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Using induction coil sensor optimization techniques for designing compact geophysical transmitters

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SUMMARY

We have developed and tested code to optimise electromagnetic (EM) sensors to improve performance of the ARMIT B field induction coil sensor at desired frequencies. We aim to use the optimised parameters to develop a compact air core transmitter, which will form the basis for developing a compact ferromagnetic core transmitter. Techniques for optimising induction coil sensors are well established in literature and use analytical equations for the objective and constraint functions. Alternatives for EM sensor design are also well documented. In contrast, the design of compact transmitter systems needed for portability or in boreholes have limited discussion in the literature and have many more design constraints than sensors. Our ultimate intention is to use established sensor optimisation techniques to build a compact transmitter with sufficient magnetic dipole moment.

To optimise an ARMIT induction current sensor we develop the algebraic expression for the total internal sensor noise to use as a constraint function. The objective function is the weight of the sensor. We aim to achieve noise goals of 1 $pT/\sqrt{Hz}$ and 1 $fT/\sqrt{Hz}$ frequencies of 1Hz and 2 kHz, respectively. 1 Hz was chosen because that is a common base-frequency for conductive sulphide exploration and 2 kHz was chosen as being appropriate for nuclear magnetic resonance investigations. We use numerical non-linear constraint optimization techniques to predict a target noise level of 1 pT at 1 Hz. , At this stage we predict the best 2 kHz sensor to have 4 fT noise at 2 kHz. This was based on existing dimensional and weight constraints on the induction coil sensor. We introduce an analogous method of transmitter optimisation using transmitter dipole moment as the objective function.

Key words: Electromagnetic, optimisation, sensors, transmitters, ferromagnetic core

INTRODUCTION

Constructing an induction coil sensor with a ferromagnetic core that is sensitive across a large frequency bandwidth 0.1Hz-100kHz is difficult, particularly at frequencies below 1Hz. Careful selection of a low-noise operational amplifier is needed to amplify the output signal for a desired range of frequencies. Optimisation techniques are then carried out for sensor design variables i.e. magnetic core volume, wire diameter and number of turns, in an effort to further minimise the weight and or dimensions of the sensor subject to the internal noise of the sensor circuit. The total internal noise is the root-sum-power of all noise components in the circuit. To reach the maximum sensor sensitivity for a given volume, a search coil should aim to minimise the internal noise by using formal optimisation techniques. This will reduce the time and cost of experimental trial and error.

A magnetic core with high permeability, small hysteresis, and low coercive force is ideal for receiving a time varying magnetic field signal. If such a core is used inside an air core sensor an increase of magnetic flux will result, thereby reducing sensor dimensions and weight with increased sensitivity levels (Tumanski, 2007). The same effect of increased magnetic flux can be attained if a magnetic core with the same magnetic properties as a sensor core is inserted into an air core transmitter.

Sensor type cores including Metglas and Nano-crystalline were experimentally tested by Jordan et al. (2011) and showed the power, weight and size efficiencies gained from the use of these cores as transmitters. In contrast Reiderman (2013) opted to use a core material with significant hysteresis to maintain magnetization to build a power efficient time domain borehole transmitter for petroleum reservoir monitoring.

The design of magnetic core transmitter is inherently a difficult task due to non-linear magnetic hysteresis effects and the selection of the optimum magnetic core material. Most importantly to build a useful geophysics transmitter would require maximising the magnetic dipole moment because it quantifies the ability to produce secondary magnetic field used for detection in distant, subsurface conductor targets. The optimum material for a magnetic core transmitter will possess a high magnetic field saturation because this is directly proportional to the maximum magnetic dipole moment (Jordan et al., 2009).

Current compact ("portable" by one or two field operators) transmitter systems in industry have small magnetic moments compared to large surface loops several hundred metres in diameter. However compact transmitter systems may serve in many useful applications in rapid surface investigations and inside boreholes for deep borehole electromagnetic surveys. Another possible application is for rapid static shift corrections in magnetotelluric surveys caused by inhomogeneities at the measurement electrodes (Macnae et al., 1998).

Optimisations of sensors and transmitters (inductors) in principle have similar approaches; both can utilise an air core or magnetic core. Stability issue arise from the use of magnetic cores inside sensors and even more so for magnetic core transmitters. Before attempting to optimise a magnetic core transmitter, we chose to investigate optimisation of coil sensors and compact air core transmitters. Air core transmitters have comparable portability issues but fewer constraints than a magnetic core transmitter. Calculation of impedance quantities for air core inductors is readily available Martinez et al. (2014) and simple expression for magnetic dipole moment is defined as the product of number of coil windings, current, and area.

