Fluxgate Magnetometer Explained – Mar. 2006

Ken Evans MEng CEng MIEE *Sensor Specialist,* *INVASENS*

What is a Fluxgate ?

The fluxgate magnetometer is a magnetic field sensor for vector magnetic field. Its normal range is suitable for measuring earth's field and it is capable of resolving well below one 10,000th of that. It has traditionally been used for navigation and compass work as well as metal detection and prospecting. Not difficult to construct it is often forgotten in today's world of silicon and MEMS sensing devices.

History

Fluxgate magnetometer designs fall into broadly two styles, those employing rod cores and those using ring cores. The rod cores were the first to be developed from about 1930 onwards, and the more convenient twin core design within this category is also split into two styles; the Forster[i] and Vaquier[ii] based. The latter is the earliest design but continues to find favour in modern designs using the latest materials and electronics, as does the Forster variant. The ring core models although appearing in the 1930s[iii] were not really developed until 1962[iv] on, when they were rapidly accepted as a serious contender to the rod core. Whilst there are many alternative designs mostly based on rod cores none have reached the state of development and performance attributed to those mentioned above. For this reason this document is intended to apply only to the twin rod and ring core fluxgate variants.

General mode of operation

All fluxgates use a highly permeable core which serves to concentrate the magnetic field to be measured. The core is magnetically saturated alternatively in opposing directions along any suitable axis, normally by means of an excitation coil driven by a sine or square waveform. Prior to saturation the ambient field is channelled through the core producing a high flux due to its high permeability. At the point of saturation the core permeability falls away to that of vacuum causing the flux to collapse. During the next half cycle of the excitation waveform the core recovers from saturation, and the flux due to the ambient field is once again at a high level until the core saturates in the opposite direction; the cycle then repeats. Despite the magnetisation reversals due to the excitation, the flux from the ambient field operates in the same direction throughout. A sense coil placed around the core will pick up these flux changes, the sign of the induced voltage indicating flux collapse or recovery. The name fluxgate clearly derives from the action of the core gating flux in and out of the sense coil. This process is shown in figure 1 as idealised waveforms, and it can clearly be seen that the sense voltage is twice the frequency of the excitation. Demodulation schemes often employ 2nd harmonic detection for this reason. In practice for a single rod shaped core the sense coil will pick up the excitation drive as

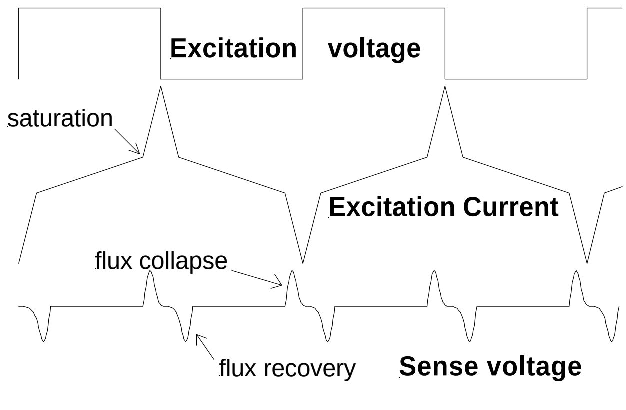

Figure 1 Ideal fluxgate waveforms

195 Prestbury Road, Cheltenham, GL52 3ES
Phone/fax 0870-3219321, e-mail *kenevans@invasens.co.uk*

well as the signal voltage, which due to its high level can prove troublesome to remove electronically. A common solution for this is to use two parallel cores with the excitation phase reversed from one to the other. The sense coil picks up the signal but the induced excitation voltage is cancelled by the phase reversal, producing waveforms similar to those in figure 1.

As described, the voltage of the flux change peaks is from Faraday's law proportional to the magnetic field; a simple sensor can be used in this way. However a superior design will employ a coil (the sense coil often doubles up for this task) to feedback a magnetic field in opposition to the sensed field such that the two fields cancel one another. In this mode of operation, where the fluxgate is used as a null detector, the current in the feedback coil is proportional to the sensed field.. The technique improves linearity of measurement, allows a much greater dynamic range to be achieved and is used by the majority of modern devices.

Rod Core design

The two common types of twin rod core design are shown in figure 2, with the Forster based one on the left and the Vacquier on the right. These designs closely follow the design principles discussed above with differences only in the sense coil configuration. The separate sense coils on the Forster design are phased such that they cancel the excitation whilst combining the signal voltages. It is possible to build a fluxgate based on the Forster using a common set of coils for excitation and sensing.

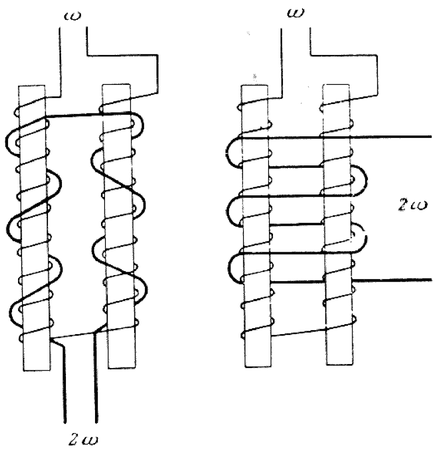

Figure 2 Rod Core Fluxgates

Core material for the rod was traditionally high mu mu-metal wire. The rod is typically 20mm in length but can vary from 15 – 75mm.

