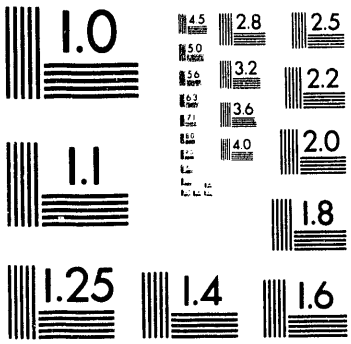
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Author(s): C. T. Olinger, M. J. Lyon, W. D. Stanbro, M. F. Mullen, and D. N. Sinha

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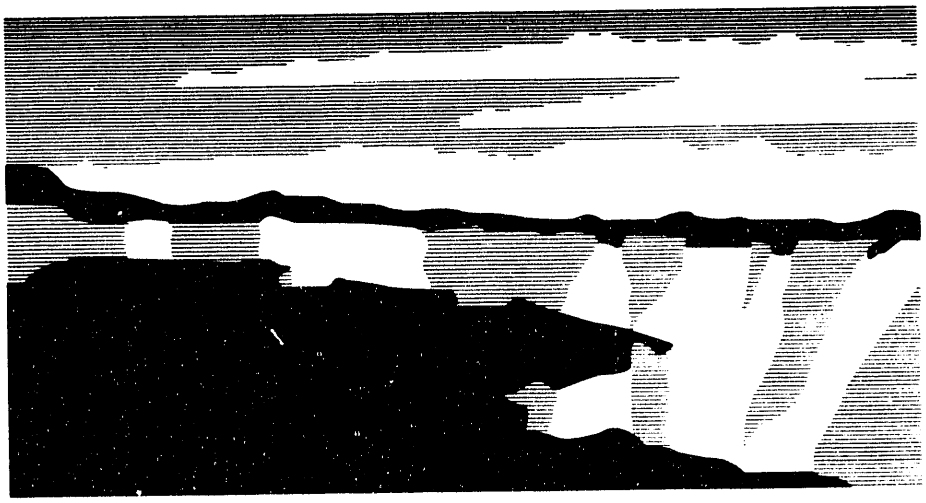

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ACOUSTIC RESONANCE SPECTROSCOPY IN NUCLEAR SAFEGUARDS*

C. T. Olinger, M. J. Lyon, W. D. Stanbro, M. F. Mullen, and D. N. Sinha
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

ABSTRACT

Objects resonate at specific frequencies when mechanically excited. The specific resonance frequencies are a function of shape, size, material of construction, and contents of the object. This paper discusses the use of acoustic resonance spectroscopy (ARS) to monitor containers and detect tampering. Evaluation of this technique is based on simulated storage situations. Although these simulations show promise for this application of ARS, final evaluation will require actual field testing.

I. INTRODUCTION

Acoustic resonance spectroscopy (ARS) is a nondestructive evaluation technique developed at Los Alamos National Laboratory to acoustically interrogate solid objects and containers.[1,2] The field-portable technique evaluates acoustic spectra rapidly, inexpensively, and non-intrusively.

All solid objects have natural modes (frequencies) at which they can vibrate relatively freely. These natural vibrational frequencies and their sharpness strongly depend on the physical characteristics of the object such as its size, shape, and material composition as well as stresses placed on the body. These spectra can be quickly and easily measured by ARS for future reference or comparison of similar items.

ARS may be useful in monitoring containers and detecting tampering. Because a large number of parameters influence the acoustic spectrum, it is nearly impossible to return a container to its original state if the contents have been significantly disturbed. An item's acoustic fingerprint provides a means to detect tampering, monitor the integrity of a container, and confirm the presence of the contents. In many ways, this fingerprint behaves as a seal, except that it also reflects some parameters of the contents, not just the integrity of the container. Thus, we refer to the ARS fingerprint as an intrinsic seal. A change in the ARS signature indicates some change in the item. After a change has been detected, more time-consuming analytical methods can be applied to determine whether the anomaly resulted from unauthorized access, removal of material, damage to the container, spillage of contents, or environmental differences between measurements. Simple, rapid, and nonintrusive ARS measurements may provide a means of screening large numbers of containers for more intrusive and time-consuming high-accuracy analyses.

