

Advanced ultrasonic measurement methodology for non-invasive interrogation and identification of fluids in sealed containers

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ABSTRACT

Government agencies and homeland security related organizations have identified the need to develop and establish a wide range of unprecedented capabilities for providing scientific and technical forensic services to investigations involving hazardous chemical, biological, and radiological materials, including extremely dangerous chemical and biological warfare agents. Pacific Northwest National Laboratory (PNNL) has developed a prototype portable, hand-held, hazardous materials acoustic inspection prototype that provides noninvasive container interrogation and material identification capabilities using nondestructive ultrasonic velocity and attenuation measurements. Due to the wide variety of fluids as well as container sizes and materials encountered in various law enforcement inspection activities, the need for high measurement sensitivity and advanced ultrasonic measurement techniques were identified. The prototype was developed using a versatile electronics platform, advanced ultrasonic wave propagation methods, and advanced signal processing techniques. This paper primarily focuses on the ultrasonic measurement methods and signal processing techniques incorporated into the prototype. High bandwidth ultrasonic transducers combined with an advanced pulse compression technique allowed researchers to 1) obtain high signal-to-noise ratios and 2) obtain accurate and consistent time-of-flight (TOF) measurements through a variety of highly attenuative containers and fluid media. Results of work conducted in the laboratory have demonstrated that the prototype experimental measurement technique also provided information regarding container properties, which will be utilized in future container-independent measurements of hidden liquids.

Keywords: Ultrasonic, Time-of-Flight, Pulse Compression, Signal Processing, Cross Correlation, Velocity, Attenuation

1. INTRODUCTION

Government agencies and homeland security related organizations have identified the need to develop and establish a wide range of unprecedented capabilities for providing scientific and technical forensic services to investigations involving hazardous chemical, biological, and radiological materials, including extremely dangerous chemical and biological warfare agents. This work addressed the government's requirements for the development of methods for non-intrusive (safe) detection and analysis of hazardous chemical liquids contained inside sealed containers. The Pacific Northwest National Laboratory (PNNL) has developed a portable, hand-held, hazardous materials acoustic inspection device that provides noninvasive container interrogation and material identification capabilities. The battery-operated, Personal Digital Assistant (PDA)-based prototype, measures ultrasonic velocity and attenuation to rapidly and reliably screen the contents of sealed containers. The contents of containers can be screened without opening the container so that mislabeled containers and intentionally corrupted fluids as well as hidden contraband are readily discernible. The prototype alpha unit was tailored to perform the following tasks that include:

- Detecting contraband and hidden compartments in liquid-filled containers and solid form commodities,
- Sorting liquid types into groups of like and unlike with respect to ultrasonic properties
- Identifying a selected number of liquids and solids as a function of temperature
- Determination of the fill-level in liquid-filled containers, and
- Rapidly acquiring data and providing easy-to-interpret measurement results

To provide a firm engineering and scientific basis for implementing proposed capabilities and functionality, proof-of-concept studies were conducted to test the viability and performance of various advanced techniques and methodologies

for developing the current prototype platform to more effectively meet the functionality and requirements of federal field assessment personnel. The prototype's liquid discrimination capabilities are targeted towards small containers, specifically from the size of a test tube to that of a 55 gallon drum. As a result of directing the design for examination of smaller containers, a platform was conceptualized and developed using automated distance and temperature measurement protocols, state-of-the-art broadband ultrasonic transducers, advanced electronic design and performance, and advanced signal processing algorithms and software that directly address pertinent inspection/examination issues for small containers.

This paper will describe the development of the ultrasonic measurement methods and signal processing techniques to achieve a high level of accuracy for the non-invasive measurement of small containers. In order to obtain high accuracy time-of-flight (TOF) measurements, traditional ultrasonic methods resort to the use of higher frequency transducers. However, many containers (plastic, glass) and/or fluids (castor oil, honey) exhibit high attenuation properties, which do not allow high frequencies to penetrate efficiently. This reduction in allowable frequencies reduces the TOF resolution/accuracy, which precludes the use of typical commercially available ultrasonic technologies. Therefore, research was directed toward employing an advanced pulse compression technique, whereby large amounts of ultrasonic energy are transmitted into the medium, which allows high signal-to-noise ratios (SNR) to be obtained and accurate TOF measurements to be achieved.

Pulse compression is a technique that has been employed in both RADAR^{1, 2} and medical ultrasound^{3, 4}. It is used to transmit large amounts of energy over a long period of time without sacrificing temporal resolution. A wide bandwidth, long duration frequency chirp is commonly used to excite the source (transmitting transducer). This pulse is received by one or more receiving transducers. Cross-correlation between the transmitted pulse and the received pulses results in a waveform containing the same time, amplitude and spectral information as the received pulse. Pulse compression has recently been used with broadband air-coupled transducers, where energy transmission, signal-to-noise ratio (SNR), and TOF accuracy are relatively low compared with conventional direct coupled ultrasound^{5, 6, 7, 8}. Gan et al.⁶ found that pulse compression provided the air-coupled system with the ability to detect received pulses even when they were well below the noise floor due to the frequency encoded transmitted pulse. In addition, they were able to resolve closely-spaced return echoes from various reflection sources with high accuracy, which was not possible with typical ultrasonic tone burst or square wave excitation technologies. The pulse compression technique has also been used in conjunction with air-coupled ultrasound to interrogate food containers⁹ and detect foreign objects within food materials¹⁰.

