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ACOUSTIC RESONANCE SPECTROSCOPY INTRINSIC SEALS*

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ABSTRACT

We have begun to quantify the ability of acoustic resonance spectroscopy (ARS) to detect the removal and replacement of the lid of a simulated special nuclear materials drum. Conceptually, the acoustic spectrum of a container establishes a baseline fingerprint, which we refer to as an intrinsic seal, for the container. Simply removing and replacing the lid changes some of the resonant frequencies because it is impossible to exactly duplicate all of the stress patterns between the lid and container. Preliminary qualitative results suggested that the ARS intrinsic seal could discriminate between cases where a lid has or has not been removed. The present work is directed at quantifying the utility of the ARS intrinsic seal technique, including the technique's sensitivity to "nuisance" effects, such as temperature swings, movement of the container, and placement of the transducers. These early quantitative tests support the potential of the ARS intrinsic seal application, but also reveal a possible sensitivity to nuisance effects that could limit environments or conditions under which the technique is effective.

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 a container such as its size, shape, and material composition as well as stresses placed on the body. Acoustic velocity, viscosity, density, and contaminants in the material stored within the container also affect resonance frequencies. Changes in any of these parameters will affect the spectrum, but various resonance peaks respond to different parameters in different ways.[2]

ARS may be useful in monitoring containers and detecting tampering. Because a large number of parameters influence the acoustic spectrum and each parameter changes the spectrum in a different way, it is nearly impossible to return a container to its original state if the contents have been significantly disturbed. Conceptually, an item's acoustic fingerprint provides a means to detect whether or not a person has tampered with the containers.

Qualitative results, previously reported, demonstrate the potential usefulness of ARS in establishing and monitoring the intrinsic seal of a container. Limited numbers of spectra were obtained in these early tests, but qualitative analysis suggested that there would be only minor changes in spectra in cases where no tampering occurred, while spectral differences were consistently more apparent when a container's lid was removed and replaced.[3]

We are now quantifying variability of spectra in cases where no tampering with the simulated special nuclear material containers has occurred and where containers have been opened. Early tests were optimized to minimize nuisance effects. Laboratory-scale testing continues to extend these results into more operationally relevant settings before field testing proceeds. Nuisance parameters being tested include effects of changes in ambient temperature, thermal cycling of containers, replacing transducers only approximately to the location where the baseline spectrum was obtained, and vibrational noises. In parallel with these efforts, we are examining different algorithms for comparing spectra of the same item to optimize analyses.

II. MEASUREMENT TECHNIQUE

The ARS technique obtains a spectrum by measuring the container's vibrational response at a series of discrete frequencies. A measurement begins when one

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transducer, which acts as a speaker, induces vibrations in the object at a given frequency. A second transducer, which acts as a microphone, detects the vibrational response at that frequency. The transducers then step to the next frequency and repeat the process until the entire frequency range has been sampled. The operator defines both the resolution (difference in frequency between steps) and frequency range (start and stop frequency) of the measurement. In Fig. 1 we show an example spectrum.

Once a baseline spectrum is established for the object, future spectra from that object can be compared to assess if tampering has occurred. In this type of application a discriminator must be used to assess whether spectra are sufficiently similar to indicate no tampering has occurred or sufficiently different to require further testing and examination of the container and its contents.

ARS has many desirable attributes, including the following: the excitation amplitude remains constant and low throughout the measurement, so the contents are only minimally disturbed; ambient noise is filtered out if it is not in a 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. A benefit beyond conventional materials control and accountability is the possibility of simultaneously monitoring for pressurization or degradation of the container for safety purposes.[4]

The entire system consists of an IBM/PC-AT 386 or similar hardware, an internal electronics board (or small battery-operated external package connected to a portable computer through an RS-232 cable) and a pair of small transducers. This makes the system portable and inexpensive, extending the range of potential applications.

