Analysis Technique for Layered Structures using Wiener Spiking De-Convolution

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***Abstract*—Soil and snow are type of media that generally contain several layers of different physical properties normally characterized by moisture, tortuosity, porosity, density, etc. The layers are generally separated by layer boundaries and each layer has different acoustic impedance. Stratigraphy studies are useful in many areas like warning of avalanches, estimation of water content of a snowpack, determination of the water content of soil, porosity and type of soil, etc. Researchers have proposed non-invasive acoustic techniques to determine the properties of media layers. An acoustic sound source placed at a distance from the layered structure under test is used to transmit the desired acoustic signal of appropriate bandwidth and frequency range towards it as per the requirement of the stratigraphy. The basic analysis technique generally used is cross-correlation in which the layer resolution depends on the probe signal bandwidth. A new technique for stratigraphy based on Wiener spiking de-convolution (WSD) signal processing technique is presented, in this paper. In the proposed WSD based signal processing technique the layer resolution is independent of the probe signal bandwidth. It has been demonstrated using the experiments conducted in laboratory that proposed technique is capable of resolving layers with much lower probe signal bandwidth that is actually required for a conventional technique.**

Keywords—Wiener, spiking, de-convolution, Acoustic reflectometry, layer resolution.

I. Introduction

Media such as soil, snow etc. are generally made of layered structure [1]- [5]. Each layer has different amount of acoustic impedance due to the different properties of the layers. Stratig- raphy of such media structures are useful in many areas like determining the water content of a snowpack, prediction of avalanches, determination of the moisture content of soil, type of soil, etc [3]. There exists non-invasive techniques that use acoustic signal to determine properties of layered structure. In non-invasive straightgraphy studies an acoustic sound source transmits an acoustic signal towards the structure under test. The acoustic signal gets reflected from the interfaces exist between different layers due to difference in impedances between the layers and the reflected signals from the interfaces are recorded and processed to obtain the layer properties.

In the conventional acoustic reflectometry technique an acoustic pulses such as linear frequency modulated (LFM) signal, exponentional chirp signal, maximum length sequence (MLS) are used as a probe signal. These all signals are broadband and the signal processing technique generally used is cross-correlation between the transmitted and the received signal. In cross-correlation technique the layer resolution depends on the bandwidth of probe signal [6]. We have proposed a noval technique based on Wiener spiking de-convolution (WSD) in which the layer resolution does not depend on the probe signal bandwidth. The proposed WSD based signal processing technique is also implemented and tested in laboratory on actual signals received from layered structure.

The next section, presents the complete reflectometry sys- tem block diagram. In the third section, the WSD filter design is given. The fourth section of the paper presents the results of experiments conducted in a full anechoic chamber. In the final section the conclusion of the paper is given.

II. Complete Reflectometry System

The functional diagram of the complete acoustic reflectometry system is shown in Fig. 1. The required test signal is generated from PC in softwares like Lab-View. This signal being digital required to be converted to an analog signal. The conversion of the digital signal to an analog signal is done using a digital to analog converter (DAC). The power amplifier is used to amplify the analog signals. The amplified signal is then fed to the loudspeaker for the transmission of acoustic signals, which is placed above the media under test.