Poor SNR is very common in air-coupled ultrasonic testing due to impedance mismatches between air and most other materials. Traditional ultrasound may improve the SNR by simply using high power pulse transmission, commonly using tone burst excitation techniques. A long duration tone burst can efficiently transmit large amounts of energy into air or any other medium. However, tone burst excitation generally results in poor TOF accuracy and provides a narrow-banded response in the frequency domain. A long-duration frequency sweep (chirp) can also efficiently transmit energy into a medium; however, as will be discussed later, signal processing techniques can be used to represent the long duration chirp as a compressed broadband pulse for extremely accurate TOF measurements and a correspondingly broadbanded response in the frequency domain.

Pulse compression is a signal processing technique carried out by cross-correlating a transmitted chirp with a received signal. The cross correlation function effectively locates the specific frequency pattern within the received waveform and outputs a compressed waveform containing information associated with the frequency-dependent amplitude, and transit time of the transmitted pulse. This procedure is extremely useful when trying to locate echoes within a signal whose amplitude is well below that of the noise floor. Gan et al.⁶ demonstrated an increased SNR using the pulse compression technique to locate an echo within a noisy return signal. The energy associated with the compressed cross correlation signal is directly related to the duration of the transmitted chirp pulse. Therefore, in order to achieve a higher SNR, a longer duration pulse is employed.

As stated earlier, the pulse compression technique results in accurate TOF measurements. This is directly related to the frequency bandwidth of the transmitted and received pulses, where a larger bandwidth results in higher TOF resolution. Effectively, the cross correlation output will appear as a broadband pulse with a width inversely proportional to the bandwidth of the transmitted chirp. This phenomenon leads to another advantage of the pulse compression technique also known as deconvolution. For a system containing multiple echoes, a traditional ultrasonic tone burst configuration

would not be able to discriminate between closely spaced echoes. However, a long-duration, broadband transmitted chirp results in a compressed cross correlation function having multiple narrow-width pulses, which allows multiple echoes to be easily resolved.

2. METHODOLOGY

1.1 Measurement apparatus

This research has capitalized on several of the aforementioned advantages of the pulse compression technique. To effectively use the pulse compression technique, a wide bandwidth pulse must be transmitted through the medium; therefore, custom small-diameter, piezocomposite contact transducers were specially ordered with a minimum 80% bandwidth (-6dB or half-power points). Both 1 MHz and 5 MHz transducers were obtained for the prototype. The small contact area of the transducers leads to more accurate and repeatable measurements of both TOF and attenuation. The 5-MHz transducer pair is typically used on small containers (e.g. test tubes) and non-attenuative containers for accurate TOF measurements. The 1-MHz transducer pair is used for highly attenuative containers/fluids. The excitation waveform for the 5-MHz transducers was chosen to span frequencies between 0 and 10 MHz. Likewise, for the 1-MHz transducers, a frequency sweep ranging from 0 to 2 MHz was chosen.

1.2 Custom pulse configuration

The pulse compression approach applies a relatively small voltage over a long period of time, resulting in a large overall amount of energy as opposed to the traditional ultrasound approach that provides a large voltage over a very short period of time. An excitation waveform was constructed to provide an optimized transmitted waveform to the transmitting transducer. Previous researchers⁶ have used a Hanning window amplitude modulated chirp, $C(t)$, as illustrated in Figure 1. This input waveform may be represented by a function (Eqn. 1) where $H(t)$ is the Hanning window function (Eqn. 2), ω_s is the starting radial frequency, T is the pulse duration, B is the bandwidth (Hz), and t is time.

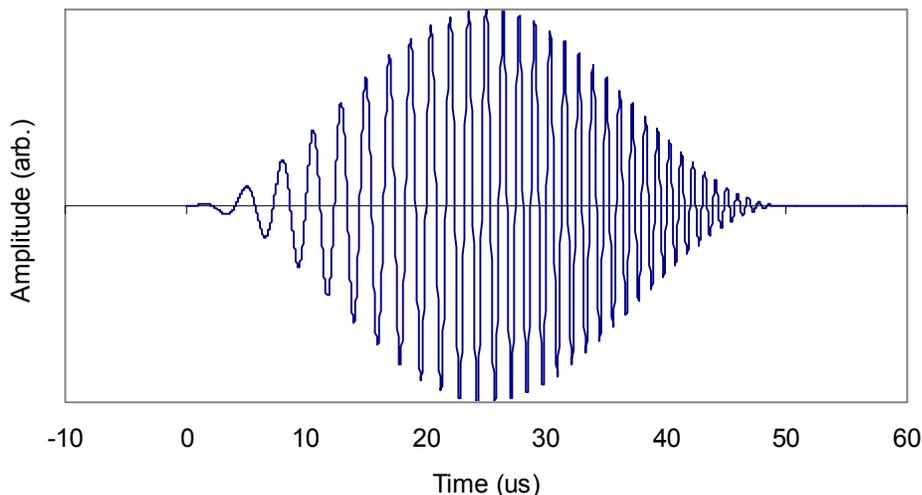


Figure 1: Hanning modulated chirp

$$C(t) = H(t) \sin \left(\omega_s t + \left(\frac{\pi B}{T} \right) t^2 \right) \quad 0 \leq t \leq T \quad (1)$$

$$H(t) = \frac{1}{2} \left[1 - \cos \left(\frac{2\pi t}{T} \right) \right] \quad (2)$$