III. DETERMINING A FREQUENCY RANGE FOR MEASUREMENTS

Useful frequency ranges for intrinsic seals may depend on such parameters as the container geometry and type of contents, so it is desirable to find a quick way of assessing a good (not necessarily best) frequency range for analysis. Qualitatively, we began by looking for a range where 1) the response amplitude is high across a large number of resonances, 2) resonance peaks are well defined and 3) resonance peaks are generally separated from each other. Conceptually, this should improve our discrimination ability because separation between peaks will reduce the probability that a comparison algorithm will associate a peak that has been shifted with a neighboring peak in the baseline spectrum. Similarly, avoiding frequency ranges where peaks are extremely sharp (only a few points wide) improves the probability that the analysis algorithm will recognize peaks, which should correlate between spectra when insignificant shifts occur.

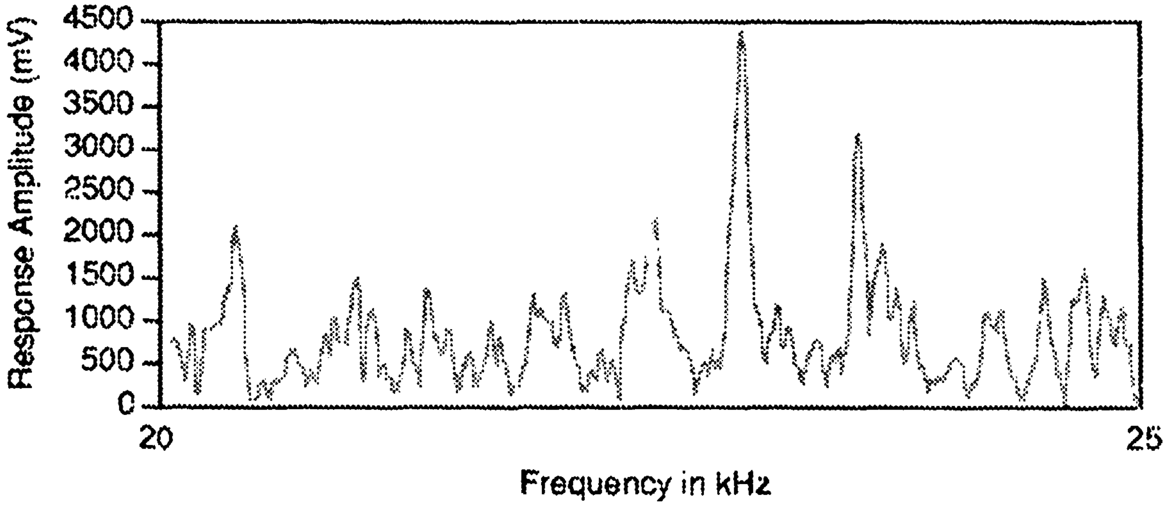

Fig. 1. An example spectrum.

We tested our qualitative determination of a good frequency range as follows: we took five high-resolution spectra of three similar test containers (without disturbing the containers) and assessed the reproducibility of different ranges by comparing the signal-to-noise ratio (SNR) across the entire frequency range. We defined the SNR at a given frequency as the ratio of the mean to the standard deviation of the five observations. We computed the SNR at each of 1000 frequencies and computed the average SNR over all frequencies. The average SNR was largest in the range that was selected by qualitative methods. See Appendix A for more details.

IV. METHODS OF COMPARING SPECTRA

Two spectra can be compared qualitatively by overlaying the two spectra and comparing them visually, which provides some insight into the ARS technique. However, visually comparing spectra to determine whether an intrinsic seal has been violated is not an effective approach for two reasons. First, even in the case of no tampering, there are always some differences between spectra, and deciding whether these small differences are significant or not becomes purely subjective; and second, visually comparing spectra in detail is very time consuming and would be extremely inefficient for verifying intrinsic seals in a storage situation involving more than just a few containers.

