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Title: **ACOUSTIC TECHNIQUES IN NUCLEAR SAFEGUARDS**

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ACOUSTIC TECHNIQUES IN NUCLEAR SAFEGUARDS

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Abstract

Acoustic techniques can be employed to address many questions relevant to current nuclear technology needs. These include establishing and monitoring intrinsic tags and seals, locating holdup in areas where conventional radiation-based measurements have limited capability, process monitoring, monitoring containers for corrosion or changes in pressure, and facility design verification. These acoustics applications are in their infancy with respect to safeguards and nuclear material management, but proof-of-principle has been demonstrated in many of the areas listed.

1. Introduction

Acoustic waves traveling through a container or process equipment are affected by material within the test item. Physical parameters such as acoustic velocity, viscosity, and density as well as interfaces between different materials can affect acoustic resonant characteristics that can be established inside the test item as well as phase relationships between excitation and detection transducers. In cases where the nature of the dependence of the resonance pattern on the various physical parameters is well understood, they can be exploited to produce a nondestructive, non-invasive means of examining a container and its contents. Potential applications that have relevance to safeguards and nuclear material management include establishing and monitoring intrinsic tags and seals on nuclear material containers, surveying areas for holdup as a complementary technique to conventional radiation-based measurements, monitoring fluid flow and fill levels in process equipment, monitoring containers for corrosion or pressurization, and verifying facility designs.

Most of these applications are beyond a conceptual level in that they have at least been demonstrated on a very limited bench-top scale. Limited support has been available for developing an acoustic fill-level monitor for facility verification, an acoustic holdup monitor, and the intrinsic seal application.

2. Liquid Fill-Level Determination

For both process monitoring and verification, it is frequently necessary to monitor the level of liquid inside a process vessel. We discuss here a non-invasive acoustic technique that can provide such information. Measuring liquid density and detecting stratification can also be achieved with this technique.

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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:

$$C_b = \sqrt{1.8 C_L t f} \quad . \qquad (1)$$

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.

The bending waves slow down when the metal plate comes in contact with a liquid. The relationship between the wavelength λ and the frequency becomes dependent on the liquid density as shown below /1/.

$$\omega^2 = \frac{Dk^5}{\rho_L + t\rho_s k} \quad , \qquad (2)$$

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 /2/:

$$C_b = \left(\frac{\omega^3 D}{\rho_L}\right)^{1/5} \quad . \qquad (3)$$

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.

These principles are used in designing a system to determine non-invasively the fill-level and density of liquid inside a tank. The technique employs a tone-burst approach and is described below.

Tone-Burst Technique

The principle of the tone-burst technique is described pictorially in Fig. 1. Here a tone-burst of a fixed frequency excites 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.

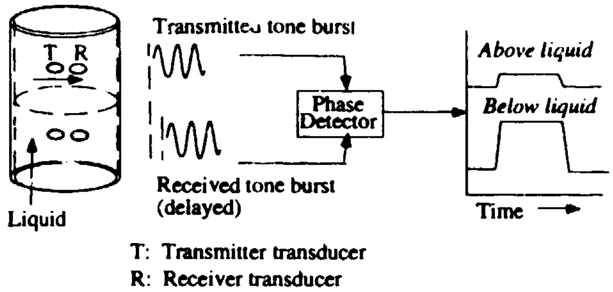

Fig. 1 – Schematic representation of the principle of the tone-burst phase measurement technique for non-invasive liquid-level measurement.

The two transducers are kept in a simple holder separated by approximately 2 cm. A conical metal piece is glued on the surface of the transducers. This allows for easy movement of the transducers on any surface. To detect the fill level, one simply slides the transducer system along the height of the vessel and looks for a dramatic change in the phase-detector signal as shown in the figure above. The transducers are 1 cm in diameter, and because of the use of the conical attachment, the liquid level can be determined to within ~1 mm of the actual value.

The density of the liquid can be judged from the magnitude of the phase measurement. Denser liquids produce larger shifts, and once a container is calibrated, the phase measurement can provide a direct measurement of liquid density or stratification. We have been able to resolve density differences as small as 0.01 g/cm^3.

With a slight variation of the technique, the liquid level can be continuously monitored. For such continuous monitoring, two transducers are placed vertically on the container with one near the top and one near the bottom. The propagation time of the tone-burst signal in this case is linearly related to the liquid level as long as the level is between the two transducers.

