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Prototype Acoustic Resonance Spectroscopy Monitor

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EXECUTIVE SUMMARY

Introduction

Acoustic measurements in arms control verification have matured over the past few years. It appeared promising to extend these techniques to nuclear safeguards, but the application environments are sufficiently different that safeguards applications require separate investigation. This work was directed toward examining possible applications of acoustics to facilitate International Atomic Energy Agency (IAEA) safeguards at bulk processing facilities.

Section Three of the System Requirements Document for this project detailed five specific areas of effort. The first three were specific to verifying the design of a simulated process tank and its internal plumbing. The fourth effort was to examine whether acoustic signatures would be adversely affected by external plumbing and whether signatures of the plumbing could be used to detect undeclared changes in the external plumbing. The fifth area was directed toward examining effects of fill material on a tank's acoustic signature, and the sixth effort was to perform simple modeling of the system to understand whether results could be scaled to other tank dimensions and configurations. A summary of the results and recommendations on future development in these areas are presented below. Experimental details are included in the appendices.

Verification of Tank Design and Internal Plumbing

The original direction of this effort was not as successful at verifying tanks as we had hoped. We demonstrated that changes in internal plumbing configuration can be detected using the tank's internal acoustic resonances (changes in plumbing will damp out certain resonance frequencies preferentially), but these measurements are most sensitive if performed at discrete frequencies, rather than across a spectrum. Because changes in the overall spectral pattern are small compared to random variations, interpretation of a detected change in the acoustic characteristics of a tank is severely complicated. It would be extremely difficult to discriminate between innocent internal changes (such as twisting of the plumbing) and undeclared changes supporting a diversion scenario using acoustic (≤20 kHz) frequencies alone.

We also attempted to use ultrasonic frequencies to detect items inside a simulated tank. In contrast with the acoustic approach, in which we monitor for changes in an overall internal resonance, the ultrasonic approach detects high-frequency wave reflections from the plumbing or other internal structures. After taking several measurements around the tank's perimeter, we can map the location of internal objects. Distances from the outer shell are determined by the pulse delay between the transmitted and detected signal. Although this approach holds significant promise, the experiments were started late in the funding cycle. Significant additional effort will be required to make this a mature, fieldable acoustics application for safeguards.

Modeling Tank Design Verification

We anticipated that the cylindrical symmetry of the tank would simplify modeling because acoustic resonance modes can be represented as Bessel functions. If successful, this would have helped us scale the experimental results and interpret spectral data. Unfortunately, convolution of the shell resonance modes with the acoustic modes made this problem intractable. Moreover, the most effective measurements were performed at discrete frequencies, where we look for shifts in resonance amplitude and phase between the transducers. Thus, spectral data that might have been useful in modeling was typically not collected.

Verification of External Plumbing and Effects on Tank Measurements

With the difficulty in interpreting acoustic measurements for tank verification, there was limited value in experimentally examining how external plumbing would impact these measurements. Moreover, the design of our test tank should essentially isolate external plumbing from the tank's shell and acoustic vibrations.

We did examine the possibility of using acoustic signatures of the pipes themselves to detect undeclared alterations to the pipe. We thoroughly characterized the harmonic acoustic signature of a 1-in. pipe borrowed from the supply shop of our plutonium processing facility. Spectra were obtained at several locations along the length of the pipe, with the receiving transducer detecting second or third harmonic frequencies of the transmitting transducer. We planned to alter the pipe by attaching a smaller tube (as might be employed in a diversion scenario) to see if this change could be detected by a change in the pipe's harmonic signature. Unfortunately, the harmonic data were plagued by instrumental artifacts that made comparisons meaningless. Conceptually this approach remains valid if the experimental artifacts can be overcome.

Effects of Fill Material

The original intent of this effort was to examine the effects of various liquids on the test tank's acoustic signature. Liquids, or variations of liquids within the tank, fundamentally alter the transmission of sound inside the tank. If spectral information had been sensitive to internal changes, then modal analysis could be used to resolve changes caused by transmission through liquid from changes caused by absorption and scattering from internal plumbing. When we realized that the acoustic technique was sensitive to internal changes only at selected frequencies (and thus spectral information became of limited value), it became obvious that fill material would change the phase and amplitude relationships at the selected discrete frequencies and these changes between measurements could not be resolved from changes in the internal plumbing.

This limitation in the acoustic resonance method is not shared by the ultrasonic ranging method. In fact, transmission of sound from the shell to the tank interior is facilitated when it is filled with liquid, reducing attenuation of the ultrasonic pulses. Effects of different types of liquid fill were not specifically investigated because this technique was pursued late in the project. The most significant impact is likely to be uncertainty in the exact distance a detected reflecting surface (tubing) is from the tank shell because of uncertainty in the speed of sound in the fluid. This uncertainty might be reduced by normalizing the apparent distance to one or several pipes where the distance is known. However, further investigation into this approach would be required.

Monitoring of Fill Level

Variability of fill material limited the original direction of this effort—verifying internal tank designs—because fill materials with different acoustic characteristics change the efficiency of transmission and reflection of sound into the tank interior. However, this effect can be exploited to verify the fill level within a tank. Sound waves travel along the surface of the shell more slowly where the adjacent internal surface of the tank is in contact with liquid. Two approaches were successfully investigated to monitor the fill level from outside the tank using sound waves.

In one case, transducers are permanently affixed to the tank wall, one above the other, and a sound pulse is transmitted between them. The fill level is a linear function of the sound pulse's propagation time between the transducers. Because this sensor is permanently affixed, this technique is best suited for situations where there is limited access to the tank.

The other sensor is a hand-held system with two transducers next to each other. Pulses are sent between the two transducers as the inspector slides the sensor vertically along the tank. When the sensor is adjacent to the liquid-air interface, the phase relationship between the two transducers changes because of the change in propagation time. A prototype sensor was constructed that gives an audible tone to notify the operator when the sensor is adjacent to the liquid-air interface. This technique can be useful to qualitatively, or semi-quantitatively, verify fill levels with declarations while minimizing intrusiveness.

In addition to identifying fill levels within tanks, both of these techniques can be used to detect stratification of fluids within the tank. This can be important in obtaining samples as well as optimizing materials processing.

Conclusions and Recommendations

The most promising safeguards application of acoustic measurements identified in this work is the possibility of monitoring the fill level of tanks and detecting stratification before assay samples are collected. Prototypes of both the hand-held sensor and the permanently affixed sensor for monitoring fill levels were developed and successfully demonstrated. However, they have only been tested in laboratory settings and are optimized for a specific container geometry. Future effort, if funded, would be directed toward improving the functionality of the hand-held sensor with different container geometries and investigating the sensitivity of the sensor in detecting stratification. The probability of success in developing a fieldable system using one or both techniques for confirming fill level is estimated to be very high based on results from the prototype sensors.

Difficulties in interpreting apparent changes in a tank's configuration based on changes in internal acoustic resonance modes suggest that this specific technique may not be viable. However, preliminary work in employing ultrasonic ranging measurements was promising. Ultrasound measurements could be used to detect changes within a tank and interpret the causes of these changes: discriminating unintentional twisting of pipes from internal fluid currents (that should be compensated for in calibrating tanks) from the addition of undeclared items to the tank to support a material diversion scenario. We recommend additional investigation of the ultrasonic technique because of its probability for success.

Verification of external plumbing using acoustic signatures remains conceptually valid, although essentially no progress was made in this area due to experimental artifacts. Further investigation of this application should be pursued, but it would most appropriately be investigated as a sub-task of a larger acoustics project.

Although this project was formally completed at the end of December 1995, we suggest demonstrating the fill-level sensor and presenting other acoustics results in Vienna after the IAEA has had an opportunity to review this report and the appendices. This would serve to address any outstanding questions from the IAEA customers.

PROTOTYPE ACOUSTIC RESONANCE SPECTROSCOPY MONITOR

by

Dipen N. Sinha and Chad T. Olinger

ABSTRACT

This report reports on work performed for the International Atomic Energy Agency (IAEA) through the Program Office for Technical Assistance (POTAS). In this work, we investigate possible applications of nondestructive acoustics measurements to facilitate IAEA safeguards at bulk processing facilities. Two different acoustic techniques for verifying the internal structure of a processing tank were investigated. During this effort we also examined two acoustic techniques for assessing the fill level within a processing tank. The fill-level measurements could be made highly portable and have an added safeguards advantage that they can also detect stratification of fill material. This later application may be particularly useful in confirming the absence of stratification in plutonium processing tanks before accountability samples are withdrawn.

