



Development of signal processing techniques for ultrasonic measurements

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Abstract

Signal processing involves techniques that improve our understanding of information contained in received ultrasonic data. Simulation and data processing in ultrasonic testing plays an important role for analyzing results and performance demonstration. Another very common application is the design and optimization of inspection methods. However, comprehensive understanding of the processes taking place in the testing specimen is available only by fully investigating testing instrumentation and method. It includes analysis of the wave propagation in the structure under investigation and analysis of the characteristics of the instrumentation being used. This paper describes the digital signal processing techniques for ultrasonic wave propagation, which is validated for experimental study.

Keywords: Ultrasonic, Signal processing, Wave propagation, Digitizer, Simulation.

Introduction

Signal processing involves techniques that improve our understanding of information contained in received ultrasonic data. Normally, when a signal is measured with an oscilloscope, it is viewed in the time domain (vertical axis is amplitude or voltage and the horizontal axis is time). For many signals, this is the most logical and intuitive way to view them. Simple signal processing often involves the use of gates to isolate the signal of interest or frequency filters to smooth or reject unwanted frequencies. When the frequency content of the signal is of interest, it makes sense to view the signal graph in the frequency domain. In the frequency domain, the vertical axis is still voltage but the horizontal axis is frequency. The frequency domain display shows how much of the signal's energy is present as a function of frequency. For a simple signal such as a sine wave, the frequency domain representation does not usually show us much additional information. However, with more complex signals, such as the response of a broad bandwidth transducer, the frequency domain gives a more useful view of the signal.

According to Fourier any complex periodic waveform can be decomposed into a set of sinusoids with different amplitudes, frequencies and phases. The process of doing this is called Fourier analysis, and the result is a set of amplitudes, phases, and frequencies for each of the sinusoids that make up the complex waveform. Adding these sinusoids together again will reproduce exactly the original waveform. A plot of the frequency or phase of a sinusoid against amplitude is called a spectrum.

Numerical Simulation- that is the use of computers to solve problems by simulating theoretical models- is a part of new technology that has taken place alongside pure theory and experiment during the last few decades. Numerical simulations permit one to solve problems that may be inaccessible to direct experimental study or too

complex for theoretical analysis. Computer simulations can bridge between analysis and experiment (Murawski, 2002).

Very often the simplest physical phenomena are described by complicated mathematical equations which cannot be solved analytically and require numerical treatment. The basic idea of computer experiments is to simulate the physical behavior of complicated natural systems by solving an appropriate set of mathematical equations that are built on the basis a physical model. A typical way for computer simulation is to develop a mathematical model of differential or integral equations and then to transform them to a discrete form that can be numerically treated. By this way, numerical simulations attempt to initiate the dynamic behavior of a system and to predict or calculate subsequent event.

In modern ultrasonic non-destructive evaluation systems, it is necessary to capture received signals so that they can be processed further and quantitatively evaluated. This is done through an analogue to digital conversion process and can take place inside the oscilloscope itself if it is a digital scope or via an external digitizer. Once in digital system, the signal can then easily be transferred to a computer for analysis.

Several numerical schemes such as Fourier method and the finite difference method were developed and compared for KdV (Kertweg-de Vries) equation by Abe *et al.* (1980). The results of this comparison revealed that the Fourier method is the most accurate and efficient.

The linear theory based on the Fourier transform was applied to the study of ultrasonic wave propagation in the polymeric film strip by Malinaric *et al.* (1998). You *et al.* (1998) studied numerical simulation of ultrasonic wave propagation in solid materials. Safari *et al.* (1997) proposed new signal processing scheme for ultrasonic imaging of high loss composite structure. Andria *et al.* (2001) presented a digital signal processing techniques