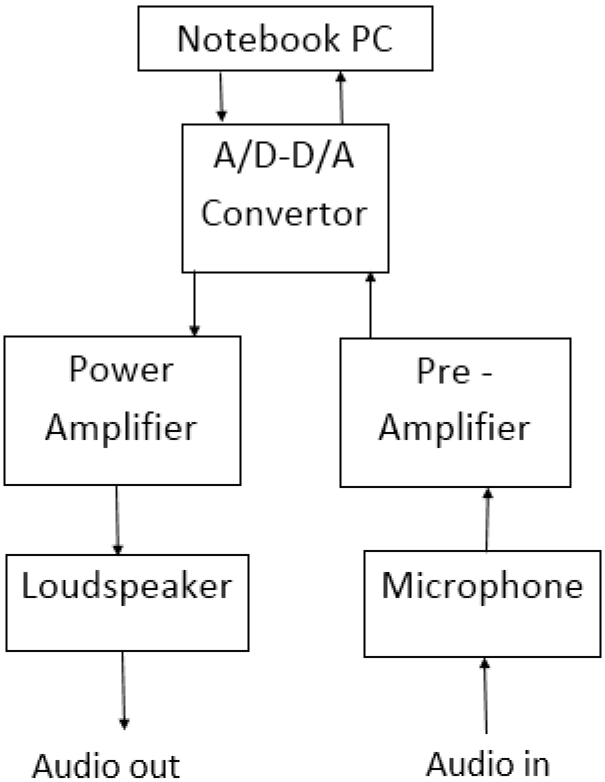

Fig. 1. Complete Functional Diagram of Acoustic Reflectometry System

The transmitted signal will be reflected whenever there is a change in acoustic impedance that generally occurs at layer interfaces. There are media such as snow where the traveling signals get highly attenuated. The WSD based proposed technique does not depend on the bandwidth of the test signal to resolve the different components of the reflected signals from the different layer interfaces. This allows one to choose the range of frequencies of the test signal that encounters relatively less attenuation in the media. The direct and reflected signals would be picked-up by the microphone. The pre-amplified version of the signal is fed to an analog-to-digital (ADC) converter. The digital signals from of the ADC are analyzed using a notebook PC and stored in memory for off-line processing.

The loudspeaker and the microphone are placed just above the surface of the media under test. The components used in actual setup are as shown in Fig. 2. The specifications of all the components of the system are summarized in table I.

The composite received signal and the transmitted probe signal are cross-correlated in acoustic reflectometry to find the layer information. The layer resolution δl for a cross-correlation based conventional system is given as [6]:

$$\delta l = \frac{S}{2B} \tag{1}$$

where B is the bandwidth of the probe signal and S is the speed of sound in the medium. For example, if the bandwidth of the probe signal and speed of sound in air are assumed to be 10 kHz and 340 m/s respectively, the layer resolution will be 1.7 cm [6].

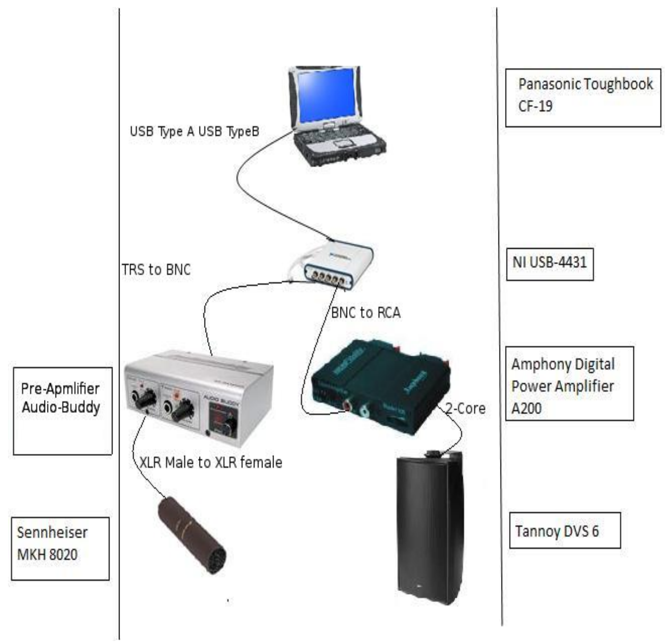

Fig. 2. Acoustic Reflectometry System with Actual Components and Cables

TABLE I. SPECIFICATIONS OF COMPONENTS OF THE HARDWARE SYSTEM

Components (Model Number)	Specifications	Value/Range
Power Amplifier Amphony (A200)	Bandwidth (-3dB)	1 Hz-70 kHz
	Power Output	80 W
	Signal To Noise Ratio	115 dBA
Pre-Amplifier (Audio Buddy)	Bandwidth (-3dB)	15 Hz-50 kHz
	Gain	60 dB
	Input Impedance	100K ohm
Loudspeaker Tannoy (DVS6)	Average Power	60 W
	Sound Pressure Level	105(dB)
	-3dB Bandwidth	85 Hz- 20 kHz
	Sensitivity	60dB 1W@1m
Microphone (MKH8020)	Maximum SPL	138 dB
	3dB Bandwidth	20 Hz-70 kHz
	Sensitivity	31 mV/Pa
DAQ NI-4431	A/D Resolution	24-bits
	PC Interface	USB
	Sampling Frequency	102.4 kS/s

III. WIENER SPIKING DE-CONVOLUTION

In the WSD model, an acoustic pulse or electromagnetic pulse is transmitted through the layered structure and reflected signals from the layer boundaries are recorded. In Wiener spiking de-convolution the inverse filter of the probe signal is designed. The recorded signal is passed from the inverse filter. The output of the inverse filter consists of series of impulse train corresponding to the each reflected signal [7]- [10].