I. INTRODUCTION

The continually growing number of facilities in the nuclear fuel cycle and large commercial reprocessing facilities is necessitating improvements in the IAEA's safeguards efficiency. If implemented, recent global fissile material production cutoff proposals, which would place all reprocessing and enrichment processes under safeguards, will significantly increase inspection commitments as well. To meet some of these existing and foreseeable needs, new safeguards techniques are being developed to help the IAEA continue to meet its challenging requirements.[1]

We recognized that acoustic measurements could help meet some of these needs. As part of the Los Alamos National Laboratory support to the DOE Office of Safeguards and Security, we have been developing domestic safeguards applications using acoustics and ultrasonics.[2-6] In this effort we also identified potential international safeguards applications that would help (1) verify and reverify plant designs particularly at reprocessing plants; (2) check the consistency of declarations with operating conditions; and (3) confirm accountability information.

Specific applications that address these agency needs include using transducers on the outside of a process tank to monitor for changes in internal tank design and using acoustics to determine fill levels on process tanks. We have studied two approaches to verifying designs. One employs relatively low-frequency vibration, where changes in internal tank configuration vary the acoustic standing wave patterns in the tank. The other employs ultrasound to detect approximate locations of internal plumbing. The first of these requires baseline measurements for each tank and may be affected by normal variations with time. The second technique is not fully developed but may prove more versatile.

In addition to design verification, two techniques have been examined for monitoring fill levels of tanks. Both of these could be useful either for confirming declarations of operating conditions (fill heights in process tanks) or confirming accountability records. One technique involves transducers that are permanently affixed to the side of a tank and monitors the traversal time of a sound pulse between the transducers. The other involves sliding a hand-held transducer along the edge of a tank to detect the fill level. This second technique can also be used to detect stratification of fill material, which can be critical to ensuring that representative aliquots are obtained when material sampling is required for destructive analysis. In the following, we present the results of our study.

II. TANK DESIGN VERIFICATION

A. Verification Using Resonant Acoustic Frequencies

1. Background. If a hollow metal object (e.g., a metal tank) is made to resonate at its various structural resonance frequencies, a large number of vibrational modes (shell modes) tend to couple with the modes inside the object. These acoustic modes are the reverberation modes that can be excited and maintained easily. In the case of a cylindrical geometry these modes can be easily modeled as Bessel functions. Because of the common boundary conditions of the tank shell and the cavity inside, resonance modes of the shell can excite acoustic cavity modes that coincide in frequency. The shell resonance modes are determined by the mechanical properties (e.g., stiffness, thickness, and density of the metal and the dimension of the tank) of the tank shell. On the other hand, the cavity modes are determined by the geometry and the sound velocity in the fluid inside the cavity.

If the shell is excited from outside at any of these overlapping resonance frequencies (modes), energy can be transferred from the shell to the air (or gas) inside the cavity very efficiently. This allows us to sense significant changes inside the tank cavity from outside the tank. This is the underlying basis of this design verification technique.

We determined the overlapping modes by doing two experiments. First, we determined the shell modes in a given frequency range by exciting the tank with a piezoelectric transducer attached to the tank through a magnetic coupling and detecting the resonance response with a similarly attached second transducer shown in Fig. 1(a).

The acoustic cavity modes were determined by using a small speaker and an ordinary microphone inside the tank as shown in Fig. 1. A DSA100 Digital Synthesizer and Analyzer provided the swept-frequency information for excitation and the electronics to process the received signal. The frequency was slowly varied (swept) from 400 Hz to 10 kHz in several ranges and the results were recorded in the form of a spectrum as shown in Fig. 2. The spectra are slightly different from each other and the overlapped resonance peaks can be easily identified.

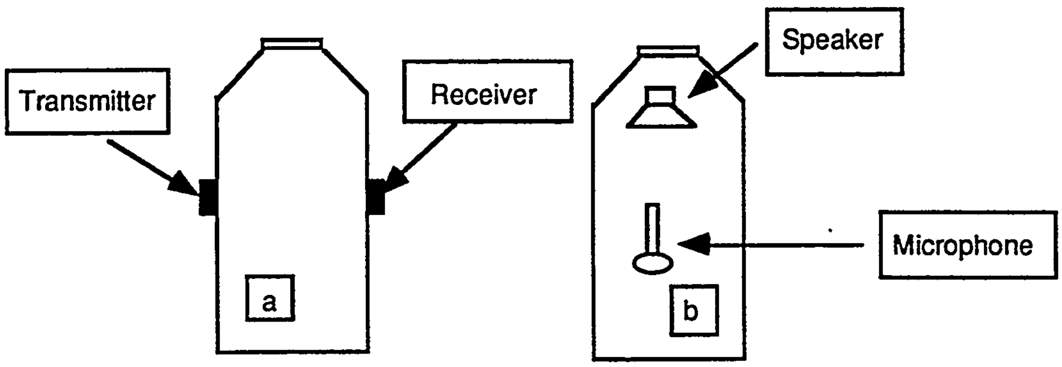


Fig. 1.
Experimental configuration for identifying tank shell modes (a) and internal resonance modes (b).

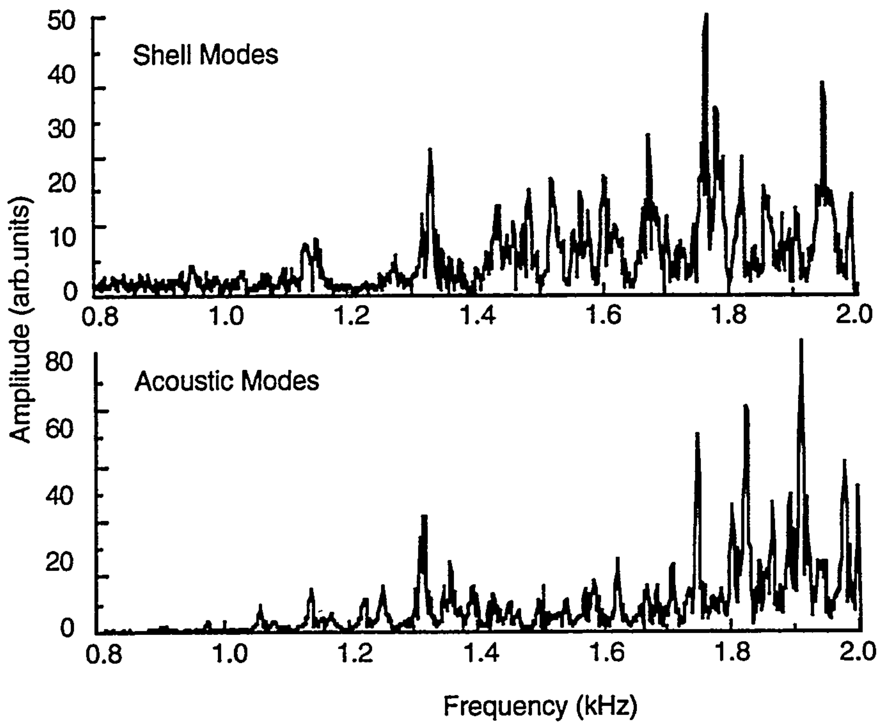


Figure 2.
The acoustic spectra of our empty simulated processing tank from 0.8 to 2.0 kHz: a) shows the resonance shell modes induced and detected with contact transducers and b) shows the acoustic (internal air) modes induced and detected by a loud speaker and microphone placed inside the tank.

Originally, we restricted ourselves to work only with these overlapping modes. If there are pipes or other structures inside the tank, then changes in its configuration will be reflected in the structural resonance modes due to efficient acoustic coupling between the two types of modes. However, in a real verification scenario, we will not have the luxury to determine the various acoustic modes of a tank or any other chamber.

Fortunately, we found through experimentation that it is not necessary to use only the overlapping modes; many strong structural modes work adequately. This immediately simplified the whole procedure because we did not have to determine the acoustic modes. Figure 3 below schematically describes the experimental set up used to carry out the simulated design verification studies. Additional details are discussed in Appendix A.

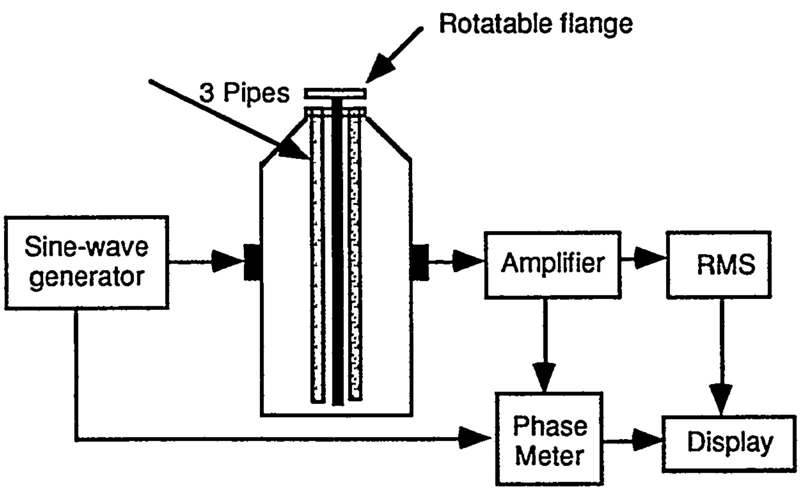


Fig. 3.
Experimental set-up.

