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Title: SWEPT FREQUENCY ACOUSTIC INTERFEROMETRY TECHNIQUE FOR CHEMICAL WEAPONS VERIFICATION AND MONITORING

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SWEPT FREQUENCY ACOUSTIC INTERFEROMETRY TECHNIQUE FOR CHEMICAL WEAPONS VERIFICATION AND MONITORING

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ABSTRACT

Nondestructive evaluation (NDE) techniques are important for rapid on-site verification and monitoring of chemical munitions, such as artillery shells and bulk containers. Present NDE techniques provide only limited characterizations of such munitions. This paper describes the development of a novel noninvasive technique, swept-frequency acoustic interferometry (SFAI), that significantly enhances the capability of munitions characterizations. The SFAI technique allows very accurate and simultaneous determination of sound velocity and attenuation of chemical agents over a large frequency range inside artillery shells, in addition to determining agent density. The frequency-dependent sound velocity and attenuation can, in principle, provide molecular relaxation properties of the chemical agent. The same instrument also enables a direct fill-level measurement in bulk containers. Industrial and other applications of this general-purpose technique are also discussed.

INTRODUCTION

To meet the requirements of the Chemical weapons Convention, the treaty that calls for eventual destruction of all chemical weapons, it is essential to have techniques that can be used to monitor compliance and destruction of existing stockpile in a verifiable way. In particular, the requirements are for nondestructive and noninvasive techniques that are fast and reliable. The Swept-Frequency Acoustic Interferometry (SFAI) technique, among several others, is being developed to meet such requirements.

In this paper, we describe the underlying principles and capabilities of the SFAI technique. The SFAI technique allows the determination of velocity and attenuation of sound in a fluid (liquid, gas, mixtures, emulsions etc.,) over a large frequency range, completely noninvasively and accurately, inside a sealed container. In addition, if the container material properties (density and sound velocity) are known, then the liquid density can also be determined. Our preliminary analysis shows that it may be possible to uniquely identify various nerve agents inside artillery shells and other chemical munitions based on these physical parameters (sound velocity, attenuation, and density).

In case of emulsions, the frequency-dependent sound attenuation information from this technique can be used to determine particle size distribution. The technique can also be adapted for direct fill level measurement in sealed containers as well. The fluid characterization capabilities of the SFAI technique have many other applications besides chemical weapons verification. Our objective in this paper is to point out some of the other interesting applications of this general purpose technique.

DESCRIPTION OF SFAI TECHNIQUE

The idea behind acoustic (or ultrasonic) interferometry is well known and has been studied for several decades. The underlying principle is simply the setting up of standing waves in a resonator cavity using external excitation and its simultaneous detection. This is described in Fig. 1 where a sine-wave voltage excitation, that is gradually increasing in frequency with time (see top frame), is applied to a disk-shaped piezoelectric transducer (transmitter) that forms one wall of an enclosure. A second identical and parallel transducer (receiver) on the opposite side of the enclosure detects the signal. The space between the two transducers is filled with a fluid. The transmitter transducer converts the sine-wave voltage signal to sound waves that propagate through the liquid and are detected by the receiver transducer as an electric signal. As the excitation signal is swept in frequency, there are regular instances when an integral multiple of half wavelengths of the sound waves fit exactly within the enclosure cavity formed by the two transducers. At any such instance, standing waves inside the liquid set up and the resulting response detected by the receiver transducer shows a pronounced peak (see bottom frame, Fig. 1). A series of equally spaced (in frequency) peaks result from such a frequency sweep measurement and these are called the interference peaks.

The spacing between any two consecutive interference peaks $\Delta f_n = f_n - f_{n-1}$ is related to the path length d (separation between the two opposing transducers) and the sound velocity c_n in the liquid at frequency f_n as $c_n = 2 . d . \Delta f_n$. Here, n simply indicates the n-th peak. The sound velocity in a liquid is not constant at all frequencies but increases with frequency at high frequencies (typically above several MHz) because of various relaxation mechanisms involved in the liquid. Consequently, the peak spacing also changes with frequency.

The width of the peaks δf_n also contain valuable information about sound attenuation α_n in a liquid. These two parameters are related as $\alpha_n = \pi . \delta f_n / c_n$. Attenuation is also a frequency-dependent parameter that depends on the particular characteristics of a liquid or emulsion. In pure liquids, the frequency dependence of attenuation (at high frequencies) provides information about molecular relaxation mechanisms in the liquid. In emulsions, frequency dependence is observed at somewhat lower frequencies (< 5 MHz) that can be related to the particle size distribution. The SFAI technique thus provides both sound velocity and attenuation information as a function of frequency in a single sweep measurement.

