Precise Measurement of Characteristic Responses for Unexploded Ordnance

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Keywords: UXO, characteristic responses, dipole model, transmitting coil.

Abstract: The equipment for measuring the characteristic responses of unexploded ordnance (UXO) is proposed in this paper. It is composed of two parts: a solenoid and a pair of rectangular coils. The uniformity of the primary field for solenoid reaches 98% and 97% for rectangular coils. The characteristic responses of six targets with different size, length and outer diameters are measured. The results indicate that the amplitude and decay rate of the characteristic responses change significantly with the length and outer diameter. The longer the target, the greater the amplitude will be. The larger the diameter of the target, the slower the decay rate will be. It means that the physical information can be well reflected by characteristic responses.

1 INTRODUCTION

Unexploded ordnance, left after wars or other military activities, is an increasingly serious international humanitarian and environmental problem, which has caused many civilian casualties. Thus, how to detect and clean up UXO has attracted wide attention all over the world(Miller R, 2008).

Transient electromagnetic(TEM) system has been widely used for UXO detection(Laurens B et al, 2013). The most frequently used model for representing the EMI response of a metallic target approximates the whole object with a set of orthogonal co-located point dipoles(Shubitidze F, 2012). Based on the dipole model, Nagi Khadr has studied the relationships between the characteristic responses and the aspect ratio of UXO(Khadr N et al, 1998). Leonard R. Pasion et al. have calculated the EMI response of an axisymmetric target and estimate the position and orientation of the target based on the measured response(Pasion L R et al, 2007). Chen Shudong and other scholars studied the influence of physical parameters on the characteristic responses of targets (Shu-Dong C et al, 2017). However, none of these studies have talked the measurement of characteristic responses in detail.

According to the dipole model, only the target is excited by a uniformly field, can the characteristic responses be measured accurately. However, it is very difficult to produce a uniform magnetic field for transmitting coil used in a TEM system. Based on the dipole model, a specially designed equipment for measuring the characteristic responses accurately will be proposed in this paper. The structure and parameters of the equipment will be listed in detail. We will measure and analyze the characteristic responses of typical targets by this equipment.

2 DIPOLE MODEL

According to the dipole model, the magnetic field (secondary field) $\boldsymbol{H}$ generated by the eddy current of targets excited by the primary field $\boldsymbol{H}_\mathrm{p}$ can be equivalent to the magnetic field generated by an induction dipole $\boldsymbol{m}$.

Liu, X., Zhang, S., Wang, H., Chen, S., Yuan, Z., Zhang, H., Fang, D. and Zhu, J.
Precise Measurement of Characteristic Responses for Unexploded Ordnance.
In *3rd International Conference on Electromechanical Control Technology and Transportation (ICECTT 2018)*, pages 498-502
ISBN: 978-989-758-312-4

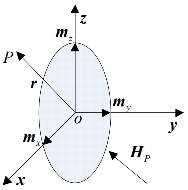

Figure 1: Orthogonal dipole model of UXO.

As shown in Figure 1, the secondary field ***H*** in point P can be calculated as:

$$\boldsymbol{H} = \frac{(3\boldsymbol{e}_r\boldsymbol{e}_r - \boldsymbol{I})\cdot\boldsymbol{m}}{4\pi r^3} \tag{1}$$

Where ***r*** represents the position vector of point **P**, *r* is the modulus of ***r***, and $\boldsymbol{e}_r$ is the unit vector of ***r***. The induction dipole ***m*** can be calculated as:

$$\boldsymbol{m} = \begin{bmatrix} \boldsymbol{m}_x \\ \boldsymbol{m}_y \\ \boldsymbol{m}_z \end{bmatrix} = \begin{bmatrix} \beta_{xx} & 0 & 0 \\ 0 & \beta_{yy} & 0 \\ 0 & 0 & \beta_{zz} \end{bmatrix} \boldsymbol{H}_p \tag{2}$$