for obtaining high accuracy in ultrasonic distance measurements. The proposed methodologies employ a suitable time-frequency representation (Wavelet Transform or Short Time Fourier Transform) to extract the envelope of the reflected pulse echo, together with a suitable pulse detection algorithm (threshold or correlation) for time-of-flight estimation. Hill *et al.* (2004) discussed the finite element modelling in simulating elastic wave propagation associated with structural vibrations, acoustic phenomena and ultrasound problems using PAFEC software. San Emeterio *et al.* (2004) presented an approximate frequency domain electro-acoustic model for pulsed piezoelectric ultrasonic transmitters, which, by integrating partial models of the different stages, allows the computation of the emission transfer, function and output force temporal waveform. Hirsekorn *et al.* (2004) described numerical simulations of acoustic wave propagation through sonic crystals consisting of local resonator using local interaction simulation approach. Local Interaction Simulation Approach (LISA) has proposed by Ruzzene *et al.* (2005) as an alternative to Finite Element (FE) and Finite Difference (FD) methods proposed by Delsanto *et al.* (1998) for the efficient simulation of ultrasonic waves in homogeneous and heterogeneous solids. LISA uses the same formalism as FD, but addresses the problem of discontinuities at interfaces by locally matching particle displacements and stresses. These results show the validity of the digital signal processing technique for ultrasonic measurements.

Simulation technique

Numerical simulations have emerged as a new branch in science complementing both experiments and theory. A simulation can sometimes replace a physical experiment, although most often a simulation and an experiment are complementary. Simulations often explain results of scientific experiments and simulations are often calibrated by experiments. The experiments provide input for the simulations, which are viewed as experimenting with theoretical models. The feedback of numerical results into theoretical modelling and continues interaction with laboratory experiments and analytical theory makes computing an indispensable tool for science (Murawski, 2002). Therefore the increase in computing power in both speed and storage has given computational science its significance. Improved computer capacity and the solution algorithms themselves, have a large effect on the quality of solution obtained.

Numerical simulations can be used to study the dynamics of complex physical systems. Although the variety of complex flows that computational fluid dynamics can analyse continues to increase, the solutions too much more complex flows are desired. A numerical model can be used to interpret measurements and observations, extend existing analytical models into

new parameter regimes and quantitatively test existing theories that can be done by comparing model predictions to experimental data (Hafez, 2003).

Modern computers are fast and do not complain of boredom when repeating the same procedure millions of times. Analytical methods, on the other hand, have been plagued with this problem. With the use of computer, one can often test theoretical predictions and approximations. The numerical methods are simpler and more idealized than the actual physical system. However, they are far more complete and realistic than we can handle analytically.

Computer simulations contain many advantages over conventional experiments. Simulation can evaluate the importance of a physical effect by turning this effect on or off, changing its strength, or changing its functional form. This way of isolating effects is an important advantage that a simulation has over an experiment.

The main advantage of computer experiments is that complicated physical system involving non-linearity and in-homogeneity can be treated without difficulty as easily as much simpler linear and homogeneous systems are dealt with. As a consequence of that non-linearity and in-homogeneity is no longer an obstacle in exploitation of physical systems. The computer simulation reproduces both linear and nonlinear behavior of a physical system (Ludwing *et al.*, 1995). One can compare the results of such calculations with the behavior of real physical systems and with theory. These results can then be used to test theoretical predictions.

Both simulations and laboratory experiments benefit greatly from focusing on specific mechanisms of complex phenomena. Therefore, much can be learned about physical phenomena by idealizing and simplifying the problem. As a consequence of that, an experiment is not always a better probe of a physical system than a simulation.

Simulation can be used to test the range of validity of theoretical approximations. For example, when a linear theory breaks down, simulations can study the reason of breakdown. The reverse case is also true as theory can be used to validate a numerical model.

Numerical simulations analysis and experiment cover mutual weakness of both pure experiment and pure theory. These simulations will remain a third dimension in fluid dynamic of equal status and importance to experiment and analysis. It has taken a permanent place in all aspects of fluid dynamics, from basic research to engineering design. The computer experiment is a new and potentially powerful tool. By combining conventional theory, experiment and computer simulation, one can discover new and unsolved aspects of natural processes. These aspects could often neither have been understood nor revealed by analysis or experiments alone.

