APPLICATION OF TRANSIENT ELECTROMAGNETIC PULSE IN DETECTING SUBSURFACE TARGETS

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Abstract A basic scheme for detecting subsurface targets with nanosecond EM pulse and an especially developed high quality travelling-wave antenna are described. The antenna is a sort of sector antenna with structure of three layers, which possesses higher radiation efficiency and better travelling-wave properties. A fine resolution graphic system and a high speed display are employed in terminal processing. Metal pipes buried about 1 m under the earth can be detected and clearly displayed. High resolution and short processing time of the system, compared with other similar devices, make it suitable for engineering use.

Key words Transient EM pulse; Subsurface target detection; Travelling-wave antenna; Target imaging system

I. Introduction

The method of detecting subsurface targets using EM-pulse has recently attracted considerable attention, and acquired great advance[1-7]. This sort of radar is called impulse radar, which possesses high resolution, simple structures, and low cost. The emitted signal is a cyclic single EM-pulse with extremely broad spectrum. The larger data capacity makes it suitable for targets discrimination. Time domain processing technique can be used in the terminal system.

Impulse radar can be widely used in civil engineering, communication, geology, archaeology, and military affairs. The main properties of impulse radar are great propagation losses of EM-wave in the earth and serious dispersion. An imaging system with microcomputer for detecting underground targets has reported[5,6] in 1986 in Japan, and thereafter underground mapping of utility lines using impulse radar[1] has developed by Ohio State University. The similar research records are also reported in China[4,7,8].

The impulse radar in this paper possesses lateral resolution of targets of 50 cm, and depth resolution of 20 cm. The results are superior to other reported results. The radar system is portable and antennas are smaller and exquisite (70 cm in length). It is suitable to operate in the open air. Recorded wave-form curves and grey scale graphs from targets can be rapidly displayed and printed within 3 min. The radar system possesses engineering value.

II. Equation of Subsurface Radar and requirements for Deepening Detection Depth

The following equation can be deduced using the principle of radar and noncontinuous condition of air and surface of the earth[8].

$$S_{\text{in}} = \frac{P_t \eta_c D_t \eta_t \sigma T A_r}{(4\pi R^2)^2} e^{-0.466R} \tag{1}$$

where, P_t—the power of transmitting antenna. D_t, η_t—the directional coefficient and the efficiency of transmitting antenna respectively. A_r—the effective area of receiving antenna; σ—the cross-section of a target; η_c—the efficiency coupled into underground EM-energy; T—the transmissivity from underground into air of scattered wave of targets; δ—the damping factor of EM-wave in medium; R—the distance of a target to antenna on the earth, when antenna is placed on surface of the earth, R equals the depth of target; S_{in}—the power of return wave to impulse radar receiver.

If $P_t = P_{t\max}$—the maximum output power of radar transmitter; $S_{\text{in}} = S_{\text{in min}}$—the acceptable minimum power of radar receiver, then $R = R_{\max}$—the maximum detecting depth of radar.

$$(4\pi R_{\max}^2)^2 \exp(0.466 R_{\max}) = \eta_c D_t \eta_t \sigma A_r T(F/M) \exp(0.23I) \tag{2}$$

where $F = S_{\text{in max}}/S_{\text{in min}}$, the dynamic range of radar receiver; $M = S_{\text{in min}}/S_N$, the discrimination coefficient of radar, S_N—the noise level of receiver; $I = 10\log(P_{t\max}/S_{\text{in max}})$ is the isolation factor between the transmitting and receiving antenna. In order to deepen the detecting depth of radar, following steps can be conducted.

(1) Enhancing the isolation factor of transmitting and receiving antenna, namely, increasing I. Decreasing various noises of radar system, especially, mismatch reflection of system parts.

(2) Enhancing the output power of transmitter, it is possible to increase EM-pulse amplitude in impulse radar, and repetition frequency of EM-pulse properly and gain of transmitting and receiving antenna. Designing an antenna with better travelling-wave properties is the key problem, which possesses high gain and little kicking amplitude or shorter trailing edge of EM-pulse.

(3) Decreasing the discrimination factor M, using various methods to eliminate background noises, and to shorten processing time and to improve the signal-to-noise ratio, so that, reconstructed images of underground pipes are easy displayed to understand for users.

III. The Block Diagram of Impulse Radar and Design of Travelling-Wave Antenna

The block diagram of impulse radar is shown in Fig.1. Broadband microwave clipper is used to limit the strong signal of through pulse from transmitter to receiver, and to protect the sampler and to compensate smaller isolation factor due to parallel arrangement of the transmitting and receiving antenna. On the other hand, the purposes in using clipper are that to cut down sharp pulse which is useless and to stand out useful signal, and this will be convenient of signal processing. The nanosecond Gaussian type EM-pulse is used in the system, its amplitude is about 100 V. The width between half power points is about 2.5 ns and 1–1.2 ns of rising period, repetition frequencies of impulse can be set at 50 kHz, 100 kHz, 200kHz respectively.