The above discussion relates to situations where the transducers are directly in contact with the liquid being studied. Often, as in chemical munitions, measurements need to be made from outside a sealed container. This does not pose any serious problems to this technique although it introduces some complications. Usually, a container has a certain wall thickness. When the liquid contents of a container is excited by a transducer attached to the wall from outside, the resulting interference spectrum is a superimposition of both the interference pattern in the liquid and that in the wall, as shown in Fig. 2. In Fig. 2 the liquid peaks are sharp with a smaller periodicity than the wall peaks that are separated farther apart. The respective peak separations depend on the width of the wall and the path length in the fluid in addition to the sound speeds in both media (refer to equations above). The peaks in the liquid are easily distinguishable from that of the wall. An additional complication is that the liquid peak widths are now influenced by the acoustic impedance mismatch (density × sound speed) between the wall material and the fluid. This complication, however, can be used to our advantage. If the wall material acoustic impedance is known then the liquid density can be extracted from the interference spectrum. This is possible because the contribution to the peak width due to the impedance mismatch is independent of frequency, whereas sound attenuation is frequency dependent. Consequently, measurements of the type shown in Fig. 2 can be used to extract the liquid density. The increase in liquid peak-width with frequency is clearly visible in Fig. 2 where the liquid is ordinary motor oil.

Note that for the SFAI technique, it is not necessary to have the transmitter and receiver transducers on opposite sides of each other as described above. We have found that custom-built dual-element transducers, that have two transducer elements side by side but are electrically and acoustically isolated from each other, can also be used for many applications requiring access from one side only. This is the approach used for testing chemical munitions, such as artillery shells.

The interference pattern that set up inside the wall material of a container can also be used to our advantage to determine the fill level of a liquid inside such a container. There are two ways to accomplish this. If a dual-element transducer system is moved up or down along the container wall from outside, the interference pattern for the liquid will disappear when the transducers are above the liquid level. This works for containers as wide as a 55-gallon drum. If the container is much wider, an alternative technique can be used. The interference peaks from the wall show damping (reduction in amplitude) when a liquid is in contact. Simply by moving the transducers in a vertical direction as before, it is easy to detect the liquid level by the sudden change in peak amplitude as the liquid level is crossed. This method works even when the container wall is as thick as 2.5 cm and is made of steel.

INSTRUMENTATION

The SFAI instrumentation is very straightforward. It uses a commercially available Digital Synthesizer and Analyzer (DSA120 from NEEL Electronics, Laguna Niguel, CA) computer plug-in card that contains all the necessary electronics for sweep signal generation and signal processing circuitry for analyzing the detected signal. The board uses sophisticated signal processing techniques that allows 90 dB signal-to-noise ratio in a single frequency sweep without averaging. The frequency range available is 1 kHz-10

MHz. The sweep time can be varied from 800 frequency steps per second to 1 step per second. The frequency resolution is 0.1 Hz over the entire frequency range. This system provides a frequency response directly in real-time.

This DSA board is plugged into a IBM PC or clone. A portable, battery operated, miniaturized version of the electronics system is currently being developed. The piezoelectric transducers are connected through coaxial cables to the board. For certain applications, the transducers are custom-built and for others commercially available broad-band piezoelectric transducers are quite adequate. Typical excitation level used for most measurements is approximately 1 V or less. The corresponding ultrasonic energy is very small that would not cause any chemical reactions in a sensitive fluid system or produce any hazards in biological systems.

APPLICATIONS OF SFAI TECHNIQUE

The technique has applications in many different fields because of its excellent sensitivity. For example, we can detect the change in sound velocity produced by a single drop of methanol in 2 liters of water. In Fig. 3, we show various ways to implement the SFAI technique for many other applications. The use of dual-element transducers extends the possibilities of this technique significantly.

Besides chemical weapons verification, the SFAI technique has applications in the following areas among others: (1) Basic Research, (2) Industrial Process Monitoring, (3) Biomedical and Health Care, (4) Food and Beverage Industry, (5) Environmental sensors, (6) Customs and drug interdiction, (7) Rock core sampling in geological prospecting, and (8) Materials diagnostics.

