A New Instrument for DC Magnetic Interference Investigation

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Abstract

The detection and location of DC or VLF magnetic interference sources is a very complicated procedure which usually necessitates a displacement or rotation of the investigated object. A new method of determining the momentum components of an equivalent magnetic dipole and its position without any displacement is proposed. It is based on synchronous measurements of different combinations of horizontal magnetic field components using two rotating platforms with fixed distance between their axes. The method makes it possible to exclude the majority of systematic errors including those due to the presence of ambient magnetized bodies and the Earth's magnetic field.

1. Introduction

At higher frequencies, the measurement of radiation and location of its source is a relatively simple procedure and a large number of instruments is commercially available for this purpose. At very low frequencies where the human brain currents range and also for static fields the measuring procedures as well as the necessary instrumentation is much more complicated because of:

- low efficiency of short electric dipole antennas at VLF due to their very high reactance and a low curl component of electric field;
- the necessity to use complicated combinations of magnetic dipoles as magnetic field sensors;
- a very high level of industrial noises in this band;
- the influence of residual magnetic fields of ambient metallic masses and the Earth's magnetic field.

At the same time, the advances of modern technology call for still more accurate determination of possible magnetic interference sources. One such case is the design of satellites with a very low level of own EM radiation for space research: the high sensitivity and precision of the measurements require a thorough compensation of possible interference by magnetic sources. This usually involves the transportation of such systems to a testing facility and their movement and rotation for determination of their own magnetic momentum. As a consequence, many technical and financial problems arise. The described method and instrumentation allow to execute the necessary measurements directly in industrial conditions with an immobile tested body.

2. Theoretical background

If the distance r_1 between sensor and interference source is much greater than the distance r_s between sensor and the investigated magnetic field source then the best results gives a differential operation of field sensors. It implies field increment measurements at a fixed distance Δl between field sensors, where:

$$\Delta l << r_s \, . \tag{1}$$

Then the signal-to-noise ratio will be proportional to $(r_i/r_s)^4$ for measurements of magnetic field increment and to $(r_i/r_s)^3$ for magnetic field. We assume also that $r_s >> l_s$, where l_s is the linear dimension of a current element. In such a case the magnetic field of the circuit may be described as a magnetic dipole (MD) field with the vector momentum $\vec{M}$ having three orthogonal components:

$$\left.\begin{aligned} M_x &= \left|\vec{M}\right| \sin\alpha \cos\beta, \\ M_y &= \left|\vec{M}\right| \sin\alpha \sin\beta, \\ M_z &= \left|\vec{M}\right| \cos\alpha, \end{aligned}\right\} \tag{2}$$

where α - angle between $\vec{M}$ and z axis, β - angle between x axis and projection of $\vec{M}$ on the xy-plane.

A magnetic dipole creates a spatial magnetic field, the components of which in spherical coordinates are [3]:

$$\left.\begin{aligned} H_r &= \left|\vec{M}\right| \cos\theta \left(2\pi r^3\right)^{-1} \left(1 + jkr\right) \exp\left(-jkr\right), \\ H_\theta &= \left|\vec{M}\right| \sin\theta \left(4\pi r^3\right)^{-1} \left(1 + jkr - k^2 r^2\right) \exp\left(-jkr\right) \end{aligned}\right\}, \tag{3}$$

where r is the distance between MD and the observation point, θ the angle between $\vec{M}$ and $\vec{r}$ vectors, and k is the wave number of the medium.

In order to detect MD it is necessary to determine the direction of the maximal increment of these components, i.e. to have an instrument which permits to measure three field increments: ΔH_x, ΔH_y and ΔH_z. This requires a too cumbersome instrument, not convenient for practical use.

Let us consider whether this problem could be solved with a ΔH-meter having field sensors in horizontal plane only. From equations (2) and (3) the field derivative in the direction $\vec{\varphi}_0$ (where $\vec{\varphi}_0$ is the horizontal vector) in the quasi-static approximation $(|kr| \to 0)$ can be written as:

$$\begin{aligned} dH/dl_{\varphi_0} &= -5xr^{-2}H_x\cos^2\varphi_0 + \left(4\pi r^5\right)^{-1}\times \\ &\times\left(4xM_x + 3yM_y\right)\cos^2\varphi_0 - 5yr^{-2}H_y\sin^2\varphi_0 + \\ &+\left(4\pi r^5\right)^{-1}\left(3xM_x + 4yM_y + 3zM_z\right)\sin^2\varphi_0 + \\ &+\begin{pmatrix} -5xr^{-2}H_y - 5yr^{-2}H_x + \\ +\left(4\pi r^5\right)^{-1}\left(yM_x + xM_y\right)\end{pmatrix}\sin\varphi_0\cos\varphi_0, \end{aligned} \qquad (4)$$