For an axisymmetric target, such as UXO, the first and second dipole $\boldsymbol{m}_x$, $\boldsymbol{m}_y$ are both perpendicular to the major axis, and the β_{xx} and β_{yy} refer to the magnetic polarizations correspondingly. The third dipole $\boldsymbol{m}_z$ is parallel to the major axis of the target, and the β_{zz} refers to the magnetic polarization parallel to the major axis of targets. The characteristic responses of targets are defined as the derivative of the magnetic polarization.

$$l_p(t) = -\frac{d\beta_{zz}}{dt} \tag{3}$$

$$l_v(t) = -\frac{d\beta_{xx}}{dt} = -\frac{d\beta_{yy}}{dt} \tag{4}$$

According to the equations (3, 4), the characteristic responses ***l***(*t*) consists of two components $l_p(t)$ and $l_v(t)$ for axisymmetric targets. It can be expressed as follows:

$$\boldsymbol{l}(t) = \begin{bmatrix} l_v(t) & & \\ & l_v(t) & \\ & & l_p(t) \end{bmatrix} \tag{5}$$

For an axisymmetric target, the characteristic responses can be divided into two kinds. One is l_p(t) parallel to the major axis, and the other is l_v(t) perpendicular to the major axis.

The EMI response of a metal target can be approximated to the response of a single dipole only when the volume of the target is small enough or the transmitting coils are far enough. The primary field is substantially uniform over the range of the target. In order to achieve the uniform primary field, two kinds of transmitting coils will be discussed in next section.

3 TRANSMITTING COILS

3.1 Transmitting Coil to Excite the Target Parallel to the Major Axis

The long straight solenoid can generate the uniform primary field along the major axis, ensuring that all parts of targets can be excited uniformly. The specific parameters of long straight solenoid can be shown in Figure 2:

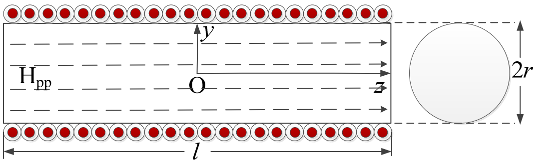

Figure 2: The parameters of a long straight solenoid.

As shown in Figure 2, the parameters of a solenoid include the length *l*, the radius *r* and the number of turns n_p. The internal primary field of a long straight solenoid is parallel to the major axis of it. If the transmitting current through the long straight solenoid is *I*, the amplitude of the primary field H_{pp} at any point along the *z*-direction can be calculated as:

$$H_{pp} = \frac{n_p I}{2l}\left[\frac{l/2+z}{\sqrt{r^2+(l/2+z)^2}} + \frac{l/2-z}{\sqrt{r^2+(l/2-z)^2}}\right] \tag{6}$$

According to equation (6), when the length *l* is 1.2 meters, the radius *r* is 0.11 meters, the number of turns n_p is 30, the current *I* is 9 amps, the distribution of the normalized primary field along the major axis can be calculated, as shown in Figure 3:

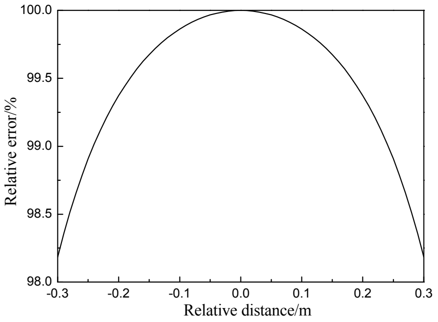

Figure 3: The relative error of field along the axial.

