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Pacific Northwest
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Density and Flow-Velocity Measurement Technology for Dredging Applications (Proof-of-Concept Study)

MS Greenwood
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October 2004

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Project 53816
Technical Letter Report

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M. S. Greenwood
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Work performed for the
U.S. Army Corps of Engineers
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Richland, Washington 99352

Summary

The U.S. Army Corps of Engineers (USACoE) is searching for advanced technologies to provide physical property information about the dredge slurry traveling through the pipe in real-time, including density and the flow rate of the slurry. During the latter part of FY07, the USACoE funded a proof-of-concept study at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington, to investigate potential technical solutions to this problem by evaluating the viability of a patented acoustic method for measuring density and the advanced measurement approach employed using pulse-compression acoustics. A trip to Coos Bay, Oregon, was taken by PNNL staff in mid-August to observe the operation of the USACoE dredger ship *Essayons*, which dredges sand from the ocean floor and to acquire samples of dredge slurry material extracted from the Bay for use in this study.

PNNL staff conducted a proof-of-concept evaluation study on these dredge slurry samples to determine the viability for eventual design and testing of an ultrasonic density sensor and flow meter. Two sets of trials were conducted in this study: 1) basic ultrasonic property measurements and signal transmission trials in through-transmission mode using both mono-frequency tone-burst and pulse-compression approaches, and 2) real-time density measurements. This technical letter report provides a summary of the work conducted and the results obtained, and documents the conclusions and recommendations from this proof-of-concept evaluation.

The *Essayons* employs both a radioactive density sensor and a sonic flow meter; both commercially available devices. The current density sensor operates and performs satisfactorily, but the USACoE wants to replace these technologies, especially the density sensor, due to cost, maintenance and security protocols, and paperwork issues associated with their use. The operation of the current sonic flow meter can be problematic.

Although the ultrasonic pulse-compression technique could not penetrate the slurry generated in the laboratory setup, the results are still inconclusive due to the large amount of air introduced into the slurry as a result of the mixing process required for particle suspension. The conditions seen in the laboratory may not be representative of the slurry conditions generated in a pipe from dredge material pulled from the sea floor during routine dredging operations. It is anticipated that a pair of transducers placed on the outside of the dredge piping may demonstrate successful penetration of the slurry and allow for observable waveforms to accurately measure wave speed and relative attenuation, which are linearly related to the density of the slurry. This would allow for an alternate indication of specific gravity to the radiation density measurement currently used, and provide a means for measurement of flow rate using through-transmission methods. Further study onboard a dredging ship is recommended.

Data were obtained using the PNNL ultrasonic density sensor for sand slurries having a density of 1.17 g/cm^3, 1.32 g/cm^3, and 1.42 g/cm^3. The transducer frequency was 2.0 MHz. The data acquisition system analyzes the signals and obtains the density and velocity of sound on-line and in real time. The values of the density were lower than anticipated. Investigation of the data indicated that these results were due to air entrapped in the slurry. Two effects are occurring during the data acquisition. Some ultrasound is reflected by the slurry and some by the entrained air in the slurry. The signals obtained during the data acquisition are compared to the signal obtained for water during the calibration of the sensor. While less ultrasound is reflected by the slurry than by water, more ultrasound is reflected by air

than by water. Thus, these two effects are in opposition and the result is that the density obtained on-line is smaller than the actual density of the slurry. An analysis was carried out to determine the fraction of air in the sample. The results show the center value of the sensor density is in very good agreement with that obtained independently for the slurry having a density of 1.17 g/cm^3. However, the sensor density is 6% low for a density of 1.32 g/cm^3 and 10% low for a density of 1.42 g/cm^3. The software can be modified to include the effects of air, which are likely to be present during dredging operations, so that the density values can be corrected for air on-line and in real time. The data on the velocity of sound shows that there is very little variation in the velocity of sound. Thus, the density can be obtained from the acoustic impedance (density × velocity) by dividing by the velocity of sound in water. Another alternative is to use a look-up table and relate the acoustic impedance to the velocity of sound. The density values have a standard deviation of about ±6% of the average value. This uncertainty can be reduced by taking several hundred values of the density, instead of 50 used in these experiments. The uncertainty is much larger than in other experiments with slurries having a smaller particle size. This difference suggests that a smaller uncertainty might be obtained using a smaller frequency for the transducer. For example, a frequency of 500 kHz yields a wavelength that is four times that for 2 MHz. The objective is to reduce the observed granularity of the slurry, by causing diffraction of the ultrasound around the particles. In this way, the bulk density of the slurry can be observed. In conclusion, the results of these experiments demonstrate the feasibility of this ultrasonic method for measuring the density of the sand slurries.

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PART I

Introduction

The Pacific Northwest National Laboratory (PNNL) has experience in design, fabrication, testing, and commercialization of portable, hand-held, acoustic technologies that provide noninvasive container interrogation and material identification capabilities for homeland security and law enforcement applications using acoustic energy to measure physical properties of a liquid inside a container. These devices have been employed in applications where acoustic energy is introduced from the outside of the container to extract accurate measurements of acoustic velocity and relative attenuation from the liquid medium inside. Past technical conversations with the U.S. Army Corps of Engineers (USACoE) have led to discussions regarding this non-conventional ultrasonic approach and its potential for applications in real-time characterization of slurries from dredging pipes. Additionally, a patented PNNL methodology to measure the density of a liquid or slurry in a pipe (from the outside of the pipe) could be integrated with this technique to form a technical solution for the USACoE and provide real-time density and flow-rate information for dredge slurries in pipes.

As an example, the *Essayons* Dredger currently in operation along the Pacific Coast of the U.S. Northwest employs large-diameter (28 to 36 inches), thick-walled steel dredge piping with characteristic wall thicknesses ranging from 1 to 2 inches under maximum pressures of 40–50 psi, to extract material from areas requiring dredging. The USACoE is searching for advanced technologies to provide physical property information about the dredge slurry traveling through the pipe in real-time, including density and the flow rate of the slurry. During the latter part of FY07, the USACoE funded a proof-of-concept study at PNNL to investigate potential technical solutions to this problem by evaluating the viability of a patented acoustic method for measuring density and the advanced measurement approach employed using pulse-compression acoustics.

In order to acoustically compute density of a liquid or slurry from the outside of a pipe, both the acoustic impedance (defined as the product of the density and velocity of sound in the slurry) and acoustic velocity of the liquid medium must be known (or accurately measured). Conventional acoustic methods have difficulty providing suitable penetration and maintaining accuracy through the highly attenuative dredge slurries. A low-frequency, tone-burst approach and a pulse-compression measurement methodology were studied to determine how effective these ultrasonic methods would be in providing enhanced penetration and accurate measurements of both the acoustic velocity and the acoustic impedance for a systematically accurate computation of the liquid-slurry density.

Technical Background

PNNL’s approach to addressing the issue of sonic penetration and measurement sensitivity/accuracy is based upon work in developing hand-held, acoustic technologies that measure ultrasonic velocity (speed of sound) and a relative attenuation metric, to rapidly and reliably screen the liquid contents of sealed containers or the liquid volumes contained in a pipe. The measurement process is conducted from the outside of the pipe wall nondestructively and non-invasively. The acoustic device employs two transducers mounted on extendable caliper arms that can be placed on opposite outside walls of a pipe or container to actively transmit and receive an acoustic pulse though the containment. The instrument simultaneously records the acoustic echo, the distance between the transducers, and the external temperature of the container in question. An attached tablet PC processes the collected data and calculates the velocity of sound through the contained material along with a measurement of the material's relative acoustic attenuation. These prototypes were engineered to measure containers ranging in size from 1-inch diameter to approximately 24 inches in diameter.

