The study of Signal Propagation in Electromagnetic –Measurement While Drilling (EM-MWD) telemetry systems

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Abstract: Electromagnetic measurement while drilling (EM-MWD) telemetry can provide real time-large amount of data to the drilling crew and this is the reason for its rapid development in the recent years. For effective and efficient design and utilization of the EM-MWD tool, one needs to understand the behavior of the electromagnetic signal as it propagates along the drill string as well as through the formation. Based on electromagnetic theory, this paper examines the behavior of the signal such as attenuation, propagation velocity with varying operating frequency and earth resistivity.

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1. Introduction

High depth drilling, increased activity offshore and rapidly escalating costs have focused attention on all potential methods of drilling safer and cheaper. Real time data delivery from the bottom of the borehole (at the drill bit) to the surface offers the greatest potential for achieving these needs. Oil company management and engineers place a lot of emphasis on well control and directional information (McDonald, 1978). It is therefore, important to understand how the data can be transferred from bottom to surface. A number of systems have been used namely hardwired telemetry, Acoustic telemetry, mud pulse telemetry, and electromagnetic telemetry. Although mud pulse telemetry is a well developed and commercially available, it has some limitations such as the high demand for drilling fluid rendering it useless in underbalanced drilling which is common in air and foam drilling. EM-MWD also offers higher data rates for good resistant earth cases, and hence more varieties of quantities can be measured simultaneously (Xia and Chen, 1993).

Electromagnetic telemetry transmits data through low-frequency electromagnetic waves which propagate through the subsurface formations from the drill string and are received by surface antennas. The successful implementation of electromagnetic telemetry requires understanding of the formation types and associated resistivities. And also knowing the behavior of the signals as it moves through the formation. The signal propagation has been studied by several authors (Jose and Flavio, 2002; Poh, David and Andrew, 2005; Xia and Chen, 1993). In this paper, the signal propagation through the drill string and formation of an electromagnetic telemetry is studied based on the Electromagnetic field theory (Bhag and Huseyin, 1998) and analysed using Matlab codes (James, 2001).

2. Methodology

2.1 Working principle of EM-MWD

The signal source emits the signal which propagates through the formation to the receiving antenna from which the surface equipments are connected as shown in figure1 above. The surface equipment decodes the data and puts in a form which is easily understandable by the driller. The driller can also send commands to the downhole assembly through the surface equipment.

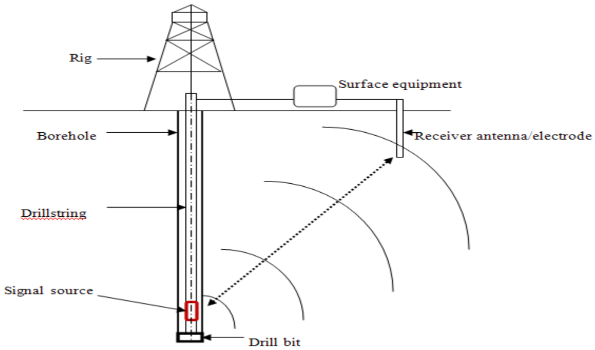


Figure 1 Schematic diagram of showing the Principle of operation of the electromagnetic MWD system. An emitting antenna in the drill string transmits the data to the surface electrodes.

2.2 Description of the configuration and formulation of solution

The geometry of the problem is illustrated in Fig.2. To specify the position of the source in the configuration, we employ the coordinates (r, θ, φ) as a spherical coordinate system with origin O (Ivo, 1996; John et al..2007; Wu et al..2009). The source is a vertical infinitesimal electric dipole antenna J=żIdzδ(z) immersed in a dielectric medium of infinite extent and excited by an impulsive current. The electric dipole antenna, located at the origin O and oriented vertically in the z-direction, is short in length, "dz", carrying a current "I".

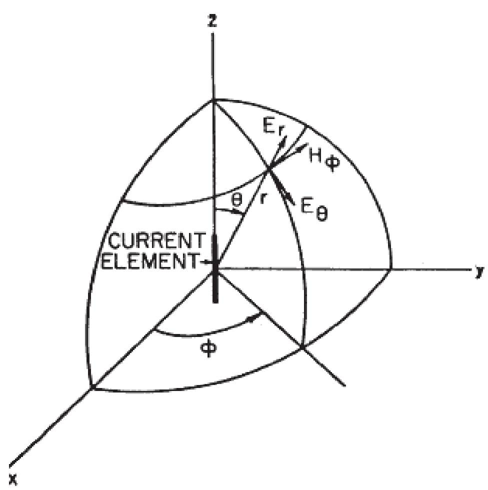


Figure 2: showing the coordinate system for an electric dipole

Maxwell's equations lead to the following formulations:

