Excitation efficiency of fluxgate sensors

Pavel Ripka a, *, William G. Hurley b

a Czech Technical University, Faculty of Electrical Engineering, Department of Measurement, Technicka 2, 16627 Praha 6, Czech Republic
b National University of Ireland, Galway, Ireland

Received 4 July 2004; received in revised form 21 March 2005; accepted 19 September 2005
Available online 18 January 2006

Abstract
Among ferromagnetic sensors, fluxgates are the most resistant to field shocks. In order to achieve low perming, the peak amplitude of the fluxgate excitation current must be high. The fluxgate excitation efficiency (I_{pp}/I_{rms}) can be increased by judicious tuning. This paper describes a simplified analytical solution for the non-linear fluxgate excitation circuit which is very different to the solution for a free-running tank circuit. The experimental results show a surprising effect: high excitation efficiency is achieved only at certain frequencies.

© 2005 Elsevier B.V. All rights reserved.
Keywords: Fluxgate; Magnetic sensors; Tuning; Low-power sensors; Magnetometer

1. Introduction
Every magnetic sensor containing ferromagnetic material has remanence, causing “perming error” [1].

AMR sensors use “flipping” field pulses to restore their magnetisation. It is difficult to reduce the perming of AMR below 10 nT for 5 mT shock. The required flipping power is about 10 mW for a 1 kHz flipping frequency [2]. The total power consumption of a high-precision analog AMR magnetometer is about 30 mW, a level comparable to low-power fluxgate sensors (typically consuming 50–100 mW), which are physically bigger, but have lower perming.

GMI sensors use AC measuring current, but this current cannot demagnetize the sensor core, because it is too small to achieve saturation and the amplitude of the associated magnetic field is zero in the middle of the core cross-section. The typical perming error is about 100 nT. The sensor can be demagnetised using a solenoid, but the circuitry is rather complex. Another possibility is to switch between two remanent states. The resulting system is similar to a fluxgate.

Hall and GMR sensors with flux concentrators usually have no demagnetisation coil. However, if the concentrators are made of low-remanence material and they have a suitable geometry, the resulting error is smaller than 1 µT (sometimes 100 nT), so that it is masked by the temperature offset drift and hysteresis of the sensor itself (for the GMR) [3].

Fluxgate sensors use a high excitation current to achieve low perming (<1 nT) and low noise. The required peak value of the excitation field should be typically 10-times to 100-times higher than the technical saturation value. A properly designed resonant excitation circuit can supply large current peaks using low power. Such a “ferroresonant circuit” was first described by Berkman [4]. Later the stability of the ferroresonant circuit was analyzed in [5] and performance of sensors working in this mode was reviewed in [6]. Parallel resonant excitation from a current source is commonly used (Fig. 1(a and b)) [7], but it is also possible to use a series resonance circuit powered by a voltage source (Fig. 1(c)) [8]. The shape of the resonance current peak is practically independent of the voltage waveform. The main advantage of the series resonant circuit is that it can be excited by switching a low voltage source—this is important especially for 3-axis sensors, which are excited in series. Excitation power of a typical untuned fluxgate sensor is 300–500 mW and it can be reduced by a factor of 5–10. Perming is a particularly serious problem in micro-fluxgate sensors incorporating flat coils, which cannot be effectively tuned.

The fluxgate tuned excitation circuit is highly non-linear, as the sensor core is saturated for a large part of the excitation cycle. Nielsen et al. [9] used numerical iteration to solve the
equations of the tank circuit, with losses, fed by a sinewave current source. The authors have shown that it is possible to find an effectively simplified analytical solution. The simplified analysis of the non-linear tank circuit in fluxgate excitation may be summarized as follows: in Fig. 2 the capacitor $C$ is charged from the current source and the excitation current increases slowly due to the presence of the large unsaturated inductance. At the onset of saturation in the sensor core the reactance of the excitation coil falls causing the capacitor to discharge, resulting in a large current peak. The magnetic field energy of the saturated inductance (which is now effectively an air coil) is then returned to the capacitor. A more detailed explanation is offered in the next section.

2. Simplified solution

The core of a high-performance fluxgate sensor is usually annealed so that it has a linear characteristic (constant permeability) up to the point of saturation. Thus, it may be stated that the excitation coil inductance $L$ in Fig. 2 has two values: a high value of $L_N$ in the non-saturated state, corresponding to a low resonance frequency $\omega_N = 1/\sqrt{L_NC}$, and a low value of inductance $L_S$ in saturation (air inductance), corresponding to a high resonance frequency $\omega_S$.

