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Ultrasound Techniques for Leak Detection in Vehicle and Pressure Vessel Production Lines

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ABSTRACT

One of the most intriguing applications of acoustic principles is for the detection of leaks, cracks, and defects in materials. Sound waves can be used to extract information about the material properties and geometry of a variety of physical structures. This is typically done by comparing the incident to the reflected and/or transmitted wave and looking at changes of features such as frequency content and level. Ultrasound-based techniques, which revolve around the generation and/or detection of sound waves with frequency content above 20 kHz, are of most interest as they can capture holes and cracks of very small dimensions and are not affected by background noise in the audible frequency range. Ultrasound-based techniques have therefore a lot of potential for production line testing because many industries are in constant search of a better and non-destructive means to identify and locate leaks and/or other defects. In this paper the authors will describe the requirements imposed for leak detection in two different products: a minivan and a water heater tank. A review of the basic principles of ultrasound leak detection techniques will be presented along with the challenges faced by the noise control engineer to generate, acquire and analyze ultrasounds capable of detecting a broad range of leakage failures

1. INTRODUCTION

The uses of ultrasound are numerous and varied, for example, from medical uses to many types of structural health monitoring for machines and materials. Ultrasound wave travel for these uses can be in liquids, solids, air, or any combination of those mediums. The frequency range for the typical uses of ultrasound can be as high as approximately 100 MHz. A survey and technical description of the broad applications of ultrasound is well described by Leighton[1].

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Some emphasis in that source is placed on the important health issues associated with the use and exposure to ultrasound passing through air and through tissue.

The two applications of ultrasound described and investigated here in this paper both fall into the category of ultrasound waves traveling first through air. The first ultrasound application is for finding leaks in passenger vehicles and the second is for finding leaks in the welded seams of tanks designed for both pressurization and holding applications. With the successful detection of the leaks of interest in vehicle applications, it was proposed to see if the exact same equipment utilizing frequencies up to 100 kHz could be successful in detecting leaks of interest in tank applications.

The major reasons for investigating the use of ultrasound energy for detecting leaks is because of (1) the ultrasound energy separation from typical audible background noise, BGN, energy, (2) structural crack or hole geometry realities that make visible and subjective detection uncertain, (3) the possibility of relatively quickly testing a structure, and (4) the possibility for eliminating or reducing the expense and need to expose the structure to pressurized test gas (helium/nitrogen) or water test environments (specifically for the testing of tanks)

The current and potential uses for ultrasound leak detection inspection can reside in production environments where there may be significant impulsive or stationary sound pressure BGN energy in the audible frequency range, and sometimes well into the ultrasonic range. Performing the leak detection with controlled ultrasound excitation well above expected BGN frequency content, or in a bandwidth of low BGN content, allows for the best success in detecting leaks with a sufficient signal-to-noise ratio, SNR. The exception to this difficulty is for the case of commercially available handheld ultrasound detection equipment for use in tank or pipe pressurization applications. These handheld detectors typically have various sized nozzles that surround the potentially leak for inspection such that the BGN is not an issue during testing.

The physical size of a structural leak will partially dictate the capability for waves to pass through the leak. Wavelengths will be in the 17 – 3.5 mm range for ultrasound frequencies in the 20k – 100k Hz range, respectively. The investigation performed for this project has not involved the quantification of the exact hole/crack size (length, width, depth) for which ultrasound wavelengths can pass through to allow for detection.

The use of ultrasound for detecting holes, cracks and internal defects in various thickness materials and structures is well studied and published for the case of an ultrasound emitter and ultrasound receiver used in various contacting and non-contacting ultrasound (NCU) pulse-echo, or pitch-catch configurations. The methods involve delivering ultrasound pulses into a structure, direct or impedance-matched contact or through air, then receiving the echo using the same transducer or the transmitted signal with another transducer located in a different position. Interpretation of the amplitude and time-of-flight characteristics of the return signal can provide internal material details about the structure. These contacting and NCU methods are used in many material inspection applications. This test method would likely not have any practical arrangement that could be used for quickly detecting leaks in structures as geometrically and materially diverse as vehicles in a production environment.

