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SHORT NOTE
Sensor response and resolution in downhole TEM data

J.P. Cull
Department of Earth Sciences,
Monash University, Wellington Rd,
Clayton, Vic. 3168.
email: jcull@earth.monash.edu.au

ABSTRACT

Downhole TEM probes can be constructed using several different types of core material. These cores are designed to concentrate the lines of magnetic flux associated with currents induced in a conductive target. In axial probes the resulting signal levels are greatly enhanced and anomalies associated with major targets are readily detected. However for crosshole sensors the advantages are not so evident. In particular the aspect ratio is greatly reduced in probes of reasonable diameter and flux densities can not be greatly improved. Variations in permeability as a function of frequency present a more serious problem. Data obtained at early times may become seriously distorted in any cored probes and deconvolution techniques may be required to compensate for permeability transfer functions. In these circumstances air-cored probes may be preferred but final response remains limited by self inductance.

INTRODUCTION

Standard axial probes used for TEM logging are usually designed around long central cores (mu-metal or ferrite). These cores concentrate the magnetic fields associated with any residual currents established in the exploration target. A good response can be obtained with systems of this type but rotational ambiguities complicate the interpretation. Several probes containing orthogonal cross-hole sensors have now been constructed to resolve this problem (Cull, 1993). However these require more complex construction techniques and great care is required to ensure a uniform response in each of the components.

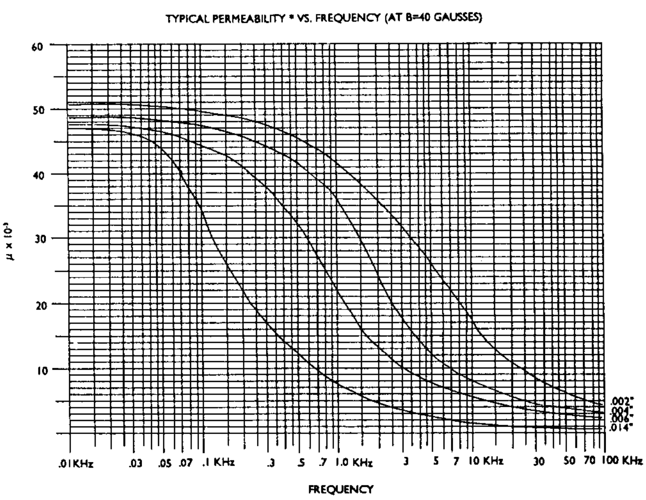
TEM probes can be constructed using a variety of core materials. Mu-metal, ferrite, and air cored coils provide a range of possibilities. Air-cored sensors provide the simplest solution with minimum expense and minimum signal distortion. Mu-metal has excellent magnetic properties for flux concentration but elaborate sample preparation is required (including annealing in hydrogen) and thin laminations must be assembled to avoid a significant self-response. Ferrites are non-conductive and are readily machined but are lower in permeability and are relatively fragile. Consequently core selection represents a critical aspect of sensor construction and probe response.

CORE TRANSFER FUNCTIONS

Mu-metal and ferrite rods are used as core materials for inductive sensors to increase the density of the magnetic flux associated with small signals. In effect they act as amplifiers for magnetic flux with gain related to the effective permeability of the core material. In general the magnetic permeability of any material is assumed to be a constant prior to saturation. However there are significant complications for broad band receivers. In particular, values of permeability are observed to vary with frequency.

Variations in skin depth as a function of frequency cause systematic trends in permeability for metals (eg Jiles, 1985). In effect there is a progressive reduction in the volume of metal conducting lines of flux through the centre of the sensor. As a result there is a decrease in the inductance (and consequently signal level) as a function of frequency. Eddy current effects can be reduced through the use of laminations in any core but systematic trends in permeability remain.