Environmental variables can influence measured spectra, so these need to be considered in assessing safeguards applications. These variables include temperature, acoustic coupling to surroundings, pressure inside the container, and ambient noise.

ARS is relatively insensitive to ambient noise because only narrow frequency bandwidths are energized and excited at each step interval. Noise outside of this interrogation band is filtered out and does not interfere with the measured signal. Atmospheric pressure and temperature variations have relatively small effects in most applications. Acoustic coupling to surroundings, however, can result in significant spectral effects; phase transitions, which may occur with UF_6 in storage, could substantially affect the signature. Except in cases of extreme temperature variations between calibration and application, temperature effects should be correctable. Acoustic coupling to a container's surroundings, such as mounting brackets or direct ground contact, can affect the spectrum. These effects need to be assessed for each application.

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II. MEASUREMENT TECHNIQUE

ARS excites a body at discrete acoustic frequencies, listens for the response at that frequency, and then steps to another frequency. Each step is close to the next in frequency and time, and the desired frequency range can be swept in just a few seconds. Peaks can then be identified to determine the resonant frequencies of a system. This series of peaks establishes a "fingerprint" or signature of the item (Fig. 1). Alternatively, peak locations can be used to assess physical parameters of the fill material (e.g., fill height, fluid density, solution concentration) if the acoustic response has been calibrated.

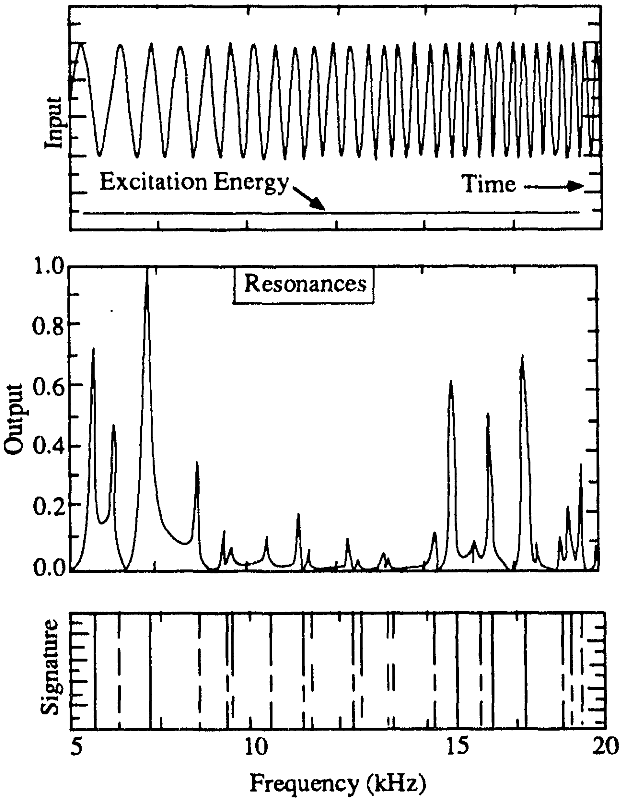

Fig. 1. The ARS method of measuring acoustic spectra.

ARS has many desirable attributes, including the following: the excitation amplitude remains constant throughout the measurement, ambient noise is filtered out if it is not in the narrow bandwidth being measured at that time, measurements can be made in less than a minute, and the acoustic spectrum can be displayed in real time. Moreover, the entire system consists of a computer, an internal board (or small external package for notebook sized computers) and a pair of small transducers. This makes the system portable, extending the range of potential applications.

Measured resonant *amplitudes* are affected by transducer placement. If the transducer is close to a node during one measurement and close to an anti-node of that frequency during another one, the relative amplitudes will not be the same, but the measured resonant frequencies remain invariant unless a transducer is close enough to a particular node to prevent detection of that particular vibrational mode. Nondetection of a single, or even a few, resonant frequencies should not significantly harm the analysis because multiple resonances are generally considered. This makes ARS a robust system for field applications where it may be impractical to reproduce exact transducer locations between measurements.

III. HARDWARE

The ARS system used for this study is based on an IBM/PC- AT 386 or similar hardware. This supports a single plug-in board (DSA 100), which generates the input and analyzes the return signal. Alternatively, the DSA 100 board can be placed in a small box containing a rechargeable battery pack and operated from a notebook-type computer through an RS-232 interface. This increases the portability of the system. A pair of transducers completes the ARS system. One induces vibrations in the object under study and the other detects the vibrational response, feeding the signal back to the DSA 100. Software necessary for data acquisition and graphical display accompanies the DSA 100, and the entire system can be procured for a few thousand dollars.