The speed of detection for leaks will almost always be important for leak testing of any production item. The cycle-time for detection of leaks can be imposed as less than 45 or even 20 seconds for some applications to compare with current leak detection methods. The realistic use of a pulse-echo type, or related methods, on items as large as tanks may not be achievable with such short cycle-time requirements.

The leak detection test methods described in this paper involve the detection of air-borne ultrasound signals. Some applications use the approach of inspecting for local structure-borne ultrasonic vibration near the source of a leak. One application is shown and proven by Holland, et al.[2,3], for the case where air is escaping from holes as small as 1 mm in a pressurized spacecraft environment into a vacuum.

2. INSTRUMENTATION

The frequency range used for the proven application of vehicle ultrasound leak testing and for the tank leak investigation study was up to 100 kHz. This was based on the availability of standard microphones and acquisition and signal generator systems capable of measuring in this range. High frequency (100 kHz bandwidth) front-ends[6], microphones[7], and hydrophones[8] were used for this project. The microphones allow for ± 1 dB response up to 100 kHz. The hydrophones selected can be used as projectors and have a linearly increasing output up to their resonance at approximately 95 kHz. Though impedance-matched and designed for use underwater, they can be used in air or gas environments with the understanding that their transmission capability will be less than in water.

3. VEHICLE ULTRASOUND LEAK TESTING

Leaks that can exist around the seams of vehicle doors and windows allow for the possibility of annoying wind noise issues for the passengers when the vehicle is traveling at a specific speed or a range of speeds. Vehicle wind noise issues due to leaks can be detected with various techniques, but the use of ultrasound allows for a unique testing solution with many advantages.

Authors[2,3] have in production, systems that detect leaks in vehicles using ultrasound emitters and microphones. One or more ultrasound emitters are placed inside the vehicle while automated robot arms carrying high frequency microphones quickly and accurately scan any desired seams on the vehicle looking for ultrasound waves passing through leaks. A frequency slice with a bandwidth surrounding the emitter frequency is amplitude inspected in the acquired signals. The systems are very effective for testing for leaks in vehicles.

The result in Figure 1 shows the sound pressure response from a microphone scan of a vehicle door seal seam with a known production leak of approximately 1 mm at its maximum diameter. A narrowband frequency slice covering the emitter's frequency was used for the detection process. A hydrophone was placed inside the vehicle and a deterministic ultrasound excitation frequency less than 100 kHz was initiated with a local SPL of 90 dB at 5 cm. In this case, the detected ultrasound leak signal is 15 dB above the portion of the scan where no leaks are present. The data processing for this quality of data can be easily handled with standard time and frequency domain presentations in a real-time production environment. These results are very typical for vehicle leak detection. Leak detection for vehicles using ultrasound has been a well-established method for the authors[2,3].

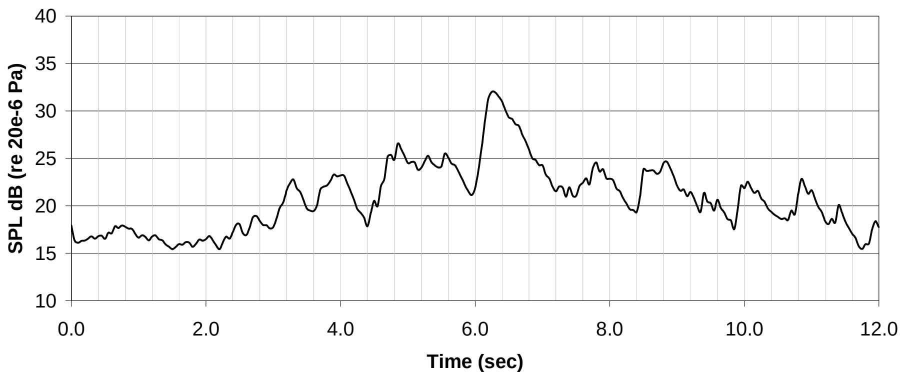

Figure 1: Sound pressure response (2 kHz frequency bandwidth slice) for a leak detection in a production vehicle

4. TANK ULTRASOUND LEAK TESTING

The testing of tanks or pressure vessels for leaks is a required validation test for almost all types of applications. The typical methods used can include (1) air decay testing, (2) air or He/N pressurization then water submersion or water coating for the inspection of bubbles, (3) mass spectrometer testing with Helium, (4) pressurization then scanning the tank with a handheld microphone or ultrasound detector, or similarly (5) placing the tank inside a small enclosed chamber, pressurizing the tank, then listening for leaks inside the acoustically isolated environment. All of the above techniques have been well developed and have many merits for many applications.

