Title: NONINVASIVE, NONCONTRACT FLUID DETECTION IN SUBMERGED CONTAINERS USING SWEPT FREQUENCY ULTRASONIC TECHNIQUE

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Noninvasive Noncontact Fluid Detection in Submerged Containers Using Swept Frequency Ultrasonic Technique

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Abstract - A noncontact technique has been developed for the remote interrogation of submerged and limited access metal containers for determining the presence of fluid inside. The technique is based on the damping effect of water on the thickness mode resonance of the container wall. A transmitter-receiver pair of piezoelectric transducers is placed at a standoff distance of 5 mm from the container wall with the water outside the container providing ultrasonic coupling medium. The excitation frequency applied to the transmitter is swept between 0.8-4.0 MHz and the receiver transducer detects the signal, in the form of a frequency spectrum, returned from the wall. By analyzing the variation in the observed spectrum, it is straightforward to determine whether the container is fluid or air backed thereby detecting if the container has leaked.

I. INTRODUCTION

Noncontact and nondestructive evaluation of large objects typically employ either electromagnetic acoustic transducers or use water jets for coupling. For smaller objects, measurements are made in a water bath where the water provides the coupling medium between transducers and the test object. We were faced with a situation where the test objects were heavy steel containers (35.4 cm in diameter and 75 cm in height) submerged in a pool of water approximately 10 meter deep. These containers were placed in rectangular metal boxes (top open) with access to the container wall only through a small gap between the container and the outside box. It was necessary to determine whether these containers were dry or had water leaking inside. Because of the limited access to the container wall, traditional method of direct contact between transducer and the container wall could not be reliably maintained. Therefore, it was necessary to develop an approach that could make reliable measurements without requiring physical contact between transducer and container wall.

Presence of water could be detected by sending an ultrasonic pulse through the container wall and detecting it after it reflected from the opposite side. However, this simple approach could not be relied upon because these containers contained various objects of irregular nature that did not permit an accurate determination from this simple pulse echo technique. Moreover, often the round-trip time of a pulse along the circumference of the container matched the reflection from objects inside the container. Therefore, we needed a technique that only relied on the container wall-water (inside the container) interface and not be confused with extraneous signal derived from unrelated sources.

In this paper, we describe a technique that overcomes many of the difficulties faced by the traditional ultrasonic methods and provides a reliable solution to our problem of determining presence of fluid inside a submerged container with limited access. In this technique, one excites the container wall over a wide frequency range to obtain a spectrum that contains multiple wall thickness mode resonances set up by higher order Lamb waves propagating in the walls of the container and derives the answer by analyzing this spectrum.

The paper begins with a description of the Ultrasonic Inspection Tool in Section II that includes construction and operational details of the mechanical hardware used. Section III describes the experiment, which details how the measurements to detect the presence of water inside a sealed cylindrical container of steel are carried out by analyzing the spectral response of the wall thickness resonance modes. Section IV discusses the results and analysis of the experiment in Section III. Section V concludes with a summary.
II. ULTRASONIC INSPECTION TOOL (UIT)

The UIT was constructed as a remote non-destructive evaluation device for inspecting steel containers, which are submerged in water for long-term storage with limited access. The primary purpose of this tool was to detect water leakage in these containers in situ. The containers are stored in a pool of water at depths upwards of 10 meters.

The UIT is comprised of a sensing probe and an integrated computer and motor control unit. (See Fig. 1) The probe head houses the two 2.25 MHz center-frequency, 1.25-cm diameter, 1-3 composite, 82% bandwidth, submersible transducers. The two transducers are positioned normal to the surface of the cylinder. The transducers are separated from each other by 2 mm and are held at a distance of approximately 5 mm from the surface of the cylinder. The probe is lowered to the containers by a long stainless steel insertion pole. The pole is constructed in 1.3-m sections that can be screwed together to give the desired length necessary.