2. Tank Description. The test tank was 138 cm in height (the cylindrical part) and 61 cm in diameter and had a 3.1-mm-thick stainless steel shell. Three hollow 100-cm-long stainless steel pipes (two were 6.7 mm in diameter and one was 13.1 mm in diameter) were inserted through the top opening. The pipes were attached to a metal circular flange with the 6.7-mm tubes placed on a diameter 1.5 inches from the center and the third pipe placed 90 degrees from these two, also 1.5 inches from the center. This flange with the pipes is left resting on the mouth of the tank (top of the conical part) as shown in Fig. 3. The pipe assembly was rotated by simply rotating the flange on the top.

3. Results. Shell resonance characteristics were determined by sweeping the excitation frequency over a range and monitoring the signal amplitude from the receiver transducer. This allowed us to identify the location of the resonance peaks for the tank shell modes. Once several high-amplitude peaks were identified, the sine-wave generator was used in the single-frequency mode and was set at the selected resonance frequency. The flange was then rotated by small amounts and the corresponding signal amplitude and phase difference were read and stored in the computer.

The quality and reproducibility of the data varied from day to day. We realized that ambient vibrations corrupted the measured phase and amplitude data. Fortunately, we found a very simple fix to this problem. Passing the amplified return signal through a high-pass electronic filter removed essentially all of the unwanted noise from the signal. This immediately improved the quality of the data by more than an order of magnitude.

Figures 4-6 present the experimental data for three different sets of measurements. In Fig. 4, the excitation frequency was arbitrarily chosen to be the 2916-Hz shell resonance peak. Both the rms amplitude and the simultaneous phase measurements are displayed as a function of the orientation of the pipe inside the tank. Large changes in phase are observed during the rotation of the pipe inside the tank. The actual volume of the pipes is insignificant compared to the dimension of the tank, yet the effect of rotation is clearly visible and it is as large as 30 degrees. The rms amplitude data do not follow the phase data. This allows for a unique configuration identification. If only the phase information is used, then it is difficult to pinpoint the orientation because several orientations provide the same phase value.

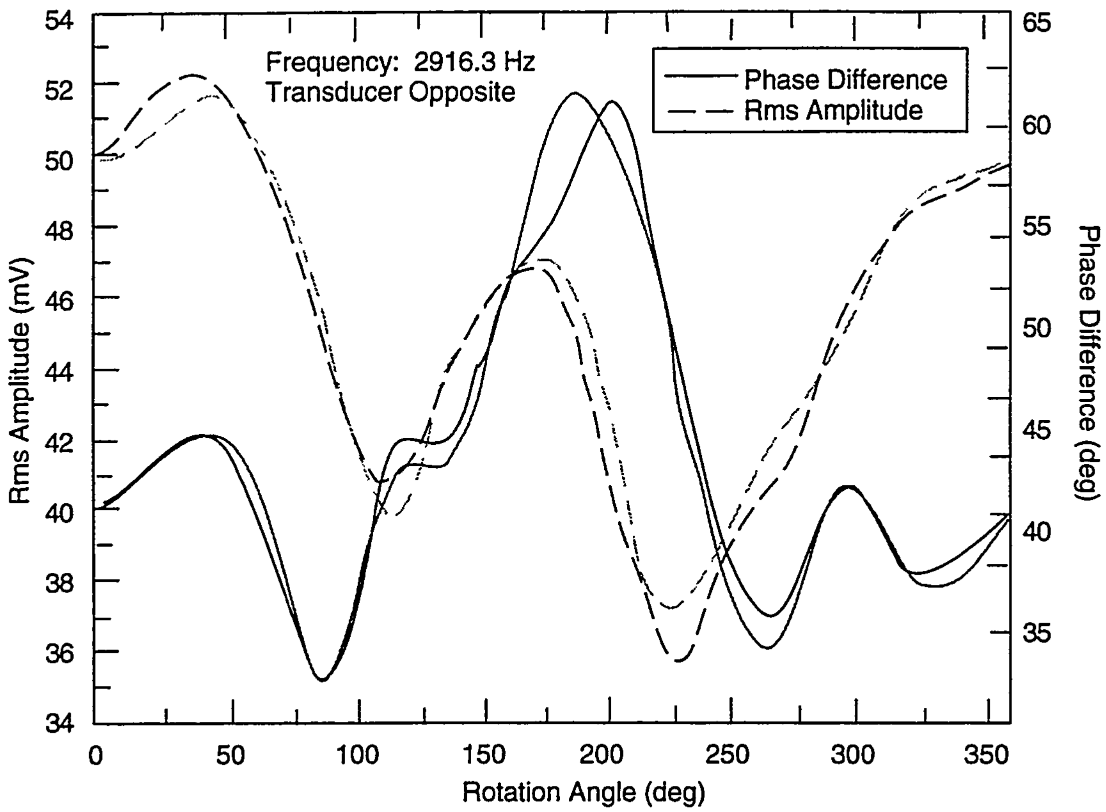


Fig. 4

Simple rotation of the plumbing fixture internal to the simulated processing tank can be detected from outside the tank. This figure shows how the phase relationship between the two transducers and the signal amplitude at a resonance frequency of 2916 Hz varies with rotation. The degree of reproducibility of these curves is also shown. In this case, transducers are placed on opposite sides of the tank.

Each figure presents two sets of data to show the measurement could be repeated. The rotation angle was measured somewhat crudely and this caused some minor variations in the data, but the overall pattern remained the same.

Figure 5 shows the measurements done at a much higher frequency: 19999.1 Hz. All other conditions remained the same as those in Fig. 4. These data show an altogether different orientation dependence of phase and rms value. This is expected because the sound wavelengths are nearly a factor of seven different from each other and the effect of orientation is different for each wavelength. Again, the data are quite repeatable as shown for two sets of measurements superimposed.

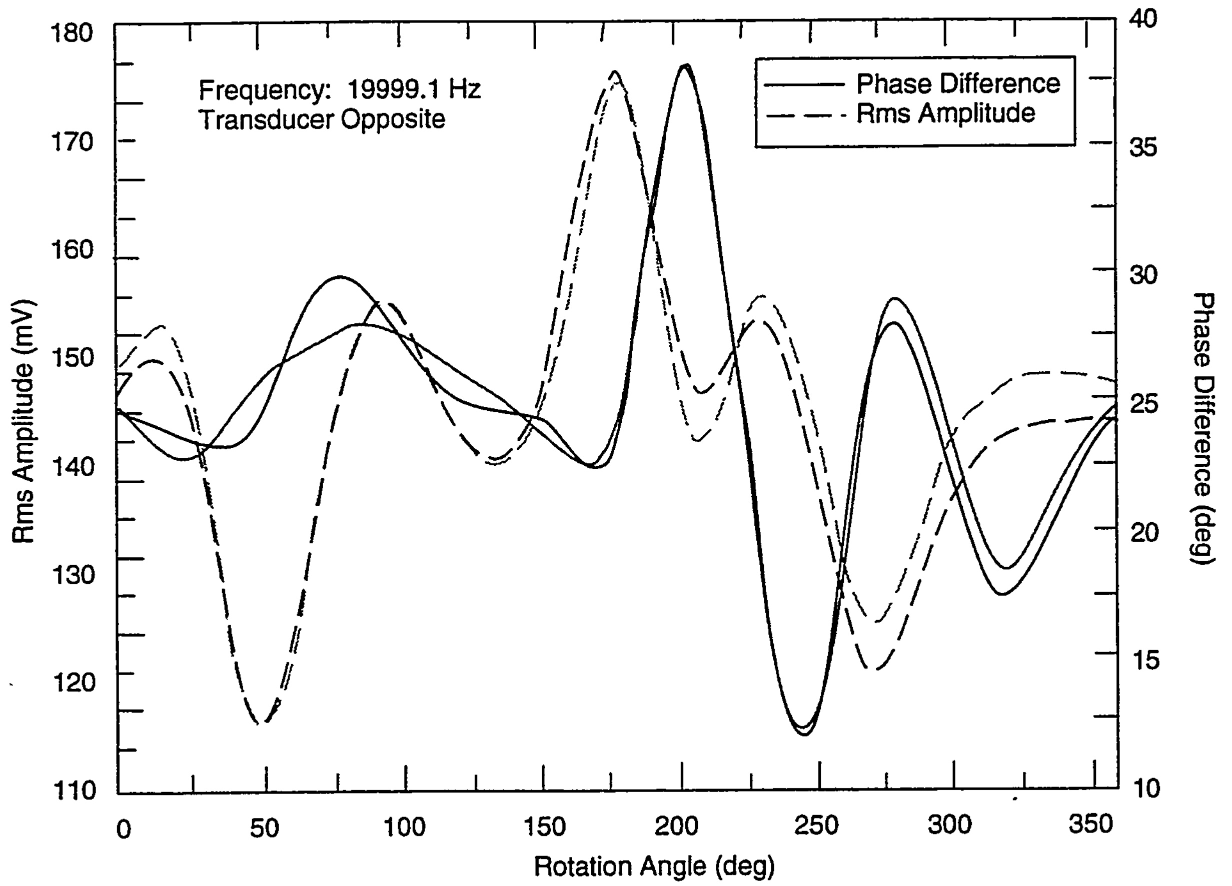


Fig. 5

As with Fig. 4, simple rotation of the plumbing fixture internal to the simulated processing tank can be detected from outside the tank. This figure shows how the phase relationship between the two transducers and the signal amplitude at a resonance frequency of 19999 Hz varies with rotation. The degree of reproducibility of these curves is also shown. As with Fig. 4, transducers are placed on opposite sides of the tank.

