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Active induction balance method for metal detector sensing head utilizing transmitter-bucking and dual current source

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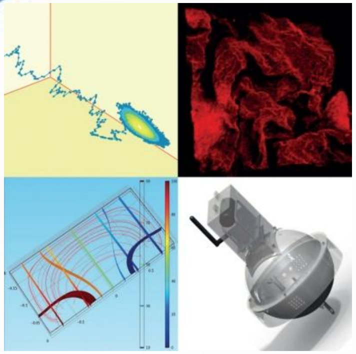


Sensors & their Applications XVII

Outline

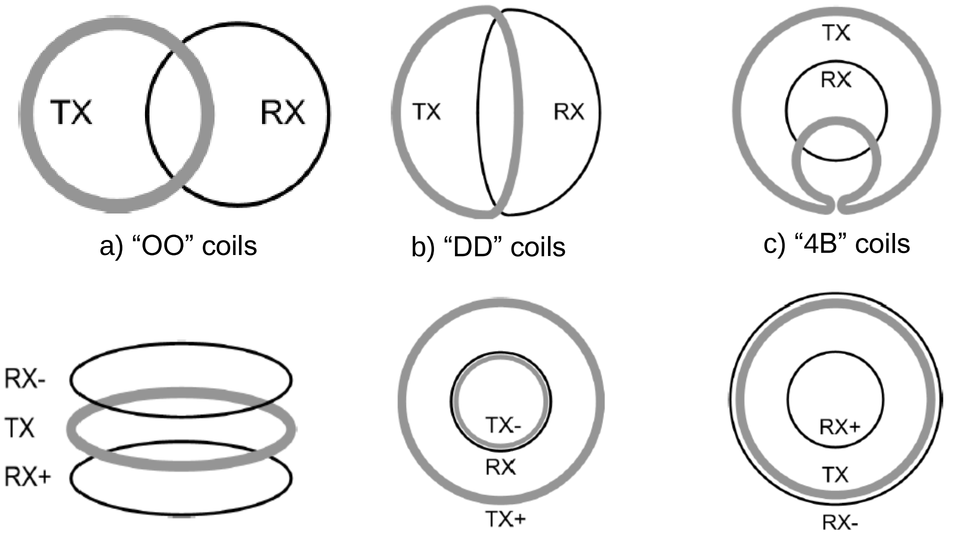
- Introduction
- Induction balance problem
- Sensing head – design and modeling
- Active induction balance technique
- Experiments and results
- Conclusions

Background and motivation

- Electromagnetic induction (EMI) sensors in humanitarian demining → still an area of active research!
- Time-domain (TD) EMI sensors:
  - Inherently balanced, but excitation spectrum limited!
- Frequency-domain (FD) EMI sensors:
  - Higher sensitivity and improved SNR,
  - Induction balance (IB) problem (i.e. direct inductive coupling between TX and RX coil) needs to be solved.

Induction balance problem

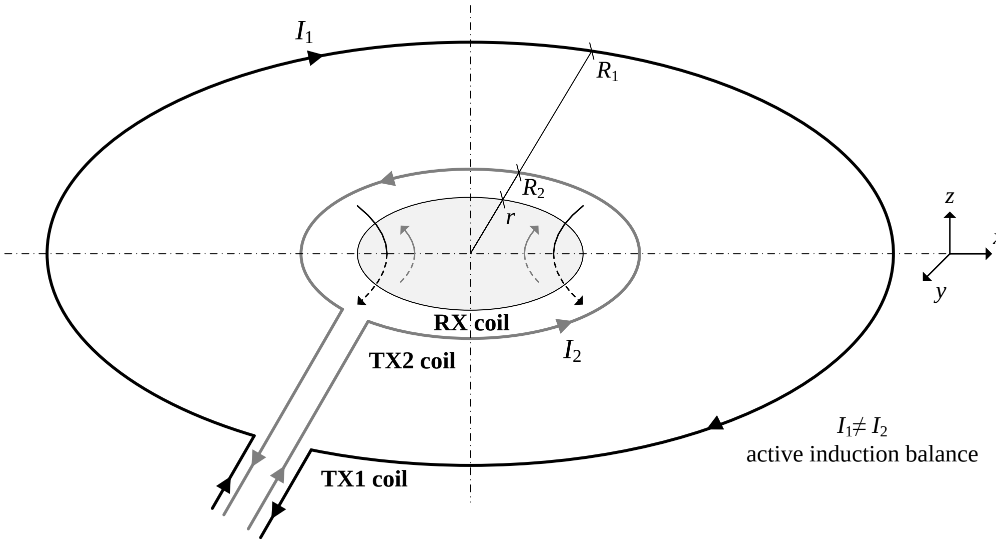
- Suppression of primary (excitation) field achieved by sensing head geometry:
  - Physical separation of coils,
  - Gradiometer configuration of RX coils,
  - Overlapping coils,
  - Orthogonal coils,
  - Transmitter-bucking,
  - …



