. supply

Internal magnetization

In the absence of a magnetic field normal to the permalloy strips, H_0 aligns the magnetization with the strip axis. If, for any reason, the sensor should come under the influence of a powerful magnetic field opposing H_0, the magnetization may flip 180° and the strips become magnetized in the opposite direction. This leads to drastic changes in sensor characteristics. As a precaution, therefore, the sensor should be provided with a stabilizing magnetic field parallel to H_0. Note, however, that the stabilizing field reduces sensitivity slightly, but since it need not to be too strong, the effect is minimal.

This field should not be confused with the linearising field H_{bias} referred to above, which is unnecessary with the MRS owing to the barberpole configuration, and which in any case, is applied perpendicular to H_0.

Practical applications

Linear position sensor. The MRS is ideally suited for use as a linear position sensor. Fig.7 shows a simple set-up for measuring linear displacement. Here a Ferroxdure disc magnet (magnetized axially) is located with its axis approximately normal to the plane of the sensor. The axis is inclined slightly to the normal to provide the sensor with the necessary stabilizing field. As Fig.8 shows, this set-up is highly sensitive to axial displacement of the magnet.

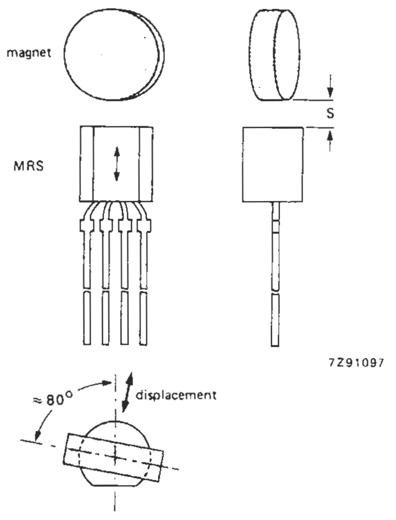


Fig.7 A highly sensitive position sensor using the MRS. A Ferroxdure disc magnet located with its axis approximately normal to the plane of the sensor chip, will, when moved axially, produce relatively large variations in the magnetic field passing through the sensor. The magnet axis is inclined slightly to the normal to provide the sensor with the necessary stabilizing field

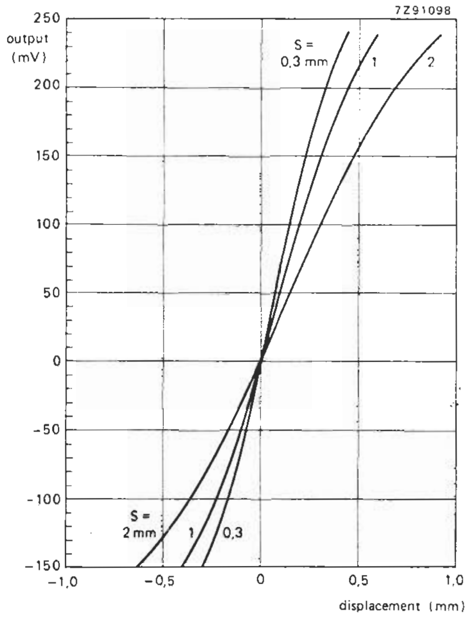


Fig.8 Sensor output versus magnet displacement for the set-up of Fig.7

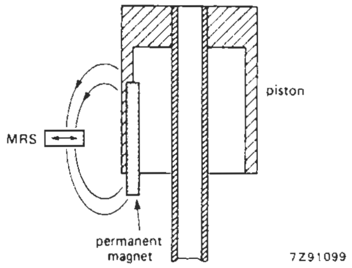


Fig.9 *The MRS monitoring* the axial position of a piston. The double-headed arrow indicates the sensitive direction of the MRS. A permanent magnet embedded in the piston body produces a field through the MRS whose vertical component forms the stabilizing field, and whose horizontal component varies with piston displacement

Fig.9 shows an example in which the MRS is used to monitor the axial position of a piston. A permanent magnet is embedded in the body of the piston, and the sensor is located off axis between its poles. The sensitive direction of the MRS (the direction in which it is sensitive to magnetic field variations) is indicated in Fig.9 by the arrows.

