Enhancing Ultrasonic Echoes of Sediment Layer Based on 2nd Iterative Passive Time Reversal Mirror

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Abstract: The amplitude difference of the sediment layer’s echoes is always so large that the acoustic time difference becomes much difficult to get correctly. The existing methods of time varying enhancement for the multipath signal like ultrasonic echo have some limits in de-noising or practical application. This paper employs the second Iterative Passive Time Reversal Mirror to accomplish time varying enhancement for the ultrasonic signal. According the principle of measuring the sediment thickness in borehole by ultrasonic, the paper has established the system model to describe the processing of ultrasonic transmitting through the mud-sediment media, and simplified the channel in a linear, space-invariant, time-invariant multipath channel with two paths. Based on the model, the process of enhancing echoes of sediment layer by 2nd Iterative Passive Time Reversal Mirror is presented. Using the echoes of sediment with different thickness obtained in lab circumstance, two typical experiments to enhance the echoes have been taken. From the two experiments’ results we can see, 2nd Iterative Passive Time Reversal Mirror is sure to give the later arrival echo bigger gain than to the earlier one, thus reduce the amplitude difference of the two echoes. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Sediment thickness, Ultrasonic echo, Iterative passive time reversal mirror (IPTRM), Time varying enhancement (TVE).

1. Introduction

Sediment is soft and incompact materials with certain thickness, which deposit at the bottom of the cavities such as borehole, slurry wall slot and so on. The main ingredients of sediment are clay, small stone, sand and etc. [1]. Measuring sediment thickness using ultrasonic is an active method in recent years. Due to the sediment layer’s severe attenuation to the high frequency ultrasonic, the echoes’ amplitude of the sediment interfaces are much different, and the echo of the sediment’s lower interface is very feeble or even submerged in the noise sometimes. This much affects the acquiring of the acoustic time difference which the sediment thickness measurement is depended on.

As for reducing the amplitude difference between the echoes of sediment interfaces, Time Varying Enhancement (TVE) or Time Varying Gain (TVG) are effective methods. TVE is often used to deal with multipath fading in ranging, locating and communication by radar, sound and laser. The principle of TVE is giving larger gain to the longer path signal than to the shorter path signal, hence to compensate the energy loss during ultrasound transmitting in the medium. Using hardware or software based on certain algorithms all can fulfill TVE. In circuits designing, some automatic gain control device, AD603 for example, can amplify a signal with rather large range of amplitude into the one with relatively small range [2]. This method is fast but can’t recognize useful signal from noise. So,
it also amplifies the noise while amplifying the signal. Among the existing algorithms for TVE, most of them take advantage of inversion of the signal’s energy loss model to realize TVE [3]. As for ultrasound, according to the extension, absorbing and scattering during propagating, TVG usually includes three relevant parts [4]:

\[ G = G_0 + 2\alpha \cdot r + \beta \cdot \log \! r, \]  

(1)

where \( G_0 \), the original gain, is the constant and its unit is dB; \( \alpha \) stands for the influence of medium absorbing on signal, unit is dB/m; \( \beta \) stands for the influence of scattering on signal, unit is dB/m; \( r \) is the propagation distance of ultrasound, unit is m.

From the above principle of TVG, at least three parameters must be determined before processing. They are so close related to the features of both signal and medium that it’s difficult to be obtained or selected properly, even though some experiences or experiments can be referred. Furthermore, this process is high complex and has more uncertainties in real application.

Time Reversal Mirror (TRM) was put forward by Professor M. Fink in France Paris University firstly [5], and was applied in ultrasonic field soon. For example, smashing kidney stone in 1992 [6], brain healing in 1998 [7], the first shallow ocean communication experiment at Italy west coast [8] and etc. In recent years, TRM absorbs more focuses in the fields of underwater acoustic signal processing, electromagnetic detection and non-destructive inspection [9-12]. Seen from its principle and features, TRM and Passive Time Reversal Mirror (PTRM) are such methods that can enhance the multipath signal blindly [5, 13]. In 2005, L. Pautet and his workmates discussed the enhancement principle of Iterative Passive Time Reversal Mirror (IPTRM) of single-element and applied it to enhance the targets echoes in ocean ultrasound communication [8]. His work showed the TVE performance of the IPTRM for the ultrasonic signal.