a) "OO" coils
b) "DD" coils
c) "4B" coils
d) coaxial coils, gradiometer conf. RX
e) concentric coils, gradiometer conf. TX
f) concentric coils, gradiometer conf. RX

Sensing head - design objectives

- Ultimate objective: handheld FD EMI landmine detector featuring model-based metal characterization and soil compensation.
- Initial design requirements:
  - High sensitivity and dynamic range,
  - Simple and compact geometry,
  - High spatial resolution,
  - Pinpointing accuracy,
  - Good invertibility of measured data.



➔ **transmitter-bucking configuration**

Sensing head model

- Vertical component of magnetic field B_Z as a function of radial distance *r* from the coil centre:

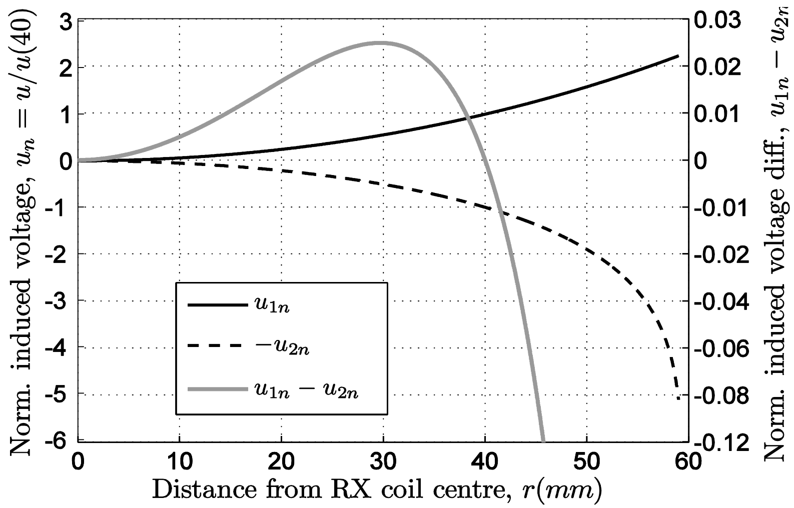
$$B_Z(r) = \frac{\mu_0 IN}{2R}\left[1 + \sum_{n=1}^{\infty}\left[\frac{(2n-1)!!}{(2n)!!}\right]^2 (2n+1)\left(\frac{r}{R}\right)^{2n}\right]$$

for $r \leq R$, inside loop (circular coil approx.)

- For a detector coil of radius *r* IB is obtained if:

$$\int_0^r B_Z^1(r)\,2\pi r dr = \int_0^r B_Z^2(r)\,2\pi r dr$$

$$\frac{N_1}{R_1}\sum_{n=0}^{\infty}\left[\frac{(2n-1)!!}{(2n)!!}\right]^2 \frac{(2n+1)}{(2n+2)}\left(\frac{r}{R_1}\right)^{2n} = \frac{N_2}{R_2}\sum_{n=0}^{\infty}\left[\frac{(2n-1)!!}{(2n)!!}\right]^2 \frac{(2n+1)}{(2n+2)}\left(\frac{r}{R_2}\right)^{2n}$$



Normalized voltages induced in RX coil in response to TX1 and TX2 coils.

