Non-invasive ultrasonic examination technology in support of counter-terrorism and drug interdiction activities – the acoustic inspection device (AID)

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ABSTRACT

The Pacific Northwest National Laboratory (PNNL) has developed a portable, battery-operated, handheld ultrasonic device that provides non-invasive container interrogation and material identification capabilities. The technique governing how the acoustic inspection device (AID) functions, involves measurements of ultrasonic pulses (0.1 to 5 MHz) that are launched into a container or material. The return echoes from these pulses are analyzed in terms of time-of-flight and frequency content to extract physical property measurements (the acoustic velocity and attenuation coefficient) of the material under test. The AID performs an automated analysis of the return echoes to identify the material, and detect contraband in the form of submerged packages and concealed compartments in liquid filled containers and solid-form commodities. An inspector can quickly interrogate outwardly innocuous commodity items such as shipping barrels, tanker trucks, and metal ingots. The AID can interrogate container sizes ranging from approximately 6 inches in diameter to over 96 inches in diameter and allows the inspector to sort liquid and material types into groups of like and unlike; a powerful method for discovering corrupted materials or miss-marked containers co-mingled in large shipments. This manuscript describes the functionality, capabilities and measurement methodology of the technology as it relates to homeland security applications.

Keywords: acoustic, velocity, attenuation coefficient, cross-correlation, homeland security, time-of-flight, ultrasonic.

1.0 INTRODUCTION

The rapid interrogation of sealed containers and bulk-solid commodities is a critical task for personnel charged with enforcing government policies, maintaining public safety, and ensuring national security. In recent years, events such as the bombings of Pan Am Flight 103 over Scotland, the World Trade Center in New York City, the Murrah Building in Oklahoma City, Centennial Park in Atlanta, and US Embassies in East Africa have riveted increasing political, media and public attention on the threat and impact of terrorism to our society and economy. In 1995, the release of the nerve agent sarin in the Tokyo subway system by Aum Shinrikyo and the discovery of a vast Iraqi network and infrastructure for the development of biological and chemical weapons have continued to bring the issues of counterterrorism to the forefront in America. Finally, the events of September 11th, 2001, served as the ultimate blow that contributed to Americans realizing we are not invincible or untouchable. With the ever-increasing prominence of methamphetamine production and other illicit substances, a second driver for development of advanced technology to support law enforcement efforts has been introduced into the equation. The war on drugs and our new war on terrorism have revived and focused our attention on the vulnerability of our society and have provided the impetus for the development of scientific and technological advances in support of our efforts to stem the flow of contraband and weapons of mass destruction (WMD). America's science, engineering and technology infrastructure plays a critical role in addressing these issues and providing solutions toward the detection, identification, response and resolution of substances and materials associated with smuggling and terrorist activities.

The acoustic inspection device (AID), shown in figure 1, is a portable, battery-operated, handheld ultrasonic inspection platform that provides non-invasive container/material examination and identification capabilities. The AID system provides the inspector with the capability to rapidly examine sealed, liquid-filled containers and large bulk-solid commodities, a requirement facing the law enforcement community, border security personnel, the military, and international treaty conventions in their efforts to support homeland defense, deter illicit drug manufacturing, stop smuggling, collect taxes and tariffs, effectively maintain inventories, and verify treaty compliance. The AID augments on-site material interrogation efforts that use the expensive and time-consuming processes of direct sampling and laboratory analysis. Specifically, the AID provides the operator the ability to:

- **Detect** contraband and hidden compartments in liquid-filled containers and solid form commodities,
- **Sort** liquid types into groups of like and unlike,
- **Identify** a selected number of liquids and solids over a wide temperature range, and
- **Determine** the fill-level in liquid-filled containers

Figure 1. The Acoustic Inspection Device (AID)

The AID technology was initially designed and fielded for non-invasive examination and identification of chemical warfare agents in munitions. The AID is a candidate item on the equipment list for the Chemical Weapons Convention, and has been deployed for chemical weapons (CW) inspections by United Nations inspectors in Iraq after the Gulf-war and more recently this year, by UN weapons inspectors again in Iraq. The On-Site Inspection Agency (OSIA) has utilized the AID for United States - Russian Bilateral Treaty verification activities over the past decade. The U.S. law enforcement community has used versions of the AID in drug interdiction operations and the U.S. Department of Energy uses the technology in controlling the excess of surplus materials. More recently, the U.S. Customs Service, the U.S. Department of Defense and the U.S. Department of State have coordinated programs for deploying the AID at international borders, including Kazakhstan, Russia, Georgia, Poland, Cyprus, Malta, Lithuania, and Uzbekistan. The IRS has funded development of this technology for providing fuel compliance officers with a tool for verifying the contents of fuel tanker trucks entering the United States in order to determine compliance with fuel tax/tariff laws. The Defense Threat Reduction Agency (DTRA) and the Defense Nuclear Agency (DNA) have also funded the development of this technology and have supported its use in international border control deployments and training. In 2001, the US Customs Service funded the technology transfer and commercialization of the AID.

Current efforts at the Pacific Northwest National Laboratory have focused on the development of the inspection platform and on the enhanced database that incorporates temperature corrected acoustic attenuation and velocity data for improved discrimination and identification capabilities. Ongoing work has included the design, fabrication, development and testing of an ultrasonic bench-top, velocity-attenuation measurement system (VAMS) for real-time, ultrasonic characterization of liquids as a function of temperature and frequency for database enhancement of the AID technology. This work has also included the development and deployment of novel, prototype dry-couplant membranes for both high and low frequency transducers.