For the purposes of the analysis, we divide one half of the excitation cycle $T = 2\pi/\omega$ into the three time intervals shown in Fig. 3:

Interval 1: $0 - t_1$
In the first interval $(0, t_1)$ the core is not saturated and the current increases from zero up to the saturation current $I_S$.

The capacitor current may be approximated to a sinewave given by

$$I_{c} = I_0 \sin(\omega t).$$

The solution for the inductor current is then (ignoring the sign):

$$I_{Ln} = I_0 \frac{\omega}{L_N} \sin(\omega t) = I_0 \left( \frac{\omega}{\omega_N} \right)^2 \sin(\omega t).$$
where $\omega_N = 1/\sqrt{L_N C}$ is a natural resonance frequency of the loss-less parallel circuit with an unsaturated inductor (in our case, $\omega \gg \omega_N$). $I_0$ is the generator current amplitude $\omega = 2\pi f$ and is the generator frequency.

Interval 2: $t_1$–$t_2$

In the second time interval ($t_1$, $t_2$) the core is saturated.

The excitation current rises to its maximum value $I_M$ and decreases back to $I_S$ at $t_2$.

We can solve the circuit as a free-running tank.

If we neglect the ohmic resistance, the solution for the excitation current is

$$I_S = A_S \sin \omega_s(t - t_1) + I_S$$

where $\omega_s = 1/\sqrt{L_S C}$ is a natural frequency for the tank circuit with the saturated sensor inductor and the saturation current $I_S$ is the value of the inductor current at $t_1$ (onset of saturation), given by

$$I_S = \frac{I_0}{\omega^2 L_N C} \sin \omega t_1 = \frac{\omega_N}{\omega} I_0 \sin \omega t_1$$

Interval 3: $t_2$–$T/2$

In the third interval ($t_2$, $T/2$) the core reverts to its unsaturated state and equations for interval 1 apply.

The circuit equations were solved separately for both modes in three time intervals, taking the boundary conditions into account, i.e. continuity of excitation current and capacitor voltage [7]. The resonant condition is

$$I_S I_0 \omega^2 L_N C = 1$$

This simplified solution adequately describes the observed behavior of tuned fluxgates: the resonance condition depends not only on $C$ and $\omega$, but also on generator amplitude $I_0$. A decrease in the number of excitation turns $n$ should be compensated by a proportional increase in $C$, because $L_N \sim n^2$ and $I_S \sim 1/n$.

Supposing that $I_M > I_S$, the maximum excitation current is given by

$$I_M = \left( \frac{I_S L_S}{L_N} \right)^{1/2}$$

Thus, if the resonance condition is met, $I_M$ does not depend on $C$. The figure of merit for deep saturation is $I_M/I_S$, which does not depend on $n$. To increase this factor we need magnetic material with low saturation induction and high permeability, which gives a high value of $L_N$. We also should keep the excitation winding close to the core, to achieve low $L_S$—this is similar to the requirements for a pick-up coil of a current-output fluxgate [10]. The ratio of inductances may be shown to be

$$\frac{L_N}{L_S} = \frac{1 + \mu_A A_{core}}{A_{air}}$$

3. The measurements

Validation measurements were performed on 30 mm long race-track fluxgate field sensors. The sensor core is made of four sheets etched from 40-mm-thick amorphous Vitrovac 8116. The core is 30 mm long and 8 mm wide, the track width is 1.5 mm [11]. The excitation current amplitude sufficient to reduce the perming effect of this sensor below 1 nT was 600 mA p-p. Fig. 4 shows the measured current waveforms: the tuned excitation current $I_M$ is 750 mA p-p with rms level of 120 mA. The current peaks are delivered by the parallel tuning capacitor $C = 1.1 \mu F$ so that the total current supplied from the generator is only 30 mA rms (middle trace). The measured waveform agrees well with the model shown in Fig. 3. The saturation current can be estimated from Fig. 5 at $I_S = 3.5$ mA. Thus, $I_M$ in this case is very high.
It was deduced from (3) that the sensor was always tuned by $f = \frac{r}{2\pi L_N}$ for minimum power.