To perform an objective comparison it is useful to describe the similarity or difference between spectra quantitatively. We examined four definitions of the similarity between spectra and two definitions of differences between spectra. These are discussed in Appendix B. To simplify discussion, we report results of one similarity measure: the Pearson correlation coefficient between normalized spectra. Although results varied, this proved the most dependable in identifying similarities between spectra where no tampering occurred.

V. DISCRIMINATION BETWEEN TAMPERING AND NO TAMPERING

Once we have identified a frequency range that gives highly reproducible results when no tampering has occurred and decided on a method for comparing spectra, we then must determine whether tampering with a container (in this case simply removing and replacing the lid) significantly changes the spectrum. Figure 2 is a histogram of the Pearson correlation coefficient between different spectra of the same container. The population on the left represents spectra where the lid was removed between measurements, while the population on the right represents spectra measured where no tampering occurred. In this instance there is clear separation between the two populations, supporting the possibility that ARS may be useful for establishing and monitoring intrinsic seals.

This test was, however, performed under optimal conditions. Spectra for a given container were all obtained on the same day, care was taken to replace transducers in the same location between measurements, the container was not moved between measurements, ambient noise was negligible, and the room temperature was stable. Each of these effects must also be examined to determine whether there are limitations on the environments in which the ARS intrinsic seals may be applicable.

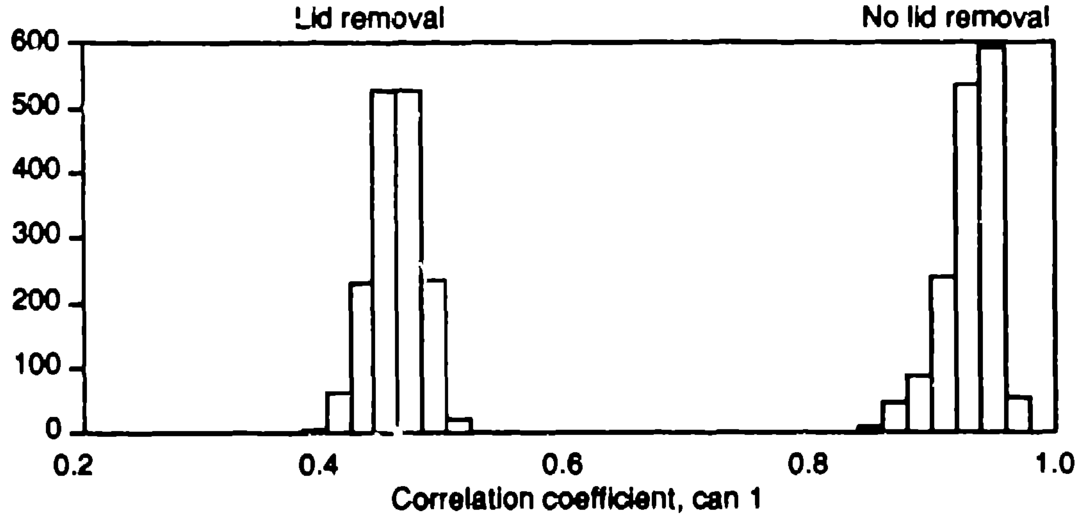

Fig. 2. Use of the correlation coefficient to detect lid removal.

VI. NUISANCE EFFECTS

We are continuing tests to examine whether environmental effects, such as noise and temperature swings, might limit this technique. Preliminary tests have been performed. The following describes some of these results.

A. Noisy Environment

The effect of ambient noise can be quickly assessed to first order by removing the transducer that would normally induce vibrations in the container, but detecting the "response" across the frequency range with the pick-up transducer connected to the container in the normal way. When we performed this test in a room having a high noise level, the ambient vibrations produced essentially no response. The technique is not sensitive to ambient noise because the vibrational response detected by the transducer is passed through a band-pass filter so that only vibrations within a 1-kHz frequency window centered at the frequency of excitation are registered. Thus, even in a noisy environment, almost all of the ambient vibrations are eliminated in the analysis process. Thus, within the noise range where operators will be comfortable making measurements without ear protection, spectra should be minimally affected by ambient noise. Experiments to test these preliminary conclusions are presently underway.