In order to obtain highly accurate time-of-flight (TOF) measurements, traditional ultrasonic methods resort to the use of higher frequency transducers. However, thick-walled dredge piping and dredge slurries exhibit high acoustic 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 and requires custom-designed transducers or other means to accomplish the measurement. Prior research at PNNL focusing on homeland security and law enforcement applications was directed toward employing an advanced pulse compression technique, whereby large amounts of ultrasonic energy are transmitted into the medium, resulting in high signal-to-noise ratios (SNR) and accurate TOF measurements.

Pulse compression is a technique that has been employed in both RADAR (Rajeswari et al. 2003; Axelsson 2004) and medical ultrasound (Chang 2003; Behar and Adam 2004). 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 (amplitude and frequency information is preserved). Pulse compression has recently been used with broadband air-coupled transducers, where energy transmission, SNR, and TOF accuracy are relatively low compared with conventional direct-coupled ultrasound (Gan et al. 2001a; Gan et al. 2001b; Gan et al. 2004; Berriman et al. 2005). Gan et al. (2001a) 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 containers (Gan et al. 2002) and detect foreign objects within food materials (Tucker and Diaz 2006).

Poor SNR is very common in air-coupled ultrasonic testing due to impedance mismatches between air and most other materials, and similar SNR problems are evident in propagating ultrasonic energy across a dredge slurry in a large-diameter pipe, where attenuation is high. 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-bust 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 convert a long-duration chirp into 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. (2001a) 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. Details of this measurement methodology and algorithm development have been reported by Tucker and Diaz (2006).

Recent work on thick-walled stainless steel containers indicates successful acquisition of multiple echo reverberations in the wall of the container, yielding additional information for calculation of the acoustic impedance of the liquid at the wall-liquid interface. This information is key toward computation of the liquid density, especially if accurate acoustic impedance and acoustic velocity data can be extracted from the liquid. This additional acoustic information was recently discussed between principal investigators at PNNL, where it became evident that an existing density measurement methodology patented by Greenwood (Greenwood and Bamberger 2004) might be integrated with the Acoustic Inspection Device (AID) measurement process to provide an effective technical solution for the USACoE.

The density of the liquid in a pipe or container can be measured using non-invasive ultrasonic approaches as well. The schematic diagram for measuring the acoustic impedance (Greenwood and Bamgerber 2004) is shown in Figure 1. The ultrasound from the transducer makes multiple reflections within the plate, having a thickness of 0.25 inches in this case.

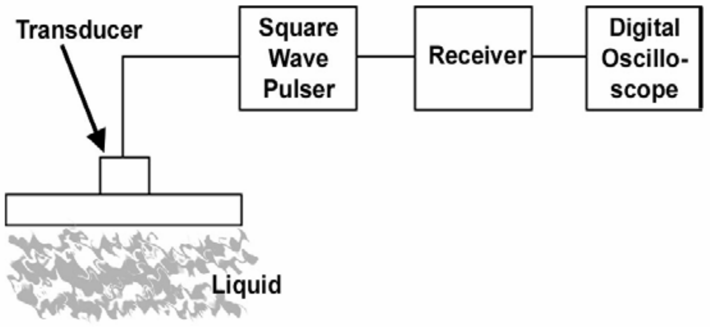

Figure 1. Schematic Diagram for Measuring the Acoustic Impedance

The transducer also acts as a receiver and the signals are shown in Figure 2 as a function of time. Each of these signals is analyzed to obtain the maximum amplitude.

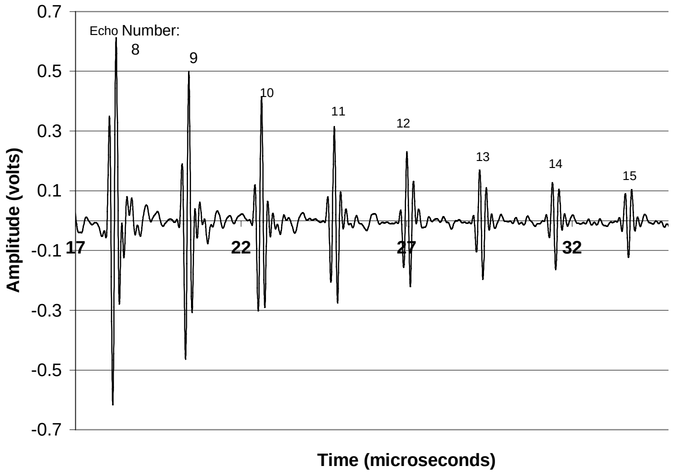

Figure 2. Example of Multiple Echo Reverberations in the Liquid-Backed Steel Wall

The amplitude is plotted on a log plot, which results in a straight line as shown in Figure 3 for a sugar water solution, 10% by weight. The acoustic impedance is determined from the slope. An important feature of this method is the patented self-calibrating technique. If, for example, the voltage to the transducer decreases by 1%, each echo changes by the *same* amount, but the slope on a logarithmic plot is *not* changed.

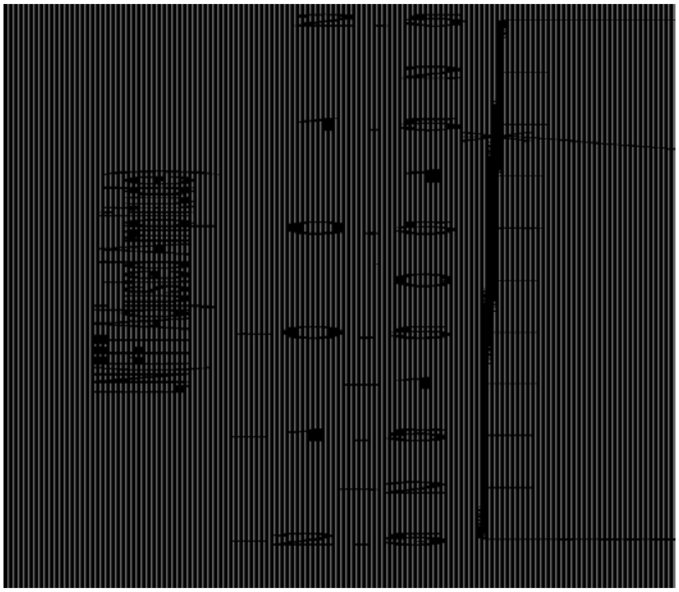

Figure 3. Logarithmic Plot of Amplitude versus Echo Number

Thus, this method does not rely on maintaining a specified voltage over a long period of time. The method described in Greenwood and Bamberger (2004) uses a 0.25-inch wall thickness and a short signal so that each echo can be separated in time. However, as discussed above, multiple reflections within a thick wall can be obtained using the pulse compression technique and these signals can be analyzed to determine the acoustic impedance using the same method as described in Greenwood and Bamberger (2004). (Bamberger and Greenwood 2004) also describes the measurement of density and the velocity of sound through the slurry using these techniques.

