

Sensor Design for an Electromagnetic Flow-Meter

S E DESA & E DESA

Instrumentation Division, National Institute of Oceanography, Dona Paula, Goa 403 004

Received 9 April 1979; revised received 18 September 1979

It is shown that in an electromagnetic flow meter the magnetic field strength, the number of turns and gauge of coil wire may be computed when the inductive and resistive effects in the coil are equal in magnitude.

1. Introduction

Several workers have published developments of electromagnetic flow-meters¹⁻³ in recent times. Aside from spar and disc shaped sensors, most instruments can be broadly classified either as single or double coil types, with excitation having the form of either ac or switched dc. It is noted from the published results that there is a wide range in coil power and sensor sensitivity. If the sensitivities are normalized to a coil power of 1W, ratios as disparate as 8.47 and 136.36 $\mu\text{V W/m}^2\text{/sec}$ are obtained—the higher efficiency figure relating to the lower dissipation. The ratios are obtained considering that the sensor sensitivity increases as the square root of coil power and the difference in the obtained ratios is traceable, therefore, to the sensor design.

Our work has been largely on double-coil ac excited sensors and we intend to show here that for this mode of excitation, several different factors like wire gauge, number of turns, radius of coil, magnitude and frequency of coil current are interactive, and when other parameters are restricted, it is possible to obtain an increase in magnetic field by a correct choice of the gauge and number of turns—accounting for both the resistive and inductive effects of the coil. More efficient coils are especially attractive for field use as well as in situations demanding long-term unattended operation.

2. Theory

Consider a coil sensor consisting of two plane parallel coaxial coils, each of radius r and separated by a distance equal to r (Helmholtz coils). By Faraday's law of induction, the voltage V_i induced in a pair of electrodes lying in a plane parallel to and midway between the coils is given by:

$$V_i = uBl \quad \dots(1)$$

where l is the distance between the electrodes and u , the flow velocity of sea-water (say) is orthogonal to

B , the magnetic flux density produced by the current flowing in the coils, and to V_i , the induced voltage.

The sensitivity V_i/u defined as the voltage induced at the electrodes per unit velocity flow is, therefore, directly dependent on B and l . Thus optimizing the flux density B , provides a method of increasing the sensitivity of the flow sensor.

The magnetic field (B) produced by two narrow Helmholtz coils carrying a current I , and each having N turns is well-known:

$$B \approx \frac{0.72}{r} \cdot \mu_0 \cdot NI \quad \dots(2)$$

In most coil sensors, N is usually large (200 to 500 turns) and it is necessary to consider inductive effects as important. A simple analysis of two series excited coils each having inductance L , and resistance R shows that the current I of frequency f lags the total applied voltage V_0 by the phase angle $\tan^{-1} (2\pi f L/R)$, and that the magnitude of the current I is⁴:

$$I = \frac{1}{2} \frac{V_0}{(4\pi^2 f^2 L^2 + R^2)^{1/2}} \quad \dots(3)$$

The value of L is obtained by substituting for the various terms in the expression $L = \phi_T/I$ where ϕ_T the total magnetic flux linkage is:

$$\phi_T = \mu_0 N^2 \pi r \cdot [(1/2) + (1/2)^{5/2}] \cdot I \quad \dots(4)$$

In Eq. (4), the first term in the square brackets is the self-inductive contribution whilst the second term is the contribution from the neighbouring coil.⁵ The expression for R is straightforward and is given by

$$R = \frac{2\pi r \rho N}{A} \quad \dots(5)$$

where ρ is the resistivity of the coil wire (namely copper), A is the cross-sectional area of the wire, and $\mu_0 = 4\pi \times 10^{-7} \text{ H.m}^{-1}$ is the permeability of

vacuum. Using Eq. (3)-(5) in Eq. (2) results in a modified expression for the flux density B

$$B = \frac{0.72 \mu_0 V_0}{4 \pi r^2} \cdot \frac{N}{[f^2 \cdot (0.677 \mu_0 \pi)^2 N^4 + p^2 N/A^2]^{1/2}} \dots(6)$$

Eq. (6) shows clearly that B is dependent on N , A , r , f , and V_0 .