It can be seen from Figure 3 that the amplitude of the primary field at the center of the solenoid is the largest. Within the range of -0.3 meters to 0.3 meters, the primary field along the major axis of the solenoid is almost uniform. The uniformity of the primary field can reaches 98%. According to the equation (6), we can see that the amplitude of primary field at the center of the long straight solenoid $H_{\mathrm{pp}}(0)$ can be calculated as:

$$H_{pp}(0)=\frac{n_p I}{\sqrt{4r^2+l^2}} \tag{7}$$

3.2 Transmitting Coil to Excite the Target Vertical to the Major Axis

According to the principle of the Helmholtz coils, a pair of rectangular coils can be applied to generate the uniform primary field being perpendicular to the major axis. A pair of rectangular coils has been designed by this way to generate the uniform primary. The structure and parameters of a pair of rectangular coils are shown in Figure 4:

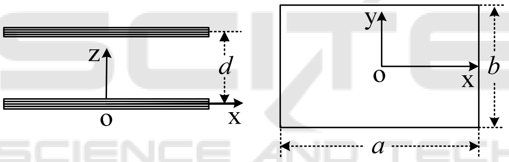

Figure 4:The parameters of a pair of rectangular coils.

As shown in Figure 4, the parameters of a pair of rectangular coils include the coil length a, the width b, the distance d and the number of turns n_{v}. For the currents in the two coils are the same, the x-component and the y-component of the primary field in the center plane of two coils cancel each other and the z-component is doubled. The primary field on the center plane can be expressed as:

$$\begin{aligned}H_{pv}=\frac{\mu_0 n_v I}{2\pi}\{&[\frac{a-x}{\sqrt{(a-x)^2+(b+y)^2+z^2}}+\frac{a+x}{\sqrt{(a+x)^2+(b+y)^2+z^2}}]\frac{b+y}{z^2+(b+y)^2}\\ &+[\frac{b-y}{\sqrt{(a-x)^2+(b-y)^2+z^2}}+\frac{b+y}{\sqrt{(a-x)^2+(b+y)^2+z^2}}]\frac{a-x}{z^2+(a-x)^2}\\ &+[\frac{a+x}{\sqrt{(a+x)^2+(b-y)^2+z^2}}+\frac{a-x}{\sqrt{(a-x)^2+(b-y)^2+z^2}}]\frac{b-y}{z^2+(b-y)^2}\\ &+[\frac{b+y}{\sqrt{(a+x)^2+(b+y)^2+z^2}}+\frac{b-y}{\sqrt{(a+x)^2+(b-y)^2+z^2}}]\frac{a+x}{z^2+(a+x)^2}\}\end{aligned} \tag{8}$$

When the current intensity I is 7.2 amps and z is 0.18 meters ($d/2$), n_{v} is 12, the distribution and the error rate of the primary field generated by a series of rectangular coils on the central plane can be calculated as:

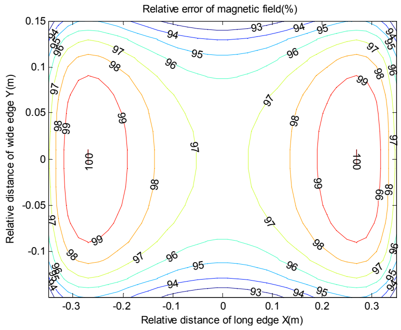

Figure 5:The error rate of the primary field.

As shown in Figure 5, due to the two rectangular coils are lied in opposite directions, the primary fields of x-component and y-component that are symmetric about the central plane almost offset to zero each other. And only the amplitude of the primary field along z-component is superimposed on each other. The uniformity of the primary field reaches 97% within a certain area, which can ensure the accuracy of the measured results of the characteristic responses.

The amplitude of primary field $H_{pv}(0,0)$ at the central plane generated by rectangular coils can be calculated as:

$$H_{pv}(0,0)=\frac{16n_v I}{\pi}\frac{ab}{\sqrt{4a^2+4b^2+d^2}}\left(\frac{1}{d^2+4a^2}+\frac{1}{d^2+4b^2}\right) \tag{9}$$

4 MEASUREMENT RESULTS AND ANALYSIS

4.1 Targets Description

The characteristic responses of six targets will be measured and analysis in this section. Three of them are tubular targets with same outer diameter and wall thickness and different length from 50mm to 300mm. The other three targets are mortar shells of different diameters. All these targets are shown in Figure 6:

Figure 6: Six kinds of typical target body.