Table 1. Excitation power vs. frequency for 1 A p-p current

<table>
<thead>
<tr>
<th>$f$ (kHz)</th>
<th>$P_{\text{pp}}$ (V p-p)</th>
<th>$C_{\text{p-p}}$ (pF)</th>
<th>$A$ (µA)</th>
<th>$P$ (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>19</td>
<td>6.7</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>15.4</td>
<td>2</td>
<td>1.78</td>
<td>17.8</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>1</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>0.2</td>
<td>0.85</td>
<td>25.5</td>
</tr>
<tr>
<td>45</td>
<td>17</td>
<td>0.07</td>
<td>0.56</td>
<td>25.2</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
<td>0.05</td>
<td>0.25</td>
<td>15</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>0.05</td>
<td>0.31</td>
<td>31</td>
</tr>
</tbody>
</table>

The sensor was always tuned by $C$ for minimum power.

$, L_q = 100L_f$ and we can calculate from (1) and (2) that $L_q = 1.1$ µH and $L_N = 1.28$ mH. This corresponds to the measured values and it was deduced from (3) that $f = 13000$.

The complex behavior of the excitation tank circuit is caused by its substantial non-linearity. In our case, the largest current amplitude achievable with a 20 V p-p output voltage generator (having 50 Ω output resistance) was 1.6 A p-p at 45 kHz, while for 5 kHz it was only 1 A. High current amplitudes at high frequency mean increased power consumption—this is true for each fixed frequency. Fig. 6 shows the excitation power versus current amplitude for frequencies between 15 and 100 kHz.

Excitation current of 1 A p-p was finally selected as it guarantees high sensor stability at reasonable power consumption. Table 1 shows the excitation parameters achieved for this current at various frequencies. $A$ is the energy required for one excitation cycle, while $P$ is the excitation power. The favourable working frequency is around 15 kHz, where the excitation power consumption has a local minimum of 15 mW. Another power minimum appears at 60 kHz.

4. Conclusions

Fluxgate sensors have the lowest perming error of all ferromagnetic sensors. It has been shown that their excitation efficiency can be increased by proper tuning—1 nT perming for 5 mT field shock can be achieved at 50 mW power consumption. The simplified model of the fluxgate excitation circuit explains the observed properties of the non-linear circuit near the favourable operating point. The model provides guidelines for sensor designers. Experimental work shows that the power consumption is not monotonically increasing with frequency: local minima appear, which illustrate that simple design rules based on linear analysis cannot be used. The given analysis is based on sinewave current excitation; the case of squarewave current or voltage excitation is quite different and was analyzed in [8].

References


Biographies

Pavel Ripka received an Engineering degree in 1984, a CSc. (equivalent to PhD) in 1989. Docent degree in 1996 and in 2002 Professor degree at the Czech Technical University, Prague, Czech Republic. During 1991–1993, he was a visiting researcher at the Danish Technical University and during 2001 he held Marie Curie Experienced Researcher’s Fellowship at the National University of Ireland, Galway. He works at the Department of Measurement, Faculty of Electrical Engineering, Czech Technical University as a professor, lecturing in Measurements, Engineering Magnetism and Sensors. His main research interests are Magnetic Measurements and Magnetic Sensors, especially Fluxgate. He is a member of IEEE, Elektra society, Czech Metrological Society, Czech National IMEKO Committee, Eurosensors Steering Committee and Associated Editor of the IEEE Sensors Journal. He was a General Chairman of the Eurosensors XVI conference held in Prague in 2002.
William Gerard Hurley (M’77, SM’90) was born in Cork, Ireland. He received the BE degree with 1st class honors in Electrical Engineering from the National University of Ireland, Cork in 1974. The MS degree in Electrical Engineering from the Massachusetts Institute of Technology, Cambridge MA, in 1976 and the PhD degree at the National University of Ireland, Galway in 1988. He worked for Honeywell Controls in Canada as a Product Engineer from 1977 to 1979. He worked as a Development Engineer in transmission lines at Ontario Hydro from 1979 to 1983. He lectured in electronic engineering at the University of Limerick, Ireland from 1983 to 1991 and is currently Vice President and Professor of Electrical Engineering at the National University of Ireland, Galway. He was a visiting professor at the Massachusetts Institute of Technology in 1997/1998. He is the Director of the Power Electronics Research Center in Galway. Research interests include high frequency magnetics, power quality, automotive electronics and alternative energy systems. He received a Best Paper Prize for the IEEE Transactions on Power Electronics in 2000. Prof. Hurley is a Fellow of the Institution of Engineers of Ireland and a member of Sigma Xi. He has served as a member of the Administrative Committee of the Power Electronics Society of the IEEE and was General Chair of the Power Electronics Specialists Conference in 2000.