This paper has established the model of the ultrasonic propagating in the mud-sediment based on the principle of measuring sediment thickness by ultrasonic. The ultrasonic channel is simplified in a multipath channel including two paths. According the model, paper explains the processing of enhancing echoes of sediment layer by 2nd IPTRM. Using the echoes of sediment with different thickness obtained in lab circumstance, some experiments to enhance the echoes by 2nd IPTRM have been made.

The results show, when the two echoes of the sediment layer have not overlapped together, IPTRM can offer an incremental gain with time increasing, then the later echo is amplified by a bigger gain than the former echo. Thus the gap between the two echoes’ amplitude is much reduced, and it produces big advantage to the subsequent processing of obtaining the time delay difference and the sediment thickness.

2. The System Model of Measuring Sediment Thickness by Ultrasonic

Fig. 1 shows the principle of measuring sediment thickness by ultrasonic. The ultrasonic probe vertically dives into the mud and emits ultrasound towards the sediment layer. Part of the sonic waves is reflected back to the probe when they meet the interface between the mud and sediment (called upper interface). Another part of the sonic waves enters the sediment and goes on to the interface between the sediment and the borehole bottom (called lower interface) where it is reflected back to the probe. Therefore, the ultrasonic probe will receive two echoes reflected by the two interfaces respectively. The time delay difference (TDD) between the two echoes is in direct proportion to the sediment thickness. Assuming the sound velocity in the sediment is \( v \), and the time delay difference is \( t \), then the sediment thickness is \( d = vt / 2 \).

Supposing emitted ultrasonic signal is \( s(t) \), the channel which ultrasonic propagates in is \( h(t) \), and the received echoes is \( r(t) \). The channel is supposed to be linear, time invariant, and space invariant processing, then

\[ r(t) = h(t) * s(t), \]  

(2)

where “*” is the linear convolution operator.

Further, if we only consider the direct waves, from the principle of the sediment thickness measurement, as shown in Fig. 1, the received signal includes two ultrasound echoes passing different paths respectively.

One path is from the probe to the upper interface and then back to the probe again, called path1; another path is probe-mud-sediment-lower interface-sediment-mud-probe, called path2. Therefore, the channel which ultrasonic signal spreads in can be regarded as a coherent multipath channel. When ignoring the non-uniform of the medium and the
randomness in the non-uniform interface, space varying characteristics of the channel can be expressed by system impulse response of a coherent multipath channel. Then, the ideal channel of the sediment measurement system in Fig. 1 can be written in a function including two impulses as

\[ h(t) = a_1 \delta(t-\tau_1) + a_2 \delta(t-\tau_2), \]  

(3)

where, \( a_1, \tau_1 \) are the gain and time delay of the first path respectively; \( a_2, \tau_2 \) are the gain and time delay of the second path. Obviously, the second path is longer and more severe damped than the first one, so \( a_1 > a_2, \quad \tau_1 < \tau_2 \). When ignoring the noise, the received echoes signal \( r(t) \) is

\[ r(t) = s(t)^* h(t) = a_1 s(t-\tau_1) + a_2 s(t-\tau_2) \]  

(4)

Obviously, the received echoes in (4) are highly similar with the emitted signal \( s(t) \). \( r(t) \) contains two echoes which undergo two different paths: \( a_1 s(t-\tau_1) \) and \( a_2 s(t-\tau_2) \). The time delay difference and amplitude ratio between the second echo and the first echo are \( \tau_0 = \tau_2 - \tau_1 \) and \( G_0 = a_2 / a_1 \). Since travelling a longer and harder path, the second echo usually has much smaller amplitude than the first echo. When using the common method of determining the wave arrival times by threshold, the big gap between the two echoes’ amplitude makes it difficult to select a proper threshold to get the correct wave arrival times. If we apply the IPTRM to enhance the echoes and reduce this gap, the threshold can be selected more easily and the TDD can be measured more correctly.