Induction balance sensitivity analysis

- IB sensitivity to small perturbations of geometrical properties of coils (R_1,R_2,r) ?

$$S_x^u = \frac{\Delta u}{u_{IB}}\left(\frac{\Delta x}{x}\right)^{-1} = \left(\frac{\Delta u_1}{u_1} - \frac{\Delta u_2}{u_2}\right)\left(\frac{\Delta x}{x}\right)^{-1} = S_x^{u_1} - S_x^{u_2}$$

  - For a given geometry: $S_{R_1}^u$= -1.057, $S_{R_2}^u$ = -1.555, S_r^u = 0.498

TX1 coil radius		TX2 coil radius		RX coil radius		Induced voltage (excitation current, I=1A)		
							f=1kHz	f=100kHz
$\Delta R_1/R_1$ (%)	ΔR_1 (mm)	$\Delta R_2/R_2$ (%)	ΔR_2 (mm)	$\Delta r/r$ (%)	Δr (mm)	$\Delta u/u_{IB}$ (%)	Δu, (mV)	Δu, (V)
1	1.5	0	0.0	0	0.0	-1.057	3.1	0.310
2	3.0	0	0.0	0	0.0	-2.114	6.2	0.621
3	4.5	0	0.0	0	0.0	-3.171	9.3	0.931
0	0.0	1	0.6	0	0.0	-1.555	4.6	0.457
0	0.0	2	1.2	0	0.0	-3.110	9.1	0.913
0	0.0	3	1.8	0	0.0	-7.775	22.8	2.284
0	0.0	0	0.0	1	0.4	0.498	1.5	0.146
0	0.0	0	0.0	2	0.8	0.996	2.9	0.293
0	0.0	0	0.0	5	2.0	2.490	7.3	0.731

Active induction balance (AIB)

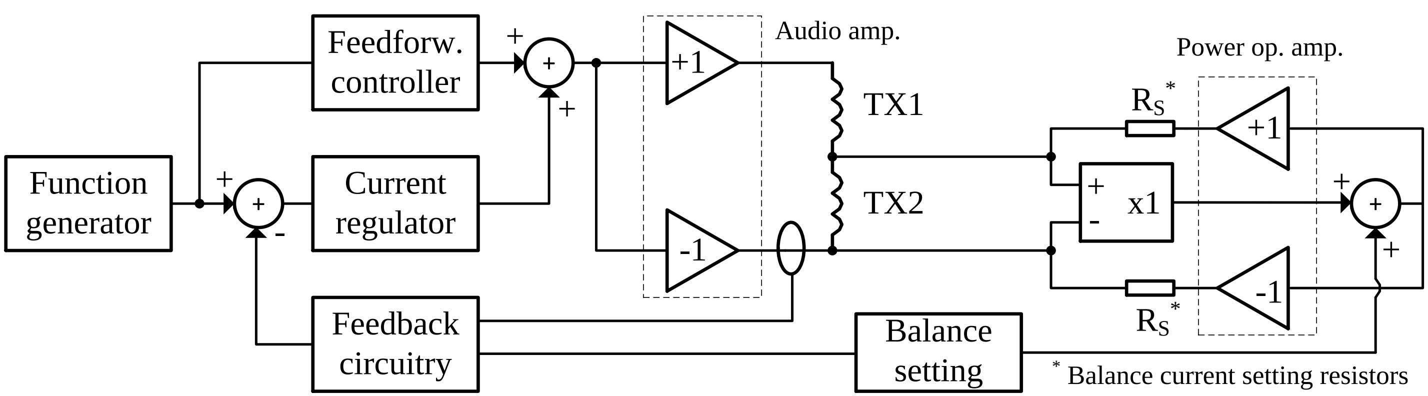
- Excitation current in each transmitter coil controlled separately:

$$\frac{I_1 N_1}{R_1}\sum_{n=0}^{\infty}\left[\frac{(2n-1)!!}{(2n)!!}\right]^2\frac{(2n+1)}{(2n+2)}\left(\frac{r}{R_1}\right)^{2n}=\frac{I_2 N_2}{R_2}\sum_{n=0}^{\infty}\left[\frac{(2n-1)!!}{(2n)!!}\right]^2\frac{(2n+1)}{(2n+2)}\left(\frac{r}{R_2}\right)^{2n}$$

- Motivation:
  - Compensation of small imperfections of sensing head geometry and the effects of finite size coils,
  - Sensing head easier to produce,
  - Potential for more efficient soil compensation (lower loss of detector sensitivity / dynamic range).