The data presented in Figs. 4 and 5 show that even a small change in orientation (change in internal configuration) can be reliably detected if measurements are made at two different frequencies and both rms amplitude and phase are measured.

In Fig. 6 we show data obtained with two transducers adjacent to each other instead of on opposite sides of the tank. Again, the data look different from that obtained at the same frequency in Fig. 5, but the same magnitude of changes are seen in phase and amplitude with orientation. We conclude from this data that all measurements should be made at the same transducer separation (not necessarily the same position) and both transducers can be placed in a single fixture in which they are fixed side by side. This simplifies the measurement procedure significantly and means the operator does not have to go behind the tank.

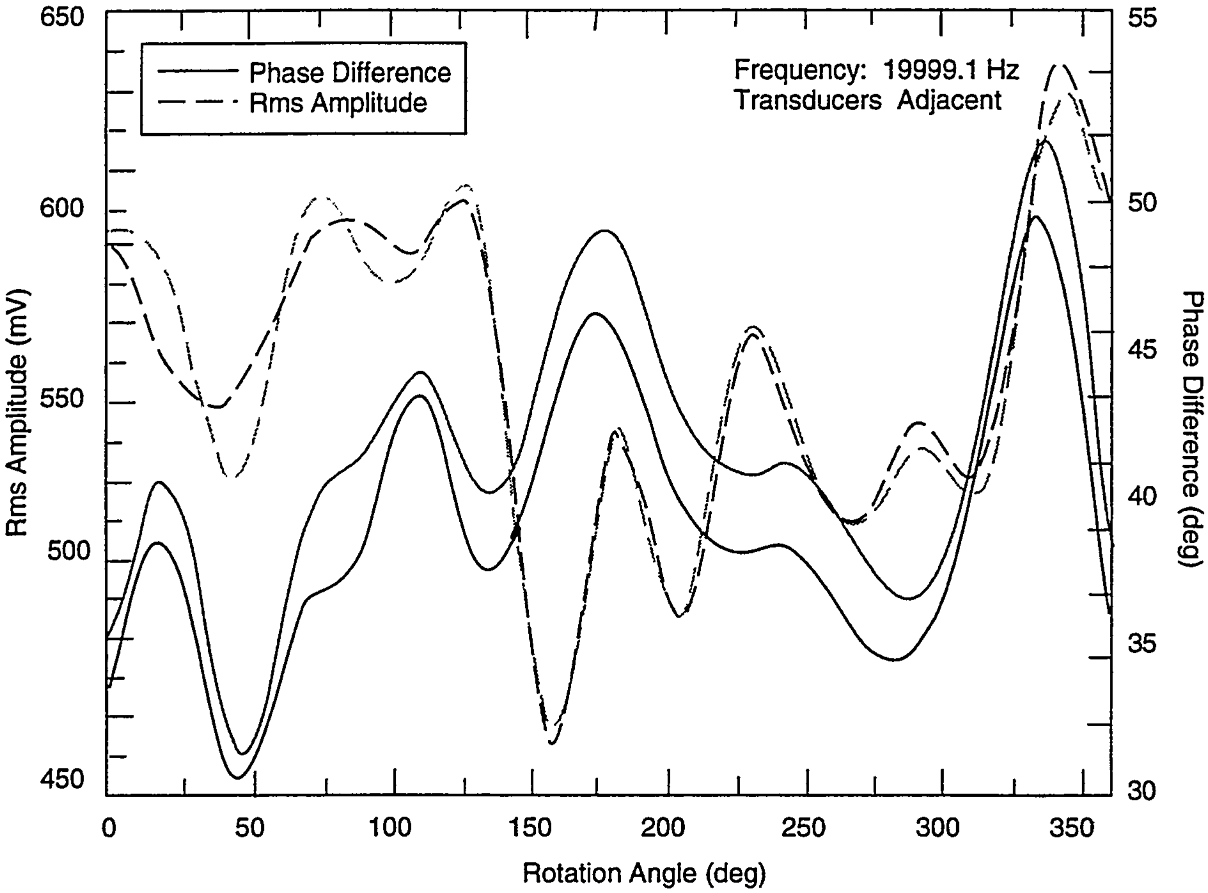


Fig. 6

Similar to Figs. 4 and 5, this figure shows that simple rotation of the plumbing fixture internal to the simulated processing tank can be detected from outside the tank. The phase relationship between the two transducers and the signal amplitude at a resonance frequency of 19999 Hz varies with rotation. In this case, the transducers are placed next to each other, indicating the possibility that such measurements could be performed using a simple hand-held sensor held against one side of the tank.

In addition to the pipe rotation tests, we also observed the changes in phase and amplitude by completely removing the pipes from the tank and covering the tank top with the flange only. We typically observed a difference of ~9 degrees in the phase relationship between the transducers when the pipes were taken out; we repeated this observation several times. In other words, it was easy to detect the removal of pipes or the insertion of additional pipes.

The issue we were not able to adequately address is the effect of changes in ambient temperature. Gradual changes in the ambient temperature over many hours can be corrected in principle because the sound speed in air (or gas) varies monotonically with temperature in a very well known manner. If we measure the temperature, we can make the appropriate corrections. However, our experiments with temperature change involved quick changes of temperature with a heat gun or putting liquid nitrogen inside the tank. These rapid temperature changes introduced large convection currents inside the tank that took many hours to settle. This affected the reproducibility. Once everything stabilized, the measurements were very reproducible. We were not able to obtain data to make temperature corrections inside the laboratory. This issue needs to be addressed before this approach can be considered for field use.

B. Design Verification by Ultrasonic "Imaging"

For design verification, it may be important to determine the locations of various objects inside a tank. Ultrasonic imaging can recreate details of 3-D objects inside a container. Our current system has only been used to detect the closest edge of an item, so the results are not a true "image," but the technique could be extended to generate images with appropriate software development. In order to keep the concept simple, we have thus maintained the use of the word imaging.

This technique is most effective when the objects to be studied are immersed inside a liquid because the differences in acoustic impedance between the metal shell and internal liquids are smaller than when air fills the container. These greater differences permit more efficient transmission of acoustic energy to the tank interior. Small wavelengths of ultrasound (approximately 1.5 mm for a frequency of 1 MHz) permit detection of small features within the tank, and transmission from the shell to the interior is minimally affected by shell resonance characteristics.

The imaging concept is simple. We use sound to determine the distance of any reflecting boundary (such as a from a solid object) inside a container (e.g., tank) from the surface of the container. If measurements are made from all around the tank, a picture of the internal object can be produced from the data. There are two ways to measure the distance. First, standing waves can be produced inside the tank (in the liquid) by exciting the tank surface with high-frequency ultrasound using a standard piezoelectric transducer and observing the response with a second transducer placed adjacent to the first one. Typically, the frequency is swept from low to high producing a periodic response in the second transducer. The periodic nature of the response results from variations in the standing wave patterns inside the tank as the wavelength changes. The periodicity is a direct measure of the distance of any reflecting surface from the excitation transducer. As the transducer is moved around the tank in regular angular increments covering 360 degrees, the observed periodicity changes. By making a polar plot of the data, it is possible to reconstruct the object. This technique is very sensitive and can measure distances quite accurately.

The second method is quite straightforward. It uses a traditional time-of-flight distance measurement method using commercially available pulse-echo thickness gages. A reasonable degree of accuracy can also be achieved with this simple technique.

We have used the latter method to study the shapes of different objects, such as cylindrical, rectangular, and hexagonal, inside a glass tank to show proof-of-principle. Figures 7-9 present the experimental data.

Fig. 7
Results from ultrasonic "imaging" of a cylindrical object inside of a small cylindrical container. Radial distance represents the time of flight for an ultrasonic pulse to travel from the transducer to the internal feature and back. Reflection time is plotted vs. the angle of rotation. A high degree of symmetry for the cylindrical object, placed in the center of the container, is demonstrated by only small fluctuation in the detected time of flight as a function of rotation.