3. The Processing of 2nd Iterative Passive Time Reversal Mirror for Enhancement

The processing of PTRM is as follow: estimate channel by using received echoes and emitted signal, then the reversed received echoes convolutes to the estimated channel to simulate the processing of the reversed received echoes transmitting through the estimated channel. The convolution result is the PTRM output \( z^{(1)}(t) \). In fact, PTRM is the first IPTRM. The second IPTRM is the processing of the reversed 1st IPTRM output passing through the estimated channel. The output of the 2nd IPTRM \( z^{(2)}(t) \) is the convolution result of the reversed \( z^{(1)}(t) \) and the estimated channel. The 1st IPTRM and 2nd IPTRM processes are shown in Fig. 2. 3rd and plus IPTRM processes can be deduced out from the above processing.

If the estimated channel is correct or much close to the real one, that is to say \( h = h' \), the self-focusing function of PTRM makes its output \( z^{(1)}(t) \) collect more energy and get bigger gain. Fig. 3 shows the paths included in the three processes: ultrasonic passing through the real channel, 1st IPTRM and 2nd IPTRM. P1 and P2 denote the two paths in the Fig. 1. In Fig. 3, the center is the emitted ultrasonic signal \( s(t) \), it passes P1 and P2 and becomes the originally received signal \( r(t) \), so \( r(t) \) includes the two paths echoes. \( z^{(1)}(t) \) seems to have four paths echoes, but because the total lengths of P1-P2 and P2-P1 are same, so the echo passing P1 and P2 the echo passing P2 and P1 arrive at the same time and overlap into one echo. So, \( z^{(1)}(t) \) actually have three paths echoes. \( z^{(2)}(t) \) have four paths echoes: echo passing P1, P1 and P1; echo passing P1, P1 and P2 (also contain echo passing P1, P2 and P1 and echo passing P2, P1 and P1); echo passing P1, P2 and P2 (also contain echo passing P2, P2 and P1 and echo passing P2, P1 and P2); and echo passing P2, P2 and P2.

Although IPTRM has the capability to enhance signal in time varying way, but the number of the iteration should not be too high. Known from [13], in order to enhance signal and maintain the signal appearance at the same time, the number of the iteration \( k \) should be an even. Overall considering the gain, computation cost and complexity, we select 2nd IPTRM to enhance the echoes of the sediment layer. From the above section, the output of 2nd IPTRM is
\[ z^{(2)}(t) = r(t) * h'(-t) * h'(t) = r(t) * C(t) , \]  
where, \( C(t) \) is the autocorrelation of \( h'(t) \). When the estimated channel matches the real channel completely, \( C(t) \) is

\[ C(t) = h(t) * h(t) = (a_1^2 + a_2^2) \delta(t) + a_1 a_2 \delta(t-t_1 + t_2) + a_2 a_3 \delta(t-t_2 + t_1), \]

where symbol “\( \circ \)” stands for the correlation operation. Deducing from (6) and (4), we can get

\[ z^{(2)}(t) = a_1^2 a_2 s(t-2t_1 + t_2) + (a_1 a_2^2 + a_1 a_3^2) s(t-t_1) + (a_1^2 a_2 + a_2 a_3^2) s(t-t_2) + a_2 a_3 s(t-2t_2 + t_1) \]

In accord with the previous analysis, \( z^{(2)}(t) \) in (7) contain four echoes. From left to right, the time delays of the echoes are \( 2t_1 - t_2, t_1, t_2 \) and \( 2t_2 - t_1 \), and time delay differences of each pair of neighboring echoes are same with that of the received signal \( r(t) \). Since the sediment thickness only relates to the time delay difference of the echoes, every couple of the neighboring echoes in \( z^{(2)}(t) \) have all information needed in measuring sediment thickness and can be used to get the sound time difference and sediment thickness. Numbering the echoes as 1,2,3,4 from left to right, known from [13], the selection of echoes 1,2 has the biggest time varying gain, the selection of 2,3 also has bigger time varying gain, both selections have the capability of de-noising.

5. Experiments

We measured the sediment thickness by ultrasonic under lab simulated circumstance of borehole and got the echoes of sediment with different thickness. Using these echoes, some experiments to enhance the echoes by 2nd IPTRM have been done.