We now present some specific application examples. Because of the excellent sensitivity, the SFAI technique can be used for noninvasive characterizations of fluids and chemicals in pipes, reactor vessels, and any containers. It can also monitor liquid concentration (or contamination) in petroleum or other chemical products. It can characterize highly attenuating fluids such as polymers.

Using miniaturized transducers, we can test microliter (a single drop) liquid samples. This allows measurements on test samples that are not available in large quantities such as pathological samples (e.g., tear drops, blood, urine, bee or snake venom, etc.,). Presence of certain bacteria or diseases can alter the physical characteristics of such samples and thus can be detected. This may provide a rapid diagnosis technique for pathological samples.

Another biomedical application is to noninvasively monitor physical characteristics of bones and joints. It has been observed in various clinical studies that sound velocity in bone is related to its porosity. Because the SFAI technique can determine sound velocity at a very low power, it may be used to test for osteoporosis. The frequency-dependent characteristics can be used to look for other diseases, such as arthritis. Our preliminary study shows that this is a potentially useful approach.

In emulsions and suspensions, sound waves are scattered by the suspended particles. The sound waves also undergo attenuation both due to viscous drag on the particles and thermal loss. These factors contribute to increase the interference peak-width. The frequency-dependent peak-width can thus be used to determine particle size distribution. Using this method, we have studied particle size growth in emulsions that are otherwise optically opaque. We have also tested this approach in noninvasively detecting particle suspensions in pure gases inside a metal pipe.

In summary, the SFAI technique is highly adaptable and versatile. It has excellent resolution in detecting minute changes in liquid characteristics. Although developed for chemical weapons verification, the technique has applications in many areas of industry.

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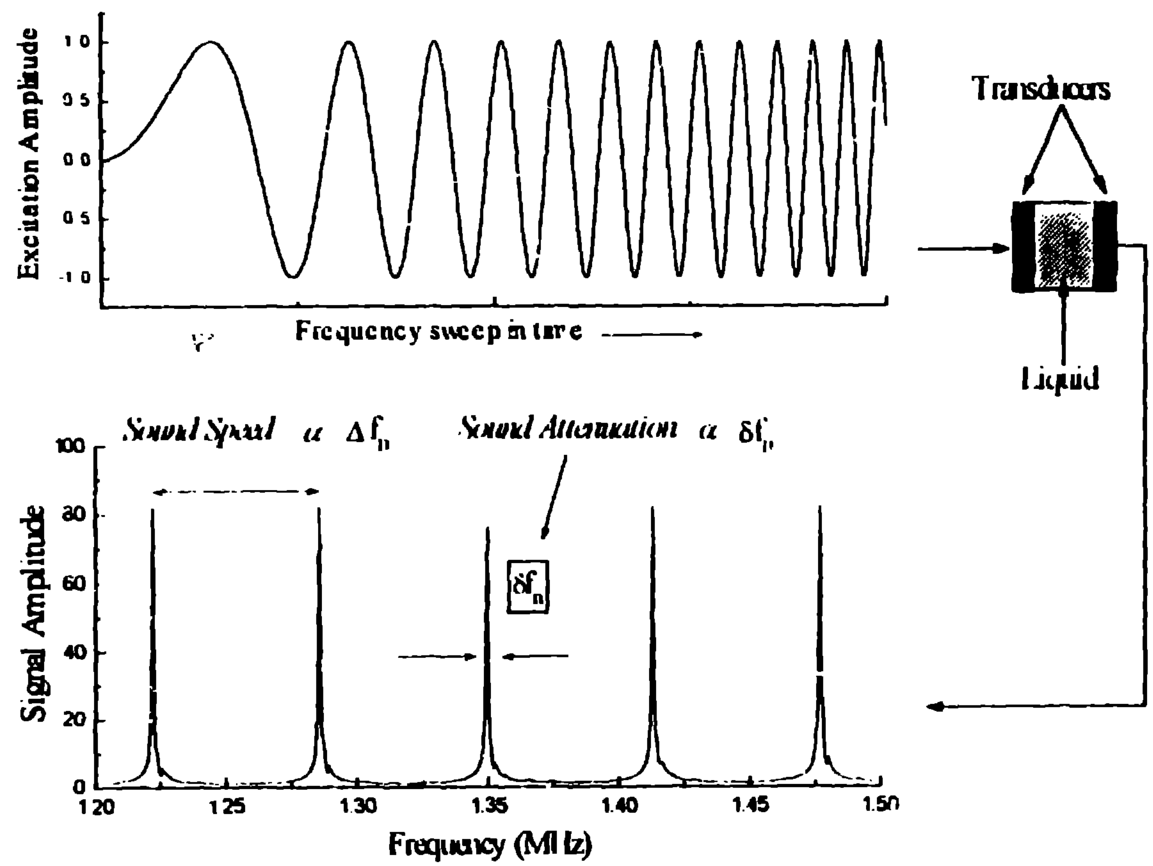

Figure 1. Principle of the swep-frequency interferometry technique. As the frequency applied to one transducer is swept from a low to a high value (see top frame), the detected signal from the second transducer shows the characteristic interference pattern (see bottom frame) that developes in the liquid in the resonator cavity.