Optimising the magnetic moment of a compact air core transmitter is not simply a task of increasing the current and number of coil windings. This option is used for large grounded loops where the constraints are flexible for example the area of the loop can vary and bulky power supplies can be used therefore compensating for the number of turns and current. But a compact transmitter has strict constraints such as dimensions, weight, power, voltage and current. A simple question to illustrate this example is to ask, what is the best combination of wire diameter and number of coil windings for a given time or frequency domain transmitter waveform? Therefore optimising a compact air core transmitter itself will lead to better understanding of the constraints. This will go a long way to build the best possible compact magnetic core transmitter.

In this work we first predict optimum parameters for the 3 component ARMIT B field sensor Macnae (2012) and Macnae and Kratzer (2013) at frequencies of 1 Hz and 2kHz. Each component of the sensor has coil windings wrapped around a ferromagnetic core and weighs around 500 grams and 0.5m in length. We then briefly discuss what is required to optimise a compact transmitter.

f	Frequency	R_f	Feedback resistance of amplifier
l_c	Length of core	SF	Scale factor V_{out}/B
d	Diameter of Tx loop	T_c	Temperature (°K)
d_c	Diameter of core	V_{in}	Input Voltage noise
dw	Diameter of coil windings	V_{out}	Output Voltage
H	Height of transmitter	W	Weight of sensor
I_{in}	Opamp current noise	Z	Impedance $R + j2\pi f L_c$
K_b	Boltzmann constant	α	Aspect ratio $l_c/d_c \approx 100$
L_c	Inductance of coil windings and core	γ	Correction factor
N	Number of windings	μ_0	Free space Permeability
P	Maximum power	ρ	Resistivity of coil
R	Resistance	τ	Time constant L_c/R

Table 1. Table of circuit parameters and symbol definition

METHOD

The mathematical model for optimisation of a system with vector design function **X** is:

Minimise

$$f(\boldsymbol{X}), [\boldsymbol{X}]_n \quad (1)$$

Subject to

$$[h(\boldsymbol{X})]_l = 0 \quad (2)$$

$$[g(\boldsymbol{X})]_m \leq 0 \quad (3)$$

$$\boldsymbol{X}^{low} \leq \boldsymbol{X} \leq \boldsymbol{X}^{up} \quad (4)$$

In words, we minimize the objective function $f(\boldsymbol{X})$, subject to l equality constraints, m inequality constraints, with n number of design variables lying between prescribed lower and upper limits. Maximisation can be recast as a minimization problem using the negative or the reciprocal of the objective function.

SENSOR OPTIMISATION

We first investigate parameters for optimum signal/noise ratio of ARMIT induction current sensor at single frequencies of 1Hz and 2 kHz. In order to apply optimisation it is necessary to use algebraic expressions coupled with circuit analysis to formulate expressions for the sensor noise. If $\alpha \geq 80$ we can use the approximate expression for the output voltage (Ripka, 2001)

$$V_{out} = \frac{R_f l_c}{2N\mu_0} B \quad (5)$$

Taking the ratio of V_{out}/B gives the sensitivity of the sensor or scale factor SF, which means we can use the output voltage from the amplifier to give a magnetic field value. The correction factor for the high pass filter of a current sensor will also have to be taken into account the expression is

$$\gamma = \frac{j2\pi f\tau}{1 + j2\pi f\tau} \quad (6)$$

The sensor has internal noise from Johnson noise V_{jon} of the induction coil, plus intrinsic voltage V_{von} and current V_{ion} input noise of the operational amplifier. The equivalent magnetic field noise output is obtained by dividing the 3 sources of noise expressed as output voltages

$$B_{jon}(f) = \frac{V_{jon}}{SF} \quad (7)$$

$$B_{von}(f) = \frac{V_{von}}{SF} \quad (8)$$

$$B_{ion}(f) = \frac{V_{ion}}{SF} \quad (9)$$

Where the output voltages are a function of the internal input voltage and current noise from the amplifier

$$V_{jon}(f) = \sqrt{4K_b T_c R}\left(1 + \frac{R_f}{Z}\right) \quad (10)$$

$$V_{von}(f) = V_{in}\left(1 + \frac{R_f}{Z}\right) \quad (11)$$

$$V_{ion}(f) = I_{in} R_f \quad (12)$$

The total magnetic field noise of the circuit is the root-sum-power of all noise components.

$$B_T = \sqrt{B_{jon}^2(f) + B_{von}^2(f) + B_{ion}^2(f)} \qquad (13)$$

Equation (13) is the constraint function and will be expressed as an equality constraint equation (2). Figure 2 shows the theoretical magnetic field noise levels Equations (7)-(9) and (13) plotted against a proprietary report of field test of sensors in Utah, USA by "Field test of noise in magnetic field sensors" by Ritchie, Kingman and Morrison (in 2011). The theoretical values were derived using the same design variables as the ARMIT sensor. The results in Figure 2 are in good agreement. However the two data points at 10 Hz and 30 Hz are in slight disagreement possibly due to unknown and hence unaccounted noise which requires further investigation. Figure 2 also shows the predicted noise threshold than can be attained for a desired frequency. Since now the theoretical noise and experimental noise are in good agreement we have confidence that our constraint function is consistent with experiment and can now be used for optimisation.

