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Multi-transmitter multi-receiver null coupled systems for inductive detection and characterization of metallic objects

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Abstract

Equivalent dipole polarizabilities are a succinct way to summarize the inductive response of an isolated conductive body at distances greater than the scale of the body. Their estimation requires measurement of secondary magnetic fields due to currents induced in the body by time varying magnetic fields in at least three linearly independent (e.g., orthogonal) directions. Secondary fields due to an object are typically orders of magnitude smaller than the primary inducing fields near the primary field sources (transmitters). Receiver coils may be oriented orthogonal to primary fields from one or two transmitters, nulling their response to those fields, but simultaneously nulling to fields of additional transmitters is problematic. If transmitter coils are constructed symmetrically with respect to inversion in a point, their magnetic fields are symmetric with respect to that point. If receiver coils are operated in pairs symmetric with respect to inversion in the same point, then their differenced output is insensitive to the primary fields of any symmetrically constructed transmitters, allowing nulling to three (or more) transmitters. With a sufficient number of receivers pairs, object equivalent dipole polarizabilities can be estimated in situ from measurements at a single instrument sitting, eliminating effects of inaccurate instrument location on polarizability estimates. The method is illustrated with data from a multi-transmitter multi-receiver system with primary field nulling through differenced receiver pairs, interpreted in terms of principal equivalent dipole polarizabilities as a function of time.

Keywords: Electromagnetic induction; Unexploded ordnance (UXO); Receiver nulling; Multi-transmitter multi-receiver systems

1. Introduction

Detection of secondary magnetic fields due to currents induced in an object by time varying magnetic fields from a source current distribution is often the method of choice for detection of buried metallic objects such as unexploded ordnance (UXO). Detection of the secondary magnetic fields is challenging as they may be as much as six orders of magnitude smaller than the primary inducing fields. One method of diminishing the problem of primary magnetic fields is to choose receiver locations and orientations such that the receiver coils are null coupled to the primary magnetic fields; that is, they have no net primary field flux passing through them, or, given a finite accuracy of manufacture, the net primary field flux through them is greatly diminished. For a single transmitter, or a pair of independent transmitter coils, for small loop receivers this can be achieved by orienting each receiver so that the receiver axis (i.e., receiver loop normal vector) is at right angles to the magnetic fields from each transmitter. A second method of diminishing the relative size of the primary magnetic fields is to transmit over a finite length of time, and to measure secondary magnetic fields after the primary magnetic fields have stopped (e.g., time domain systems). In general, to be sensitive to the smaller secondary magnetic fields, the receiver outputs must be amplified, and the front end of the receiver amplification system must be designed to withstand the much larger voltages due to the primary magnetic field signals. So even in time domain systems it can be advantageous to reduce the primary fields seen by the receiver by (approximately) null coupling them to the primary magnetic fields.

To fully characterize the inductive response of an isolated conductive object, one needs to measure its response to stimulation by primary magnetic fields in three linearly independent (e.g., approximately orthogonal) directions (Khadr et al., 1998, Baum, 1999 and Smith and Morrison, 2004). This can be achieved either by measuring the response to magnetic fields of three independent transmitters arranged to have magnetic fields that are linearly independent, or by measuring the response to a single transmitter which is moved to illuminate prospective object locations with magnetic fields which are linearly independent. In the latter case, system location and orientation errors are a major source of error (Barrow and Nelson, 2001 and Smith and Morrison, 2005), and given current size errors in differential GPS location (3 cm), one would do better to use multiple transmitters and receivers of known relative position and orientation on a single platform than to combine multiple sittings of a single transmitter system with errors in location (Smith and Morrison, 2005). Adding a third transmitter makes it impossible, at most locations, to null couple receivers to all three transmitters, at least when receivers are considered individually.

Huang et al. (2005) observe that for a pair of axially oriented circular loop receivers located symmetrically on axis of a circular loop transmitter, one above, one below, contributions due to the primary fields cancel in the differenced output of the two receivers. Here, the method is extended to allow cancellation of primary fields from multiple transmitters simultaneously, with more complicated transmitter and receiver geometries. When transmitter systems are constructed symmetrically with respect to (inversion in) a central point, and receiver pairs are similarly constructed, the differences between receiver pairs are insensitive to the primary magnetic fields, and thus null coupled in a difference mode, for as many transmitter loops as needed. Or, because of source receiver reciprocity, one can similarly construct transmitter systems that are anti-symmetric with respect to the central point, and use sums of output from corresponding receiver pairs.