The response curves for mu-metal are illustrated in Figure 1. These curves resemble the output of a filter with corner



*** All tests were conducted using ring laminations 1/2 I.D. x 3/4" O.D., annealed at 1040°C for 2 hours and cooled at 4°C/minute minimum. Higher permeabilities are possible by annealing at higher temperatures.**

Fig. 1. Variations in permeability as a function of frequency for mu-metal strips demonstrating potential for distortion of decay curves in early-time windows (Spang, 1985).

frequencies around 10 kHz. Consequently a linear response can be expected at late times in a transient decay but severe distortion may occur at the very early times dominated by high frequency components. To some extent this behaviour is beneficial since it does provide a form of dynamic filtering prior to any electronic amplification. However deconvolution may be required to compensate for the transfer function of the sensor prior to detailed modelling of an early time response.

DISACCOMMODATION

Ferrite cores can be manufactured with high resistance to electric currents. Consequently skin depth effects can be minimised and transfer functions can be engineered to ensure an optimum corner frequency for any application (MMG Neosid, 1982). However the initial permeability is generally less than available with mu-metal and some serious complications result from grain or domain migrations.

After a ferrite core has been subject to a shock (thermal, mechanical, or magnetic) there is an abrupt increase in permeability followed by a slow decline (MMG Neosid, 1982). The magnitude of this effect is known as the Disaccommodation Factor (comparable to magnetic viscosity involving domain boundaries). It is given by the expression

$$D = \frac{(\mu_2 - \mu_1)}{\mu_1 *(\log t_2 - \log t_1)}$$

For many grades of ferrite values of *D* for this effect exceed 10^{-5}.

Typical TEM signals decay over several decades of amplitude within a few milliseconds. Consequently the output of a ferrite-cored sensor will normally decay monotonically towards a base level of much greater time constant than the current filament associated with the primary target. Disaccommodation acts to introduce a further decay effectively mapping

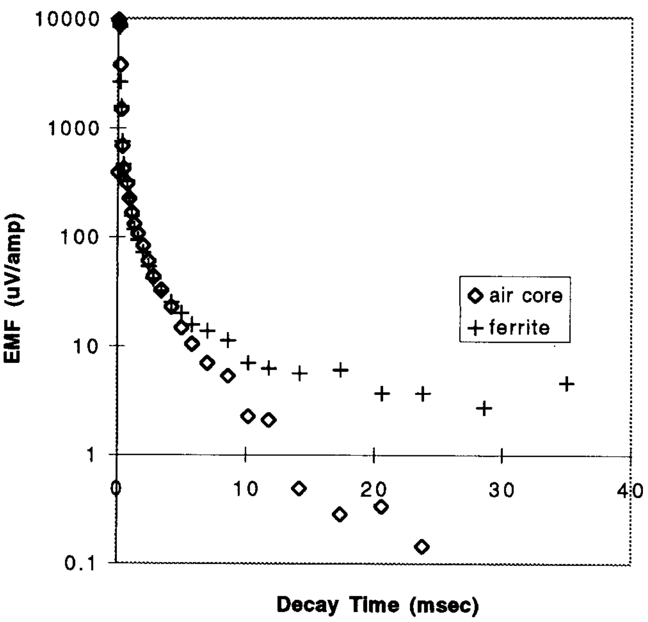


Fig. 2. Comparison of decay curves obtained with ferrite-core and air-core sensors demonstrating the effects of disaccommodation evident as a 'tail' at low signal levels.

dμ / dt. This can result in a significant offset in zero levels resembling the classical 'tail' previously observed in faulty probes and attributed to self induction in mu-metal cores. Examples are given in Figure 2.

AIR CORED PROBES

The VECTEM probe (developed at Monash University) can be fitted with three sets of air-cored receiving coils; the standard axial component is designated according to the AMIRA convention as the *A* axis and the two orthogonal axes are designated as *U* (up) and *V* (horizontal) respectively. Each sensor can be selected in turn providing sequential input to a battery operated preamplifier via a multiplexer which is controlled from a surface adapter unit.

The probe can be attached to a standard 4-core logging cable providing sufficient capacity for the receiver signal and the multiplexer control codes. The orientation of the probe is detected using a gravity based reference system also addressed via the multiplexer along with a battery voltage monitor. Fittings are designed for the Sirotem III system but the TEM signals provided at the surface via the winch assembly can be recorded using a variety of proprietary systems.