Whereas the leak sizes in the vehicle application may be greater than or equal to several hundred microns in size, some typical leaks of interest for tank applications can be as low the tens of microns in size. This decrease in size of the classification for a leak when testing tanks makes the inspection more difficult for any test method. The molecular size of air, or whatever test medium or pressurized gas used, becomes an issue for leaks in this smaller size range.

When specifically focusing on ultrasound leak detection for tanks, the test methods may fall under the categories of (1) pressurizing the vessel then passively listening for ultrasound emission from the tank, or (2) actively introducing ultrasound energy inside of the tank and then listening for any escaping ultrasound waves coming through leaks.

The first category described is the more standard passive method of pressurizing a tank to potentially its maximum pressure level with air, helium, and/or nitrogen, then for example using a handheld ultrasound detector or microphone and listening for broadband or narrowband ultrasound response. The ultrasound response will have a source originated at the leak location and is due to air passing through a leak with a Reynolds number describing turbulent flow, and/or the turbulent flow generated when the airflow hits the microphone's surface. The detection will be both amplitude and frequency dependent for this method.

The second category described is an active ultrasound method and is largely the same as the vehicle detection method where an emitter is placed inside of a tank and a microphone scans the exterior welded seams for possible leaks. The detection will be only amplitude dependent for this method since the emitter's excitation frequency is known in advance of the testing. The ultrasound tank testing performed in this study does not make use of pressurization.

Due to safety concerns with some tanks in their final pressurized application environments, they are required to be pressurized during leak testing due to the fact that some leaks don't exist until the tank is pressurized. Also, cracks may begin to propagate after pressurization, so in many cases there exists no substitute for various forms of pressurized leak detection testing. The method investigated in this paper could only be considered in compliment to the pressurization techniques for certain pressure vessel applications.

The result in Figure 2 shows an example of an ultrasound leak test performed on a water tank with a crack in a weld having an approximate width of 350 microns.

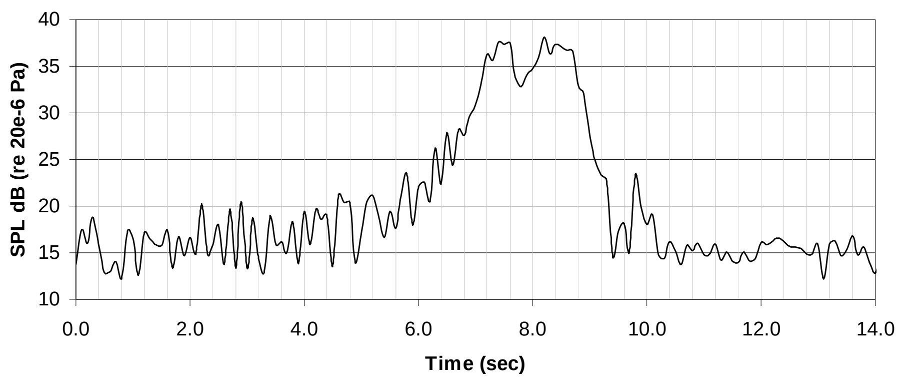

Figure 2: Sound pressure response (2 kHz frequency bandwidth slice) for narrowband ultrasound leak detection in a water tank with a 350 micron leak

The detection of relatively large tank leaks such as this is very easy with this ultrasound test method and does not require any difficult data processing techniques other than standard time and frequency domain amplitude inspection methods easily performed in real-time. This detection method has currently been statistically successful for other tanks with comparable leaks of the same order of magnitude as the tank described by the data in Figure 2.