Technical Objective and Scope

The objective of this effort is to provide a proof-of-concept justification for employing an acoustic methodology for characterizing the slurry-dredge medium and measuring density and mass flow rate in a pipe from the outside surface of the dredge-piping network. The proof-of-concept effort summarized here consisted of the following primary activities:

1. Measurement Concept Development
2. Field visit to the *Essayons* (Acquisition of Samples)
3. Data Acquisition Configuration, In-Lab Measurements and Feasibility Evaluations
4. Signal Processing, Data Analysis and Development of Results
5. Documentation (Technical Letter Report)

Technical Approach/Concept

PNNL staff conducted a proof-of-concept evaluation study on dredge slurry samples (obtained from Coos Bay, Oregon, during a visit to the USACoE dredger ship *Essayons*), to determine the viability for eventual design and testing of an ultrasonic density sensor and flow meter. Two sets of trials were conducted in this study: 1) basic ultrasonic property measurements and signal transmission trials in through-transmission mode using both mono-frequency tone-burst and pulse-compression approaches, and 2) real-time density measurements. For through-transmission tone-burst and pulse-compression measurements, a set of small-scale trials and a set of larger-scale trials were conducted.

Dredge Slurry Specimens Used in This Evaluation

A trip to Coos Bay, Oregon, was taken by PNNL staff in mid-August to observe the operation of the USACoE dredger ship *Essayons*, which dredges sand from the ocean floor, and to acquire samples of dredge slurry material extracted from the Bay for use in this study. Five 5-gallon bucket samples were extracted from actual dredging operations while onboard the *Essayons*. These samples were roughly 50% sand and 50% water by volume. Measured amounts of sand and water were extracted from these buckets to obtain slurry specimens consisting of specific gravities of 1.1, 1.2, 1.3, and 1.4.

Laboratory Data Acquisition Set-Up

Figure 4 illustrates the laboratory data acquisition configuration for initial measurements of basic acoustic properties.

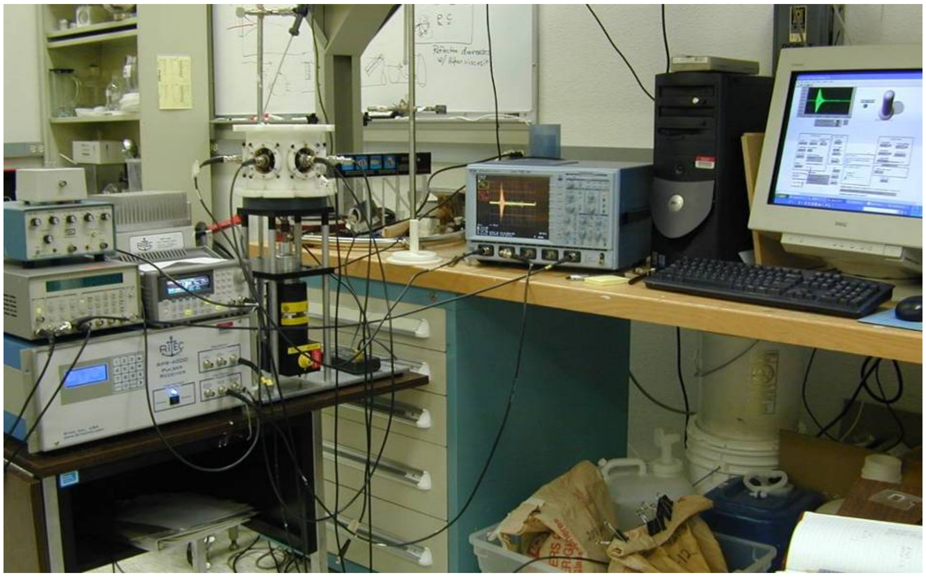

Figure 4. Laboratory Measurement Configuration for Basic Ultrasonic Slurry Property Measurements

Small-scale Testing

A 4-inch inside diameter container was used to take initial measurements on the dredge slurry (Figure 5 and Figure 6). The container houses six ultrasonic transducers allowing for three direct through-transmission paths and six backscatter measurements at various frequencies. For this study only one set of 5-MHz transducers was used for a direct transmission path to measure both attenuation and wave speed. An impeller located at the bottom of the measurement chamber was powered with a motor positioned below the chamber. This configuration was necessary to keep the large, high-density particles in suspension for a measurement condition analogous to the actual dredge slurry conditions.

A pulse-compression excitation technique was used to obtain a high signal-to-noise ratio of the ultrasonic waveform through the slurry. The pulse-compression enables accurate transit time measurements across the slurry without compromising the frequency content for attenuation measurements. The data was subsequently analyzed and is presented Figure 7 and Figure 8. As the specific gravity of the slurry increased, the wave speed increased and the attenuation decreased. This is similar to results we have observed with previous slurry testing. These changes exhibit a linear relationship between specific gravity and the ultrasonic parameters, which indicates that the specific gravity could, indeed, be monitored with this method.