The inverse filter is generally designed using least-squares method. Inverse filtering operation attempts to reshape the each reflected signal into the desired output normally an impulse by minimizing the mean-squared error between the actual filter output and the desired filter output as given in (2).

$$\begin{pmatrix} r_0 & r_1 & r_2 & \cdots & r_{n-1} \\ r_1 & r_0 & r_1 & \cdots & r_{n-2} \\ r_2 & r_1 & r_0 & \cdots & r_{n-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ r_{n-1} & r_{n-2} & r_{n-3} & \cdots & r_0 \end{pmatrix} \begin{pmatrix} f_0 \\ f_1 \\ f_2 \\ \vdots \\ f_{n-1} \end{pmatrix} = \begin{pmatrix} g_0 \\ g_1 \\ g_2 \\ \vdots \\ g_{n-1} \end{pmatrix} \tag{2}$$

Where, ri are the autocorrelation lags of the input probe waveform and fi are Winer filter coefficients. The gi are the cross-correlation lags of the desired output with the input probe signal. The range of i is from 0 to n – 1.

The desired filter output is obtained by convolving input received signal with the Wiener filter coefficients [7].

When the filter output is an impulse with zero delay the technique is called Wiener spiking de-convolution and mathematically given by (3) [8]. In case of Wiener spiking de-convolution the elements of the left hand side matrix of (2) and (3) are calculated using auto-correlation with different lags performed on the received signal. In least squares inverse filtering the elements of the left hand side matrix of (2) and (3) are computed directly from the known probe signal. If the probe signal is not a minimum phase signal, Wiener spiking de-convolution filter will not be able to convert the probe signal to a perfect zero lag spike [8]- [10].

$$\begin{pmatrix} r_0 & r_1 & r_2 & \cdots & r_{n-1} \\ r_1 & r_0 & r_1 & \cdots & r_{n-2} \\ r_2 & r_1 & r_0 & \cdots & r_{n-3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ r_{n-1} & r_{n-2} & r_{n-3} & \cdots & r_0 \end{pmatrix} \begin{pmatrix} f_0 \\ f_1 \\ f_2 \\ \vdots \\ f_{n-1} \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \end{pmatrix} \tag{3}$$

IV. EXPERIMENTS AND RESULTS

To study the performance of the WSD technique based acoustic reflectometry system, a layered structure is constructed using three sheets made up of thermocol as shown in Fig. 3. The height of both the transducers is kept 87 cm from the lower thermocol sheet and 50 cm from the top thermocol sheet respectively. The third sheet between the top and the bottom thermocol sheets is kept at a height of 20 cm from the bottom sheet. The path distance between the loudspeaker and the microphone is 30 cm. The calculated signal path distance from the loudspeaker to the microphone from the top sheet is 72 cm.

For layer interface structure shown in Fig. 3, apart from a direct pickup signal there will be mainly three dominant reflected signals in the received signal. The reflected signal will come from top, middle and bottom layer interfaces. The calculated path distance corresponding to these signals are 30 cm, 72 cm, 137 cm and 175 cm respectively. The time taken by each of these components to travel are 0.88 ms, 2.12 ms, 4 ms and 5.15 ms respectively, if the speed of sound in air is assumed to be 340 m/s. Apart from these components, the received signal also consists of signal components due to multiple reflections from the interfaces and loudspeaker. The concept of two times reflected signal between the loudspeaker and the top thermocol sheet is illustrated in Fig. 4. This multipath signal has to travel a distance of 100 cm, which will take 2.94 ms.