This research examined the possibility of using an exponentially (non-linear) varying frequency dependence on time to obtain a more accurate TOF measurement as represented by Eqn. 3, where n is the exponential rate of frequency change with time. However, the exponentially varying frequency approach did not yield substantially better results (in accuracy or amplitude) than the linear frequency chirp.

$$C(t) = H(t) \sin \left(\omega_s t + \left(\frac{t}{T} \right)^n \pi B t \right) \quad 0 \leq t \leq T \quad (3)$$

Additionally, the pulse amplitude modulation was altered to include a portion of the transmitted waveform at full amplitude, with a ramp up and ramp down period at the beginning and end of the waveform, respectively. This was performed by altering the Hanning function based on the time and the percentage, P , of the waveform at full amplitude (Eqn. 4). This allowed more energy to be transmitted into the medium while minimizing the large transient “start and stop” pulses associated with non-amplitude modulated waveforms.

$$H(t) = \frac{1}{2} \left[1 - \cos \left(\frac{2\pi t}{T(1-P)} \right) \right] \quad 0 \leq t \leq \frac{T(1-P)}{2}$$

$$H(t) = 1 \quad \frac{T(1-P)}{2} \leq t \leq \frac{T(1+P)}{2} \quad (4)$$

$$H(t) = \frac{1}{2} \left[1 - \cos \left(\frac{2\pi(t-TP)}{T(1-P)} \right) \right] \quad \frac{T(1+P)}{2} \leq t \leq T$$

The final waveform (Figure 2) chosen for the prototype platform used a linear frequency sweep with 60% of the waveform at full amplitude. A frequency spectrum comparison of the two amplitude modulation methods is presented in Figure 3 for frequency chirps with a bandwidth extending from 0.2 to 1.2 MHz.

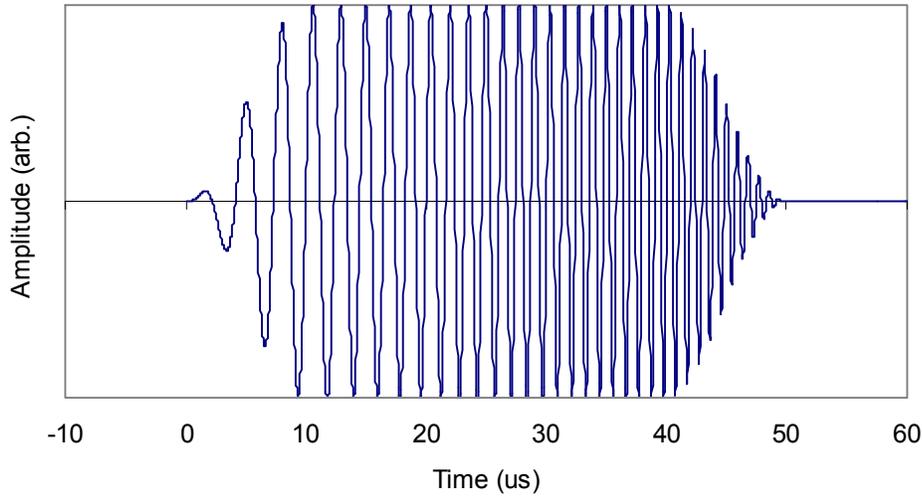


Figure 2: Final output waveform chosen for prototype platform

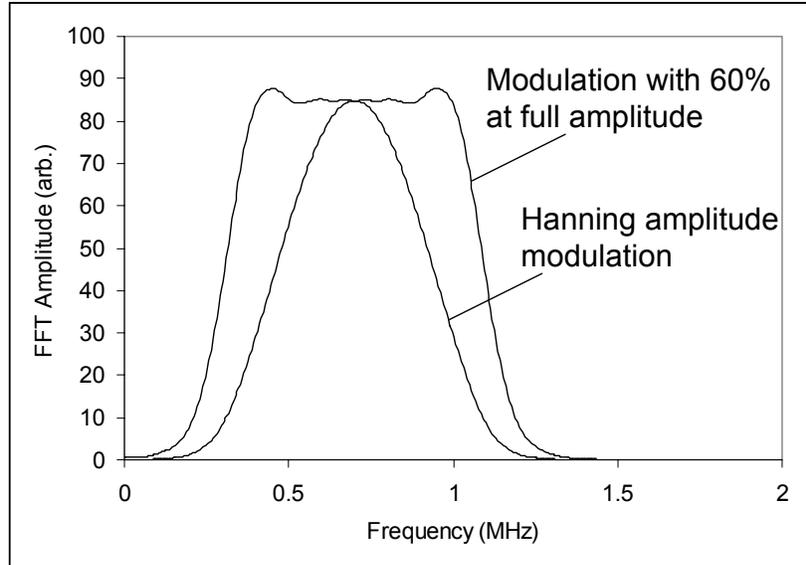


Figure 3: Comparison of full Hanning and partial Hanning amplitude modulation methods

The transducers were arranged in a through-transmission configuration to allow for both pitch/catch (P/C) and pulse/echo (P/E) inspection modalities (Figure 4). A P/C inspection uses two transducers, one for sending and another for receiving the ultrasonic pulse. Only one transducer is used in P/E mode, which functions as both the sending and receiving sensor. Using both measurement modalities allows for a comprehensive analysis of the container contents.