The parameters and numbers of the six targets are listed in the table below.

Table 1: Parameters of targets.

Number	Length (mm)	Diameter (mm)	Thickness (mm)	Diameter (mm)
N1	300	75	4	\
N2	200			\
N3	57			\
N4	\	\	\	120
N5	\	\	\	82
N6	\	\	\	60

4.2 Characteristic Responses Analysis

The characteristic responses $l_{\mathrm{p}}(t)$ and $l_{\mathrm{v}}(t)$of three tubular targets numbered as N1, N2 and N3 are calculated, as shown in Figure 7:

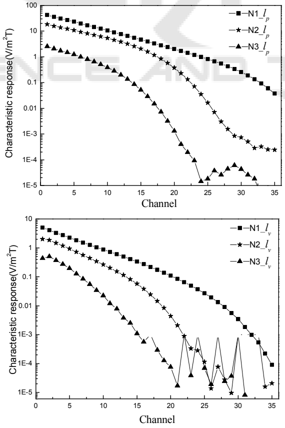

Figure 7: The $l_{\mathrm{p}}(t)$ and $l_{\mathrm{v}}(t)$ of tubular targets.

The characteristic responses $l_{\mathrm{p}}(t)$ and $l_{\mathrm{v}}(t)$of three mortar shells numbered as N4, N5 and N6 are calculated, as shown in Figure 8:

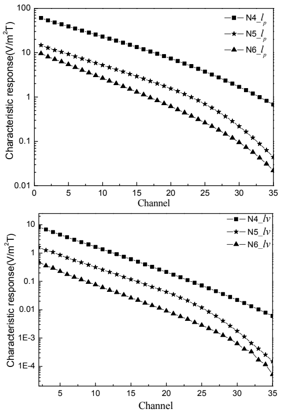

Figure 8: The $l_{\mathrm{p}}(t)$ and $l_{\mathrm{v}}(t)$ of mortar shells.

As shown in Figure 7 and Figure 8, the characteristic responses $l_{\mathrm{p}}(t)$ decay more slowly with larger amplitude compared to $l_{\mathrm{v}}(t)$. For tubular targets, the amplitude of $l_{\mathrm{p}}(t)$ and $l_{\mathrm{v}}(t)$ both increase with the length of targets. When the length of the tubular targets reduce to 50 mm, the characteristic responses decay so fast that the signal-to-noise ratio of the signal is too low to be used at late time. For mortar shells, the larger the volume, the greater the amplitude of $l_{\mathrm{p}}(t)$ and $l_{\mathrm{v}}(t)$ and the slower the characteristic responses attenuation will be.

5 CONCLUSIONS

An equipment which can generate uniform primary field is proposed in this paper. The uniformity of the primary field produced by the equipment reaches 97%. The characteristic responses of six targets have been measured and analyzed.

According to the dipole model, the characteristic response $l(t)$ of an axisymmetric target can be accurately measured only when the targets are excited uniformly by the primary field. The calculated results show that uniformity of the primary field reaches 98% for solenoid and 97% for rectangular coils.

By the equipment designed in this paper, the characteristic responses of six targets have been measured. The results show that the amplitude of the $l_{\mathrm{p}}(t)$ is about ten times than that of $l_{\mathrm{v}}(t)$, at the early stage. The longer the length of the target, the larger the amplitude of responses will be.

The equipment designed in this paper can be used to measure the characteristic responses of targets precisely. The physical information, such as the shape, structure can be well reflected by their characteristic responses. The work described in this paper is important for accurate detection and identification of unexploded ordnance.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China under Grant No. 41704145 and the Science and Technology on Near-Surface Detection Laboratory under Grant No. TCGZ2017A003.

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