The purpose of this document is to report on the AID's development status, functionality and measurement methodology as it relates to homeland security activities. This report describes the underlying theory for the ultrasonic velocity and attenuation measurement methodologies, and discusses the discrimination and identification capabilities of the AID platform.

2.0 PRINCIPLES OF OPERATION

In order to provide the operator with a tool that is most useful in the field for the vast array of commodities and containers typically encountered in US Customs related activities, the AID platform must utilize measurement methods that are robust and reliable. Acoustic velocity and attenuation data are valuable tools for the study of the physical properties of solids and liquids.

The AID is roughly the size and shape of a large flare gun and contains a replaceable ultrasonic sensor head. It is tethered to a personal digital assistant (PDA) and linked to a data library that consists of a listing of solids and fluids

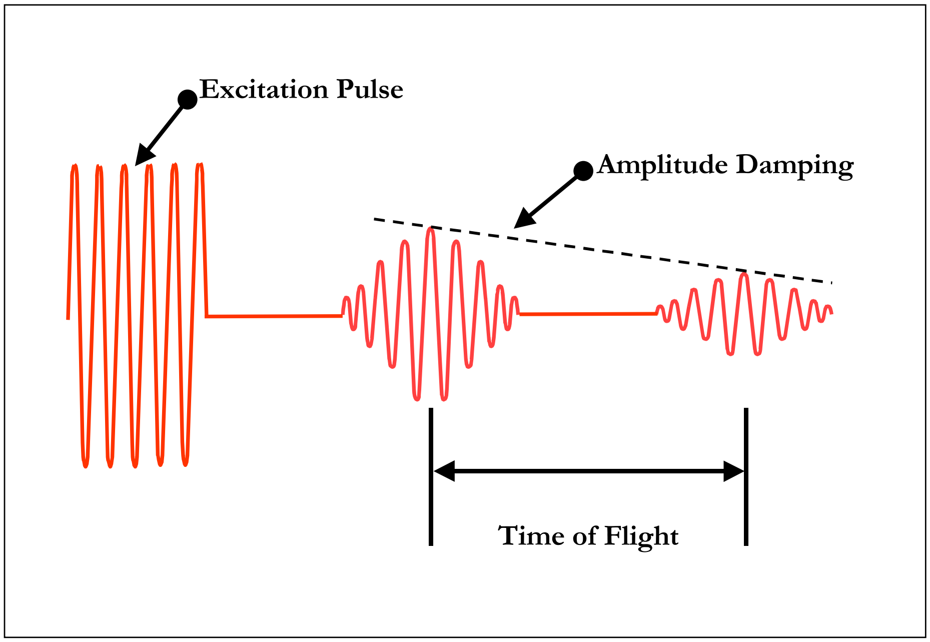

Figure 2. Illustration of ultrasonic echoes and time-of-flight data used to calculate the acoustic velocity and attenuation coefficient parameters for liquid/material identification

with their associated acoustic property data as a function of frequency and temperature. The technique governing how the AID functions entails measurements of ultrasonic pulses in the range of 0.1 to 5 MHz that are launched into a container, easily penetrating many solid materials and liquid commodities. The AID uses two interchangeable, broadband, ultrasonic transducers (200 kHz and 1 MHz nominal center frequencies) that can interrogate containers ranging in size from approximately 6 to over 96 inches in diameter. The return echoes from the injected ultrasonic pulses are analyzed in terms of time-of-flight and amplitude decay/frequency, in order to extract physical property measurements of the material being inspected (see figure 2). These parameters (acoustic velocity and attenuation coefficient) are used to sort and identify specific components in a sealed container. Mislabeled containers and intentionally corrupted fluids can be readily discerned. The presence or absence of an ultrasonic echo from the far wall of the container is used for determining fill level in storage containers and for locating cavities and packages hidden in outwardly innocuous commodity items such as shipping barrels and metal ingots. The ultrasonic velocity and the attenuation coefficient are temperature-dependent physical properties of the propagation medium. The AID collects and passes ultrasonic data to the PDA platform in the form of digitized waveforms. On the PDA, a PNNL-developed algorithm uses this information, along with the path length and temperature measurement input, to calculate the acoustic velocity and attenuation coefficient. These calculated results are automatically compared to the database and an identification is attempted. The technical details of these calculations are transparent to the operator. The necessary information is automatically uploaded from the acoustic gun to the PDA platform when the operator depresses the trigger. Prior to interrogation, the user is required to input the container diameter and other inspection details deemed necessary. This may include information from the manifest, the driver, and the conveyance. The inspection results are presented graphically for clear and immediate interpretation by the user. The results are then merged with the user input to form a file that may be saved, transmitted electronically or printed out on paper. The AID liquid/material database resides on the PDA and can be readily updated with additional liquids or materials using data collected in the field or in the laboratory using the VAMS technology. The work to date has utilized an automated Laboratory system called VAMS to acquire acoustic velocity and attenuation data on select fluids as a function of temperature and frequency. Of particular importance is the acoustic attenuation coefficient as a secondary discrimination parameter.