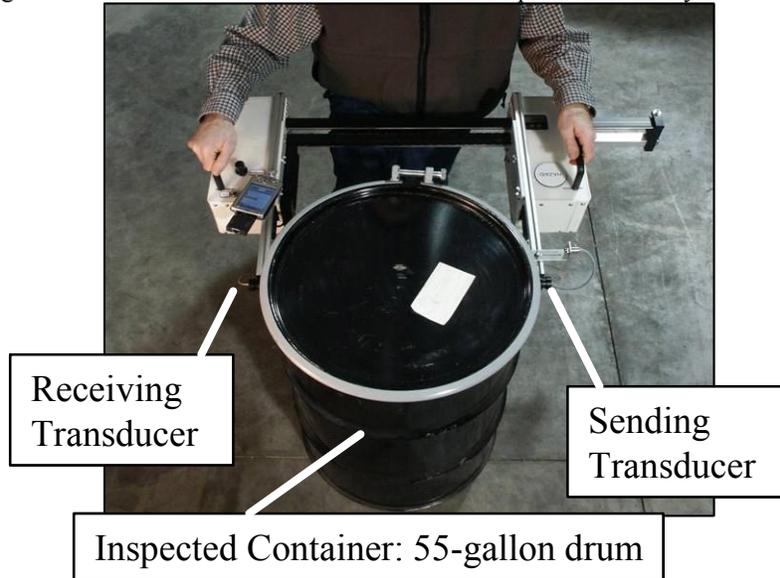


Figure 4: Inspection of container with prototype

1.3 TOF Measurements

For acoustic velocity computations, measurements are acquired using both P/C and P/E modalities. Signals were captured for a variety of liquid-filled containers, geometries, and wall thicknesses over a diverse range of liquids. The custom chirp discussed earlier was then cross-correlated (Eqn. 5) with the output signals from both P/C and P/E inspection modalities. In the Laboratory, a custom Labview™ analysis program was used to perform the cross

correlation (CC) function and store the results (Figure 5). Software algorithms were subsequently written to perform the processing and analysis on a personal digital assistant (PDA) platform. The CC processing yields a short time-duration, broadband pulse. The time associated with the maximum amplitude of the cross-correlation pulse corresponds to the transit-time of the received pulse, resulting in an accurate measurement of transit time.

$$R_{xy}(t) = x(t) \otimes y(t) = \int_{-\infty}^{\infty} x(\tau)y(t + \tau)d\tau \tag{5}$$