An induction coil sensor can have $[\boldsymbol{X}]_n$ design variables but for now we choose to vary the coil windings diameter (**dw**) and a number of winding turns (**N**). The design variables are vectors that cover lower and upper bounds for the wire diameter and number of turns that can feasibly be used for constructing the sensor. We minimise the objective function in this case we use the weight of the sensor and keep the aspect ratio fixed. The aim is to achieve a total internal noise level of around 1 pT for 1 Hz and 1fT for 2 kHz. The optimisation is as follows

Minimise $\quad Weight(\boldsymbol{dw}, \boldsymbol{N}) \qquad (14)$

Subject to $\quad B_T(\boldsymbol{dw}, \boldsymbol{N}) = 1pT \qquad (15)$

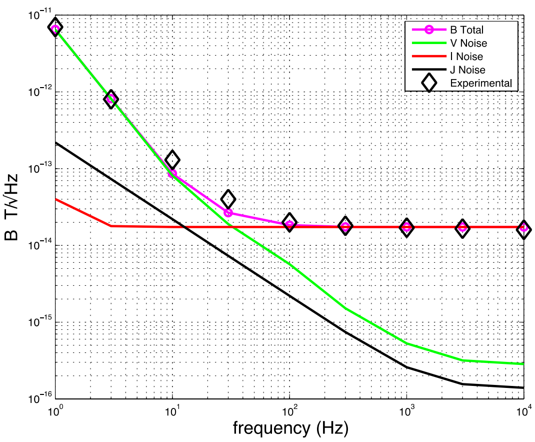

Figure 1. Theoretical noise values against experimental field test in Utah U.S.A. Theoretical value of B Total is predicted closely to field test.

Since our problem is of 2 variables (wire diameter and number of coil windings) we can make use of contour plots. This provides selection of an initial guess at the optimum solution easier by identify the point of intersection between the contour lines of the weight and total noise level. Also using the method of contour plots we can easily see if lower noise levels are possible for the given aspect ratio by simply plotting it. A contour plot of the results for 1Hz is shown in Figure 2, which illustrates an initial guess at a solution at the intersection between 0.35-0.40 kg weight contour lines (coloured). On the 1 pT noise line there are two points of intersection on 0.40kg weight line. We choose to optimise at the point with lower number of turns and larger wire diameter as shown in Figure 2. This is because construction is easier with larger wire diameter and lower number of coil windings, although this choice can result in greater offset voltages at the output. Next requires the correct choice of optimisation algorithm. In this case our objective and constraint function is nonlinear, therefore a numerical nonlinear constraint optimisation algorithm was used.

The results from nonlinear constrained optimisation are shown in Equation (16) for optimum design at 1 Hz and 2 kHz. For 2 kHz we aimed to achieve the 1fT level required for NMR measurements however this was not possible at this stage due to current ARMIT sensor i.e. max weight, length and electronic hardware. The best predicted noise floor is 4 fT at 2 kHz shown in Equation (16). 1 fT at 2 kHz is attainable if we use a longer core to increase $\alpha\ to \approx 220$.

$$@\,1\,Hz \begin{cases} \mathrm{dw} = 0.15\,\mathrm{mm} \\ \mathrm{N} = 14100\ \mathrm{turns} \\ B_T = 1\ pT/\sqrt{Hz} \\ W = 0.43\,kg \end{cases} \qquad (16)$$

$$@\,2\,kHz \begin{cases} \mathrm{dw} = 0.4\,\mathrm{mm} \\ \mathrm{N} = 153\ \mathrm{turns} \\ B_T = 4\ fT/\sqrt{Hz} \\ W = 0.35\,kg \end{cases}$$

To be certain of the above predictions, the results in Figure 2 should be further revisited to account for discrepancies from theoretical and experimental data points at 10Hz and 30Hz. Also in practice we need to investigate sensor behaviour below 1Hz to optimise over a bandwidth from say 0.1 to <1Hz. Additional constraints can be implemented to the optimisation design such as minimising offset voltages or maximising the output from the amplifier. Output amplitude can be adjusted by changing the resistance of the feedback resistor. However ensuring the voltage output close to a transmitter does not saturate the data acquisition system is vital. Small adjustments to the aspect ratio of the ferromagnetic core will increase the sensitivity of the sensor. Using commercial cores, the aspect ratio can be a strict constraint, but with some engineering, small changes could be made and the effect of these implemented in the code as an inequality constraint. Changing the aspect ratio will require core saturation considerations because the Earth's magnetic field can potentially saturate cores that are long and thin. Unavoidably our optimisation will then turn into a problem of three or more design variables, which are more challenging but can be illustrated through iso-surfaces or sequences of two-dimensional plots comparable to contours.