$$\nabla^2 E + \omega^2 \mu\varepsilon E = \frac{1}{\varepsilon}\nabla\sigma - j\omega\mu J \qquad (1)$$

$$\nabla^2 H + \omega^2 \mu\varepsilon H = -\nabla \times J \qquad (2)$$

$$k^2 = \omega^2 \mu\varepsilon \qquad (3)$$

Where: E=Electric field intensity (v/m); H=electric field intensity (v/m); J=electric field intensity (v/m^2); B=Magnetic flux density (wb/m^2); σ=conductivity (Ω/m); ε= permittivity F/m); and μ= permeability (H/m)

Considering the infinitesimal electric dipole antenna J=żIdzδ(z), as illustrated in figure 2 above, the electric and magnetic field components obtained from equation (1) or (2) are given by

$$E_r = \frac{k^2 Idz\, e^{-j\omega t}}{2\pi\omega\varepsilon}\left[\frac{1}{(kr)^2} - \frac{j}{(kr)^3}\right]e^{-jkr}cos\theta$$

$$E_\theta = \frac{jk^2 Idz\, e^{j\omega t}}{4\pi\omega\varepsilon}\left[\frac{1}{kr} - \frac{j}{(kr)^2} - \frac{1}{(kr)^3}\right]e^{-jkr}sin\theta$$

$$H_\varphi = \frac{jk^2 Idz\, e^{-j\omega t}}{4\pi}\left[\frac{1}{kr} - \frac{j}{(kr)^2}\right]e^{jkr}sin\theta$$

3. Results and Discussions

3.1 Case I: Near field (r<<)

When the distance (r) between the observer and the centre of the electric dipole is too short, only values of high-order terms are of significant effect, hence low-order terms can be ignored yielding the following set of equations:

$$E_r = \frac{jIdz}{2\pi\omega\varepsilon r^3}e^{-j\omega t}cos\theta$$

$$E_\theta = \frac{-jIdz\, e^{j\omega t}}{4\pi\omega\varepsilon r^3}e^{j\omega t}sin\theta$$

$$H_\varphi = \frac{Idz}{4\pi r^2}e^{-j\omega t}sin\theta$$

It can be observed from the above set of equations for the near field that when the electric field is at its maximum, the magnetic field is zero and vice versa, and the average energy-flux density vector is zero. This means that there is no radiation in the near field.

3.2 Case II: Far field (r>>)

When the distance (r) between the observer and the centre of the electric dipole is too large, only values of low-order terms are of significant effect, hence high-order terms can be ignored yielding the following set of equations:

$$E_r = 0$$

$$E_\theta = \frac{-jIdz\omega\mu}{4\pi\varepsilon r} e^{-j(\omega t - kr)} sin\theta$$

$$H_\varphi = \frac{-jIdz\omega\sqrt{\mu\varepsilon}e^{-j\omega t}}{4\pi r} e^{-j(\omega t - kr)} sin\theta$$

3.3 Attenuation

The earth being a loss dielectric, k the propagation constant is generally a complex number and can be expressed as:

$$k = \alpha + j\beta$$

Where

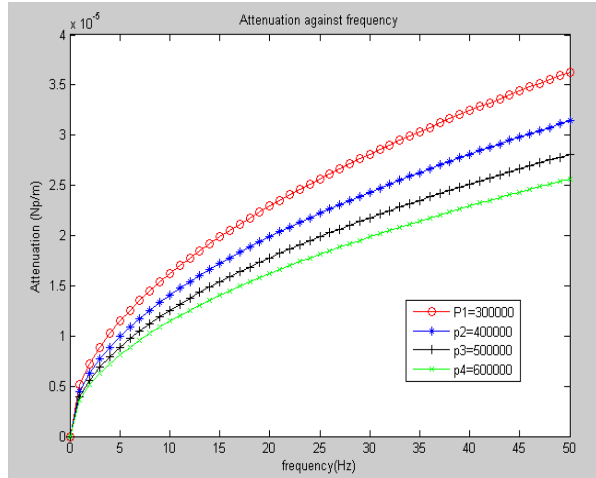
$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}}\left[\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon}\right)^2} + 1\right]^{1/2}$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}}\left[\sqrt{1 + \left(\frac{\sigma}{\omega\varepsilon}\right)^2} - 1\right]^{1/2}$$