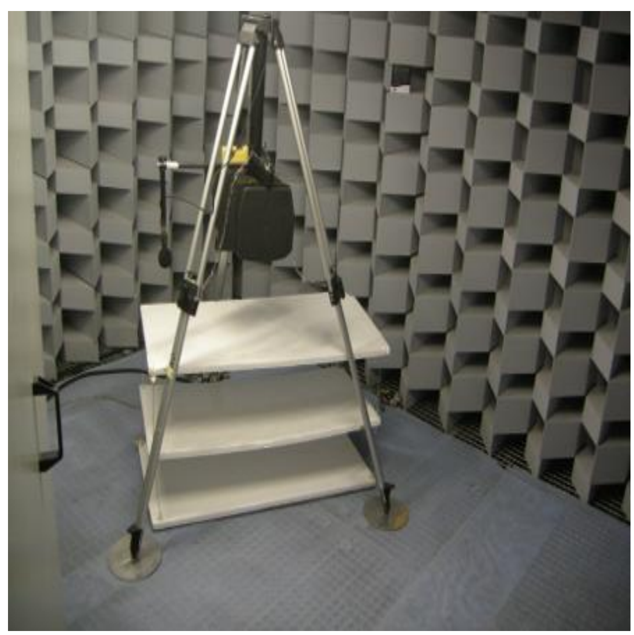

Fig. 3. Actual Experimental setup in Anechoic room

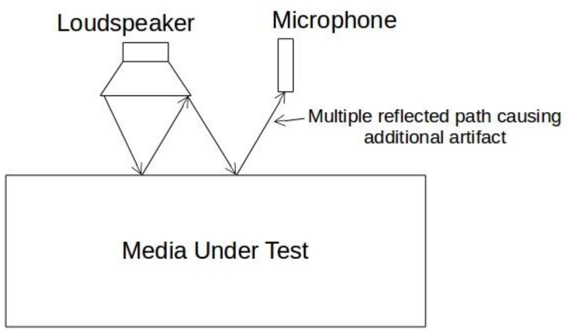

Fig. 4. Illustration of reflections from layer interfaces between the media and the loudspeaker box

The distances traveled by all the components of the received signal and their corresponding travel time are summarized in table II. Some of the reflected signals can merge with the multiple times reflected signal.

A linear frequency modulated signal also known as chirp signal is used as a probe signal. The start and stop frequencies of the chirp are taken as 100 Hz and 500 Hz respectively, and the duration of the sweep is taken as 1 second. The calculated layer resolution using (1) for cross-correlation based conventional technique for the above probe signal is 42.5 cm that corresponds to a time resolution of 1.25 ms. The received signal is analyzed using WSD technique as given in (3). It is observed from the WSD filter output shown in Fig. 5 that all the spikes corresponding to each component of the received signal are present even the layer separation is less than 40 cm. The time resolution is of the order of 0.1 ms as the width of the spikes is only about 0.1 ms as observed from Fig. 5. So, we have obtained an improvement factor of 12.5 in layer resolution using the proposed method on actual signals recorded in the laboratory. The WSD analysis based acoustic reflectometry system has successfully detected the various components of the received signal from a three interface structure.

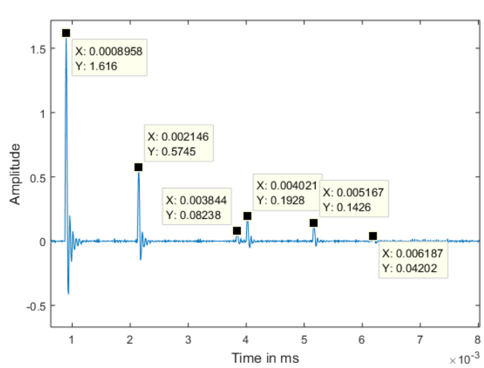

Fig. 5. WSD filter output for the received signal from a three layer interface structure

It is demonstrated that the designed acoustic reflectometry system based on WSD analysis technique can be used for stratigraphy studies.

V. Conclusion

In conventional acoustic reflectometry system the probe signals used are generally broad band and analysis technique used is cross-correlation. The layer resolution in crosscorrelation technique strictly depends on the test/probe signal bandwidth. A novel approach based on Wiener spiking deconvolution technique is proposed in which the layer resolution is independent on the probe signal bandwidth. It has been demonstrated using laboratory experiments conducted on a three layer interface structure that the proposed WSD analysis technique for acoustic reflectometry can be used for stratigraphy.

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