On-time response of unexploded ordnance-like targets detection with transient electromagnetic system

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Abstract. Time-domain electromagnetic induction method including on-time and off-time illumination is widely developed in unexploded ordnance (UXO) detection. The secondary field response detected in off-time is almost ineffective for targets with small size and great depth due to fast signal attenuation and low signal-to-noise ratio at late stage. In this paper, the on-time response for UXO detection with TEM system is discussed in detail. Firstly, the on-time response of a sphere is calculated theoretically and compared with the off-time response. Secondly, the transmitting circuit with four NMOS is designed to generate desired transmitting current to measure on-time response effectively. Finally, the on-time and off-time response of several targets are measured simultaneously. Results show that the late signal-to-noise ratio of on-time response is much higher and the attenuation of target with small size and iron pipe is slower than the off-time response, which is consistent with the theoretical results.

1. Introduction

More than 83 countries in the world are contaminated by unexploded ordnance to varying degrees [1]. Almost all the geophysical detection technologies, such as magnetic detection, electromagnetic induction (EMI), and ground-penetrating radar (GPR) have been used for UXO detection[2-3]. EMI method has been found to be the most effective for detecting and characterizing shallow UXOs due to its strong anti-interference and high target recognition abilities[4]. The typical system with EMI method includes NanoTEM, MPV, BUD, and MetalMapper developed by the United States Zonge company, the United States Sky company, American Berkeley, and Geometrics respectively [5-6].

EMI method operates in the frequency range from tens to hundreds of kilohertz to make the ground TEM response transparent. The secondary field is measured at the interval of transmitting current to avoid the influence of the primary field. According to the different transmitting current in the transmitting coils, the TEM system can be divided into on-time and off-time measurements. However, the signal-to-noise of off-time response is quietly low since the signal attenuate fast at late stage. In addition, with the increase of the conductivity of the target, the amplitude of the off-time response will also decrease sharply, failing to achieve the ideal detection results [7]. The amplitude of on-time response is basically not affected by the conductivity, and the signal attenuation is slow, with high signal-to-noise ratio in late stage, which has a better detection effectiveness for good conductors and small objects [8].

In this paper, the on-time response is measured and analysed by the TEM system. In section II, on-time response of a sphere is modelled and calculated theoretically and compared with the off-time response. In section III, the transmitting circuit is designed for ideal on-time response and the actual transmitting current is measured. In section IV, the on-time response and off-time response of various
targets are measured and the characteristics of on-time response are analysed to provide theoretical
guidance and experimental basis for further implementation of on-time detection.

2. On on-time response of a sphere
The secondary field response of the general finite conductor cannot be expressed by an explicit
mathematical expression, except the sphere. The on-time response of a sphere is conducted.

All buried conductors illuminated by a pulse magnetic field are modelled as a single magnetic dipole
model based on the Huygens Equivalent principle, as shown in Figure 1. In free space, the radius of the
sphere is \(a\), the conductivity is \(\sigma\), the permeability is \(\mu\), and the relative permeability is \(\mu_r\).

![Figure 1: Sphere response induced by primary field.](image)

As shown in Figure 1, when the primary field \(B_p\) (along Z direction) is turned off, the secondary field
\(B_s\) at the point \(r\) directly above the sphere is:

\[
B_s = B_p \frac{a^3}{r^3} L^\beta(t)
\]

where \(L^\beta(t)\) is the attenuation function of the secondary field:

\[
L^\beta(t) = 6\mu \sum_{s=1}^{\infty} \frac{e^{-\sqrt{s}r_t}}{q_s^2 + (\mu_r - 1)(\mu_r + 2)}
\]

where \(r_t = \sigma \mu a^2\), \(s\) is the response mode starting from 1 to infinity, \(q_s\) is the solution of the transcendent
equation, the formula is:

\[
\tan(q_s) = \frac{(\mu_r - 1)q_s}{q_s^2 + (\mu_r - 1)}
\]

The characteristic response of the sphere can be calculated as:

\[
l(t) = \frac{6a}{\sigma \mu_0} \sum_{s=1}^{\infty} \frac{q_s^2 e^{-\sqrt{s}r_t}}{q_s^2 + (\mu_r - 1)(\mu_r + 2)}
\]