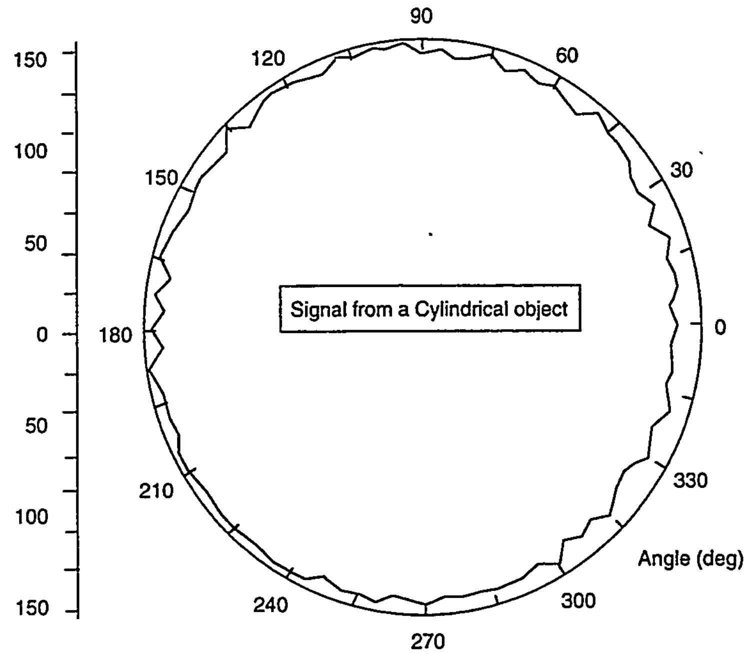


Fig. 8
Results from ultrasonic "imaging" of a square object inside of a small cylindrical container. Radial distance represents the time of flight for an ultrasonic pulse to travel from the transducer to the internal feature and back. Reflection time is plotted vs. the angle of rotation. The small apparent time of flight when the transducer is not perpendicular to one of the flat surfaces is due to scattering of the incident wave, so the return signal is not detected. When the flat surface is perpendicular to the transducer, a strong signal is returned and the time of flight (and thus distance from the container wall) can be inferred. An inspector could thus confirm the internal geometry of this tank as long as the square shape of the internal object is declared.

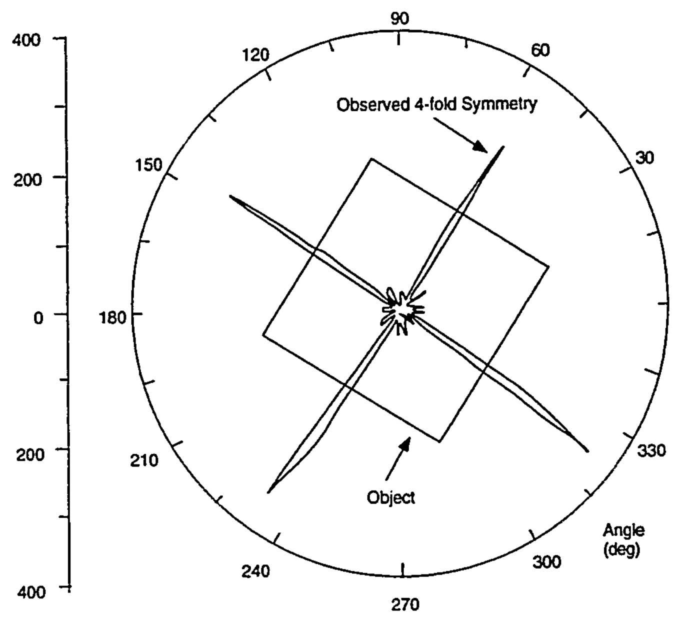
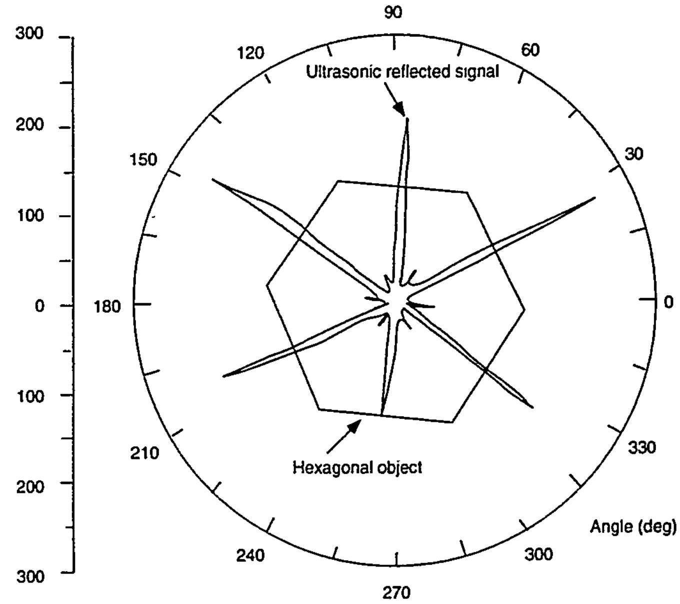


Fig. 9
Results from ultrasonic "imaging" of a hexagonal object inside of a small cylindrical container. Radial distance represents the time of flight for an ultrasonic pulse to travel from the transducer to the internal feature and back. Reflection time is plotted vs. the angle of rotation. The small apparent time of flight when the transducer is not perpendicular to one of the flat surfaces is due to scattering of the incident wave, so the return signal is not detected. When the flat surface is perpendicular to the transducer, a strong signal is returned and the time of flight (and thus distance from the container wall) can be inferred. An inspector could thus confirm the internal geometry of this tank as long as the shape of the internal object is declared.



III. FILL-LEVEL SENSOR DEVELOPMENT

A. Prototype Hand-Held Fill-Level Sensor

A prototype hand-held fill-level detector was built and tested on the tank described in section 1. The prototype consists of a small electronics box and a small fixture for two transducers. This fixture is connected with a cable to the electronics box. The working principle and electronics design of this instrument is discussed in Appendix B.

1. Sensor Design. The sensor consists of two piezoelectric transducers in a holder that maintains a constant separation between the transducers as the system is slid vertically along the container surface. The actual separation distance between transducers is not critical. For our test tank, a separation of just 2 cm was sufficient. In thin metal containers, the effect of the liquid on the propagation speed is much more pronounced, and thus a separation smaller than 2 cm is quite adequate. On the other hand, for large tanks or containers with thick shells, larger transducer separations can improve measurement sensitivity.

The size of the piezoelectric transducers is also not critical. For small containers one can use very small transducers, and for 55-gallon drums, transducers of 1-cm diameter are adequate. Figure 10 shows the actual transducer holder arrangement. One of the transducers acts as a transmitter and the other as a receiver. Each transducer consists of three components. The basic component is a commercially available wide-band piezoelectric disk-shaped transducer. A 0.5-in. diameter neodymium-boron-iron disk magnet is glued to the transducer. A conical stainless steel wear plate is glued to the other surface of the magnet.

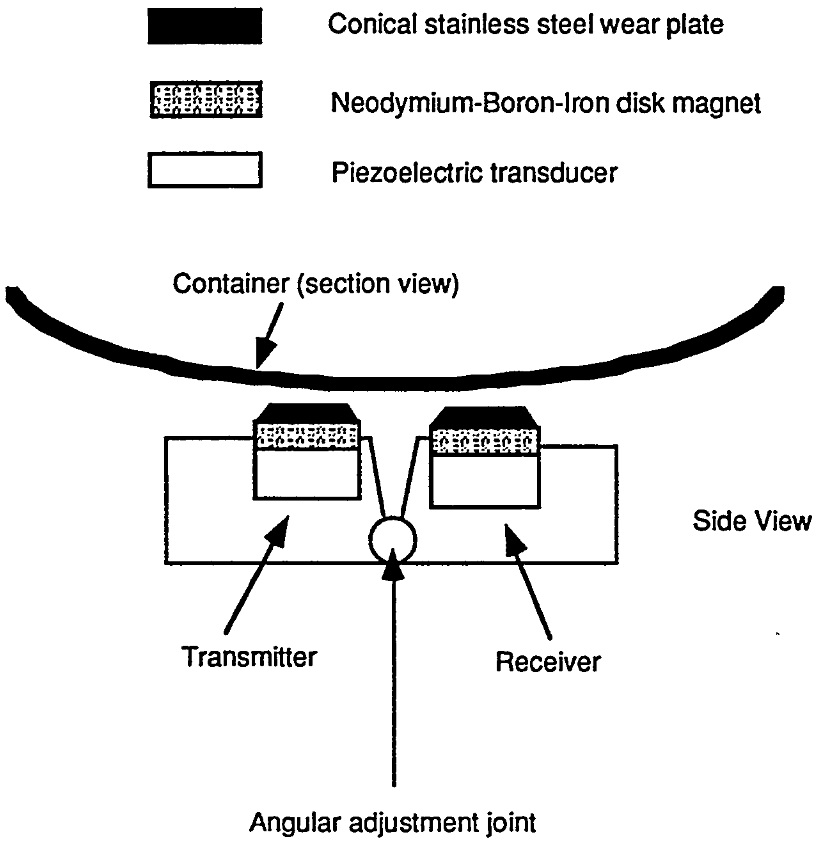


Fig. 10
Details of transducer design

The conical part makes contact with the measuring surface. The conical tip is somewhat rounded to allow easy gliding over a metal surface. If the metal container surface is magnetic, then the magnet acts to attach the transducer nicely to the surface but still allows easy sliding. A joint between the two transducers allows the angle between the two transducers to be adjusted to match the curvature of the container being tested.