IV. EXPERIMENTAL DESIGN

We have tested ARS in establishing and monitoring intrinsic seals on 55-gallon drums. These, or drums of similar design, are used in several applications of nuclear safeguards concern such as storing weapons components, heavy water, and nuclear wastes. Intrinsic seals may also be useful in monitoring UF_6 cylinders and smaller cans of special nuclear material.

The application of ARS in establishing intrinsic seals involves two independent questions. First, can material be removed from a sealed item without significantly altering the seal? Second, does the intrinsic seal change naturally so as to be unidentifiable at some later time?

To gain experience with potential pitfalls in applying ARS to safeguards, we have performed preliminary, laboratory-scale tests to assess whether removal and replacement of the container's lid (without disturbing the interior) can be detected. Tests of natural variation in a container's signature have so far been limited to thermal cycling by exposure outside and tests performed in a laboratory with high ambient noise levels.

All of these tests were conducted with the transducers magnetically attached to the lid of the drum. The transducer locations were marked directly on the lid so the transducers could be precisely replaced. In many cases tests were duplicated. In one, the transducers remained affixed to the container and in another they were removed and visually aligned to closely approximate their previously marked positions.

V. RESULTS

Acoustic spectra obtained on a given container under different conditions generally support the possibility of using ARS in establishing intrinsic seals. In cases where the container was not tampered with, the relatively mild environmental conditions did not adversely affect the signature. Conversely, every time the container was opened and resealed, clear spectral differences occurred. These results are only preliminary, and field testing is required to assess the effects of environmental conditions on the acoustic signature.

A. Signature Stability

To test the stability of the signature with temperature shifts, we placed the barrel in full sun for 5 days. After exposure to this thermal cycling, we returned the container to a climate-controlled room where the reference spectrum was measured. New spectra revealed approximately 40-Hz shifts in resonant frequencies when the container was still warm, but within approximately 3 hours the spectrum regained its original structure. Figure 2 compares the reference spectrum with the final spectrum after thermal cycling and cooling. Resonance peaks of these spectra show no significant differences within the resolution of the measurement. Limited thermal cycling had negligible effects on the acoustic signature. The initial differences in spectra reflect a slight thermal dependence of an object's acoustic signature. We should be able to correct for thermal effects, which will permit field applications where temperatures cannot be controlled.

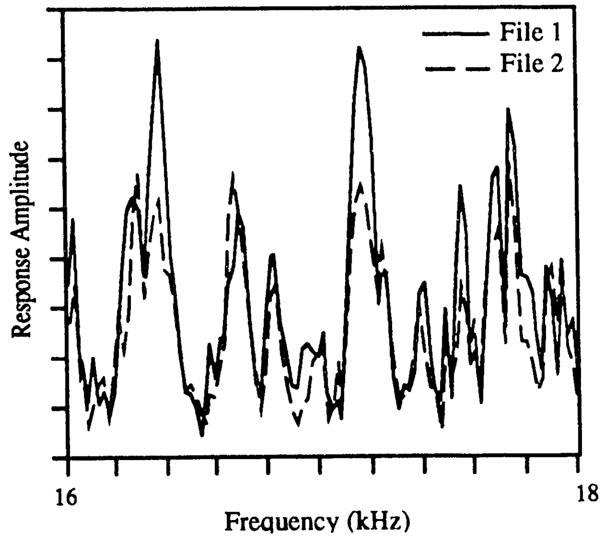

Fig. 2. Comparison of acoustic signature after thermal cycling.

A high-noise environment does not adversely affect the ARS technique. The system was placed in a room with a large air conditioning unit. This does not match the very high noise levels found in some industrial applications, but it is sufficient to warrant limiting worker exposure to the noise. All major resonances were reproducible between analyses.

B. Tamper Indication

Preliminary tests have also been performed to detect intrusion into the container. The lid of this particular container has a padded ring where the lid meets the edge of the drum. The lid is held in place by a keeper ring that engages both the lid and the top ridge of the container. The keeper ring is secured by bolting the opened ends together.