2.1 AID system components

The primary function of the acoustic gun is to provide a portable, handheld mechanism for contacting the ultrasonic transducer to the wall of the container or material commodity that is to be examined. The enclosure comprising the acoustic gun houses the primary electronics (pulser board, receiver board, 8-bit, 20 MHz analog-to-digital converter (ADC), and 8-bit Ethernet board) as well as the transducer of choice for transmission and reception of the acoustic pulse. The trigger of the gun functions as the toggle switch for acquisition of acoustic data during testing. The function of the pulser board is to provide the appropriate excitation characteristics to the transducer of choice, (either high frequency or low frequency). In the high frequency mode, the transmit pulse consists of a 385 Volt, single, negative square wave pulse for broadband excitation. In the low frequency mode, the transmit pulse consists of a 600 Volt peak-to-peak, 5 cycle sinusoidal wave tone-burst. The transducers are fitted with a robust, novel, dry-couplant membrane with a glycerol filled cavity that provides efficient coupling of acoustic energy without the need for wetting agents or gels. These membranes are easily replaced and can be refilled as well. The transducers also house thermistors for real-time temperature measurements that are automatically ported to the PDA. The function of the receiver board is to provide a means for amplification and signal conditioning of the received acoustic signal response. The function of the ADC is to convert the analog rf signal response to a digitally sampled representation of the acoustic response. The function of the Ethernet board is to perform data transfer from the ADC to the PDA where the digitized acoustic signal response is used as input to various algorithms for determining inspection results. Results returned to the user occur in two stages. Initially the operator views a main screen to input parameters and when the trigger is depressed and the sound field enters the container, the ultrasonic waveform (signal response) is illustrated on the PDA (as shown in figure 3). When the trigger is released, the PDA toggles back to the main menu screen where the database listing highlights the identified commodity.

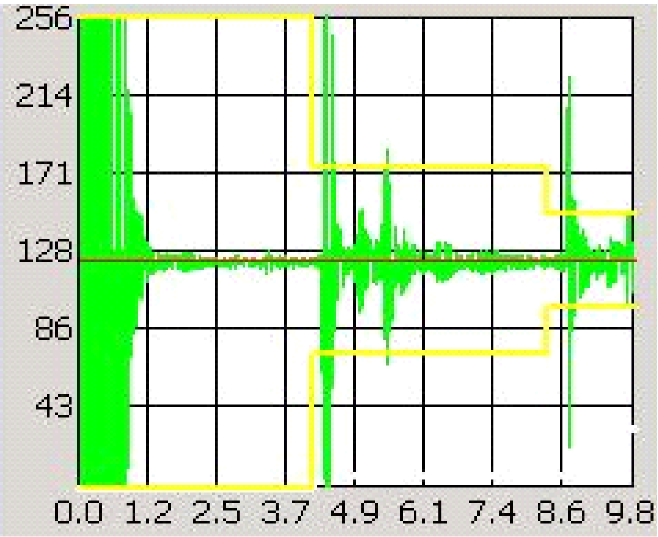

Figure 3. Ultrasonic waveform as seen on the PDA display of the AID

The AID employs a modular design that incorporates a battery powered base unit (acoustic “gun” with various measurement peripherals), including a high-frequency (1 MHz) transducer and a low-frequency (200 kHz) transducer. The current operations platform is a commercially available Windows CE -based personal digital assistant (PDA). The PDA controls all peripherals through a common graphical users interface (GUI) and contains a system library of liquids and materials. This system library, or database, can be updated with additional liquids and materials. The control unit uses a sunlight readable, backlit LCD display with a touch-screen interface and provides connectivity for an Ethernet connection, a serial port, a keyboard, and can also be docked to a PC. The PDA platform provides a means to upload/download information and share critical examination results with inspectors at other ports-of-entry through normal communications infrastructure (internet, LANs, etc.). The PDA provides quick start-up times and a familiar Windows-CE environment. The function of the PDA is to provide a platform for ultrasonic examination parameter control and data analysis. The tablet provides the platform for invoking the necessary software for operational control of the acoustic gun as well as a platform for immediate analysis of acoustic data acquired from a container or bulk-solid commodity. This unit provides the inspector with both visual and audible indicators to enhance his/her capability to rapidly inspect a large number of items and make an immediate decision regarding disposition. The 12-Volt, 2-amp rechargeable battery allows the unit to be used for 8-10 hour periods of time without interruption.

3.0 MEASUREMENT THEORY AND METHODOLOGY

3.1 Velocity measurements

Acoustic velocity information is a very valuable and widely used tool for the study of the physical properties of solids and liquids. Velocity measurements are routinely used to determine elastic constants and characterize material microstructures and mechanical properties[1-3]. The objective is to accurately determine the time delay between two successive echoes using the pulse-echo technique. In many field applications, the echoes may be weak, distorted by the medium, or highly attenuated and close to the level of the noise. Using digitized, broadband waveforms, the AID utilizes a cross-correlation method that allows for accurate TOF measurements without the requirement for identifying specific waveform features such as a zero-crossing, a peak, or a zone for phase slope[4]. Given two time domain functions h(t) and g(t) representing two successive echoes (time-series), and their respective real frequency domain representations H(f) and G(f), the cross-correlation function $c_{gh}(\tau)$ is defined as

$$c_{gh}(\tau) = \lim_{T\to\infty} (1/T) \int_o^T g(t)\, h(t+\tau)\, dt \quad , \tag{1}$$

where t is time, f is frequency and τ is called a lag or "delay interval". $c_{gh}(\tau)$ is the correlation function formed by summing the lagged products of two waveforms, in this case, g(t) and h(t). If h(t) is replaced by g(t), we have the auto-correlation function, given by

$$c_{gg}(\tau) = \lim_{T\to\infty} (1/T) \int_o^T g(t)\, g(t+\tau)\, dt \quad , \tag{2}$$