The probe is guided into place with the aid of two miniature submersible color-video cameras. One camera is located at the bottom of the probe and another camera can be positioned anywhere above the probe head. The probe is lowered into place along the side the container. Then a four point suction mechanism is used to hold the probe in position while data are collected. The sensors can be moved along the vertical length of the container by a stepping motor system, which is controlled through software. This allows for multiple points of interrogation along the vertical axis of the cylinder.

Figure 1. Diagram of the Ultrasonic Inspection Tool (UIT). A computer system was custom built to operate the UIT. A submersible stepper motor controls the vertical position of the sensors. A 500-watt submersible pump creates the suction necessary to secure the probe against the container using silicone suction cups. Two submersible transducers with a center frequency of 2.25 MHz are used for the ultrasonic sensors.

Figure 2. Experimental setup for leak detection in sealed, steel container. One transducer creates a frequency sweep from 0.8 MHz - 4.0 MHz that excites the first three wall thickness resonance modes in the containers walls. The vibration response is measured with the second transducer. Analysis of the change in the spectral response allows for determination if the sealed container is fluid backed or air backed.
III. EXPERIMENTAL

The experimental setup is shown in Fig. 2. The UIT is placed along side of the submersed, sealed, steel container; the suction mechanism is turned on, securing the probes position to the side of the container. For laboratory measurements, the container is placed inside a 55-gallon drum. The transducer position is shown in Fig. 3.

The stainless steel container has an outside diameter of 35.4 cm, thickness of 0.03 cm and a height of 74 cm. A frequency sweep from 0.8 MHz - 4.0 MHz is used to excite the wall thickness vibrational modes. This frequency range spans the first four resonance modes associated with the turn on of the S1, A3, S4, and A5, Lamb wave modes (See Fig. 5). Figure 4 displays the resonance response for a fluid filled container and an empty container.

From the figure it is obvious that the major effect of the fluid loading is to reduce the amplitude response of the wall thickness resonance by a factor of 1.5. This is due to energy lost by leaky Lamb waves. The reduction in the amplitude response is the primary indicator for a water-backed container.

IV. RESULTS AND ANALYSIS

Figure 4 shows the behavior of a single wall-thickness-mode resonance peak with and without water present in the container. It shows how leaky Lamb waves contribute to the decrease in the amplitude of the wall thickness resonance detected by the sensors. This is due to the closer acoustic impedance matching of water to steel as compared to that between steel and air, which allows energy to be coupled into the fluid as the Lamb waves are guided along the wall. This effect is depicted in a schematic diagram in Fig. 6. As the guided wave propagates along the radius of the water-backed container energy is leaked into the interior. By adjusting the separation of the transmitting and receiving transducers the change in the amplitude of the reflected signal can be maximized. Do to the physical constraints of our system a maximum of 2 mm separation between the two transducers was possible. Moreover, by separating the two transducers the specular reflection can be avoided, which can cause complication in the analysis of the signal response.
Figure 5 shows a typical full spectrum. In this figure, the four major peaks correspond to the S1, A3, S4 and A5 guided wave modes. The agreement of the experimental results for the peak position with theoretical prediction is very good. All four of these guided waves are longitudinal, which couple energy into the system more efficiently for an acoustic excitation signal close to an incident angle normal to the surface of the container. The largest peak, which is associated with the A3 guided wave mode, is close to the center frequency of the transducers.

The difference between a water-filled container and an air-filled container is easily discerned because of the large change in the amplitude of the wall resonance peak. It should be mentioned that it is important to have proper alignment of sensors with the wall. Poorly aligned transducers can lead to erroneous results.

V. SUMMARY

The work presented in the paper describes a remote interrogation system capable of detecting leaks in submerged container using a noncontact method. The technique utilizes the amplitude change of the response signals set up by higher order Lamb waves excited in the container walls. The observed decrease in amplitude of a dominant resonance peak when water is present is typically a factor of 1.5 or higher making it easy to determine containers that have water leaking into them.

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