2. Construction of suitably symmetric transmitter systems

Under a quasi-static approximation, the contribution to the magnetic field dB(r) at point r due to a current element Idl in the dl direction at point q (along path a(α) tracing out a transmitter loop as α is varied) is

equation (1)

(Biot-Savart law). For simplicity of exposition, we choose the center of a prospective ensemble of receivers and transmitters as the coordinate origin. To construct transmitters that are symmetric with respect to inversion in the origin, for each section of transmitter loop in direction dl at point q, we also include a corresponding section in direction - dl at point - q so that the field at point r due to the two sections is

equation (2)

A simple example of a single loop so constructed would be a circular loop in the x–y plane centered at the origin, of some radius c, diagrammed in Fig. 1. If a current I is flowing counter clockwise when viewed from above, a current element at (x,y) = (c $\cos\alpha$,c $\sin\alpha$) would be Idl(x,y) = I(- $\sin\alpha$,$\cos\alpha$), with α the angle of the current element from the x axis. Adding π to α flips the sign of both (x,y) and dl(x,y) as needed. This single loop example can be trivially extended to loops in the y–z and x–z planes by interchanging x and y with y and z or z and x.

FIG1

Fig. 1. Geometry of simple symmetric loop, showing differential loop segment dl at point q, and complimentary differential loop segment - dl at - q. Magnetic fields of current in loop, at any point r and complimentary point - r are the same.

For more complicated loop shapes the same symmetry may be obtained by using a loop and a mirror image of the loop, as diagrammed in Fig. 2. If one is centered at (x,y,z) with 'normal' oriented in the (u,v,w) direction, centering the other at (- x,- y,- z) oriented with 'normal' in the (- u,- v,- w) direction, with the loop rotated so that an 'up' bump on the first at a point (x1,y1,z1) corresponds to a 'down' bump on the second at point (- x1,- y1,- z1). More precisely, if the first loop is described by curve a(α), the second is described by - a(α). For some loop shapes and positions, after the mirror copy has been repositioned and oriented, the two loops coincide with current in the same direction in each, so only one is needed (e.g., the loop of Fig. 1). Otherwise the two may be wired in series to form a single transmitter loop with the proper symmetry (neglecting any fields due to their leads).

FIG2

Fig. 2. Geometry of less simple (non-coplanar) symmetric loop pair, showing differential loop segment dl at point q, and complimentary differential loop segment - dl at - q. Magnetic fields of current in loop, at any point r and complimentary point - r are the same.

3. Suitably symmetric placement of receiver pairs

The magnetic fields given by Eq. (2) are symmetric on change of sign of r; at point - r the fields point in the same direction as the fields at r, with the same magnitude. This suggests differencing the output of pairs of receivers placed at mirror points to eliminate their response to primary fields. For inductive receivers that are of small dimension, a receiver is sensitive to the magnetic field normal to the plane of the receiver, or for solenoidal receivers, the magnetic field in its axial direction. A simple system is shown in Fig. 3. If a receiver at point r sensitive to changes in magnetic fields in the p direction, is coupled with a receiver at point - r oriented at 180° from the first, so that it is sensitive to changes in magnetic fields in the - p direction, for the duplicated current element of Eq. (2) (Idl at q and - Idl at - q), the sum of the outputs from the two receivers is sensitive to changes in the p component of

equation (3)

FIG3

Fig. 3. Geometry of simple symmetric receiver loop pair, one receiver loop centered at r with loop normal p, and the other centered at - r with loop normal - p. Primary magnetic fields at any point r and complimentary point - r are the same, so summed response of complimentary receiver loops to magnetic fields due to currents in transmitter loop (Tx) is zero.

All terms cancel, so with transmitters that are symmetric (on inversion in the origin) and symmetrically placed receivers with opposing orientations summed, or symmetrically placed receivers with a common orientation differenced, the summed (or differenced) receiver coil response to the primary fields vanishes, so the pair of receiver coils, as a unit, is null coupled to the primary fields of the transmitter coil. Thus such paired receiver coils are null coupled to any transmitter coils that are symmetrically constructed, so can be made to be null coupled to a plurality of transmitter coils providing a plurality of source magnetic field polarizations.