3. Design Analysis

In most electro-magnetic flow-meters, the parameters f , V_0 , and r may have design constraints imposed on them. For example, f may be fixed by electronic design considerations, and V_0 (and consequently I) may be limited by the battery supply used. In a similar way, r could be restricted by the constructional details of the flow-meter. We need, therefore, consider only, the effect produced on B by changing N and A . The dependence of B on N for different cross-sectional areas (A) is shown in Fig. 1. These curves have been plotted using $r = 0.92$ m, $f = 20.8$ Hz, and $V_0 = 10$ V as representative values of a flow-meter developed by one of us (to be published). Also shown in Fig. 1 is the dependence of the current I on N for the same values of A . [see Eq. (3)]. The information presented in Fig. 1 allows us to investigate the dependence of magnetic flux density B on gauge cross-section A for a given rms value of current I . The latter dependence is shown in Fig. 2 for representative values of $I = 250$ mA, and 600 mA. It is also possible to extract the dependence of B on N at constant I from the curves given in Fig. 1, as shown in Fig. 3. The expected linear dependence is consistent with Eq. (2).

The behaviour in Fig. 2 shows that no appreciable change in B is obtained at large values of A , in contrast to the linear change for small values of A . A close examination shows that the knee point on the graph at which the asymptotes to the two portions of the curves intersect, takes place at a value of B for which the two terms in the denominator of Eq. (7) are equal to each other. Making use of this fact, we have after rearrangement :

$$N = \frac{p}{0.677 \mu_0 f \pi A} \dots(7)$$

Similarly, equalizing the terms in the denominator of Eq. (3) and using Eq. (7), we have :

$$A^2 = \frac{4 \sqrt{2} r p^2 I}{0.667 \mu_0 f V_0} \dots(8)$$

The formulae (7) and (8) enable one to calculate the number of turns N , and the wire gauge required in the design of the sensor when the magnitude and frequency of the maximum current allowable from a

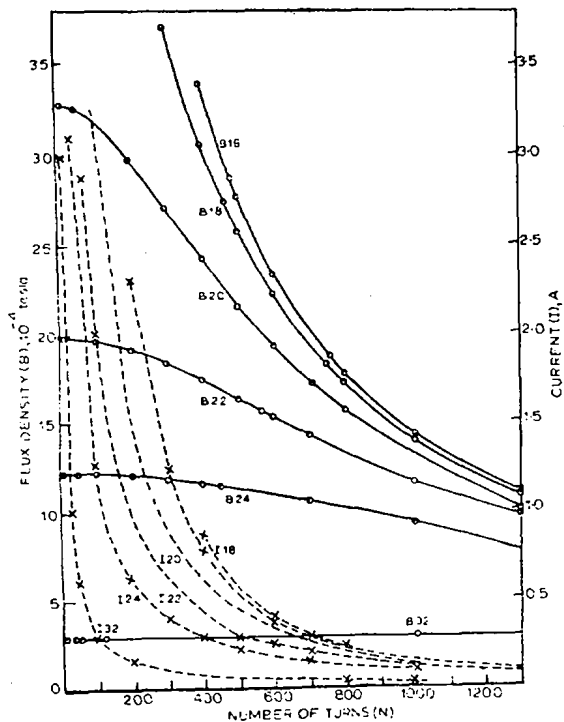


Fig. 1—Calculated dependence of magnetic flux density B and current I on the number of coil turns N for different gauges of coil wire (shown by numbers against each curve)

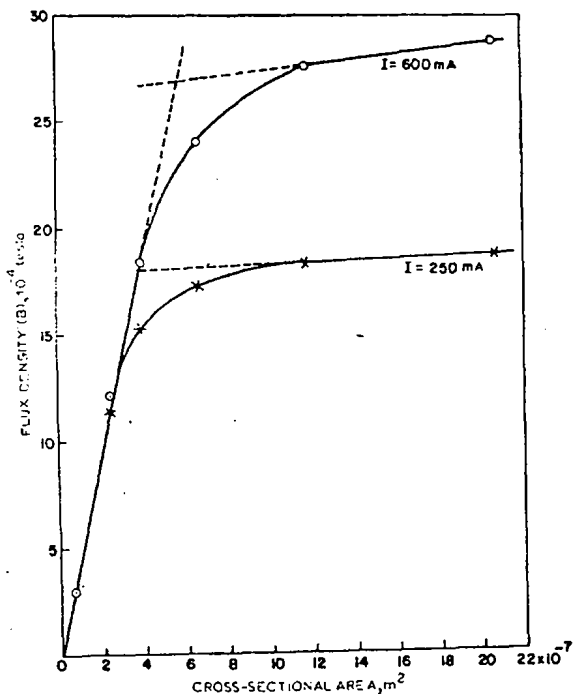


Fig. 2—Calculated curves of magnetic flux density (B) as a function of the cross-sectional area of coil wire (A) for constant rms values of the current (I) (The dotted lines are the asymptotes to the branches of each curve)