2. Description of Technique. The principle of the tone-burst technique is described pictorially in Fig. 11. Here a tone-burst of a fixed frequency is used to excite one of the transducers, which in turn generates a burst of bending waves in the container shell. The second transducer detects this burst, and the propagation time between the two transducers is determined by measuring the phase difference between the two signals. Phase measurement is very accurate, simple, and, to a large extent, independent of the received signal amplitude. The reason for using a short tone burst is that reflections from other parts of the container (e.g., the perimeter) are avoided. Only the transit time between the two transducers is monitored. However, in situations where one simply is interested in monitoring a change in the liquid level and not the actual position of the liquid level, continuous wave excitation is very useful. In this case, the transducers can remain in one position. Any extraneous reflections remain steady while the observed change in phase is caused by the variation in the liquid level.

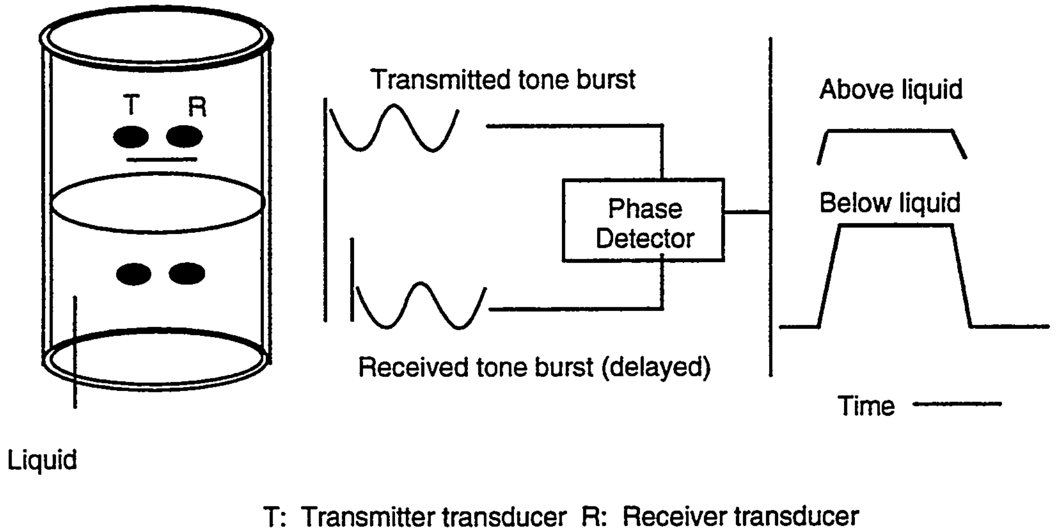


Fig. 11
Schematic representation of the principle of the tone-burst phase measurement technique for noninvasive liquid level measurement.

3. Operation of the Hand-Held Fill-Level Sensor. Operation of this fill-level sensor is quite simple. Once the appropriate signal frequency is determined, the operator simply moves the sensor head vertically along the outer surface of the container. When the electronics package detects a change in the transmission time (or phase relationship) between the two transducers, it emits an audible signal. The operator can then move the sensor more slowly in the area where the audible signal is generated to pinpoint the exact fill level.

Using this technique the level of the liquid can be determined within approximately 1 mm of the actual level. For a water-filled tank, the accuracy of the fill determination depends on the thickness of the tank shell and becomes less sensitive when the shell thickness increases. The total measurement time for our tank is less than 10 sec. In addition to our test tank, we have tested the instrument on a large variety of containers: from soup cans to standard 55-gallon drums.

As with any fill-level measurement, the relationship between fill level and volume must still be determined. However, even if this relationship is simply estimated from tank dimensions, it can provide inspectors a simple screening tool to verify that tank levels are qualitatively or semi-quantitatively consistent with declarations and records. Quantitative comparisons would require calibration of tank volume with detected fill height.

This technique can also be used to detect layers of liquids. In this case the safeguards application would be to ensure that there is no stratification of material within an accountability tank before an accountability sample is obtained. Stratification in containers with layers of oil and water has been detected with approximately the same precision as described above for liquid-air interfaces within containers.

B. Continuous Fill-level Measurement

For continuous fill-level measurement, the transducer arrangement is somewhat different. Instead of a closely spaced horizontal arrangement, the two transducers are now placed vertically one above the other, separated by distances up to ~50 cm. In this arrangement, part of the excited flexural wave propagates through a portion of the metal wall in contact with liquid on the inside of the tank, and the rest of the path through the metal wall is in contact with air. The total propagation time between the two transducers is directly and linearly related to the liquid level between the two transducers.

The propagation time is effectively measured by comparing the phase relationship of the transmitted and received waves. Thus, spacing between the two transducers and the tone burst frequency is chosen such that the phase shift remains within 360 degrees. Alternatively, electronic circuitry can keep track of phase wrapping (where the phase relationship can vary by more than 360 degrees as the fill level moves from the bottom to the top transducer). However, if the transducer separation becomes too large, then interference caused by reflections from the edges (top or bottom) of the container can degrade the signal. In tall containers, it would be preferable to use a series of fixed transducers separated by a fixed amount. It is simple to scan all the transducers to find the pair that straddles the liquid level.

The fill level is measured with respect to the bottom transducer, e.g., R (receiver) as shown in Fig. 12.

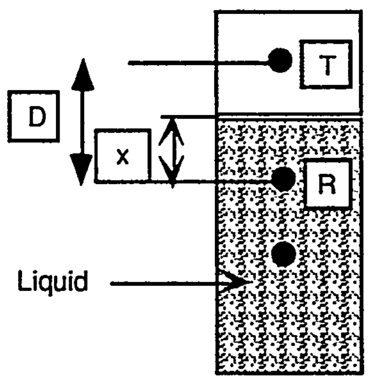


Fig. 12.
Continuous liquid-level measurement setup.

The phase difference measurement is a simple way to accurately measure the time difference between two signals. This continuous level determination technique can be described more clearly in terms of time difference.

In Fig. 13, we present experimental data on continuous fill-level measurements. The measurements were made in a steel container with the following dimensions: diameter 17 cm, height 20 cm, and thickness 0.025 cm. The two vertically placed transducers were separated by 7.5 cm. The liquid level was changed from above the top transducer to below the bottom transducer. The inset in Fig. 13 shows the experimental arrangement.

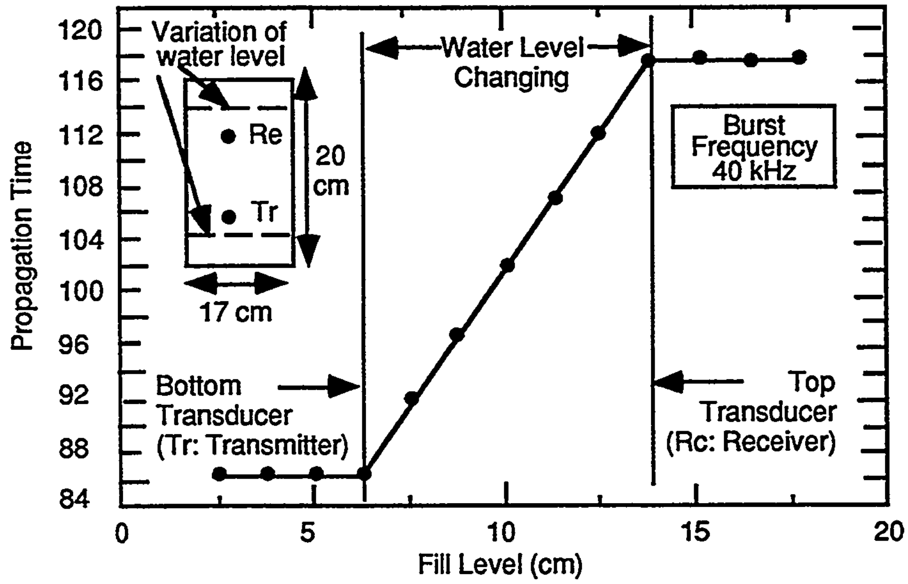


Fig. 13.
Experimental data on continuous liquid-level measurement. The data are consistent with Eq. (4). As can be seen, the liquid level can be monitored with excellent linearity.