Experiment 1: The used ultrasonic signal is shown in Fig. 4(a). There are three wave clusters, the first one is the signal emitted by ultrasonic probe, the second one is the echo of the sediment’s upper interface (called echo 1), and the third one is the echo of the lower interface (called echo 2).

Because the sediment is rather thick in this experiment, the space between the two echoes is big enough to separate them. If the channel is close to a linear time invariant system, the three clusters should be homologous, attenuated and delayed [14-15]. So, they are much similar with each other, and reasonably, echo 1 can replace the emitted signal which is distorted because of saturation to estimate the channel. Fig. 4(b), called \( r_1(t) \) includes the two echoes of the signal in Fig. 4(a) and is crucial for measuring sediment thickness.

Fig. 5(a) is the estimated channel from Wiener filtering when using \( r_1(t) \) as the received signal, and the first echo in \( r_1(t) \) as the emitted signal. In this processing, the so-called emitted signal is same with the first echo in \( r_1(t) \), so, the first impulse amplitude in estimated channel is unit, and the second impulse corresponding to the second echo is much feeble. Fig. 5(b) is the 2nd IPTRM output based on estimated channel in Fig. 5(a) and \( r_1(t) \). It can be seen that the first echo has not be amplified, but the second echo becomes much larger than before. To be clear, the received echoes signal \( r_1(t) \) and the output of 2nd IPTRM are shown in the same plot of Fig. 5(c). In Fig. 5(c), the blue line is the output of 2nd IPTRM, and the red line is \( r_1(t) \).

With the values shown in this figure, the gain of the second echo can be calculated out and it is about 3.5. That is to say, after 2nd IPTRM, the first echo keeps no changing, and the second echo is zoomed in 3.5 times. It is sure that the gap between the two echoes’ amplitude becomes smaller than before.

Experiment 2: Fig. 6(a) is the ultrasonic signal obtained under thin sediment layer condition. There also are three wave clusters, but the sediment is so thin that the echoes of the two interfaces are jointed together. Fig. 6(b), called \( r_2(t) \), only includes the two echoes of the signal in Fig. 6(a). The part between the two blue lines in \( r_2(t) \) is selected to be used in channel estimation as emitted signal. Fig. 6(c) is shown the output of 2nd IPTRM and the amplified original echoes \( r_2(t) \). The gain of the second echo can be calculated out and it is larger than 3. The gap between the two echoes’ amplitude is also much reduced.
5. Conclusions

Measuring sediment thickness by ultrasonic is usually dependent on the measuring of the time delay difference of echoes. In practice, the echo of the sediment’s lower interface is feebler than that of the upper interface because of the sediment’s severely attenuating effects. This worsens or invalids the result of the traditional method using threshold to determine the acoustic time difference of the echoes.

The time-space self-focusing function of IPTRM can perform time varying enhancement for the multipath signal like ultrasonic echoes. Just based on this fact, this paper utilizes 2nd IPTRM to enhance the echoes of the sediment layer.

The paper establishes the system model of ultrasonic transmitting through the mud-sediment media. According the principle of measuring the sediment thickness in borehole by ultrasonic, the channel which ultrasound passes through is ideally...
simplified in a linear, space-invariant, time-invariant multipath channel of two paths. Based on this model, the paper gives out the output of 2nd IPTRM of the echoes. Two typical experiments to enhance the echoes of sediment layer with different thick by 2nd IPTRM have been made. From the experiments’ results, 2nd IPTRM is sure to give the later arrival echo bigger gain than the earlier one, thus the amplitude difference of the two echoes is reduced and the aim of time varying enhancement is realized. Comparing the two experiments’ results we can see, the result of 2nd IPTRM is better when the two echoes separated largely in time axis. When the difference of the two echoes’ arrival time is so small that the two echoes overlaps together, the result of 2nd IPTRM has more noise and may disorganize the later echo. Therefore, the 2nd IPTRM can accomplish TVE of the echoes of thick sediment layer, and must be used carefully when the sediment layer is too thin.

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