It is certainly of note that the environment that exists inside of a tank is acoustically much different than the inside of a passenger vehicle. A vehicle will have door trims and body-side components that form structural channels that lead up to the areas where seal leaks can exist. The inside of a tank is diffuse and the location of a leak has no significant internal boundaries that can direct the ultrasound waves towards a region of a potential leaks. This is an added difficulty in the detection process in addition to the smaller leak sizes required for passing a tank leak test.

With the potential difficulty in passing an ultrasonic wave through a much smaller hole than described for vehicle structures, the measured SNR may be very small. The ultrasound leak signals of interest may be anywhere in a range of just above, or just below the background noise levels even in acoustically controlled environments. The amplitude inspection method previously described for larger leaks may not be sufficient for these low SNR situations. To determine if or not an ultrasound signal has passed through a hole, it becomes important to use some standard signal filtering techniques to inspect the low level signals in the presence of noise.

Additional tanks with known smaller leaks than the one described in Figure 2 have been inspected with the current technique and have not given results indicating that a leak exists. This is true for the frequency range currently tested up 100 kHz. A simple frequency slice and amplitude inspection that was successful for the previous tank gives results for the smaller leaks that give the appearance of just background noise.

The use of a matched filter has been employed when inspecting these low SNR signals for the tanks with smaller leaks to determine if an ultrasound signal has passed through the leak. A matched filter is one option that allows for the best possible signal to noise ratio at its output when an acquired signal has significant noise or a low SNR. The use of correlation functions for processing signals with noise is described fundamentally by Lee, et al.[4] Matched filtering is a common technique and is described, for example, by Widrow and Steams[5]. Depending on its implementation, it involves simply convolution in the time domain or cross-correlation in the frequency domain. When described in terms of cross-correlation the process is simply correlating the acquired signal with a desired signal. This desired signal can be described as a template signal. The template signal for this application is known in advance of acquisition and is simply the deterministic sine wave with the same frequency as the emitter's driven excitation frequency.

With a relatively slow scan rate and a small time record, if the deterministic signal of interest has passed through the leak and exists in the acquired signal, then the output of the matched filter will be a tapered sine wave since it will exist for the entire, small time record. To show the results for a tank with a detectable leak, a matched filter is applied to the results for the tank previous described in Figure 2. Figure 3 shows the matched filter output for a single time record near the known leak.

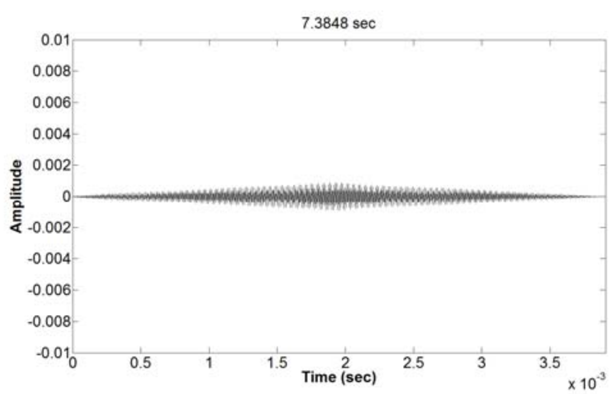

Figure 3: Matched filter output for a single time record for a tank with a relatively large 350 micron leak.

Inspecting a larger scan distance for a weld seam gives the results shown in Figure 4. In both Figures 3 and 4, the expected output peaks at the center of the total correlation time scale. The leak in this tank was a crack, so the matched filter output shows correlation over a length or time, and thus distance, resulting in an obvious amplitude based detection compared with the background noise level seen prior to and after the leak.

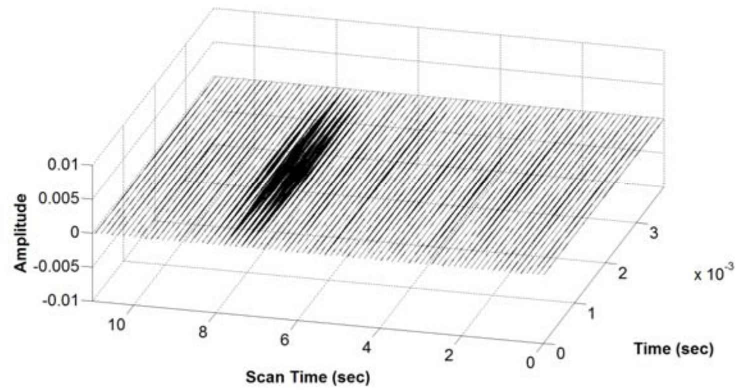

Figure 4: Matched filter output for a full scan of a welded seam for a tank with a relatively large 350 micron leak.