The use of receivers in a difference mode as in the previous paragraph has the advantage of cancelling out noise that is common to the two receivers, such as motion noise from changing orientation in the Earth's magnetic field, or magnetic field noise due to distant current sources. Cancellation of primary transmitter fields may also be obtained if the duplicate section of transmitter loop at point - q is in the + dl direction. This creates source magnetic fields that are anti-symmetric on change of sign of an observation point r; fields that at point - r are in the opposite direction as the fields at its mirror point r, with equal magnitude. With such a source configuration the receiver coil at point - r needs to be sensitive to changes in the magnetic fields in the + p direction instead of in the - p direction (its sign is reversed), so both receiver coils in a pair are sensitive to changes in the same direction. Such a configuration variant lacks the common mode noise cancellation of the configuration of the previous paragraph so is more susceptible to external noise and motion noise.

For receivers of large enough extent that changes in the primary field over the receiver coil are significant, the same symmetry arguments hold. For transmitters that are constructed to be symmetric on inversion in the origin, as leading to Eq. (2), receiver loop pairs are arranged symmetrically on inversion in the origin, so if one receiver loop path is described by a path $\Gamma(\alpha)$ its complimentary receiver loop is described by path - $\Gamma(\alpha)$. In practical terms, this means that if an arbitrarily shaped loop is centered at r with ‘normal’ p, its compliment is a mirror image centered at - r, rotated 180° about an axis through their centers, with ‘normal’ - p: an ‘up’ wiggle on one corresponds to a ‘down’ wiggle on the ‘far’ side of the other. A symmetric system with arbitrarily shaped receivers is shown in Fig. 4. The electromotive force in the first is then

equation (4)

where the integral is over a surface S bounded by the loop path $\Gamma(\alpha)$, and da is a surface differential (normal), and in the second is

equation (5)

where - S is the same surface with reversed coordinates (bounded by curve - $\Gamma(\alpha)$), and da points in the opposite direction for the surface of the second integral. For transmitter loops that are symmetric on inversion in the origin, the primary magnetic fields are symmetric on change of sign of position r, so integrals (4) and (5) cancel for the primary magnetic fields, and the summed pair is null coupled to the transmitter coils.

FIG4

Fig. 4. Geometry of less simple symmetric receiver loop pair, one receiver loop centered at r with loop ‘normal’ p, and the other centered at - r with loop ‘normal’ - p. Primary magnetic fields at any point r and complimentary point - r are the same, so summed response of complimentary receiver loops to magnetic fields due to currents in transmitter loop (Tx) is zero. Schematic wiring for symmetric transmitter loop pair shown.

4. Construction of multiple transmitter multiple receiver pair systems

The method of constructing transmitters that are symmetric (on inversion in the origin) given in the earlier section on symmetric transmitter construction, and the symmetric receiver placement method of the previous section are entirely general. To make a multi-transmitter multi-receiver pair system one merely includes several suitably symmetric transmitters giving primary magnetic of desired orientations, and an array of symmetrically placed receiver pairs. An example three transmitter array is shown in Fig. 5. The two vertical transmitters loop operated independently give magnetic fields oriented primarily in the x and y directions below the transmitter assembly, the pair of horizontal transmitter loops gives magnetic fields primarily in the z direction. (A single horizontal transmitter loop at the height of the assembly center would also be an acceptably symmetric source of vertical magnetic field, but gives smaller amplitude fields at depth for the same net magnetic moment.) An example receiver pair array is shown in Fig. 6. Eight pairs of receiver coils are shown, with one element of each pair in the lower plane, and the other element in the upper plane diagonally across from it. The lower receiver plane is slightly below the lowest transmitter coil so that together the transmitters and half the receivers are as close as possible to objects to be detected. The receivers shown are oriented to be sensitive to vertical magnetic fields, as vertical magnetic fields tend to be a bit more sensitive to objects below the sensors.

FIG5

Fig. 5. Practical 3 transmitter system with symmetry on inversion in origin, appropriate for null coupling receiver pairs to all transmitters. Loops Tx1 and Tx2 are run independently. Loops Tx3a and Tx3b are run together as a unit.