These designs are good for directional sensitivity with the anisotropy of the core defining the sense direction, and are universally favoured by the geomagnetic community for their long term stability. This can be better than 3nT per year.

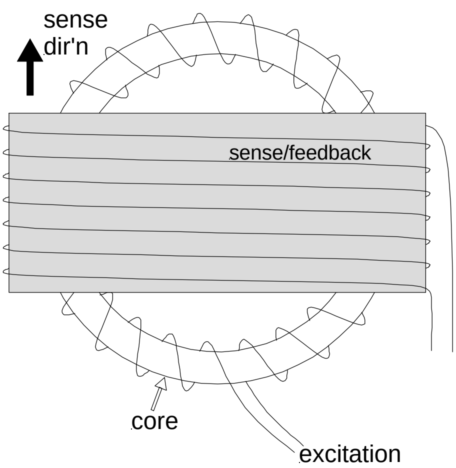

Figure 3 Ring core fluxgate

Ring Core design

The ring core is really a logical extension of the twin rod core where the rods are connected top and bottom and a continuous magnetic circuit is formed. These normally use a toroidal excitation winding spread evenly around the ring core, with a sense winding around the outside and orthogonal to the plane of the core, equivalent to the Vaquier rod core design. The axis of the sense/feedback winding defines the sensitive direction of the sensor, since the core is isotropic. It is feasible to put two sets of sense coils over the toroid at right angles to one another and create a two axis (XY) sensor. These coils are short to avoid cross coupling effects. For a single axis device it is common to extend the sense/feedback winding to completely cover the core and

195 Prestbury Road, Cheltenham, GL52 3ES
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provide an improved feedback field geometry. It is also common to use larger separate external feedback coils with improved field gradients, indeed a complete tri-axis system can be built in this way with two rings. With this type of sensor the central field is completely cancelled along all axes by the feedback action.

The ring can be a simple ferrite or tape wound core intended for more mundane electronic applications, but the best results are obtained by custom winding the core using permalloy or amorphous metal tapes. Designs similar to figure 3 are used on modern satellite missions for mapping the magnetosphere and deep space applications. They possibly have the advantages of lower noise and less power needs than rod core devices.

Gradiometers

Field gradient measurement fluxgates or gradiometers can be designed to measure axial or transverse magnetic field gradients. They are usually based on two conventional fluxgates separated by a certain distance, the baseline, on a rigid boom or tube. The difference in output between the fluxgates over the baseline is a measure of the field gradient.

Any type of fluxgate can be used, but if a twin axis ring core is used both axial and transverse gradients can be measured by selecting the desired outputs and differencing them. A rod core device based on the Forster design has the advantage that the two core halves and their respective coil assemblies can be physically separated whilst remaining operational. If the excitation and sense coil phases are reversed to one core[1] the device will now measure the magnetic field difference between the cores. In this mode the feedback current does not null the "average" field but rather equalises the fields seen at each core. All that remains is to place the core assemblies along an appropriate baseline and the device becomes a true gradiometer, which can be configured to measure axially or transversely. The electronic operation of these sensors is generally the same as normal fluxgates. This class of fluxgate gradiometer will not react to normal Earth's field in a clean magnetic environment but only gradients in the field produced by magnetic anomalies.

Fluxgate performance

The table below attempts to draw comparison between the various types of state of the art 2nd harmonic "twin core" fluxgates discussed in this document. Where possible like is compared with like. For example similar size cores are compared for noise since it reduces as the size increases, and the core material is amorphous metal with the exception of the Ferrite ring. It is however still difficult to compare different sensor types because of variations in electronics employed.

Stability of rod cores is regarded by the Geomagnetic community, who have much experience in the use of fluxgates, as superior to that of ring cores. However modern space missions without exception use ring cores, which although admittedly lower power, still require exceptional performance generally. Indeed Ripka[v] suggests that offset stability is probably worse for rod cores. So it would appear that the more stable device is unproven at the present time.

When compared to an advanced ring core or racetrack design, a well performing rod core fluxgate or a commercial ferrite core device is relatively easy to construct; although the latter will have the poorer performance.

[1] A phase reversal is the equivalent of turning the core/coil through 180° with the wiring unaltered.