Traditionally, the study of acoustics begins with the analysis of mechanical waves Kinsler *et al.* (2000). This quickly leads to the wave equation, which relates the

motion of particles in time and space. Soon after, to account for losses, a lossy wave equation is derived. One of the solutions for this differential equation is, for harmonic plane waves,

$$p(x,t) = ae^{-\alpha x} e^{j(\omega t - \omega x/v)} + be^{\alpha x} e^{j(\omega t + \omega x/v)} \quad (1)$$

Where p is the particle displacement and ω is the angular frequency ($2\pi f$). The first term of the solution describes a wave progressing at a velocity ' v ' in the positive x direction with initial amplitude ' a ', which attenuates exponentially at a rate ' α ' per meter. The second term of the solution describes a wave with initial amplitude ' b ' travelling in the other direction with the same speed ' v ' and decaying at the rate ' α ' per meter. The coefficient ' a ' and ' b ' depend on the boundary and initial conditions within a single medium.

The above solution is for a single frequency (i.e., monochromatic) and most of the ultrasonic systems use a pulse. This can be perceived as a problem because a pulse contains several signals of various frequencies and to obtain the desired information, it has to be mathematically modeled. One way to view the pulse is as

$$p(x,t) = A(t) e^{-\alpha x} e^{j(\omega t - \omega x/v)} \quad (2)$$

where the A , α and v are frequency dependent.

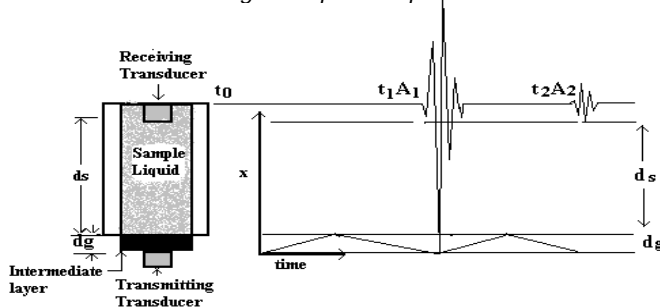
A piezoelectric element picks up the acoustic echo as it passes through and transforms it into an electrical signal. This piezoelectric element is a point of reference where x finds a home and can be set as the origin ($x = 0$). The received electrical signal can then be modeled as

$$p(t) = A(t) e^{-\alpha x_r} e^{j(\omega t - \omega x_r/v)} \quad (3)$$

Where x_r is the distance travelled by the pulse.

The first setup is used to describe the signal processing in liquid sample (Fig.1). The receiving transducer is aimed downwards in the measurement cell towards the sample. And the transmitting transducer is attached to bottom surface of pyrex glass bottle (intermediate layer). The bottom surface has smooth, flat and parallel surfaces and a thickness d_g . The receiving transducer is located at a distance of ($d_s + d_g$) as shown in Fig.1.

Fig. 1. Liquid sample cell.



At time t_1 , an echo from the liquid-intermediate layer interface is received. It has amplitude A_1 that is related to that of the original pulse A_0 , sent out at time t_0 , as

$$|A_1| = |A_0| \times R_{gs} \times e^{-\alpha_g d_g} \quad (4)$$

where R_{gs} is the reflection coefficient of glass-sample boundary.

Such that the received signal can be described as

$$e_1(t) = A_0 \times R_{gs} \times e^{-\alpha_g d_g} \times e^{j\omega(t - d_g/v_g)} \quad (5)$$

The signal is attenuated exponentially over distance traveled by the pulse (d_g) at a rate of α_g , the acoustic coefficient of attenuation in intermediate layer (glass). v_g is the speed of sound in intermediate layer. Presenting τ_g as the time needed for the pulse's round trip in glass:

$$\tau_g = t_1 - t_0 = d_g / v_g. \text{ The equation (5) reduces to}$$

$$e_1(t) = A_0 \times R_{gs} \times e^{-\alpha_g d_g} \times e^{j\omega(t - \tau_g)} \quad (6)$$