B. Transducer Placement

Operationally, it is important to examine the sensitivity of spectral comparisons to accurate placement of transducers between measurements. Limited tests were performed on containers where no tampering occurred but where transducers were removed and only approximately replaced to the same location. We estimate that the transducers were generally replaced within a centimeter of the location where baseline spectra were obtained, and the container was not tampered with. As shown in Fig. 3, the comparison algorithm produced a much wider distribution than in the test described in Section V, suggesting that the technique may be highly sensitive to careful placement of transducers. Further testing will be directed at quantifying how far the transducers can be moved without adversely affecting the ability to discriminate between cases where tampering has or has not occurred.

These results may also depend on the comparison algorithm applied. Use of a screening tool such as identifying peak locations and comparing these between spectra, instead of comparing spectra point-by-point, may improve these results. Even if this does not improve the results, a number of relatively simple alignment procedures could prevent this effect from significantly limiting the applicability of the technique. To date we have used only the four similarity measures and two distance measures described in Appendix A for discrimination. We plan to experiment both with other pattern recognition tools and controllable parameters to determine if sensitivity to transducer placement or other nuisance effects can be reduced.

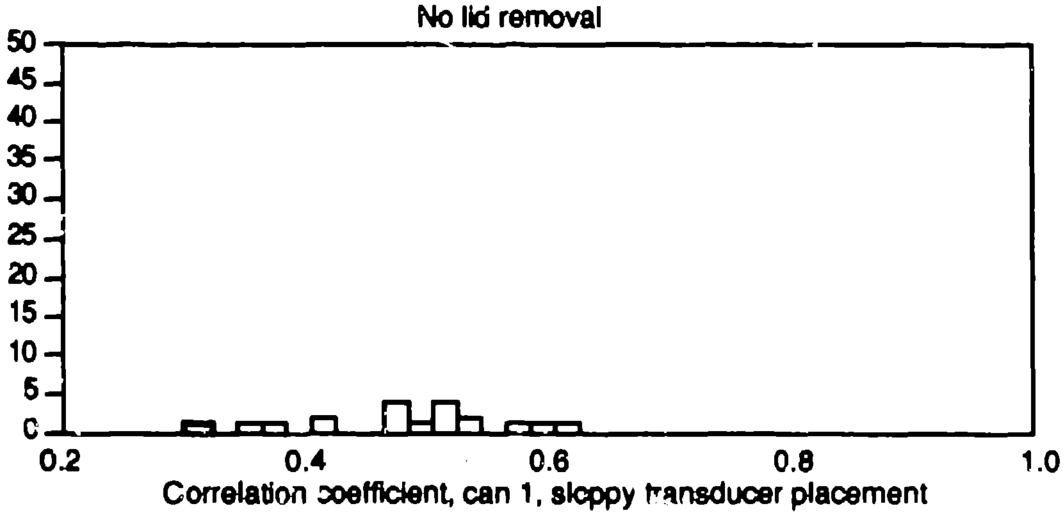

Fig. 3. Sloppy transducer placement effect.

C. Thermal Cycling

Previous results based on qualitative comparisons between spectra suggested that thermal cycling should not adversely affect the similarity of spectra when no tampering occurs. However, a less subjective analysis suggests that the qualitative comparisons may have been biased. Figure 4 shows a number of tests in which containers were moved outside to warm up in the sun after a baseline measurement was made, then returned inside until their temperatures stabilized with room temperature, which varied less than 0.5°C. In these cases, we see that the distribution representing the case where no tampering has occurred spreads out, with the left tail of the distribution approaching the distribution associated with the tampering case. Depending on how a discriminator threshold is set, such an effect would result in either a higher false positive rate or a lower sensitivity to tampering.