The digital cross-correlation method can be thought of as a comparison or matching up of waveform characteristics, and is fairly simple to implement using FFTs[5]. The two waveforms being correlated, g(t) and h(t) are transformed to the frequency domain, one term is conjugated, denoted by an asterisk (*) and then the complex product is formed to give

$$C_{gh}(f) = G(f)\, H^*(f) = [G^*(f)\, H(f)]^* \quad , \tag{3}$$

Performing the inverse transformation of $C_{gh}(f)$ back to the time domain yields $c_{gh}(\tau)$. The product of the Fourier transform of one function by the complex conjugate of the Fourier transform of the other, yields the Fourier transform of their correlation[6]. By analyzing the propagation paths associated with the two successive echoes in pulse-echo mode, accounting for accumulated random noise, waveform inversions, and defining the delay time as $2d/v$, where v is velocity and d is path length, we can write h(t) as[4]

$$h(t) = g(t - 2d/v) \quad , \tag{4}$$

Substituting equation 4 into equation 1 gives

$$c_{gh}(\tau) = \lim_{T\to\infty} (1/T) \int_o^T g(t)\, g(t+\tau - 2d/v)\, dt \quad , \tag{5}$$

This is equivalent to the auto-correlation function $c_{gg}(\tau_1)$ where

$$\tau_1 = \tau - 2d/v \quad , \tag{6}$$

Therefore, since the auto-correlation function $c_{gg}(\tau_1)$ peaks at a time lag where $\tau_1 = 0$, we can write

$$\tau = 2d/v \quad . \tag{7}$$

3.1.1 Signal analysis for automatic temperature-compensated velocity measurements

The analog signal containing the acoustic return from each pulse is digitized into a 16 K-sample record. These records are segmented into 1024-byte packets and sent over an Ethernet port to the host computer using the Universal Datagram Protocol (UDP). The computer application, hosted on the PDA, re-assembles these packets into individual waveforms for analysis (see figure 4). The waveform is analyzed to calculate the time of transit for the acoustic signal to travel the distance from the transducer to the far wall of the container and then back to the transducer. By dividing the distance the acoustic signal travels (path length) by the time of transit, also described as the time-of-flight (TOF), we obtain the acoustic velocity, which is an intrinsic property of the material in the container. The TOF value may be obtained very accurately by measuring the number of samples between two successive returns received from the far wall of the

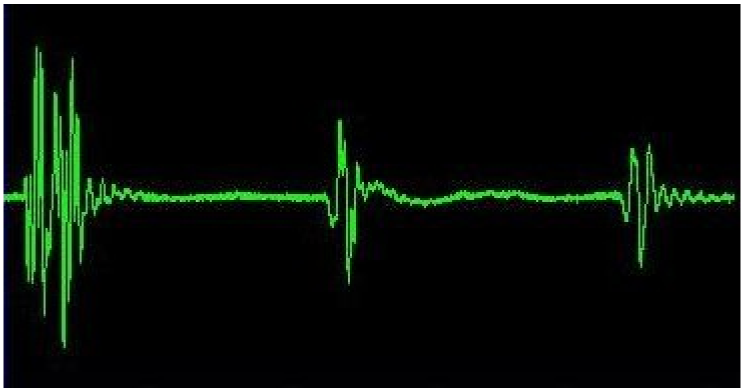

Figure 4. Acoustic waveform

container using a cross-correlation acoustic velocity, which is an intrinsic property of the material in the container. The TOF value may be obtained very container using a cross-correlation algorithm based upon the method discussed in section 3.1[6]. Our application of the cross-correlation algorithm requires two equal sized segments of the sampled waveform, each containing a peak of interest from the far wall echo, as inputs. A correlation array is returned with each element containing the correlation in the frequency domain between the elements of the segments shifted by the number of samples of the element index. The element index containing the maximum value indicates the number of samples of shift required to align the two peaks.

Since the acoustic signal received at the transducer is highly symmetric about its mean value, one can use the mean value as a baseline for threshold comparisons (above and below) to locate and window the echo peaks. The first step then of the waveform analysis is to simply calculate the mean value of the signal. It doesn't matter if the amplitude is described as a voltage or by raw D/A counts, the mean value of either may be used as the baseline. Once the signal baseline is established, we need to determine a threshold value to use to identify the echo peaks. Due to the variety of container materials and configurations one encounters in the field, it is not practical to establish a fixed threshold value that works under all conditions. Instead we use the average noise level of the signal to set the threshold in order to adapt to the variations observed in the signal quality. The acoustic waveform is characterized as echo peaks with relatively quiet sections of signal between them. In order to set the threshold properly, we are interested in measuring the average noise level of this quiet signal between the echo peaks. It was found by experimentation that a good value for the average noise is obtained by building a histogram of the amplitudes of all samples and finding the amplitude below which 75% of the samples are contained (red vertical line in figure 5).