One of the key problems is to design broadband travelling-wave antenna with high quality for the impulse radar. T. T. Wu et al.[9] put forth a symmetric cylindrical antenna with continuously varying resistive loading, which can be formed an unreflective travelling-wave antenna. As shown in Fig.2, let the antenna possesses constant radius, a length of single arm l, $I(z)$ is total axial current, $Z(z)$ is resistivity distribution.

When resistivity distribution is

$$Z(z) = \frac{60\psi}{l - |z|} \tag{3}$$

$$\psi = 2\left[\mathrm{sh}^{-1}\frac{l}{a} - c(2K_0a, 2K_0l) - js(2K_0a, 2K_0l)\right] + \frac{j}{K_0 l}(1 - e^{-j2K_0 l})$$

$$C(a,x) = \int_0^x \frac{1 - \cos\sqrt{a^2+u^2}}{\sqrt{a^2+u^2}}du, \qquad S(a,x) = \int_0^x \frac{\sin\sqrt{a^2+u^2}}{\sqrt{a^2+u^2}}du$$

K_0—the wave number in the air. Then a pure outward travelling-wave exists on an antenna of finite length. Namely $I(z) = C(|l| - |z|)e^{-jK_0|z|}$. C—a constant, $C = j2\pi\omega\varepsilon_0 V_0/\psi(1 + jK_0 l)$. The amplitude of travelling-wave current on the antenna presents linearly diminishable distribution. The terminal end of antenna is no longer reflective. But, lower radiation efficiency is a shortcoming of the antenna. Undistorted outward travelling-wave of current with diminishable amplitude can also be held on the antenna, when antenna is driven by nanosecond EM-pulse. Orthogonal orientation of antennas with decoupling polarization was used in many reported papers[1,4,7]. We have developed a dipole system of transmitting and receiving antenna with parallel orientation and with particular resistive loading. It is shown in Fig.3.

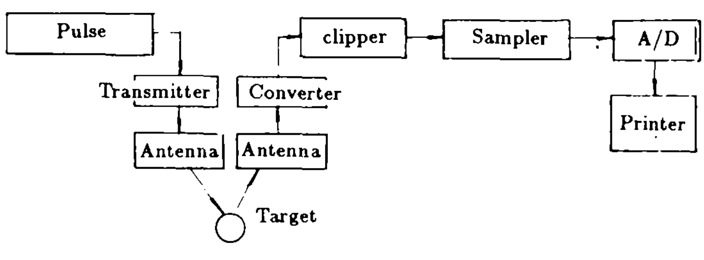

Fig.1 Block diagram of the system

A sector antenna with three layers is used in our system. The lower layer is consisted of metal, the intermediate and upper layers are consisted of dielectric and a coating of resistive absorbent materials respectively. The resistivity distribution of absorbent materials is different from other reported antennas. On the other hand, resistance values at terminal ends on antennas approach to zero and at driving points of antennas approach to maximum in our antenna. It is contrary to other reported designs, so that, metal part of antennas can

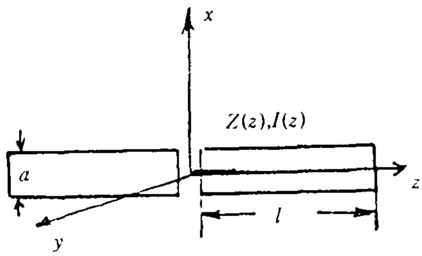

Fig.2 Cylindrical antenna of continuously varying resistive loading

produce strong radiation. Substantially, antenna designed by us is a sort of folded dipole antenna, which possesses better travelling-wave property, higher radiation efficiency, and simple structure.

The peculiar loading method and resistivity distribution can be considered a creative research results. This system of impulse radar can meet the requirements of practical operation.

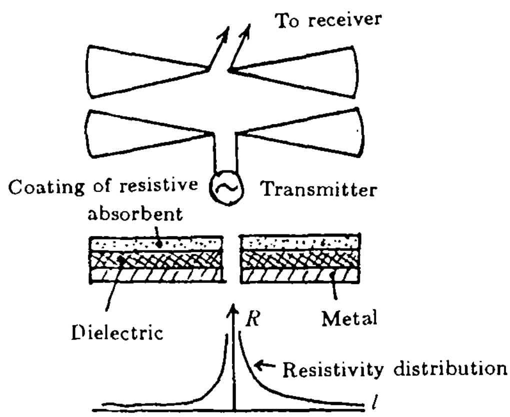

Fig.3 Antenna of three-layers structure

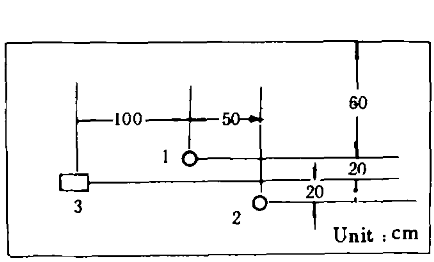

Fig.4 Experimental pit

IV. Terminal Signal Processing And Experimental Results

Microcomputer of APPLE—II and A/D converter of 12 bits are used in this radar system. Conversion time of A/D converter is less than 60μs. A waveform in time domain is sampled 256 points.