According to equation (4), the sphere response \(h(t)\) induced by the pulse current excitation can be
directly obtained as:

\[
h(t) = \frac{dl(t)}{dt}
\]

Based on the signal processing principle, the response of the sphere can be calculated induced by the
excitation of arbitrary transmitting current \(I(t)\) as:

\[
V(t) = I(t) * h(t) = I(t) * \frac{dl(t)}{dt} = l(t) * \frac{dl(t)}{dt}
\]

According to equation (6), we defines the response generated by negative step current as off-time
response and during ramp step as on-time response. The off-time and on-time transmitting currents are
depicted in Figure 2.
As shown in Figure 2, when the transmitting current drops along the time $t_0$ is 10ms, the radius of the sphere is 5cm, the conductivity is $1.5 \times 10^6$ S, and the relative permeability $\mu_r$ is 150, the off-time and on-time responses can be calculated by equation (6), as shown in Figure 3:

![Figure 2: Off-time and on-time transmitting current waveforms.](image)

As shown in Figure 3, the initial signal magnitude of the on-time response is lower but the attenuation is slower than the off-time response. After 10ms, the off-time response attenuates by 5 orders of magnitude, while the on-time response only attenuates by one order of magnitude with the result that the late signal-to-noise ratio of on-time response is much higher.

### 3. Transmitting current of on-time response

Figure 4 shows transmitter circuit to produce the desired current signal.

![Figure 4: Transmitter circuit.](image)

As shown in Figure 4, four NMOS are designed in the transmitter to achieve current positive and negative alternation by altering the switching time. At the same time, the current turn-off time is controlled by adjusting the resistance and inductance of the sensor resulting in the ideal current waveform that can be measured for on-time response precisely. Transmitter current waveform is measured as shown in Figure 5.
Figure 5. Actual measurement of on-time transmitting current waveform.

As shown in Figure 5, switch the transmitting current extends from tens of subtle to a several milliseconds, enabling measurement of on-time response.

4. On-time response characteristics experiment of multiple target bodies

On-time response measurement was carried out with seven targets depicted in Figure 6, and the parameters of these targets are shown in Table 1.

| Name | U1 | U2 | U3 | U4 | O1 | O2 | O3 |
|------|----|----|----|----|----|----|----|
| Length(cm) | 24 | 26 | 27 | 34 | 30 | 20 | 10 |
| Diameter(mm) | 60 | 57 | 82 | 70 | 75 | 75 | 75 |

The seven targets are divided into two groups. U1-U4 are four UXOs with small sizes, and O1-O3 are three iron pipes with different lengths. The on-time response and off-time response are measured simultaneously, as shown in Figure 7.

It can be seen from Figure 7 that although the on-time signal is temporarily affected in the early stage by transmitting current, the slow attenuation characteristic of the on-time response is still reflected. The initial amplitude of the on-time response is slightly lower than the off-time response, but after a few milliseconds, the amplitude of the on-time response is generally consistent with the off-time response. Whether the small UXOs or iron pipes, there is still a high signal amplitude in the late stage. Thus, more complete response signals can be obtained by the on-time response comparing with the off-time response measurements.
5. Conclusion

The research on the on-time response characteristics of finite conductors is quietly crucial to the development of TEM detection. In this paper, the characteristics of on-time response are modelled and analysed by comparing the on-time response and the off-time response based on theoretical calculation and measurements. In the response calculation of the sphere, when the transmitting current turn-off time is 10ms, the on-time response attenuation is very slow. Although the on-time initial value is 3 orders of magnitude lower than the off-time response, the late signal amplitude is still an order of magnitude higher than the off-time response. The switch time of the transmitting current is extended from tens of microseconds to several milliseconds, making it possible to perform on-time response measurement. In the response measurement experiment to several targets, the results show that whether it is a small UXO or an iron pipe with an excessively fast response attenuation, the signal-to-noise ratio of on-time response is much higher. It is concluded that on-time detection can be used to detect finite conductors induction when the secondary field response is too small such as small sizes or great depth.

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