A buffer amplifier is provided in the probe to enhance the output of any component selected by the adapter unit. At present the gain of this amplifier is set at x51 providing a balanced output with a 10 kHz bandwidth. Trimset resistors have been provided to ensure a gain consistent with the output of a standard axial logging system based on a 10^4 receiver area.

Air cored sensor elements can be selected for the VECTEM probe to minimise the risk of self response. Consequently the total sensitivity of the probe is less than in standard axial probes. Furthermore there are substantial differences between the axial and the cross-hole components resulting from the physical limitations associated with the circular cross section of the probe housing. The coils arranged in banks are centre tapped and each half is individually damped.

To provide sufficient signal amplitude for the crosshole components it is necessary to use induction coils containing a large number of turns compensating for a reduction in the effective cross-sectional area. A total of 40,000 turns may be required to obtain a physical area exceeding 20 m^2 in a typical probe housing. In these circumstances there is considerable risk of excessive self capacitance accompanied by a reduction in bandwidth for these critical components giving a response function similar to that observed for mu-metal in Figure 1.

The sensor response for the VECTEM probe has been investigated using synthetic signals to approximate a typical transient signal. Ramp functions were first applied to Helmholtz coils so the (differentiated) sensor output could be compared to square waves of the same frequency. The rise time for the probe demonstrates a minimum curvature and negligible self response ensuring stability within 0.2 msec. Consequently in normal circumstances no corrections are required to compensate for the transfer function of the sensor coils.

DISCUSSION

Standard single component axial probes for TEM logging are relatively easy to construct. Adequate physical area can be generated simply by lengthening the probe to accommodate a coil with a moderate number of well spaced turns. Good signal levels are assured by including core materials of high permeability which act as flux amplifiers. However permeability decreases with frequency causing some distortion in spite of coil spacings designed to minimise the effects of self capacitance. As a result deconvolution may be required for some applications.

The construction of orthogonal cross-hole sensors for TEM logging is not so simple. In particular there are few options with sensor length and aspect ratio for coils designed to fit within slim-line probes. The effective permeability of metal and ferrite rods can be severely reduced through the effects of demagnetisation in short samples selected according to the probe diameter. Flux densities for typical probes may be increased only by factors of 5 for short crosshole sensors compared to factors exceeding 100 for the much longer axial direction (giving virtually unlimited aspect ratio and negligible demagnetisation).

If core materials are rejected on the grounds of frequency distortion the available signal levels may only be adequate for a short time after the start of any TEM decay. To obtain data at later times additional turns may be required to compensate for a reduction in the effective physical area. However in this case self capacitance is greatly increased and the desired early time response can not be preserved. Consequently a trade-off may be required depending on the primary application of each probe for early time or late time targets.

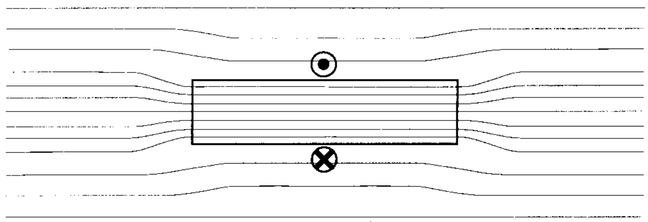


Fig. 3. Flux gathering in a core of high permeability and an equivalent current acting to maintain the original field. For a resistive host, this 'parasitic' response will resemble the inductive self-response normally associated with eddy currents in the case or core of the probe.

The selection of mu-metal, ferrite, or air cored sensors may be further complicated by the appearance of a 'parasitic' response similar to self response resulting from eddy currents in conductive core. For highly resistive ground the primary flux densities are concentrated by core materials in the vicinity of the probe providing a significant moment around the perimeter of the borehole (Figure 3). Local currents may then be established in the conductive fluids of the borehole acting to preserve the initial field. In these circumstances TEM data will contain systematic trends reflecting variations in borehole/loop coupling. A 'parasitic' response of this type should not be confused with self-response associated with conductive core; it can only be reduced using air-cored probes minimising local flux concentrations.

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