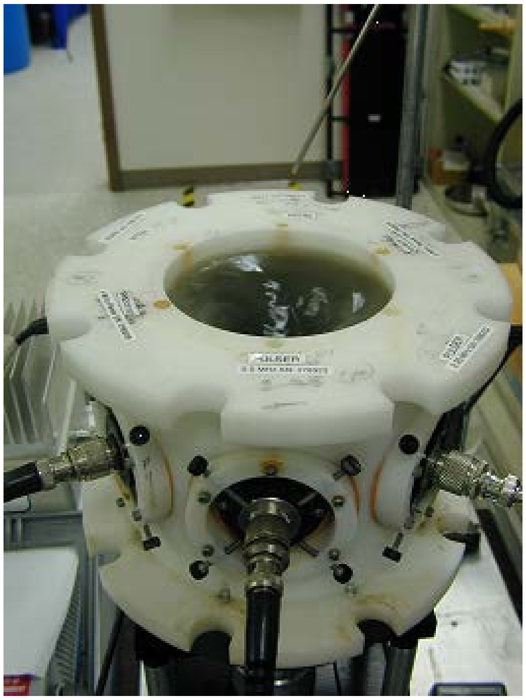

Figure 5. Measurement Chamber

Figure 6. Measurement Chamber and Mixer

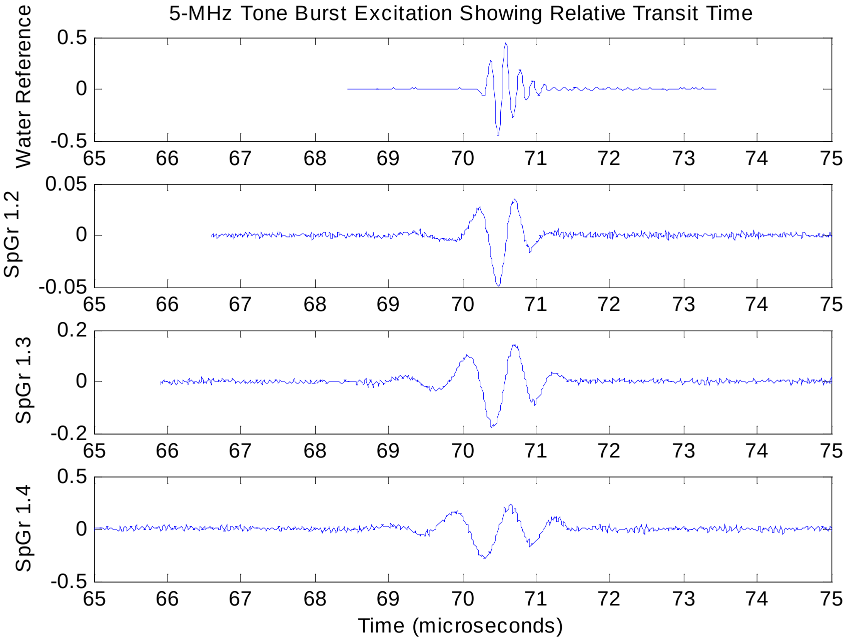

Figure 7. Cross-Correlated Ultrasonic Waveforms through Various Slurry Densities

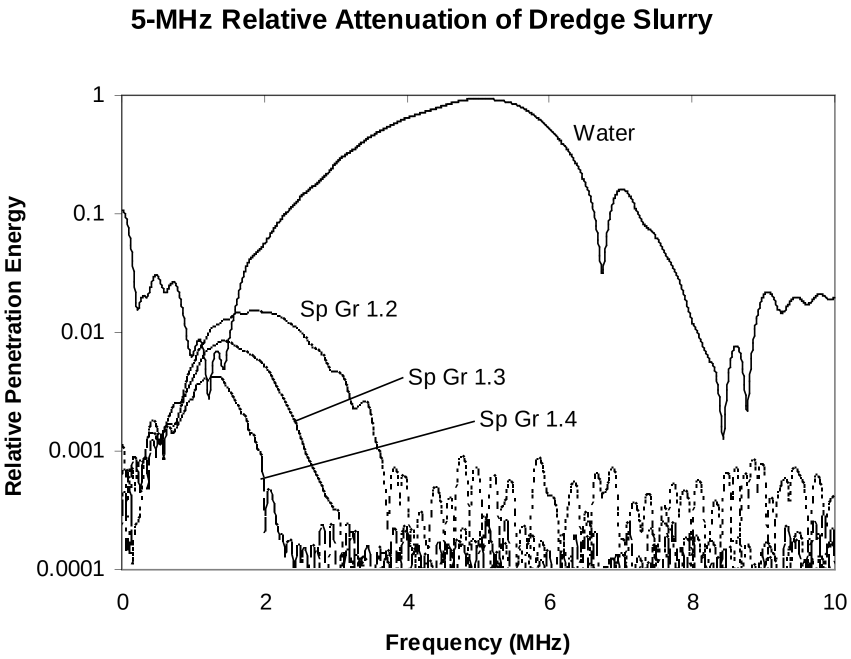

Figure 8. Ultrasonic Energy Transmission Through Various Slurry Densities with Sensors Immersed Directly into the Medium (no walls). Most of the energy capable of traversing the slurry is in the 0 to 2-MHz range.

Large-scale Testing

To determine if the through-transmission pulse-compression method would work on an actual dredge pipe, a large-scale measurement setup was constructed. An 8-inch deep by 14-inch wide by 48-inch long rectangular Plexiglas container was used to house the slurry and provide for mixing and ultrasonic measurements (Figure 9and Figure 10). Two transducers were mounted on the outside of the tank at opposite ends to transmit ultrasonic waveforms along the 48-inch dimension. The transmitting (sending) sensor was a broadband 250-kHz transducer while the receiving transducer was a broadband 100-kHz transducer. This frequency range was chosen because of the propagation distance, high attenuation, and high excitation voltages needed to penetrate the slurry. A pulse-compression technique was again used to obtain the highest possible SNR by exciting the sending transducer with a 500-microsecond, 1200-volt frequency sweep from 0 to 250 kHz.

Initial measurements were taken in water and subsequent measurements were taken at specific gravities of 1.2, 1.3, and 1.4 by adding air-dried dredging particles (sand and silt) to the water. To keep the slurry suspended in this configuration was not a trivial matter. Two sump pumps and two high-speed mixers were used and located in the chamber to produce the most thorough suspension of the particles. This resulted in an extremely turbulent measurement chamber exemplary of the dredging operation; however, this also began to introduce air into the system. Mixer and pump placement were chosen to maximize mixing and minimize air intake.

Figure 9. Plexiglas Measurement Tank

Figure 10. Plexiglas Measurement Tank

Processed waveforms from the large-scale study are shown in Figure 11. A much higher frequency content is observed in the waveform received through the “water”-only condition. In order to visually detect the waveforms on an oscilloscope for the higher specific gravity slurries, a gain of 100 dB was used. The processed waveforms for the higher specific gravity slurries resulted in almost identical waveforms (transit time and energy transmission, leading us to the conclusion that these waveforms were not likely traveling through the slurry, but through the container itself. A further study was performed by placing the transducer on the outside of the tank ABOVE the water line. With a gain of 100 dB, a waveform was observed arriving at approximately the same time as the waveforms obtained from the high density slurries.

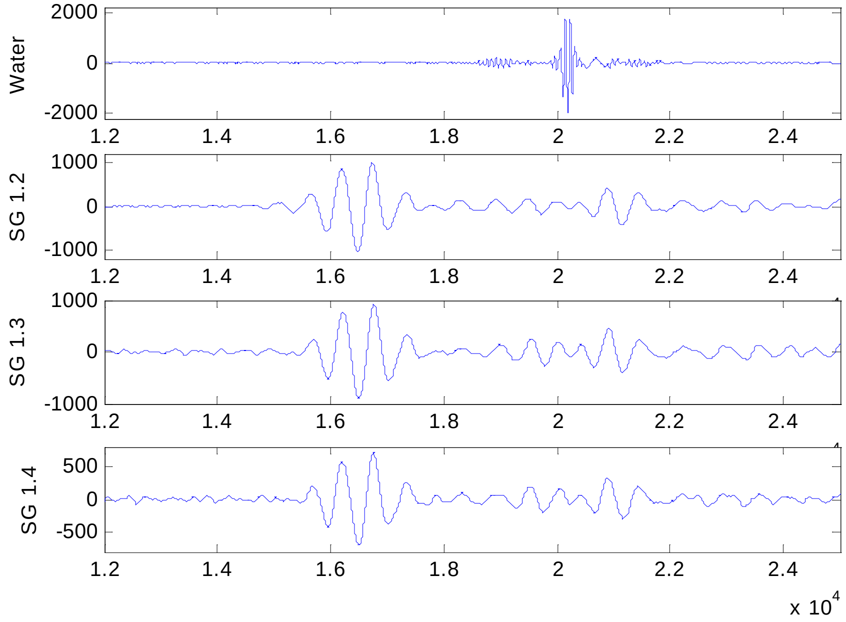

Figure 11. Processed Ultrasonic Signal Through Large-Scale Measurement Tank

Discussion and Recommendations

Although the ultrasonic pulse-compression technique could not penetrate the slurry generated in the laboratory setup, the results are still inconclusive because of the large amount of air introduced into the slurry as a result of the mixing process required for particle suspension. The conditions seen in the laboratory may not be representative of the slurry conditions generated in a pipe from dredge material pulled from the sea floor during routine dredging operations. It is anticipated that a pair of transducers placed on the outside of the dredge piping may demonstrate successful penetration of the slurry and allow for observable waveforms to accurately measure wave speed and relative attenuation, which are linearly related to the density of the slurry. This would allow for an alternate indication of specific gravity to the radiation density measurement currently used, and provide a means for measurement of flow rate using through-transmission methods. Further study onboard a dredging ship is recommended.

PART II

Measurement of the Density of Sand Dredged by the Ship *Essayons* – Experimental Setup

The experimental apparatus, shown in Figure 12, consists of a pipeline unit having a hexagonal cross section. Transducers having a frequency of 500 kHz, 1 MHz, 2.25 MHz, 5.0 MHz, and 7.5 MHz are fastened on the outside. The wall thickness ranges from 0.3 inches to 0.5 inches. The distance between the two inside walls is 1.75 inches. The bottom plate contains a propeller blade and the shaft is connected to a mechanical mixer. The mixer is connected to a Variac (transformer) and the output voltage is an indication of the rotational rate of the mixer. In the experiments with the sand, the Variac was usually set to 90 V, but 70 V was used in one experiment.