In order to pick up the reflected signal from underground targets and display grey scale graphs rapidly, the softwares compiled higher order language and 6502 assembler language are used in the system. Total process from sampling data to displaying and printing results of an image can be done in 3 min. A graph of high clearness on entire screen is displayed in 20s only.

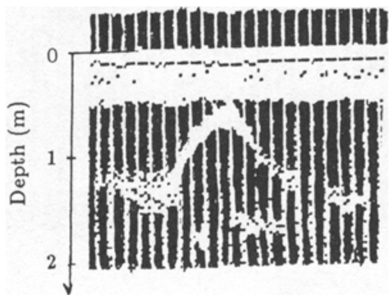

Fig.5 Experiment of single target

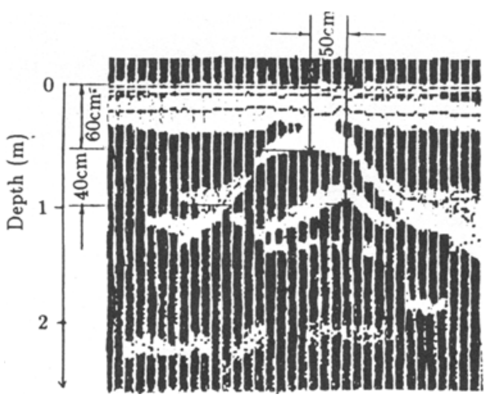

Fig.6 Experiment of two targets

In experiments, arms of antennas are in parallel to axis of a underground pipe and moving the antennas rapidly. At the same time, sampling data and processing signal can be conducted also. When metal layer of antennas is close to surface of the earth, which is corresponding to a strong coupling load, so that EM-energy coupled into the underground is increased. Experiments show that the back radiation (in air) of antenna is negligible.

In general, in order to efficiently detect return wave from targets, it is desirable to control wave form of EM-pulse source strictly, especially, to generate a EM-pulse with shorter trailing edge. As pulses transmitted and received will be distorted when passing through converter. To solve the problem, to design broadband balanced transformer and employ efficient cancellation technique due to noises in signal processing are very important. The method of longitudinal waveform comparison has been used in our terminal system, which is conducted that a sampling point of the first waveform is compared with the same sampling point of the second waveform. As a result of comparison, the changeable parts of waveforms

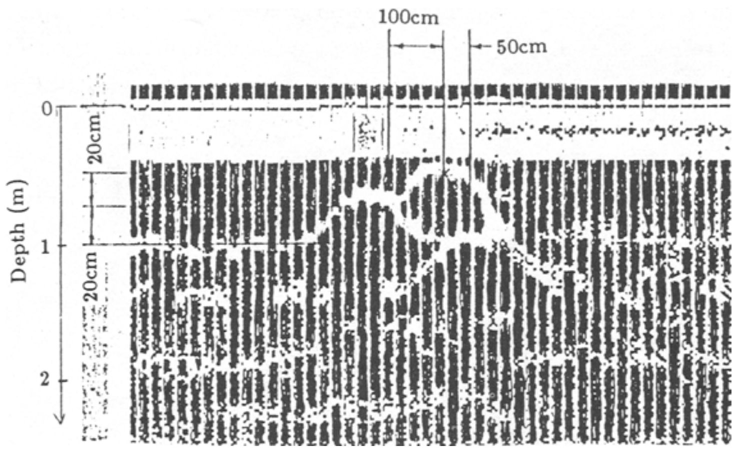

Fig.7 Experiment of three targets

are reserved and the fixed parts of waveforms can be canceled, so effect of trailing edge of impulse is overcome and smaller isolation factor of two antennas is compensated.

The experimental results and block diagram of experiment is as follows.

The experiment field is shown in Fig.4. Volume of a pit are $5000\times2300\times1100\mathrm{mm}^3$. Natural soil is filled in the pit, to simulate the earth. Target 1 and Target 2 are formed by cast-iron pipe, which are placed in 60cm and 100cm depths respectively. Target 3 is formed by $7\times4\mathrm{cm}^2$ square empty copper duct, which is buried at 80 cm in depth. Fig.5,6,7 show experimental results of single target (Target 1), of two targets (Target 1,2), of three targets (Target 1,2,3) respectively. Each bell curve of Fig.5,6,7 represents a target. The image of each target can be easily discriminated. The system of impulse radar can detect underground metallic pipes about 1 meter in depth.

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