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Restoration of Transient Electromagnetic Signal based Incremental Wiener Filter

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Abstract

Duo to the effect of receiving antenna, there is a certain deviation between the transient electromagnetic signal and the observation signal outputted from receiving antenna, leading to large blind areas in the shallow exploration of TEM. In order to improve the distortion of the outputted signal, the algorithm of deconvolution based on incremental wiener filter is proposed to recovery the signal in this paper. The influence of receiving antenna to transient electromagnetic signal is eliminated, and the optimum estimated is obtained after the algorithm is applied to realize the deconvolution of observation signal. Theoretical analysis and experimental results show that: compared with traditional damping matching method, the recovery signal by the algorithm has a better approximation to the theoretical signal, a higher resolution in shallow exploration, and the damping state of antenna has no influence on the recovery signal. It is of importance for improving transient electromagnetic shallow exploration.

Keywords*: transient electromagnetic, blind areas, incremental wiener filter, deconvolution*

1. Introduction

Transient electromagnetic method (TEM), also known as time domain electromagnetic method, is a time domain electromagnetic detection method on the basis of the principle of electromagnetic induction [1-3]. A primary magnetic field is send to ground by un-grounded loop or grounded line source. The eddy currents stimulated in underground geologic body by the primary magnetic field produce a secondary magnetic field, which contains ample geoelectric information. The underground geologic body is explored after the secondary field is extracted and analyzed by receiving antenna during the turn-off period of primary field [4]. Duo to the influence of transient process of receiving antenna, the observation signal outputted by antenna, especially the early signal, is a distorted signal. TEM early signals decay rapidly, rich in high frequency components, and the late signals low frequency in major decay slowly. The frequency response of receiving antenna performs as a low pass filter, which has little influence to late signals and attenuates the high frequency components of early signals seriously, leading to the distortion of early signals [5-7]. In order to reduce the impact of transient process of antenna to TEM signal, damping matching method is mainly applied to improve the outputted signal at present [8]. This method can effectively improve the frequency response of antenna including cut-off frequency, pass-band gain, etc. However, it is unable to compensate for the attenuation of the high frequency components caused by the receiving antenna, and it is hard to get the critical damping resistance to make the antenna at the right state.

The deconvolution technique has been widely applied in many fields of electronics, optics, spectroscopy, spectroscopy and image restoration, and commonly used in solving the problems of signal restoration and system identification [9-11]. Practical applications are limited out of observation signal with noise which leads to no convergence of deconvolution results [12]. The deconvolution technique is applied to recovery the TEM signal to eliminate the effect of receiving antenna on the TEM signal in this paper. Deconvolution is realized by incremental winner filter, and parameter g is introduced into this filter to solve instability of deconvolution system caused by high-frequency noise. The best estimation of the TEM signal is obtained by an iterative algorithm when observation signals get through the filter. Measured data shows that

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the method proposed in this paper effectively reduces blind areas and improves the resolution of shallow exploration.

2. The Effect of Damping Matching Method on the Performance of Antenna

The receiving antenna is the type of multi-turn air core coil. The equivalent circuit is shown in Figure 1:

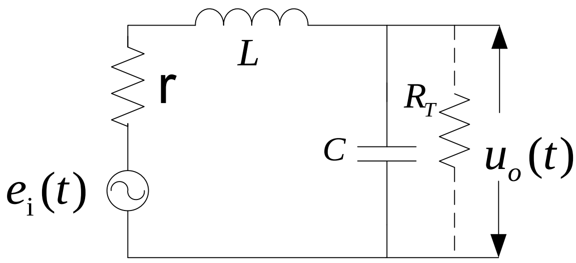

Figure 1. Equivalent Circuit of Receiving Antenna

Where $\varepsilon_i(t)$ is the induced electromotive force of receiving coil; L is the total inductance of the coil; C is the equivalent distributed capacitance of the coil; r is the resistance of coil; and R_T is matching resistance of coil. Assumed that the output signal of receiving antenna is $u_o(t)$. The second order system equation of the circuit is available by Kirchhoff's law, as shown below:

$$LC\frac{d^2u_o(t)}{dt^2}+(\frac{L}{R_T}+rC)\frac{du_o(t)}{dt}+(1+\frac{r}{R_T})u_o(t)=\varepsilon_i(t) \quad (1)$$

Let K= $\frac{RrC+L}{2\sqrt{LCR(r+R)}}$, called damping coefficient, $w_o=\sqrt{\frac{1}{LC}(\frac{r}{R}+1)}$, called resonant frequency, then the second order system equation is simplified as:

$$\frac{d^2u_o(t)}{dt^2}+2Kw_o\frac{dV}{dt}+w_o{}^2u_o(t)=\frac{\varepsilon_i(t)}{LC} \quad (2)$$