Principles of the Density Measurement

A schematic diagram of the apparatus is shown in Figure 13. A short pulse of ultrasound from the send transducer strikes the pipeline wall, and it is reflected at the steel-slurry interface back to the send transducer, which also acts as a receiver. Multiple reflections occur within the pipeline wall and each one is recorded by the send transducer, producing a signal shown in Figure 14. The + signs in this figure indicate the limits of each echo. Echoes 2 through 11 were used to calculate the density. Each pulse of ultrasound produces this type of response and each one is analyzed by the data acquisition code. The transducer produces 200 short pulses per second. Typically, 50 pulses constituted one data set, and each one of the 50 is called a "case."

The system is calibrated using water and the signal similar to Figure 14 would show slightly higher amplitudes for each echo. In Figure 15, the natural logarithm of the amplitude for each echo for the slurry and for water is shown. We see that the amplitude for water is larger than that for the slurry and that this difference increases with larger echo number. The reason is that the amount of ultrasound reflected at the interface depends upon the properties of the slurry and of steel. This property is called the acoustic impedance, which is defined as follows

$$\text{Acoustic impedance} = \text{density x velocity} \qquad (1)$$

Since the slurry has a greater impedance than water, the difference in the impedance of water and steel is larger than that for steel and the slurry. That is, more ultrasound will be reflected by the steel-water interface than by the steel-slurry interface, as shown in Figure 15.

The amount of reflection at the interface is determined by the following formula, involving the impedances. Note the difference factor in the numerator.

$$\text{Reflection coefficient} = (Z_{st} - Z_{liq})/(Z_{liq} + Z_{st}) \qquad (2)$$

where Z_{liq} is the acoustic impedance of the liquid in contact with the steel wall and Z_{st} is the acoustic impedance of the steel. For water, the velocity of sound is 1482 m/sec with a density of 998 kg/m^3 and for steel, the velocity is 5736 m/sec and the density is 7900 kg/m^3. Inserting these values in Eq. (2) shows that the reflection coefficient at the steel-water interface is 0.93. This means that 93% of the ultrasound is reflected at the interface.

Figure 12. Photograph of the Experimental Apparatus. The 2.25-MHz transducers are located close to the bottom plate and mixer.

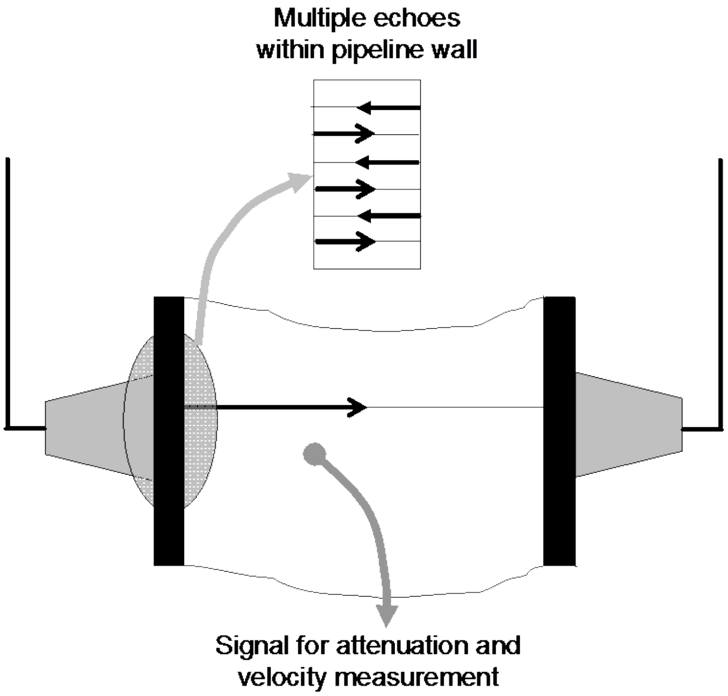

Figure 13. Schematic Diagram Showing a Cross Section of the Pipeline

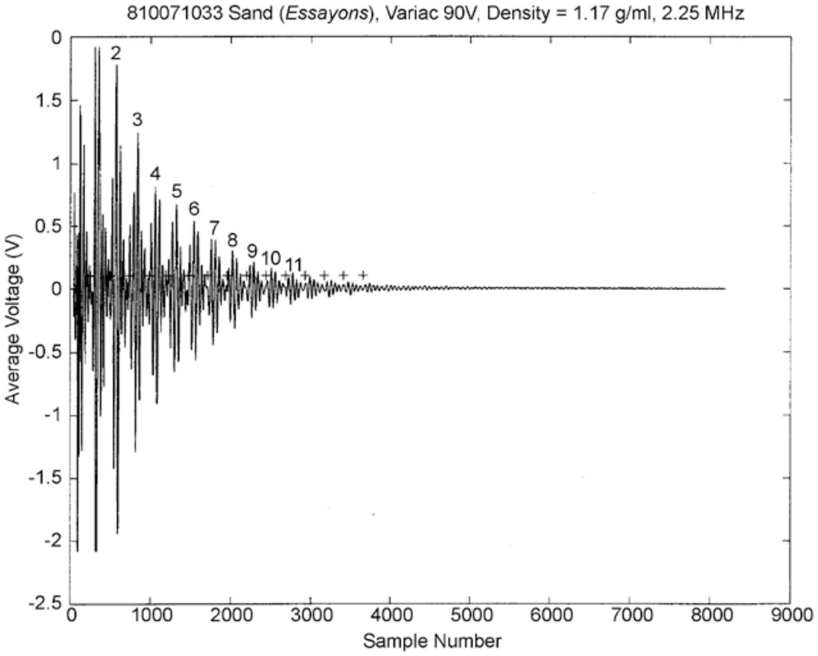

Figure 14. Ultrasonic Signal Showing Multiple Echoes Produced within the Stainless Steel Wall