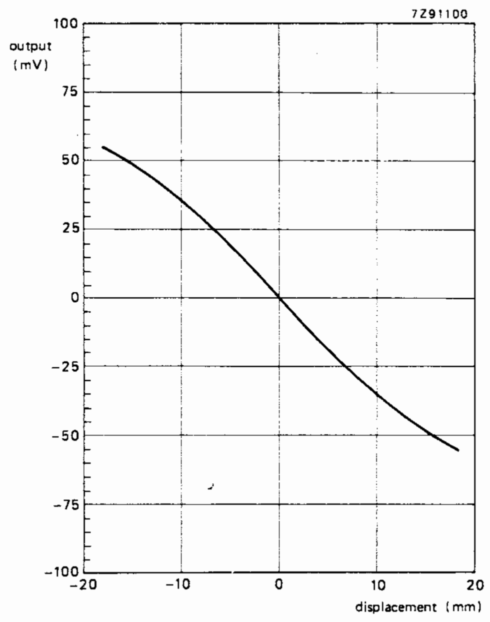


Fig.10 MRS output versus piston displacement

In this set-up, as in the one shown in Fig.7, both the stabilizing field and the varying field are produced by the same magnet. The vertical field passing through the MRS varies only slightly over the axial travel of the magnet and can be regarded as a constant stabilizing field. As the piston and magnet move axially, variations in the horizontal off-axis field are detected by the sensor, which produces a d.c. signal (Fig.10) proportional to piston displacement.

Angular position sensor. Fig.11(a) shows an experimental set-up in which the MRS is used to detect the angular position of a toothed iron wheel. The set-up could find application in, for example, electronic ignition systems. The sensor is located between a rotating iron wheel and a permanent magnet oriented with its magnetic axis parallel to the axis of the wheel. To provide the biasing field, the magnet centre is displaced slightly relative to the MRS.

Figure 12 shows the time varying output from the sensor, for sensor/wheel spacings S of 0,1 mm, 0,4 mm and 0,8 mm. The output is approximately sinusoidal with an amplitude strongly influenced by the spacing S. However, the interesting point emerging from Fig.12 is that the crossover point of the sinusoid is independent of S, and could therefore be used as the trigger point in an electronic ignition system.

Figure 11(b) shows a variation on the set-up of Fig.11(a) in which a non-metallic wheel bearing a steel tab rotates beneath an MRS. This set-up produces a similar output to that of Fig.11, again with the crossover point independent of sensor/wheel spacing.

The obvious advantage of both these set-ups lies in the fact that precise location of the sensor/magnet combination is unimportant as far as ignition timing is concerned, so adjustment procedures in a practical device would be greatly simplified.

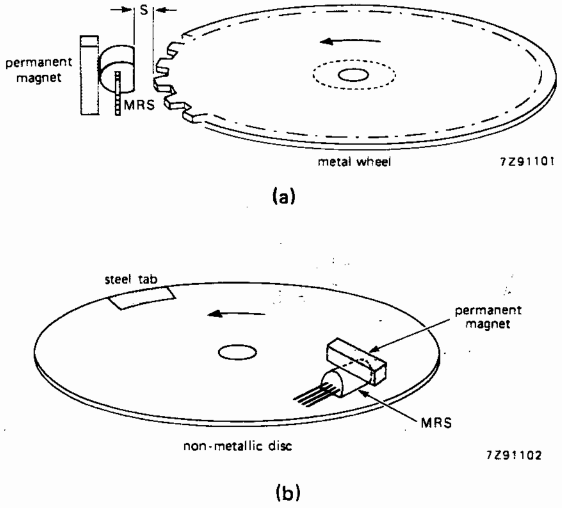


Fig.11 An MRS monitoring the angular position of (a) a rotating toothed iron wheel and (b) a rotating non-metallic wheel bearing a steel tab. Both these set-ups may find important applications in electronic ignition systems

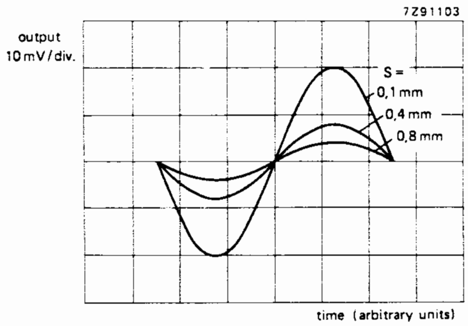


Fig.12 Time varying output of the MRS for the set-up of Fig.11(a), for different values of sensor/wheel spacing S. The output is approximately sinusoidal with an amplitude strongly influenced by S, but with a crossover point independent of S

These examples serve only to illustrate the many roles the MRS can fill. Other uses will become apparent as the device becomes more readily available. It's already quite possible to produce devices sufficiently sensitive to detect variations in the Earth's magnetic field. Such devices could be used to monitor traffic flow for example. Or they could be used to monitor electric current in, say, car-headlight circuitry, and to trigger a warning signal if the lights should fail.