where φ_0 is the angle between x axis and $\vec{\varphi}_0$ vector,

$$\left.\begin{aligned} H_x &= \left(4\pi r^5\right)^{-1}\left(\left(2x^2 - y^2 - z^2\right)M_x + 3xyM_y + 3xzM_z\right), \\ H_y &= \left(4\pi r^5\right)^{-1}\left(3xyyM_x + \left(2y^2 - x^2 - z^2\right)M_y + 3yzM_z\right)\end{aligned}\right\} \qquad (5)$$

3. Measurement of the EM source parameters

The EM test involves three steps: determination of the existence of an EM source, EM source location (i.e., determination of its coordinates) and calculation of three components of the magnetic moment vector in the same coordinate frame from the measured ΔH_i, for $i=x,y$ values.

It is clear that the vertical axis OO' (see Fig. 1) of the EM source can be located with a ΔH-meter measuring the horizontal increment of the magnetic field vector. Analyzing equations (4), (5) one can see that in order to avoid the singular case when the horizontal component of the magnetic field vector equals to zero, such a location has to be at two horizontal levels along the vertical axis OO'.

To determine the coordinates of the EM source at the vertical axis with both components of the magnetic moment $\vec{M}$, some algorithms were proposed and their complexity was analyzed. It was shown that the simpler the measurement procedure, the more complicated is the corresponding mathematical calculation. The simplest from all examined algorithms was obtained for an 8-steps procedure, using combined measurements of both magnetic field increment ΔH and its absolute value H [1]. The last peculiarity considerably reduces the signal-to-noise ratio (see above) that leads to a loss of precision with which the source parameters are determined.

Much more convenient is a pure ΔH-algorithm based on measurement of the increments of the horizontal magnetic field components along and across the OO' axis [2]. In this case the plane POO' is determined (P - geometric centre of the sensor system) by the maximum of

$$\Delta H = \Delta|H| = \left(H_{x1}^2 + H_{y1}^2\right)^{0,5} - \left(H_{y1}^2 + H_{y2}^2\right)^{0,5}. \qquad (6)$$

At this maximum the following values must be measured:

$$\Delta H_i = H_{i1} - H_{i2}, \quad i = x, y. \qquad (7)$$

The OO' axis is localized by the maximum of the ΔH value from Eq. (6) in point P_2 which is found by moving the ΔH-meter along a line parallel to the plane P_1OO'. Then the OO' axis is at the intersection of two planes P_1OO' and P_2OO'. The position and orthogonal components of $\vec{M}$ can be found from corresponding equations based on combinations of values determined according to equations (6), (7).

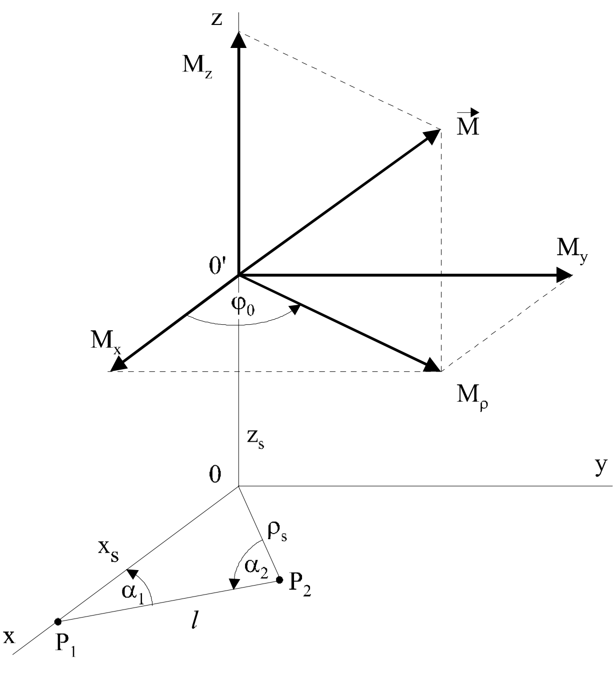

Figure 1: Geometry of the magnetic source localization. ΔH-meters are in points P_1 and P_2, magnetic source is in point O'.