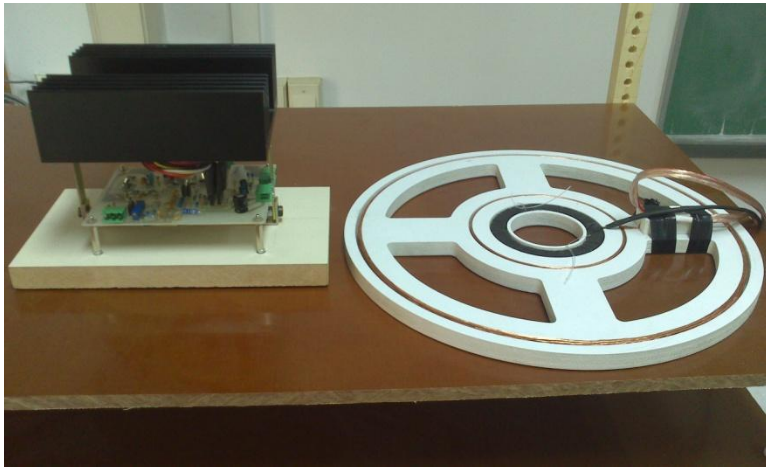
AIB implementation

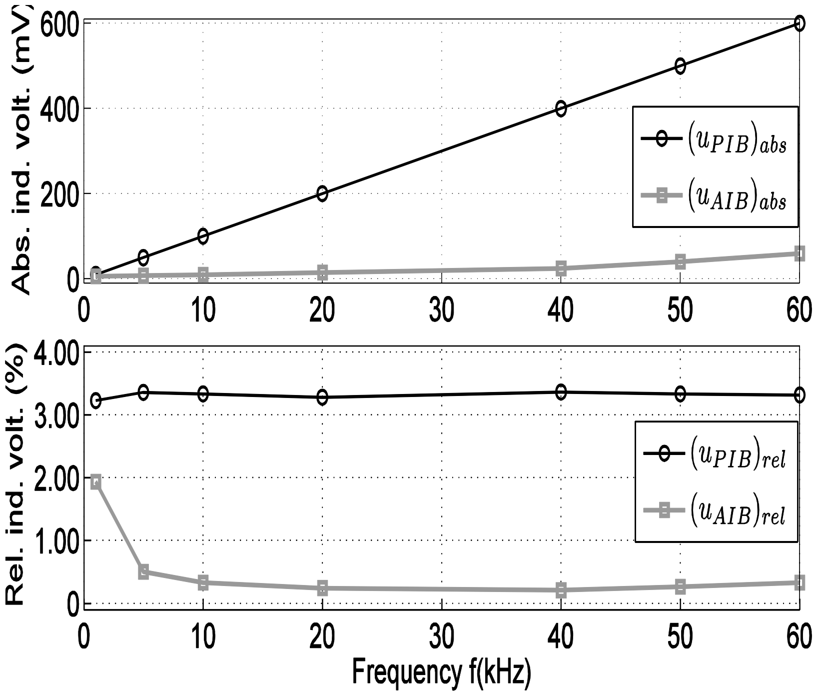
- Transmitter coil driven by current source → transmitted field unaffected by changes in coil impedance, soil properties, lift-off and orientation of the sensing head.
- Dual current source scheme:
  - Main (excitation) current source drives both TX coils,
  - Balancing current source additionally drives only inner TX coil.



Experiments and results

- Dual current source and sensing head in transmitter-bucking configuration implemented as laboratory prototypes.
- Induced voltage imbalance measured for passive IB and AIB at different frequencies (in absolute and relative terms).
- Residual imbalances from passive IB can be effectively compensated by AIB.





Conclusions

- For a design of novel, frequency-domain EMI landmine detector, we propose a sensing head configuration based on the transmitter-bucking approach.
- Overall, IB sensitivities to small perturbations of sensing head geometrical properties are rather low.
- Total sensor imbalances in absolute terms can become large, resulting in significant loss of sensitivity / dynamic range.
- Prototype sensor with AIB and dual current source overcomes the limitations of passive IB.
- Future work: further characterisation of the method, automatic compensation of soil-related imbalances.

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