FIG6

Fig. 6. Practical 8 receiver pair system with symmetry on inversion in origin, appropriate for null coupling to symmetric transmitter system, such as shown in Fig. 5. Each receiver pair consists of one lower receiver (a), and upper receiver diagonal across from it (b), with receiver outputs differenced.

5. Example

Data was collected using a three orthogonal transmitter loop, eight receiver coil pair system, with transmitter loops as in Fig. 5 and receiver pairs as in Fig. 6. Transmitter loops were two nestled orthogonal vertical loops 0.941 × 0.680 m and 0.942 × 0.651 m driven with 611. and 563. amp-turns current (peak) respectively and a pair of 0.983 × 0.983 m horizontal loops separated 0.642 m vertically with 307. amp-turns current (peak) each. Receivers were 500 turn 6 inside diameter solenoids approximately critically damped with a nominal resonance frequency of 20 kHz, on the diagonals of the two horizontal transmitter loops, with centers at 27.3 and 50.2 cm laterally from the transmitter loop centers. The transmitters were operated with a 340 μs half sine pulse waveform repeated every 1852 μs with alternating polarity, with a series of nine pulses to each of the three transmitters in turn, and stacked over 20 such sequences, cancelling harmonics of 60 Hz. Data from the first pulse in each series to a transmitter was omitted from the stack. In the system as built, null coupling by receiver pair differencing reduces the magnitude of the primary field signals by factors between 0.006 and 0.16 compared to values calculated for what would appear in single coil measurements, for the various receiver coils operated with the three transmitters. This gives maximum primary field transients of 0.3 to 13 V.

To distinguish the response of a target object, from the background response of other objects in the room where measurement were made, background reference measurements were made, and subtracted from subsequent measurements with a target object near the detection system. Data from the system operated above a horizontal 75 mm mortar shell (empty) oriented in the x direction is shown in Fig. 7, as a function of time after transmitter current shut-off, with separate traces for each of the eight differenced receiver pairs. The measured object response to the horizontal loops (upper panel) is roughly symmetric as the mortar is horizontal and directly below the system, with a greater response measured by the inner receiver pairs. Object response to the two vertical loops (middle and lower panels) is smaller in magnitude, and changes sign on opposite sides of the object in the direction of the primary (transmitted) fields.

FIG7

Fig. 7. Response of 75 mm mortar with center 86 cm below system. (upper) Object response to Bz transmitter (horizontal loops). (middle) Object response to By transmitter (vertical loop with normal in y direction). (lower) Object response to Bx transmitter (vertical loop with normal in x direction).

The data of Fig. 7 was smoothed using a variable length half-sine window, with length 10% of the time after transmitter shut-off, and equivalent dipole polarizability (rates) and dipole position estimated using the methods of Smith and Morrison (2004). Estimated principal equivalent dipole polarizability as a function of time is shown in Fig. 8. The close agreement of two estimated principal polarizabilities (transverse) is consistent with an object symmetric about an axis of rotation. The considerably greater other principal polarizability (axial) is consistent with an elongate magnetic (ferrous) object at 'late' time. Object axis orientation estimated as a function of time shown in Fig. 9 agrees with the true orientation. Equivalent dipole position was estimated as (- 0.022, 0.000,- 0.837) ± (0.001, 0.001, 0.001) m which differs from the actual center position by 0.032 m. Similarly estimated principal equivalent dipole polarizabilities for an asymmetric piece of shrapnel is shown in Fig. 10. Lack of axial symmetry of the shrapnel is immediately evident in its three widely separated principal polarizabilities.

FIG8

Fig. 8. Principal equivalent dipole polarizabilities of 75 mm mortar, estimated from data of Fig. 7.

FIG9

Fig. 9. Axial direction of mortar estimated from data of Fig. 7.

FIG10

Fig. 10. Principal equivalent dipole polarizabilities of irregular piece of shrapnel.

6. Conclusion

Differenced outputs from symmetrically placed receivers offer a viable means of reducing system response to primary fields due to multiple symmetrically constructed transmitters. Response of objects to such a system allows estimation of polarizability responses from measurements with the system at a single location relative to the detected object, allowing direct evaluation of object symmetries.

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