3. Detection of Holdup or Corrosion

In this section, we discuss a sensitive acoustic technique for detecting holdup in metal walls. In many situations, it is necessary to determine the location of holdup materials inside a nuclear material container from outside of the wall. There are occasions where radiation-based sensors are not adequate for detecting holdup either because of high-background radiation fields or equipment geometry constraints. In such cases, this acoustic technique can provide a complementary technique to conventional holdup measurements.

Principle

A metal plate can be used as an acoustic resonator because of the parallel geometry of the plate walls. If two piezoelectric transducers are coupled to either side of the plate such that one excites mechanical vibrations and the other detects the vibrational response, the resonator characteristics of the plate can be observed. If the frequency of the source transducer is adjusted to generate a sound wavelength inside the plate material that is an integral number of the half wavelength, then a pronounced resonance peak can be observed by the receiver transducer. So, whenever a standing wave is set up inside the plate, the response is a pronounced resonance peak. This resonance represents the thickness resonance mode of the plate (localized in the sound path between the transducers). Because the thickness is significantly smaller than any other geometric parameters, generally this mode will have negligible interference from resonances associated with any other structural vibrations that depend on the overall geometry of the test item.

We have found that it is straightforward to excite and detect such thickness-mode resonances of a metal plate by using a dual-element transducer in which both the exciting and the detecting elements are on the same side of the plate instead of on opposite sides as described above. This particular innovation of using a dual-element transducer opens up the possibility of using acoustics in locating holdup.

The frequency at which a standing wave can be established depends on the sound speed in the material of the plate and the thickness of the plate. Experimentally, there are two simple ways to find an appropriate standing wave (resonance) frequency. In the first method, a feedback loop technique is used that automatically locks on a resonance frequency of the plate within a frequency window. The second, more versatile, approach uses a frequency sweep in which a resonance spectrum of the plate is obtained. We prefer the swept-frequency approach over the impulse response followed by a fast Fourier transform (FFT) to derive the spectrum. The FFT approach provides very poor quality data in practice. We have used a commercially available DSA120 Digital Synthesizer and Analyzer (Neel Electronics, CA) PC plug-in board to carry out the sweep measurements. The DSA120 board has a frequency range of 1 kHz–10 MHz and includes both sweep frequency generation and signal processing circuitry in a single board. We typically used Panametrics D7076 dual-element, 0.5-inch-diameter, 5-MHz center frequency transducers for our measurements.

The amplitude of any of the resonance peaks depends on the interface condition of the boundary wall on the opposite side of the plate. Because of the extreme acoustic impedance mismatch between the metal plate and air, very little of the sound field leaks out and the amplitude is determined by the internal loss in the plate material. However, when a layer of a second material is placed on the surface of the plate, the impedance mismatch is reduced, and this is reflected in the reduced amplitude of the resonance peak.

Results

Figure 2 shows experimental data on an aluminum plate. The measurements were repeated with two different types of coating on the plate surface so that we could observe the effect of the presence of the coating. Only one resonance peak is shown for clarity. A very thin layer of vacuum grease reduces the amplitude quite significantly. The presence of salt mixed with vegetable oil to form a paste produces intermediate results because the salt particles are not strongly attached (or glued) to the surface. Corrosion or rusting produces similar results. We have used this technique to detect the presence of foreign material on steel plates as thick as 2 cm.

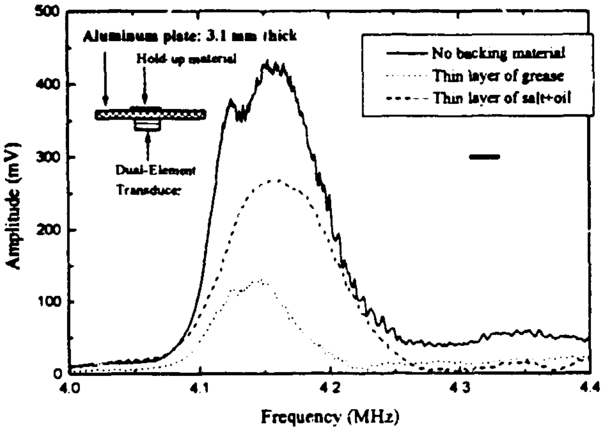

Fig. 2 – Detection of holdup material using plate mode resonance. The holdup material is simulated using thin layers of grease and a paste made from salt and oil.