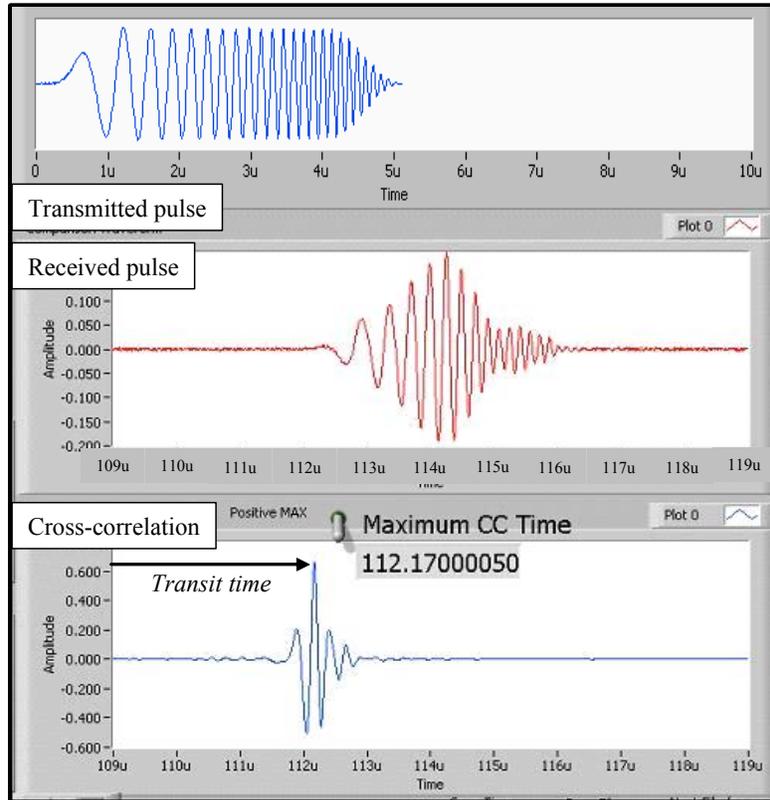


Figure 5: Custom Labview™ cross-correlation waveform analysis

1.4 Attenuation measurements

As stated earlier, the CC contains frequency-dependent time *and* amplitude information. During testing, it was noted that multiple container wall reflections were easily distinguished in the CC waveform (Figure 6). This information allowed identification of the waveform of interest to be isolated from the adjacent reflections, which is not easily accomplished using tone burst excitation or other conventional excitation techniques. Using signals from the P/C transducer, the arrival of the first and second arrival of the chirp pulse train were identified. The first and second arrivals correspond to the pulse travel having traveled through the media one and three times, respectively. Each arrival of the pulse train may be composed of multiple echoes (each corresponding to a pulse in the CC waveform) due to in-wall and/or interface reflections. By extracting the appropriate CC pulses and performing a Fast Fourier Transform (FFT), the frequency-dependent amplitude is determined. A customized analysis program written in Labview™ was used to compare the frequency spectra of the two arrivals. When divided by the appropriate distance (twice the container diameter in this case), this results in a frequency-dependent measure of attenuation. Custom software algorithms were written to perform this processing scheme on the PDA. The benchtop Laboratory-based, Labview™ user interface of the analysis program is presented in Figure 7.

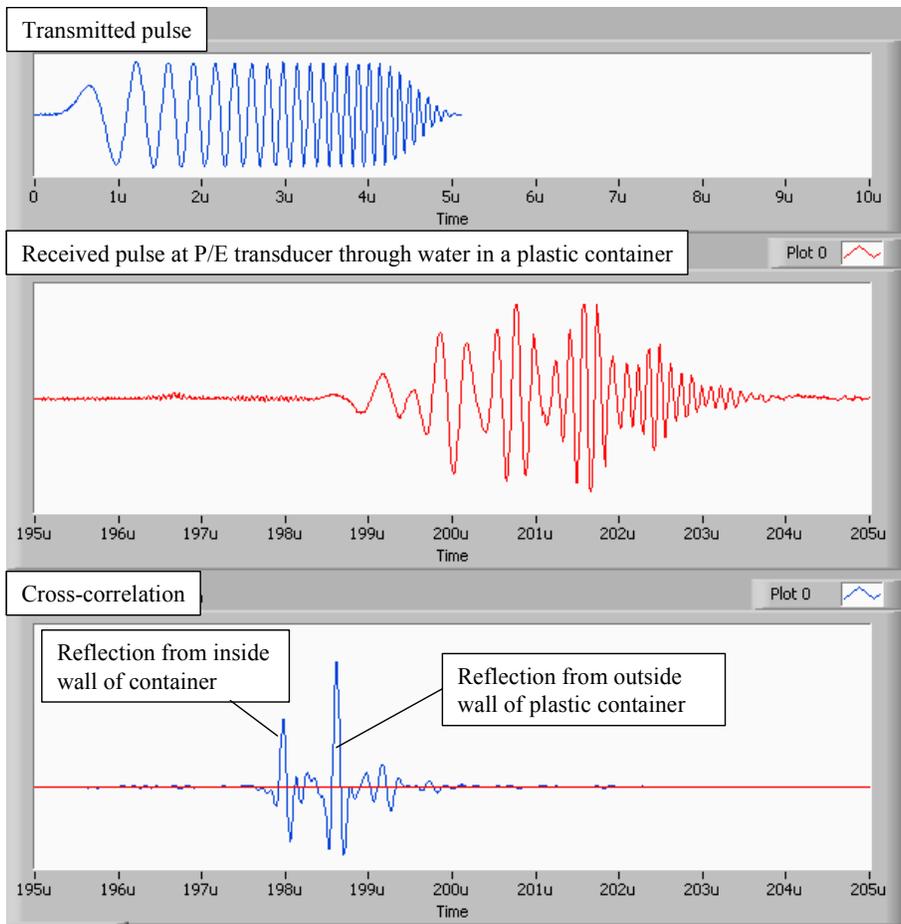


Figure 6: Deconvolution of multiple echoes in a water-filled plastic container.