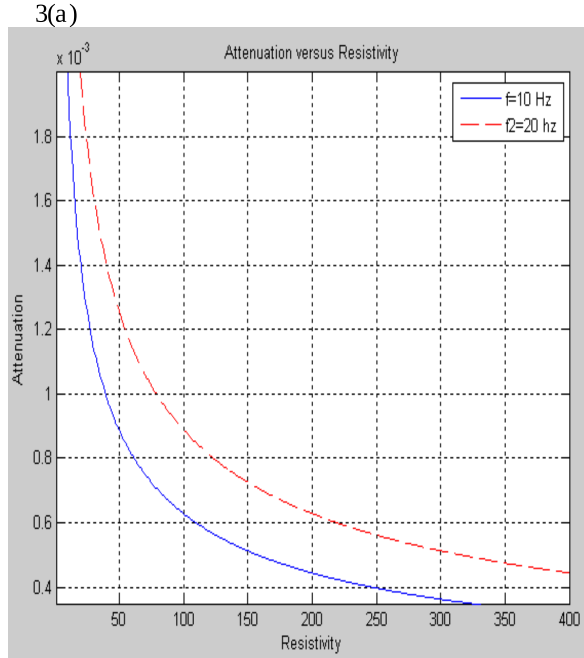
Considering $\frac{\sigma}{\omega\varepsilon} \gg 1, \alpha = \sqrt{\frac{\omega\mu\sigma}{2}}$, which leads to the relationship between attenuation, frequency and resistivity as below:

$$\alpha = \sqrt{\frac{\omega\mu}{2\rho}} = \sqrt{\frac{\pi f\mu}{\rho}}$$

A plot of attenuation against frequency (using Matlab) is shown below:



3(a)



3(b)

Figure 3(a) Shows attenuation against frequency with resistivity's p1=300,000Ω.m, p2=400,000Ω.m, p3=500,000Ω.m and p4=600,000Ω.m; and 3(b) shows attenuation against resistivity at frequencies of 10Hz and 20Hz.

The signal attenuates as it propagates through the media (formation or drill pipe) and this attenuation with increasing frequency but reduces with increasing resistivity of the medium (fig.3).

3.4 Velocity of propagation (u_p)

The velocity of propagation (also referred to as the wave propagation speed) is defined as the speed at which an electromagnetic signal passes through a medium[4], and it is expressed as:

$$u_p = \sqrt{\frac{2\omega\rho_m}{\mu_m}}$$

A plot of the velocity of propagation against frequency through media of different resistivity is shown below:

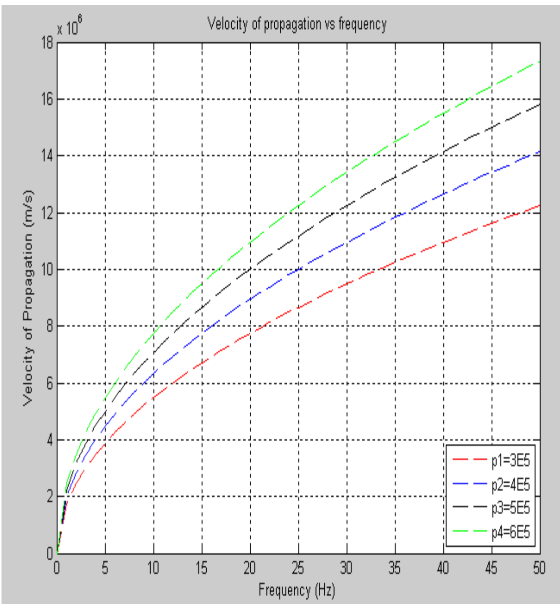


Figure 4 Shows velocity of propagation against frequency with changing resistivity

It is observed from figure (4) that the velocity of propagation increases with both increasing frequency and resistivity. This implies that velocity of propagation reduces with increasing conductivity of the medium through which the signal is passing. The increase in propagation velocity means increased data rate transfer from the bottom to the surface and vice versa.

4. Conclusion

In the process of electromagnetic wave propagation, the signal will be lost gradually with increasing frequency and reducing formation resistivity, indicating that a high frequency cannot be used. However, data transfer rate increases with both increasing frequency and resistivity. In this study frequencies above 20Hz may lead to a higher attenuation where as those below 5Hz will limit the data rate transfer.

The above conclusion has a strong influence during the design of an EM-MWD tool as one must strike a balance between frequency and the data rate transfer as they greatly affect the performance of the tool.

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