The disadvantage of this method is not only the complexity of some equations (e.g. the determination of the vertical coordinate of the source necessitates the solution of a 7th order algebraic equation) but also the inconvenience of maintaining an exact orientation of the sensors when moving the ΔH-meter along chosen directions. Moreover, the change of ΔH- meter position leads to changes of the distances to outer interference sources not connected with the investigated object. For example, when a DC MD is investigated, the ΔH-meter displacements lead to considerable errors caused by changes of magnetic fields of surrounding metallic objects (due to the change of ΔH-meter position) and of the Earth (due to the change of ΔH-meter orientation).

The new method overcomes these problems in the following way: The ΔH_i values are measured simultaneously by two ΔH-meters in points P_1 and P_2, separated by a distance l (Fig. 1). The ΔH-meter consists of a system of collinear (S_1, S_2 and S_5, S_6) and parallel (S_3, S_4) magnetic sensors mounted on a rotating horizontal platform (Fig. 2) with the possibility to measure the rotation angle of the main AA_1 axis relative to the base line P_1P_2. (Axis BB_1 is perpendicular to axis AA_1.)

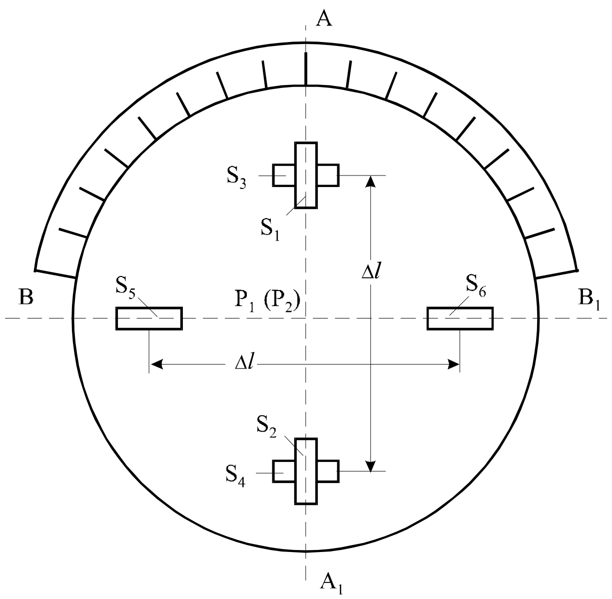

Figure 2: Platform of the ΔH-meter: AA_1 – main axis, BB_1 is perpendicular to AA_1, S_1 to S_6 – fixed magnetic sensors.

The direction to the field source can be found with the help of Eq. (6) from the maximum of ΔH in points P_1 and P_2. The OO' axis can be determined by simple trigonometry as the intersection point of lines of maximum P_1O and P_2O. From this, distances x_s (segment P_1O) and ρ_s (segment P_2O) can be determined:

$$x_s = l \sin\alpha_2 \left(\sin(\alpha_1+\alpha_2)\right)^{-1}, \tag{8}$$

$$\rho_s = l \sin\alpha_1 \left(\sin(\alpha_1+\alpha_2)\right)^{-1}, \tag{9}$$

where α_1, α_2 - angles between main axes AA_1 of ΔH-meters relative to P_1P_2 base line (Fig.1).

All other unknown values can be determined using equations (1)-(9) in the following way:

$$\Delta H_{x(P_1)} = 3\Delta l\left(4\pi\rho_1^7\right)^{-1}\times \times\left(\left(-5x_s^2+\rho_1^2\right)\left(x_sM_x+z_sM_z\right)+2\rho_1^2x_sM_x\right), \tag{10}$$

$$\Delta H_{y(P_1)} = 3\Delta l\left(4\pi\rho_1^5\right)^{-1}\left(x_sM_x+z_sM_z\right), \tag{11}$$

$$\Delta H_{x(P_2)} = 3\Delta l\left(4\pi\rho_2^7\right)^{-1}\times \times\left(\left(-5a^2x_s^2+\rho_2^2\right)\left(ax_suM_x+z_sM_z\right)+2\rho_2^2ax_sM_x\right), \tag{12}$$

$$\Delta H_{y(P_2)} = 3\Delta l\left(4\pi\rho_2^5\right)^{-1}\left(ax_suM_x+z_sM_z\right), \tag{13}$$

where

$$\rho_1 = \left(x_s^2+z_s^2\right)^{0,5}, \tag{14}$$

$$\rho_2 = \left(\left(a^2-1\right)x_s^2+\rho_1^2\right)^{0,5}, \tag{15}$$

$$a = \sin\alpha_1 / \sin\alpha_2, \tag{16}$$

$$u = \mathrm{tg}\,\varphi_0 \sin(\alpha_1+\alpha_2) - \cos(\alpha_1+\alpha_2), \tag{17}$$

φ_0 - angle between M_x and horizontal projection M_ρ of vector $\vec{M}$ (Fig.1).