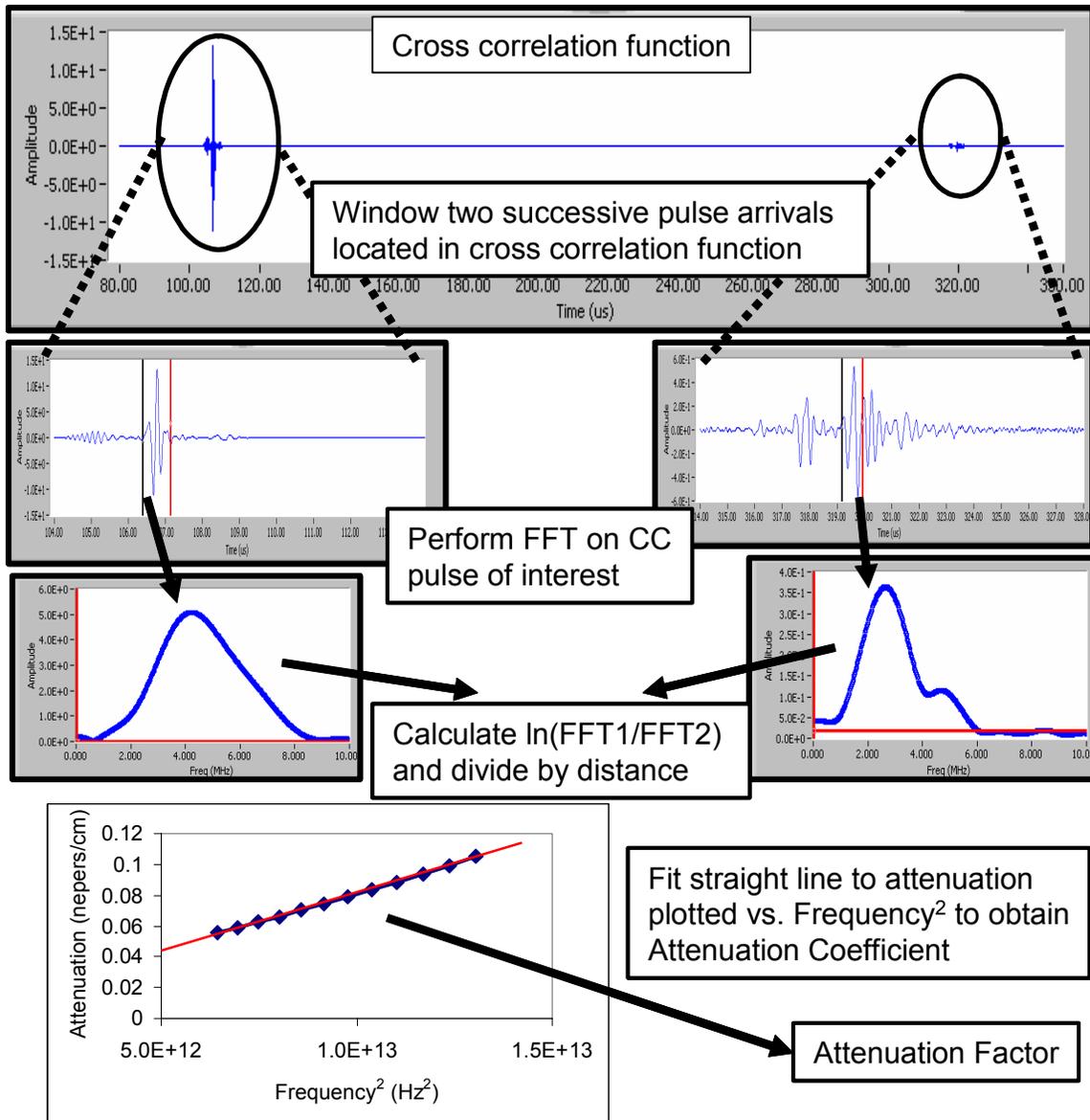


Figure 7: Custom Labview™ waveform spectral analysis

1.5 Container wall effects

Initial testing revealed the ability of pulse compression to dramatically increase SNR and deconvolve multiple pulse reflections within the container wall, into narrow broadband pulses. Figure 8 illustrates the increase in SNR using 5-MHz transducers to send a broadband pulse through a thick-walled, water-filled metal container. Multiple echoes due to reverberations within the container wall are also visible in the second pulse arrival. This ability to resolve multiple echoes will enable future research to obtain more in-depth information regarding the nature of the container wall and the interaction of the ultrasonic pulse at the fluid-wall interface.