The coefficient of reflection R_{gs} for a plane wave front parallel with the intermediate layer surface is

$$R_{gs} = \frac{Z_s - Z_g}{Z_s + Z_g} \quad (7)$$

Where Z_s and Z_g are the specific acoustic impedances of sample and the intermediate layer (pyrex glass) respectively. The coefficient of transmission is related to the amount of energy that was not reflected but transmitted into the sample such that

$$T_{gs} = \frac{2Z_g}{Z_s + Z_g} = 1 + R_{gs} \quad (8)$$

The signal received by the receiving transducer at time t_2 is

$$e_2(t) = A_0 \times T_{gs} \times R_{gs} \times e^{-\alpha_s d_s} \times e^{-\alpha_g d_g} \times e^{j\omega(t - \tau_g - \tau_s)} \quad (9)$$

Where τ_s is the time delay necessary for the sound to travel through the sample:

$\tau_s = t_2 - t_1 = d_s / v_s$, where ' v_s ' is the speed of sound through the sample, and ' α_s ' is the coefficient of attenuation in the sample.

First and foremost, it should be clear that each signal is a unique combination of harmonic waves. A signal at one frequency cannot be implemented with any combination of signals at any other frequencies. Since the systems dealt within here are assumed to be linear, the signals can be added together or superimposed on each other to form a combined signal. Gathering harmonic waves of different frequencies and amplitudes together breeds a unique time varying signal. At times, the superposition of all those harmonic waves cancels each other such that the resulting signal is silent. At other times, they do not cancel each other as exemplified by the occurrence of the echo. Combining harmonic waves with their respective magnitudes results in a signal similar to $e_1(t)$.

The time when the echo occurs can be shifted if the harmonic waves are slightly delayed with respect to each other or a common origin. For the echo to occur at the right time, a unique combination of time shifts is required. This information can be stored with the amplitudes such as $|A_0|$. Combining the frequency dependent magnitudes and time or phase shifts ϕ gives the Fourier transform. Then, for example

$$A_0(\omega) = |A_0(\omega)| e^{j\phi(\omega)} = a_0(\omega) e^{j\phi(\omega)} \quad (10)$$

These complex values can also be represented by

$$A_0(\omega) = x_{a0}(\omega) + jy_{a0}(\omega) \quad (11)$$

by using Euler's equation such that

$$a_0(\omega) = \sqrt{x_{a0}^2(\omega) + y_{a0}^2(\omega)} \quad (12)$$

and

$$\phi(\omega) = \arctan \frac{y_{a0}(\omega)}{x_{a0}(\omega)} = \angle A_0(\omega) \quad (13)$$

The combination of the harmonic waves is represented by the inverse Fourier transform (Kreyszig1993).

$$e_1(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} A_1(\omega).e^{j\omega t} d\omega \quad (14)$$

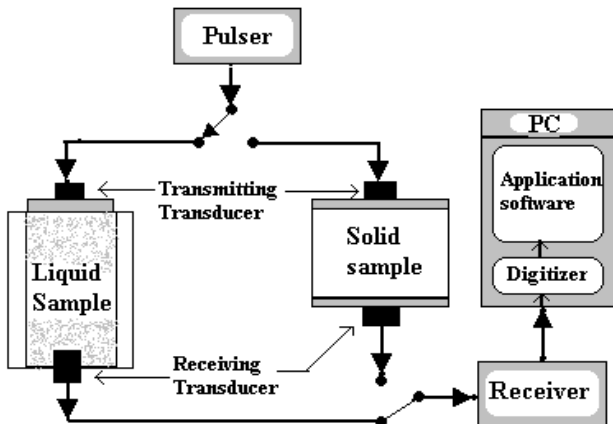
where the harmonic waves $e^{j\omega t}$ with unit amplitude are amplified to their spectrally respective magnitude of $|A_1|$ and shifted by their spectrally respective phases $\angle A_1(\omega)$.