The next step is to set a threshold level by which the peaks of interest are initially identified, and this threshold level is set at an amplitude level which is an operator selectable multiple of the calculated noise level. A multiplier of 3 to 6 has been found to handle the majority of situations. At the beginning of each waveform there is a period of saturated samples representing the ring down of the initial pulse against the container wall. Since we are using an amplitude threshold to locate the echo peaks of interest, the search for peaks must start after this initial ring down. One method found useful for detecting the end of the ring down is described as follows. Divide the entire waveform into fifty segments of equal samples. Sum the amplitudes of each segment. Beginning at the start of the waveform, compare each segment's sum with three times the sum of the waveform segment with the smallest sum. Continue comparing each segment until the current segment's sum is less than or equal to three times the smallest sum. Then begin the peak search at the start of this segment. The next step is to locate peaks in the remaining part of the signal. To compensate for the amplitude attenuation of the return echo as the path length increases, the threshold level is stepped up to 1.5 times the calculated threshold at the beginning of the search. Peaks are identified when three consecutive samples occur above the threshold. The sum of the area under the curve of each peak is calculated and used to reject smaller peaks that have been observed to occur between far wall echoes in some containers. Once the first far well echo peak is located, further

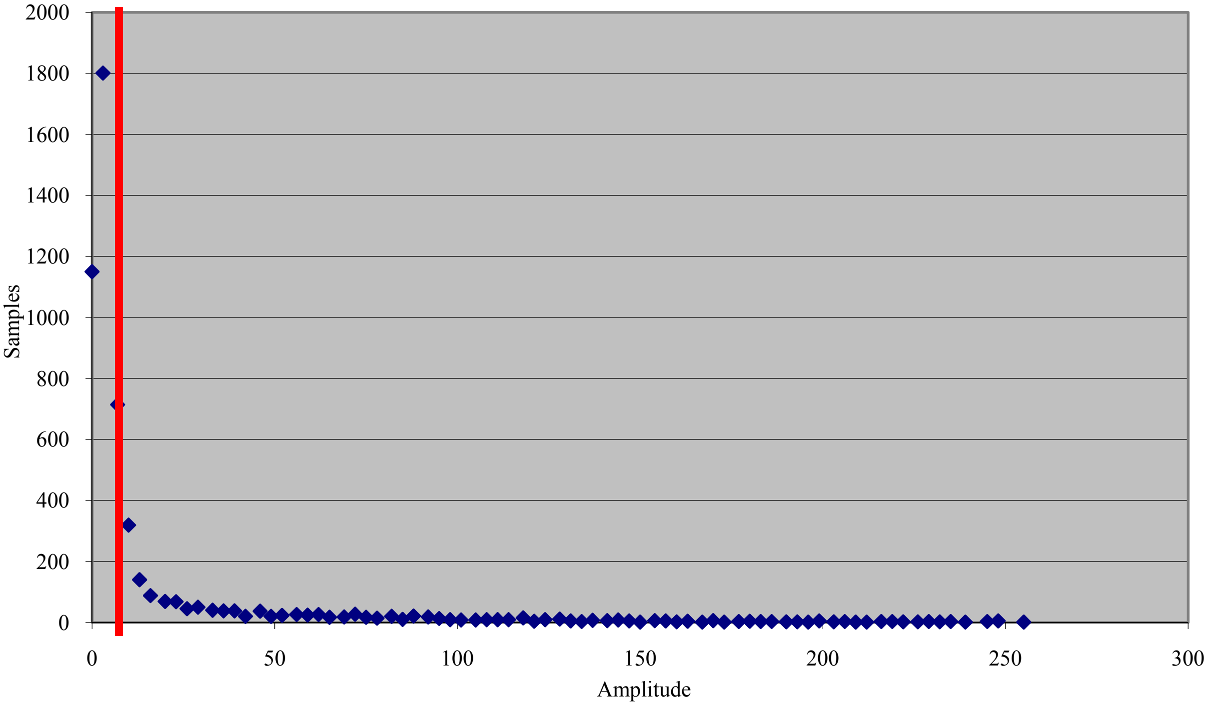

Figure 5. Amplitude histogram

rejection of smaller peaks in between the far wall echoes may be accomplished using the knowledge that additional far wall echoes will be received at multiples of the first echo TOF. When at least two far wall echoes have been identified, we may finally window the two peaks (figures 6 and 7) and use them as the inputs to the cross correlation algorithm mentioned earlier. The TOF is calculated by subtracting the starting sample index of the two windows and adjusting this by the positive or negative shift returned from the cross correlation routine. The result is multiplied by the sample period to obtain the TOF.

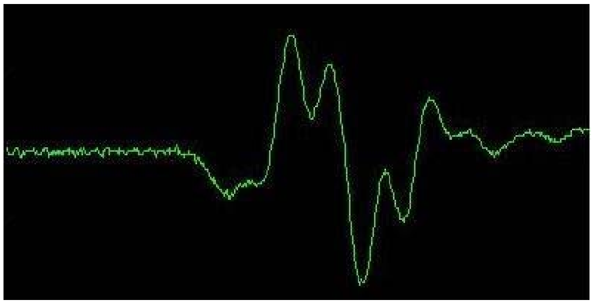

Figure 6. Peak 1 windowed

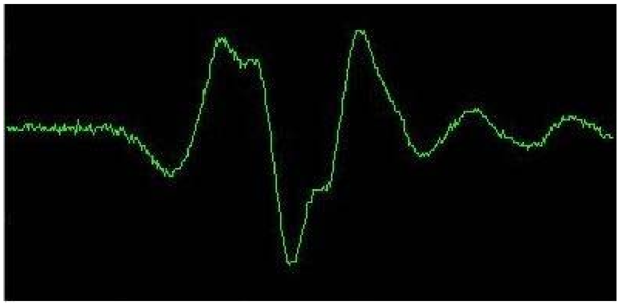

Figure 7. Peak 2 windowed

Figure 8 shows the returned correlation array. Figure 9 shows a display of the overlay of the two echoes using the shift returned from the correlation routine. Figure 10 shows an analyzed waveform as displayed on the application’s graphical user interface. The yellow line is the threshold amplitude used to identify the far wall echo peaks. The white line at the bottom shows the time between the first and second far wall echo.