For formula (2), according to Laplace transform, the transfer function of receiving antenna can be written as:

$$H(s)=\frac{u_o(s)}{\varepsilon_i(s)}=\frac{1}{LC(s^2+2Kw_os+w_o^2)} \quad (3)$$

Do Laplace inverse transform to formula (3), then the impulse response of receiving antenna can be expressed as:

$$h(t)=\frac{1}{LCw_o\sqrt{K^2-1}}e^{-Kw_ot}\sinh(w_ot\sqrt{K^2-1}) \quad (4)$$

According to Laplace integral property, step response $u(t)$ equals to $L^{-1}[\frac{H(s)}{s}]$, then:

$$u(t)=\begin{cases}\dfrac{1}{LCw_o^2}\left\{1-e^{-Kt}[ch(w_ot\sqrt{K^2+1})+\dfrac{K}{w_o\sqrt{K^2+1}}ch(w_ot\sqrt{K^2+1})]\right\},K\geq 1\\ \dfrac{1}{LCw_o^2}\left\{1-e^{-Kt}[\cos(w_ot\sqrt{K^2+1})+\dfrac{K}{w_o\sqrt{K^2+1}}\sin(w_ot\sqrt{K^2+1})]\right\},K<1\end{cases} \quad (5)$$

Formula (4) and (5) show that impulse response and step response are affected by damping coefficient K, as shown in Figure 2 and Figure 3:

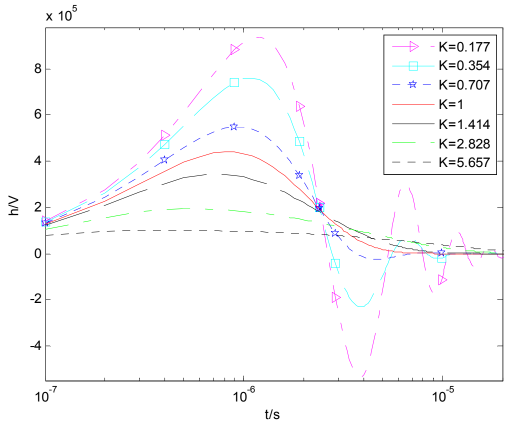

Figure 2. Impulse Response of the Different Damping Coefficient Receiving Antenna

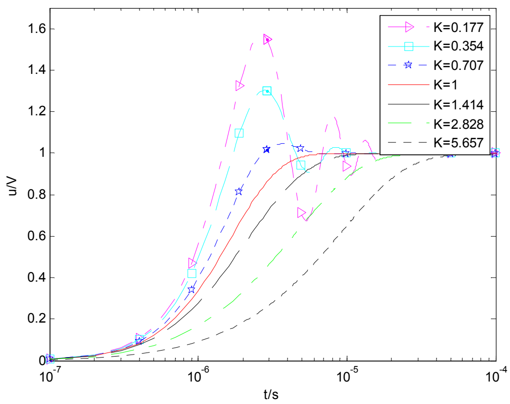

Figure 3. Step Response of the Different Damping Coefficient Receiving Antenna

Impulse response and step response reflect the performance characteristics of receiving antenna. The comparison of curves indicates damping coefficient has great impact on the performance of receiving antenna; the value of coefficient determines the response rate and the stability of antenna. As the observation signal is the convolution of TEM signal and impulse response of antenna, the performance of antenna greatly effect on observation signal. That is the damping coefficient determines the quality of observation signal. The impact of damping coefficient on TEM observation signal have been discussed in detail in literature [8], in which it was been presented that the effect is the smallest in the critical damping and observation signal distort seriously in over damping or under damping states.

The performance of antenna is improved by adjusting damping resistance in the damping matching method. However, the damping resistance is hard to just get the critical one duo to damping states are affected by many factors, as electromagnetic properties of geological body, surrounding electromagnetic environment, etc. Different critical resistances are needed at different environment, which is unpractical in the application. In order to reduce the effect of transient process of antenna to the TEM signal, improved deconvolution algorithm is presented in this paper.