Digitizer technique

Increasing number of ultrasonic applications reflect the power lying in this method. As broader is the range of areas involved in ultrasonic measurement, as more essential becomes the question of universal concept for generating and acquiring the ultrasonic data. The principle and a method of processing an ultrasonic signal originating from a probe using digitizer technique is described here.

The basic conceptual model for the ultrasonic measurement system for solids and liquids is shown in Fig.2.

Fig. 2. Conceptual model for the ultrasonic velocity and attenuation measurement system.



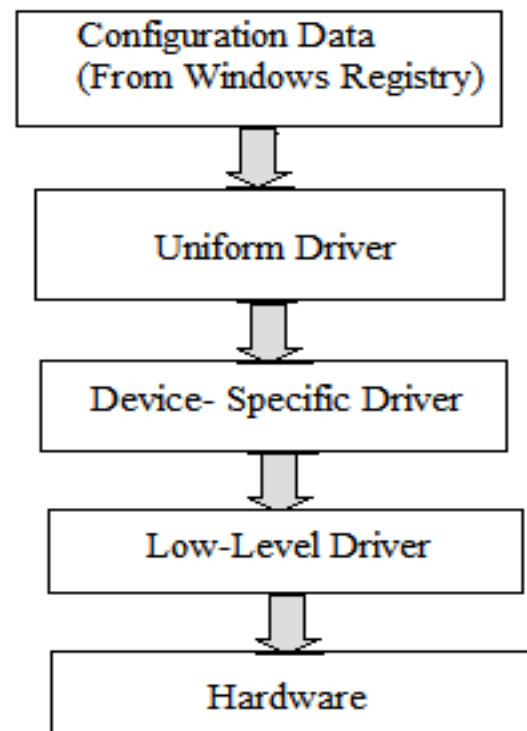
The ultrasonic transducer is excited by generation of electrical pulse and transmits the ultrasonic pulse to the media under investigation. The ultrasonic pulse travels in the material reflected, refracted, scattered or transmitted through its in- homogeneities. The affected signal is picked by receiving transducer and is converted to the electrical signal. This signal is then amplified, filtered and converted to the digital form using digitizer. After the raw data has been acquired from the pulser-receiver by the digitizer, but before a velocity and attenuation estimate can be made, a significant amount of signal processing must be done for a successful measurement to occur. There is some basic processing that is needed for all sets of data.

Control program structure

The overall control program consists of three modules. These are the main module, the communication module and the baseline acquisition module. The main module is what the user interacts with when acquiring data, and it is also the program, which contains the bulk of the signal processing and interpretation software. The communication module has only one function: to control and communicate with (including retrieval of raw data) all hardware in the system. The baseline acquisition module, as the name implies, acquires the baseline sample, which will be used to normalize all future data. This module performs a limited amount of signal processing, and will be addressed briefly.

Communication module

Fig. 3. Driver software structure



Driver Software Structure

The driver software is structured as follows (Fig.3).

Configuration Data: The windows registry stores configuration data of hardware devices. This data will be used by the Driver function during an I/O access.

Uniform Driver: Provides uniform interface between the applications and device specific driver. It handles the management of the device specific drivers, so the applications will not utilize the underlying drivers. The format of the driver is in standard windows Dynamic Link Library (DLL).

Device Specific Driver: Provides board-specific functions. The format of the drivers is standard windows Dynamic Link Library.

Low-Level Driver: Performs physical hardware operations. The format of the driver is Kernel-mode driver for WIN98/2000.

Creating windows applications using microsoft VC++: Created the source files calling DLL functions as typical function calls. Included the DLL header file, namely "Dynadrvr.h", which prototypes all DLL routines. Added the DLL import library namely "Dynaapi32.lib" to the project module.