195 Prestbury Road, Cheltenham, GL52 3ES
Phone/fax 0870-3219321, e-mail kenevans@invasens.co.uk

	Rod Core	Ring Core	Racetrack	Ferrite ring (commercial)
Noise/resolution	46pT rms	15pT rms	~15pT rms	~10, 000pT
Stability	***	**		
Linearity	10ppm	10ppm	10ppm	
Ease of manufacture	***	**	*	***
Power needs	High	Low	Moderate	Moderate
Feedthrough	***	**	*	**
Crossfield	***	*	***	*
Perming	*	***	**	

In theory the racetrack sensor should be the ultimate device with all the best points of the other two designs however it has little published data to corroborate the theory. On balance the ring core device is probably the higher performing of the three amorphous metal cored fluxgates, with excellent noise, resolution and low power requirements. Stability is arguably the equal of any design with crossfield effects remaining a possible Achilles heel.

General electronics requirements

Good results for excitation of the core can be obtained with a square wave and this is certainly easier to generate than a sine, so is to be recommended. Digital generation of square wave excitation together with a 2f reference frequency is conveniently accomplished by means of a microcontroller or a few discrete logic devices. To ensure good low noise the core material should be driven well into saturation by 10 to 100 times its saturation field. Operational frequencies for typical fluxgates lie between 1 and 10kHz, with the ring cores more towards the top end. Transformer drive is often employed although easier capacitive drive can also be used, providing low leakage capacitors are chosen to avoid spurious and variable offsets. The voltage drive to the fluxgate together with the excitation coil inductance, determine the current ramp rate in the coil, and therefore the maximum frequency attainable. See figure 1 above. The drive voltage should therefore be chosen to suit the frequency desired, with attention paid to the saturation point of the core within the cycle. In this context one advantage of using a microcontroller to generate the waveforms is the ability to easily adjust the phase shift between the f and 2f outputs for better control of the demodulation.

The sense winding is normally fed into a preamp with mild tuning at the 2nd harmonic of excitation frequency. In practice this can cause problems because of pulse stretching of the voltage spikes passing through, and a broader band amplifier with a reasonably high slew rate can help avoid this.

Demodulation is usually accomplished with a phase sensitive detector, typically a CMOS analogue switch, following the preamp. It is important to chose a switch with low charge injection to avoid further offset problems. The switch drives an op-amp integrator, which needs to be a low offset, low temperature coefficient device. The integrator time constant is chosen as a compromise between response time and noise performance.

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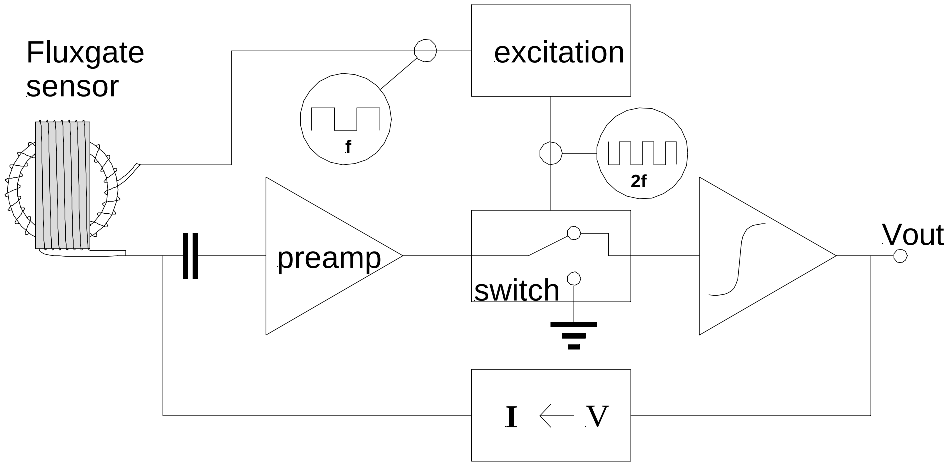

Figure 4 Classic 2nd harmonic demodulator scheme

The feedback voltage to current converter can be as simple as a resistor, or an active device such as a transconductance amplifier can be employed. When a resistor be used, its temperature coefficient will be added directly to the magnetic field measurement, so care needs to be taken here. In addition should the voltage from the integrator be taken as the field output, the proportion of voltage across the feedback coil will be subject to the large temperature coefficient of copper. This can be taken out in software or by the use of additional analogue circuitry. Where a microprocessor is available the former solution is preferable, providing a more accurate result and less interference to the low level sense signal from the fluxgate.

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[i] Forster, "A method for the measurement of DC fields and DC field differences and its application to nondestructive testing," Nondestruct. Test., vol.13, pp. 31—41, Sept.-Oct. 1955
[ii] Vacquier, et al, "A magnetic airborne detector employing magnetically controlled gyroscopic stabilization," Rev. &i. Instrurn., vol. 18pp. 483-487,1947
[iii] Aschenbrenner, H. and 0. Goubau, "Eine Anordnung Registrieung rascher magnetischer Storungen", Hochfreg Tech. Elektroakust. 47, pp 178-181, 1936
[iv] Geyger, W. A., "The Ring Core Magnetometer - A New Type of Second-Harmonic Flux-Gate", AIEE Trans. Communications and Electronics, 81, pp65-73, 1962
[v] Ripka: "New Directions in Fluxgate Sensors", JMMM (2000) 215-216 (2000), 735-739

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