If a metal plate, vessel wall, or process pipe has holdup material attached to it in a few areas, these locations can be detected and mapped by sliding the transducer along the surface of the plate on the outside and observing the amplitude variation. Once a particular resonance peak is chosen, the instrument is set at that particular frequency and the amplitude value is observed on a bar graph display. The whole system can be built into a hand-held, portable, battery-powered unit.

The data shown in Fig. 2 were taken with vacuum grease as coupling material between the transducer and the plate surface. This coupling can also be accomplished using a polytetrafluoroethylene (PTFE) pouch filled with coupling gel material attached on the top surface of the transducer /3/. The coupling medium is contained within small pores in the pouch, which nearly eliminates any coupling gel residue on the sampled surface, but still permits convenient movement of the transducer across the surface to locate holdup.

It is possible to devise a system using electromagnetic acoustic transducers (EMATS) that would allow measurement without any contact. We are currently developing such a system.

4. Intrinsic Seals

The acoustic resonance spectrum of a container can be used as an indicator of that container's integrity. If a tight-fitting lid is removed or the contents disturbed in any significant way, the transmission of sound waves traveling within the container walls, between the lid and container walls, and through the contents is irreversibly altered. In laboratory tests we have demonstrated that simply removing and replacing the lid on a 210-L drum measurably alters the drum's resonance characteristics.

Principle

In this application we obtain a resonance spectrum of a container and compare subsequent spectra obtained under nearly identical conditions with this baseline measurement. To obtain the spectra, one transducer (acting as an energizer) is placed on the container's side and a second transducer (acting as a detector) is placed on the lid, adjacent to the first. These positions are marked for subsequent measurements. For 210-L drums we obtain spectra from 20 to 30 kHz, with 1-Hz steps.

A large number of options exist for comparing spectra. So far the most useful have been 1) using a simple correlation coefficient and 2) correlating frequencies of the major peaks between two measurements.

Results

In laboratory-scale tests, this technique proved relatively successful. Figure 3 shows the distribution of values representing peak comparisons between spectra.

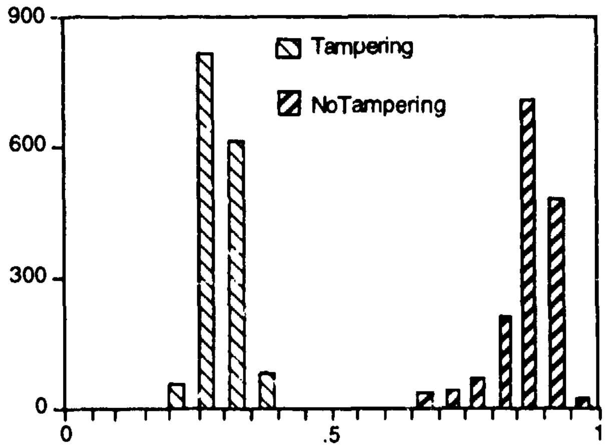

Fig. 3 – Histogram of pairwise spectra comparisons. These data were obtained in a laboratory setting and show clean separation of cases where tampering occurred between measurements from cases where no tampering occurred between measurements.

Spectra with identical resonance patterns have a coefficient of one and totally dissimilar spectra tend toward a coefficient of zero.

This figure shows that when a container's lid has not been removed between measurements, the coefficients indeed tend toward one, as expected. If the lid is simply removed and carefully replaced, to very nearly the same conditions, the spectra are sufficiently different to shift these correlations to significantly lower values. In fact, there is clean separation between these two populations. However, this test was performed under idealized conditions in a laboratory setting using new containers, where temperatures were relatively stable, and containers were not moved between measurements. Results for existing containers in an operating vault have not been as encouraging.

We repeated the above test for several containers in an operating vault at Los Alamos National Laboratory. These containers represented three different sizes, contained a variety of dry material types, and many had a light coating of rust where transducers were placed. Over the course of the experiment, three different operators took measurements at various times.