From equations (10)-(17) the necessary values may be calculated as:

$$z_s = \left(\rho_1^2 - x_s^2\right)^{0.5}, \tag{18}$$

where ρ_1^2 is determined from:

$$a_1\rho_1^{10} + a_2\rho_1^8 + a_3\rho_1^6 + a_4\rho_1^4 + a_5\rho_1^2 + a_6 = 0, \tag{19}$$

where

$$a_1 = A_2^2 - A_1^2, \tag{20}$$

$$a_2 = 5X^2A_2^2 + 2A_2B_2 + 2A_1B_1, \tag{21}$$

$$a_3 = 10X^4A_2^2 + 8X^2A_2B_2 + B_2^2 - B_1^2, \tag{22}$$

$$a_4 = 8X^6A_2^2 + 12X^4A_2B_2 + 3X^2B_2^2, \tag{23}$$

$$a_5 = 5X^8A_2^2 + 8X^6A_2B_2 + 3X^4B_2^2, \tag{24}$$

$$a_6 = X^{10}A_2^2 + 2X^8A_2B_2 + X^6B_2^2, \tag{25}$$

$$A_j = 3\Delta H_{y\left(P_j\right)} - \Delta H_{x\left(P_j\right)}, \quad j = 1, 2, \tag{26}$$

$$B_1 = 5x_s^2\Delta H_{y\left(P_1\right)}, \tag{27}$$

$$B_2 = 5a^2x_s^2\Delta H_{y\left(P_2\right)}, \tag{28}$$

$$X = \left(a^2-1\right)^{0.5}x_s, \tag{29}$$

$$\varphi_0 = \mathrm{arctg}\left(\left(u+\cos(\alpha_1+\alpha_2)\right)\left(\sin(\alpha_1+\alpha_2)\right)^{-1}\right), \tag{30}$$

where

$$u = a^{-1}(\rho_2/\rho_1)^3 \times$$
$$\times\left(\rho_2^2\left(\Delta H_{x(P_2)} - \Delta H_{y(P_2)}\right) + 5a^2 x_S^2 \Delta H_{y(P_2)}\right)\times \quad (31)$$
$$\times\left(\rho_1^2\left(\Delta H_{x(P_1)} - \Delta H_{y(P_1)}\right) + 5x_S^2 \Delta H_{y(P_1)}\right)^{-1}$$

follows from Eqs. (10) - (13).

Finally the three components of the $\vec{M}$ vector are determined as follows:

$$M_x = 4\pi(3\Delta l x_s (au-1))^{-1}\left(\rho_2^5 \Delta H_{y(P_2)} - \rho_1^5 \Delta H_{y(P_1)}\right), \quad (32)$$

$$M_y = M_x \operatorname{tg}\varphi_0 = M_x(u + \cos(\alpha_1+\alpha_2))\times$$
$$\times(\sin(\alpha_1+\alpha_2))^{-1}, \quad (33)$$

$$M_z = z_s^{-1}\left(4\pi(3\Delta l)^{-1}\rho_1^5 \Delta H_{y(P_1)} - x_s M_x\right). \quad (34)$$

The systematic errors related to the surrounding magnetic disturbances including magnetic masses and the Earth’s magnetic field are taken into account by the initial ΔH-meter setting (without investigated object) in connection with a PC using special software. The ambient field components for different rotation angles of the sensors are stored in the PC memory using simultaneous registration. Then the tested object is brought in and the necessary measurements are executed and automatically stored by the same PC.

4. Conclusions

The proposed method and instrumentation makes it possible to solve the difficult task of locating an interfering DC or VLF magnetic source without any displacement of the investigated object. Besides that, it permits to considerably increase the accuracy of such a location thanks to the reduction of errors caused by vertical sensor displacement, non-simultaneous field readings and extraneous interference sources, in particular magnetic masses and the Earth’s magnetic field.

Further development of the functional algorithm will allow to scan the magnetic pattern of the investigated object.

References

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