VII. SUMMARY AND CONCLUSION

In an optimized storage situation where containers are not disturbed unless simulated tampering occurs, these tests suggest that the ARS intrinsic seals technique could provide an alternative to conventional seals. The advantage of the ARS intrinsic seal is that it reflects not only the integrity of the container but the integrity of the contents as well. If further tests confirm that the technique is even more sensitive to cases where contents are actually removed, then ARS may improve the confidence provided by conventional seals. Under this assumption, a 100% tag-and-seal check performed by ARS might permit a reduction in sampling plans for confirmatory measurements while maintaining high confidence in the inventory. A second benefit to the technique is that it might allow simultaneous assessment of internal pressure. This has particular implications for long-term storage situations as the DOE complex moves away from production toward a storage mode.

On the other hand, nuisance effects may constrain the use of ARS intrinsic seals to environments where movement of containers will occur only rarely and thermal cycling can be minimized. Further testing is required to examine effects of moving containers around, settling of contents, temporal stability of the acoustic signature, thermal effects, and transducer placement. In the context of statistical design of experiments, we must choose good settings for controllable parameters such as frequency range and resolution, so that nuisance effects are reduced. Also, some adverse effects may be mitigated by pre-filtering data or applying alternative comparison algorithms or both. Sensitivity to transducer placement should be easy to overcome, but the approach may depend on how precisely the transducers must be relocated. Other effects may simply limit locations where ARS should be applied. As we develop an understanding of these effects, the ARS intrinsic seals technique may become an important safeguards option, particularly as the nuclear weapons states move from a production mode to a storage mode.

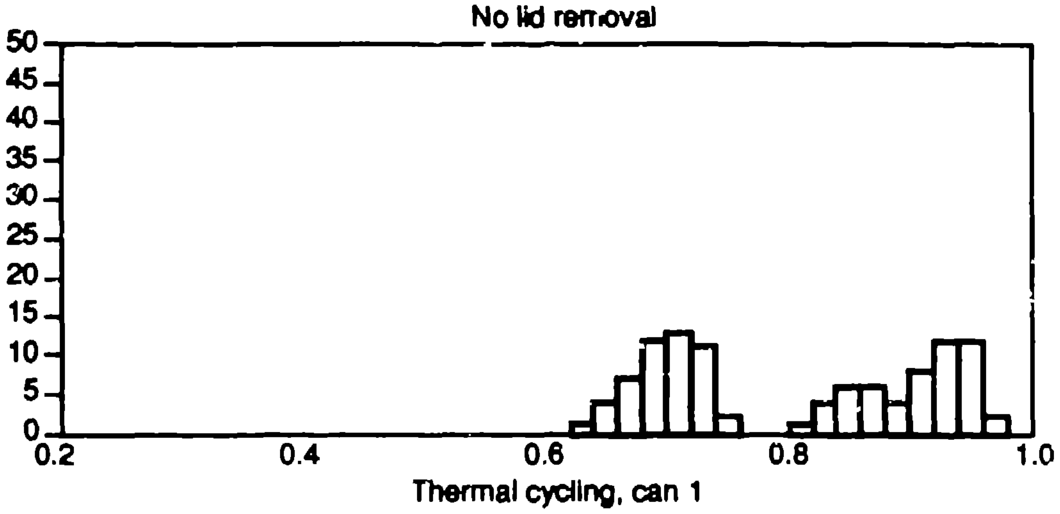

Fig. 4 Thermal cycling effect.

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APPENDIX A

In Appendix A we describe the way we tested our qualitative method to determine a good frequency range.

For each of the 10 ranges, 1000-10,000, 10,000-20,000, 20,000-30,000, ..., 80,000-90,000, and 1000-90,000 (kHz), we recorded five spectra. For each of 1000 frequencies at each range, we computed the signal-to-noise ratio (SNR), which we defined to be the ratio of the mean of the five observations to the standard deviation of the five observations. We then computed the average of these 1000 SNRs.