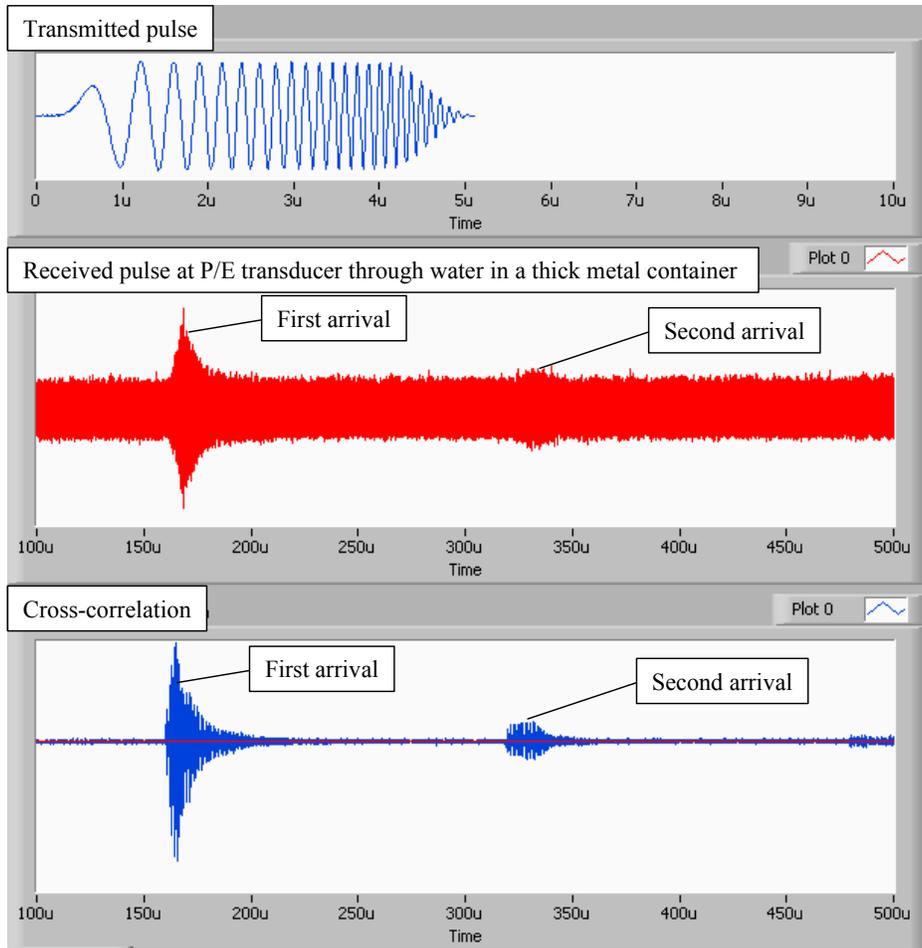


Figure 8: Increased SNR of pulses received at P/C transducer using pulse compression technique on water-filled thick metal container.

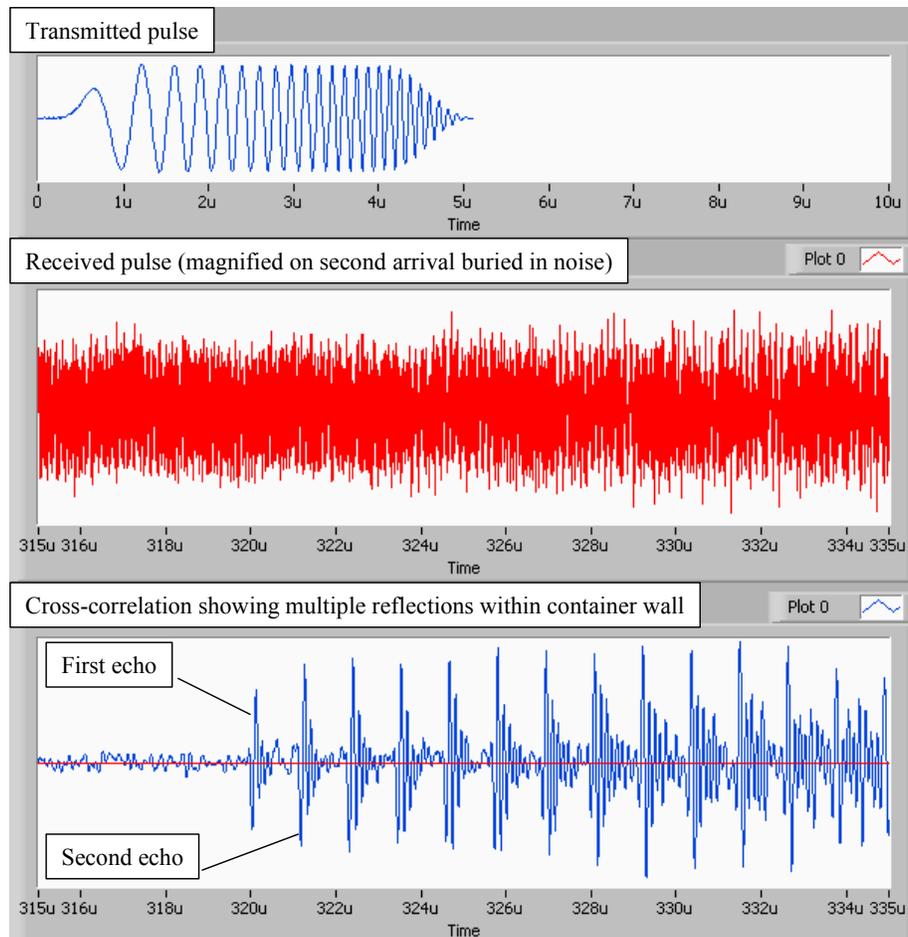


Figure 9: Deconvolution of multiple echoes in second arrival of pulse at P/C transducer within a water-filled thick metal container using pulse compression technique.

3. RESULTS

1.6 TOF measurements

Container wall thickness can greatly influence the accuracy of the fluid velocity measurement. With smaller containers, the wall thickness to fluid path ratio begins to increase, which can cause significant errors in velocity measurement. Thicker walls are often found in wine bottles and test tubes. The pulse-compression technology used in the prototype can provide accurate wall thickness data and in turn effectively compensate for thicker container walls, thereby increasing the accuracy of the measurement. Accurate velocity measurements also require accurate measurements of time, which are more readily attainable at higher frequencies. For the prototype instrument, which will primarily be used for smaller containers, higher frequencies may be utilized for a much higher resolution in time measurement. Adequate SNR (achievable through pulse-compression techniques) is also important to accurately measure the velocity.