Applying a matched filter to the data from tanks with known smaller leaks gives results, for example, as shown in Figure 5. With it known that the leak was passed over at the 7 second point shown in the graph, it is not clear that there is any ultrasound signal that has passed through the leak. The acquired signal is potentially just background noise.

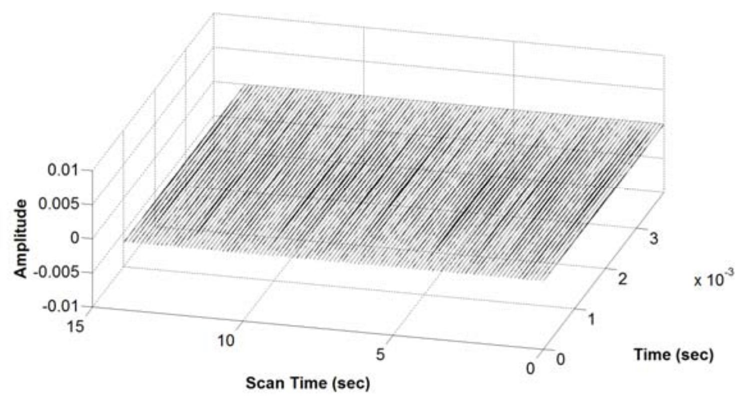

Figure 5: Matched filter output for a full scan of a welded seam for a tank with a relatively small leak.

Additional measurements were made over the same welded seam area with the excitation source turned off. Applying the matched filter to the acquired BGN signal results in the output shown in Figure 6, where again, the leak was passed over with the microphone at the 7 second point shown in the graph.

Statistically understanding the characteristics of the background noise allows for a better understanding of the likelihood of detection when a scan is performed with the ultrasound emitter active. This allows for properly determining threshold settings for leak detection and avoiding any false leak detection readings.

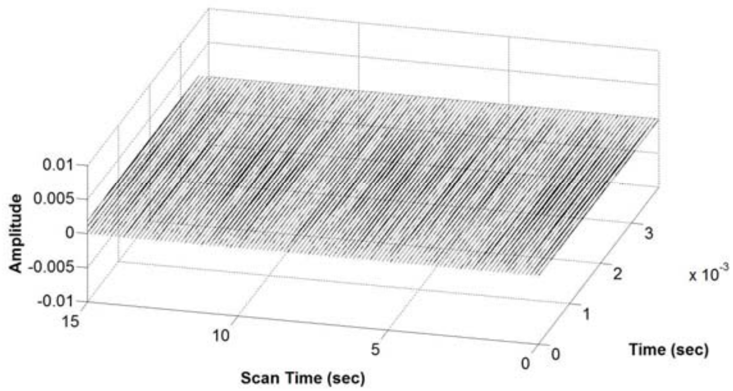

Figure 6: Background noise output from a matched filter for a full scan of a welded seam for a tank with a relatively small leak (same tank as shown in Figure 5). The ultrasound emitter was turned off for this background noise acquisition.

The filter output for Figure 5 with the ultrasound emitter active looks statistically the same as the filter output for Figure 6 where the ultrasound emitter was turned off. With the ultrasound emitter active, numerous scans were acquired using slightly different microphone scanning angles and heights from the welded seam surface. All results were statistically the same as the results shown in Figure 5 with no clear detection of the known leak.

4. CONCLUSIONS

As was initially discussed, the use of ultrasound for non-destructive testing is a broad field that has many uses. Two applications for the use of ultrasound testing have been described here. The successful detection of vehicle window and door seal leaks that contribute to wind noise issues has been described using ultrasound in a production environment with automated test systems that already exist. Additionally, the testing for leaks in tanks or pressure vessels has been described as more challenging with additional work currently being performed at the time of this writing.

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