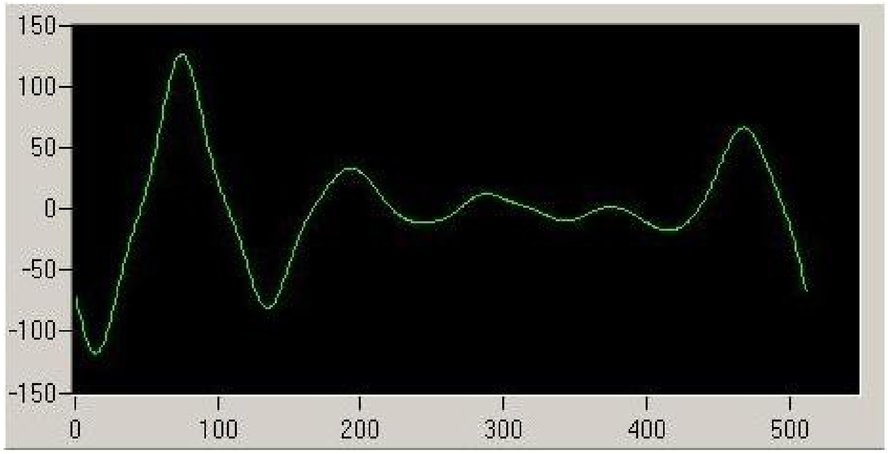

Figure 8. Correlation array

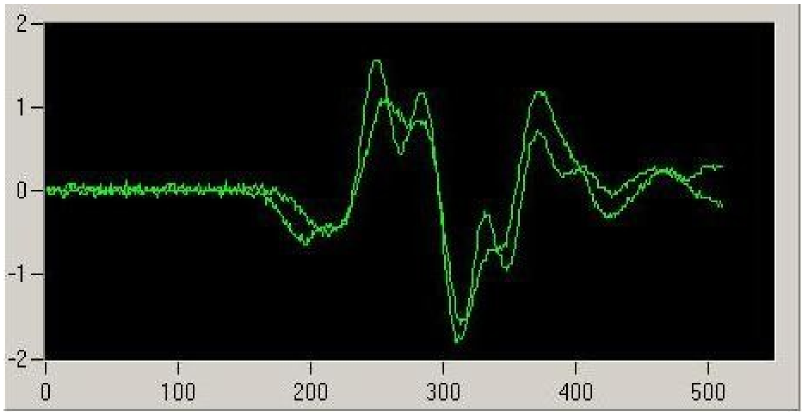

Figure 9. Overlay of peaks 1 and 2

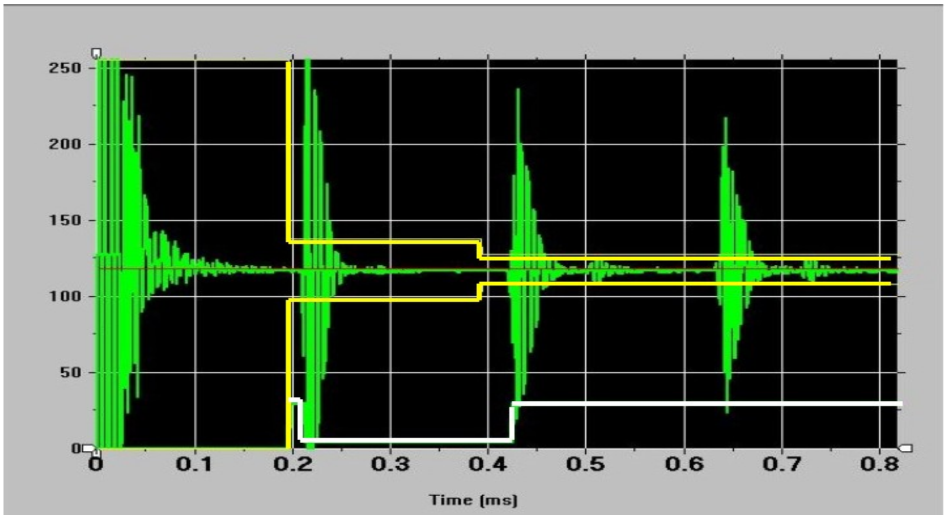

Figure 10. Analyzed waveform

The acoustic velocity is calculated by dividing the acoustic path length (input by the operator) by the TOF. The calculated velocity is compared with a material database having reference information from a large number of reference