Main module

The radio frequency (RF) signal received by the digitizer from the transducer via the pulser/receiver consists of the desired signal, in addition to a much larger amount of "noise". In this case, "noise" does not refer to the traditional Gaussian "white noise", but rather to artefacts in the form of unwanted portions of the signal which contain no useful data and which obscure the useful data that is present. These artefacts include the result of such phenomena as grain scattering within the solids and the boundary interface echo. The relative magnitudes of the desired (data-containing) signal and the artifact signal result in an extremely low effective SNR (Signal to Noise ratio). This SNR varies with the fluid and with the thickness of the solid sample, but averages roughly 0.1 (= -20dB). However, since the artifact components of the received signal can be mostly removed, a significant SNR improvement can be achieved. The reason for this nearly complete removal is that both the grain scattering from within the solid sample and the intermediate boundary echo are very repeatable.

Since the raw RF signal from thin fluid layers is simply a sum of the artefact signal and the data-containing signal, only the useful portion of the signal remains once the previously recorded or calculated artefact signal is subtracted. By doing this point-by-point subtraction, which is computationally very simple and thus does not add much time to the data processing, the SNR is improved greatly.

A problem occurs, however, with operation under MS Windows. A Multitasking window is not a real time operating system. Consequently, the amount of time during which a given task or process is interrupted while