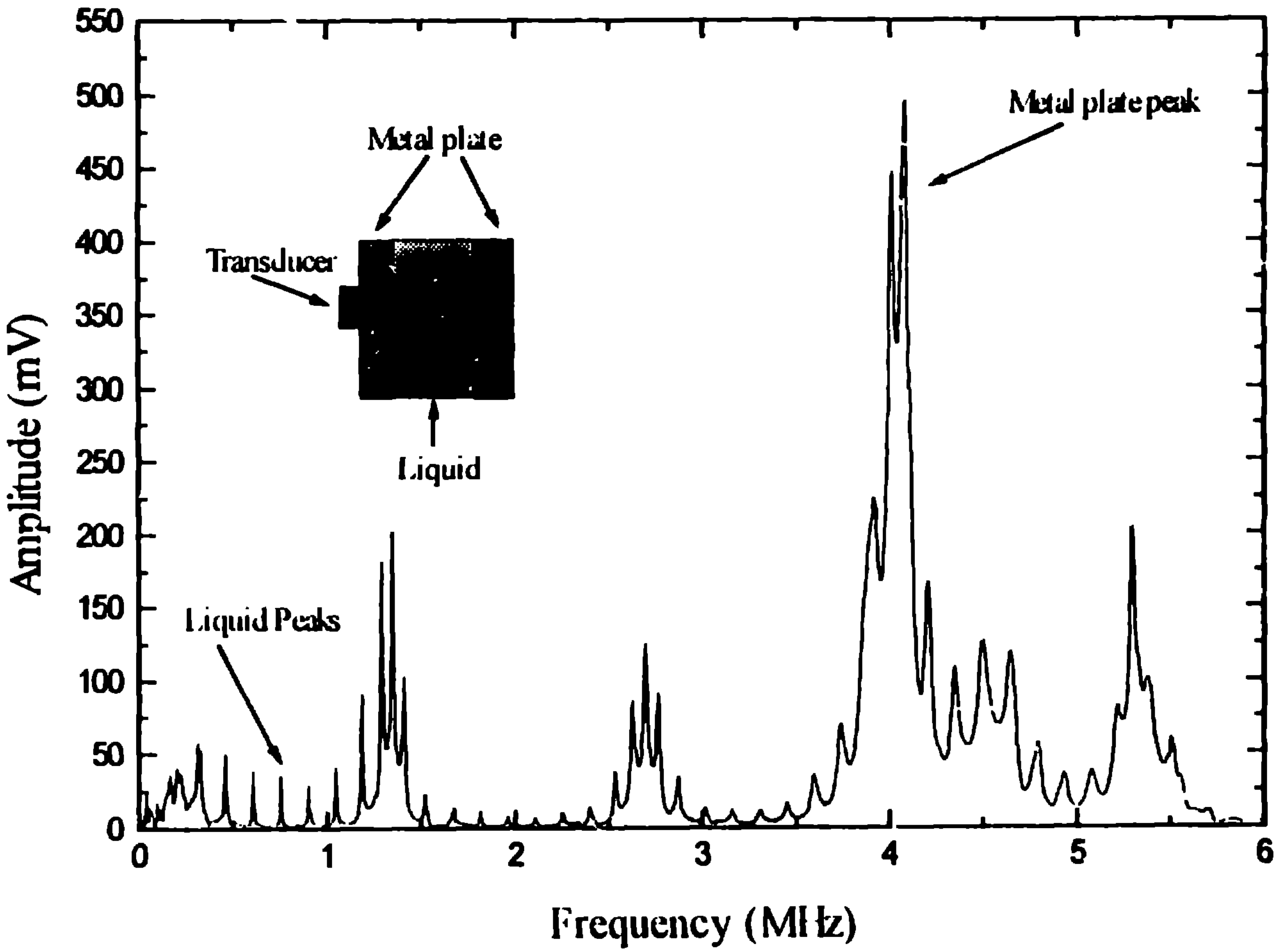

Figure 2. Interefrence patterns in a multilayered system. It shows how the resultant patern is a superimposition of the liquid peaks and the peaks due to interference in the metal plate itself.