We then removed and replaced the lid of each of three containers and repeated the procedure, taking five spectra at each frequency range again. For the first five spectra, we computed the simple Pearson correlation, r (Appendix B), of each of the $\binom{5}{2} = 10$ pairs, and did the same for each of the second set of $\binom{5}{2} = 10$ pairs, as well as for $5 \times 5 = 25$ pairs of spectra that were separated by a lid removal and replacement. We used the difference d between the smallest of the 20 correlations that corresponded to no lid removal and the largest of the 25 correlations that corresponded to a lid removal as a measure of discrimination ability of the candidate frequency range.

We averaged d for each frequency range over all three containers and averaged the average SNR for each frequency range over all three containers. The conclusion was that the average SNR is a good indicator of discrimination ability. That is, a high SNR tends to produce a large d, which indicates good discrimination ability. The frequency range having the largest SNR and one of the largest average values of d was from 20,000 to 30,000 Hz.

APPENDIX B

In Appendix B we define the four similarity and two distance measures that we have experimented with to compare two spectra.

Similarity Measures

The first three similarity measures use the Pearson Correlation Coefficient between three different vector-valued functions of the original spectra. The Pearson correlation coefficient between two vectors $\mathbf{x} = x_1, x_2, \ldots, x_n$ and $\mathbf{y} = y_1, y_2, \ldots, y_n$ is

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 (y_i - \bar{y})^2}} ,$$

where $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$ and similarly for $\bar{y}$.

We denote the original scaled spectra (divide all values by the maximum value) by $\mathbf{x}$ and $\mathbf{y}$.

The three similarity measures that use the Pearson Correlation Coefficient are:

1. Pearson Correlation Coefficient between $\mathbf{x}$ and $\mathbf{y}$.
2. Pearson Correlation Coefficient between the magnitudes of the Fourier Transform of the two spectra.
3. Pearson Correlation Coefficient between the circular autocorrelation function of the two spectra. The circular autocorrelation function of a vector is the same as the autocorrelation (ACF) of the vector provided we assume that data repeats itself as follows: append the original data, $x_1, x_2, \ldots, x_n$, with $x_{n+1} = x_1, x_{n+2} = x_2, \ldots, x_{2n} = x_n$. Then the lag k ACF of $x_1, x_2, \ldots, x_n$ is

$$\frac{\sum_{i=1}^{n}(x_i - \bar{x})(x_{i+k} - \bar{x})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} ,$$

for $k = 0, 1, 2, \ldots, n - 1$.

The fourth similarity measures involves identifying peaks in the spectra. All local maxima in the x spectra are identified. Those maxima above an absolute and noise threshold are considered to be peaks, and the width W between the inflection points surrounding each peak in the x spectra is recorded. For each frequency f at which there is a peak in the x spectra, we record a 1 if the y spectra has a local maxima within W of f and 0 otherwise. Let the number of 1's recorded be n_x, the number of "matching" peaks found in the y spectra. Reverse the procedure to define n_y similarly. Denote the number of peaks in spectra x as N_x, and similarly for y. Then, the fourth similarity measure is $(n_x + n_y)/(N_x + N_y)$.

Distance Measures

As above, we denote the original scaled spectra (divide all values by the maximum value) by x and y, and let the sum $\sum_{i=1}^{n} x_i$ be denoted F_x, and similarly for the y spectra.

1. *First Distance Measure.*

$$\sum_{i=1}^{n} \left| \left(x_i / F_x - y_i / F_y \right) \right|$$

Let $f_{x,i} = \sum_{j=1}^{i} x_j$, and similiarly for the y spectra.

2. *Second Distance Measure.*

$$\sum_{i=1}^{n} \left| \left(f_{x,i} / F_x - f_{y,i} / F_y \right) \right|$$

We plan to experiment with pattern recognition methods other than these simple similarity and distance measures.