The tone-burst frequency used for the data was 40 kHz. Only three cycles of a tone-burst were used. The measurements were repeated with tone-burst frequencies from 20 kHz to 100 kHz at steps of 20 kHz. Data at all frequencies showed excellent linearity of propagation time with liquid level except at the lowest frequency of 20 kHz. We measured a 55-gallon drum with similar results. Measurements on a 55-gallon drum were so sensitive that even the slightest vibration (sloshing) on the liquid surface could be detected. We estimate that a liquid level variation of less than 1 mm in a 55-gallon drum can be detected by this method. Our equipment failed before our tests on the tank, so we were not able to test the continuous fill-level determination on the tank.

This continuous level monitoring technique is particularly suitable for remote monitoring of tanks. One simply needs to add commercially available remote interrogating circuitry. Using such a system, the tank fill-level could be queried and the result transmitted by satellite link or another long-distance communications method, which could be useful in future verification regimes.

IV. SUMMARY

The studies presented in this report are primarily the proof-of-principle type. These show that some techniques have the required sensitivity to accomplish the goals of the design verification requirements. For example, the acoustic technique to detect variation in the internal configuration is sufficiently sensitive to detect even small changes. However, we have not shown how to implement this system in a realistic situation. A major issue to be pursued is to find a way to correct for changes in ambient conditions, such as seasonal temperature variation and other external conditions. Also we do not have a portable system that can be tested in the field. We propose to design and fabricate a prototype system that can be used for both controlled laboratory study and field study. A major part of the study would be to determine the influence of external conditions, such as temperature, on the accuracy and robustness of the technique. Essentially, this would be a true feasibility study of the technique that would involve developing correction algorithms and significantly refining the technique.

A second development effort would involve the design of a portable electronic system that can be used for continuous fill-level measurement on various types of tanks. Although the technique in which the fill level is detected by moving the sensor heads along the side of a tank is at a reasonably advanced stage from the electronics design point of view, it requires refinement to automatically determine the various parameters, such as tone-burst frequency and delay, so that it can be adapted to any geometry. At the present time, the system needs to be manually tuned for a given container. It also requires further refinement of the sensor head (the transducers).

The continuous fill-level measurement approach will require further simplification in its design to be easily adaptable to any geometry. Currently, this technique suffers from a lack of sensitivity when the container wall thickness exceeds 0.4 cm. This can be largely remedied by refining the electronics design. The technique is also limited to measuring liquid between two transducers that are no more than 50 cm apart. This limitation is primarily due to the phase-wrapping problem when the phase angle exceeds 360 degrees. We have developed a new concept, amplitude modulated tone burst, that remedies this problem and can extend the measurement range significantly. This needs to be experimentally verified.

The ultrasonic "imaging" technique shows promise. Before this can be developed into a fieldable system, further investigation would be required to assess whether the quality of the data is adequate for design verification work. Assuming this work is successful, it would also be worth investigating techniques to extend the technique to measurement in air to detect parts that are above the liquid.

All of the above methods will benefit from noncontact transducers. Our preliminary work has shown that electromagnetic acoustic transducers hold promise for these applications. Recently, a company has produced proprietary ferromagnetic transducers that, according to the company's claims, are excellent for noncontact ultrasonic measurements. It will be a major improvement if these types of transducers can be adapted for the studies we propose. Such noncontact transducers can significantly increase the reproducibility of the measurements and are highly desirable. We thus propose to study the applicability of such noncontact transducers for all our studies.

V. CONCLUSIONS

We have developed several potential technical approaches to solving some of the design verification problems. The studies completed look promising based on laboratory measurements. Most of the techniques are very sensitive and can detect small changes in the internal configuration of a tank. We have not, however, proven the feasibility of these techniques for applications in the field. The instruments used are laboratory bench-top instruments. For field use, portable systems need to be developed and tested. Below we discuss our conclusions on the present task, and in Appendix C we identify other acoustic applications that have been investigated at Los Alamos. Many of these have potential applications in safeguards that could be investigated.

The most promising safeguards application of acoustic measurements identified in this work is the possibility of monitoring the fill level of tanks and detecting stratification before assay samples are collected. Prototypes of both the hand-held sensor and the permanently affixed, continuous fill-level sensor were developed and successfully demonstrated. However, they have only been tested in laboratory settings and are optimized for a specific container geometry. Future effort, if funded, would be directed toward improving the flexibility of using the hand-held sensor on different container geometries and investigating the sensitivity of the sensor in detecting stratification. The probability of success in developing a fieldable system using one or both techniques for confirming fill level is estimated to be very high based on results from the prototype sensors.

Difficulties in interpreting apparent changes in a tank's configuration based on changes in internal acoustic resonance modes suggest that this specific technique may not be viable in field settings. However, preliminary work in employing ultrasonic ranging measurements was promising. Ultrasound measurements could be useful in detecting changes within a tank and interpreting whether these changes are caused by such effects as unintentional twisting of pipes from internal fluid currents that should be compensated for in calibrating tanks or, if undeclared items have been added to the tank to support material diversion. We recommend additional investigation of the ultrasonic technique because of its chances for success.

Verification of external plumbing using acoustic signatures remains conceptually valid, although progress in this area was limited due to experimental artifacts. Further investigation of this application should be pursued, but it would most appropriately be investigated as a subtask of a larger acoustics project.

ACKNOWLEDGEMENT

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APPENDIX A

DISCUSSION OF THE ACOUSTIC VERIFICATION SYSTEM

In Fig. A-1, the sine-wave generator used is a highly stable Hewlett Packard 3325A synthesized function generator. This function generator drives a transducer coupled magnetically to the side of the tank as shown. Several Nd-Bo-Fe 1-cm-diameter magnets were glued to the outside of the tank surface at several places. The transducers also have similar disk magnets glued to their front surface. This system allows quick and reproducible placement of transducers. The positions of the transducers are not critical for these measurements. We verified this by repeating the measurements with two transducers (transmitter and receiver) placed on diagonally opposite sides of the tank and also next to each other. Both transducer locations provided the same answer.

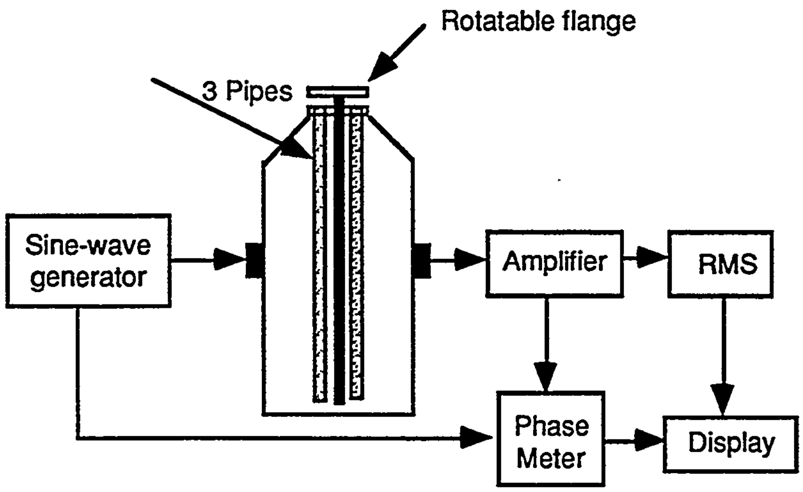

Fig. A-1. Experimental set-up.

The signal from the receiver transducer was amplified by 40 dB and fed to two different instruments: (1) a phase meter that measures the phase difference between the excitation signal and the received signal and (2) an rms-to-dc converter that provided the root-mean-square value of the received sine-wave signal. Both signals were displayed digitally. Although not shown in the figure, a personal computer with a data-acquisition card can record all of the output from the display units.

APPENDIX B

ACOUSTIC FILL-LEVEL SENSOR

I. WORKING PRINCIPLE

It is well known that sound propagates through a metal plate in the form of flexural (or bending waves). The speed, C_b, of this so-called bending wave depends on the thickness t and the frequency f as follows:

$$C_b = \sqrt{1.8 C_L t f}\,. \tag{1}$$

In Eq. (1), C_L is the speed of the longitudinal wave. This is the speed of sound in the metal in the bulk form.

Note that bending wave propagation is not restricted to metal plates. Any elastic or stiff material can sustain such waves.

The bending waves slow down when the metal plate comes in contact with a liquid. The relationship between the wavelength λ and the frequency depends on the liquid density as shown below.

$$\omega^2 = \frac{Dk^5}{\rho_L + t\rho_s k}, \tag{2}$$

where $\omega = 2\pi f$ is the angular frequency, $k = 2\pi\lambda$ is the wave number, D is the rigidity modulus, and ρ_L and ρ_S are the metal plate density and liquid density, respectively.

Equation 2 is nonlinear and can be solved iteratively. A somewhat simpler form of this equation, although not as accurate, is the following:

$$C_b = \left(\frac{\omega^3 D}{\rho_L}\right)^{1.5}. \tag{3}$$

This equation clearly shows how the bending waves are affected by the presence of a liquid of density ρ_L. The higher the density, the slower the wave velocity.