Fig. 4. GUI Screen of experimental ultrasonic signal processing

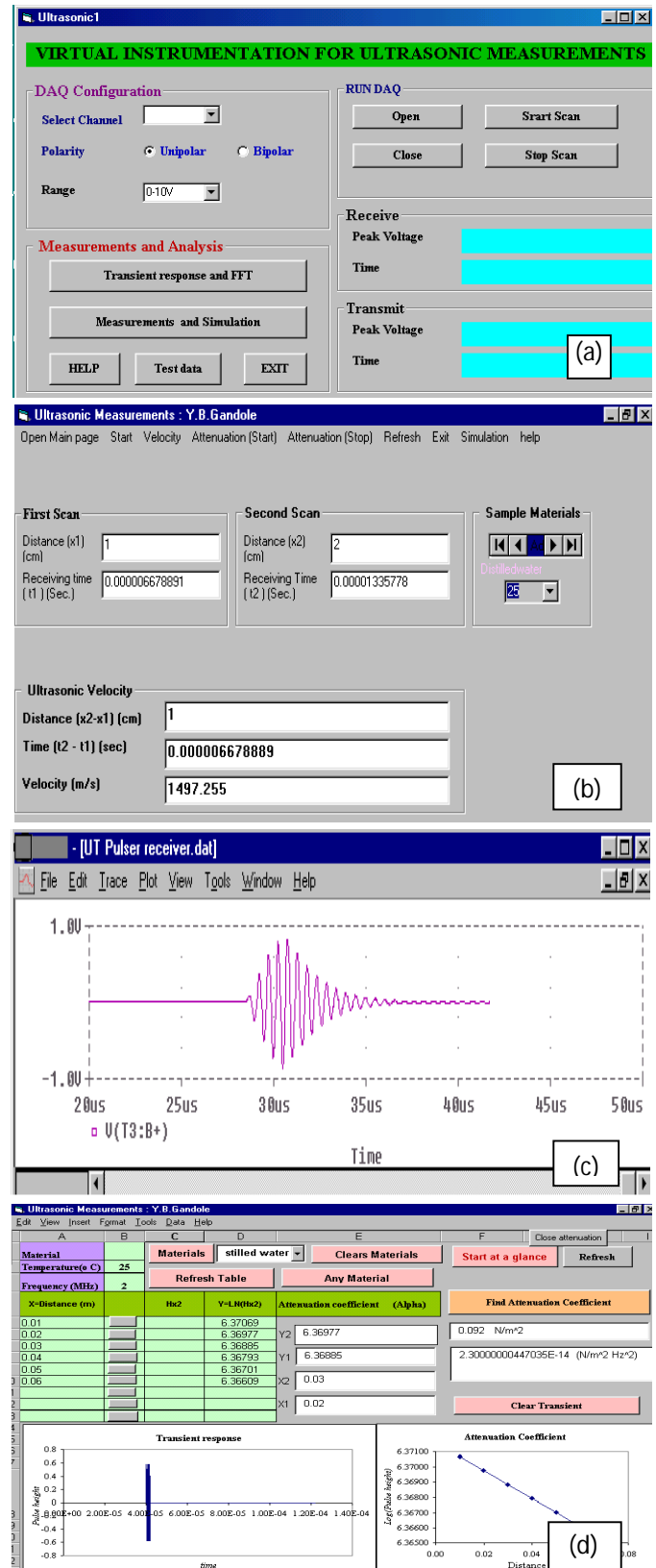


Table 1 (a-b). Ultrasonic velocity and attenuation at 25 ° C for 5 MHz frequency (a)

S.N.	Sample (Liquid)	Velocity (m/s)		
		Experiment	Simulation	Literature
1	Distilled water	1497.255	1497.0056	1497 (Weast Robert ,1964)
2	Benzene	1310.230	1310.0436	1310 (Weast Robert ,1964)
3	Ethanol	1207.536	1207.2434	1207 (Weast Robert ,1964)
4	Acetone	1174.851	1174.6280	1174 (Schaaff, 1967)
5	Methanol	1103.648	1103.3468	1103 (Weast Robert ,1964)

Ultrasonic velocity and attenuation at 25 ° C for 5 MHz frequency (b)				
S.N	Sample (Liquid)	Attenuation(α/f^2) $10^{-15} \text{ s}^2/\text{m}$		
		Experiment	Simulation	Literature
1	Distilled water	22.056	21.9782	22 (Weast Robert ,1964)
2	Benzene	874.002	873.2724	873 (Weast Robert ,1964)
3	Ethanol	48.954	48.3151	48.5 (Weast Robert ,1964)
4	Acetone	54.054	53.6800	54 (Schaaff, 1967)
5	Methanol	32.210	31.9376	30.2 (Weast Robert ,1964)

Windows services other tasks is indeterminate. As a result, no repetitive waveform capture performance can be guaranteed under windows. Guaranteed, reliable performance is paramount during the system's fast-axis scan, where not even a single trigger can be missed. The solution for this requirement is ultra-deep onboard acquisition memory. The digitizer will require enough onboard acquisition memory to hold data from an entire fast-axis scan. To determine the amount of memory required, the number of samples in a single 100 μ s ultrasound record must be calculated:

Record length = Number of record x Sample rate of DAS card.

Record length= 100 μ s x 80MS/s = 8000 S = 8kS

Acquisition memory size =Number of records x Record length.

For convenient processing, digitization of signal is desired. Using the A/D converter signal is sampled in time domain and its amplitude is quantized. (Kazys, 1995). Analog signal sampling can be presented as multiplication with *shah function III* (Bracewell, 1986).

As multiplication in time domain correspond to convolution in frequency domain, one can see, that sampled signal spectra will be periodical with period of sampling frequency harmonics. Furthermore, because of discrete presentation of spectra in computer adaptation of Fourier transform, the signal investigated using the fast Fourier transform is also interpreted as periodical. For instance, multiplication in frequency domain with filter function correspond to convolution time domain, so unwanted influence of signal tail will occur in signal head which might cause confusing results.

Everything said above puts some limits when setting the sampling interval. As we have noted, sampling usually is performed at some particular depth, therefore it is necessary to introduce the possibility to shift the A/D converter buffer memory address to any depth. Such concept allows sampling virtually any depth of material, using relative small capacity buffer memory.

In this experimental work, the author have sampled 2MHz center frequency transducer signal processing in liquids and solid samples. A windows-98 based

application was written in C++ and Visual Basic environment. Since the digitizer card is a PCI plug-and play device, low-level configuration details are handled by Windows. No low-level hardware programming is required. The windows application sets up the scan of the part under test, and then calls C ++ subroutines to acquire and download data from the digitizer. Every A-scan was stored on disk separately. Ultrasonic parameters were measured using user-friendly application software created in visual Basic (Fig. 4 a-d).