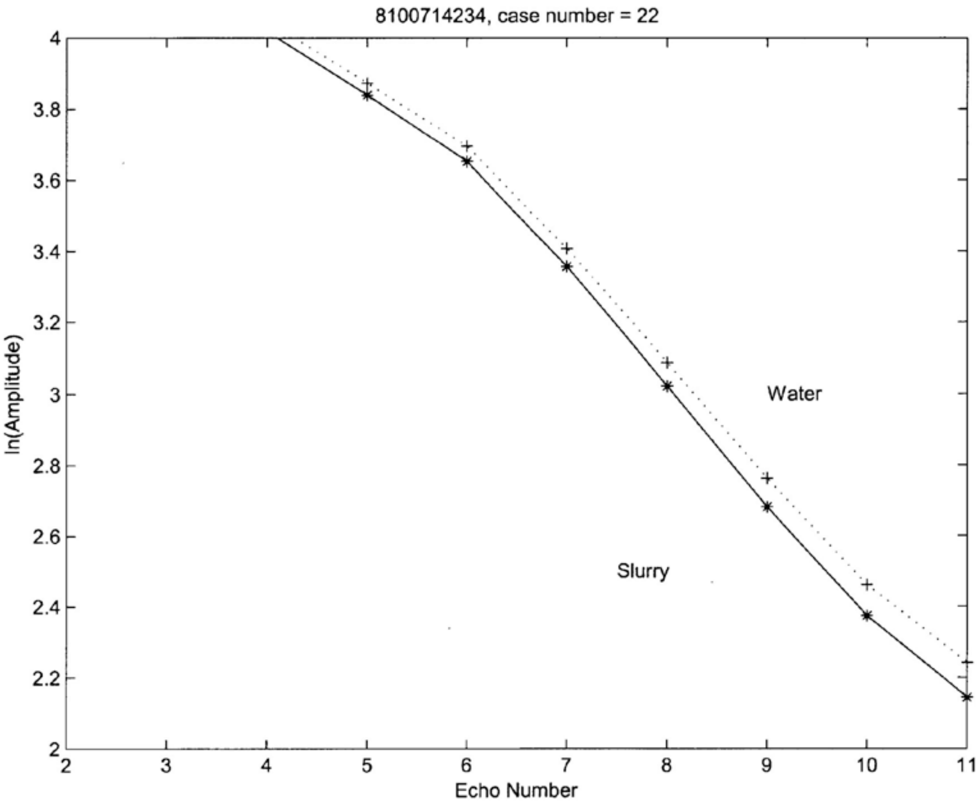

Figure 15. Natural Logarithm of the Amplitude for Each Echo versus the Echo Number for Water and for a Slurry

The objective of the measurement is to determine the reflection coefficient of the ultrasound at the steel interface for a liquid of unknown acoustic impedance. Using Eq. (2) and solving for Z_{liq}, we find the following:

$$Z_{liq} = Z_{st} (1 - RC_{liq}) / (1 + RC_{liq}) \tag{3}$$

The information about the amplitudes, such as shown in Figure 15, is used to determine the reflection coefficient at the interface. For each echo, the amplitude for the slurry is divided by the amplitude for water. Then the natural logarithm of this ratio is obtained. The results for the data in Figure 15 are shown in Figure 16. The best straight line fit to the data is obtained and the value of the slope is recorded. In the journal article by Greenwood and Bamberger (2004), the following result is derived:

$$RC_{liq} = (RC_{wtr}) \exp (\text{slope}) \tag{4}$$

where exp (x) means e^x, and e = 2.7183. Since the slope is negative, less ultrasound is reflected at the steel-slurry interface for the slurry than for water, which agrees with the preceding discussion. If the liquid is water, then the slope in a graph like Figure 16 is zero, which is a horizontal straight line. Since $e^0 = 1$, Eq. (4) shows the reflection coefficient of the liquid (water, here) is equal to RC_{wtr}. Also, for liquids that have a smaller acoustic impedance than water, the slope will be positive.

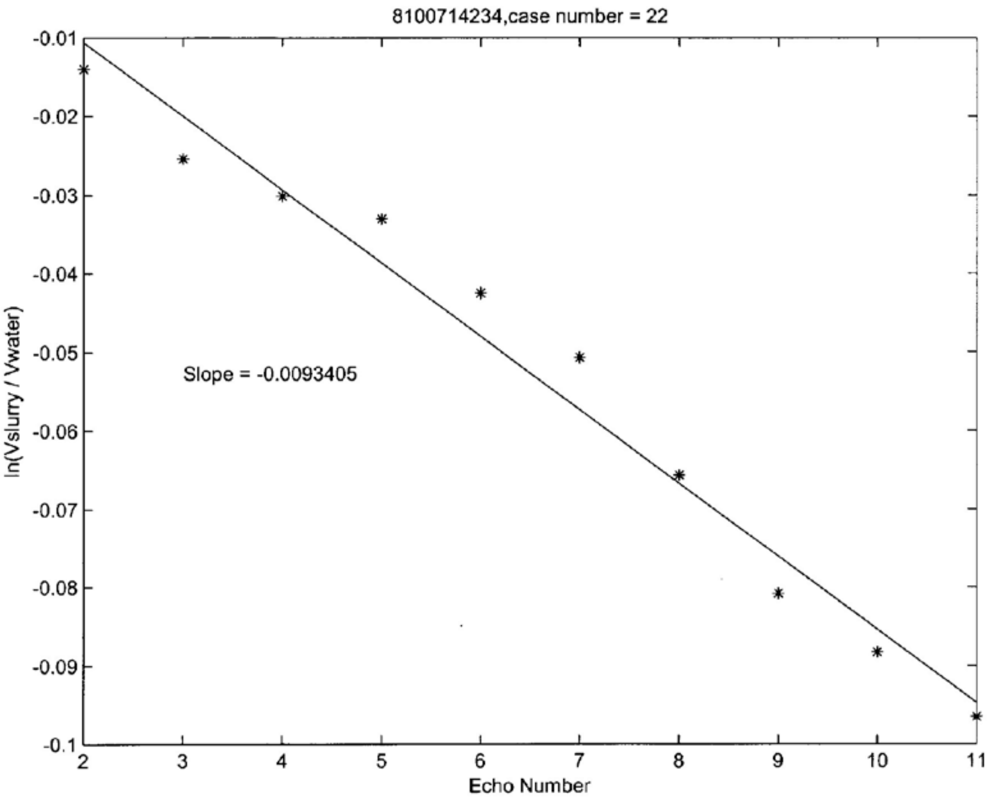

Figure 16. Material Logarithm of the Ratio V_{slurry}/V_{water} versus the Echo Number

After obtaining the reflection coefficient for the slurry in Eq. (4), the acoustic impedance is determined in Eq. (3). The velocity of sound is determined by measuring the time-of-flight of the ultrasound through the liquid or slurry. The density is determined as follows:

$$\text{Density} = \text{Acoustic impedance of liquid} / \text{Velocity of sound} \tag{5}$$

Measurements with Sugar Water Solutions

In order to test the apparatus and the code, measurements were made with two sugar water solutions: 26% by weight and 32% by weight of sugar in water. The densities were 1.112 g/cm^3 and 1.137 g/cm^3, respectively. The results, shown in Table 1, illustrate the sensitivity and repeatability of the measurements.

Table 1. Measurement of Density and Velocity of Sound for Two Sugar Water Solutions Using Ultrasonic Sensor and Comparison with Independent Measurement of Density

File ID	Liquid	Trial Number	Sensor Frequency (MHz)	Density (g/cm^3)	Velocity of Sound (m/sec)	Independent Density Measurement (g/cm^3)
25907159	26 Wt% Sugar Water	1	2.25	1.114	1581	1.112
259071520		2	2.25	1.113	1581	
259071529		3	2.25	1.114	1581	
259071511		1	5	1.103	1582	
259071522		2	5	1.103	1583	
259071531		3	5	1.105	1582	
259071513		1	7.5	1.099	1580	
259071523		2	7.5	1.090	1580	
259071532		3	7.5	1.102	1580	
249071610	32 Wt% Sugar Water	1	2.25	1.143	1611	1.137
259071358		2	2.25	1.145	1612	
259071446		3	2.25	1.145	1612	
249071624		1	5	1.141	1613	
259071413		2	5	1.132	1613	
259071449		3	5	1.134	1613	
249071536		1	7.5	1.109	1612	
259071428		2	7.5	1.125	1611	
259071451		3	7.5	1.125	1611	

Measurements with Sand Slurries

The slurry densities of 1.2 g/cm^3, 1.3 g/cm^3, and 1.4 g/cm^3 were chosen for measurement. In order to know how much sand to add to the water, the density of the sand particulate was measured. This was done by adding a known mass of sand to a glass vessel (called a pychnometer), which has a narrow neck and a well-known volume indicated on the glass. In this case, the volume was 25.0 ml. A known mass of sand was added to the glass vessel and water was added to fill it to the 25.0 ml level. Knowledge of the amount of water added permitted the determination of the volume of the particulate, and thus, the density of the sand particulate. The result was 2.61 g/cm^3, which is in agreement with the density for silica.