3. Improved Deconvolution Algorithm

Deconvolution results don't converge if deconvolution is computed using FFT in frequency domain duo to deconvolution being sensitive to measurement error or noise, called deconvolution ill-posed problems [13-17]. Deconvolution filter is built to estimate the original signal, eliminating the effects of the system and noise in signal, shown as:

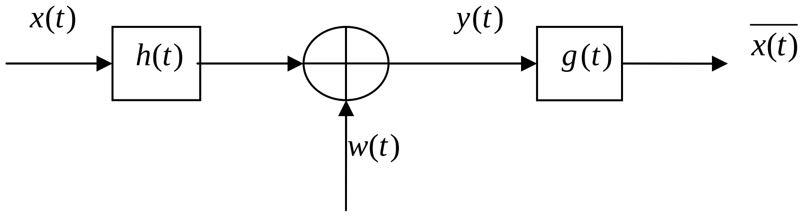

Figure 4. The Model of Distortion and Reconstruction of TEM Signal

Where $x(t)$ represents the TEM actual signal; $h(t)$ stands for receiving antenna; $w(t)$ is the noise; $g(t)$ is the deconvolution filter; $\overline{x(t)}$ is recovery signal.

The deconvolution filter built in this paper is incremental winner filter introduced constrains on the basis of winner filter. The optimal solution is obtained by iterative algorithm in the frequency domain when the observation signal gets through the filter. According to the criterion of winner filter, winner deconvolution filter is $\frac{H^*(w)}{|H(w)|^2+g}$, and g is the inverse of signal-to-noise ratio; $H(w)$ is the frequency response function of antenna; the output of winner deconvolution filter is as fellows:

$$\overline{X_b(w)} = \frac{H^*(w)Y(w)}{|H(w)|^2+g} \tag{6}$$

Define the error function of winner filter:

$$S(w) = Y(w) - \overline{X(w)}H(w) \tag{7}$$

then the error of $\overline{X_b(w)}$ is expressed as below:

$$S_1(w) = Y(w) - \overline{X_b(w)}H(w) \tag{8}$$

The new estimation is the output of incremental winner filter when the L_2 normal square of error is smallest. The new estimate of incremental winner filter is expressed as fellows:

$$\overline{X_f(w)} = \overline{X_b(w)} + \frac{H^*(w)S_1(w)}{|H(w)|^2+g} \tag{9}$$

Then the error of the new estimation is:

$$S_2(w) = Y(w) - \overline{X_f(w)}H(w) = \frac{gS_1(w)}{|H(w)|^2+g} \tag{10}$$

Where γ≥0, $|H(w)|^2$ ≥0, the new error satisfies the following formula:

$$\|S_2(w)\|^2 \le \|S_1(w)\|^2 \tag{11}$$

That indicates the deconvolution error can be reduced and the estimation from incremental winner filter provides a better approximation to the TEM theoretical signal.

The parameters of receiving antenna are as follows: L=31.5mH, C=22pF, r=26Ω. Then establishing three layers geoelectric model: $r_1 = 100\,Wm$, $r_2 = 10\,Wm$, $r_3 = 1000\,Wm$, the depth of each layer is as follows: h_1=100m, h_2=100m, h_3=300m. Firstly, using 1-D forward method to get the theoretical TEM signal x (t) of this model; with this signal getting through the receiving antenna, and adding white-noise w (t) on the output of antenna, then getting the noisy outputted signal y(t). Secondly, constructing the incremental winner filter based on frequency response function $H(w)$; with the noisy outputted signal as the input of the deconvolution filter, then getting the recovery signal $\overline{x(t)}$. Thirdly, employing damping matching method; obtaining the matching signal $u_o(t)$ at different damping states.

Figure 5 shows that the curves of recovery signal $\overline{x(t)}$ and the output signal of matching antenna $u_o(t)$ coincide with the theoretical signal x(t) on the late time, but there are large difference on the early time. When damping matching method is adopted to improve the distortion, the curve of signal in critical damping state gets consistent with that of theoretical TEM signal only when the time get closely to 900us; The curves at under or over damping states distort more seriously. The curve of recovery signal using deconvolution algorithm proposed in this paper coincides with theoretical one on 100us. This algorithm greatly reduces the distortion of the early signal.