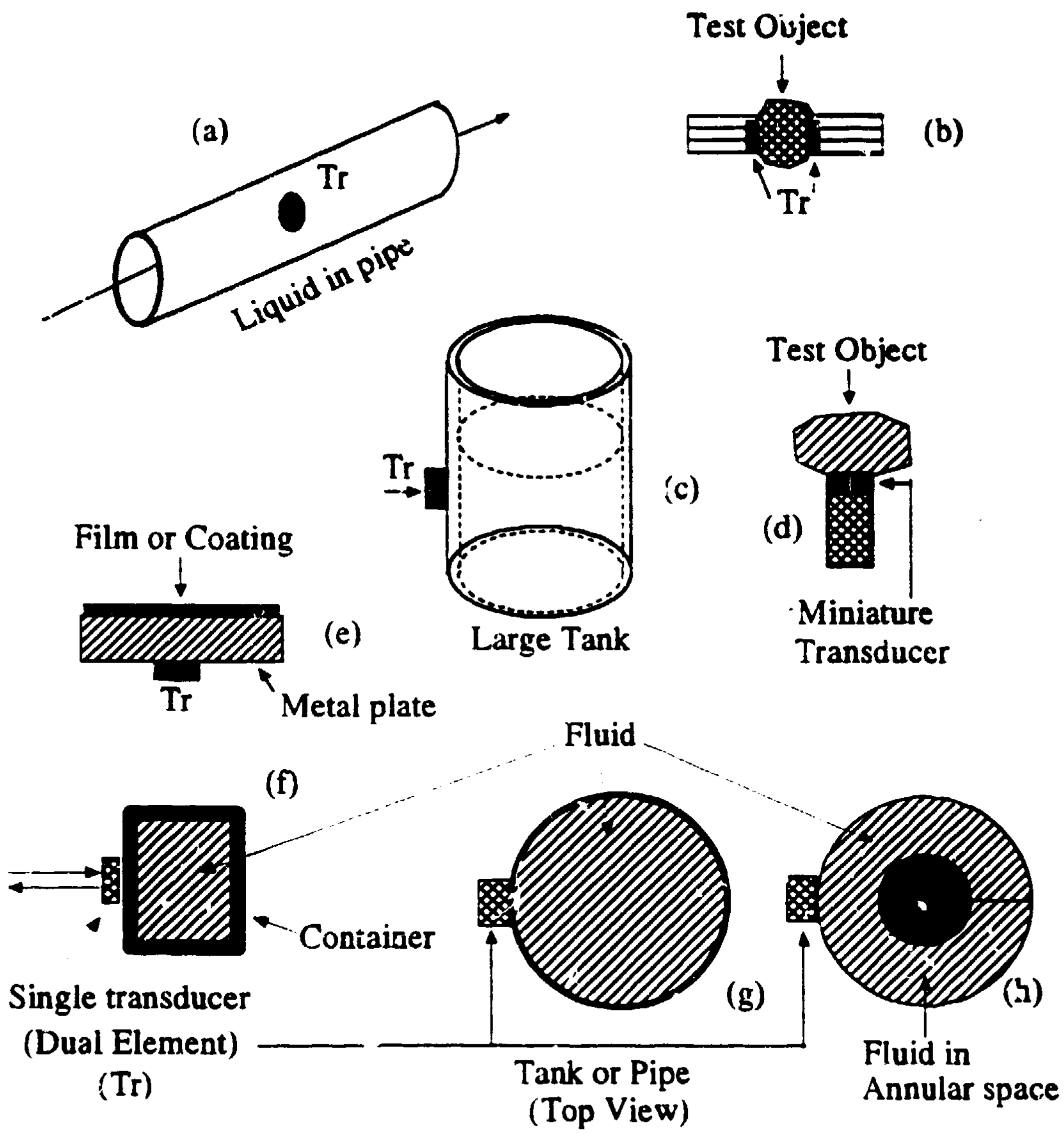

Figure 3. Various ways the SFAI technique can be used. In most cases the transducer is a dual-element piezoelectric transducer. The chemical weapons applications is shown in (h) where the liquid is in the annular space.