A metal container, such as our test tank, can be considered as a roll of metal sheet. When there is liquid inside the drum, Eq. (2) is obeyed for any bending waves excited below the liquid level. In other words, if one measures the bending wave propagation in a region above the liquid level and also in a region completely below the liquid level, one would find a change (decrease) in the observed speed of sound. Detection of this change in the speed of bending wave propagation is the underlying basis of this technique.

II. ELECTRONICS DESIGN

The electronics design of the fill-level sensor consists of the following sub-units as shown below in the schematic diagram in Fig. B-1. A sine-wave generator is used to generate the required excitation frequency. The frequency value is not critical. For most applications, a frequency value anywhere between 20 and 100 kHz is sufficient. The burst gating circuit provides a burst output (a few cycles of the generated frequency) at a desired rate. The repetition rate is chosen such that any resonance mode excitation in the container has had time to die down. The signal level of the burst output can be controlled by the amplitude control circuit. In fact, this can be part of the sine-wave generator. The output is applied to one of the transducers while the transducer holder is gently pressed against the container surface.

The transducer excites bending waves in the container shell. The second transducer picks up this signal and the signal is first amplified using an automatic gain control (AGC) circuit to boost the output and maintain it at a constant level. The AGC circuit is not absolutely essential but helps in the phase detection circuit. Usually by sliding the transducer holder, one changes the degree of physical coupling, which makes the detected signal amplitude fluctuate in value. The AGC circuit maintains the received signal at a constant value.

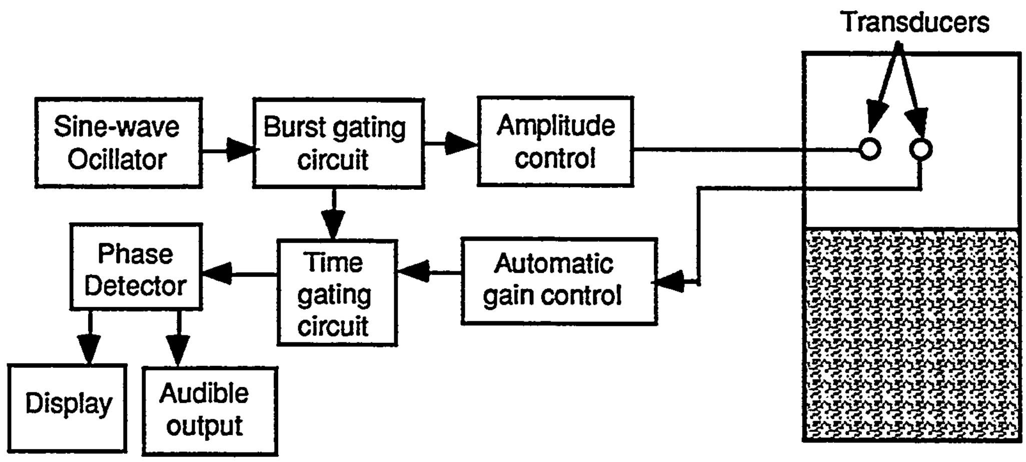

Figure B-1.
Schematic diagram of the electronics design used for the tone-burst phase.

A time-gating circuit is included following the automatic gain control circuit. This circuit extracts a region of the detected waveform (sine-wave) that overlaps with the transmitted signal and rejects any signal after that. This eliminates initial transients and spurious signals from reflections originating from container edges such as the rim for small containers. This circuit enhances the usability of this tone-burst technique for various applications.

Following phase detection, the information is displayed to the user. The display can be digital or analog. For quick liquid-level detection, an audible alarm output is often the most practical. Whenever the liquid level is detected through a phase change, an alarm is sounded.

III. THEORY FOR THE CONTINUOUS FILL-LEVEL MEASUREMENT

The phase-difference measurement is simply a convenient way to measure propagation time. Therefore, in our discussion we will use propagation time. Assume the measured total propagation time is t for the bending wave signal to travel the distance D between the transducers T and R in Fig. B-2. The bending waves travel at a velocity V_L between the bottom transducer R and the liquid surface: the distance x. In the part D-x, where the metal is air-backed, the bending waves travel at a velocity V_A that is less than V_L. So, we can express the total time t as the sum of two propagation times:

$$t = x/V_L + (D-x)/V_A$$

or

$$t = (1/V_L - 1/V_A)x + D/V_A \qquad (y = mx + c\text{, a straight line}) \qquad (4)$$

For a given container in which levels are monitored continuously, the parameters V_L, V_A, and D are known. Thus, a measurement of the time delay of a tone burst between two vertically placed transducers provides a continuous measurement of the liquid level: the distance x. For tall containers with multiple sensors, one simply adds the height of the highest transducer that is below the liquid level.

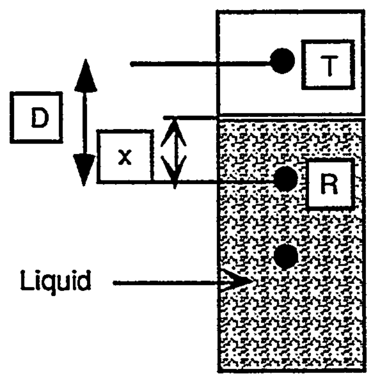

Figure B-2.
Continuous liquid-level measurement setup.

APPENDIX C

APPLICATIONS OF ACOUSTIC RESONANCE SPECTROSCOPY (ARS) AND ULTRASONIC INTERFEROMETRY TECHNIQUES

Dipen Sinha has been exploring various applications of the ARS technique for the past 5 years. The development of the ultrasonic interferometry technique has been more recent (two and one half years). The interferometry technique is very powerful and has a wide range of applications. The following is a list of some relevant applications.

1. Noninvasive clamp-on ultrasonic flowmeter

We have adapted the ultrasonic interferometry technique for noninvasive fluid flow measurements (both liquids and gases). The transducers are clamped on a pipe from the outside. The liquid flow measurements can be made over a large range of flow rates. More recently, we have extended the technique for gas flow measurements. The concept is well established but the instrumentation will require further refinement for field use. The instrumentation is very simple and all the electronics can be contained inside a small box.

2. Detection of proper seating of valves

The ARS technique appears to be highly sensitive in determining whether a valve is properly seated when closed or not. Usually, if a valve is not properly seated, there is very slow leakage. Such leakage cannot be detected with most existing instrumentation used in the industry. We have found that the ARS signature on any given valve is very repeatable and the signature of a seated valve as compared to an unseated valve is very different and is easily identifiable. So far we have shown proof-of-concept on a very limited set of valve types and do not know whether this technique will be usable for every type of valve. However, the prospects of this approach are very promising. The electronics package for this is commercially available (DSA300 from Neel Electronics, Laguna Niguel, California).

3. Detection of deposition or coating inside containers and pipes

The ultrasonic interferometry technique can be a highly sensitive tool in detecting deposition of even very thin layers of any material on the inside surface of a container or pipe. The determination at any given location can be made in a matter of seconds. Large areas can be easily scanned mechanically. Our laboratory research shows that for homogeneous materials, the thickness of the deposited layer can also be determined from the measurements. Currently, the transducer requires physical contact with the outside surface of the container (or pipe). However, completely noncontact measurements using EMATs (Electro-Magnetic Acoustic Transducers) are possible, although this approach has not been fully developed.

The same concept can be adapted to detect fill edges of materials (or boundaries between different materials) inside pipes.

4. Determination of missing plate in a stack

Ultrasonic interferometry can be adapted to detect whether a stack of metal plates contains one or more plates of anomalous composition. If one needs to determine if a stacked pile of metal plates, or plates of a similar material, contains some that are not of the same type, ultrasonic interferometry can be adapted to detect any variation. The success of this approach depends on the fact that the plates are in direct physical contact with each other without any air gaps. The technique will still work if there are gaps between the plates if the plates are immersed inside a liquid.

5. Imaging of internal construction of systems

We have demonstrated the feasibility of imaging geometrical objects (small pipes and other shapes) embedded inside other objects, e.g., plates. The technique can be generalized and used for other imaging purposes, such as the internal construction of tanks. Again, the underlying technique is ultrasonic interferometry. The tanks are required to contain liquids and the objects to be imaged must be immersed in the liquid.

6. Noninvasive liquid fill level and density determination

We have developed a novel ultrasonic noninvasive technique to determine the liquid fill-level inside tanks very accurately (~1 mm or better). There are two ways of using this technique. First, a transducer pair can be moved along the outer surface of a tank and the liquid level determined. Second, the transducer pair can be fixed (vertically separated) on the surface of the tank and continuous level changes can be monitored in real time. The technique can be adapted for remote monitoring relatively easily. The same technique can also determine density variation in the liquid fill and thus can detect stratification. The sensitivity of the technique depends on the thickness of the container wall and will not work well for wall thicknesses greater than 5 mm.

A combination of this technique along with the interferometry technique can determine very small changes in the liquid fill characteristics of a tank. Even very small changes in the liquid fill (liquid physical property) can be easily detected.

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