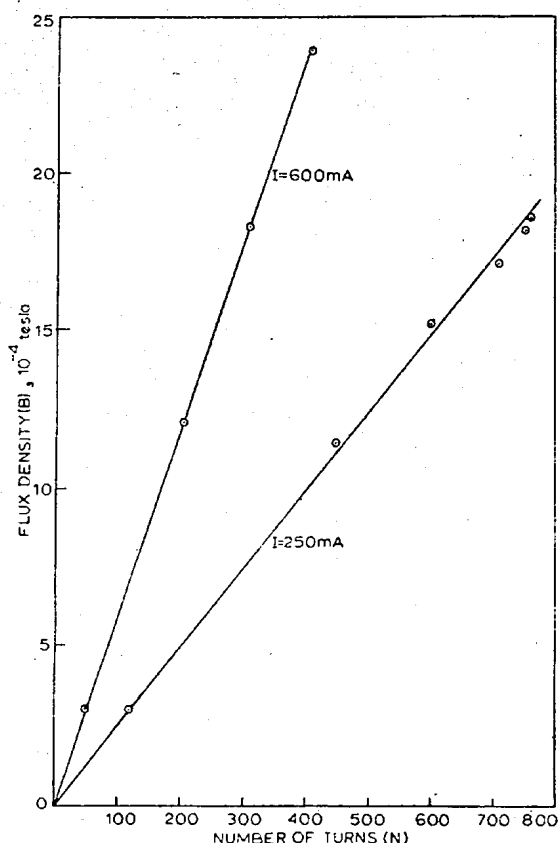


Fig. 3—Calculated dependence of magnetic flux density (B) on coil turns (N) at constant rms values of the current (I)

supply voltage V is known. As an example, using the values of r , f , and V_0 quoted above and also $I = 250$ mA, we have by substitution in Eq. (1), (2), (7) and (8) :

$N = 663$ turns. $A = 4.6 \times 10^{-7}$ m² (SWG ≈ 21), $B = 16.3 \times 10^{-4}$ teslas, sensitivity = $190.7 \mu\text{V/m/sec}$ and 1.76 W for the power dissipated in the coils.

The physical picture of the origin of the 'knee' in Fig. 2, may be given as follows. It arises when the resistance and inductive reactance of the coil are equal in magnitude. When such a balance exists, the current I lags the applied voltage V_0 by 45° , and the power dissipated in the coils is $V_0 I / \sqrt{2}$ where V_0 and I are the rms values of voltage and current.

In the analysis above, it was assumed that the Helmholtz coils were of sufficiently narrow cross-section so as to justify the use of Eq. (2). In practice, the large number of turns used, results in

typical coil cross-sections of the order of 10^{-4} m². If we consider a coil width equal to 10% of the coil radius, then a corresponding percentage change in flux density B is produced. The effect is small, and may be neglected in the treatment above.

If the constraints on parameters r , f , and I are removed, it would provide a means for increasing the field strength and sensitivity still further. This may be seen from Figs. 2 and 3 where large values of B correspond to higher values of I . In addition, it is seen from Eq. (6) that $B \propto 1/r^2 f$ when the expressions for N and A from Eqs. (7) and (8) are used. Hence, a low frequency current and a smaller coil are favoured, but the obvious advantages of a small coil are marked by the closer operation of the electrodes [see Eq. (1)], thus reducing the overall sensitivity. Also, at smaller coil radii, the effect of coil thickness is more marked and the allowance would have to be made in Eq. (1) for magnetic fields.

4. Conclusion

It has been shown that a proper choice of the gauge of wire and the number of coil turns can lead to the construction of an efficient sensor. The resulting improvement in the sensitivity of the sensor means that the power dissipated in the coils can be usefully conserved without having to pump current into the coils in order to increase its sensitivity. The saving of power is an important consideration for portable field instruments, and more so in oceanographic work where ocean current flows need to be monitored continuously.

Acknowledgement

The authors wish to thank Dr S Z Qasim, Director National Institute of Oceanography, Goa, for going through the manuscript.

References

1. Kanvisher J & Lawson K, *Limnology & Oceanography*, 20 (1975), 174.
2. Olson J R, *Two-component electromagnetic flow-meters*, *Marine Tech. Soc J.*, 6 (1972), 19.
3. Tucker M J, Smith N D, Pierce F E & Collins E P, *A two-component electromagnetic ship's log*, *J. Inst. Navig.*, 23 (1970), 302.
4. Nelkon M & Parker P, *Advanced level physics* (Heinemann, London), 3rd Edn, 1969.
5. Carter G W, *The electromagnetic field in its engineering aspects*, Electrical Engineering Series (Longmans, London), 2nd Edn, 1967.