The independent measurement of density was obtained by using a pipette to extract the slurry from the vessel a number of times to fill the 25 ml glass vessel, just described.

The data acquisition code sets the parameters for the pulser-receiver, the settings on the digitizer card linked to the computer, and carried out the calculations of the slope, reflection coefficient, the acoustic impedance, the velocity of sound, and the density. A run consisted of 50 cases. Each case resulted from one pulse of ultrasound transmitted by the send transducer. Thus, the density was determined 50 times and the average value of the density was obtained as well as the standard deviation about the average value. The results are shown in Table 2.

Table 2. Summary of Results Obtained by the On-line Data Acquisition Code

Run ID	Density by Mass & Volume (g/cm^3)	Variac Voltage (volts)	Ultrasonic Sensor Average Density	Standard Deviation about Average	Velocity of Sound in Slurry (m/sec)	Average Density of Runs	Number of Positive Values of the Slope
81007911	1.17	70	0.9997	0.057	1469		23
81007951	1.17	70	1.007	0.064	1466		26
810071033	1.17	90	0.9695	0.048	1501		33
810071052	1.17	90	0.9648	0.060	1499	0.98525	32
810071135	1.32	90	1.018	0.064	1475		25
810071152	1.32	90	1.027	0.065	1474	1.0225	17
810071423	1.42	90	1.058	0.074	1480		16
810071447	1.42	90	1.058	0.076	1479		13
81007158	1.42	90	1.058	0.076	1479	1.058	14

While the average density values for the three slurries are different, the standard deviation shows that there is a large uncertainty in the density. There is a very nearly linear relationship with the sensor density and the independent measurement of density, which is shown in Figure 17. Even so, the results of several measurements are very repeatable. The important question is, “Why are the density values so low?”

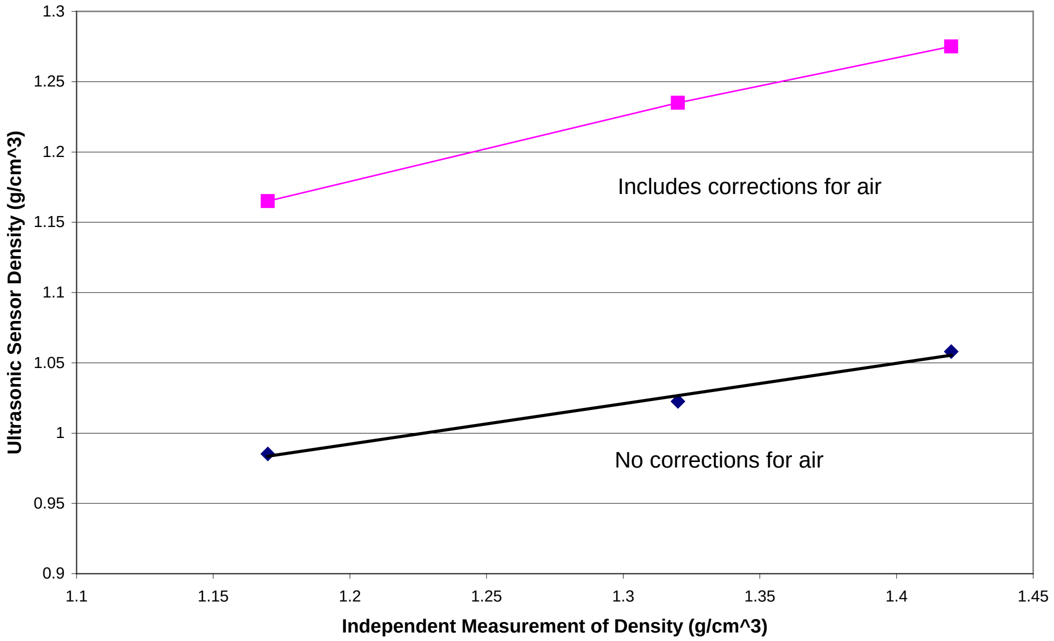

Figure 17. Sensor Density versus Independent Measurement

The data had been saved to files and was analyzed off-line. The data showed that there were a number of POSITIVE values of the slope. A typical case is shown in Figure 18, which shows that a straight line is a reasonable fit to the data. Table 2 shows the number of cases having a positive slope. We note that the slurry with a density of 1.17 g/cm^3 has the largest number, while a density of 1.42 g/cm^3 has a smaller number. Certainly very interesting!

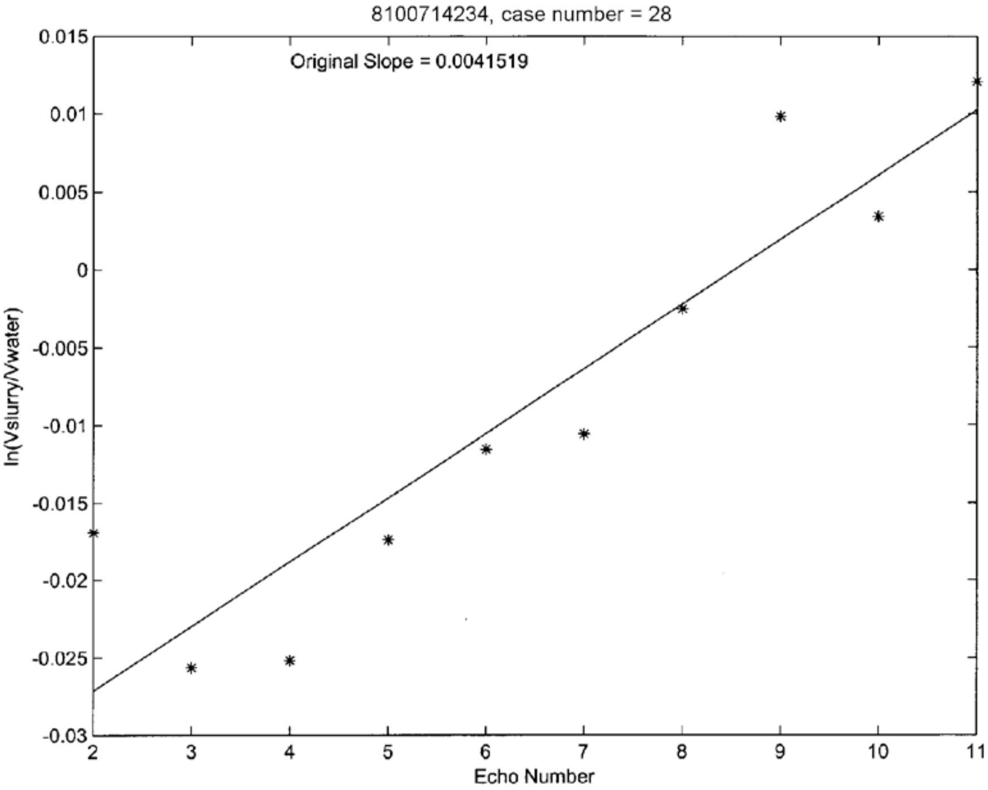

Figure 18. Data for the Natural Logarithm of Ratio V_{slurry}/V_{water} versus the Echo Number showing a Positive Value of the Slope

A positive value of the slope means that the density of the slurry is *less* than that of water. Water produces a slope of zero. Dense slurries produce a negative slope. A low density produces a positive slope. Therefore, the data acquisition code produces densities smaller than that of water. When all of these low values are included in the average, the average value is smaller than one would expect.