Figure 4 shows one example of the results. In this case, the container was not moved between measurements, but the surface was slightly rusted. Using the same analysis procedures as described for the laboratory tests, this figure shows a significantly worse separation in the two populations. In a similar test, where the container was moved between each pair of measurements, the populations merge even more. This distribution represents a false positive rate of approximately 30% under these conditions.

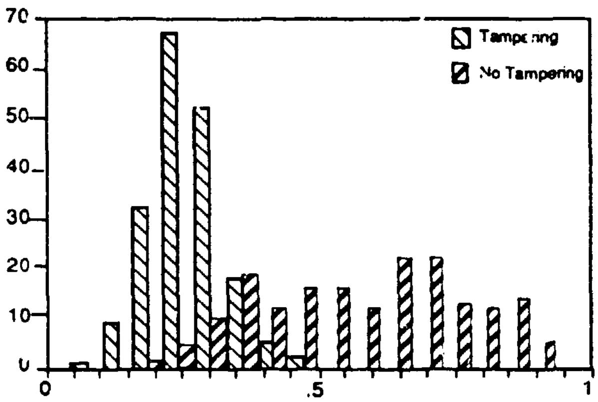

Fig. 3 – Histogram of pairwise spectra comparisons. These data were obtained in an operating vault under variable conditions. Separation of tamper from no-tamper cases is much worse than in the controlled laboratory setting (Fig. 3), suggesting some operational limitation of the intrinsic seals technique.

It is not clear whether the degradation in separation of populations between Figs. 3 and 4 results from different environments, different operators, or uneven surfaces of aged containers. However, it does appear that movement of containers significantly reduces the reproducibility of spectra even when no tampering occurs. This probably results from redistribution of material within the container as well as residual stresses in the container and its interface with the lid.

These results suggest that if intrinsic acoustic seals are to be useful in safeguards, the technique will probably be limited to long-term storage environments where material handling is minimized. It may also be necessary to use pristine containers that are protected from corrosion.

5. Summary and Conclusions

Acoustic techniques have the potential for filling a variety of safeguards needs. All of these areas require further development for field implementation, but each appears promising in the appropriate regime.

Fill-Level Determination

Monitoring a tank for fill level appears to be relatively straightforward by monitoring the transit time or the relative phase of a tone burst between two transducers. The advantages of this technique are 1) there is no need to retrofit tanks that were not designed for fill-level verification (the sensors are fully external to the tank), and 2) it can also be used for detecting stratification and estimating liquid densities. Sensors can be either permanently affixed or portable, depending on the specific application.

Detection of Holdup or Corrosion

A dual-element transducer can establish and monitor ultrasonic resonance within the wall of a container or other process equipment. The operator moves a sensor along the outer surface of a process tank while monitoring a display that reflects the phase and amplitude of the standing wave established in the wall of the tank. When the sensor is adjacent to a coating of holdup, the change in impedance mismatch between the tank wall and internal contents shifts both the phase and amplitude of the standing wave. Hold up areas can be mapped by marking the sensor location where these changes occur. Once the offending location is identified, the holdup can be cleaned out or quantified using conventional techniques. This technique holds significant promise in surveying areas for holdup in locations where conventional radiation-based measurements are inefficient or difficult due to high background radiation or constraining equipment geometry.

This technique can be useful in improving estimates of holdup and in optimizing decontamination procedures by identifying the exact location of material. Field inspectors could also use this technique to confirm fill levels of tanks or monitor for stratification of liquid before obtaining aliquots.

Intrinsic Seals

Acoustics can be useful in establishing and monitoring intrinsic seals of containers. The resonant spectrum of a container is a complex function of the container geometry, stresses placed on the container and lid, and distribution of the contents. It is nearly impossible to open a container and re-seal it without irreversibly altering the container's acoustic pattern. Unfortunately, the resonant spectrum is also sensitive to other changes that do not necessarily indicate tampering, resulting in a potentially high false-positive rate, depending on the exact environment.

Sensitivity to innocuous changes may limit the applicability of this technique to long-term storage environments. However, alternative comparison algorithms are being examined to improve the flexibility of this technique.

6. References

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/2/ Frank Fahy, *Sound and Structural Vibration* (Academic Press, 1985), p. 130.

/3/ C. F. Buynak and R. L. Crane, "A Novel Acoustic Coupling Device Using Permeable Membrane," Materials Evaluation, **45** (June 1987), pp. 743 746.