1.7 Attenuation measurements

Factors influencing the accuracy of attenuation measurements include transducer coupling to the container, beam divergence, container material, container geometry, distance measurement, temperature measurement, transducer alignment, and frequency bandwidth of the transducers. The most crucial component for accurate attenuation measurements is coupling. In order to efficiently transmit 5-MHz energy into a container, adequate coupling is required,

which is attainable using either an ultrasonic gel couplant or a custom-designed dry couplant membrane. Container wall material plays a significant role, in that different materials will absorb varying amounts of ultrasonic energy. In addition, container material and geometry variances lead to variations in reflection coefficients, thereby changing the amount of energy transmitted and reflected at each interface. With advanced signal analysis (utilizing both P/C and P/E information), a future algorithm may be developed to compensate for these fluctuations in wall material (and thickness). Container walls can also be flexible leading to incorrect distance measurements. This is overcome by the design of the prototype fixture to accurately measure the distance between transducer faces in real time. Transducer alignment is critical for the accurate measure of attenuation. The transducer faces must be directly opposite and aligned parallel to each other for accurate transmission and reception of ultrasonic waves. The prototype fixture has been machined with strict tolerances to allow for precise transducer alignment. As with velocity, distance and temperature measurements are critical for accurate attenuations measurements. Divergence is a physical phenomenon associated with ultrasonic wave propagation whereby the energy begins to “spread out” as a function of distance from the source, similar to a flashlight. The divergence error varies depending on the ultrasonic wave speed in the fluid. This divergence of the beam spreads the energy over a larger area, which decreases the energy along the straight-line path between the transducers. Since divergence is dependent upon the fluid velocity and container geometry, a computer algorithm could be developed to compensate for this “apparent” change in energy. Finally, transducer bandwidth plays a role in accurate attenuation measurements. With a larger frequency range over which to calculate the attenuation spectra, a more consistent estimate of the attenuation can be obtained.

The utilization of two inspection modes (P/C and P/E) allows for 1) increased accuracy of velocity and attenuation measurements and 2) measurement redundancy for more confidence in measurements. Velocity and attenuation measurements can be obtained from both inspection modes and exhibit close agreement. The P/C transducer for the prototype system allows for an improved measurement over commercially available ultrasonic systems in that the ultrasonic waveform travels across the fluid medium one less time than that required for the P/E technique. Using the pulse-compression technique, additional information is available for addressing container wall thickness issues (from the P/E configuration). A known (or computed) container wall thickness combined with data from the P/C configuration will provide an extremely precise measurement of velocity. In addition, the added information will provide container wall attenuation information, allowing for an improved liquid attenuation measurement. With the requirement of accurate and automated distance measurement with the prototype instrument, the physical addition of a P/C transducer has readily been achieved.

4. CONCLUSIONS

Pacific Northwest National Laboratory (PNNL) has developed a prototype portable, hand-held, hazardous materials acoustic inspection device that provides federal law enforcement officers with noninvasive container interrogation and material identification capabilities using nondestructive ultrasonic velocity and attenuation measurements. The prototype is capable of making consistent measurements of velocity and attenuation, compared with commercially available technology units. The prototype was developed using a versatile electronics platform, advanced ultrasonic wave propagation methods, and advanced signal processing techniques. Employing high bandwidth ultrasonic transducers in combination with an advanced pulse compression technique allowed researchers to 1) impart large amounts of energy into the inspected media, 2) obtain high signal-to-noise ratios, and 3) obtain accurate and consistent time-of-flight (TOF) and attenuation measurements through a variety of highly attenuative containers and fluid media. The prototype experimental measurement technique also provided information regarding container properties (e.g. thickness, material properties), which will be utilized for future container-independent measurements of hidden liquids.

5. REFERENCES

1. Axelsson SRJ. 2004. Noise radar using random phase and frequency modulation. *IEEE Transactions on Geoscience and Remote Sensing* 42(11):2370-2384.
2. Rajeswari KR, N Gangatharan, GEM Abraham, GSVRK Rao, and DE Rani. 2003. Algorithm for design of pulse compression radar codes. *Electronics Letters* 39(11):865-867.

3. Behar V and D Adam. 2004. Parameter optimization of pulse compression in ultrasound imaging systems with coded excitation. *Ultrasonics* 42(10):1101-1109.
4. Chang YF. 2003. A software controlled pulse compression technique applied to ultrasonic non-destructive testing. *Journal of the Chinese Institute of Engineers* 26(2):147-153.
5. Berriman J, P Purnell, DA Hutchins, and A Neild. 2005. Humidity and aggregate content correction factors for air-coupled ultrasonic evaluation of concrete. *Ultrasonic* 43(4):211-217.
6. Gan TH, DA Hutchins, DR Billson, and DW Schindel. 2001. The use of broadband acoustic transducers and pulse-compression techniques for air-coupled ultrasonic imaging. *Ultrasonics* 39(3):181-194.
7. Gan TH, DA Hutchins, DR Billson, and FC Wong. 2001. Ultrasonic tomographic imaging of an encased, highly attenuating solid medium. *Research in Nondestructive Evaluation* 13(3):131-152.
8. Gan TH, DA Hutchins, and RJ Green. 2004. A swept frequency multiplication technique for air-coupled ultrasonic NDE. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 51(10):1271-1279.
9. Gan TH, DA Hutchins, and DR Billson. 2002. Preliminary studies of a novel air-coupled ultrasonic inspection system for food containers. *Journal of Food Engineering* 53(4):315-322.
10. Cho BK and JMK Irudayaraj. 2003. Foreign object and internal disorder detection in food materials using noncontact ultrasound imaging. *Journal of Food Science* 68(3):967-974.

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