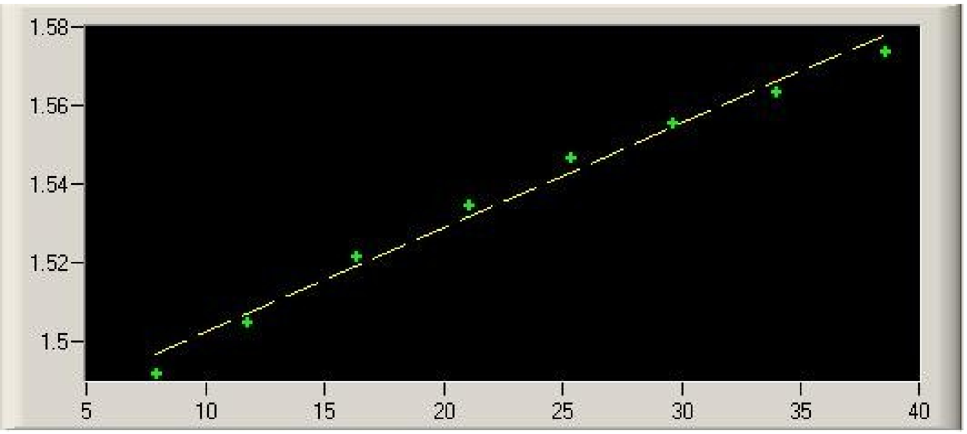

Figure 11. Acoustic velocity (km/s) as a function of temperature (deg C)

waveforms acquired from materials at various temperatures under controlled conditions. Let us now turn our attention to the manner in which the temperature measurement is incorporated into these calculations. During the time that the waveforms are acquired, temperature readings are also acquired using a thermistor mounted to the ultrasonic transducer or they are manually entered. Since the acoustic velocity of a material is a function of the temperature, the measured acoustic velocity of a sample under test must be compared to the acoustic velocities of materials measured at the same temperature. Figure 11 shows the relationship of acoustic velocity as a function of temperature for apple juice. In the temperature range of practical interest, the acoustic velocity of most materials measured in the lab may be described by a simple linear relationship. After each measurement, the acoustic velocities in the material database are calculated at the measured temperature of the sample and displayed in an ordered list (ascending by acoustic velocity). The calculated acoustic velocity of the test sample is inserted into this ordered list, positioning the sample adjacent to the closest matches in the material database.

3.2 Attenuation coefficient measurements

The attenuation coefficient yields information about absorption and scattering processes occurring in the specimen under test. Absorption describes acoustic energy that is turned into heat directly, while scattering redistributes the energy into a multiplicity of other wavelets from which it is finally attenuated by absorption mechanisms. The attenuation coefficient is a function of frequency with temperature providing secondary effects. Acoustic instrumentation such as the AID attempt to identify fluids based on properties such as acoustic velocity. The inclusion of other parameters into the measurement scheme helps provide enhanced capability for fluid identification[7]. One parameter that can be easily added to the measurement suite is acoustic attenuation. While acoustic velocity varies by less than a factor of two over a wide range of fluids, attenuation can vary by several orders of magnitude[2,3,7,8]. Conversely, acoustic velocity can be measured very precisely while attenuation is difficult to measure with high accuracy. This section describes the most viable method for determining acoustic attenuation from acoustic pulse echo measurements where multiple echoes are recorded. In the cases where multiple echoes can be obtained, very reliable measurements of attenuation can be made. In cases involving large acoustic transit distances or very high attenuation of sound, where only a single echo can be recorded, the attenuation cannot be estimated in a reliable fashion, as the number of measurement variables are too high to control, thereby requiring the operator to obtain two echoes at a minimum, for an effective attenuation value to be computed.

3.2.1 Frequency spectrum of the acoustic pulse

The acoustic pulses generated in the AID are characterized by a distribution of amplitudes over a range of frequencies. In the case of 1 MHz excitation, the applied electric pulse to the transducer is a square wave and the transducer responds over a range of frequencies, typically between 600- and 1400- kHz. This response is quite typical of pulsed acoustic systems. However, even in the case of 200 kHz excitation where the transducer is excited by a 5-cycle sinusoidal pulse (a tone burst), it is experimentally observed that the output wave train from the transducer exhibits a frequency bandwidth ranging from 140- to about 260-kHz. Since attenuation of sound scales as the square of the frequency for a wide range of attenuation factors, it is seen that return signals will suffer relatively more loss for higher frequencies than for lower frequencies. Hence if the frequency content of an acoustic pulse (i.e., the Fourier transform) is known initially or after some known distance of travel and if this signal can be compared to the pulse after traveling some other known distance then the acoustic attenuation coefficient can be determined[8]. The amplitude A of the acoustic pulse after traversing a distance x in a fluid is given by

$$A(f,x)=\frac{A_0(f)\cdot g}{x}\cdot\exp(-\alpha f^2 x) \quad , \tag{8}$$

where f is the frequency, A_0 (f) is the initial frequency distribution immediately at the output of the transducer, g is a geometric factor that depends on the shape and size of the fluid containment vessel and possibly the container material, and α is the attenuation coefficient. The measurements seek to determine α, which is a property of the fluid.
In general, A_0 (f) is not known for any measurement nor is the factor g. Hence, measurement methods that eliminate the need to know these quantities are desired. The acoustic flight distance x is a known quantity. It is assumed here that this distance is always so great that in all practical cases the transducer is operating in the far-field regime where acoustic amplitude diminishes inversely as the distance traveled by the sound. There are two cases of interest, one where only a single acoustic echo is received from reflection from a far boundary and another where two echoes from this same boundary are recorded from multiple crossings of the sound through the fluid. If attenuation is severe or the flight distances are very long it may be that measurements can only record one echo. Conversely, there will be many cases where these two conditions do not apply and multiple (two) echoes are received during an examination. We consider only the double echo case.