The results for positive slopes can be seen from Eqs. (3) and (4). If the slope is positive, Eq. (4) shows that the reflection coefficient for the liquid is larger than that for water. If the reflection coefficient is larger, then Eq. (3) shows that the acoustic impedance of the liquid is smaller.

Effects of Air

There are two very important questions: 1) How can one interpret the fact that some density values are less than the density of water? And 2) Why are the average values of the density so much smaller than those obtained by independent measurements?

If any amount of air is present in the sample, this can lead to increased reflection because the reflection coefficient for air is 1.0. This means that 100% of the ultrasound traveling in the steel is reflected at the steel-air interface. So, if a small amount of air is present in a dense sand slurry, there are two competing effects: Reflection from the sand slurry will be *less* than from water, while reflection from air will be *greater* than from water. The net result of the analysis in the data acquisition code is that the slurry appears to be less dense than its actual value.

Corrections for Air

Let us suppose that there is a small fraction of air in the sand slurry. This certainly seems reasonable, since the mixer is rotating quite rapidly. Therefore, the total reflection consists of reflection from the slurry and reflection from the air.

In order to determine the fraction of air, all of the runs obtained at a Vairac voltage of 90V were searched to find the run and case with the largest positive slope. This is assumed to be due to water with a small fraction of air. This occurred for run 1052, case number 48, where the slope was +0.0112 and the corresponding reflection coefficient was 0.9473. The objective is to find the fraction of air (f_{air}) and to assume that it was the same in all seven runs. Thus, the reflection coefficient that is measured by the data acquisition (D_{aq}) system is the sum of that due to water and to air. That is,

$$D_{aq} \text{ reflection coefficient} = (1 - f_{air})\, RC_{water} + f_{air}\, RC_{air} \tag{6}$$

Substituting values into Eq. (6), we find the following

$$0.9473 = (1 - f_{air})(0.93678) + f_{air}\,(1.0)$$

And $$f_{air} = 0.1668$$

This means that the slurry contains 16.68% air.

The value of f_{air} is used to process all of the data to find the so-called true reflection coefficient for the 50 cases in all 7 runs, using the following relationship:

$$D_{aq} \text{ reflection coefficient} = (0.8332)RC_{true} + (0.1668)(1.0) \tag{7}$$

The D_{aq} reflection coefficient was substituted into Eq. (7) and the values of RC_{true} were determined. Then, the value of RC_{true} was used in Eq. (3) to determine the true value of the acoustic impedance $Z_{liqtrue}$. The density was determined from $Z_{liqtrue}$ / velocity of sound. The results are shown in Table 3. The density values have a large distribution as shown by the maximum and minimum values of the density, as well as the standard deviation about the average density value. For a given density, the results of several runs are quite consistent. The results are in very good agreement for a slurry having a density of 1.17 g/cm^3. However, for a slurry density of 1.32 g/cm^3, the sensor density is about 6% low; and for 1.42 g/cm^3, about 10% low. While the average values of the density show distinction, this is clouded by the large uncertainty about the average value. This is addressed below.

Table 3. Results Obtained by Correcting the Data for the Effects of Air. The percentage of air in the slurry is 16.68%

Run Number	Density by Mass & Volume (g/cm^3)	Average Density Corrected for Air (g/cm^3)	Standard Deviation about Average Density (g/cm^3)	Maximum Density Value in Run (g/cm^3)	Minimum Density Value in Run (g/cm^3)	Velocity of Sound (m/sec)
1033	1.17	1.171	0.058	1.331	1.012	1501
1052	1.17	1.165	0.072	1.307	0.987	1499
1135	1.32	1.23	0.077	1.387	1.046	1475
1152	1.32	1.241	0.079	1.476	1.07	1474
1423	1.42	1.279	0.09	1.449	1.089	1480
1447	1.42	1.267	0.087	1.516	1.135	1479
1584	1.42	1.279	0.092	1.477	1.054	1479

Discussion and Recommendations

The air-corrected results show reasonable agreement with the densities measured independently, as has just been discussed. In Table 2, the number of cases with a positive slope shows clearly that the sensor can distinguish between the sand slurries of three different densities.

The values of the velocity of sound in the slurries in Table 2 show very little difference from the velocity of sound in water, 1482 m/s at 20°C. Therefore, a good value of the density can be obtained by using the acoustic impedance from the multiple reflections and dividing by the velocity of sound in water. Another possibility is using a look-up table to find the velocity associated with a given acoustic impedance.

The data from the on-line data acquisition code yielded values of very low density for the three sand slurries. Investigation of these results indicated that these results were due to air entrapped in the slurry. Most likely, air will also be present in slurries from the dredging operation. These analyses show that the effects of air can be observed. The software in the on-line code can include a similar analysis and the effects of air determined on-line.

The data for the slurries were obtained using 50 cases for each run with the transducer frequency of 2.0 MHz. The variation in the data suggests that in the future, many more cases be included in each run. However, for the slurry having a density of 1.42 g/cm^3, the three runs of 50 cases do show very good agreement. Using more cases in each run would reduce the standard deviation.

The standard deviation of the density values, shown in Table 2 and Table 3, are quite large. However, experiments with slurries of, say, 20 microns at 2.25 MHz, yields density values with a much smaller uncertainty (Hylton et al. 1998). What is the reason for this and how can we "duplicate" that in experiments with the sand slurries?

For slurries of 20-micron-diameter particles in water, the wavelength of 2.25-MHz ultrasound (as it travels in the solid before striking the solid-slurry interface) is about 50 times larger than the diameter of the 20-micron particles. As a result, the ultrasound cannot distinguish individual particles, but rather sees the overall bulk density of the slurry. When the ultrasound encounters a particle, diffraction occurs around the particle. In the current experiments, the diameter of the sand particles are fractions of a millimeter, and the wavelength is only slightly larger than the particle size. This means that it may be possible that the ultrasound is able to detect individual particles, rather than seeing the overall bulk density. Since the wavelength of ultrasound is given by the velocity of sound divided by the frequency ($\lambda = c/f$), the wavelength can be increased by decreasing the frequency. Therefore, the first step in designing a unit for testing aboard a ship should be to do preliminary experiments to determine the optimum frequency. For example, one could carry out similar experiments in the lab using a 500-kHz transducer and measure the density. This would increase the wavelength by a factor of 4, compared to that using 2 MHz. Is there a difference or not? At this lower frequency, a 1-inch thickness of steel is needed, but this is not a problem because the pipeline walls on the ship are also about this thickness. The objective is to see if the uncertainty in the density measurement can be reduced using a larger wavelength. Based upon the work reported here, we recommend a two-phased approach for developing a prototype ultrasonic device. Phase 1 would focus on refinement of ultrasonic measurement parameters, design, and fabrication of the prototype device; while Phase 2 would focus on implementation, testing and evaluation of the device in the field, on-board a dredging ship.

PART III

Glossary

AID	Acoustic Inspection Device
PNNL	Pacific Northwest National Laboratory
SNR	signal-to-noise ratios
TOF	time-of-flight
USACoE	U.S. Army Corps of Engineers

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