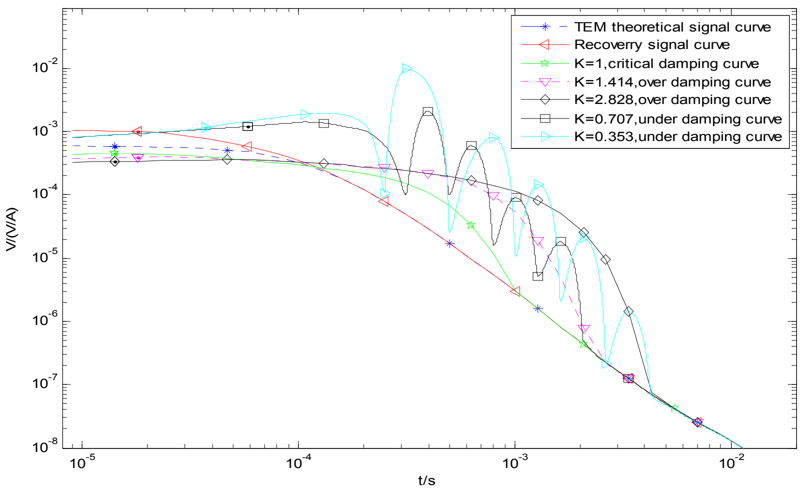

Figure 5. Different Response Curve of TEM Signal

4. Application Example

There are measured data in the mine of Shanxi measured by the device of TEM 57. The transmitting antenna is a square loop of 500 m in length. Bipolar rectangular pulse is sent; the transmitting current is 20 A; and the off-time is 100 μs. Figure 6 and Figure 7 show the results when data is processed by different methods (the vertical axis value on the right is relative apparent resistivity). Figure 6 shows the profile of observation signal when the antenna is just close to critical damping state. Figure 7 shows the profile of recovery signal by deconvolution algorithm. It is known that the gob of this area locates in depth of 450~500m, which is already full of water and part of the roof has caved, there are k2 limestone water at about 550m.The quaternary system aquifer is located in 10~70 m, where surface water is abundant.

From Figure 6 and Figure 7, it's shown that Low resistivity area is located at the horizontal number ranging from both 0 to 70 and 250 to 280, the depths ranging from 430~500 m, which's consistent with actual water areas. The collapsed Roof lead to the water being segmented and high resistivity area is formed. The Low resistivity area which is located at the horizontal number ranging from 120 to 300 crosswise and the depths ranging from 550~600 m has connected with the Low resistivity area which is located at the same depth and ranging from 250 to 280 crosswise; goaf water is just caused by k2 limestone water pressured. The inversion results of deep area are corresponded to actual geological structure. It suggests that the late transient electromagnetic signal has no distortion.

Figure 6 shows that there is high resistance area in depth of 0~300m, where no quaternary system aquifer appears; that indicates the early signal output from receiving antenna has seriously distorted. Due to the shallow blind area is more than 70m, then an exact shallow geological condition cannot be seen. However, there are many low resistivity anomaly areas at the horizontal number ranging from both 0 to 250, the depths range from 15 to 80m in Figure 7, which is the quaternary system aquifer. It's indicated that shallow blind area can be reduced to about 15m by the processing of improved deconvolution algorithm. Compared with the actual measurement results, the proposed algorithm is an effective method for improving TEM early signal.

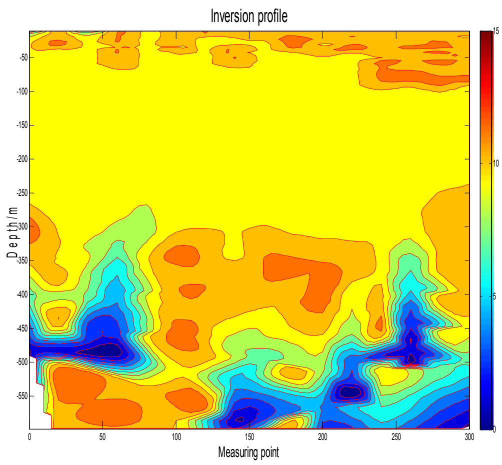

Figure 6. The Profile of Observation Signal

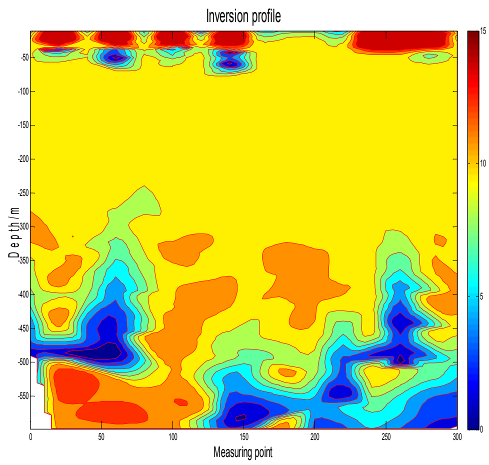

Figure 7. The Profile of Reconstruction Signals by Deconvolution

5. Conclusion

Due to the nonlinear system of receiving antenna, the early signal of receiving antenna is seriously distorted, leading to shallow blind areas becoming much larger. The early signal in critical damping state still has much deviation by damping matching method, let alone the signals in over damping and under damping; moreover it is difficult to match the damping. The deconvolution algorithm based on the incremental wiener filter is used to reconstruct transient electromagnetic signal in this paper; Compared with damping matching method, this method can reduce the signal distortion and make blind areas smaller to 15m whatever the damping state is. In a word, it is an effective method to reduce transient electromagnetic blind areas shallow exploration and have practical application value for improving the accuracy of exploration.

Acknowledgments

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