Time domain analysis

The developed signal processing technique is validated by measuring the velocity and attenuation of some organic materials using experimental and simulation techniques. The Table 1 (a-b) shows the comparison between the literature values, simulation values and experimental values of ultrasonic velocity and attenuation for the liquid samples.

Conclusion

Simulation and data processing in ultrasonic testing plays an important role for analyzing results and performance demonstration. Another very common application is the design and optimization of inspection

methods. However, comprehensive understanding of the processes taking place in the testing specimen is available only by fully investigating testing instrumentation and method. It includes analysis of the wave propagation in the structure under investigation and analysis of the characteristics of the instrumentation being used. In many cases simplified methods can be used, however they are not based upon the differential equations and, consequently, present only rough evaluation of the wave propagation. On the other hand, finite element or finite difference methods enable to get adequate representation of the process; however, computer resource requirements are usually too great for problems of a practical value. The situation can be improved by developing efficient algorithms of numerical modeling based on deeper analysis of the wave propagation phenomenon.

Any simulation tool for ultrasonic systems craves information about the different media it is supposed to imitate. Signal processing techniques are able to extract the desired information from the received signal when a sample medium is being questioned. Using a pulser-receiver method the group information can be obtained at approximately the center frequency of the ultrasonic transducer. Much more efficient in terms of information extraction is the Fourier transform of the pulser-receiver system. With it, frequency dependent information can be obtained over the bandwidth of the transducer.

Whether it is for material characterization or sensor accuracy, prediction and reliability, signal processing is a requirement.

References

1. Abe K and Igoue O (1980) Fourier expansion solution of the Korteweg-de Vries equation. *J. Computational Phys.* 34, 202-210.
2. Bracewell RN (1986) The fourier transform and its Application. 2nd ed., revised. McGraw-Hill. pp: 172.
3. Delsanto PP and Scalerandi MJ (1998) A spring model for the simulation of the propagation of ultrasonic pulses through imperfect contact interfaces. *Acoust. Soc. Am.* 104(5), 2584-2591.
4. Hafez MM (2003) Numerical simulation of Incompressible flows. *World Sci. Pub. Pte. Ltd.* pp: 109.
5. Hill R, Forsyth SA and Macey P (2004) Finite element modelling of ultrasound, with reference to transducers and AE waves. *Ultrasonics.* 42, 253-258.
6. Kazys R and Svilainis L (1995) Analysis of adaptive imaging algorithms for ultrasonic non-destructive testing. *Ultrasonics.* 33(1), 19-23.
7. Kinsler LE, Frey AR, Coppens AB and Sanders JV (2000) Fundamentals of acoustics. 4th ed., John Wiley & Sons. pp: 121.
8. Malinaric Svetozár and Kostial Pavol (1998) Contribution to the signal processing of ultrasonic pulses. *J. Phys. D Appl. Phys.* 3, 970-977.
9. Murawski Krzysztof (2002) Analytical and numerical methods for wave propagation in fluid media. *World Scientific Publi. Co. Pte. Ltd.*, pp: 2.
10. Ruzzene M, Jeong SM, Michaels TE, Michaels JE and Mi B (2005) Simulation and Measurement of Ultrasonic Waves in Elastic Plates Using Laser Vibrometry. *Rev. Quanti. NDE, ed. by D.O. Thompson & D.E. Chimenti (AIP).* 24, 172-179.
11. Weast Robert C (1964) ed. Handbook of Chemistry and Physics. 45th ed., Chem. Rubber Co., Cleveland Ohio. pp: E-28.
12. Schaaff W (1967) Numerical data and functional relationships in science and technology, New series group II: Atomic and molecular Physics, Vol.5: Molecular Acoustics, Eds: K.H.Hellwege and A.M. Hellweg, Springer-verlag, berline, Heidelberg, NY.