COMPACT TRANSMITTER

In this section we introduce the objective and constraints functions for a compact air core transmitter. For a transmitter the magnetic dipole moment defined in terms of maximum available power is

$$m = \frac{\boldsymbol{dw}^2\sqrt{\frac{\pi}{2}}\sqrt{\frac{\boldsymbol{d}^2\boldsymbol{nP}\pi\rho}{\boldsymbol{dw}^2}}}{4\rho} \quad (17)$$

The turn density $\boldsymbol{n}$ is the number of turns divided by a fixed height of the transmitter $\boldsymbol{n} = \boldsymbol{N}/H$. The weight constraint is contribution from the coil windings excluding the weight of the battery pack. The battery pack see Figure 3 weighs 7 kg and has adjustable voltage and current outputs with maximum output power of 400W to suit our optimisation problem, which is

Minimise	$-m(\boldsymbol{dw}, \boldsymbol{n}, \boldsymbol{d}, \boldsymbol{P})$	(18)
Subject to	$Weight(\boldsymbol{dw}, \boldsymbol{n}) = 5kg$	(19)
	$\boldsymbol{d} \leq 0.5m$	(20)
	$\boldsymbol{P} \leq 400W$	(21)

Figure 3. Variable 1000 kW-h LiIon battery pack with adjustable Voltage and Amperes by connection in series, parallel or a combination of both.

CONCLUSIONS

We adapted established sensor optimisation techniques to predict that very different coil winding choices were needed to minimise ARMIT sensor noise at 1 Hz and at 2 kHz. Any wide-band sensor is necessarily a compromise, as it cannot be optimum at both low and high frequency. Compact transmitter optimisation for maximum sustained dipole moment is constrained by more parameters such as power, voltage and current than sensor optimisation.

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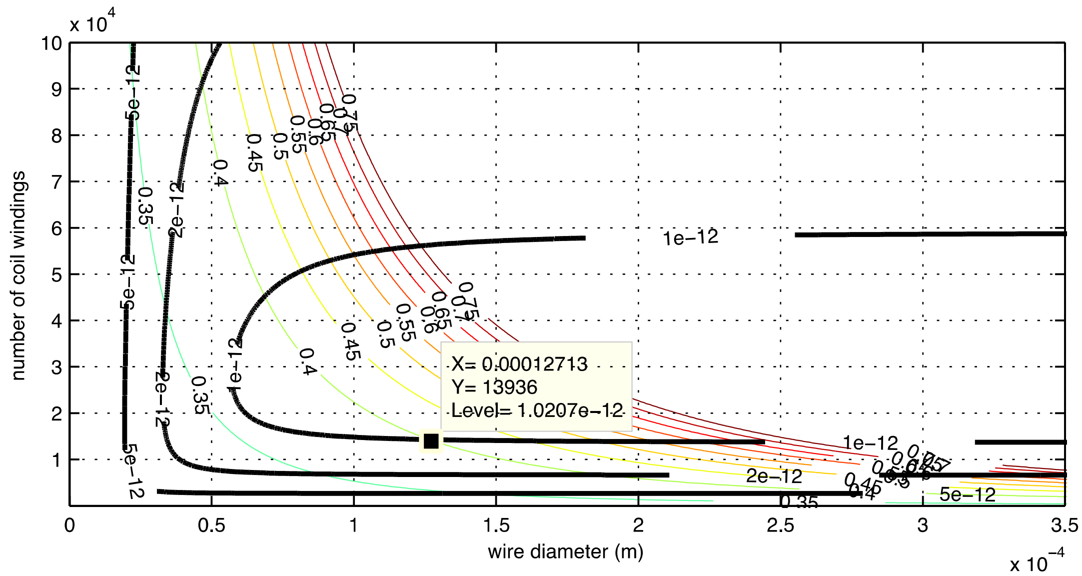

Figure 2. Contour map of the equivalent input magnetic noise level (in Teslas black) and predicted sensor mass (kg, coloured). The desired noise level of 1 pT optimised for 1 Hz by the intersection of 1pT and weight line