Repeated attempts were made at opening the container, replacing the lid and adjusting the tension on the keeper-ring bolt to reproduce the original spectrum. Many individual resonance peaks were invariant between measurements, but we could never reproduce all of the major resonances. Reproducing the torque on the keeper-ring bolt upon resealing the container still results in significantly different spectra. This is probably due, in part, to the fact that the ring is deformed slightly each time it is removed, so the locations of maximum pressure on the lid are irreversibly altered.

No attempts were made at circumventing the lid to gain entry. A padded ring between the lid and container prevented effective acoustic coupling. Thus, acoustic signatures obtained from the lid will not reflect the integrity of the rest of the container. To get this information, a second spectrum should be taken from the container walls. Because the rest of the container is contiguous, this second measurement may be sufficient to monitor for intrusion scenarios that circumvent the lid.

VI. DISCUSSION

Tests on the stability of an item's acoustic signature indicate that some resonant frequencies shift slightly, but in every case these were within a peak half-width of each other. Comparing these shifts relative to the peak widths may be useful in assessing whether or not the shifts are significant.

Potential complications do exist in using ARS to establish intrinsic seals. Environmental variables such as temperature and atmospheric pressure do affect a container's acoustic spectrum. Bench-top tests indicate that these may not be significant, but field tests are now required to assess whether long exposure to environmental conditions adversely affects the stability of ARS intrinsic seals.

Another question in using ARS to establish and monitor intrinsic seals is whether the system can be spoofed by replacing authentic material with a surrogate. We have not performed any surrogate tests directed at nuclear safeguards applications, but relevant testing has been performed for applications of ARS in monitoring the chemical weapons convention.[3] In these tests, a surrogate chemical was engineered to closely match the acoustic velocity, density, and viscosity of the VX chemical agent. Comparing the spectra of similarly filled munitions, acoustic resonances for surrogate-filled rounds were significantly shifted from those of the VX-filled round (Fig. 3). These results suggest that diversion scenarios in which nuclear material is replaced with a surrogate would still be detectable in many intrinsic seal applications.

In some cases (such as assessing the significance of small shifts in resonance peaks), it may be desirable to monitor spectral shapes as well as resonant frequencies. Comparison of spectra can be facilitated if transducers are precisely repositioned on the container each time. One approach would be to permanently attach the transducers to the item, but this would add substantial cost to each item. An alternative solution is to epoxy magnets to the sealed items. The transducers could then be magnetically repositioned to the same location. Tests on this approach are currently underway.

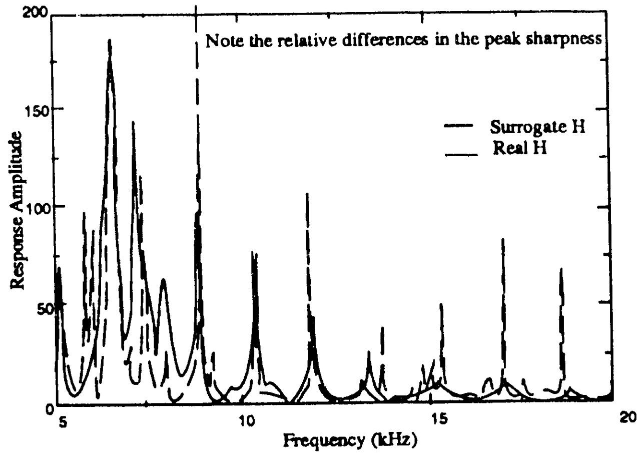

Fig. 3. Comparison of real (H) vs. surrogate-filled munitions.

VII. SUMMARY AND CONCLUSIONS

In the future, ARS may play a useful role in safeguards applications. Spectra obtained using ARS have high noise rejection; measurements are rapid, typically requiring only about 10 seconds; the systems are portable, with a lap-top computer housing all required hardware; and acoustic spectra are sensitive to changes in a variety of independent parameters.

These attributes make ARS attractive in field applications and where radiation fields may be high. In the near-term, ARS may be useful in establishing and monitoring intrinsic seals on individual items. In particular, we hope to test the technique on pit containers and UF_6 cylinders.

In addition to establishing intrinsic seals, ARS may have safeguards applications in process monitoring and facility design verification. These applications are being pursued in separate studies.

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