3.2.2 Algorithm for determination of the attenuation coefficient in the double echo case

In the case of multiple echoes, for which we will consider only the subset of two echoes, determination of the attenuation coefficient proceeds as outlined below. With two echoes we obtain two sets of amplitudes,

$$A_1(f,x_1)=\frac{A_0(f)\cdot g}{x_1}\cdot\exp(-\alpha f^2 x_1) \quad , \tag{9}$$

and,

$$A_2(f,x_2)=\frac{A_0(f)\cdot g}{x_2}\cdot\exp(-\alpha f^2 x_2) \quad , \tag{10}$$

where,

$$x_2 = 2x_1 \quad .$$

There are at least two ways to analyze the frequency data to obtain the attenuation coefficient. The simplest method is to determine ratios of amplitudes at various frequencies. From Eqs. (9) and (10) we obtain

$$\ln\left[\frac{A_1(f,x_1)}{A_2(f,x_2)}\right]=\ln 2-\alpha(x_1-x_2)\cdot f^2 \quad . \tag{11}$$

Hence a plot of the left hand side of Eq. (11) vs. the square of the frequencies at which measurements are obtained, will yield a straight line of slope $-\alpha(x_1-x_2)$, from which the attenuation coefficient can be determined. Hence the algorithm requires the acquisition of the FFT for two consecutive return echoes with a test material, measure and recall the acoustic path lengths associated with each echo. For each frequency, form the ratios of the amplitudes provided by the FFTs. The numerator represents the first echo while the denominator represents the second echo. Numerically plot the natural logarithms of the ratios against the square of the frequencies. The next step is to fit a straight line through the curve and determine the slope of the best fit line along with the uncertainty of the slope. Finally, the algorithm sets the slope equal to $\alpha(x_1 - x_2)$ and determines the attenuation coefficient α along with its uncertainty. If x_1 and x_2 are in cm and f is in Hz, the attenuation coefficient will be in s^2/cm.

3.3 Measurement uncertainty

The measured quantities are the amplitudes of the first and second echoes over a range of frequencies. Standard error analysis using Equation (11) leads to the following result if errors in distance measurement and frequency are small compared to amplitude measurement errors.

$$\Delta\alpha = \frac{\Delta A / A}{\sqrt{2} \cdot (x_1 - x_2) \cdot f^2} \tag{12}$$

The uncertainty in α depends on the operation frequency and the distance traveled by the acoustic wave between echoes. For 1 MHz frequency and a distance of 100 cm and for 3% measurement error in the amplitudes (typical values) we obtain

$$\Delta\alpha \cong 2x10^{-16} \frac{s^2}{cm} \tag{13}$$

The attenuation for water is about 2.4 x 10^{-16} s^2/cm and so for this example the relative error would be near 100 % and attenuation coefficients near the value for water become impossible to measure with close precision. More accurate measurements become possible with higher frequencies or longer acoustic pathlengths. As a secondary parameter, this data point is useful in cases when the acoustic velocity (at a specific temperature) overlaps but the attenuation characteristics are sufficiently different to provide a substantial shift in the measured/compared values.

With regard to TOF and velocity calculations, a number of factors can be identified as sources of measurement error[3,4,7]. Due to the fact that the AID utilizes low frequencies (long wavelengths) and is primarily used for larger containers (with thinner walls), we assume that the error due to the container-wall reverberations (transit time) is negligible. More critical toward acquiring accurate velocity values, sources of error include the temperature measurement, the TOF measurement (triggering, data sampling errors and jitter), and the measured path length. Qualitatively, for small containers, the measurement of the container diameter needs to be more accurate than for a larger vessel. Although a substantial body of statistical calculations does not exist as it relates to the velocity measurement error, experimental work suggests that the combined effect of these error sources (for containers 2 feet in diameter and larger) typically result in velocity measurements with a relative error of approximately ±1%.

3.4 Example data

The table below illustrates data acquired with the AID and VAMS platforms at PNNL.

LIQUID	**TEMPERATURE (degrees C)**	**MEASURED ACOUSTIC VELOCITY (m/s)**	**MEASURED ACOUSTIC ATTENUATION COEFFICIENT (s^2/cm)**
Water	20□C	1492.8 m/s	2.0e-16
Orange Juice	20□C	1531.2 m/s	2.2e-15
Tequila (80 proof)	20□C	1610.8 m/s	7.2e-15
Paint Thinner	20□C	1304.0 m/s	7.0e-16
Honey (food grade)	20□C	1876.0 m/s	2.5e-13

As discussed earlier, in some cases the acoustic attenuation coefficient shows a measurable difference between liquids and can be used effectively as a secondary discrimination and identification parameter within the bounds of the measurement accuracy defined in section 3.3. These data were calculated using laboratory measurements and employing the VAMS technology platform and subsequently verified with field tests conducted using the AID platform. The output of the VAMS platform provides a slope and an offset value for both acoustic velocity and attenuation coefficient data as a function of temperature. The attenuation amplitudes were acquired from broadband spectrums centered about the nominal operational center frequencies of the transducers at 1 MHz and 200 kHz.

4.0 DISCUSSION AND CONCLUSIONS

It is shown that the acoustic velocity and attenuation coefficient are functions of the chemical make-up of liquids and help describe the material state of solids. The temperature and frequency dependence of these physical properties are the basis for an acoustic signature of a wide array of liquids and solids. Using these physical properties as an acoustic fingerprint, PNNL has developed a handheld, portable technology that provides a platform for in-field ultrasonic measurements to identify fluids and materials, and to non-invasively inspect homogeneous bulk solid materials and fluid filled containers. The AID takes advantage of the cross-correlation method for determining accurate TOF data under field-measurement conditions and employs a method for acquiring the acoustic attenuation coefficient as a secondary metric for improved discrimination and identification capabilities.

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